SALT-ICE WORLDS: AN ANTHROPOLOGY OF SEA ICE

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Abstract

Anthropogenic climate change brings into focus the entanglements of humans and nonhumans, a kind of collective world-making that cannot be captured in terms of a divide between separate 'natural' and 'social' orders (Latour 2014; Haraway et al. 2016). Anthropological attunement to these collectives have simultaneously enlarged the field of view and decentered human beings as just one entity among many others (e.g., Kirksey and Helmreich 2010). My dissertation builds on these efforts by conducting an anthropology of sea ice—more specifically, 'sea ice' as constituted by scientific knowledge. It is based on 12 months of fieldwork (2014-2016) among sea ice scientists at the Polar Science Centre and various academic departments at the University of Washington in Seattle, WA.

In this dissertation, I seek to shift from sea ice-worlding as 'becomings-with,' in which human-sea ice relationships are basic units of analysis (Haraway 2008), to explore how sea ice itself orders myriad things. My dissertation is self-consciously ice-centric without being post-humanist. This is, perhaps, an effort to explore the possibility of anthropology "after ethnos" from that which exceeds the human (Rees 2018). This dissertation does not seek to make ontological claims about the world as it *is* in a metaphysical sense, but explores a conceptual provocation—one that enters sea ice-worlding through scientific knowledge as a human practice. As a conceptual departure point, scientific knowledge makes visible 'sea ice' as *produced*, historically contingent, and open to change. This forms the basis of Chapter One ("Making Sea Ice: A Field Guide") and informs my analysis in Chapter Two ("Rotten Ice"), which followed in real-time the making of 'rotten ice'—a type of heavily melted sea ice that is likely becoming more prevalent in the Arctic. Scientific knowledge is made by human practitioners, but it is not reducible to them. Such knowledge can offer a provisional 'window' onto times and domains beyond the strictly human: What order of things comes into view through scientific knowledge of sea ice? How does sea ice potentially destabilize, inflect, or reconfigure concepts of 'world' and 'time'? Chapter Three ("Non-Predictability") examines how sea ice makes visible a collective temporal reckoning that does not ground in clocks, consciousness, or social relations. Chapter Four ("Salt-Ice Worlds") shows how sea ice gives rise to a non-teleological worlding that is not fully captured by either 'livability' or 'extinction' as the Other to life. The implications of these findings are discussed in conversation with anthropological scholarship on thinking human-nonhuman collectivities in the context of anthropogenic climate change.

Résumé

Le changement climatique anthropique met en lumière l'enchevêtrement entre humains et non-humains, une façon collective de produire le monde qui ne peut être réduite à une séparation entre les domaines du « naturel » et du « social » (Latour 2014; Haraway et al. 2015). L'attention impartie par les anthropologues à ces formes de collectif a simultanément élargi le champ d'horizon et décentré les êtres humains de leur place privilégiée en les situant comme une entité parmi tant d'autres (par exemple Kirksey and Helmreich 2010). Ma thèse s'appuie sur ces efforts pour mener une anthropologie de la glace de mer. Plus spécifiquement, ce travail étudie « la glace de mer » telle que constituée par le savoir scientifique. Cette thèse est fondé sur douze mois de recherche de terrain (2014-2016) parmi les scientifiques étudiant la glace de mer au Polar Science Centre de l'Université de Washington, à Seattle, aux États-Unis.

L'objet d'analyse de cette thèse n'est pas tant la relation humain-glace de mer, et comment ceux-ci co-deviennent ou se co-constituent (Haraway 2009). Ce travail cherche plutôt à déplacer l'objet d'étude pour explorer comment la glace de mer *elle-même* catégorise une multitude de choses. Ce travail est sciemment « glace-centré » sans être pour autant post-humaniste. Ceci pourrait être compris comme un effort d'explorer la possibilité d'une anthropologie « post-ethnos » par ce qui dépasse le domaine de l'humain (Rees 2018). Cette thèse n'a pas l'ambition d'avancer des conclusions ontologiques à propos du monde et sur ce qu'il *est* dans un sens métaphysique, mais il examine une provocation d'ordre conceptuel. Cette provocation conceptuelle pénètre dans les mondes engendrés par la glace au travers du savoir scientifique compris comme une pratique humaine. Comme point de départ conceptuel, le savoir scientifique rend visible la « glace de mer » telle que *produite*, soumis aux contingences historiques, et ouverte au changement. Ceci constitue le cadre pour le Chapitre 1 (« Fabriquer la glace de mer : une guide pratique ») et sous-tend l'analyse du Chapitre 2 (« Rotten Ice »), qui suit en temps réel la fabrication de « rotten ice » — un type de glace en grande partie fondue qui est probablement en passe de devenir plus prévalent dans l'Arctique. Le savoir scientifique est produit par des professionnels humains mais il ne leur est pas réductible. Ce savoir peut offrir une « fenêtre » provisoire sur des temps et des domaines au-delà de ce qui est purement humain. Quel ordre des choses se profile à travers le savoir scientifique à propos de la glace de mer ? Comment est-ce que la glace de mer déstabilise, module, ou reconfigure les concepts de « monde » et de « temps » ? Le Chapitre 3 (« Non-prédictibilité ») examine comment la glace de mer met au jour une façon collective d'appréhender le temps qui n'est pas basée sur les montres, la conscience, ou les relations sociales. Les implications de ces conclusions sont présentées en conversation avec la littérature anthropologique qui a cherché à qualifier les collectivités humain-non-humain dans le contexte du changement climatique anthropique. Le Chapitre 4 (Salt-Ice Worlds) illustre comment la glace de mer donne naissance à une façon non-téléologique d'être au monde qui ne peut se résumer ni en « habitabilité », ni en « extinction » comme l'Autre à la vie.

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Introduction

The first time I saw it, I mistook it for the moon.

Suspended in the sky far above the city, it hung. A weathered face, just like the moon seen at a great distance and from beneath an ocean of air. I was touring downtown Seattle with my parents in July 2014 and we had gone to the Columbia Tower Observatory to get views of the city. Compared to the Space Needle, the admission price at the Columbia Tower was far more reasonable and the wait non-existent. We were pleased at our own cleverness and the fine views of the city, which unfolded before us like an architectural model: skyscrapers of glass and steel, concrete highways and streets dividing the city into regular blocks, glittering streams of automobiles, and the even more diminutive figures that were human people.

What I did not expect to see was this enormous moon that-could-not-be. I was familiar with day moons. At certain times of the month, the moon can make an appearance in the daytime when it is bright enough and out of the direct path of sunlight. At these times, the moon is visible as a ghostly balloon riding high in the sky. But what I saw was far too large and square to the sun to be a day moon. Removed, alien and indifferent, this *thing* loomed over the city.

What planetary body could this be?

The face floated above the horizon, out of sync with night, discontinuous with the mountains below. Of course, I reasoned, this face in the sky must be the moon. Something so large but indistinct, distant and detached could not possibly be of this world; it belonged in the heavens. Or, better yet, Outer Space—that catchment for all that escapes our sensible, earthbound world.

Suddenly, and for the same reasons that one sees a vase instead of two faces, or finds a frog in an ink blot, it dawned on me: I was looking at Mount Rainier, also known in Salishan as Tacoma, the ice-capped volcano south of Seattle.

With a stomach-dropping jolt, the ground went out from beneath me.

I could finally see Mount Rainier for what it was. But *sense* no longer made sense. Mount Rainier was simply too big to be at that distance. It was nearly 100 kilometres away and should have been just a point on the horizon. But Mount Rainier did not scale with distance; it was stupendously large and insoluble within my perspectival conventions. I was not sure which was easier: to continue in my state of confusion, or to overhaul my entire perspectival framework. I was reminded of Jorge Luis Borges' short story, "There are more things," whose protagonist escapes a storm to enter a house he once knew—long abandoned but still a haunting presence on the hill. Upon switching on the light to find his way through its rooms, he is confronted by indescribable sights: "I will not attempt to describe them, because in spite of the pitiless white light I am not certain I actually saw them. Let me explain: In order to truly see a thing, one must first understand it" (Borges 2007: 41-42).

Only months later could I begin to describe my encounter with Mount Rainier. The sight of the volcano still confused me in ways that compelled wonder, but more overwhelming was my desire to enjoy the uncertainty it produced. On clear evenings, I would pause on my bike ride home along the Burke Gilman Trail. Seating myself on a bench under the Aurora Avenue Bridge, I would admire the mountain, its peak pink with snow. Looking and looking, I tried to train myself to recognize what I knew was there but still could not see. I had to let incoherence be; to let Mount Rainier do its work on me.

Sea ice is somewhat like my first encounter with Mount Rainier, but not because I did not know what it was when I first laid eyes on it. Sea ice produced a different kind of disorientation; a more gradual and systemic reordering of my conceptual coordinates that occurred, moreover, through months of practiced curiosity. *What is sea ice? Why does it matter? What can I learn from scientists to make sense of sea ice?* These are the questions that guided my fieldwork as I listened to and watched scientists at work, held instruments and ice cores for them, asked questions and attended workshops to understand a part of the world I knew very little about.

Context

When I first began my dissertation research in 2013, I did not know what sea ice was. I was more familiar with glaciers and ice sheets, those charismatic figures of the Earth's cryosphere that formed the backdrop to my childhood home in the Rocky Mountain foothills. Glaciers were striking, both aesthetically and scientifically; sea ice was more remote, not only geographically but imaginatively. For these reasons, sea ice on its own was not an obvious object of study for my dissertation research. What directed me to sea ice at all was anthropogenic climate change. More specifically, the storied Anthropocene of the early 2000s, a new geological epoch that would formally recognize the lasting impact of human activities on planet Earth in its four billion-year history (Zalasiewicz et al. 2008).

The Anthropocene concept undoes taken-for-granted conceptual orders. Scientifically, the entry of this time unit into public and academic consciousness began *not* with the testimony of rocks, but with "a change in the air" (Zalasiewicz 2017: 97). Atmospheric changes—in the form of climate change and, especially, the ozone hole over Antarctica with its indisputably anthropogenic causes—cast into sharp relief the collective capability of humans to influence the Earth itself. This anthropological lens brought into focus other global environmental changes: enormous land surface transformations, biodiversity loss, ocean acidification, and disruptions to biogeochemical cycles. When atmospheric chemist, Paul Crutzen, and diatom biologist, Eugene Stoermer, wrote their landmark article on the Anthropocene in 2000, they sought to foreground *anthropos* as that which unified these distinctive global environmental changes into a single phenomenon. Perhaps more significantly, by framing this phenomenon in terms of a geological epoch—as the Anthropo-*cene*—Crutzen and Stoermer sought to produce a more fundamental shift in thinking *anthropos*.

To be clear, Crutzena and Stoermer's claims of a new geological epoch did not meet formal stratigraphic criteria for declaring a new time unit (Lewis and Maslin 2015). Their argument was based on observational evidence from the present and recent past, rather than the study of global strata patterns. As geologist and leader of efforts to stratigraphically define the Anthropocene, Jan Zalasiewicz, remarked, their observations were "almost perversely counter-geological" (2017: 97). But this incongruity spoke to the profound categorical shift that Crutzen and Stoermer sought to bring forth; that is, the impact of collective human activities is not only remarkable for its globally-encompassing reach, but for its legibility in the geological record. From the perspective of Earth, *anthropos* had joined the ranks of geological forces, of a kind with the movement of tectonic plates, meteor impacts, solar variations, and orbital shifts, which shape the course of Earth's history—and future.

Ordering conventions, like the perceptual frameworks that I unwittingly brought with me to make sense of Mount Rainier, fail observers. Claims about the Anthropocene, however, produce a different kind of disorientation in its derailment of nature/culture divides. Anthropogenic climate change is not tractable in terms of 'culture,' 'society,' 'history,' or 'politics'; nor is it 'natural' either, insofar as it is anthropogenic. The Anthropocene's irreducibility not only points to the limits of these concepts but destabilizes them altogether. Here, is a "nature-culture monster" (Latour 1993), a cyborg and trickster (Haraway 1991). Such conceptual disorientation is perhaps more revealing of my own presuppositions, which I have inherited from sources too general and diffuse to name. But without this conceptual inheritance, the 'jolt' that the Anthropocene and anthropogenic climate change produce would not have been possible.

The jolt in and of itself is intellectually productive. Over the course of this dissertation, I want to stabilize this moment as much as possible so that it can be contemplated and worked over in various ways. This jolt made visible the conceptual *a priori*—basic presuppositions, epistemological frameworks, aesthetic sensibilities—that I brought into my dissertation research. At the same time that these givens lost their obviousness, I wondered what would come into view when released from these taken-for-granted frameworks? What would it mean to let climate change work people over, as I tried to come to terms with Mount Rainier?

How, indeed, to *think* in the Anthropocene? (And what can this thinking do for everyday practices, as well as politics and decision-making?) The term itself has come under intense scrutiny in the human sciences, itself, for placing human beings at the centre.

As several human scientists have argued, the 'Anthropocene' as a concept homogenizes differences between peoples (e.g., Moore 2015). It ignores inequalities, disparities, capital, world systems, etc. Furthermore, the centrality of *anthropos* ignores the entanglements that make humans and nonhumans an indivisible collective. As Donna Haraway (2016) argues, neither man-as-species or technologically-aided man makes history alone. To prefix the present times with *anthropo-* ignores how this figure is relationally produced via interactions with nonhuman others, which thereby risks re-entrenching human exceptionalism, and concomitant assumptions of human mastery over a nature independent of it. It also has the potential to give license to technological fix-it mentalities; if collective human activities are the source of global warming, so thinking goes, then these human activities are the site of intervention through which reality can be transformed. In short, the Anthropocene as a term is a double misconstrual insofar as: a) it does not rethink the past; and b) allows potentially harmful presuppositions to define the present and future.

That said, the Anthropocene as a concept can be useful. The Anthropocene has thus given human scientists, anthropologists included, renewed visibility and credibility as *de facto* experts on human beings (e.g., Fiske et al. 2014; Palsson et al. 2013). Natural scientists have turned to psychologists for insights on the human mind and behaviour (especially to explain climate denialism); to anthropologists for their expertise on culture and cultural change; to communications experts for their know-how on effective means of messaging; to politicians for their analyses of power; as well as to sociologists for their understanding of social action and social movements. Solving anthropogenic climate change requires expertise from the human sciences (see Fleischmann 2018).

The Anthropocene is useful in other ways. As Anna Tsing argues, 'Man' does not mean humans, "but a particular kind of being invented by Enlightenment thought and brought into operation by modernization and state regulation and other things" (see Haraway et al. 2016: 541). To differentiate this 'Man' in the singular from human beings in the plural is productive. It enables analysts to get away from a master narrative and enlarge the possibilities for other stories and new forms of storytelling, arts of encounter, and modes of attending (Tsing 2016). Anthropologists have, contrary to placing 'Man' at the centre of their analysis, turned away from human beings toward nonhumans. As Tsing writes: "We are surrounded by world-making projects, human and nonhuman. To see them in the shadow of 'anthropo-' we must reorient our attention" (Tsing 2016: 1).

This dissertation takes up the challenge of thinking in the context of anthropogenic climate change. It does so by conducting an anthropology of sea ice. Empirically speaking, rapidly declining sea ice in the Arctic has become an icon of global warming in the media and academic literature. The reduction of Arctic sea ice makes climate change an immediate and concrete threat to both forms of life and "life as a form" (Kohn n.d.). But beyond the immediate consequences it poses, I want to take up sea ice—more specifically, 'sea ice' as an epistemic object constituted by scientific knowledge—as a conceptual reference frame for exploring new possibilities for thinking.

Theoretical Differentiations & Research Questions

In 2012, *Cultural Anthropology* published a special edition to commemorate the 25th anniversary of "Writing Culture." In it, Hugh Raffles meditates on what it means to conduct an anthropology of stones: How does one, as an anthropologist, approach something that is pre-, post-, necessary to, transcendent of, indifferent to, 'culture' and 'society'? With what tools and concepts can one think about stones if they are not tractable in terms of sociocultural anthropologists' trusted tools-of-the-trade?

Raffles' methodological tactic is to reformulate his question away from "What *is* a stone?", which seemed to lead into a "metaphysical morass," towards the question, "What do stones *do*?" The differentiation is an important one. To ask what stones *do*, Raffles argues, redirects anthropological attention away from ontological questions to more familiar sociocultural ones. One can attend to a stone's reality effects in sociocultural worlds; for instance, how stones engender a philosophy in Chinese thinking, aesthetics, and poetry; or how Italian artists 'found' scenes of desolate landscapes and epic battles in stones, confounding subject and medium. These encounters with stones at the limits of human cultural worlds allow Raffles to approach stones tangentially, without reducing them to culture or social relations.

Raffles' work can be situated within a larger field of studies in anthropology, philosophy, history, and humanities, which seeks to enlarge the field of view take nonhumans seriously. In anthropology, humans find themselves in the company of mushrooms (Tsing 2016), microbes (Helmreich 2009; Hird 2009; Paxson 2008; Rees, forthcoming; Schrader 2010), insects (Raffles 2010), plants (Myers 2017), and life itself (Kohn 2013). In the domain of the non-living, anthropologists have turned to viruses (Lowe 2006), air (Choy 2011), sand (Zee 2017), stones (Povinelli 2016; Raffles 2012), wildfires (Petryna 2017, 2018), ice (Cruikshank 2005; Hastrup 2013; Boyer and Howe 2018), waves (Helmreich 2014), things (Holbraad 2011), and the dynamics of matter itself (Ingold 2007). These studies have rendered visible human-nonhuman "becomings-with"; the ways in which things do not exist as discrete, self-contained, and autonomous units but come into being through "relentlessly relational worlding" (Haraway 2006). Insofar as these studies seek to enlarge the field of view beyond strictly human beings, my exploration of sea ice-worldings is complementary to such work.

In my own anthropology of sea ice, however, I want to understand how sea ice *produces* its own order of things. Let me turn to one of Raffles' own questions to differentiate what I mean yet further.

In his meditation, Raffles thinks with/through a stone he picked up off a beach in Oregon. *But what about,* people ask Raffles, *the stones he left behind?* What about those stones that do not enter 'culture' or society'?

These are the rocks I am interested in. Or, more precisely, this is the category of things I am interested in, whether they be rocks or ice. They do not participate in the kinds of 'becomings-with' that anthropologists have so far engaged, and through which anthropologists have indirectly accessed insects, dogs, or mushrooms. Stones, the ones left behind on the beach, remain distant and inscrutable. So, how does one approach these kinds of stones? Is this even possible from an anthropological perspective?

The limits of social and cultural analyses, especially when it comes to grasping global warming, collapsing ice sheets, or toxic waste piles, have led to the re-emergence of ontology as a central problem. Ontological framings arise in response to the unmistakable effects of nonhuman things on human worlds. These things, in their general capacity to act upon the world, must be agents, too. What if, various thinkers have asked, 'agency' is not necessarily individual, self-conscious, rational, intentional, intrinsically given, universal, or even uniquely human? The question has unleashed a flood of philosophical arguments as thinkers struggle to give this residual a name: vital materiality (Bennett 2009), lines (Ingold 2011), thing-in-itself (Harman 2011; Holbraad and Pederson 2017), thirdness (Kohn 2013), and geontopower (Povinelli 2016). The re-introduction of non-human agents has opened up the possibility for more ambitious undertakings to recompose the order of things (e.g., Latour 2013). The Order of orders is at stake.

These waters are too deep and turbulent to casually wade into. There are unseen riptides that could carry one out, far from safety and even further from where one wanted to go in the first place. Anyways, it is the wrong entry point. I am neither adequately equipped or ambitious enough to try and capture the irreducibility of things living or nonliving, to discern in what things-in-themselves consist, or to recompose the world itself.

Perhaps I need to ask the question a different way. Here is another reformulation: What if, on the beach in Oregon that Raffles found his stone, it is not that humans have left the other stones behind, but that humans are left behind by stones? How could one think from the perspective of these stones—or sea ice—that leaves in its wake humans beings?

To speak of being 'left behind' bears suspicious resemblance to conceptual divisions that made it possible for 'nature' to separate from 'culture' or 'society.' In addition, the phrase suggests a *telos* that, depending on one's perspective, makes either humans or geology the vanishing point from which something can be seen as 'left behind.' 'Nature,' however, as science studies have amply shown (Hacking 1983; Haraway 1991; Latour 1993), is *produced* not given. My goal is not to re-establish familiar meta-narratives or to construct new ones.

Nor is my goal, in 'leaving human beings behind,' so to speak, to argue for post-humanism or a naïve escapism. As various thinkers have argued, it is not only difficult to ignore or move ‘beyond’ human beings, but it is not conceptually, politically, or ethically desirable to do so (Haraway 2016; Latour 2014). The figure at stake in the Anthropocene, and which various thinkers have challenged, are not human beings *per se* but ‘the Human,’ an invention of the Enlightenment in Western Europe (Rees 2018; Tsing 2016)—a historically contingent formation that has not always existed, and can just as well dissolve (Foucault 1970). Perhaps “after ethnos” (Rees 2018) rather than post-human or ‘beyond the human’ provides a more comfortable fit. The idea of an anthropology ‘after ethnos’ is, on one hand, an effort to conduct “an anthropology ‘of’ the human/after ‘the human.’” (Rees 2018: 34). It does not seek to transcend humanity, but to decouple humans from ‘the Human.’ Its goal is “to render visible ruptures and mutations of established conceptions of the human… by way of bringing into view how instances in the here and now derail and defy the normative conceptions of the human” (Rees 2018: 41).

To inquire after the stones, sea ice, or other nonhuman entities that were on the beach before human visitors came, and which remain after their departure, is an effort to understand worlds beyond human making—beyond, even, worlds that emerge through human-sea ice “becomings-with” (Haraway 2008, 2016). Broadly speaking, then, my dissertation asks: What worlds does sea ice bring into focus and how, among many other things, do humans figure within these worlds? How does sea ice potentially destabilize, inflect, or reconfigure concepts of ‘world’ and ‘time’? What potential implications do these conceptual derailments have for thinking contemporary problems, such as anthropogenic climate change?

Methodological Approach

My entry point into sea ice-worlding is scientific knowledge of sea ice. In turning to scientific knowledge, I am not claiming that scientific knowledge has access to true knowledge of sea-ice-as-it-really-is. Nor do I want to erase or diminish by omission indigenous ways of knowing sea ice, which contain their own possibilities for understanding how sea ice worlds (e.g., Aporta 2011; Laidler 2006; Krupnik et al. 2010). I turn to natural scientific knowledge because it can offer a non-anthropocentric entry point into the world of sea ice. Certainly, human beings are implicated insofar as they produce this knowledge and seek to know about nonhuman things in the first place. But this knowledge is not reducible to human scientists. Scientific knowledge is productive to think with, given its focus on nonhuman things. Some of these phenomena are entirely independent of human beings, such as the movements of tectonic plates, the oxygenation of Earth's atmosphere, or the composition of planetary bodies. Other phenomena, such as matsutake ecologies (Tsing 2016) and Amazonian ecologies (Raffles 2002), are not understandable without bringing human activities into the field of view. And with respect to yet other phenomena, including the emergence of antibiotic resistant bacteria and anthropogenic climate change, humans play a crucial role in their emergence. But for all these phenomena, in the natural sciences human beings are not a primary departure point or the organizing principle for scientific understanding. These phenomena require a different analytic vocabulary that does not ground in human beings; a framework that, on one hand, decentres human beings as one entity among many, and on the other, opens onto a space larger than the worlds made by humans.

My treatment of scientific knowledge is deeply informed by insights from Science and Technology Studies (e.g., Knorr-Cetina 1981; Latour and Woolgar 1979; Pickering 1992) and the history and philosophy of science (e.g., Bachelard 1986 [1934]; Hacking 1983; Rheinberger 1997). Two major insights form the basis of my methodology. First, I treat scientific knowledge as *produced*. Sea ice is not given, a pre-existing object that can be approached through scientific knowledge by increasingly accurate approximations. Nor is it reducible to constructs in human minds. Approaching scientific knowledge as practice—as a matter of intervening, manipulating, and experimenting with material conditions of production—makes visible the ways in which 'sea ice' as an epistemic object is constituted in the course of being studied (e.g., Rees 2016; Rheinberger 1997). This frame of reference sensitizes one to science as *poeisis*, a kind of making or "bringing into being that which did not exist before." Scientists tinker with "fragments of thought" (Rees 2016: 176-181), whether they are pieces of equipment, concepts, arranging and rearranging these pieces in order to compose an object or idea (Rees 2016). These practices of *poeisis* are not equivalent to an 'anything goes' approach, but disciplined by material constraints, conventions, forms of communication, etc., each component of which is historically contingent.[1] This space is tentative provisional, and subject to change.

Second, and following from the first insight, scientific knowledge is historically contingent, variable, and changeable. Sea ice science, then, is not a stable field of knowledge production, and neither is 'sea ice' as its object of study. The mutability of scientific knowledge is not just a key takeaway from STS studies and the history of science, but opens a space of possibility for making anthropological provocations without ontologizing scientific knowledge. Scientifically inflected anthropological provocations are just as tentative and fragile as the scientific claims on which they rest. They are not a claim about how things really are but a speculative space that is neither true or false.

Fieldwork

For my fieldwork, I followed sea ice scientists and glaciologists at the Polar Science Centre (PSC), the Atmospheric Sciences Department, and Department of Earth and Space Sciences at the University of Washington in Seattle, WA. Fieldwork lasted a total of 12 months over the course of two years (July 2014 to December 2016). In North America, the UW is a major centre of action for the study of sea ice, glaciers, ice sheets, snow, and permafrost. The UW offered a microcosm of the global community of sea ice science and trained many cryospheric scientists now working in different parts of the world. Within its institutional boundaries, there were scientists who specialized in sea ice physics at the microscopic scale to the Arctic regional and global scales; experts on sea ice biology from microbes to mammals; scientists who studied sea ice in both the Arctic and Antarctic, modern-day Earth and paleo-Earth; experimentalists, observationalists, remote sensers, modellers, technicians, and logisticians; undergraduate research assistants, graduate students, post-doctoral researchers, junior and senior research scientists. Often, the UW also hosted guests from afar (China, Norway, Russia, Canada) for short-term collaborations.

My initial reason for embedding myself at the UW was the rotten ice project, led by Principal Investigators Bonnie Light, Karen Junge, and Monica Orellana. This project was an opportunity to see a scientific object-in-the-making. At the time, the rotten ice project was still in the early stages of unfolding, which meant I could track how scientists designed their methodology, adjusted their research questions, collected field data, and analyzed their results. Moreover, the rotten project lent itself to participant-observation with its laboratory and fieldwork components, which included accompanying the scientists on three 10-day trips to Utqiagvik, Alaska in Spring/Summer 2015 to collect sea ice samples. Moreover, the rotten ice project offered a gateway into the sea ice community and other research activities.

Over the course of fieldwork, my focus widened from the rotten ice project to include activities on sea ice prediction, sea ice and climate interactions, modelling, and remote sensing. I embedded myself on a day-to-day basis with scientists, routing my fieldwork through already established activities on campus, such as weekly lab meetings, lunch seminars, social coffee hours, and research in the cryolaboratory. My weekly calendar, especially lunch hour, steadily filled with activities. Monday was spent with Cecilia Bitz's lunchtime group meeting, Tuesdays was Glaciology lunch (or G-lunch), Wednesday afternoons were PSC coffee hour, Thursday mornings were the rotten ice lab meetings, and Fridays were Polar Science lunch talks. In between, I spent my time chatting with scientists in their offices or in the halls, conducting formal interviews, and typing up field notes if I was not attending a major scientific meeting in other parts of Seattle or elsewhere. Some of the workshops and meetings I attended included: the 2015 Forum for Arctic Modelling and Observations Synthesis in Cape Codd, MA; the 2016 American Geophysical Union Meeting in San Francisco; the 2016 Arctic Observing Network meeting in Seattle; the 2016 UW Program on Climate Change Retreat; and the Sea Ice Prediction Network meetings in Bremerhaven, Germany (2017) and Montreal, Canada (2018). I also had the opportunity to return to the Alaskan Arctic for short field trips to follow scientists. In Spring 2016, I attended the Sea Ice Summer Camp that brought together modellers and observationalists in Utqiagvik, AK for 10 days to foster closer interdisciplinary collaborations (see Holland and Perovich 2017). And in August 2016, I accompanied scientists on flights as they collected data over the Chukchi-Beaufort Seas during the Seasonal Ice Zone Reconnaissance Surveys, led by Dr. James Morison.

Chapters

Chapter One, "Making Sea Ice: A Field Guide" is an account of how 'sea ice' as an epistemic object has been variously constituted. The account is not a history of sea ice science, if by that one assumes a trans-historical rubric by which a coherent field of practices and concepts becomes recognizable as 'sea ice science' that is continuous with the earliest documentation of sea ice sightings by the Greeks. Nor is it genealogical (Foucault 1970), which would examine subtle mutations in the conceptual configuration of the study of sea ice encoded at the level of discourse and practice. Such a genealogy would be a dissertation project in itself and is outside the scope of what I set out to do. Instead, this chapter models itself instead after a field guide. It consists of a collection of moments in which 'sea ice' is differently constituted as an epistemic object over time.

Chapter Two, "Rotten Ice," follows the making of 'rotten ice' as a scientific object from 2014 to 2016. The rotten ice project both began before my arrival and continued after my departure from the field. In its goals to characterize sea ice as a bio-chemical-physical unit, the project's scientific framing spoke directly to 'becoming-with' as a key analytic in multispecies ethnography. But as my fieldwork unfolded, my questions departed in a different direction. 'Rotten ice' itself had not quite stabilized sufficiently to begin interrogating how this bio-chemical-physical thing emerged relationally. Instead, what came into view was a practice of *making objectivity* at stake in giving shape to 'rotten ice' as an object.

Chapter Three, "Non-Predictability," began out of my interest in the science of sea ice prediction and predictability. Its empirical departure point was the Sea Ice Outlook, an activity that brings together modellers and observationalists, academics and non-academics to estimate the annual September minimum sea ice extent. The Outlook was established in 2008 in response to the 2007 record-low sea ice extent, which took scientists by surprise. It is the *non*-predictability of sea ice, its irreducibility to either predictability *or* unpredictability as the flip side of the same coin, that caught my attention. The ways in which sea ice escaped prediction as a framework prompted me to examine how sea ice produces its own time. Along this line of inquiry, I consider how sea ice and recurring world weather patterns, such as El Niño and the Arctic Oscillation, produce a collective time not grounded in clocks or social life. Taking seriously the idea that nonhumans have a time of their own, I argue, has implications for thinking about prediction as a technology as well as concepts of human agency.

Chapter Four, "Salt-Ice Worlds," concludes this dissertation with an exploration of what it means for sea ice to 'world.' Insofar as humans are meaning-producers, they are thought to have 'world.' Conversely, nonhuman things cannot make meaning and therefore do not 'world.' Worlding is also considered exclusive to humans insofar as they are capable of altering their own conditions of existence and, hence, their own natures. But what if sea ice also 'worlds'? Sea ice plays a profound role in shaping worlds as we know them today—and in the past. Through various physical processes, sea ice can modify its own conditions of existence. Sea ice can 'world' but in ways not based on meaning-making. What does this do to taken-for-granted concepts of 'world' and 'worlding'? What I aim to produce are not necessarily answers but to find ways of framing questions such that a new conceptual possibility becomes thinkable. By way of concluding both this chapter and the dissertation altogether, this chapter includes reflections on Edward Burtynsky's (2004) photographic retrospective, "Manufactured Landscapes."

Lastly, in between the chapters are interludes that illuminate the arguments of the previous chapter.

Glace de la mer[2]

Sea ice is an occurrence at the meeting point between winds and waves, sunlight and salt. It is frozen seawater. Scientifically speaking, sea ice can be defined "as any type of ice that forms in or on the surface of the sea by the freezing of seawater" (Weeks 2010: 1). This excludes icebergs, which are broken-off pieces of glacier, and spray icing that forms on the surface of ships or rocks. One of the key properties of sea ice is salt. As sea ice freezes, it rejects impurities, such as dirt, bacteria, and salt from its crystalline structure. As freezing proceeds, salt concentrates in the boundaries between ice crystals, which form brine pockets, tubes, and channels within the ice interior. Consequently, sea ice is porous, relatively soft, and milky in colour. Because it is full of holes, the microstructure of sea ice has been compared to Swiss cheese or a sponge. This basic feature shapes the behaviour of sea ice from the microstructure of sea ice to the mechanical behaviour of sheets of sea ice (Petrich and Eicken 2010).

In winter, sea ice covers up to 7 percent of the earth's surface and constitutes one of the largest biomes on Earth (Dieckmann and Hellmer 2010). Its overall extent and thickness is controlled by growth and decay, as well as drift. The life cycles of marine plants and animals ranging from micoorganisms to whales and even humans, are also influenced by the large-scale cycles of ice formation. Today, sea ice is found on Earth in both at high latitudes in both the northe and south hemispheres. While the focus of this dissertation is Arctic sea ice, a comparative look can provide helpful background knowledge to put Arctic sea ice in perspective.

One major difference between the Arctic and Antarctic is geographic. Whereas the Arctic is an ocean surrounded by continents, the Antarctic is a continent surrounded by seas, collectively known as the Southern Ocean. Some have compared the Arctic Ocean to the frozen Mediterranean Sea insofar as it is encircled by land. The Arctic Ocean is the catchment basin for rivers flowing out of Canada, Alaska, and Russia. Consequently, it is fresher than the Southern Ocean that surrounds Antarctica. This fresh layer insulates sea ice from warmer deep waters that flow into the Arctic Ocean from the North Atlantic.

Sea ice cover in the Antarctic is seasonal whereas the Arctic is perennially ice-covered. Until recently, sea ice that has survived at least one annual cycle of growth and melt (multiyear ice) was more common in the Arctic than in in the Southern Ocean, though recent reports show that older ice is rapidly disappearing (Osborne et al. 2018). While Arctic sea ice extent showed a steady decline since 1979, until 2017 Antarctic sea ice extent was actually growing.

When sea ice forms, it constitutes a major surface layer of the Earth. Interposed between ocean and atmosphere, this layer shapes, and is shaped by, the fluxes of heat, momentum, and moisture across its surface. Sea ice is like a thin blanket lying on the ocean's surface. The relative thinness of sea ice makes it sensitive to small perturbations within the ocean and atmosphere. These changes in the sea ice cover in turn influence the state of the ocean and atmosphere. "Due to this complex interaction between key components of the earth's climate system," write Thomas Dieckmann and Harmut Hellmer, "sea ice has become one, if not the most important, component in the research of the past, present, and future climate" (2010: 6).

The formation and drift of sea ice influences global ocean circulation. In both hemispheres, sea ice tends to form on the continental shelves. In the Antarctic, intense cooling combined with brine rejection that occurs through the formation of sea ice formation can densify surface waters to a point that initiates deep water and bottom formation. In the Arctic, the outflow of sea ice from the Arctic Ocean into the North Atlantic can perturb deep water formation in the northern hemisphere (see Chapter 4: Salt-Ice Worlds).

On the atmosphere side, sea ice influences the atmosphere by insulating the atmosphere from the warmer ocean below. Sea ice also mediates the amount of solar energy that gets absorbed or reflected back to space. Snow on sea ice can reflect up to 80 percent of sunlight during the polar summer, which would otherwise warm the ice or ocean surface (Weeks 2010). During winter, sea ice radiates heat back out to space, keeping surfaces cool. In other words, the presence of sea ice acts to maintain the low energy state of the Arctic, which in turn further stabilizes the presence of sea ice. This is an example of a positive feedback mechanism.

In the last four decades Arctic sea ice has undergone clear changes. Arctic sea ice is declining steadily. Reports show that it is thinning, shrinking in extent, and becoming more mobile. Older (multiyear) sea ice is also disappearing from the Arctic while more and more sea ice is 'first year' ice, or sea ice that grows in the autumn and winter but melts in spring and summer. Parts of the ocean that used to be ice-covered are now seasonally ice-free. Except for the coldest northern regions of the Arctic Ocean, the length of time that parts of the ocean are ice-covered is shortening. According to some projections, the Arctic could become free of ice for at least some periods of the summer as early as the late 2030s (AMAP 2017). That is less than two decades from now.

Arctic temperatures are rising faster than the global average. The period from 2011 to 2015 was warmer than at any time since instrumental records began around 1900, and warmed more than two times faster that the world as a whole in the past 50 years (AMAP 2017). This is likely due to increasing concentrations of greenhouse gases that trigger a cascade of feedbacks that amplify Arctic warming. According to climate models, one of the feedbacks is related to the Arctic's inefficiency at radiating heat. In the Arctic region, heat tends to get trapped at the surface, far from the top of the atmosphere where this heat can be radiated to space. The next major feedback is related to changes in reflectivity of melting snow and ice. As snow and ice melt to reveal the darker open water and land surfaces beneath, more sunlight is absorbed (and less is radiated to space), which melts yet more snow and ice. As well, a warmer atmosphere can hold more water vapour, which can trap more heat and in turn raise temperatures that increase rates of evaporation, and so on and so forth (AMAP 2017). Studies are ongoing to tease out the relative contributions and significance of these different feedback mechanisms to the amplification of warming in the Arctic.

The changes in the Arctic are expected to continue until the middle of the century. That said, authors of the 2017 Snow, Water, Ice, and Permafrost (SWIPA) assessment note that substantial reductions in global greenhouse emissions can still make a difference.[3] Reductions could at least stabilize some trends, although the Arctic would enter a 'new normal.' According to SWIPA authors, "the near-future Arctic will be a substantially different environment from that of today, and by the end of this century Arctic warming may exceed thresholds for the stability of sea ice, the Greenland ice sheet, and possibly boreal forests" (AMAP 2017: 6). The world as we know it is changing and with it, the assumptions in which it grounds. How we choose to meet this challenge is part of what this dissertation sets before itself.

Chapter 1.

Making 'Sea Ice': A Field Guide

the joke

There is a joke about Norbert Untersteiner, the late scientist cited who founded the Polar Science Centre in 1979 and who was a major figure in sea ice science up until his death in 2012. Some years ago, when asked to introduce himself and his research during an informal lunch seminar, he proceeded to say *"My name is Norbert… and I invented sea ice."* Another one of my friends remembers the moment differently. In her memory, after giving his name Norbert stated non-chalantly that he *"*invented polar science*."*

A short pause follows both my friends' re-tellings as they wait for my reaction. Their silence is meant, perhaps, for dramatic effect. *How could one make such a preposterous statement, that sea ice could be 'invented,' as if it were a product of human artifice, a purely human construct? And who would have the audacity to say that he had* invented *sea ice or, though it is no less extravagant, to have* invented *polar science?* These are the things they might have added but didn't; these are the questions I could have asked but didn't. Instead, we share a mutual shrug and let the tensions in Norbert's joke remain unresolved.

My friends did not recall this moment to suggest that Norbert was full of self-importance. If anything, he is affectionately remembered by colleagues, friends, and students as warm, playful, witty, and full of an "indescribable sense of humour" (Wettlaufer 2012: 67). Several people enjoy re-telling clips from an interview of Norbert in 2001 where he relates growing up in Austria: "…so when I was twelve in March of 1938, Austria was taken over by the Germans, by Hitler. And that profoundly changed everyone's life. I was immediately told that I had to march and sing these idiotic songs. I have fulfilled my lifetime allowance of marching right then and there and since then I have not even marched in academic processions when I was Dean because I told the President of the university that I have a medical condition that prevents me from marching, no matter what the cause" (Untersteiner interviewed by Shoemaker, 2001).

Norbert, it seemed, loved to make jokes. The notion of 'inventing' sea ice is laughable among his scientist friends and colleagues. A joke that, furthermore, admonishes others to not take him so seriously since no one, and certainly not Norbert, could singlehandedly *'invent'* sea ice or polar science. But at the same time, the joke works within this group of scientists precisely because Norbert is being perfectly serious: he means exactly as he says. Norbert has been cited by some as the "father" of sea ice geophysics and conducted seminal studies on sea ice since the late 1950s. In addition, he not only founded the PSC but was instrumental to establishing snow and ice science at the UW. In short, he *invented* sea ice and polar science. As a joke, Norbert's claim is neither here nor there. His joke opens up an indeterminate space for making contradictory claims; to joke about being serious but to be serious in the exact formulation of his joke.

The singularity of Norbert's joke persists, years later, recalled by two separate scientists on independent occasions. Exactly *what* was invented—whether it was sea ice or polar science—is almost secondary; what they remembered most vividly was the provocation that a scientist could 'invent' their very object of study.

To 'invent' a scientific object smacks of fraud, cheating, flawed reasoning, or even innocent carelessness. In a phrase: bad science. Etymologically, 'invention' comes from the Latin *inventus*, past participle of *invenire* "to come upon; devise, discover" (OED, 2nd ed.). The meaning to "make up, think up"—a conceptual mutation closer to how the word is commonly understood today—arose in the 1530s, as is the related meaning to "produce by original thought." Interestingly, this shift in meaning brings into view the process of human mediation and intervention.

Norbert certainly *did* something to turn sea ice into a particular object of scientific inquiry. And he was key to giving polar science a coherent identity at the UW. His joke suggests that 'sea ice' is a scientific object in the making, not something ready-made, waiting to be stumbled upon.

What would it mean to take Norbert's joke seriously (inasmuch as a joke can be taken 'seriously')? That is, to consider how 'sea ice' is mediated by human practices, techniques, and conceptual frameworks? What insights about 'sea ice' might we develop from approaching it as an object that is continually made and unmade, rather than pre-given, waiting to be found?

Not only do I want to take seriously Norbert's joke but to broaden its boundaries beyond his individual involvement. Sea ice science exceeds Norbert; before his entry into sea ice science, there were other researchers doing work on sea ice. And today, there are others extending sea ice research in new directions. The rotten ice project that I followed was exemplary of a new scientific object in the making (see Chapter 2: Rotten Ice).

A history of the science of sea ice would gather up British, Scandinavian, Russian, and American histories of colonial exploration and conquest that science often went arm-in-arm with (Bravo and Sörlin 2002; Bocking 2007; Levere 1993), as well as mythologies about the North (Davidson 2005; Grace 2007). There are many comprehensive accounts of polar science and exploration but in my early attempts to write a history of the science of sea ice science in particular, I immediately encountered difficulties.[4] Neither 'sea ice' as a distinctive object, or 'sea ice science' as a coherent epistemological practice, could be located in the archives of history. A solution came from practices of fieldwork in general, in the form of field guides that accompany naturalists into their research sites, or which make up the introduction to textbooks in the natural sciences.

Field guides are valuable insofar as they mediate seeing and help novices to pick out ideal types. Like the 'scientific atlases' used by anatomists and botanists examined by historians of science Lorraine Daston and Peter Galison (1992), field guides "drill the eye of the beginner and refresh the eye of the old hand" (Daston and Galison 1992: 85). While Daston and Galison emphasize how these atlases standardized ways of seeing and faculties of judgment, I turn to field guides insofar as they are *guides*—a framework that develops practices of seeing and attunes epistemic sensitivities rather than prescribing strict rules on how to see and know. As a guide, it offers a form of thinking that shifts focus away from facts about sea ice or the history of sea ice science, i.e., content information, to the different conceptual frameworks, techniques, and practices that mediated how scientists brought sea ice into the field of view, and constituted it as an epistemic object. Thus, the field guide I write on 'sea ice' is less about providing an exhaustive catalogue on types of ice than *ways of seeing* sea ice.

In its form and subject matter, the field guide calls to mind Franz Boas' efforts to document the different Inuit terms for 'snow,' which bears mentioning, since it points to the ways in which Arctic indigenous peoples have developed their own rich and nuanced ways for differentiating snow—and sea ice—over generations (see Krupnik and Müller-Wille 2010). This is a distinctive body of knowledge in its own right that has received renewed attention in the last two decades as Arctic resident experts and visiting researchers document sea ice knowledge and use (see Krupnik et al. 2010). Insofar as these contemporary and historical anthropological efforts seek broadly to understand how worlds can be ordered in different ways, this field guide shares their sentiment.

Instead of documenting Inuit concepts of 'sea ice,' however, this field guide turns instead to different conceptions of 'sea ice' in modern science.

This field guide is not a traditional one. Included within it are not only kinds of sea ice, but sea ice typologies as a kind in itself. As well, there are instruments and individuals, institutions and ideas. This is a guide to sea ice, yes, but also a guide to the epistemological terrain on which 'sea ice' gains form.

Field Guide to Sea Ice

marine lung (pleumōn thalattios)

"Land properly speaking no longer exists, nor sea nor air, but a mixture of these things, like a 'marine lung,' in which it is said that earth and water and all things are in suspension as if this something was a link between all these elements, on which one can neither walk nor sail."

– Pytheas of Massilia, *On the Ocean*; Quoted in Chevalier (1964) *The Greco-Roman Conception of the North from Pytheas to Tacitus*

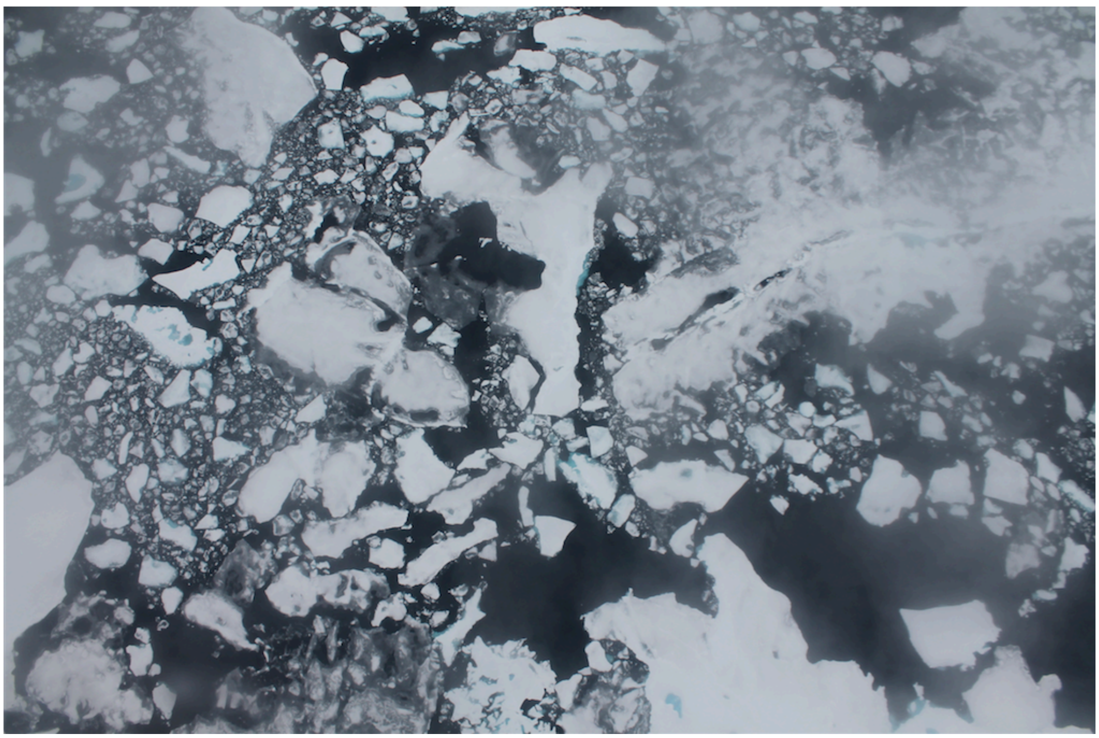
Around 330-325 B.C., Greek merchant, geographer, and explorer Pytheas voyaged to northwestern Europe and circumnavigated what we know today as Great Britain. His travels were described in a *periplus*—a manuscript listing ports and coastal landmarks in order and with intervening distances—called *On the Ocean*. Only excerpts of the document, however, have survived, which have been quoted or paraphrased by other authors. Perhaps the most well-known citations of Pytheas' travels appear in Strabo's *Geographica* and Pliny the Elder's *Natural History*, neither of whom saw his text firsthand (Chevalier 1964).

Among the discoveries Pytheas described was an island six days sailing north of Great Britain. He called the island Thule. Here, the sun went to sleep and nights lasted only two to three hours. Even further north of Thule began the 'congealed' sea, the place where Pytheas sighted something in the mists. It was insubstantial, indefinite, and undefinable. What he called a 'marine lung.'

It is possible that Pytheas was describing jellyfish. As some historians have noted, a 'marine lung' in Greek refers to this translucent, lung-like sea creature. But, modern scientists argue, Pytheas may have been trying to describe the formation of pancake ice at the edge of drift ice. The texture and appearance of the ice may have called to Pytheas' mind a group of jellyfish. As glaciologist Shawn Marshall observes, "sea ice must have been a difficult notion for someone that hailed from the Mediterranean" (Marshall 2011: 104).

How, indeed, does one make sense of such a phenomenon? Pytheas' poetic description of sea ice is an effort to invent a language to describe what was previously unthinkable. To bring it into the realm of thought and find words with which to think it.

How does one learn to 'see' sea ice? In what ways is it described? How do scientists order their observations of sea ice?



seasonal ice zone

def'n: an area of ocean that extends from the permanent ice zone to the boundary where winter sea ice extent is at a maximum; here, sea ice is present only part of the year; this zone primarily consists of first-year ice. (*Cryosphere Glossary,* National Snow and Ice Data Center). Photography by author: Chukchi sea ice as seen from a plane during the Seasonal Ice Zone Reconnaissance Survey, August 2016.

Sarah waited three years before she finally saw sea ice. Until her first flight to survey the ice in 2012, she had only studied this phenomenon from afar as a doctoral student based in Seattle. She admits how she was overcome by emotion the first time she saw sea ice firsthand.

Four years after her first flight, Sarah tells me how she still finds the ice overwhelming. She was on a regular flight in the fall of 2015 to survey conditions of the seasonal ice zone, the region of ice that grows and contracts from its winter maximum extent to summer minimum extent. These flights are part of a multi-year observational study led by Dr. James Morrison at the Polar Science Centre to understand air-sea-ice interactions. The flights are conducted monthly from June through October, expanding research coverage beyond the typical summer field season (June to September).

The ice has already started to re-form after reaching its summer minimum extent in September. As the Earth begins to tilt away from the Sun, daylight hours begin to shorten. With lessening sunlight, temperatures dip and the ocean surface begins to cool. Once the water column reaches the salinity-determined freezing point, ice begins to form.

In agitated conditions, common in the open Arctic ocean, small ice platelets and needles form called *frazil ice*. Ocean mixing and winds keep these ice crystals in suspension until a surface layer of ice slush builds up into a slurry, termed *grease ice*. Bonding between the individual ice crystals reduces their mobility, damping agitation from the winds and encouraging the transition to a solid ice cover. This takes the form of *pancake ice*, penny-sized floes of ice that accrete into plate-sized pans of ice. At the mercy of the wind and waves, these pans bump and grind against each other to produce a semi-consolidated ice cover comprised of ice discs with raised edges. Further freezing and snow cover turns them into a continuous, solid sheet of ice.

"It was *textbook*," Sarah tells me. As she traveled North along the survey line, she could see the progression of sea ice formation, through all its different stages. The sight left her in tears. She laughs at how she must have appeared to her colleagues, frozen in place as she looked out the porthole, transfixed by the ice. But Roger Andersen, the research scientist who has been involved in over 40 field seasons at the Poles, and Sarah's close collaborator and friend on these flights, does not chide her. He lets Sarah have her moment. Meanwhile, he continues to keep a careful record of measures from the instrument deployments.

Sarah shows me a short video she shot on her smart phone through the plane porthole to illustrate what she means. But she does not need to. That the ice was, in her words, "textbook" has already unfolded like the 2 x 3 panel of photographs I've seen in reference volumes depicting sea ice growth.

Like Sarah, I saw pictures of sea ice before seeing it firsthand. These pictures, what Daston and Galison (1992) call 'scientific atlases,' "habituate the eye," standardizing both practices of observation and that which is observed. They educated me more than any other textual description could on what sea ice looks like. I learn that there are different kinds of sea ice, each with their own identifying characteristics and properties. But beyond this, as a unit they offer a classificatory schema that can be transported into the Arctic. This schema provides a grid through which to order the time and space of sea ice, as one type of sea ice transitions to another or vice versa. And it orders how I arrange thinking about sea ice, how I establish a relation with ice by first identifying it and finding its place within this framework.

"snow and ice for ever"

> "…to see, to have seen, ice and snow, to have felt snow and ice for ever, and nothing for ever but snow and ice, during all the months of a year, to have seen and felt but uninterrupted and unceasing ice and snow during all the months of four years, this it is that has made the sight of those most chilling and wearisome objects an evil which is still one in recollection, as if the remembrance would never cease."
>
> -- Captain John Ross, 14 September 1835, from *Narrative of a Second Voyage in Search of the Northwest Passage and of a Residence in the Arctic During the Years of 1829, 1830, 1831, 1832, 1833*

Uniformity—endless, white, frozen—not to mention despair—defined John Ross' relationship to the snow and ice in the winter of 1831. It was Ross' third winter in the Arctic after he and his men were unable to free their ship, *H.M.S. Discovery*. Ross' description of the ice that winter could not have been in starker contrast to his earlier enchantment with ice on his first voyage to the Arctic in 1818: "It is hardly possible to imagine any thing more exquisite than the variety of tints which these icebergs display; by night as well as by day they glitter with a vividness of colour beyond the power of art to represent" (Ross 1819: 30).

Ross and his crew had come into an abundance of ice, but it was the last thing they desired. The ice had frustrated their goals of finding the Northwest Passage, a sea corridor from the Atlantic Ocean on the east through the Canadian archipelago to the Pacific Ocean on the west.

This was not the first—or last—time that the ice edge would mark the limit to commerce, imperial ambitions, and geographic discovery. Since the 17th century in England, these three interests had become co-terminous in the ship, which could serve as instrument of exploration, holding vessel for men, goods, and scientific specimens, as well as symbol of territorial ambitions.[5]

Trade, science, and imperialism simultaneously drove and routed themselves through marine voyages; in turn, the fortune of these ships stood in for the successes and failures of these various interests. What stopped the ships, whether it was mutiny, scurvy, storms, or ice, halted the advance of this trinity of interests.

Ice was not just an absolute, appearing in the form of an ultimate physical, geographical, and epistemological limit. Knowing how to distinguish ice into different kinds was integral to Arctic-bound expeditions, despite the impression of uniformity that dominated Ross' observations of the ice. Borrowing terminology from whalers, explorers including Ross became literate in ice conditions. They learned to recognize different ice forms, from a *tongue*, or "piece of ice projecting from an iceberg or floe, which is under water," to a *calf*, or "piece of ice which breaks from the lower part of a field or berg, and rises with violence to the surface of the water" (Ross 1835: xxvii).

Explorers not only learned ice conditions for navigational purposes, but were *instructed* to make detailed observations of the extent of open water, as well as the quantity, position, and nature of the ice. Beginning with Ross' 1818 expedition to search for the Northwest Passage, the British Admiralty and Royal Society of London issued Official Instructions to Arctic explorers, which outlined the various kinds of scientific observations to make.[6] Besides noting the position of ice and their conditions, foremost among the scientific observations were: the dip, variation, and intensity of the Magnetic Needle; the temperature; the barometric pressure of the atmosphere; such other meteorological phenomena of note; the depth, temperature, and specific gravity (density) of the sea; as well as the number of whales sighted (Levere 1993). Other observations included those on the regional geology and local flora and fauna. These scientific findings often appeared as appendices to explorers' accounts (see, for example, Parry 1828; Ross 1819).

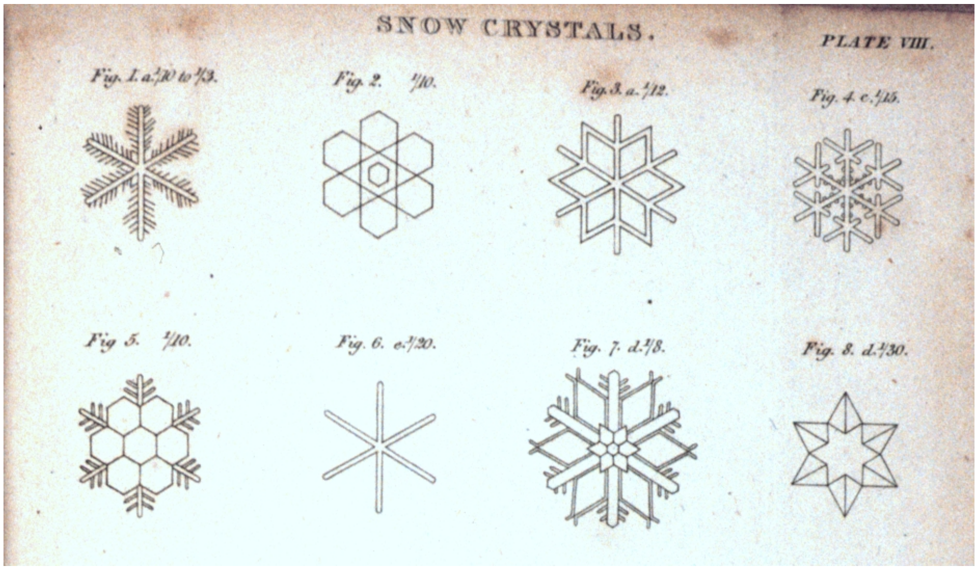
Observations on the ice *itself*, however, did not constitute a separate appendix. Rather, ice structured the narrative of these early expeditions. Such narratives, such as those written by Ross, comprised the main body of text and often related in vivid detail the trials and tribulations, achievements and losses of the captain and crew. It was here that ice could be found.

As Ross and his contemporaries sailed into polar waters, ice was variously the object of admiration and wonder, of contemplation or caution. Ice appears with the regularity of the passing of the days, showing up one-at-a-time or as an innumerable presence. Ice is sometimes present in its absence, observed in the strength of the swell or the temperature of surface waters. Ice is constant, a substance through which the narrative coheres from one day to the next, from week to month, and from year to year.

Ice was both friend and foe. It could ‘nip’ the ship, forcibly squeezing it between sheets of field or drift ice. But ice, specifically bergs, could offer shelter from these very dangers. In writing about his decision to overwinter in the ice after in September 1829, Ross recommended that “the safest, and indeed the only prudent practice, is to take to the ice” (1835: 180). If he was not mistaken, the ice was “the refuge furnished by Providence” (Ross 1835: 180). Ice was both protagonist and antagonist. No other entity—human or otherwise—receives as much attention in the theatre of action that Ross described.

Ironically, it was when Ross is closest to ice—when he had to spend two, long winters working, waking, sleeping—*waiting*—amongst ice that this frozen substance grows invisible. In Ross’, “Narrative of a Second Voyage,” he cannot suffer to mention the monotony of ice and when he does, it is with great pain: “The rocks that had been laid bare were once more covered, so that the landscape was one indiscriminate surface of white; presenting, together with the solid and craggy sea, all equally whitened by the new snow, the dreariest prospect that is possible to conceive” (1835: 240). Ice is a silent background that has not only disappeared from view, but obliterates vision.

“The voyager may be a painter, or he may be a poet,” Ross writes bitterly, “but his talents of description will here be of no value to him; unless he has the the hardihood to invent what there is not to see” (Ross 1835: 240).



salt-water ice

"What is considered *salt-water ice*, is porous, white, and in a great measure opaque (except when in very thin pieces), yet transmits the rays of light with a greenish shade. It is softer, and swims lighter than fresh-water ice, and when dissolved, produces water sometimes perfectly fresh, and sometimes salty…"

--William Scoresby, 1815, from *On the Greenland or Polar Ice.* Figure made by William Scoresby. In: *An account of the Arctic regions with a history and description of the northern whale-fishery*, by W. Scoresby. 1820. P. 588, Vol. II, Plate VIII

William Scoresby was an unusually gifted observer of natural phenomena. Among his scientific interests were meteorology, atmospheric electricity, refraction in cold climates, the natural history of the Greenland whale (*Balaena mysticetus,* or Whalebone Whale), the effect of iron ships' magnetism on the ship's compass—and the formation of ice and snowflakes (McConnell 1986). On his many trips to Greenland, Scoresby placed snow and ice crystals under his microscope and was surprised to discover that the extraordinarily cold Arctic air produced a much wider range of forms beyond the hexagonal form of plane ice-crystals commonly known about. Scoresby quickly captured their forms with pen and paper before they melted, and classified them according to shape and number of axes.[7] Their distinctive forms, Scoresby learned, could be associated them with distinct types of weather. The most beautiful crystals, it appeared, were produced when they fell through extremely cold air.

Scoresby was born in 1789 to an English whaler. He first visited Greenland at age eleven. From the age of thirteen until his early thirties, Scoresby spent every summer with his father on whaling expeditions. In light of these circumstances, members of the Royal Society of London encouraged Scoresby—and often equipped him with the necessary instruments—to make observations of the sea and its phenomena (McConnell 1986). His many voyages to Greenland during this period allowed Scoresby to make repeat observations.

The result was Scoresby's luminous paper, "On the Greenland or Polar Ice," published in 1820 as part of a larger account on the Arctic regions. In content, the paper outlines the physical properties of ice found in the frigid Arctic seas. But Scoresby's paper was not merely a report on his observations; Scoresby offered a language with which to discern order within the world of white. His account begins with a typology of ice:

> The ice in general, is designated by a variety of appellations, distinguishing it according to the size or number of pieces, their form of aggregation, thickness, transparency &c. I perhaps cannot better explain the terms in common acceptation amongst the whale-fishers, *than by marking the disruption of a field*. (Scoresby, 1820: 264 [emphasis added])

By 'field,' Scoresby was referring to a vast sheet of ice, the limits of which could not be discerned from the top of a ship's mast. But his description of the production of difference could just as well have referred to a blank conceptual field on which language dissects space; that epistemic plane on which difference is produced, but which also contains and delimits difference.

Scoresby proceeds to describe, in their succession from large to small, the various kinds of sea ice as they derive from a 'field.' A 'field' can be broken into a 'pack,' the spatial arrangement of which resulted in either a 'patch,' if the ice formed a circle or polygon, or a 'stream,' if the ice was more oblong in shape. Pieces of large dimensions but smaller than a field were called 'floes,' which, if broken into let smaller pieces through attrition, were called 'brash ice.' In this manner, Scoresby stated, "a *field* may be compared to a *pack*, and a *floe* to a *patch*, as regards their size and external form" (Scoresby 1820: 265). Thus, the conceptual field that Scoresby unfolds was co-extensive with the icy material on which he marked discontinuities and grouped things together.

There are striking resemblances between Scoresby's taxonomy of ice and modern ones, despite some subtle differences (WMO 2014; NSIDC 2018). It is easy to conclude that Scoresby's taxonomy was the earliest written incarnation of how scientists think about ice today. But Scoresby did not invent these taxonomies, nor was he the only person to publish them. Such taxonomies were common in explorers' accounts, included as a list of "technical terms" to assist non-sailors in the reading of their narrative (see Parry 1828; Ross 1835); moreover, "whale-fishers," of whom Scoresby counted himself a member, had long used this vocabulary in their daily sailing practices. Scoresby explicitly tapped into this rich tradition of identifying and naming ice to lend science a language for studying ice. Thus, though there is a direct lineage between Scoresby's taxonomy and that of today's, his typology is not presented here because it represents an origin point for ice science, if one can be pinpointed at all.

What is striking about Scoresby's account is the emergence of ice as an entity in itself:

> Of the inanimate productions of Greenland, none perhaps excites so much interest and astonishment in a stranger as the *ice* in its great abundance and variety. The stupendous masses, known by the name of *Ice-Islands, Floating-Mountains,* or *Icebergs*, common to Davis' Straits and sometimes met with here, from their height, various forms, and the depth of water in which they ground, are calculated to strike the beholder with wonder: yet the *fields* of ice, more peculiar to Greenland, are not less astonishing. Their deficiency in elevation, is sufficiently compensated by their amazing extent of surface. Some of them have been observed near a hundred miles in length, and more than half that breadth; each consisting of a single sheet of ice, having its surface raised in general four or six feet above the level of the water, and its base depressed to the depth of near twenty feet beneath. (Scoresby 1820: 263-4)

Ice in Scoresby's paper is not merely the silent background against which other scientific activities, including geographic discovery, take place. Scoresby covered not only a wider breadth of sea ice facets, but extended understandings of sea ice in the temporal dimension: from its formation to its decay; its motions in connection with the winds and currents; its uses among the "whale-fishers"; its changes in spatial distribution and character with the seasons; and its effect on the atmosphere and surrounding sea. He provided a depth of detail on polar ice not available elsewhere in Western European circles at the time. In addition to speaking at length about the differences between "salt-water ice" and "fresh-water ice," he addressed the differences between formation in the open ocean versus formation in sheltered situations and the kind of ice produced in these different circumstances, as well as theories about the formation of field ice and icebergs. In his description of the ice, Scoresby anticipated many of the topics that occupy modern sea ice scientists today, including studies of sea ice optics, dynamics, thermodynamics, physical strength, and interactions with both the atmosphere and ocean.

Scoresby's writing gave ice new dimensions. Instead of being subsumed to a record of operational conditions, sea ice was foregrounded as a substance with a seasonal rhythm, behavioural habits and idiosyncracies, as well as preferred places of residence. Writing within the genre of a scientific paper, sea ice became visible as having an inner life of its own, apart from human interests and activities, which is intrinsically interesting. Arguably, a difference in the *form* and *purpose* of writing made possible a new rendering of ice. But more than this, palpable in Scoresby's writing is an exceptional intimacy with ice. Such intimacy went beyond wonder, which was commonly expressed by explorers visiting the Arctic. In the words of these explorers, the Arctic was invariably described as 'awesome,' 'sublime,' or beyond the power of representation altogether. Wonder certainly illuminates Scoresby's scientific observations, but it did not wholly define the intimacy with which he wrote about ice.

Scoresby's intimacy with ice emerged out of his attentiveness to detail. Like the ephemeral snowflakes that he painstakingly drew, Scoresby gave form to ice in writing. But Scoresby went beyond direct observations of ice, crossing out of the realm of the visible to imagine processes that could not be seen, such as the formation of these fantastic ice masses.

Out of the field of white, Scoresby observed a richness of forms. Perhaps Scoresby had what Ross lacked, an ability rare or even absent even among painters and poets, which was the "hardihood to invent what there is not to see."

"le régime des glaces"

> "The purpose of the expedition is to make, in the Arctic and Antarctic regions, or in the vicinity of these regions, and on as many stations as may be established, synchronic observations, according to a program drawn up in concert. (…) The investigations to be made jointly relate meteorological phenomena, to those of terrestrial magnetism, to the aurora borealis and to the regime of ice."
>
> –Wilczek and Weyprecht 1877, "Scientific Program of Polar International Expedition," translated from the French version by Colin Summerhayes, October 2007

To speak of a 'régime' is to bring into focus a ruling or prevailing system, a form of governance determined by a set of mechanisms. In terms of sea ice, a 'régime' refers to the spatial and temporal patterns of sea ice circulation and the physical processes that govern these patterns. At stake here is not the speciation of sea ice types but a synoptic picture of the ice-covered Arctic Ocean. Curiously, what emerges at this historical juncture is not so much a new concept of 'sea ice,' but a new form of collective scientific activity that would become known as the First International Polar Year (1882-83).

For most of the 19th century, European explorers from different nation-states had competed to be the first to reach the North Pole (e.g., see Berton 1988). The competition had left Karl Weyprecht, a lieutenant in the Austro-Hungarian Navy, and geophysicist and explorer, extremely frustrated. He himself had narrowly survived the unsuccessful Austro-Hungarian North Pole Expedition of 1872-74. After his crew's ship, the Tegethoff, was frozen into the ice, Weyprehct and his crew had to overwinter near Svalbard for two years. This time stranded among the ice and snow gave him plenty of time to think. Weyprecht and other scientists sought to understand large-scale phenomena, from terrestrial magnetism to the "the regime of ice." These phenomena, however, exceeded the efforts of any individual scientist or even nation-state. What was required to study such phenomena was a model of international scientific cooperation that would not only share the burden of cost and risk, but also expand the observational capacity to match the spatio-temporal dimensions of the phenomena under study.

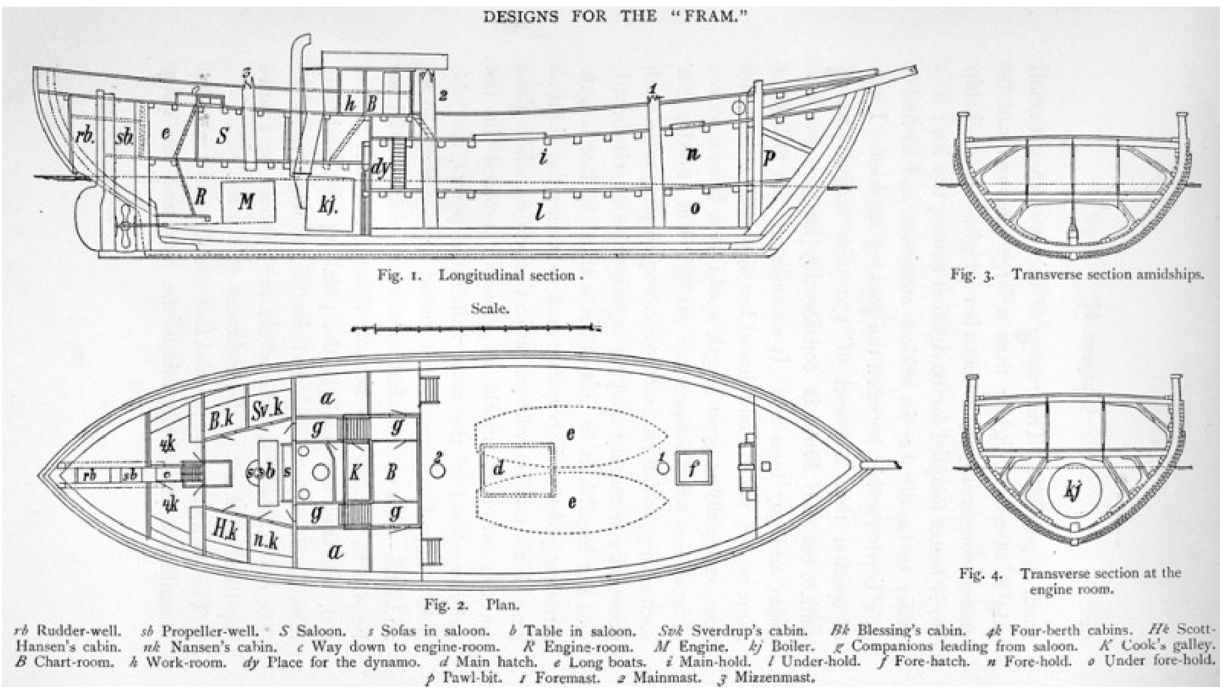
Models for such an approach could be found in the examples set by scientific initiatives of preceding decades.[8] In 1836-1841, the Göttingen Magnetic Association had established an international network of 53 magnetic stations, which culminated in the British 'Magnetic Crusade' to find the magnetic pole of the southern hemisphere. In addition, in 1853 the first International Meteorological Conference was convened by Matthew Fontaine Maury of the US Navy to extend the system of meteorological and oceanographic observations around the globe, which he had introduced on board ships of opportunity of several nations (Tammiksaar et al. 2010). Twenty years later, the International Meteorological Organization (IMO)—predecessor to today's World Meteorological Organization—was established. During the first International Meteorological Congress at Vienna in 1873, scientists sought to standardize methods of observations and analysis, the use of the same units of measure and a single set of symbols, the publication and exchange of results, as well as the completion and extension of the existing observational network. These international organizations, networks of observing stations, and standards of data collection and reporting provided the infrastructure for global scientific cooperation that Weyprecht could tap into (see Edwards 2010).

After returning home from the failed North Pole Expedition, Weyprecht and his friend and supporter, Count Wilczek, developed a scientific proposal for presentation to the second

International Meteorological Congress in Rome in 1877.[9] The presentation laid out six "Fundamental Principles of Arctic Science Investigation," which amounted to a series of conceptual displacements. First among these displacements was the pursuit of knowledge of natural phenomena over exploration. This was encoded in the principle stating that Arctic exploration was of greatest importance not for its own sake but "for a knowledge of the laws of nature." Second, and following from the first, was the de-prioritization of detailed Arctic topography. The North Pole did "not have a greater value than any other point situated in high latitudes," therefore displacing the North Pole from a primary point of interest to just one among many geographical sites of scientific interest. Third, the outlines of natural phenomena would displace geographical features as determinants of northern activities. Weyprecht and Wilczek underscored that the placement of observing stations should be determined by the intensity of the phenomenon under investigation, rather than latitude. Lastly, they argued that isolated series of observations were of only relative value. In other words, continuous, coordinated observations would displace isolated observations. Altogether, Weyprecht's idea could be summed up in the motto *Forschungswarten statt Forschungsfahrten* ("Research observatories instead of research voyages") (Tammiksaar et al. 2010: 9).

Collectively, these displacements suggested a different way of organizing scientific activity that emphasized systematic and synchronous activity through international cooperation. In 1881, organizers finalized the dates of the first International Polar Year (IPY), regular observing days, and the suite of measurements to be taken. In total, 11 nations agreed to send expeditions up to the Arctic to set up special observing stations for the year, which would be supplemented by 30 permanent stations and many ships of opportunity (Baker 1982). Although utilization of the data after the IPY's conclusion was less smooth, the first IPY developed and enshrined principles of polar research: international cooperation, standardization of data collection and reporting, cross-disciplinary exchange, synchronous and systematic observation to yield a synoptic picture of geophysical phenomena (Krupnik et al. 2011).[10] These remain cornerstones for global-scale enterprises like the International Geophysical Year (1957-58) and subsequent IPYs (1932-33, 2007-08), but also for smaller-scale international cooperation in specific communities of research, including sea ice science.

Remarkably, what had guided the organization of coordinated scientific activity was a picture of phenomena on such large scales, from terrestrial magnetism to "le régime des glaces," that it demanded a different configuration of collective activity. It was this vision of meteorological phenomena on global scales, of which sea ice was considered one element, that inspired scientists to weave a net that would be strong and wide enough to capture a picture of the circulation of sea ice. Scientists might even, Weyprecht and Wilczek teasingly hinted, finally capture "a theory of the movement of ice in Arctic regions" if the weave of their net was regularly-enough spaced and cast in sync.



drifting ice station

def'n: Temporary or semi-permanent facility built on drift ice (pack ice or ice islands) in the high latitudes of the Arctic Ocean (from *Wikipedia*, 'drift station,' 'drifting ice station'). Section and plan drawings for *Fram*, as agreed upon by Nansen and shipbuilder, Colin Archer, from Nansen's (1897) book "Farthest North."

The forms that sea ice took in its encounters with European explorers and scientists alternated uneasily between hazard and scientific object of study. In between the two was a sharp, and sometimes fatal, discontinuity. So when Norwegian polar explorer and scientist, Fridtjof Nansen, proposed an expedition in the 1890s that would literally freeze his ship into the ice, his contemporaries were immediately critical. Admiral Adolphus Greely bitingly summed up Nansen's plan as an "illogical scheme of self-destruction" (Greely cited in Nansen 1897). When

Nansen and his crew finally returned from their three-year drift across the Arctic, their expedition introduced the possibility of a new concept of sea ice as neither object of study or hazard, but as scientific instrument.

Nansen's expedition began as an attempt to prove the existence of a trans-Polar current across the Arctic Ocean. Just a few years before, items from the shipwrecked *Jeanette* were discovered on the west coast of Greenland. Contrary to every other expedition that had tried to reach the North Pole, the *Jeannette* had drifted *north* in the desired direction. Every other attempt to reach the North Pole—namely those that approached from the west near Greenland—had been blocked by ice floating southwards, and were even carried away from their goal by masses of drifting ice. In only two cases, that of the ice-bound *Jeannette* and *Tegethoff*—both of which approached the North Pole from the east—had the vessels drifted northwards within their icy prisons. Nansen was convinced that there existed a prevailing current that crossed the central Arctic Ocean and left through the strait between the coasts of eastern Greenland and western Svalbard.

Nansen outlined his plans for the expedition. He would take a small but strong ship to the Arctic, supplied with enough coal and provisions to last five years for twelve men. The ship would have an engine and also be rigged for sailing, but the vessel would mainly act as a fortified holding place built to withstand the pressures of ice. Nansen envisioned building a ship with rounded sides "like a bowl, or half an egg" that would simply rise "like an eel out of the embraces of the ice" (Nansen 1897: 62) instead of being crushed by it. The ship would sail up through the Bering Strait towards the New Siberian Islands and advance as far north as possible. When the time came, they would let the ship freeze into the ice: "Henceforth the current will be our motive power, while our ship, no longer a means of transport, will become a barrack, and we shall have ample time for scientific observations" (Nansen 1897). By these means, Nansen hoped to drift across the North Pole. He was confident that once the ship traveled into more southerly latitudes, the ice would release the boat and they would be free to return home. The metamorphosis of ship into sea ice and back again was fundamental to the success of Nansen's proposed expedition.

Nansen's plans provoked vociferous criticisms. Broadly speaking, Nansen's plan transgressed the rule of maintaining independence from the ice, which was seen as incompatible with the ship. As Admiral Sir George Nares noted, "when once frozen into the polar pack the form of the vessel goes for nothing. She is hermetically sealed to, and forms a part of, the ice block surrounding her. The form of the ship is for all practical purposes the form of the block of ice in which she is frozen" (Nares cited in Nansen 1897). Thus, by freezing into the ice, the ship underwent annihilation, not necessarily physically but in terms of functional irrelevance. Moreover, by freezing his ship into the ice, Nansen would relinquish navigational control and the autonomy that the ship's form provided; in Nares words, he would "be forced to submit to drift helplessly about in agreement with the natural movements of the ice in which he is imprisoned" (Nares cited in Nansen 1897). Lastly, critics argued, there was no record of any ice-beset ship that had managed to separate from the ice even in the height of summer. The very premises of Nansen's plans, in other words, were the basis of the criticisms directed against him. According to the navigational rules that guided explorers in icy Arctic waters, Nares pointed out, Nansen's proposal was irresponsibly reckless.

In addition, Nansen's plan flew in the face of accepted knowledge about the physical conditions of the polar regions. No one had yet reached the North Pole and so it was unclear what, exactly, lay at this geographic point. The theory of an "Open Polar Sea" enjoyed wide support at the time (Summerhayes 2008). The theory—evinced in world maps from the 16th century, which depicted an open sea circled by a ring of islands connected by four channels to the world's oceans—had been revived in 1818 when Scoresby reported that the waters were remarkably ice-free, and rekindled the search for a Northwest Passage. The notion of an open polar sea motivated the succession of voyages in search of Captain John Franklin's lost expedition from 1848 onwards whose commanders supposed that the expedition had become trapped in the open polar sea and were trying to penetrate the surrounding icy barrier to return home (see Kane 1853). The theory received support from various scientific luminaries including M.F. Maury of the Naval Observatory, Harvard zoologist Louis Agassiz, Columbia anthropologist Franz Boas, and Yale geologist James Dana (Summerhayes 2008). Others contended that an enormous continent of ice must lie northward. Should Nansen encounter land or a continent of ice, his expedition would founder on its shores.

Although Nansen's plans were controversial, competition among nation-states to reach the North Pole first worked in Nansen's favour. He received financial support from the Norwegian government, as well as from private sources, to launch his expedition. With these funds, Nansen hired Colin Archer, Norway's leading shipbuilder, to design and build his ship. The result was the *Fram*, meaning "forward" in Norwegian, a ship designed with a shallow draught and a 'double-ended' body. Of the crew, Nansen selected 12 men from among thousands of applications from around the world, among whom was included future Antarctic explorer Roald Amundsen and scientist Otto Sverdrup. On 24 June 1893, the *Fram* left Christiana (today's Oslo) to great fanfare.

On 8 October 1893, the *Fram* froze itself into the pack ice north of the Lena River in eastern Russia. For three years, the pack ice carried it across the Arctic. In April 1896, the ice began to break up and soon afterwards, the steam was raised for the first time since *Fram's* besetment. By June, a lane of water opened up and the ship was 'warped,' or hauled by anchoring to a fixed object, into a larger basin of water: "After three years, *Fram* was no longer a hulk, but a living ship once more" (Huntford 2001: 425). Although over the course of her drift, the ship never made it further than 86 degrees North, the *Fram* emerged from the ice just northwest of Spitsbergen in agreement with Nansen's original predictions. On 9 September 1896, *Fram* and her crew arrived in Christiana, today's Oslo.[11] The strait through which the ship and her crew passed is known today as Fram Strait. It is the main route that sea ice takes when it floats out of the Arctic Ocean.

The *Fram* expedition gave rise to a new conception or, and way of relating to, sea ice. Ice motion was not only treated as an object of scientific inquiry but as a technology, a scientific instrument in itself. Rather than set a course independently of, and more often against, the ice, one could submit to it. The beauty of *Fram* was its design. Built into the design of the *Fram* was Nansen's understanding of the dynamics of sea ice and his hypothesis of Arctic Ocean circulation.[12] Nansen had in effect, produced a conceptual reversal of sea ice from limiting condition to the condition of possibility for Arctic exploration and scientific investigation. Starting in 1930 until 1979, the Soviet Union organized a series of secret scientific ice drifts, in which a handful of scientific men set up camp directly on the ice.[13] The first American ice drift for scientific purposes was not initiated until 1952 during the Cold War with Fletcher's Ice Island or T-3. Since then there has been a succession of ice drift experiments conducted by the US and nations from around the world that are too numerous to mention here.

"an ocean painted white"

> "The earliest 'global climate models' were energy balance models…These models accounted for the ice-albedo feedback by parameterizing the ocean surface albedo as a function of sea surface temperature. Thus, sea ice was essentially modelled as an ocean painted white."
>
> --Cecilia Bitz 2010, "Numerical modelling of sea ice in the climate system"

Beyond ongoing efforts to classify sea ice and describe its patterns of circulation, sea ice began to figure differently in the 1950s with the emergence of global climate models. From the perspective of the global climate system, sea ice was neither peripheral, or inconsequential, to the climate system because of its geographic location but key to shaping climate on global scales. What nudged sea ice into a position of global significance was its reflectivity or, more precisely, its albedo.

In Latin, the term 'albedo' means "whiteness." Scientifically speaking, albedo is the ratio of sunlight reflected by a surface to the amount of sunlight that strikes a surface. It is a dimensionless metric with values that scale from zero (a surface that absorbs all incident light) to one (a surface that is perfectly reflective). Freshly fallen snow is the brightest naturally occurring substance on the Earth's surface with an albedo of 0.9. Ice and clouds (albedo 0.4-0.8) follow in succession with their relatively high albedos. By contrast, the ocean (albedo 0.1) is one of the darkest naturally occurring surfaces on the Earth's surface.

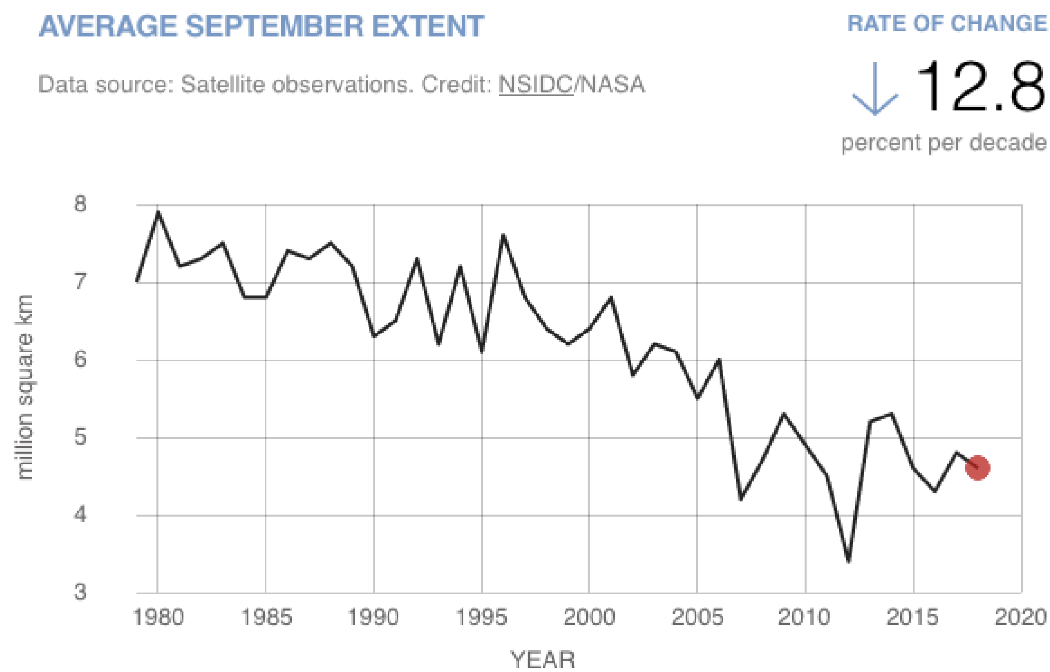
Early global climate models (GCMs) were relatively simple. Conceived in terms of an 'energy balance,' these models accounted for all the energy that entered and left the climate system. The term 'balance' assumes that the system is at equilibrium—there is no loss or accumulation of energy. Assuming that the Earth receives more solar energy compared to at the poles, another key assumption in energy balance models was the redistribution of heat from the equator to the poles to stay in radiative equilibrium. Together, the concepts of radiative balance, heat transport from warmer to colder regions, and albedo—which determines how much energy is reflected or absorbed at Earth's surface—formed a "minimal model of climate" (Thorndike 1999). In this minimal model, the most important feature of sea ice is its albedo. Since snow-covered sea ice reflects more than 80 percent of sunlight, it helps keep the Earth in radiative equilibrium, without which the ocean would absorb much more heat. Put simply, climate at global scales encouraged modellers to treat sea ice as "an ocean painted white."

For decades, 'sea ice' remained highly simplified, despite the emergence of growing computational power. 'Sea ice' remained simplified because its reduction to a single metric, albedo, was a powerful way to mediate between observations and models. Albedo offered modellers a convenient 'tuning knob'; that is, "adjustments made to model parameters to produce a reasonable sea ice cover" (Bitz 2010).[14] Instead of tinkering with the model's structure, which risked disturbing the intricate machinery of the model, scientists could simply adjust a single number—sea ice albedo. Compared to other components in a model that are explicitly calculated from constitutive equations, the values of albedo were assigned an empirical value based on observations; or, in scientific terms, parameterized.[15] In other words, tuning parameters offers an easy solution to generate plausible results (see Edwards 2013). Although modellers are aware of its shortcomings, tuning is a common practice, and speaks to the constant balancing act that modellers face as they choose between level of detail against computational cost, or realism against idealizations (Edwards 2010; Lahsen 2005; Sundberg 2007, 2008).

What finally motivated scientists in the early 1990s to revisit their simplifications of sea ice was *not* the incongruence between the simplified 'white sea' in models, and the much more complex 'sea ice' that emerged from observations. Rather, shortcomings in the models themselves catalyzed efforts to reconceptualize 'sea ice.' Scientists were aware of the sensitivity of global climate to processes occurring in the Arctic Ocean, but there remained great uncertainty about its magnitude and overall effect (Curry et al. 1996: 27). In addition, there were large discrepancies in GCM predictions of both present and future climate in the Arctic (Randall et al. 1998). Simulations suggested that climate feedback mechanisms among the sea ice, snow cover, and Arctic clouds might be responsible for the large uncertainty, or spread in results. But as long as sea ice cover was represented in GCMs as a uniform and static white surface, this model component obscured the complex physical processes at work in the ocean-atmosphere-ice system that produced such feedbacks. In short, modellers sought to 'see' sea ice as more than "an ocean painted white."

To remedy the situation, a year-long ice drift expedition called the Surface Heat Budget of the Arctic Ocean (SHEBA) was conducted in 1997-98. This was a large, interdisciplinary project funded by the NSF's Office of Polar Programs Arctic Systems Science program and Office of Naval Research's High Latitude Dynamics program. The goals of SHEBA were to understand the ice-albedo and cloud-radiation feedback mechanisms to improve treatment of the Arctic in GCMs (Perovich et al. 2003). Consequently, scientists took measurements to improve the parameterization of key processes and to integrate new and improved parameterizations. Informed by this framework, scientists designed data collection around the elucidation of these feedbacks, to collect observational datasets of ocean, ice, and atmosphere quantities over an annual cycle. "The expectation is that incorporation of realistic representations of these processes into large-scale models will lead to a much more complete understanding of the total sensitivity of the Arctic air-sea-ice system" (Uttal et al. 2002: 256).

Models, one could say, tuned scientists' sensitivities to sea ice. They expanded scientists' dynamic range of sight, from seeing 'sea ice' in GCMs as a non-uniform, unchanging 'ocean painted white' to a melt-ponded, fractured, brine-pocketed, and topographically variable surface.



sea ice extent

def'n: Sea ice extent is a measurement of the area of ocean where there is at least some sea ice. Usually, scientists define a threshold of minimum concentration to mark the ice edge; the most common cutoff is at 15 percent. Scientists use the 15 percent cutoff because it provides the most consistent agreement between satellite and ground observations (*Quick Facts on Arctic Sea Ice*, National Snow and Ice Data Centre). Figure by NSIDC/NASA.

In the 1970s, satellite data finally granted scientists the ability to grasp global sea ice cover in a single glance. What the network of observing stations first proposed by Weyprecht and Wilczek sought to achieve from the ground could now be seen from a single point in outer space. But satellite data did more than offer scientists a global scale of observation; over nearly four decades, scientists could now give *temporal* contours to long-term variations in sea ice cover.

Long-term records of sea ice are based on passive microwave data. Unlike visible energy, which is how humans see, or infrared energy that corresponds to heat, microwave radiation is less related to temperature than to an object's physical properties, such as atomic composition or crystalline structure (NSIDC 2018). Thus, differences in physical structure allow microwave sensors to differentiate solid sea ice from liquid ocean. Microwave radiation has very low energy levels, requiring sensors to collect emissions over a much larger area—and potentially overlook details such as 'leads,' or openings, in the ice cover. That being said, the microwave radiation emitted by sea ice can be picked up through the cloud cover, as well as by day or night. Thus, microwave sensors can 'see' beyond the limits of both visible and infrared sensors. [16]

The ability to detect microwave emissions of sea ice at all times and regardless of cloud cover allowed scientists to acquire more continuous coverage than ever before. Remote sensing using passive microwave sensors first began in 1972 with the Electrically Scanning Microwave Radiometer (ESMR) on NOAA's Nimbus-5 satellite. In 1978, NASA launched the Scanning Multichannel Microwave Radiometer (SMMR). Although satellite data reach as far back as 1972, these data are not compatible with later records. Consequently, the starting year of graphs begins in 1979. The succession of satellite data has generated almost 40 years of near-continuous coverage of the sea ice cover. Using these data, scientists could begin to sketch the outlines of a new picture of 'sea ice.'

First, satellite data gave rise to new metrics of the sea ice cover. 'Sea ice extent' was one such metric. Strictly speaking, satellite sensors do not 'see' sea ice extent; this is a calculated quantity that scientists derive from passive microwave data. Sensors produce digital images that scientists treat pixel-by-pixel. To calculate sea ice extent, scientists set up a threshold percentage—in this case 15 percent—that sea ice cover must meet or exceed for a pixel to count as 'ice-covered.' Though less accurate than a straightforward summation of the amount of sea ice in the total area (sea ice area), this binary threshold approach ensures that ice coverage observed by satellites is real. Moreover, comparisons in the late 1980s between plane surveys of sea ice and satellite observations established that 15 percent ice concentration showed greatest agreement between the two types of remote observation (Cavalieri et al. 1991). In scientific algorithms to calculate sea ice extent, the 15 percent threshold is just one variable among others that account for the shortcomings of satellite observations, which can be imprecise due to limited spatial resolution, interference from weather, how land is subtracted from ocean, and inter-satellite differences in measurements and flight paths (Eicken et al. 2009). In developing algorithms that produce these metrics, human scientists have had to learn to 'see' like satellites.

Since the 1970s, sea ice extent has since become a proxy for the state of pan-Arctic sea ice cover. If satellite sensors returned images of sea ice cover in a single glance, metrics like sea ice extent enabled scientists to diagnose sea ice cover with a number. Scientists were aware that this abstraction of sea ice to a single dimension came at the expense of other information, such as sea ice thickness, which can inform scientists about the rates of melt (or freeze-up) (NRC 2012). But the reduction of sea ice cover—with its intricate spatial outlines—into a single quantity made possible a new perspective on sea ice: scientists could compare sea ice extent over time.

Two major features stood out in this time series: variability and long-term trends. The 'wiggles' in the plots show the annual variability. This variability is strongly shaped by the seasonal cycle in which sea ice grows in fall and winter, and melts in spring and summer. Peaks and valleys correspond to the maximum sea ice extent in March and minimum in September, respectively. In addition, the time series of sea ice extent cast into sharp relief the steady decline of sea ice extent from 1979 to the present. As one can see from the plot, the seasonal cycle of ice growth-and-melt follows this downward trend; that is to say, over time both the maximum and minimum extent sea ice extent are falling lower and lower on average. In 2007, the rate of decline was 11 percent per decade; as of 2018, this had increased to 12.8 percent per decade. Said differently, the last six lows in the satellite-record had all occurred in the last six years since I began fieldwork in November 2014. In 2007, sea ice extent bottomed out at an unprecedented low of 4.67 million square kilometres, which was shattered again in 2012. The sea ice minimum from 2012 holds the record low at 3.61 million square kilometres. For reference, the September sea ice minimum for 2018 was 4.59 million square kilometres, tying with 2008 and 2010 for the sixth lowest minimum extent in the satellite record.

Besides the decline in Arctic sea ice, what the long-term satellite record made clear was the value of taking consistent longitudinal measurements. Without a time-series of data, environmental 'change' as an epistemic object would have been invisible, or at least more difficult to discern from other surface-based data. This recognition has motivated efforts to ensure there are no gaps in the remote sensing data record and to ensure compatibility between measurements to continue this long-term record. This is the motivation behind Operation IceBridge, a series of annual plane surveys conducted by NASA to "bridge the gap" in polar observations between the decommissioning of the Ice, Cloud, and Land Elevation Satellite (ICESat) in 2010, and the launch of ICESat-2 in Fall 2018.

Satellite data have had a profound influence in spheres beyond the strictly scientific realm. In the public consciousness, as well as philosophy and politics, satellite images of Earth from outside itself provided a new visual language and analytic vocabulary for thinking human collectivities and being human (Jasanoff 2001; Lazier 2011). In this view, images of pan-Arctic sea ice extent have become a global icon and sentinel of anthropogenic climate change.

first-year ice

def'n: floating ice of no more than one year's growth developing from young ice; thickness from 0.3 to 2 meters (1 to 6.6 feet); characteristically level where undisturbed by pressure, but where ridges occur, they are rough and sharply angular (*Cryosphere Glossary*, National Snow and Ice Data Centre). Photography by author: Chukchi Sea, May 2015.

"The ice looks flat."

Melinda Webster, at the time a doctoral student at the Polar Science Centre and now a NASA research scientist, shares this observation with her scientist colleagues and I. She gestures outside the cafeteria window of Ilisagvik College to the plateau of first-year ice, stretching from the shores of Utkiagvik out into the Chukchi Sea.

I trust that her observation carries meaning, especially to the other scientists attending the 2016 Sea Ice Summer Camp (see Holland and Perovich 2017). But I'm insensible to its larger significance. The flatness of sea ice is so basic to how I have come to know sea ice, I have forgotten to see it at all.

Flatness is what I associate with the ice-covered sea just off the coast of Utkiagvik. In Utkiagvik, relatively flat first-year ice gives dimension to the outside world. It makes a smooth surface over which our sled runners glide as we travel from laboratory to sampling sites on the Chukchi Sea and Elson Lagoon. First-year ice joins distant places but stretches distance, too, turning the ocean and land into a continuous plane. Where the frozen sea meets sky there is a faint line delineating one plane from another. The ice flattens space, reduces perspective to a horizon.

In the two trips that I have come here—for a month in Summer 2015 with the rotten ice team, and for 10 days in 2016 at the Summer Camp—the ice I know best is flat. I'm aware that sea ice can contort into fantastic, tortured shapes, thrust upwards and under each other by ocean currents and winds. One afternoon, a group of us travels by snow machine over the pan of first-year ice extending out from the coast. We pass a solitary, broken mound of ice. It towers in my memory from a greater height than the photographs show. But within the field of uniform, flat topography in which it stood, the sudden appearance of this cairn of ice is eerie, mysterious, and bewildering. An anomaly in my field of vision reminding us that sea ice can be a highly dynamic layer, buckling and spreading, faulting and folding, building its own topography.[17]

But in my limited experience I take flatness for granted as not only an identifying characteristic of first-year ice but, letting myself slip into stereotypes, as synonymous with it.

Flatness has conditioned how I see; this trait even comes before sea ice as a frame of reference, flattening out the possibility to see sea ice independent of my typology.

So Melinda's remark about the first-year ice this spring takes me by surprise. Is the ice flatter than usual, then? And what does this flatness potentially indicate? For months afterwards, I carry her remark around, not sure why it floats to the surface of countless fieldwork impressions and not others.

The topography of sea ice, she explains to me after I have left Seattle and returned to Toronto to write, is potentially changing in the Arctic, although scientists debate in what way. First-year ice in the Arctic is becoming more prevalent. As the summer season lengthens in the Arctic and more sea ice melts, first-year ice may become more prevalent. What might the effects of the ice cover have on surface heat budget and ice motion? On one hand, the overall surface of the region could become smoother. But on the other hand, since first-year ice is also thinner it is also susceptible to more frequent and stronger dynamic forcing than before, making the surface rougher.

At Summer Camp, Melinda and her colleague, Chris Polashenski, who works for the Army Corps of Engineers Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire, had shared similar observations about how vast the flat patches were. It seemed, at least to them, that there was more ice being crushed and forming fields of ice rubble in their previous visits to the field. Regions of deformed ice still exist but they were not as extensive as they remember; by contrast, the stretches of flat ice seemed to be growing larger.

Of course, these impressions are anecdotal and must be borne out through more rigorous research. A reader might even suggest that residents in Utqiagvik could offer some crucial insights that would contextualize and enrich this observation. The challenge of investigating changing surface topography in the Arctic requires keeping in view both multiple conceptual frameworks, such as the thermodynamics *and* dynamics of sea ice; the anecdotal and the systematic. All these dimensions are inseparable in efforts to understand sea ice. And that, Melinda tells me, is the beauty of the challenge. It pushes people "to think beyond narrow, pre-given boundaries"; to work at, and within, the interstices of accepted concepts against which 'sea ice' gains definition, in order to understand the "bigger picture." It is the way in which 'sea ice' exceeds these basic conceptual frameworks that she finds most interesting.

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'Sea ice' does not stay still. It drifts and deforms, reforms and ruptures. 'Sea ice' is an object in motion. The ways in which sea ice as a scientific object has so far come into being—from Rossby's ice blindness to Scoresby's intimate studies of salt-water ice, Wilczek and Weyprecht's displacements of international competition to make room for international science, to Nansen's inversions of navigational rules—are neither given or self-evident. The works of Scoresby, Wilczek and Weyprecht, as well as Nansen speak to the labour of producing 'sea ice.' Constituting sea ice requires the development of classificatory schema, different modes of organizing scientific activity, and innovations in instrumentation. These different techniques also speak to the multiplicity of ways in which sea ice is conceived and engaged as a scientific object. The forms that sea ice have taken in the previous entries show an inextricable coupling between epistemic techniques and the object of interest.

In the emergence of different taxonomies, research initiatives, and conceptual frameworks to render sea ice intelligible, 'sea ice' has crystallized in variable and impermanent ways. The historical contingency of this knowledge inflects modern concepts of 'sea ice' today, which scientists treat as self-conscious representations, subject to change or to dissolve altogether.

As Arctic explorer Frederick Cook remarked on his attempt to reach the North Pole in 1911:

> All the world on which we travelled was in motion. We moved, but we took our landscape with us. Our footing was seemingly a solid stable ice crust, which was, however, constantly shifting. (Cook 1911 cited in Gosnell 2005: 191).

To follow in the footsteps of sea ice scientists is to travel on this moving landscape, to track the movements of knowledge as it takes form through 'sea ice,' and to follow 'sea ice' as it emerges through scientific activities. As sea ice scientists encounter a changing Arctic in the context of global climate change, sea ice science and conceptions of 'sea ice' itself are still in-the-making.

Interlude: Metamorphosis

Sea ice belongs to both sea and sky, and also to neither. In North America, the academic department in which sea ice science is housed often reflects this ambiguity. Sea ice scientists are variously incorporated into Departments of Atmospheric Science, or Oceanography, or both. Sometimes, it is found in Geography, a relic of how climate science became a field of its own. Today's Atmospheric Sciences Department at the University of Washington, which currently houses cryospheric research, was formerly a meteorology degree program offered within the Geology and Geography Department. It was not until 1947 that a separate Department of Meteorology and Climatology was established, its members motivated by the desire to emphasize their field as a physical science and differentiate their work from geography as a social science.

The integration of ice research into the UW's Department of Meteorology and Climatology was more the outcome of idiosyncratic research interests than historical necessity. At the time, acting Department Chairman Phil Church was particularly interested in air-sea interactions, boundary layer processes, and glaciology. These interests led him to invite Norbert Untersteiner, at the time an Austrian scientist at the University of Vienna, to become a permanent faculty member in 1962.

Norbert had just finished working as Chief Scientist on Ice Station Alpha for the 1957-58 International Geophysical Year (IGY) where the UW led the research program on Arctic sea ice physics. Previously, Norbert had conducted research on glaciers in the Alps and in Pakistan. His turn to sea ice as an object of study emerged out of a serendipitous turn of events: the evaporation of funding for a post-doc on glacier research, which was compensated for by offering him a position to work in the Arctic.[18] Studying sea ice *on* sea ice was not only a first for Norbert, but also a first for the United States as a nation, which had until now established drift stations for scientific and military purposes on icebergs in the Arctic (e.g., T-3).

When Norbert accepted Phil's offer, his arrival at the UW coincided with several more transformations in the Department of Meteorology and Climatology. Beginning in 1965, faculty began to work on establishing a new interdisciplinary Geophysics Program that would focus on Quaternary research, snow and ice research, upper atmosphere research, and air-sea-ice interactions. The program became operational in 1967, the same year that Norbert became Chair of the Department. In his position as Chair, Norbert recruited several experts on snow and ice, who have collectively transformed the UW into a global centre of cryospheric research. These changes in the Department also marked the beginning of the UW's long-term and systematic study of the Arctic.

In particular, Norbert, together with his colleagues in the Department, Gary Maykut and Allan Thorndike, began a new initiative: the Arctic Ice Dynamics Joint Experiment (AIDJEX). In the years after doing work at Ice Station Alpha, it had become apparent that the "missing link" in developing a more physically-sound model of sea ice was better understanding of the mechanical behaviour of sea ice: Why did a crack form here, and not there? How did a crack at this point in a floe of ice influence morphological features at a different location on the same floe? What could the morphological features of ice—its ridges, hummocks, leads, shapes and sizes of floes—tell scientists about past stresses and strains internal to a field of ice? AIDJEX would address these kinds of questions by approaching sea ice as a deformational field, an assumption reflected in its experimental setup, which consisted of four manned ice stations around a central point to make systematic and synchronous observations at different spatial locations (see Untersteiner et al. 2007).

AIDJEX lasted from 1970-78. At its completion, scientists were able to produce a model on ice thickness distribution (Thorndike et al. 1975), which remains the cornerstone to sea ice models today. But beyond generating a valuable dataset and knowledge about sea ice dynamics, AIDJEX morphed into today's Polar Science Centre and the International Arctic Buoy Programme. Both these mutations would see to it that the work initiated by AIDJEX would continue in the future, even though AIDJEX itself had come to an end. Thus, the PSC grew directly out of the study of sea ice, though the interests of its scientist members today include glaciers and ice sheets, marine mammals, Arctic microbiology, and extraterrestrial ice. From material substance to research project, from long-term science programme to research centre, sea ice metamorphoses over and over again.

Chapter 2.

Rotten ice

The interview

The month of May this year in Seattle (2015) has been warm and dry. Sunshine strikes foliage and splits into a thicket of green; where air meets water, light scatters into a dazzle of reflections. The world takes on crisp definition: boats glow, cars flash, planes shimmer. Even the sky has a rare clarity to it.

The Polar Science Center sits at the top of a bight of water, where the waters of Portage Bay loop around a point and flow into South Lake Union. The south-facing window of the Polar Science Center conference room frames the view in one long sweep, wrapping around from Montlake in the east, to the Space Needle in the west. The Interstate-5 bridge makes a dark slash across the scene, segmenting the downtown skyline from the rest of the cityscape.

The view offers a panoramic background to the Rotten Ice team's weekly lab meetings. For months, the team has wrestled within the walls of the conference room, ironing out sampling plans, negotiating competing disciplinary conventions and personal priorities, tinkering with equipment, and establishing self-imposed deadlines to give concrete shape to their project. As the team members engage in friendly intellectual sparring, sunshine fades into rain; rain gives way once more to sunshine. And the city silently moves on by.

A tableau is also in the making inside the conference room. Bonnie, Karen, and Carie—three of the five-member Rotten Ice team—arrange themselves on the side of the oval table, facing the window. Hovering over the team is a padded microphone, its slender arm extending across the table and down into the hands of our visitor, Brian Rasmussen, the Communications Manager for the UW's Applied Physics Laboratory (APL). He has come to conduct a video interview of the scientists and their research on rotten ice. The team generally understands that this footage will probably be included in the APL's annual report, although the video interview lends itself as well to public outreach and APL promotional material.

The Team nods and signals for the interview to begin.[19]

"We are studying the ice as it melts," Karen explains, looking at Brian, "and we are really interested in studying a kind of ice type that hasn't been looked at before that we call 'rotten ice.' So, it's like heavily melted ice."

"Usually," Brian comments, "when I think of 'rotten,' I think of chemical and biological transformation. I think of *flesh*…"

Bonnie corrects him. "The rotting is *physical*," she explains. I remember Bonnie describing rotten ice to me for the first time almost a year previously. *Think of Swiss cheese*, she had said, *a solid full of holes, something compromised structurally from the inside-out and ready to give out*.

Bonnie elaborates on the physics of melting ice. "During the melt season, sea ice can melt from the top by absorbing solar radiation. It can melt from the bottom because the ocean around it absorbs solar radiation and heats up and then there's warm water underneath the ice. But it can also melt kinda from the inside-out because of its microstructure. So it has these sort of conduits of fluid inclusions throughout it."

"So," Bonnie continues, "I think that's kind of where the name, the moniker, 'rotten ice' came from because sometimes it can just literally melt from the inside out at the same time it's melting from the edges and the top and the bottom."

The team comments on its composition. Bonnie is a physicist, Karen a microbiologist, and Carie a geomicrobiologist. The other two team members, biological oceanographer Monica and microbiologist Shelly, could not be present.

"It's really important that the team is interdisciplinary," Karen explains, "because there's the structure of the ice and the ice harbours these organisms—the algae and bacteria produce substances that are called polymers and gels and they all interact with each other and also they seem to interact with the ice structure."

These biological properties, Bonnie adds, have sometimes been treated as "impurities" in sea ice, at least among sea ice physicists. But, Bonnie comments, "I'm warming up to the idea of thinking about this kind of whole system of these constituents in the ice because they're very much a part of the ice system."

This interview offers a short cut of the rotten ice project. First, the interview arrests in time the rotten ice project at a specific moment, specifically before they had completed their 2015 field campaign. Second, it captures some of the aspects of the rotten ice project that drew me to this research in the first place: its inter-disciplinarity, the choreography between Arctic fieldwork and laboratory experimentation, and its novel conceptualization of ice. From my understanding, the team was attempting to study a type of ice that had received little attention to date, but they were approaching it as a bio-chemical-physical *unit*.

The very tentativeness of the rotten ice project, and its conceptual framework as a bio-chemical-phyiscal unit, made it fascinating from an anthropological and STS perspective interested in science as practice. On one hand, 'rotten ice' invited anthropological engagement with sea ice as a situated 'becoming-with' (Haraway 2008). On the other hand, in their efforts to think sea ice differently, the rotten ice team proposed to work in a space unbounded by their individual disciplines. This epistemic space, though, did not yet exist. It was the scientists' primary task to give shape to this space. A completely different configuration of equipment, standards of practice, and disciplinary knowledge had to be put together in which rotten ice could be provisionally stabilized, approached, and tested for coherence, durability, and reliability. In short, before rotten ice could be brought into being, the scientists first had to prepare the technical conditions of possibility for rotten ice to emerge.

How would the rotten ice team construct their object of study? In what ways was 'rotten ice' an outgrowth of previous conceptions of sea ice (and hence, an extension of my field guide to sea ice in Chapter One)? What possibilities for thinking and understanding sea ice was the work on 'rotten ice' giving rise to? These were the questions that initially guided my anthropological exploration.

But as I revisited the rotten ice project, again and again, in my field notes, and then in writing and revising this chapter, I realized that my sketches might not just be a moving picture of 'rotten ice' in-the-making. In fact, as I looked at the images I wrote, 'rotten ice' the object was nowhere in sight. Instead, there was a dizzying assortment of measurements and a string of moments in an ongoing process of making (and unmaking) that did not add up to a coherent object, to which one could point and say, "A-ha! *That* is rotten ice." This unfinished aspect could be explained away by fact that I had not stayed to the 'end' of the team's research (if such a time exists). But this does not provide a satisfactory account for how and why the team continued on with their research *in media res* without a clear object before them that, furthermore, may not be realized at all. What was I writing about, then, if it was *not* about 'rotten ice'? It occurred to me that I was not writing about a scientific object, per se, but objectivity as a process. This particular practice of objectivity was not reducible to a technical or organizational problem but suggested a certain orientation or attitude that was necessary in making a scientific object without the certainty of it becoming as such.

Scientific objectivity, as various scholars have shown, is *produced* and not given. Scientific objectivity is not necessarily about 'truth to nature' (see Daston and Galison 1992), but, rather, success (Knorr-Cetina 1979), do-ability (Fujimura 1987), translations and displacements (Latour and Woolgar 1979; Latour 1987), or 'what works' (Bemme, forthcoming). In feminist studies, scholars have shown that taken-for-granted universals can silently encode and re-entrench biases in its selection (or omission) of what counts as research topics and in the language of scientific descriptions (e.g., Fox Keller 1983; Haraway 1989; Harding 1991; Traweek 1988). 'Objectivity,' in other words, is not a timeless, stable or unitary concept (Daston and Galison 2007), but a set of practices, rules, and attitudes that has been, and can be, *otherwise.*

What situated practice of objectivity was taking shape through the rotten ice project? This chapter is organized as a series of 'slides,' much like the microscopy slides that the scientists put together. The arrangement of the project as 'slides' reflects the forward moving, uncertain trajectory the rotten ice project at the time of its happening, as much my own attempts to make sense of these moments. Each 'slide' seeks to stabilize, rather than dissolve, the distinctive uncertainties and difficulties in the making of 'rotten ice.' The project both preceded my arrival in the field in July 2014 and continued after I had left in December 2016. At the time of this dissertation's completion, the team was submitting a paper for publication on the physical and optical characteristics of rotten ice (see Frantz et al. 2019). The work of the rotten ice project, however, is not yet finished.

SLIDE 1: The Plan

The seed for the rotten ice project came from the field. Bonnie was conducting fieldwork on the Healy icebreaker in July 2010 when she noticed chunks of ice floating around the boat. The ice, Bonnie remembers, was riddled with holes and discoloured. As she studied the ice from aboard the Healy, the word '*rotten*' surfaced to mind. The term lent specificity to the kind of ice before her. What held her captive was the idea that there might be some important interplay between the physics of sea ice and the biology in this kind of ice. As Bonnie notes, rotten ice is not necessarily new in the Arctic. In fact, there was probably rotten ice floating around on her previous trips to the Arctic but she had not noticed it before. After the research cruise, Bonnie carried the idea of rotten ice back to the Polar Science Center where she recruited the expertise of microbiologist, Karen Junge who had recently returned from maternity leave, and biochemist, Monica Orellana. With their help, Bonnie's observation germinated into a full grant proposal, which Bonnie, Karen, and Monica wrote together.

The team's first submission in 2011 to the National Science Foundation did not pass peer review. It is commonly difficult to find reviewers who had the expertise to evaluate the feasibility and scientific merit of interdisciplinary proposals such as this one proposal. Typically trained in a specific scientific discipline, reviewers' evaluations were limited to those parts of the proposal that corresponded with their disciplinary expertise; they were less equipped to assess the project as a whole. If the proposal failed in the first round of reviews, it was likely because it fell outside the sphere of traditional expertise rather than because it lacked scientific rigour or feasibility. After a re-submission in 2013, the rotten ice project finally received funding.

In brief summary, the rotten ice project situated itself within the context of a longer, and warmer Arctic melt season. Summer sea ice cover is changing in dramatic ways. Not only is the summer sea ice cover shrinking, but the *kind* of Arctic sea ice was changing. One of the clearest signals of change is the disappearance of multiyear ice, or sea ice that has survived several melt seasons and is anywhere between two and five meters thick. Until the mid-2000s, multiyear ice had characterized the Arctic, whose land-locked ocean acts like a pen for growing and protecting ice. But since 2007, multiyear ice has disappeared from the Arctic with alarming rapidity. Today, the Arctic Ocean is shifting into a different ice regime dominated by younger and thinner ice. But, argued the rotten ice team, pan-Arctic sea ice cover is not the only metric of change that merits attention.

Ice integrity, the scientists argued, also warrants close study. Due to its salt content sea ice is highly porous, filled with air bubbles and brine channels. The size and distribution of these features on the microscopic level influence ice integrity on larger scales—that is, the ability of sea ice on meter- to kilometer-scales to resist disintegration due to winds and waves, or to seasonal changes in temperature and insolation. But in addition to the effects of salt on ice growth, the rotten ice team argued that the microbiological communities residing inside the ice play an important role in determining ice integrity.

In particular, the team was interested in polymer gels produced by algae. Polymers, as molecules composed of many repeating units, are nearly ubiquitous in the environment. They encompass all manner of synthetic materials, such as nylon and epoxy, to natural materials, such as hair and nails. 'Polymer gels' are conceived as soft, wet, and elastic materials that can undergo large deformation (Osada and Gong 1998).[20] Polymer gels produced by algae, the team hypothesized, could potentially accelerate or retard ice melt by influencing the way fluid, heat, and salt is transported internally within pore spaces of the ice microstructure. Understanding ice integrity, then, must take these biological constituents into account. This becomes especially important in light of the lengthening Arctic melt season, which allows microbiological communities to grow, thrive, and hence exert a greater role on ice-melt behaviour. Sea ice, in short, is changing from the inside-out, and this is precisely what the rotten ice team sought to investigate.

Using this context as a platform, the rotten ice team constructed their two working hypotheses. First, summertime melt processes transform the microstructure of sea ice, which in turn transform large-scale biological, chemical, and physical properties of the ice. And second, that the polymer gels help to preserve ice integrity, thereby providing a crucial link between algae, bacteria, and ice structure. As polymer gels become less prevalent and smaller in size, the scientists expected sea ice to become more 'rotten.'

The aims of the project were ambitious. In basic outline, the PIs would devote the first year of the project to 'methods development' in the laboratory. More specifically, this involved adapting an existing suite of methods for studying more stable, colder sea ice to characterizing laboratory-grown rotten ice.

The first task of laboratory work was learning how to produce rotten ice under artificial conditions. Using artificial seawater, they would grow sea ice as closely as possible according to known natural processes and melt their samples by raising the temperature of the cold room. Different preparations of laboratory-grown ice would be made: pure ice with no added constituents, ice amended with polymers, algae, or bacteria alone, and ice grown with different combinations of biological constituents. On these laboratory-grown samples, the scientists would test and refine existing techniques for characterizing sea ice.

In particular, the team planned to adapt traditional microscopy techniques at cold temperatures to image ice as it melted at warmer temperatures. They would stain the ice with different chemicals to identify the bacteria, algae, and polymers and look at the different preparations of laboratory-grown ice under the microscope, checking to see how the distribution of biogenic particles and ice microstructure changed with warming temperatures. Other techniques to be tested in the laboratory included X-ray tomography of the microstructure of rotten ice and permeability measurements.

The second phase of their project would involve a summer field campaign to sample landfast ice off the coast of Point Barrow, Alaska and in nearby Elson Lagoon.[21] Their choice of sampling location was guided by feasibility considerations as well as previous sea ice research in the area. Since sea ice near Barrow has been well-characterized by previous scientists, findings on rotten ice could be more easily related to existing work on colder, more stable ice.

In addition, the long-standing existence of basic research facilities in Utqiagvik, formerly known as Barrow, and scientific logistics support would make sampling was easier. In 1947, the Arctic Research Laboratory, as it was first known, was established under the US Office of Naval Research amidst the Navy's exploration for oil in the area (Reed 1969).[22] In the following 30 plus years, the research laboratory would come to be a major site of Arctic research activity, which often required recruiting members of the Iñupiat Barrow community for their expertise with the area.[23,24] After a brief period of low research activity following the closure of the Naval Arctic Research Laboratory in 1980, the Barrow Arctic Research Center (BARC) was established in 2002. Run by UIC Science, part of the Barrow village corporation established in 1971 as part of the Alaskan Lands Claim Settlement Act, scientists could secure local logistics support and basic research facilities to facilitate their Arctic studies.

The team's goal was to capture sea ice that had frozen to the coastline, or 'landfast ice,' near Point Barrow over the course of the melt season. They would sample at different time points over the summer and test their lab-developed techniques to get a basic measure of the ice—its thickness, density, salinity, temperature, and microstructure. In addition, they hoped to characterize the bacterial populations, algae abundance, and productivity of these organisms. More specifically, they would measure cell counts and biomass with epifluorescence microscopy, as well as primary and secondary production rates. They also wanted to carry out molecular analyses to determine the genetic diversity of microbial communities and the temporal patterns of their activity as the ice melts.

Last but not least, the proposal mapped out the various roles and responsibilities of the team members. The conceptual partitioning of rotten ice into biological, chemical, or physical components corresponded with the individual expertise and responsibilities assumed by each of the three PIs. Crucially, coordinating and managing the many pieces of the project was a role in and of itself—one which the team hoped to fill by hiring a post-doctoral researcher. Candidates needed to have a high degree of competence in all the disciplines, as well as a head for details, strong organizational abilities and teamwork skills. The person who successfully met these criteria was geo-microbiologist Carie Frantz. In addition, the team recruited research scientist Shelly Carpenter, who had two decades of experience doing cold microscopy and an equal amount of field experience both in the Arctic and Antarctic. She could provide invaluable expertise on field logistics planning and help with processing samples in the laboratory.

The proposal—in ordering the research project as a sequence of events and diagramming the conceptual relations between scientific aims, activities, epistemic sites, and equipment—was a scheme for acting, doing, making, proceeding, etc. It was, simply put, a plan.

From the beginning and throughout its execution, the rotten ice team was preoccupied with plans and plan-making: plans for laboratory experiments, plans for new sampling devices, plans to coordinate workflows in the field, contingency plans, plans for communication, plans to make more plans.

Plans were useful to the rotten ice team because they projected reality in a single glance, whether as a chart of outcome-contingent decisions or as a prototype design for a new instrument. These plans did not assume a simple identity relation between a pre-existing process or object and its representation. These plans were more of a 'project' in that they involved a drafting and redrafting, the iterative inclusion and exclusion of elements and choices about how to arrange these elements into a coherent order from among a multitude of possible arrangements.[25]

If I have reiterated the rotten ice proposal in more detail here, it is because the proposal was the first of the scientists' many plans. It was *the* plan against which their other plans took shape. But for various reasons, and in different ways, the plan would be rewritten and redrafted as it unfolded.

SLIDE 2: Open Plan

324 data points.

Carie shows her supervisors the spreadsheet she has developed. Although it is still November 2014 and the field campaign is not due to start until May 2015, she is preoccupied with drawing up a sampling plan. After all, the scientists must pack the laboratory with them to Utqiagvik.

Carie has never been to BARC before. Reports state that the laboratory facilities are standard but basic. They can expect a Millipore water purification system, sinks with hot and cold water, electrical outlets, fume hoods, refrigerators and freezers. But otherwise, the team has to transport everything else they need, including not only the more specialized equipment (e.g., cold room microscope, centrifuge, microtome, chop saw, pH and temperature probes, salinometer, and ice corer) but sundry laboratory items including pipettes and pipette tips, disposable nitrile gloves, Ziplock bags, whirlpack bags, plastic tubing, falcon tubes, bottles, vials, buckets, weigh scales, ethanol, tape, ruler, markers, and pencils. But to determine which items they need in Barrow and in what quantities, the scientists need to have a detailed sampling plan.

For today's lab meeting, Carie has organized their sampling plan around the anticipated publication of three scientific papers (what Bonnie had called "dream papers"), which they will write together. Moving from left to right, the spreadsheet reads like a conceptual distillery, with overarching research questions processed into specific measurements, concrete sample types, estimated volumes and masses of sample materials, which are further refined into pieces of equipment and supply amounts. A multiplier column lists the number of time points, sampling locations, replicates, and ice sections, which increases the number of measurements several folds over. Carie calculates that the team will need a total of 324 data points to answer their research questions.

The document is impressive. Carie has managed to decompose the project into its component pieces, devise categories into which these parts could be slotted, and project these multiple facets onto a single viewing plane.

There is a moment of silence as the team takes it all in.

"It's probably overly ambitious to try and collect all 324 data points…" Karen begins. They will have to settle initially for the collection of field data; their first paper will thus be *observational*, setting up the team for further lab work to "nail it, perhaps."

Carie is undaunted. She has endured tough assignments in the past and is not afraid of the challenge. In drawing up the current plan, she just wants to make sure they get *results*. She hopes that they can find a way to show that interactions exist amongst the ice, microbes, and polymers without doing any laboratory work.

All at once, Karen, Bonnie, and Monica jump in. *There isn't going to be any 'proof,'* they say. At least, not from field data alone.

"What we hope to get from the data collection is just a snapshot…" says Bonnie.

"…a suggestion…" Monica adds.

"In the end," Karen states, "we hope to generate a hypothesis."

Karen and Monica try to reassure Carie; they are no less concerned about trying to control the variables at play in collecting data and making suitable measurements. And yes, their current understanding is that the polymers are the entities that matter. They must make this statement and design their methods accordingly "while knowing that it may very well be different." It is very likely that they they will go to the field and come back with a different understanding of rotten ice than they arrived with.

"We have to keep our approach open to that," Karen explains. "We don't have a perfect hypothesis or question."

The tension in this early exchange—between preparing for the unknown and allowing for surprise; between arriving in the field with pre-conceptions about rotten ice and encountering something that alters or overturns this idea—re-emerges regularly throughout the planning stages of the project, and is a thread that runs through this chapter. As designated overseer of the project, Carie experiences the tension most acutely. She is the one responsible for preparing the team for the worst: What if the ice blows away from shore and there is nothing close enough to sample? What other contingencies need to be accounted for, and what should be done in each scenario? The field, in this sense, presented a space of divergent possibilities that had to be contained and managed. But beyond the need for contingency plans, the field presented a challenge insofar as it was an unbounded and undifferentiated space. How to delimit the 'field' into a productive epistemic site? How to design fieldwork such that it gave definition to 'rotten ice'? It was precisely the openness of the 'field' that Carie sought to constrain in her sampling plan.

Ironically, but not atypically in scientific research, the "dream papers" that Carie had envisioned publishing with the PIs enabled her to define the field through a series of progressive delimitations. It was a kind of reverse-engineering, if you will, which worked backwards from the claims envisioned for the "dream papers" towards the kinds of measurements required to support those claims. The choice and number of measurements were further constrained by disciplinary standards and conventions[26] Further shaping the choreography of field measurements were assumptions about the epistemological relation of laboratory to field. This was made apparent in Carie's remark about the imperative to design fieldwork so that it could stand alone, apart from the laboratory as the privileged site for producing universal scientific knowledge and a space where nature could be taken apart so as to understand how it works, thereby producing causal claims.[27] The strength of fieldwork, by contrast, lay in opportunities to observe rotten ice *in situ*, the conditions of which cannot be reproduced identically in a laboratory.[28] Altogether, these background considerations narrowed down the 'field' to a set of concrete sampling locations and time-points. Visible in this sampling plan was a progressive tightening of the relationships between hypotheses and sampling plans, which could close in on 'rotten ice.'

But the PIs were wary of precisely such closures. They did not want to design their plans so tightly at the expense of coming across something that did not fit their initial conceptions of 'rotten ice.' What was striking in their orientation was a conscious effort to relax control over their designs—not as an abandonment of reason or reaction against method (e.g., Feyerabend 1975)—but as part of a practice of objectivity. That is, to be 'objective' was to open oneself up to an outside not reducible to human design or preconceptions, whether in the field or in the laboratory.[29] As the scientists suggested in the meeting, 'rotten ice' can, and likely will, exceed their pre-conceived frameworks. Admitting the inevitable inadequacy of one's plans was not fatalistic but the very challenge of their work: to resist completely enclosing 'rotten ice' within definite measures and to design, instead, a net that was tight but flexible, targeted but capacious enough to accommodate its unknowable shape.

Rotten ice was, in other words, an *open* plan.

SLIDE 3: Unplanned

The phase of 'methods development' in the laboratory was one of the most carefully described parts of the scientists' proposal. It was surprising, then, to learn upon my visit to Seattle in March 2015 that scientific plans had gone most awry where the laboratory was involved.

At first, the problem centered on how to grow realistic sea ice.

Usually, Bonnie explained to me, she grows sea ice at lower than natural salinities—24 ppm instead of mean Arctic ocean salinities of 32 ppm—to compensate for the effect of increasing salinity as the ice freezes. In natural conditions, the freezing water is in free exchange with the ocean below, so salty water can be rejected into an infinitely large reservoir as the ice grows. In the laboratory, however, ice formation is limited by the size of the container in which it is grown. As ice forms under laboratory conditions, the water in the reservoir becomes becomes progressively saltier and saltier. The resulting ice tends to have an unrealistically high salinity and a correspondingly unrealistic microstructure. This is why Bonnie begins with lower salinity seawater.

But the microbiologists ruled this possibility out. For their biological experiments, they required salinities closer to what was found in natural sea water (30-32 ppt) in order for their organisms to grow. Otherwise, the algae and bacteria would burst from osmotic shock.

The problem of growing ice to meet these conflicting requirements became a nightmare for the technicians. If they grew ice from seawater at 30 to 32 ppt, it was too salty. The ice would disintegrate even when lightly handled, let alone cut and shaved with a microtome to make thin sections for microscopy.

Trying to grow ice within mutually agreeable parameters was further complicated by volume requirements. Typically, Bonnie continued, she grows sea ice in the laboratory in a 1-metre by 1-metre tank. Again, the larger volume helps counteract the effects of salinity increases with ice growth. But the very idea had driven Monica crazy. For her own experiments, Monica grew volumes of algae on the order of millilitres. She could not begin to wrap her head around growing such large volumes of algae. Karen's own cold microscopy research in the past had involved only ice cube-sized samples.

Different disciplinary practices had exposed a plurality of empirically different sea ice***s***. Moreover, these sea ices were mutually incompatible, given that they had conflicting salinity and volume requirements, and followed different disciplinary standards of validity and replicability. At stake was not only mutually realistic 'sea ice' but the co-production of a shared epistemic space. The two were one and the same.

As various scholars in science studies have demonstrated, lack of consensus does not preclude scientific collaboration (Callon 1986; Latour and Woolgar 1979; Fujimura 1987; Galison 1992; Star and Greisemer 1989). In fact, consensus is rarely its starting point. Rather, different mechanisms, which social scientists have variously called ‘boundary objects,’ ‘immutable mobiles,’ ‘trading zones,’ and ‘standardized packages’ are developed to mediate differences between theoretical frameworks and conceptual assumptions, infrastructures, equipment, disciplinary conventions or standards, institutional demands, and funding mandates to name a few elements that shape collaboration. If anything, these analytics indicate that the goal is *not* to assimilate but to conserve often irreconcilable differences.[30]

Internal heterogeneity, however, was untenable when it came to making rotten ice in practice. To begin making sea ice in the laboratory, the team members had to resolve incommensurabilities into a single set of parameters. The problem of scientific collaboration in this case shifts back onto the grounds of scientific realism, though not in the sense of determining the ‘really real’ sea ice that would judge ‘right’ from ‘wrong’ representations.[31] Such an understanding rehearses well-worn arguments of theory versus observation, idealism versus empiricism, etc. at the expense of taking seriously the activities, interventions, and experimentations that constitute these scientific objects (see Hacking 1983). Put simply, the problem of scientific realism at stake in the rotten ice project revolved around *practice*. To make mutually realistic ‘sea ice,’ it was not going to be sufficient to simply add up the different realisms that grew out of their individual practices; the team had to draw up from scratch a collaborative practice that would produce mutually realistic sea ice. This, however, proved to be more difficult than the team had first anticipated.

“It’s like trying to catch a tiger by the tail,” Bonnie muses out loud, “It’s a hard thing to think about…”

“Of course, all these attempts to reproduce natural conditions in the laboratory don’t matter,” Bonnie adds. “Outside the lab, nature just takes care of it.”

In a first pass, it is easy to dismiss Bonnie’s remark as an assumption that scientific objects are already given and waiting to be found. Such a claim, however, flies in the face of the team’s hard work to produce ‘rotten ice.’ As shown earlier in the ‘open plan,’ neither ‘the field’ or samples of ‘rotten ice’ were given or self-evident, ready to be plucked out of the Arctic Ocean. Far from letting ‘nature’ take care of the science, the team’s plans to sample rotten ice were highly mediated and choreographed. Central to their designs was the making of a ‘field’ and field-*work* in the production of ‘rotten ice.’

Upon closer examination, what is curious about Bonnie's remark is not so much the question of the nature of 'nature,' so much as *what*, exactly, was being taken care of. What is the 'it' in her comment?

At stake was a collective reality, which belonged to no individual scientist or discipline. 'It' was not given in nature, either. Curiously, 'it' could not be produced positively but only in the negative through a series of displacements, from individual disciplines to a collaborative project, from lab-work to field-work. Letting go of growing sea ice in the laboratory, at least for the moment, marked the beginning of a movement of continual displacements during the time I observed the project. These displacements share a likeness with Hans Jörg Rheinberger's (1992) description of "differential reproduction" in experimental systems, which seek to elucidate a scientific object that "is not and cannot be fixed from the beginning," and therefore has a "precarious status of being, in a way, absent in its experimental presence" (Rheinberger 1992: 310).[32] As Rheinberger argues, the object is not absent in the sense of being hidden, but undergoes a process of becoming materially defined. However, whereas scientific objects in Rheinberger's account of experimental systems are only "moments" of an experimental arrangement sufficiently stabilized so to be transformed into the technical conditions for making new scientific objects, the rotten ice team sought a terminal endpoint to their fieldwork. Ultimately, they wanted to collect samples of 'rotten ice' from the field.

The displacements at work in the rotten ice project, moreover, did not consist of a continual relation of exchange and mutual transformation between technological objects and epistemic things. Rather, the displacements of the rotten ice project consisted of a series of unanticipated disruptions in equipment, interdisciplinary practices and relationships, as well as conceptual presuppositions. Displacements were, on one hand, a strategy to locate 'rotten ice' safely outside these breakdowns and not make them contingent upon these mishaps. But on the other hand, displacement in the manner that Bonnie gestured to in her remark was an admission that 'rotten ice' is neither physical, biological, or chemical, but exceeds these knowledges, both individually and collectively. To let go, then, and let 'it' come into being on its own terms was a way to let go of disciplinary differences, as well as acknowledge that these differences did not matter from the perspective of rotten ice. These displacements were a way of creating scientific realism in the negative. As philosopher of science, Ian Hacking, writes: "Reality is bigger than us" (Hacking 1983: 274).

SLIDE 4: Refined Plans

18 cores. 162 samples.

Two months before their first field trip in May, the team begin to refocus their efforts away from laboratory work towards developing more detailed plans for fieldwork. Carie has a new plan: the 'Core Plan' document. Compared to her earlier plan from November, this rendering in terms of ice cores gives the plan a concrete specificity.

Carie has calculated the total number of cores required, and how many to allocate to various analyses. There are cores dedicated to permeability measurements and laboratory optics, microstructural analysis, physical properties (temperature, density, salinity), casting, biology, diversity, chemistry, and ice-brine fractionation. Some of the biological analyses require additional cores to make replicate measurements.

In addition, Carie has colour-coded the different kinds of samples: red for whole cores; blue for horizons; purple for pieces (because it is a mixture of red and blue); and yellow for the samples she is uncertain about.

The Team jokes about the colour-coding scheme.

"Someone must think, *What are these guys doing?*" Bonnie laughs.

"This is still science!" Karen jokes, "it's at the forefront of science."

A long laugh ensues. Karen puts her head in her hands and squeezes her temples.

More serious questions follow. *Eighteen cores is quite a lot… In terms of workflow, how will they work out what gets done and when? Will they take all these cores in one day? Is this possible?*

The team examines the workflow plan more closely. They need to consider the amount of time required for melting the ice, filtering the melt-water to extract dissolved carbon, proteins, nutrients, and other chemical constituents, preparing ice thin sections and microscopy work, as well as the casting of ice cores. Different tasks also require specific temperature settings, so that certain tasks exclude others. Changing the temperature of the cold rooms requires additional time to let the spaces come to the designated temperature. All these details must be considered, if not explicitly calculated into their workflows.

Bonnie turns to me to apologize.

“It must seem like all we do is plan,” she says. It must seem like I never get to see them actually *do* anything.

In my head, I disagree. This planning is a kind of doing that has grown in importance as fieldwork draws near—and especially as the team encountered difficulties with laboratory work. The team could displace the co-production of ‘rotten ice’ and a shared epistemic space within workflow plans, which would mediate differences and provide a means of coordinated action. In a way, the workflow plan was like a ‘boundary object,’ insofar as it allowed cooperation to proceed despite lack of consensus (Star 2010). A workflow plan, unlike laboratory-grown ice, could accommodate heterogeneous parameters, different disciplinary conventions and standards for the choice and number measurements, all without falling apart. As such, the team members were accountable to the plan rather than any one person in the successful realization of ‘rotten ice’ as a scientific object. But beyond helping to maintain team cohesion, this plan was a means of producing objective knowledge about rotten ice. Though crafted by the team, this plan gained an autonomy apart from its producers that would give ‘rotten ice’ definition from without the team’s differences.

SLIDE 5: Reference Plans

After months of preparation, on May 4, 2015 the team finally arrives in Utqiagvik for the first trip of their field campaign. From the plane, the town of Utqiagvik appears in plan view. Small houses are concentrated to the south; the large building to the north is BARC where the scientists are. There is still snow on the tundra. At the edge of the continent, shorefast ice joins land to sea as one surface. We arrive at nine o’clock in the evening, but the light has still not gone out of the sky. Though the days have started to overtake nights, there are still discrete intervals of light and dark.

As we drive through town to BARC, the team express curiosity about the town and its inhabitants: *What must life be like for these people living in the Arctic? How do they make a living here? What kinds of pastimes do people have?* But we have precious little time to explore the town; in the 10 days the team has given itself, they must conduct science. In the meantime, we pass by the high school, the bank, the Top of the World Hotel, the jawbones of a bowhead whale erected like an archway, the recycling depot. Painted dumpsters sign to us with beautiful depictions of marine mammals; others hail us with positive, sometimes humorous messages: “Save the whale…for dinner.” Beneath the snow, rusting cars sleep like strange beasts.

Our first priority is to unpack the laboratory equipment and supplies we have shipped to BARC. Shelly directs our unpacking. Carie tapes to the back of the lab door legal-sized sheets of paper with a colour-coded chart outlining daily workflows. All of us, including me, have been assigned specific tasks and timelines (I am designated “able-bodied helper” and “observer of action, finally”). This is the plan according to which our fieldwork will unfold. After a day of sorting and organizing the laboratory we are ready to look for sea ice outside.

The first day we set out, it is windy. Even though it is only -10 degrees Celsius, the wind strips heat away from us. We follow our bear guide on snow machines, taking the whaling trail that hugs the coast towards Point Barrow. We have not yet arrived at the Point when we peel away from land towards a colleague’s ice mass balance site. As we travel, I forget that only 1.5 to 2 m of ice lie between our snow machines and the Chukchi Sea. The seemingly infinite extent of sea ice in the horizontal belies its shallow depth. After rejecting the first potential site as unsuitable, Shelly extracts a core from a second site, which we lay out in a PVC cradle to assess. The scientists find this core more acceptable, so we begin to set up.

Coolers of supplies are set onto the snow, a short distance from the first core hole. Somehow, a pit in the snow has already been cleared, making space for Shelly to begin coring. Monica is on her knees, clearing away ice chips from the corer as it spins material up out of its path. Carie stands at the ready with pencil and notebook in hand, jotting something down. I am certain Carie is taking more intelligent notes than me as I do not have the presence of mind to note much else besides brace myself against the wind and cold. I find myself seated on the ice next to a cooler opposite Karen. After following Karen’s instructions to put on vinyl gloves and wash them with a squirt of ethanol, I hold the core steady in the cradle as she cuts it into sections. With a satisfying pull, her hacksaw draws through to the other side of the core. I am surprised to find an ice section in my gloved hands. What should I do with it? I look to Carie for help, who fishes out a labelled whirlpack bag from another cooler. After dropping the ice safely inside, I have difficulties closing the bag. Reluctantly, I remove my insulated gloves to twist the top off. Later, Shelly points out that I have closed the bags incorrectly; I must wrap the top down at least two times and then twist them off. The cost of my mistake is a pair of stiff, cold hands.

Slowly, awkwardly, the tasks sort themselves out. In the cold, simple tasks—coring ice, cutting ice sections—break down. Work that can normally be delegated to instruments and completed in fluid motions by a single individual at room temperature divide into parts. We assume the role of specific instruments: Shelly is ice corer, Monica ice chip clearer and ice thickness tape, Carie pencil and notebook, Bonnie shovel and optics instrument, Karen hacksaw, while I am ice core clamp and ruler. Individual instruments join together to reform tasks: hacksaw, clamp, and ruler to cut ice sections; shovel, ice corer and chip clearer to take cores. Altogether, we form a makeshift and clunky, but functional six-person machine.

Karen and I work out a system. After Shelly deposits a core in the cradle, we let Carie first photo-document it. Then, with the ruler I take the total length of the ice to the nearest half-centimeter. Using the ruler as a guide, Karen marks off the top, middle, and bottom 20-cm horizons that we will take back to the laboratory. As Karen moves down the core to cut each section, I call out the distance from the top of different points of interest: the bottom of the surface scattering layer, the position of natural breaks in the ice, coloured bands. Carie sits nearby to record the measurements and hand us labelled whirlpack bags in which to deposit the ice horizons. She has anticipated each and every ice section that is cut, how it will be processed, and affixed to each bag its own sticker label. Despite the cold, she writes measurements into pre-made tables. As her fingers stiffen, she forces her whole hand across the page, tracing out in exaggerated motion the shapes of numbers.

I can only admire the foresight, tenacity, and fortitude of Carie in the cold. The array of measurements, their relations to each other, and significance to the project makes my head spin under the best of conditions. I focus instead on placing the ruler against the edge of the core and count the marks, calling out the horizon measurements as Carie records them.

Six hours and 22 cores later, we have completed collecting samples. We are spent—but buoyed by the success we have had so far. We have a better sense of what to do out on the ice and what to expect from the samples taken when we embark on our second sampling trip onto the ice, this time to Elson Lagoon.

The day we visit Elson Lagoon, the air is strangely still. Without the wind, sound folds back in on its source. We make conversation amongst ourselves and with the bear guard, who points out a flock of eider ducks as they cross the sky in the distance. Warmth builds itself up in sites of labour, the surplus heat shunting us out from our parkas, which have until now permitted us to work within this sub-zero environment, out of our comfortable habitable zone. Identifiable individuals emerge from the mass of fabric, which we toss on the snow machines.

After the first day of fieldwork, we have developed an economy of tasks. We pair off to complete specific tasks and the plan unrolls itself through each of us, working together as a unit. At the ice-sawing station with Karen, I hold up one of the ice core horizons. I examine it thoughtfully: this is our 'baseline,' or sea ice in early May at the end of the winter season. How will it compare to 'rotten ice'? Will 'rotten ice' be visibly different?

When we leave Utqiagvik, the team has completed its objectives. The scientists have collected samples that will serve as reference points for later analysis, and established a workflow to guide fieldwork on their next two trips.

SLIDE 6: Plans Afield

When not collecting ice samples or doing field optics measurements, the team spends the rest of its time processing samples in the BARC laboratory facilities. Ideally, the ice samples must be processed and stored as quickly as possible to capture *in situ* conditions. Some of the samples must be melted, others spun out for brine, still others cut and shaved to make microscopy thin sections, and even more that will need to be cast so that their structure is preserved. The liquid from any ice melts must in turn be filtered, put into containers, labelled, and shipped for later analysis in Seattle. After months of making plans, things seem to be unfolding according to plan.

My offer to help with some of the less technically challenging tasks finds me by the sink, either rinsing out Cubit containers or whirlpack bags for re-use. Shelly has insisted on trying to reduce the amount of waste generated by scientists concerned about the environment. For her, the irony of scientific work is not a wry joke; as Shelly emphasized during one lab meeting, "recycling must be factored into the scientific equation." I study the make-shift recycling bags for used/broken latex gloves, plastic bags, and sharps that Shelly has taped to the wall, trying to choose the appropriate bag to dispose of an item. We will also pack our recycling out with us on the return trip to Seattle.

The odd jobs I take up are not limited to rinsing whirlpack bags. On our last three days in Utqiagvik, I volunteer to help Monica and Karen with the cold microscopy work. Given their difficulties with the manufacturer until now, I have not had a chance to see the microscope at work.

Gladly, Monica and Karen accept my offer, assigning me the task of entering file names for images as they manipulate the microscope. The ZenPro software package allows the microscope to communicate with the computer, so that its field of view appears on the computer monitor and images can be saved directly to the computer. Unwittingly, I also invite myself into what would become one of the most fraught spaces of the rotten ice project. Below, I bring readers into the cold room as the scientists conducted microscopy to see what came into view. Like the scientists examining thin sections of sea ice, I place the rotten ice project under examination and rotate through different objective lenses to resolve the difficulties they encountered in this space.

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The cold microscope room in BARC hovers at around -5 degrees Celsius. Donning our winter coats, Monica and I head in. Orange light casts the room in a dim, eerie low. Whirring fans fill the room with noise, below which sits the microscope and computer that the team had set inside to run the microscope's accompanying imaging software.

I draw the keyboard up to the edge of the table and flex my gloved fingers in the cold. Patiently, I wait for Monica to give me instructions. She points at the clock on the computer.

"We leave here in 20 minutes," she states.

Monica searches through the box of zip-locked ice thin sections that Carie has carefully prepared and labelled. She targets the bottom section of the Chukchi Sea ice core where the scientists observed an algal band. It will be easier to detect "something interesting," Monica comments, if we begin here.

"On," Monica says. I flip the camera on.

Brilliant geometries of light and shadow appeared on the screen: the crystalline microstructure of sea ice. I let out a gasp. The sea ice is so detailed, light and shadow casting into relief the three-dimensional structure of ice crystals.

Monica maneuvers the lens across the surface of the thin section, bringing into view field after field of patterned arrays of light interlocking with shadow. Mentally, I try to point out the different features of interest: brine channels, air bubbles, particles. But without any training in ice microscopy, I cannot be sure if I have identified them correctly.

"Okay," Monica said, "take a picture." I follow Monica's instructions and return the camera to "live" mode. The file name that Monica assigned to the picture is descriptive but long.

We continue to examine the ice. The ice appears colourless, both on the slide and on the computer screen. But when Monica inserts the polarizer filter, the computer screen image lights up like a Matisse painting. A gallery of paintings *sans* painter scrolled by, a continuous stretch of technicolour quilt work. The polarizer illuminates individual ice crystals, each one refracting the light differently so that they appear different colours. There are so many possible frames, masterpieces in their own right, each captivating and, to me, impossible to choose between. Monica randomly selects a few fields to photograph.

Having taken a few pictures with transmitted light and through the polarizer filter to get a sense of the ice's microstructure, Monica felt ready to try the chlortetraclycine stain, a chemical that stains polymers so they appear green when examined under the proper filter set.[33] This will be a first exploratory look at the ice with the stain. With an eye-dropper, she carefully loads a drop of stain onto the edge of the ice thin section. Her fingers stiff, she awkwardly replaces the slide on the stage, muttering with frustration as the piece refuses to catch properly in the cold. After a few adjustments, it clicks in place and Monica adjusts the filter set to match the stain.

"Live!" Monica uttered, and I clicked the button on the screen.

The whole field of view appears in shades of green, as if we are viewing the slide through night vision goggles. Different features in the ice appeared like green phantoms, their edges fuzzy, resistant to clearer focus. Smudges of green with a slightly brighter intensity appear in long lines in the boundaries between ice crystals.

"Those are all polymers!" Monica declares, gesturing at the long green lines that appeared to me as brine channels, in which the scientists expected to find higher concentrations of polymers. Indeed, polymers seemed to have both penetrated and saturated all the brine channels that came into view. Not a single field appears dark.

Propelled by Monica's excitement, I look eagerly for the first time at these microscopic entities. With all of this green in view, Monica and I had only to randomly select fields of interest and capture them. Our first day of cold room microscopy has been productive. We have images of the chlortetracycline-stained ice, which seems to be a step forwards for the project.

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The next day, Karen and I take a turn in the cold microscopy room. The work rhythm today is different from yesterday. Karen makes it her first order of business to decide on a filing system for all the images. She does not look through the eyepiece as often, using the computer as a reference point for what could be captured with the imaging software—and hence what is worthy of publication. After selecting a field of view, Karen takes her time manipulating the knobs and dials to bring certain features into focus in a way that I was not aware was possible.

The ice thin section, though only a few millimetres thick, is a three-dimensional structure, and has to be approached accordingly. Depending on which objective lens is in place, and the microscope's given range of motion, Karen focuses on features at different depths within the structure. Karen points out diatoms in the ice structure, slightly discoloured ovals that can be seen with transmitted light. Other features appear at first as a distinct point in the ice, then split and diverge as she manipulates the focus. Focusing in the other direction, the two points would slide towards each other and merge once again as a single feature. These things are probably trapped in a water bubble, Karen explains, which refracts the light differently, and hence, deforms the light path picking out the feature of interest.

What appeared yesterday as a pretty pattern of ice crystals becomes legible as specific features of scientific interest. Some warrant further investigation while others can be ignored. Some are within the visualization range of the microscope and imaging software, while others are not. Working with a single field of view, Karen images it with the different filters. The logic of microscopy imaging begins to resolve into focus for me.

We proceed apace. Every 30 to 40 minutes, we leave to warm up with a cup of hot tea.

In six hours, we have barely finished one sample—and there are still two left that we hoped to inspect and image.

But the cold has has percolated too deep. The cold is a continuous trickle that pools in my gut, claiming me from the inside-out. The movement of my fingers begins to slow, stiffen. My fingers disconnect from my brain and each movement is an independent effort. One action divides an infinitesimal series of parts that are all but impossible to join back up as one. Thinking in the cold is a physical effort. At this point, even hot drinks do nothing to melt lump of cold.

"I'm not doing it. I'm done," Karen declares. I look up, relieved. We will have to finish the work another day.

In Seattle, the team examines the microscopy images they have acquired in May. There are concerns about the chlortetracycline stain. The very fact that everything appears green under the microscope has raised questions about the stain's effectiveness. If everything appears green, how can the team be certain that the stain is specific to polymer gels?

The question is more than a technical one. It exposes tensions amongst the team members, especially since the expertise on the biological, chemical, and physical components of rotten ice have been delegated to specific individuals with the corresponding scientific background. Any questions that targeted a specific facet of rotten ice would single out individuals for explanations. Thus, the question about chlortetracycline staining is a highly scientific and at the same time deeply personal issue.

For the gels, Monica had chosen chlortetracycline as a stain because of her experience with it in a different experimental set-up (the flow cytometer). The team accepted that the stain still needed to be tested for use in ice microscopy but trusted Monica to provide the expertise to lead them through trouble spots. The rest of the team, in its turn, understood that they had to clearly communicate their questions so that Monica could help. Working together, the team had to address the emergent problems with chlortetracycline.

As for the significance of the chlortetracycline stain, the team could not be more aware of its centrality to the rotten ice project. As described in their proposal, the team hypothesized that polymer gels produced by algae (and bacteria) potentially controlled melt processes in the ice interior. Most likely, these polymer gels would be co-located with the micro-organisms in brine channels, which served as conduits for heat and salt. Capturing where the polymer gels were located in the ice was therefore critical to evaluating their hypothesis. Without chlortetracycline to visualize the gels, they would not be able to make these claims about the interactions of polymers with ice structure.

The team considers their options. They could use a different stain to capture the polymer gels. But these stains would colour both bacteria and polymers both orange-red. Another candidate stain was Alcian Blue, which would give the team a "yes/no" answer about the presence of polymers. Monica, however, treats Alcian Blue with skepticism. Despite being commonly used amongst microbiologists, the acidity of the stain shrinks the polymers. This would undermine

Monica's later plans to determine the concentrations of differently-sized gels. Though the team is respectful, their frustration is evident. At least the Alcian Blue would provide some indication of whether or not polymers are at all present in their samples.

In defence of her choices, Monica goes up to the whiteboard and begins drawing plots of kinetics reactions to explain how the polymer staining process works. The team studies her figures in earnest. They value the intimate knowledge of chemistry that she brings to the table, but they struggle to find a way to convey the need to move from these detailed explanations to concrete steps that will advance microscopy work.

The team reassures Monica that they have no doubts in her expertise. But what Monica says she saw and what Karen says she saw simply do not match up. They need to learn to see the same things in the same field of view!

"What we saw were nicely stained, green samples," Karen says, "What I can imagine seeing is a nicely stained green sample!" Her joke momentarily relieves some of the tension in the room before everyone hunkers down again.

The team moves on to think about what they need to do to optimize the chlortetracycline stain for use in ice. One test would involve preparing known concentrations of polymers, which they could stain in solution and then examine under the microscope. This would give the team members a sense of how sensitive the chlortetracycline is to different concentrations of polymer, as well as help them distinguish the background colour from the stained molecules of interest.

In addition, Monica explains that they would also need to calibrate chlortetracycline for variations in temperature, salinity, and pH. Differences in these parameters can affect the fluorescence of the stain. Once they have properly calibrated chlortetracycline, they can account for the effects of these conditions in their ice samples.

The team, however, is pressed for time. Their next trip is scheduled to depart in three weeks at the beginning of June. Conducting a full suite of tests to optimize the stain before then is not feasible.

"So we can't do polymers," says Carie, her voice breaking. "That would be sad…"

The team manages to settle instead on establishing positive and negative polymer controls that they can test the stain against when they return to Utqiagvik. But their discussion remains to be continued as Monica must run to another scheduled meeting.

We nod as she takes her leave. A brief silence follows in the wake of her departure.

The remaining five of us take stock of the situation. Perhaps, there is a communication problem. Monica does not seem to be getting emails.

"We need to bring everything together so that it all gels," Karen says. After a moment, she laughs, realizing the pun she has made. The discussion shifts to questions that can be managed without Monica's expertise. Mostly, the scientists reflect on their own team dynamics.

As the meeting comes to a close, Bonnie reminds everyone that they are a team. "No one person is the core of the project; the core of the project lies with *us*."

She continues. "At the end of the day, when you strip away the plane tickets, the stains, the microscope—all that's left are good intentions."

❄ ✱ ❄

In spite of the team's best efforts, it seems that the microscope has other developments in stock for the team. Near the end of our last trip to Utqiagvik in July, the LED lights fail. Without a light source to illuminate the samples, the microscope is non-functional. Without ceremony, Carie carefully packs up the delicate—and temperamental—instrument and sends it back to Seattle. Just as the delay of the filter sets hid from sight any fundamental differences in teamwork style, so the LED failure closed from view—at least temporarily—the theatre of major team conflicts.

It goes without saying that the microscope failure was unplanned. Of course, the scientists anticipated some equipment mishaps to occur along the way and regularly engaged in troubleshooting problems as they arose. The microscope could be added to the list, besides the problems of growing realistic sea ice in the laboratory, communication difficulties, personality differences, and contrasting styles of teamwork, as yet another instance of unplanned occurrences. At what point does the accumulation of disruptions overturn a project's viability? When does the concatenation of unexpected events overwhelm a project or experiment? The series of disruptions that the team had encountered threatened to unravel the rotten ice project. And yet, it held together.

As Bonnie had put it, when one strips away the plane tickets, the stains, the microscope—the various material means of producing knowledge—what held the possibility of knowledge production in place were the plans they had initially made. These plans had grown out of collectively-made objectives and relationships amongst the team members with their diverse skill sets. The production of rotten ice belonged to no one member of the team or even piece of equipment but was a space apart. More importantly these plans were a means for producing objective knowledge of rotten ice.

On another note, and as several social scientists have observed, the unexpected is not intrinsically negative to scientific research. In fact, surprise or derailment can be the very aim of experimental work (e.g., Rheinberger 1992; Rees 2016). As Rheinberger notes, an experimental system is "a device for producing epistemic things whose possibility is beyond our present knowledge, that is to behave as a 'generator of surprises'" (Rheinberger 1992: 307). This notion of surprise introduces a distinction between different kinds of unexpected occurrences. Between, on one hand, the merely unplanned that must be avoided or mitigated, such as the microscope breakdown; and on the other, the unplan*nable*, which is not the kind of uncertainty that threatens to overthrow a project, but the possibility of generating "knowledge that we do not yet have" (Rheinberger 1992: 309). Unplannability makes possible a kind of scientific inquiry into the open (Rees 2018).

SLIDE 7: Unplannable

For the third—and last—time this year we take the road along the coast towards Point Barrow. This time in July, we go by boat towed by trucks. A film of clouds shimmers in the sky. To the north, an unbroken expanse of water stretches to the horizon. The boat shudders and shakes along the dirt road, threatening to upend its contents—human scientists included. The weight of our own bodies is all that prevents us from being flung in separate directions, away from the tenuous space that we hold in common.

Summer is in full swing in Utqiagvik. The beach is ice-free. At the end of June, the ice had finally "gone out"—a surprisingly early departure for the ice. Typically, the beach remains ice-locked until early July. Even from this height, standing on the deck of the boat, we cannot pick out anything white in the distance; only blue sea divided from blue sky.

As we put the boats into the water and load them with the scientific equipment, I deliberate about what to wear. We have traded our parkas for insulated, orange life jackets. The weather is fine but always liable to change, and quickly. I decide to go with several warm layers—what I would wear on the rare, but not impossible, occasion that it snows in Seattle. I wonder if I will be too hot.

Shelly stands at the stern snapping photos of us, of BARC and the weather station in the background. We hope to see some whales. Carie, on her reconnaissance trip to find rotten ice shortly before the PIs' arrival, had seen not only bearded seals and walruses—the usual suspects out in the Chukchi Sea—but a huge pod of beluga. She had also learned that it was possible to step out onto an ice floe and take ice cores, finally providing a definitive answer to the team's questions about ice-capture.

We drive around in the boat, keeping our eyes peeled for signs of ice. Shelly stays inside the cabin, chatting with the bear guards. The smell of gasoline and cigarette smoke drives the rest of us outside to find a seat on the bench or on top of one of the coolers filled with equipment. We gaze seawards, wrapped up in our own thoughts, the drone of the motor too loud to carry a proper conversation with anyone except those who sit next to us.

In the distance, we spot white specks on the horizon. The bear guards steer us towards these floating points.

As we draw up alongside a floe, multiple questions present themselves: *Will we be able to step on it? Does it look 'rotten' enough? How can one tell?*

"So," asks the bear guard for clarification, "do you guys want brown ice, or white ice?"

Shelly laughs, "We want the *rotten* ice!" Her response could not be more on the mark—and yet be so frustratingly non-specific.

The question of how to identify—and then sample—rotten ice had become increasingly vexing to the scientists as they neared the date to rotten ice capture. The question was foregrounded in their initial ideas to design a specialized ice-capture device to their interrogations of locals and other scientists in Utqiagvik. But they still had no better ideas about how they would 'know' rotten ice when they saw it. There was no literature to make an informed decision with; it was precisely the team's goal to go out and characterize rotten ice for the first time. Knowing that speculation would only drive them around in circles, the team had to let the question lie. Now was the time for them to resurrect these questions. As it turned out, re-opening the question also forced into the open unspoken assumptions about what 'rotten ice' was for each of the PIs.

Bonnie takes stock of their current position relative to the original plan. "The goal of the project was to understand the fate of landfast, first-year ice in Utqiagvik," she reminds the others.

"The premise of our proposal was that landfast ice disintegrates in place. But this year, the ice took off. It left! It didn't melt in place. This doesn't usually happen…"

The sudden departure of ice presents other kinds of problems. Karen expresses concerns about trying to find rotten ice in July that could be related to the ice sampled in May and June. Since the ice is drifting freely, they cannot return to their original sampling site. At minimum, however, she would like to sample ice that is at least similar in *kind* to the May and June ice, i.e., landfast, first-year ice.

"But how can you *tell* just by looking at the ice whether it's first-year ice or multi-year ice?" Karen wonders out loud.

Can they do chemical tests? Or does ice thickness potentially provide a proxy for landfast, first-year ice? The team looks to Bonnie for guidance. As the expert on ice morphology, she is better able to judge.[34]

Bonnie is skeptical about a hard and fast rule for identifying ice. Ice thickness does not sign for multiyear ice. First-year ice can raft together and consequently thicken. The size of an ice floe is also no clean indicator of landfast ice. The most reliable way to distinguish first-year ice from multi-year ice is by taking a salinity core. She explains that they would need to have a history of the ice to be sure about what kind of ice it is.

"You simply can't tell if it's rotten," Bonnie emphasizes, "it's not something you can *see*."

Karen asks about the discolouration of ice as an indicator, which is often a marker for the presence of biology. As a rich harbor for microbial life, rotten ice should be identifiable by its colour. Her voice trails off as she notices the others' expressions change.

Monica warily interjects. In her reading and writing of the proposal they submitted, they had nowhere implied that the ice would be "teeming with life."

Bonnie adds to Monica's comment. In April there is an algal spring bloom. But by July, the biology has already sloughed off. When she was on the ICEScape cruise in 2010, the microbiologists on board had used fairly strong language to describe the ice they were studying. In their words, the ice was "sterile." It is very possible, Bonnie cautions, that the ice they sample in July will be filled with just water. As for the discolouration, this was from sediment in the ice, not any biology.

Hesitantly, incredulously, more in disbelief at her own discrepant assumptions than in an attempt to persuade the others, Karen repeats herself. *But she thought that there would be all this* *biology—algae and bacteria—inside the ice… She thought that rotten ice would provide a rich harbour for life…*

There is little more the PIs can say to one another at this point. There is no need. The brief but intense exchange has revealed far more about each other's assumptions than any other discussion that I have been observer to.

From this exchange, it seems as if the whole premise of the rotten ice project is thrown into question. The project had come together based on a jointly crafted working hypothesis about 'rotten ice.' Presumably, this conception of 'rotten ice' formed the basic framework for the whole project that would hold together its heterogeneous parts. But the scientists apparently had very different conceptions of 'rotten ice.' How had these incongruent conceptions guided their scientific questions—and their very involvement in the project in the first place? Where did this revelation of conceptual mismatches leave them now? Could 'rotten ice' the project and object of study survive this potential moment of disintegration?

The scientists are at sea. Literally and figuratively, the team are out on the open waters of the Chukchi Sea in July, faced once again with the question of collectively identifying rotten ice.

"Do you like the ice?" asks the bear guard, pointing at a floe with his chin. His framing of the question—as a matter of preference rather than of definition—is perhaps best suited to the occasion. The scientists can more readily answer if the ice meets their needs—whether it is large enough to land on, whether it looks sufficiently different from June ice, whether it has (or does not have) certain features they would like to investigate—rather than determine for a fact if it is 'rotten ice.' Working together at the level of practical questions has gotten the team this far, and it will hopefully hold the team together going forwards. They will have to identify 'rotten ice' through trial and error.

After turning down two candidate floes, we finally make anchor on a floe that is hummocky, ponded, and discoloured. We hop out and take the ice corer with us. The first core looks acceptable, so we begin to unload the rest of the equipment and set up our usual processing station. Karen and I sit down to begin cutting up the ice. In the warmth, it is no longer necessary to divide a task into parts. Seeing that Karen can handle cutting up the ice on her own, I lend Bonnie a hand with the field optics.

Once again, work falls into established patterns. I am in the midst of putting away some of the optics sensors when Karen asks me to return to the boat. I look at her in confusion. *Why*? But

I can see she is dead serious. As I turn to go back to the boat, I see all the equipment that still needs to be packed away. Dismayed, I pause to pick up some items to take with me but Karen firmly repeats herself: *Go back to the boat*. *Immediately*. Her command does not permit questioning. I board the boat, still confused. The sky is clear and blue, the temperature warm and the work rhythm reassuring in its familiarity.

From the boat, I watch helplessly as the team quickly gather up their equipment and samples. I resist the urge to step out again and give them a hand. As the team boards, I breathe a sigh of relief. With the last body on board, bear guards begin unfasten the ropes and draw up anchor. There is excited, adrenaline-fuelled chatter among the scientists about something I did not see. As we pull away from the ice, I see a piece of ice on the far side of the floe separate from the main body. Within minutes of our departure, the one large ice floe on which we just stood has become many. The transformation is smooth, and, at least to me, its initiation imperceptible.

"*That's* rotten ice!" Bonnie exclaims on the boat, as we speed back towards land, "Ice that's holding on to the bitter end!" I lean in closer to hear her over the engine. If it wasn't already rotting, she explains, the ice would have stayed all in one piece and wouldn't crack like it did. The action of waves moving under it was enough to break apart the floe.

"It's just king of hitting me that this is it," she remarks. "*This* is rotten ice!"

I am also stunned, not necessarily because of the break-up but because of my own obliviousness to the event. Our workflow habits on the ice in May and June had conditioned me to expect more of the same. I had not thought, after all this time, that I would miss the discovery of rotten ice.

"It's kind of like a rollover," Bonnie says, apologizing at the same time for the expression. "But the difference is so dramatic! It's kind of like seeing a car turned on its side and you wonder how it came to be that way."

Joyfully, Bonnie makes exclamations about the ice they found. It was more rotten than anything in her wildest dreams. *You can't make this stuff up!* She shakes her head in astonishment. The rest of the team is likewise pleased with their encounter on the floe.

The team has finally discovered rotten ice.

Karen and I go for a walk along the beach, just the two of us. In silence, we watch the sky and water. As we make our way along the water's edge, we head into the sun. It could be west or east, I don't remember. At this time of year, the sun does not set.

Our angle of approach quenches colour. In the sea, shadow collapses into shadow, drawing back from land to leave a dark, unreflecting surface. The wet strip of beach sucks up the light, absorbing the houses along the bluff into one silhouette. The sky is water in motion, coalescing into indefinite shapes and then slowly, imperceptibly dissolving.

Something by my feet catches my eye. Droplets of water that defy both dissolution and evaporation. They remain perfectly intact, these tiny lenses of light.

I bend down closer to investigate. It seems improbable that they could be droplets of water. Are they perhaps pieces of ice? Gently, I pick one up. Under the pressure of my finger, the lens collapses, becoming instead a translucent bladder speckled with grains of sand. I try to comprehend how these fragments of light can have a skin. And then I realize that these are not droplets of water, but animals. They are jellyfish. I look out towards the waves that delivered them onto shore.

So many tiny jellyfish but no sea ice in sight.

If Pytheas had no terms to describe sea ice except the jellyfish he knew and was familiar with, then I was not able to see jellyfish for the sea ice I had come to expect. The mismatch gives me pause to wonder about the discrepancy between Karen's conception of rotten ice and that of the others. The incongruence is baffling. All the previous months, it hadn't occurred to me to ask what their individual conceptions of 'rotten ice' were; I assumed that they shared the same picture of rotten ice, so there did not seem to be any reason to ask otherwise. Even amongst themselves, this question seemed unnecessary.

Tentatively, I begin to ask Karen about what picture of rotten ice she had in mind when first starting the project. Karen does not defend her initial ideas of rotten ice against the ideas of others. But to my surprise, she is bemused by her own misconceptions.

"If it was all inside my head, it would be boring," Karen says. "That's what's so interesting about science. To find out what you don't expect."

Her comment offers me a different glimpse on the idea of scientific discovery.

"To discover" something is commonly understood today to mean "to see, get knowledge of, learn of, find, or find out" (OED, 2nd ed.). In older usages of the term, "to discover" meant "to divulge, reveal, or disclose" as from the Latin *dis-* "opposite of" and *cooperire* "to cover up." To discover something, then, was to uncover what was previously concealed from (human) sight or knowledge. Furthermore, the meaning of the term suggests that what was discovered had already existed prior to its being known; it just had to be found and revealed. In this sense, the verbs "to discover" and "to invent" are conceptual cousins, given their early connotations "to come upon."

The team's discovery of rotten ice, however, is not easily characterized as a simple stumbling upon of rotten ice, lying in wait ready to be brought to light. As repeatedly emphasized throughout this chapter, neither the 'field' or 'rotten ice' were given or self-evident. Contrary to this picture of discovery, the team made choices about what counted as 'rotten ice.' Not all ice floes in the Chukchi Sea were candidates for their study. Rather, the team decided where, when, why, and how to sample the environment to generate the kind of knowledge about rotten ice that would test their hypotheses. 'Rotten ice,' in other words, was produced through field-*work*. From this perspective, the team's discovery involved an element of invention in the sense of Norbert's joke. That is, "to invent" something is "to produce by original thought," rather than "to come upon" it. Human intervention was a key ingredient in the production of rotten ice as a scientific object. But rotten ice is not *reducible* to these human activities or the conceptual frameworks used to make this object tractable to thought.

It is in this light that 'discovery' retains its sense "to come upon," insofar as what we encounter is underdetermined by human concepts and practices—they come from outside our conceptual frameworks and assumptions. This 'outside' is *not* a supposed realm in which true knowledge or perfect beings reside. Nor is it synonymous with an idea of 'nature' that puts humans (as more-than-'nature') on an opposing side. It is an 'outside' insofar as it is not exhausted by our conceptions of things, and in this sense, is independent of human knowers and knowledge.

It is from this perspective that the continual displacements during the project can be understood. The project was continually displaced, for various distinct reasons, into an unknown. Displacement was sometimes the product of fickle equipment but it was also precipitated by the realization that 'rotten ice' simply could not be produced in the positive. Its production had to be placed outside individual disciplines, outside the desire for tight control, outside the laboratory, and outside, even, interdisciplinary collaborations, into an undefined space where practical and disciplinary differences did not matter. These differences did not matter because 'rotten ice' was not dependent on these details to begin with. 'Rotten ice' in some ways displaced humans as the origin of knowledge production itself. In response to these displacements, the project moved continually away from the making of a stable, definite object towards the making of a practice of objectivity. That is, a practice of objectivity that is a commitment to remaining open to this 'outside,' to make a practice out of displacing one's conceptions of the world so as to learn something new and unexpected.

On the beach, I look back in the direction Karen and I have come. Square to the sun, red, white, blue, and gray come to light; beach, houses, and waves appear in clear outline. The jellyfish, in turn, have all but disappeared. Unless you know where to look, they are invisible. I marvel at the difference a change in direction can make. That the strange lights on the beach were not water droplets or ice, but jellyfish, is a discovery of its own even if it is of a lesser kind.

SLIDE 8: Escape Plan

When I began anthropological fieldwork, the rotten ice project was its centre. But this was not necessarily so for the scientists involved. As researchers working on 'soft' money, they often had to build up a portfolio of projects to maintain a full salary. What other projects were they working on, and possibilities of understanding might they make available? In this spirit, I ask Bonnie about one of her other research projects. Will she study the microstructure of the sea ice in that project, too?

Bonnie tries at first to force her response to conform to my question. *It would be possible to look at how things are changing, such as the seasonal evolution of permeability*… But then she breaks off.

"The problem is, you think you know what to expect, but what you find will totally take you by surprise," she says instead. Bonnie elaborates. Take lightning. Lightning is one of those phenomena that, until you observe it, you cannot believe it. People thought that they could predict lightning using models or intuition. But somehow, lightning escapes these pre-conceptions, it exceeds our expectations, or what can be expected. Today, they've learned a lot about lightning (although, admittedly, lightning as a puzzle is not completely solved).

Bonnie thinks sea ice is like this, or even rotten ice. Neither are well studied but to a certain extent, we know what to look for. We have to *be* there to see what we can learn.

One can always be prepared and organized and thoughtful. You just have to put your best foot forward. Of course, there are some people who do a "mish-mash," "reckless science" that *can* work for them, but doesn't work for her.

"There are things," Bonnie explains, "that you will just *never* know." She repeats. You just have to be organized and, importantly, open-minded.

I ask her to elaborate on what lessons she took from those times when field work didn't work out as expected. She doesn't look very comfortable going into the details of the actual work. In hindsight, she recognizes where she could have done things differently to have a better outcome. It was her first project as a full PI. She seems somewhat embarrassed about the whole project. When she went up to do fieldwork, nothing worked as planned.

In that project, the pieces just didn't come together. The data she collected was not publishable. She shrugs. You just have to take whatever lessons you have to take. *Today is not the day, try again tomorrow.* Also, humility is a good thing to have. Other lessons: make as many contingency plans as possible but know that you are not going to be able to think of all of them. Despite knowing these limits, you just have to "march into it, standing tall" and "start with what we *can* do."

On the flip side, you don't want to go into the field with a closed mind. There are things that would have otherwise gone unseen if one's mindset was too closed.

Bonnie elaborates. For instance, on ICEScape, they went out to make measures but did not know what to expect. The results are not hard to explain and make sense of, but they were totally unexpected at the time.

Anyhow, she explains, on ICEScape they sent an optode into the water and noticed that the instrument was detecting less and less light, but at a certain depth the amount of light detected suddenly increased! After some thought, it became apparent to them that this was just a geometry thing. One can envision how an optode directly beneath the sea ice would register less and less light as it moved away from the surface. But within the sea ice surface there are openings, kind of like skylights. The deeper the object is, the more exposed it is to a collection of skylights. The readings of their optode made total sense.

Bonnie looks at me. "It's the kind of thing that you kinda hope for? I mean, it's kinda boring if you get exactly what you expected." The appeal of science, she says, doesn't necessarily come from checking things off a list. One should be really well prepared but not *over*-prepared. This is the only way there can be new discoveries, new connections.

The methods they currently have are the ways they've always done it, or can think of. "Some of our descriptions," Bonnie admits, "will be useless." She suspects that permeability will be one of these measures. But necessity, she continues, is the mother of invention. "It's good to have pre-conceived notions so you know what to test." You don't get what you expected. And that's cool.

Society thinks that scientists are rigid. But they're actually "good escape artists." Bonnie hesitates immediately after saying this. She regrets her use of the term "escape artists" and what this might imply. No, she corrects herself, they're very "creative." Things go sideways and you have to think up a new way to do the experiment. *And you do*.

The appeal of science, she remarks, is asking "blue-sky questions." Not that she's a cowgirl—far from it. As much as possible, Bonnie likes to try and control as many unknowns as possible. But, she adds: "If you know what you're doing, you're not doing it right."

Interlude: Visitations

Fieldwork in June 2015 has been productive but exhausting for scientists and anthropologist alike. The team has collected samples from both the Chukchi Sea and Elson Lagoon. Although melt ponds have formed on the ice, the sea ice remains intact as a single sheet. The team has fallen into a familiar work pattern: on the ice, we assume our individual responsibilities as part of unified six-person apparatus; in the laboratory, I have resumed rinsing whirlpack bags and Cubit containers.

One night, after a long day in the laboratory, we receive an unexpected visitor.

Carie is in the kitchen, pouring us all a well-earned dram of bourbon from a bottle she brought all the way up from Seattle. Monica, Bonnie, Karen, and Shelly have seated themselves around the coffee table. We are making jokes with the wildlife staff who have left some strange 'gifts' for us in the cold room, communicating to us through written signs that the dead specimens they have stored will be there only 'temporarily.'

All of a sudden, there is a knock at the door. We all look around at each other. *Who could it be?*

Shelly, whose jokes had us doubled over with laughter, suddenly snaps to attention. She pokes her head through the window closest to the door to get a look at who is knocking, but our visitor has already entered the inner vestibule of the Quonset hut and is out of sight.

Shelly opens the door a crack. It becomes apparent that there is no chain to secure the door; nothing to resist whoever is knocking at our door.

The door is open all the way now but Shelly's height obscures my view.

A croaky voice breaks across the silence:

"Where's Robert?"

Our collective discomfort is palpable. We are shocked into silence, looking helplessly at one another.

"I'm sorry, you must have the wrong house," Shelly says calmly, "Robert isn't here."

"Where's Robert?" the woman repeats.

"Robert doesn't live here. We're not from here, either. We're just visitors."

Shelly releases the door momentarily and it swings open. A woman comes into view. Her face lights up as she sees all five of us sitting in the living room, our conversation arrested by her sudden visitation. Before Shelly can stop her, she steps past the doorframe and enters the living room. She is wearing a wind-breaker and some sports tights with sneakers—clothing that seems too little for the weather outside. Her cheeks are slightly flushed.

The woman pauses and takes a few steps further in, moving closer to the wall where she can put a hand out to steady herself.

"Do you live around here?"

The woman does not answer. Instead, she asks: "Where's Robert?"

Do you have Robert's number? we offer, *Can you call him?*

She closes her eyes. With some effort, her hand anchored to the wall, she replies:

"No." And then, "Have you seen Chase? She went out with Sadie."

There is some confusion. *Who is Chase? Who is Sadie?*

"Chase is my dog. Sometimes, she runs off with Sadie. I don't like Sadie."

We all smile nervously, not sure what to do. She is one of the Iñupiat community members, someone we have never seen before. Until now, our only contact with the community has been through UIC logistics support, who hired people from town to serve as bear guards, machines operators, and the odd mechanic. None of us are sure what to do.

She makes a step towards the chair that Shelly had vacated to answer the door, and sits down.

"Would you like a cookie?" Shelly offers, referring to what she calls her home-made "chocolate bombshells." They sit in a coveted stash on top of the fridge.

The woman pauses.

"No," she says emphatically.

There's a moment of silence. After a moment passes, she asks another question.

"Where are you from?"

We all reply: "Seattle."

Shelly waits, then adds: "We're scientists." We search her face as we wait for a response.

"What are you studying?"

Simply, and more assuredly now, Bonnie replies: "The sea ice."

The woman's face flickers for a moment, as if something has come into focus for her. A hush settles over everyone.

Her eyes have fixed on Bonnie. "And what does the ice say?" she asks.

She speaks more calmly, all her previous agitation about finding Chase and Sadie momentarily forgotten. The mention of sea ice pulls all of us in closer, anchored to the what is unfolding before us.

"What is the ice telling you?" she asks again.

Bonnie responds gently. "Well, we're trying to listen to what the ice says. But…," she pauses reflectively, "we're still learning."

There is a fleeting sense of resolution, as if all the unforeseen elements that have been set into motion have come to rest in sea ice.

But before anything more can be said, there is a sudden exclamation from Shelly. "I just saw two dogs run by!" she cries, pointing outside the window that she has been busily scanning for signs of life, "I think I saw Chase!" The spell breaks.

Our visitor gets to her feet and follows Shelly's finger out the window, searching for Chase.

After some coaxing, our visitor ventures outside where she is reunited with Chase. In their wake, I am left wondering what to make of such an encounter. In reflecting on this encounter, I want to emphasize that I am thinking through the *visit* rather than the visitor herself; to focus on the situatedness of this encounter, rather than a generality, and what it makes thinkable in its specificity.

This visit had momentarily, but powerfully, displaced all of us outside familiar coordinates, the scientific activities that had occupied us over the last week and circumscribed the boundaries of our world. As we moved within this world, we were aware of its limits, their contingency upon the choices we had made. But the visit shook up these reference points, making visible taken-for-granted assumptions and shifting what had remained peripheral until now to the centre of our attention. On one hand, this visit made plain that there is no clear 'inside' or 'outside' to scientific activity. Although BARC demarcated the space of scientific activity, this was not 'outside' to the community whose members have been closely involved with scientists for many years and share a close stake in scientists' findings about sea ice. In fact, the collective weaving together of a world over years by visiting scientists and Arctic resident meant that we shared a wall with members of its community who resided on BARC grounds. On the other hand, this visit foregrounded awareness of a community that has made a living on the sea ice for generations, which has developed an extremely precise and richly developed body of knowledge about this substance (see Krupnik et al. 2010). Scientists are not the only ones who attend closely to the inner workings of sea ice—though the means and ends of these of different forms of knowledge production are sometimes radically different.

In this enlarged field of view of view, I do not want to assert either the displacement of scientific knowledge or the marginality of indigenous ways of knowing. Perhaps, I wonder, sea ice displaces both these forms of knowledge. In our visitor's question, "what is the ice telling you?", and in Bonnie's response, "we're still trying to listen," there is only curiosity and a willingness to be open to an 'outside,' which exceeds one's own presuppositions. Sea ice does not belong to any one form of knowledge, biological, chemical, or physical; scientific, anthropological, or indigenous. I am still left wondering.

This two-way visitation remained brief. Just as quickly as our visitor entered our space, she left. Within a few days, we would be gone as well.

Chapter 3:

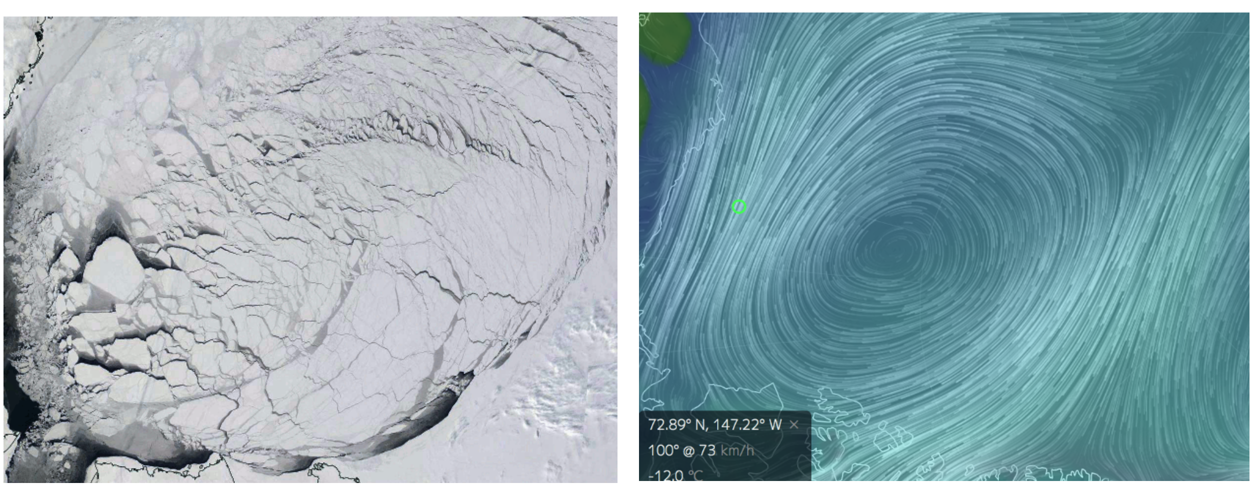
Non-predictability

Unexpected melt

As the Earth orbits the Sun, Arctic sea-ice cover grows and shrinks. From mid-September to mid-March, Arctic ice cover expands until it reaches its winter maximum. After spring equinox, when the northern hemisphere emerges out of darkness and tilts towards the Sun, the Arctic floods with light. Ice thaws, fragments, and shrinks until it reaches its summer minimum in mid-September. As the northern hemisphere passes once more into shadow, the long polar night begins anew. These celestial periodicities give us the seasons; their invariability lends the passage of time a circularity that seems to transcend temporal change. Less predictable are the weather conditions on Earth's surface.

The summer of 2007 is particularly unusual. Like a lidless eye, the midnight sun has beat down on the Arctic Ocean for nearly 12 weeks since June, seven days a week, 24 hours a day. There is unusually little cloud cover for this time of year, exposing the ocean to the sun's full strength.

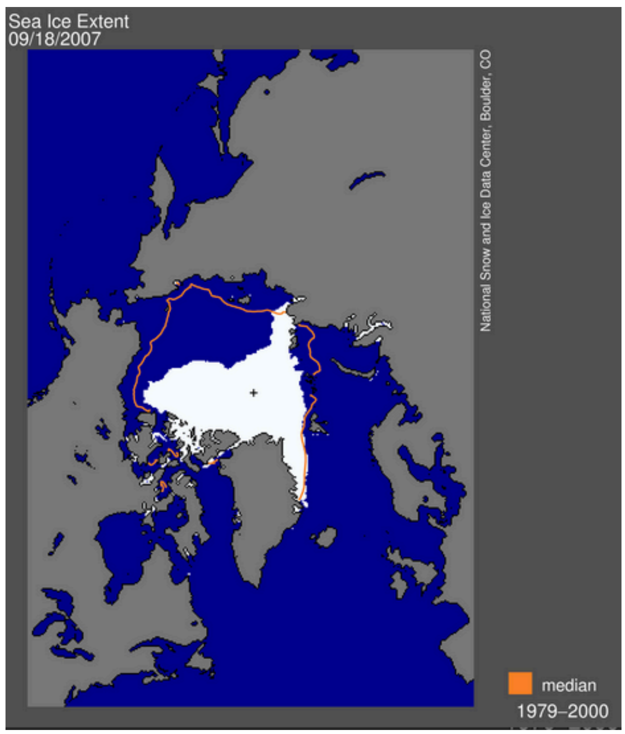
Invisible, a column of air hundreds of kilometres wide sinks above a point located in the northern Beaufort Sea. At the surface, the dense, dry, and cold air curves in a clockwise direction, a pattern sometimes legible in the fracture patterns of pack ice. This large-scale feature is known as the Beaufort Gyre.



Fracture patterns of sea ice in Beaufort Gyre (left) and wind circulation fields in Beaufort Gyre (right) in 22-26 April 2016. Figures courtesy of 'A-Team,' Arctic Sea Ice Forum, https://forum.arctic-sea-ice.net/index.php?topic=1493.550

As the high pressure system persists over the Beaufort Sea, sea ice drifts into tighter formation. To the south, in western and central Siberia where a high-pressure system usually resides, there is, instead, an unusual low-pressure system. The pressure difference between Eurasia and the Beaufort Sea directs warm winds from the Bering Strait across the North Pole, melting back the ice edge and pushing ice further north. The winds this summer are unusually persistent. Rather than blow in many directions, they blow in one prevailing direction: northwards.

Beneath the relentless midnight sun, sea-ice dissolves in place. Cerulean melt ponds form and grow on the ice, darkening its surface and absorbing more sunlight. From below, warmer seawater eats away at the edges of ice floes, leaving behind a watery blue iris around a bobbing white pupil. The reflective shield of ice that only months before had capped the Arctic Ocean disintegrates and dissolves.[35]



September sea ice minimum 2007.
Figure by NSIDC.

On 18 September 2007, Arctic sea-ice extent reaches its absolute minimum for the year: **4.28 million** square kilometres. Alone, it is difficult to grasp the significance of this number. The number gains clearer meaning in the context of previous years. In September 2005, which held the previous record-low, sea-ice extent was **5.32 million** square kilometres. By comparison, the 2007 minimum was **over a third lower** than the 30-year average sea-ice minimum for September (Meier et. al 2014). So much ice had melted that, for the first time in human memory, the fabled Northwest Passage was open for a period, even allowing ships through with no ice protection.[36]

Scientists had been aware of Arctic sea-ice extent as a sensitive indicator of global warming.[37] But the 2007 September minimum came as a great surprise to scientists. It was not so much the direction of change that caught them off guard—after all, the long-term September sea-ice extent showed a clearly declining trend since the satellite record began in 1979. In addition, all climate model simulations in Coupled Model Intercomparison Project phase 5 indicate that the Arctic will eventually lose summer ice cover as atmospheric greenhouse gases increase (Stroeve et al 2012). No one, however, had expected the drop in 2007 to be so precipitous.[38] The abrupt decline in sea-ice extent over a single year gave sea-ice scientists reasons to pause and take stock. What did they know about sea ice and its temporal variability?

As a direct consequence of the 2007 minimum, the Sea Ice Outlook was established in 2008. At first, the Outlook was an *ad hoc* collective activity within the relatively close sea ice community, rather than a formal organization, which sought to advance understanding of sea ice predictability through an annual 'competition.' The Outlook's goal was simple. It sought to predict just one number: the total Arctic sea-ice extent in September. This is when sea ice extent has reached its minimum after the summer melt season. The Sea Ice Outlook marked the beginning of a proliferation of predictability initiatives in the subsequent decade. The World Climate Research Programme established the Polar Climate Predictability Initiative in 2012 to better understand the role polar regions play in the predictability of climate. In 2017, the World Meteorological Organization launched the Polar Prediction Project, a 10-year program to improve weather and environmental prediction services for the polar regions. And beginning in 2013, the Sea Ice Outlook itself was formalized into the Sea Ice Prediction Network, which connects actors from different sectors in academia, government, the private sector, and the public, all of whom share an interest in sea ice prediction. As these activities illustrate, predicting Arctic sea-ice conditions has become an organizing framework for the sea ice community, bringing together observationalists, modellers, and remote sensers, as well academic and non-academic actors around sea ice prediction as a shared focus.

Sea ice predictability piqued my curiosity as a site of anthropological turbulence. On one hand, prediction is assumed to be foundational to the definition of being human today. Knowing the future is key to human agency. As anthropologist Kirsten Hastrup argues: "It is a part of human and social life to take action. For social agents to act consistently and to take responsibility for their community, they need to have reasonable well-founded expectations to the future" (2012: 1).

But in recent times, this model of being human has been challenged by the emergence of fundamentally unknowable and unpredictable phenomena. Anthropogenic climate change (Petryna 2018), the collapse of the West Antarctic Ice Sheet (O'Reilly et al. 2011; O'Reilly et al. 2012), rogue wild fires (Petryna 2018), as well as pandemics (Caduff 2015; Lakoff 2008) are phenomena that cannot be contained within an envelope of probability and managed in terms of 'risk' (Samimiman-Darash and Rabinow 2015). At the heart of these contemporary phenomena is irreducible uncertainty, the intractability of which threatens to undo human agency and the figure of 'the human' on which it rests.

This chapter traces the paths that I followed, which move continually away from predictability or even un-predictability towards *non*-predictability. More precisely, my focus is the time of sea ice. 'Non-predictability,' as I use the concept here, is not a reaction against, abandonment of, or critique of sea ice prediction. Sea ice prediction plays a crucial role in decision making for people who make a living on or near the ice, as well as for policymakers and private industry that must navigate the Arctic's icy waters (see Eicken and Mahoney 2015). The importance of sea ice prediction for these aspects of human life should not be discounted.[39] Rather, by pre-fixing predictability with its negation (rather that the opposite or reverse of it), I want to open up a space that suspends the imperatives of prediction; namely, to know environmental futures in order to bring them within the sphere of human control. This impulse still conditions the ways in which the scientists I met approach the time of sea ice; hence, my framing of this chapter as non-predictability rather than temporal variability. Prediction as a basic research topic, at a slight remove from the pressures of decision making, allows for a different mode of attending to sea ice and other environmental phenomena, which potentially inflect conceptions of 'prediction' in the first place.

In this chapter, then, I do not follow scientists' everyday practices in conducting sea ice prediction research, nor do I examine the various conceptual frameworks, tools, and techniques used to generate sea ice predictions and make uncertainty tractable. This is not an ethnography of the Sea Ice Outlook/Sea Ice Prediction Network, even if these were the empirical departure points that set me on my path of inquiry. Now that this chapter has been outlined in terms of what it is not about, let me move on to what I found.

Lost time

I raise my hand to knock on the partially closed office door in the Atmospheric Sciences-Geophysics Building. I have crossed the distance between the Polar Science Center and main campus for an interview with Cecilia Bitz, a climate scientist in the University of Washington's Department of Atmospheric Sciences. Taped to the door are a few pictures, but in my memory one image eclipses the rest: it is an 8" x 11" sized-printout of a plump, furry seal pup. A pair of enormous dark eyes looks out at the viewer, its gaze searching, unrelenting, and profoundly inscrutable. I reckon that I have the right office, based on the seal.

Cecilia was involved in initiating the annual Sea Ice Outlook in 2008.[40] In this interview, I want to know how the 2007 minimum impacted scientists' attitudes, especially in the context of global climate change. She rises from her desk and we both seat ourselves at the small, round table near the doorway. I smooth out the list of questions I have printed out and begin.

"How did the 2007 sea-ice minimum become a turning point for sea-ice scientists?"

"It became a turning point because the minimum was unprecedented," Cecilia explains. "We saw a positive incursion [increased sea ice extent] in 1996, so we probably should have expected a negative excursion." She notes that the summer of 1996 was unusually cold and there was a large negative North Atlantic Oscillation signal—an atmospheric circulation pattern characterized by lower-than-average surface pressures and colder surface temperatures. Cecilia heard from her colleagues that the snow did not melt and melt ponds did not form on the sea ice that year, further preserving sea ice. In fact, there were large climate anomalies all over the world.

I nod at Cecilia's response. But I am not satisfied; I want to take the temperature of the 2008 workshop in Palisades, NY, which began the Sea Ice Outlook, even though it happened almost a decade ago. My thoughts snag, absurdly, on a pang of regret as the anthropologist who always seems arrive too late. "Were you—the community of sea ice scientists—surprised in a positive or negative way?" I insist.

"From an environmental perspective, it was a *disaster*," Cecilia admits. "But from an intellectual point of view, it was… exciting."

I look up at her in surprise. *How so?*

"Your system did something you didn't anticipate!" she says. "*That* is exciting."

In Cecilia's excitement about the unexpected, I suddenly glimpse an opening—a possibility for thinking otherwise about uncertainty. In her comment is a different understanding of the unpredictability of sea ice. It is an understanding that treats the unexpected as an exhilarating opening through which scientists can produce new understandings, rather than as a disappointing and even risky gap in knowledge. What captivated scientists' interests and motivated their research was precisely the ways in which sea ice exceeded accepted frameworks. Epistemic uncertainty after the shocking 2007 sea ice minimum was a moment of opportunity and growth, rather than an intellectual dead end.

Cecilia's surprise, moreover, is not mediated by anxiety or fear. This is not to dismiss the seriousness of scientists' concern over the environmental implications of reduced sea ice extent, or the gravity of consequences of sea ice variability on people living in or on sea ice.[41] These issues matter deeply to Cecilia whose interest in climate science grew out of a concern about global warming as a doctoral student in the 1990s. Today, in addition to her commitments as a Professor, she has joined various committees to advise different stakeholders—from Iñupiat walrus hunters in Alaska to the US Coast Guard—on the effects of sea-ice cover on human activities. But Cecilia's comment offers a glimpse onto a different relationship to the uncertainties of sea ice. There is a touch of amazement and no small measure of curiosity that underpins her relationship to Arctic sea-ice and its unexpectedness.

In this particular moment of our interview, Cecilia suggests a relationship to uncertainty that runs orthogonal to the problematization of uncertainty described by anthropologist Adriana Petryna (2016). In her study, Petryna examines how ecologists problematize abrupt change, or 'tipping points,' and the profound epistemological uncertainty associated with it. 'Tipping points' are thresholds, which, when crossed result in non-linear responses to environmental changes. Examples include the collapse of the West Antarctic Ice Sheet, the dieback of the Amazon rainforest and boreal forests, the shutdown of the Atlantic thermohaline circulation, or the transition to a seasonal ice-free Arctic. The system in question experiences a "regime shift," or "a rapid modification of ecosystem organization and dynamics, with prolonged consequences" (Carpenter 2003 [quoted in Petryna 2016]) that may be irreversible.

Epistemologically, non-linear change presents a challenge insofar as it can occur "without signs of any apparent proximate cause" (Petryna 2016: 151). Abrupt change contradicts traditional ecological assumptions about a smooth, gradual transition—and the predictive techniques grounded in this temporal assumption. Abrupt change robs one of the possibility of extrapolating the future from the present or past.

Besides this temporal rupture, there is another kind of epistemological gap implicit in the concept of 'tipping points.' Petryna alludes to this by way of lake life as an example. As American ecologist Stephen Forbes (1887) remarked, a lake is a "remarkably isolated" ecosystem. If terrestrial animals were suddenly annihilated, it would be a long time before lake life would feel the effects in any significant way. Petryna calls this being "blindsided," a turn-of-phrase that implies a kind of epistemological 'blind spot' to introduce my own term.

This epistemological blind spot, as Petryna point outs, is furthermore a structural feature of climate science. As Petryna notes, more monitoring and observations cannot compensate for this epistemological shortcoming. Even our conceptual tools and frameworks are inadequate: "Current assemblies of models and tools are not enough on their own to explain apparently idiosyncratic, ecosystem behaviours or to forecast regime shifts" (NAS 2013 [cited in Petryna 2016]). But even more troubling is the realization that "as understanding of these systems improves, uncertainty around system behaviour tends to increase rather than decline" (Boyd 2012 [cited in Petryna 2016]). There is, in other words, a fundamental and intransigent uncertainty that resists both conceptual frameworks and practical intervention (see Samimian-Darash and Rabinow 2015).[42]

This intransigent uncertainty can invoke paralyzing fear and/or apathy. We might, as a consequence of collective inaction in the face anthropogenic climate change, be working in this blind spot at the very moment. As various climate projections indicate (IPCC 2014), there is a time lag between the temperature increase associated with carbon dioxide emissions in the present and eventual stabilization. This is captured by Petryna in her characterization of living in the midst of an environmental crisis:

> Anthropologically speaking, blindsidedness is a state in which sudden and undeniable realities (…) strike individuals or groups who have no time to craft or recover tools for guaranteeing business as usual or survival. Blindsidedness is a manifestation of extreme isolation and ***lost time***. (Petryna 2016 [emphasis added])

'Lost time' is a curious formulation. The phrase refers, in one sense, to time lost due to a lack of knowledge about the future. In another sense, it speaks to the loss of a particular concept of the ‘future’ as the grounds for human historical agency. As historian Reinhart Koselleck (2004) outlines, at the end of the 18th century a new shape of the ‘future’ emerged unbound from a divinely or naturally-given order. It was precisely the open-endedness of the future—its escape from, rather than continuity with, the past—that made human historical agency possible. Facing an unknowable future, “it becomes plannable—indeed it must be planned” (Kosselleck 2004: 39). The ability to not only know the future, but to *produce* it, became a distinctive trait, even a moral imperative, that made human beings exceptional. But Petryna’s ‘lost time’ suggests a future that has slipped beyond even the reach of plannability—and, hence, human historical agency. ‘Lost time’ thus evokes a sense of melancholy over the loss of ‘the human’ as it emerged out of the Enlightenment.

Astrid Schrader’s (2012) problematization of efforts to predict ‘harmful algal blooms’ helps sharpen the edges that define sea ice prediction as a contemporary challenge. Harmful algal blooms arise from the runoff of agricultural fertilizers into the ocean, which lead to the proliferation of algae, bacteria, and jellyfish. As its name suggests, there is no effort to disguise the anthropocentrism in the study of these algal blooms, which are ‘harmful’ from the perspective of human health, the economy, and ecological systems that humans value. To mitigate losses in economic and biological productivity, scientists have developed more sophisticated biomonitoring techniques that can detect algal blooms as they emerge in ‘real time.’ These “just-in-time technologies” are not only shaped by short-term economic logics but reduce algae to a collection of genes or chlorophyll that can be quickly quantified and thereby inscribed within anthropocentric temporalities. What is ignored, Schrader notes, is “the contribution of the microorganisms to their scientific determination” (Schrader 2012: 87).

As marine microbiologists relate, many dinoflagellate species have dormant cyst cycles, which allow them to survive adverse conditions until more favourable circumstances arrive for growth and germination. More importantly, cell division is regulated by environmental conditions; many species can switch between sexual and asexual reproduction depending on nutrient availability and the stage of a bloom. Algae, in short, can alter their very nature. Far from existing in a fixed relationship to an environment that they presumably cannot change, Schrader points out, these algae are able to transform themselves in dynamic interactions with their environments (see Schrader 2010). The time of marine microorganisms cannot be captured by current technoscientific means, no matter how speedy they are.

Detection of harmful algal blooms, Schrader concludes, "requires the reconstruction of a 'shared time,' such that 'time' would no longer be ours alone" (Schrader 2012: 89). In making this claim, Schrader puts environmental prediction—whether of ecological transitions or sea ice conditions—into new perspective. Prediction is not necessarily an effort to 'recover' lost time (e.g., Petryna 2018), nor the "mere affirmation" of a nonhuman temporality (Schrader 2012: 73), but a practice of making collective time. One that begins, furthermore, by trying to grasp the contours of times not of human making.

What if, instead of being a 'blind spot,' the epistemological uncertainty associated with prediction of sea ice can be a window onto a time not made by human beings—and which, furthermore, produces a time that coordinates the lives of many beings, both human and nonhuman? How might understandings of sea ice temporalities in turn shape concepts of 'prediction'? To focus on the time of sea ice is to work against the imperative of predictability that folds nonhuman times into that of human beings, but which still gains definition against predictability as a problem. One could say this is an inquiry into the 'non-predictability' of sea ice.

A different unit of time

Before going further into the time of sea ice, I want to explain a curious concept that populates the climate sciences: the climate anomaly. A climate anomaly is a departure from average values of a given climate variable, such as sea surface temperature or sea ice thickness, over a given time period.[43] In everyday language, an anomaly indicates whether sea ice is thicker or thinner than usual, or if the atmosphere is warmer or cooler than average. Weather forecasts and climate projections are expressed in terms of climate anomalies: Is this year going to be wetter and warmer, or drier and colder than last year? For climate scientists, the anomaly is a useful concept because it isolates quantities of interest from background variability (what scientists call 'climatology'), such as the seasonal cycle or global warming. It is also a *relative* value, which allows comparability across time and space. Anomalies are how climate scientists characterize climate variability (Hurrell and Deser 2009; Wanner et al 2001).

Perhaps most significantly, anomalies set in motion physical mechanisms that grow, develop, unfold, evolve, magnify, dilate, contract, dissipate, decay, and fade. An anomaly is a nucleus of time from which weather and climate—or sea ice conditions—emerge. As will become apparent in the following, anomalies make visible non-human temporalities in-the-making.

Persistence, Memory

Sea ice is fairly constant. It does not vary quickly in area or volume, nor are these variations large in magnitude. The constancy of sea ice is a curiosity, rather than a negative observation. It drew the attention of Norbert Untersteiner, who remarked that swings in atmospheric energy transported from mid-latitudes were "not reflected in the sea ice cover" (1990). The atmosphere and likely the ocean, Untersteiner noted, should lead to greater interannual variability in the ice cover "than the one we see." So where—and how—does the sea ice conceal the effects of these energetic influences? This was one question that motivated Cecilia's dissertation research in the late 1990s who sought to understand how the storage of energy was partitioned between the atmosphere and sea ice cover.

The thermal properties of sea ice help explain its persistence. Sea ice has a relatively large thermal inertia, meaning that it does not warm or cool very quickly. This is directly related to the relatively high *heat capacity* of sea ice, or the amount of energy it takes to warm sea ice.[44] In the same sense that heavier objects are harder to lift because of a greater intrinsic resistance to change (in motion), sea ice's higher heat capacity imparts thermal 'inertia' to its subsequent evolution. Thus, sea ice can linger on even when the atmosphere or ocean warms.

Furthermore, sea ice can conceal the influence of warmer or cooler conditions within its interior. Though sea ice is frozen, it is far from inert. When surroundings cool, brine pockets freeze and shrink until they reach the equilibrium salt concentration for that temperature. Conversely, as ice warms brine is diluted to a new equilibrium concentration by melting ice along the walls of the pocket. In this way, brine pockets shrink and dilate like "thermal irises," absorbing and releasing energy within the interior of the ice to balance out differences in temperature or salinity within the total ice structure—all without effecting macroscopic changes to the entire system (interview with Cecilia Bitz, November 14, 2016).[45]

Sea ice can also integrate thermal changes within its interior by thinning or thickening without any observable changes in extent. At present, however, such changes in sea ice thickness escape detection. Satellites cannot 'see' below a certain depth from the surface of the ice. Even with other observational methods (e.g., airborne electromagnetic induction surveys), these observations do not achieve the same areal coverage as satellites. Sea ice extent remains the most visible and easily obtainable metric of interannual variability.

Sea ice, in short, is a heat sink. It acts as a reservoir that can absorb and integrate atmospheric and oceanic heat fluxes, storing them as anomalies in the sea ice cover. For instance, warmer ice (a positive temperature anomaly) potentially accelerates the rate of melt and leads to earlier melt onset, while thicker sea ice (a positive thickness anomaly) can slow the rate of melt and lead to later melt onset. In this sense, anomalies in the sea ice cover release temporalities that develop and decay on their own terms.

Thermal inertia lends to sea ice what scientists call a high degree of 'persistence'—which is to say present sea ice conditions will continue into the future. Persistence allows for a very simple kind of forecast: tomorrow's conditions will be like today's. In fact, scientists noted that "persistence of Arctic sea ice can offer some degree of predictability even without the use of a numerical model" (Blanchard-Wrigglesworth et al. 2011: 232). The promise of persistence in sea ice predictability has motivated further scientific investigations: how long does the persistence of, for instance, sea ice area last? Does the degree of persistence in sea ice area vary over the course of the year? And what physical mechanisms are related to the time of areal persistence?

In 2011, Edward Blanchard-Wrigglesworth and Kyle Armour—then doctoral students under Cecilia's supervision—addressed these very questions in a seminal paper on sea ice persistence. Selecting this paper among others is, in part, a contingency of the directions my fieldwork took me, which itself reflects a transition between earlier research from the 1990s through the early 2000s that sought to determine patterns of sea ice variability, and more recent research post-2007 that has shifted emphasis towards sea ice predictability. But beyond these contingencies, the study offers insights on the time of sea ice insofar as it focuses specifically on sea ice as its unit of analysis.

Edward and Kyle's study sought to measure the degree of persistence by assessing the strength of correlations between total sea ice area at different times of the year in both observations and models. A strong correlation in sea ice area indicated persistence, and vice versa. For instance, if there was an anomaly in the sea ice cover on New Year's Day, it was likely to be there one day afterwards, or even a month later. The correlation will be stronger the shorter the intervening time. Correlation tends to decrease the further away in time from the initial anomaly so that the anomaly from New Year's Day might have disappeared by July. Edward and Kyle discovered that correlations in sea ice area quickly weakened within two to five months. But after the initial drop, the correlation increased again. As they state: "Such an increase in correlation after some time has been described as a *re-emergence of memory*, and it signals a return of persistence after a gap" (Blanchard-Wrigglesworth et al. 2011: 234 [emphasis added]). This statement merits dwelling upon. What do the they mean by 'memory'? Can sea ice 'remember'?[46]

'Memory,' as taken up by sea ice scientists, is the storage of information—more specifically, anomalies in sea ice (temperature, sea ice area, thickness, volume). These anomalies comprise basic units of information in the sea ice cover at a given moment in time and, hence, memory beyond that moment. As described earlier, sea ice can store heat fluxes as anomalies in its coverage conditions, which influences how sea ice evolves in the future. Moreover, memory allows for continuity despite momentary lapses in the persistence of, say, sea ice thickness or sea surface temperature. In this manner, anomalies in sea ice perform the functions of 'memory' insofar they store information, encode, and retrieve this information. The transformation and exchange of anomalies from one type to another allows for the conservation of information within the system.

By correlating anomalies of sea ice area in one month with those in later months, scientists could ascertain patterns of 'remembering' distinctive to sea ice. They discovered that sea ice has a seasonally variable memory with two main branches. First, a 'summer limb' of memory characterized by high anomaly correlations between the following pairs of months: August-September; July-October; June-November; and May-December. These pairings suggested a relationship between sea ice cover from melt to grow season.[47] And second, a 'winter limb' of memory, in which late fall/early winter anomalies were correlated with anomalies the following summer.[48]

The timing and duration of these mnemonic 'limbs' correspond to different kinds of anomalies in the sea ice system. For the summer limb, scientists hypothesized that there was an exchange between anomalies in sea ice area with sea surface temperature. Less ice (a negative area anomaly) at a particular location during the summer melt season was associated with warmer sea surface temperatures (positive temperature anomaly). When sea ice cover shrank over the course of summer, the high heat capacity of seawater allowed positive anomalies in sea surface temperature to persist for several months. When the ice began to grow again during the fall, it would re-encounter this warmer water and 'inherit' the anomaly, thereby influencing the rate at which sea ice forms.

For the winter limb, anomalies in sea ice thickness were implicated. Thicker ice (positive thickness anomaly) in a given location was associated with earlier freeze-up in the winter. During the spring when the ice retreated northward back to sites with thicker ice, the thickness anomaly would impart a positive anomaly to sea ice area. Thus, anomalies in sea ice area between, for example, January and April were closely correlated. In the heart of the central Arctic, which is dominated by perennial ice, persistence of sea ice thickness could last up to a year. By contrast, in the seasonal ice zone, which experiences variable ice cover with the melt-grow season and higher ice motion, anomalies in sea ice thickness did not persist as long. Thickness anomalies in this region typically lasted only a few months. The persistence of thickness anomalies was therefore not just a function of thickness, but also ice movement. From these findings, Edward and Kyle concluded that anomalies in sea ice thickness lent a summer-to-summer persistence to sea ice.

Perceptible in the background of Edward and Kyle's paper is a distinctive temporality of sea ice. Between spring and fall of the same year, the time of sea ice is shaped by the exchange of anomalies in area and sea surface temperature. And from one summer to the next, the time of sea ice was determined by thickness anomalies. These variations in sea ice follow the seasonal cycle insofar as it grows and melts from winter to summer. But as the timeframes of these anomalies suggested, which were both shorter and longer than a year, the time of sea ice is not *reducible* to the seasonal cycle over the course of a year. This claim is crucial. As another scientist explained the aims of sea ice prediction to me, she pointed out that sea ice scientists want something "better" than long-term averages and natural variability, i.e., the basic pattern of sea ice growth in fall and melt in spring. In this view, Edward and Kyle's paper delivers the kind of knowledge that can improve sea ice predictions. It does so by attending to the specificity of how sea ice produces its own time through the evolution of anomalies internal to the ice itself, and through the exchange of anomalies with the upper ocean.

One parting remark on the time of sea ice: persistence lends predictability, but not only, or simply because, sea ice is constant and unchanging. What makes persistence a powerful predictive tool is, ironically, acknowledging the possibility that sea ice can change. That said, the possibility of environmental change is not one that people, even seasoned scientists, are readily willing to admit. Cecilia recalls a moment from when she began her dissertation research on long-term natural variability of the sea ice cove. Her supervisor mentioned that Norbert, one of her committee members, would not like the topic. Norbert was proud of the data that he had collected from his previous Arctic field campaigns; he had to managed to produce a good picture of the Arctic, to which there was nothing to add. The idea that natural variability, and the possibility that one had to go back to the Arctic to collect new data to modify this picture over time, was unsettling to him. But, as Cecilia poignantly observes, to study the time of sea ice one has to "at least allow for it not to be the same." One must let go of the assumption that sea ice is forever. And as sea ice thins, the time of sea ice may be becoming more variable (Holland et al. 2008; Goosse et al. 2009). In this light, persistence can lend predictability insofar as it heightens scientific sensitivities to the changeability of sea ice, not only in the invisible integration of heat within its interior, but in its transformations from sea ice to seawater and back again.

Oscillations

Enlarging one's scale and unit of analysis to 'coupled' climate systems can open up temporal horizons on the order of decades to centuries. This understanding formed the basis of Edward and Kyle's treatment of sea ice, which allowed them to resolve sea ice-temporalities on seasonal (up to three months) to interannual (more than one year) scales. Just as 'sea ice' is a provisionally stabilized occurrence at the boundary between atmosphere and ocean, the time of sea ice is not hermetically closed. It is an open and distributed time—one that implicates, and is implicated by, other dynamics in the climate system. Expanding one's frame of view to consider the atmosphere, ocean, and sea ice on large-scales has brought into view decadal-to-interdecadal variability of sea ice, especially its patterns of circulation. To grasp the difference that coupled climate systems make, however, requires a protracted detour to the tropical Pacific and the makings of collective time in this region of the world. As will be shown, processes in the tropics provided scientists with an analytic frame that could be transported into the Arctic.

Couplings bring into focus that which exceeds individual components of the climate system. Ice, ocean, and atmosphere are, on one hand, physically distinct components with their own dynamics. But ice, ocean, and atmosphere do not exist in isolation; they are in mutual communication or, in scientific terms, 'coupled.' Anomalies in sea surface temperature, for instance, influence the strength and direction of winds, which in turn shape the pattern of sea surface temperatures. These dynamics are known scientifically as 'feedbacks.'[49] As the circularity of this concept suggests, it is difficult to determine 'cause' and 'effect,' which presupposes independent components. Anomalies set in motion "dynamically growing and receding (and in some cases oscillating) patterns with definable and predictable characteristics and lifetimes" (NRC 2010: 27). Significantly, these temporal patterns are not necessarily synchronous with the seasonal cycle; they suggest temporalities that are not only distinct from the calendar year but are also not fully determined by the seasonal cycle.

The most well-defined 'oscillation' is El Niño, or the Southern Oscillation, a world weather pattern that alternates between warm phases (El Niño) and cool phases (La Niña) every four years or so. This alternating pattern has been shown by scientists to result from ocean-atmosphere feedbacks in the tropical Pacific.[50] Its time scale is set by a difference in the temporal evolution of the ocean, which is very slow in responding to changes in the winds, and the atmosphere, which can adjust swiftly to altered ocean temperatures (Philander 2004). This delayed response—of the ocean to a change in the winds—determines the period of El Niño's oscillation. And though its dynamical heart lies along the equator of the Pacific Ocean, the effects of El Niño can be communicated to remote parts of the world, which influence the timing and duration of regional weather patterns and events.

El Niño has shaped in profound ways the lives of humans and non-humans around the globe. Before it became intelligible as a recurring world weather pattern, El Niño shaped human lives through episodic, and often disastrous, events. It has been responsible for the onset of monsoons in India; extended droughts over large areas in Africa; the disappearance of fish off the coast of Peru; floods in California and Kenya; and mild winters in Canada. In 1982-83 and 1997-98, the El Niño episodes were particularly severe; its impact could be counted in the number of human deaths and injuries, as well as the wild swings of stock market indices (Philander 2004). As scientific understanding of El Niño has grown over the 20th century, however, the singularity of these events could be normalized into a regularly occurring pattern, and its severity the result of intensity rather than unexpectedness.

El Niño, and other 'modes of variability' as scientists call them, suggests a collective time of its own not fully determined by celestial periodicities. El Niño produces, moreover, a collective time distinct from the universal time that regulates modern human life today. As Paul Edwards (2010) recounts, it was the standardization of clock time in the late 19th century, rather than the mechanical accuracy of clocks, that produced universal time. Before, time was kept according to solar noon in a given locale, which varied with longitude. As a result, there was a multiplicity of times, along with multiple time standards. The establishment of a uniform time standard, known today as Greenwich Mean Time, created a universal time precisely because it transcended the particularities of any given location and unified time around the globe. More specifically, it provided a time decoupled from the local diurnal cycle. "Where solar time was tied to one's exact location, universal standard time created large, abstract zones within which time would be the same at all latitudes and all times of year" (Edwards 2010: 47). Standardization enabled the synchronization of human activities around the globe, from the activities of markets to the advancement of meteorological understandings through simultaneous, standardized observations around the globe.

The very emergence of universal time also made visible a different order of collective time based in the global climate system itself. El Niño influences the timing of the monsoon season in India, the failure of which can lead to famine. The onset of El Niño changes the composition of marine and terrestrial ecosystems in Peru. Desert plants flourish with the arrival of El Niño, and tropical species of fish are more populous than the cold-adapted Peruvian anchovy, which shrink in number. An intense El Niño can be devastating to anchovies, but their four to six-year life cycle, as well as their smaller size, allow anchovies to recover over time (Philander 2004). "Earth's fauna and flora have come to terms with the seasonal cycle," writes oceanographer George Philander, "To them the irregular, whimsical Southern Oscillation is as much part of the rhythm of life as is the more predictable cycle of summer and winter" (Philander 2004: 241). Commercial fishing and global markets, however, are not as capable in adjusting to these rhythms. When the 1972 El Niño event hit, anchovy stocks plummeted and remained low for more than a decade. There were severe economic consequences: by the end of 1975, there were only 530 boats and 51 factories in operation (Philander 2004). El Niño, in short, produces a collective time that includes not only humans but nonhumans as well. It is like universal clock time, insofar as it is collective and coordinates activities around the globe via a single phenomenon. But in contrast to standardized universal time, which produces a collective time by decoupling time from the environment, the collective time of El Niño is internal to the global climate system.

Also emergent from El Niño is a concept of collective time that does not gain definition from human society. According to Émile Durkheim, time was collective because social life is.

Time, Durkheim argued, did not passively reflect something already given 'out there,' but was a 'collective representation' that emerged from social life, and according to which social life organized itself (Durkehim 1911). This claim was further reinforced in Edward Evans-Pritchard's (1939) socialization of 'ecological time' in his ethnography of the Nuer people in southern Sudan. Although ecological time concerned the relations between people and their environment, this order of time was at base social insofar as it referred to "successions of events which are of sufficient interest to the community for them to be noted and related to each other conceptually" (Evans-Pritchard 1939: 94). Collective time in the long-term was even more fundamentally social. Beyond the annual cycle, Evans-Pritchard argued, nature repeats itself. Thus, to differentiate longer periods than the seasons, Nuer relied on relations among groups of people in the social structure. Insofar as nature was constant, unchanging, and in effect, *timeless*, and to the extent that 'society' was a separate reality unto itself, human social life could provide a principle of intelligibility for the emergence of 'time' as a category of understanding.

El Niño, however, produces a collective time that does not ground in social life or human-made timekeeping devices. It is a collective time with its own internal structure, according to which the lives of humans and nonhumans alike are ordered. Furthermore, the time of El Niño is not bound to a constant and unchanging cycle, whether on an annual or interannual timeframe. Its timeframe of growth and retreat is shaped by the strength and location of climate anomalies, which can vary from one cycle to the next—and may even be changing with global warming[51]—which in turn shapes the time of response of physical systems. El Niño, in short, offers a way to reckon time apart from human social life. Although not as regular as the seasonal cycle, which follows the revolution of the Earth around the Sun, or the oscillations of a cesium atom that calibrates the time of clocks, growing scientific understanding of El Niño offers a rough kind of 'calendar' on four- to seven-year time scales.

As oceanographer George Philander (2004) notes, a 'calendar'—or, more precisely, knowledge of regularly occurring weather patterns that correspond to the seasons—helps humans to cope with enormous climate change. That is, the seasonal cycle. Calendars can help synchronize the time of human life with nonhuman temporalities. A calendar provides predictability of a different kind than from a weather forecast. Unlike numerical forecasts, which simulates the short-term evolution of the atmosphere, calendars offer predictability based on repetition or regularity. The promise that El Niño holds in providing such a 'calendar' opened new frontiers in climate prediction (see NRC 2010, 2016). It led scientists to look for recurring circulation patterns, or 'modes of variability,' in other parts of the world.

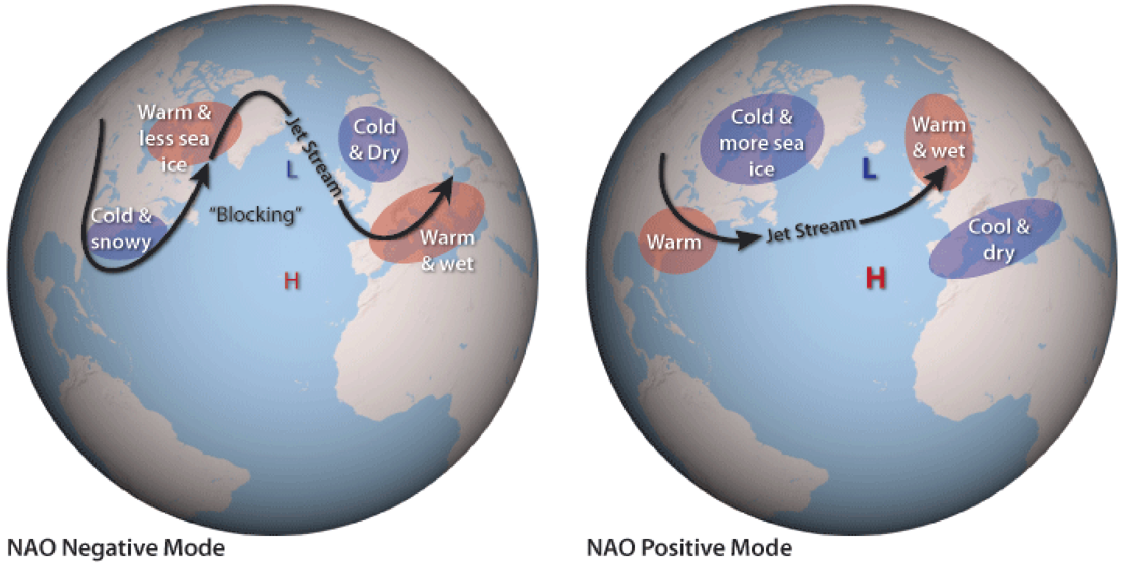
Outside the tropics, there is a recurring circulation pattern in the North Atlantic known as the North Atlantic Oscillation (NAO) or Arctic Oscillation (AO). The two names refer to the same phenomenon, but vary depending on one's method of analysis. For simplicity, I refer to the NAO. In very basic terms, it refers to a redistribution of atmospheric mass between the sub-polar low near Iceland and the sub-tropical high near the Azores Islands. In terms of its influence on global climate variability, the NAO rivals El Niño in significance (Wanner et al. 2001). The NAO shapes the speed and direction of winds across the Atlantic, modifies the sinking branch of the ocean's overturning circulation, the position of the Gulf Stream, the strength and direction of winter storm tracks, temperature and precipitation in northern Europe, agricultural harvests, water management, energy supply and demand (Hurrell et al. 2003; Wanner et al. 2001). The circulation patterns of sea ice extent have been found to be closely associated with the NAO (Deser et al. 2000).

Compared to El Niño, the NAO is not a well-defined or clear oscillation, but neither is it random. It appears to fluctuate on multiple time scales, from 6 to 10 years and from 60 to 70 years, with no preferred time scale of variability.[52] Temporal regularity aside, it is one of the oldest known world weather patterns. As early as the late 18th century, Danish missionaries documented it as an opposition of winters: when the winters in Denmark were severe, winters in Greenland were mild, and vice versa (see Van Loon and Rogers 1978). The pressure difference between Iceland and the Azores has since provided a simple index of the state and strength of the NAO. Reconstructions from instrumental records have allowed scientists to trace the NAO back to 1821 (Hurrell 1995); in paleoclimate reconstructions, the NAO is detectable as a robust and coherent signal to thousands of years ago.

The dynamical mechanisms that determines the variability of the NAO are not well understood. It is not determined, like El Niño, by coupled ocean-atmosphere interactions (Czaja et al. 2003; Visbeck et al. 2003). Several scientists argue that the NAO is driven entirely by processes intrinsic to the atmosphere, for instance through stratosphere-troposphere interactions (Thompson et al. 2003; Thompson and Wallace 2000). The collective time at stake in the NAO, then, can be understood not so much in terms of an oscillation that keeps time through periodicities (much as a clock mechanism or even coupled climate components do), so much as a fluctuation that dynamically *resolves* temporalities that unfold in response to atmospheric perturbations. Grasping the time of the NAO requires a basic understanding of the average patterns of atmospheric circulation.

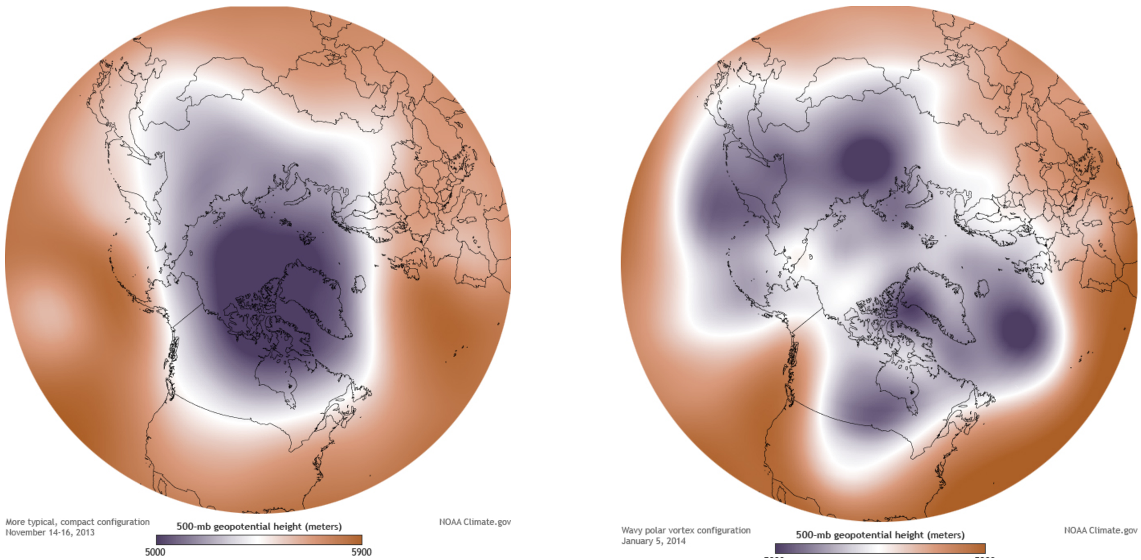
In very basic terms, the atmosphere can be understood as a fluid responding to the motions of a rotating sphere (the Earth) heated by an external source (the Sun). The rotation produces planetary-scale wave patterns that tend to persist over time and are ‘locked’ to certain geographic features, such as mountain ranges or land-sea boundaries. These stationary wave patterns have a major influence on the strength and location of the jet stream, as well as pressure systems and weather. Sometimes, however, these patterns change in time because heating patterns in the atmosphere vary or because of internal processes (Hurrell and Deser 2009). The transient response of planetary-scale waves appears as anomalies in climate over large geographic regions, with some regions experiencing cooler or drier than average weather, while at the same time thousands of kilometers away, warmer and wetter conditions prevail. “These simultaneous variations in climate, often of opposite sign, over distant parts of the globe are commonly referred to as ‘teleconnections’” (Hurrell and Deser 2009: 30).

The influence of the NAO, then, lies in producing a collective time through *simultaneity* of spatially disparate climate anomalies, rather than through *regularity*. The NAO brings disparate weather phenomena over a large geographic region into a shared time. In its positive phase (i.e., the subtropical high is stronger than usual and the Icelandic low deeper than usual), the greater pressure difference drives storm tracks further north, producing warm and wet winters in Europe and cold and dry winters in northern Canada and Greenland, while the eastern US experiences mild and wet winter conditions. In its negative phase (i.e., the pressure systems are not as well-developed), the opposite conditions prevail. Fewer and weaker storms cross from west to east, moist air enters the Mediterranean and cold air blasts northern Europe, while the US east coast experiences more cold air outbreaks and snowy weather conditions. Greenland, meanwhile, has milder winter temperatures. These weather phenomena, though disparate in character and separated in space, can be unified in a shared time through the NAO.[53]



Schematic of the North Atlantic Oscillation in its negative phase when the Iceland low and Azores high are not as well-developed (left) and positive phase when the pressure systems are highly developed (right). Figures by NOAA.

More recently, the NAO has received greater attention in the public consciousness but under its 'alter-ego,' the Arctic Oscillation (AO). As mentioned earlier, the NAO and AO both refer to the same spatial pattern. They differ, however, in terms of which dynamical mechanisms they implicate.[54] Whereas the NAO tends to look for mechanisms in atmosphere-ocean interactions, the AO emphasizes stratosphere-troposphere interactions. In particular, the AO brings into focus the polar vortex, a statistically regular feature found in the stratosphere above the Arctic. The polar vortex contains very cold air, with air to the south being much warmer. The sharp boundary between these different air masses gives rise to the polar front jet stream. Spatially, the shape of the polar vortex is irregular, characterized by southward-bulging 'troughs' and northward-extending 'ridges.' When the AO is positive, the polar vortex tends to be tighter and shifts toward the pole. In its negative phase, the polar vortex becomes wavier, with more pronounced troughs and ridges.



A strong polar vortex configuration in November 2013 (left) compared to weak polar vortex configuration on January 5, 2014 (right). Figures by NOAA/PMEL, Wikimedia Commons.

In January 2014, a lobe of the polar vortex sagged into the mid-latitudes, bringing with it an extreme cold snap and heavy snowstorms. Temperatures hit record lows for the calendar year in eastern and central US, the eastern Canadian provinces and Northwest Territories. On January 6, temperatures in Winnipeg hit -37 degrees Celsius and were -26 degrees Celsius at the Chicago O'Hare International Airport. Heavy snowfall closed roads, businesses, and schools, as well as cancelled flights. These extreme weather events, combined with the publication of a scientific paper only two years earlier in 2012, led journalists to pick up on the Polar Vortex as a powerful explanatory framework. The White House itself became keenly interested in this phenomenon and Jennifer Francis of Rutgers University, one of the co-authors of the 2012 paper, became an informal consultant to John Holdren, science advisor to then President Barack Obama.

In their paper, Francis and Vavrus (2012) had suggested that the loss of Arctic sea ice was responsible for the increased waviness of the polar jet stream. Briefly put, the warming of the Arctic was reducing temperature gradients that give the jet stream is power. Consequently, the jet stream was slowing down and its structure becoming wavier. The waviness, in turn, was retarding the eastward movement of weather patterns. As a result, breakdown of the polar vortex was leading to persistence of extreme weather events of all sorts: prolonged dry periods and warm spells, as well as protracted storms and cold snaps. The theory remains highly controversial amongst scientists who called for caution around such arguments, which could not be confirmed using alternative observational analyses and simulations with climate models (Wallace et al. 2014). For these scientists, it is still an open question as to whether the loss of Arctic sea ice drove changes to the large-scale atmospheric circulation.

Its facticity aside, the Polar Vortex as a figure threw people living at mid-latitudes into the time frame of sea ice. "If a warming Arctic is already affecting weather in the mid-latitudes," noted Walt Meier, a remote sensing sea ice specialist at NASA Goddard's Space Flight Centre, then climate change "no longer becomes something that's remote, affecting polar bears. Instead, it's a day-to-day reality affecting billions of people—and a challenge to policy makers responsible for assessing and reducing the risks" (Meier quoted in Kintisch 2014: 250). The Polar Vortex as a figure introduced into the public a consciousness about the simultaneity of changes in the Arctic with those in the mid-latitudes. But beyond this, the Polar Vortex also suggested an alignment between the time of the mid-latitudes with the unprecedented linearization of sea ice time in the long-term. Although sea ice grows and melts with the seasons, as mentioned at the beginning of this chapter, since the 1970s there has been a steady decline in sea ice extent due to anthropogenic climate change (IPCC 2014). Studies suggested that the Arctic may even become 'ice-free' in the summers by 2030 (Meier et al. 2014). In other words, human beings are changing the time of Arctic sea ice. What the Polar Vortex made apparent, however was the coupling of human times with the changing time of sea ice; a joint time that is opening, moreover, onto unknown horizons not fully determined by the annual cycle, or given in its recent past.[55] Although the Polar Vortex requires much more research to determine its facticity in the scientific community, it has become a charismatic social actor that has effected a shift in thinking about collective human-nonhuman temporalities.

To reiterate, even though the NAO/AO does not have the same regularity (and predictability) as El Niño, it is a recurring world weather pattern that produces a collective time through simultaneity. The vast distances that separate the poles and mid-latitudes are conceptually collapsed in the making of this shared time. It is also, like El Niño, not a time based in human social life but internally generated and differentiated. And yet, the time of the NAO/AO, as well as El Niño, is not fully separable from human activities. The temporalities of world weather patterns are potentially changing with anthropogenic climate change—an interaction that further undermines conceptual divides between, on one hand, the time of a separate social order, and that of a presumably constant nature that repeats itself.[56] Humans and global climate systems are, like the ocean and atmosphere in El Niño, or the troposphere and stratosphere in the NAO/AO, *coupled* and mutually changing one another.

Calendar-making

The time of sea ice, weather, and climate is not constant and unchanging. As the loss of Arctic sea ice indicates, this temporality is not necessarily even cyclical but unfolds into an unknown future. This temporal openness, I argue, challenges assumptions that underpin 'prediction' as a concept—and brings us round to the questions that initially framed this chapter. After spending so much time attending to the time of sea ice and weather, how do such understandings potentially inflect 'prediction' as a concept?

Returning to Kosselleck's (2004) account of the concept of 'history,' human scientists took it for granted that the time of nature was closed. Nature was locked into a cycle that repeated itself, and consequently, could not produce anything fundamentally new. Only humans, as distinct from nature, could produce futures that were fundamentally underdetermined by the past and opened into the as-yet unknown. As scientific studies indicate, however, the time of environmental phenomena such as sea ice, El Niño and the NAO/AO are hardly repetitions. They may demonstrate some periodicity, but they can also depart from these regular variations in radical and unprecedented ways. This is not just because contemporary anthropogenic climate change is altering the temporalities of the global climate system; paleoclimate studies show that world weather patterns and sea ice extent have been dramatically different in the past and changed within the span of a human lifetime (e.g., Alley 2000). Sea ice, weather, and climate, in other words, can, have, and will, produce difference.

To allow that environmental phenomena *can change*—both radically and abruptly—rather than assuming it is immutable, or varying so slowly as to be unchanging, is the condition of possibility for prediction research. It is this assumption, as Cecilia observed, that allows scientists to grasp the time of sea ice, weather, and climate—its historicity and capacity for change. Such sensitivities can in turn help scientists generate tools and concepts that are attuned to the ways in which sea ice produces its own time. In doing so, scientists must be ready to meet the challenge that these environmental phenomena pose as they overturn assumptions on which scientists based knowledge about them. This is the dilemma that Petryna (2018) describes in her anthropological study of wildfires. With anthropogenic climate change, wildfires are becoming both more frequent and severe, as well as changing in kind. Wildfires are spreading against the wind and burning into old fire scars where they should not be able to burn. These wildfires have prompted fire behaviour analysts and firefighters to revisit taken-for-granted assumptions, to adjust their frameworks, or draw up from scratch entirely new conceptual models of understanding. As one fire behaviour scientist poignantly states: “We no longer know what fire is” (Petryna 2018: 585).

Wildfires are outrunning human projections, and in doing so, wresting away a temporal horizon that enables humans to make decisions and act accordingly. In characterizing prediction activities as a “race against (lost) time” (Petryna 2018: 571), one gets the impression of human agency as a ragged figure struggling to keep up with raging wildfires, severe storms, and melting sea ice, running to get just far enough ahead of a changing nature not only to take action, but to quickly throw in place the conditions that make human agency possible. Namely, to stabilize nature. It was the constancy of nature or, at the very least, a nature that changed so slowly or remained so regular as to be constant, that allowed human agency to take form. The environment, however, changes; it is not identical but produces difference. And this changeability appears to be taking agency away from humans. So long as ‘prediction’ is conceived as a technology that shores up human agency on the basis of an unchanging nature, prediction activities will have difficulties come to terms with environmental phenomena.

To be clear, to problematize prediction is not meant as a dismissal of the need to find ways of making choices and acting accordingly. These are still crucial for the living of life. And as the work of sea ice scientists and fire behaviour analysts illustrate, consciousness of the changeability of environmental phenomena—in the past, present, and future—permeates their prediction activities. What I am suggesting is not an abandonment of prediction activities, but a reorientation in thinking ‘prediction’ as a concept. Concrete examples of activities that follow from this concept are not to be found in this dissertation. My goal is simply to frame a possibility in the form of a question: What if ‘prediction’ could be conceived, instead as the making of a shared time? This time would be shared insofar as human and nonhuman temporalities are *both* understood to be in motion and, hence, collective time must be articulated as “motion in terms of motion” (Rees 2018).

Interlude: The Sound of Sea Ice

In July 2017, Cecilia organized a mini, one and half-day workshop on sea-ice predictability. It convened not only sea ice scientists from the different departments at the University of Washington, but sea ice scientists from institutions across the United States. We have gathered in a medium-sized seminar room in the Atmospheric and Geophysical Sciences Building. There are short talks on the potential influence of Arctic cyclones on sea-ice extent, Arctic amplification, re-emergence.

The workshop closes with “The Sound of Sea Ice,” a presentation by a doctoral student, Judy Twedt, in the Atmospheric Sciences Department. *This will not be a recording of sea-ice and the sounds it makes,* the student explains. Several artists and scientists have made such recordings to bring sea ice and other Arctic phenomena into the range of human hearing.[57] Her experimentation with sound is slightly different, though it still draws on the effort to move people via sensory modes of understanding.

She pauses. Judy does not want to add anything more before we listen. She wants to know what we think of the piece before continuing. With a light touch, she taps a key on the computer and the audio piece begins.

There is a low hum. An expansive, mournful sound fills the room. A filigree of high-pitched notes in a minor key plays around this hum. There is no pattern to the notes as they dance around the low hum, the latter of which slides progressively down the scale by semi-tones. Every now and then, there is the echo of something animal. As the piece continues, there is a gradual diminuation in volume.

The plot of September sea-ice extent appears plainly before me like a piece of sheet music: the low hum is the trend, the notes the natural fluctuations of September sea-ice extent, and the decreasing volume of the whole ensemble the vanishing of sea-ice, from sight and sound.

We follow the sound of sea-ice as it fades. Listening, waiting, trying to discern the end. And then the silence continues.

The piece is just over a minute long.[58]

Judy watches the listeners from the front of the room, carefully observing their reactions before taking questions. It is clear that the elements of ice are not easily identifiable, even amongst this group of sea-ice experts. It is a highly abstracted piece, which has required several mediations not only in its composition as a sound piece, but in its making as a scientific object, from the image-processing algorithms that determine sea ice extent, to the plotting of these data points over time and the application of smoothing factors to bring out variability on different time scales, and to the fitting of trend lines to the data. Perhaps, listeners are not only hearing the 'sound' of sea ice, but also hearing the sound of scientific abstractions, the manifold analytic decompositions that make up variability of sea ice extent over time. Producing sea ice variability as an object, I have learned, is not unlike a sound engineer trying to optimize the right wavelengths so that a coherent signal is audible. In fact, scientists and sound engineers share the same methods, such as spectral analysis and Fourier wave transforms.[59]

The piece requires a different mode of listening. It requires one to listen against the grain of naturalistic sensibilities that train one's ear to detect recognizable sounds made by an object in the world. It requires developing an ear for something that has no corresponding referent in the world, but to not, for this reason, dismiss it as too abstracted to be moved by it. To listen to sea ice requires tuning into multiple frequencies, adjusting one's range of hearing.

Judy patiently explains the four elements of the piece, confirming what I had inferred from the sound piece. There are questions about the kind of effect this piece will have on listeners, the 'takeaway' message that it elicits. The piece also raises questions about the aesthetic choices it encodes, from its choice of instrumentals and the inclusion of more naturalistic sounds, to its transposition in to a minor key. But beyond explicit messaging and sensory effects, what strikes me as remarkable about the piece is its time. For the duration of just over a minute, listeners are all brought together into the same time. This time is a scientific construction, yes, but it is made in an attempt to find a mode of listening that will make the time of sea ice over decades, audible to the human ear.

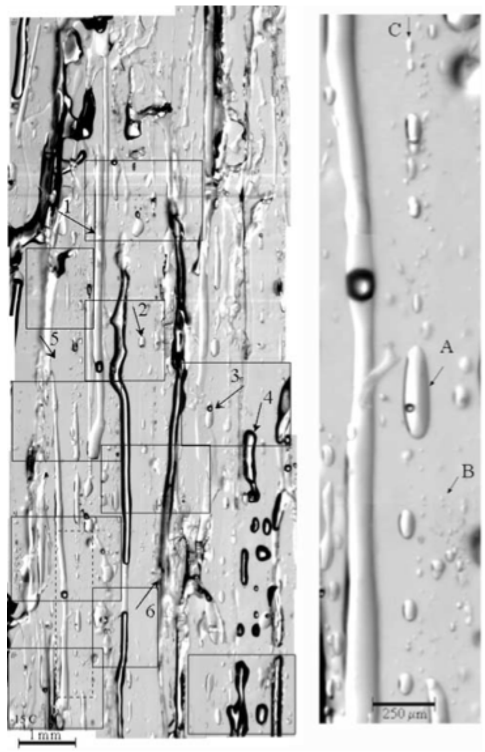
Chapter 4.

Salt-Ice Worlds

Before I joined the rotten ice team in Fall 2014—before I had officially begun fieldwork at all—I wanted to know what, if anything, was interesting about ice science. I made a preliminary visit to the Polar Science Centre where I interviewed many of the resident scientists. There were scientists who expressed deep satisfaction in being able to take the measure of the physical world; pleasure in finding an organizing principle to the world in terms of physics; delight in working out the details of scientific logistics; and adventure in the heroic tradition of Arctic fieldwork. These were all compelling reasons to do science. But what about ice itself?

Do not get me wrong; all the scientists I befriended were deeply interested in ice and this interest organized the shape of their work. But this elementary interest came out later, after many conversations over coffee or on the ice, through targeted questions and incidental comments.

But before then, and in her office on my first visit, Bonnie directs my attention to a 5 mm x 12 mm figure of sea ice on her computer screen. Arrows point to different elements of interest trapped within the ice microstructure. Within the matrix of pure ice are numerous inclusions: brine, gas, precipitated salt crystals, and other impurities. *There is so much that happens at the solid-liquid boundary*, she says, *and what happens at this solid-liquid boundary is governed by material physics*.



Photomicrographs of sea ice at 1 mm and 250 µm scales. Arrows point to brine tubes, pockets, and bubbles. Figure courtesy of Bonnie Light, reprinted from Light et al. 2003.

Bonnie continues. For her research, she does not look at satellite data. Closing the digital image, she points at her computer's desktop background. It is a photograph of sea ice in July when the ice is interspersed by melt ponds. Low, slightly broken cloud cover diffuses the sunlight, throwing a silvery cast over the ice.

This, she says pointing at the desktop background, is the largest scale at which she might look at sea ice.

Arctic sea ice as seen from the US Healy Icebreaker, 2010. Photograph courtesy of Bonnie Light.

Bonnie explains that different amounts of sunlight will be backscattered to the atmosphere, absorbed by the sea ice, and transmitted to the ocean. When Bonnie carried out her dissertation research, she wanted to develop a quantitative understanding of how the type and distribution of microscopic inclusions affect the way energy from the sun interacts with sea ice. Such knowledge, she says, can provide more precise values about the relations between radiant energy and sea ice for integration into climate modelling. To this day, Bonnie continues to, in her words, "fight for physics," as she works with modellers to update parameterization schemes for physical processes, such as sea ice albedo and melt ponds.

At the time of my first visit, though, Bonnie warns me that her most recent research project has little to do with the Arctic. In fact, it has little to do with modern-day Earth. Her latest project relates to 'Snowball Earth,' a hypothesis that gained momentum in the late 1990s. Based on evidence in the geologic record and the results of some models, this hypothesis argues that the Earth's surface was almost entirely, or completely, ice-covered about 650 million years ago. During this Snowball Earth episode, global temperatures averaged -50 degrees Celsius and ice stretched at least down to 30-degree latitude, parallel with Cairo in the northern hemisphere and Cape Town in the south.

What would the icy surfaces of Snowball Earth be like? What kinds of properties and behaviours would these icy surfaces exhibit? And what implications would this ice-covered surface have on global climate—not to mention life itself?

Answering these questions is difficult. Not least because scientists cannot simply go into the field and take measurements. Modern-day analogues for Snowball Earth-like ice cover are rare or non-existent, found only in the Dry Valleys of Antarctica, saline lakes in Siberia, or some extremely cold parts of northern Canada. From a modelling perspective, since the representation of physical processes in models are based on the physics of modern Earth, it is hard to get models to exit a 'snowball' state. And, given the difficulties of taking field measurements that reflect Snowball Earth, it is difficult to correct these representations based on empirical data. Snowball Earth pushes both models and field studies beyond their limits.

But in her laboratory, Bonnie can achieve precisely what these methods cannot do. She can manipulate what is otherwise uncontrollable; stretch environmental parameters to recreate inaccessible times or places, from Snowball Earth to Mars; isolate a single variable and test its relationship to others; adjust the ratio of signal-to-noise; and make empirical measurements of properties incalculable from first principles. What was considered intractable in the field or arbitrary in models becomes experimentally testable in the laboratory.

Just before my arrival at the PSC, Bonnie had spent months growing sea ice at -27 degrees Celsius in a 1-metre cubic tank. As expected, when temperatures dropped below its freezing point at -1.8 degrees Celsius, sea ice began to form. But as Bonnie exposed the sea ice to -30 degrees Celsius temperatures for six months, the surface of the ice began to transform in composition and texture. On top of the ice there formed a fragile crust of fine, white salt crystals.

"It was like lace," Bonnie says. If one blew gently over the surface, the delicate crust would loft into the air.

The surface transformation was most obvious in its colour. Sea ice is white under ordinary circumstances. But in Bonnie's experiment, the whiteness of cold sea ice had a brilliant, unreal intensity. Its incandescence was difficult to capture in photographs.

On one hand, the salt crust's formation matched Bonnie's expectations. Glaciers and sea ice, without snow cover and exposed to continuously low temperatures, will sublimate—that is, transition directly from solid to gas without passing through a liquid phase.[60] On Snowball Earth, models suggest that climatic conditions near the equator favoured sublimation. Given the high salt content of sea ice, if the frozen surface of an equatorial ocean sublimated, Bonnie hypothesized that it would likely leave behind a deposit of salt crystals. Such salt precipitates have been observed before under laboratory conditions, in natural ice samples transferred into the laboratory and cooled to below -23 degrees Celsius, as well as in laboratory-grown ice (Perovich and Grenfell 1981; Light 2004, 2009). Observers consistently remarked upon the bright white colour of the ice, which they attributed to the presence of precipitated salt crystals within brine inclusions.

And yet, even though she had read earlier descriptions, the sheer white brilliance of the salt crust still took Bonnie's breath away. Furthermore, the high albedo, or reflectivity, of this salt crust also gave her pause to think. As mentioned in Chapter One, sea ice has a relatively high albedo. It is well known that sea ice plays an important role in the global climate system because of its participation in the positive ice-albedo feedback. Relatively small changes in temperature can drive large changes in sea ice coverage, and global climate in turn, is highly sensitive to changes in the sea ice cover (e.g., Meehl and Washington 1990). Bonnie suspected that a salt crust at Earth's surface could dramatically raise the planetary albedo, not just because of its high reflectivity but because, on Snowball Earth, sea ice would also exist at the equator where the planet receives much more solar energy compared to the high latitudes. Salt crusts sitting on top of tropical sea ice could intensify the ice-albedo feedback, lowering global temperatures even further.

At the same time, and in the opposite direction, Bonnie was curious how a salt crust might initiate the melt-out of Snowball Earth. The presence of salts in seawater lowers the freezing/melting point to about -1.8 degrees Celsius, although the exact temperature varies depending primarily on the salt concentration, but also on the salt species. What if, Bonnie had wondered, this salt crust allowed for the formation of a liquid melt pond on the surface of Snowball Earth *despite* frigid temperatures? The presence of such salty—and relatively dark—melt ponds might catalyze a positive feedback process whereby salty melt ponds on Snowball Earth would lower albedo and cause ice to melt, which would lower albedo still further and melt more ice, and so on. What if, in a variant of the ice-albedo feedback, there was a '*salt-albedo* feedback' (see Light et al. 2016; Carns et al. 2015, 2016)? Salts-in-ice might hold the key to undoing the runaway effects of sea ice that had locked Earth in ice in the first place.

I am transfixed by Bonnie's telling of sea ice. Through salt, one could move into spaces beyond the range of human vision and travel well far outside the reach of human times and worlds. I was aware of how the albedo of sea ice could work such worlds into existence. Albedo, after all, was the concept that initially put sea ice onto the global stage as a key player in the climate system. What had not occurred to me was the way in which sea ice albedo is shaped by physical chemistry—in particular, the presence of salts. Salts give sea ice its specificity, not only with respect to albedo but in many of its other properties and behaviours, which extend over many scales. My conversation with Bonnie sensitized me to the worlds of difference that salts-in-solution can make, which are influential in ways apart from albedo. It became my entry point into exploring how sea ice worlds. What world(s) does sea ice potentially produce? How do humans get entrained in these ice-worlds? And how does sea ice produce human beings?

The anthropological challenge of exploring sea ice-worlding presents itself in this chapter as a problem of genre. Like Stuart McLean (2011) in his effort to find an idiom that makes palpable the irreducibility of peat bogs to human beings, I am looking for a mode of presentation that can accommodate both scientific knowledge and anthropological provocations; a *register* in which I am not strictly retelling scientific claims as absolute truth, nor privileging anthropological questions at the expense of scientific details that become either secondary or unnecessary; and a *language* that allows me to take scientific knowledge seriously as an anthropologist but introduces just enough distance that my account differentiates itself from a strict report on science. In working my way towards a solution, I turn to multispecies ethnography, creative non-fiction, popular science books, STS, and history of science to craft a space of possibility in which my arguments can unfold.[61]

To show how sea ice worlds in this chapter, I present readers with a few sea ice 'fables.' The hallmark of classic fables is anthropomorphism; that is, the attribution of human traits to nonhuman animals, inanimate objects, or forces of nature. Anthropomorphism as a literary conceit produces a double displacement: it substitutes nonhuman protagonists for human ones, and in the same move replaces individuals with general types. In this manner, animals-as-human-types can comment on power relationships and social inequalities. They become timeless and placeless exemplars, ready to do the philosophical labour of moral instruction. Although animals are a defining feature of fables, such tales are decidedly anthropocentric.

By contrast, the fables I write are unapologetically and relentlessly sea ice-centric. In these fables, sea ice may be an abstraction but it is not a caricature of human types. Sea ice is central in these fables not for the purposes of drawing a moral lesson from human life, but for its own sake. Humans occasionally, and rarely as a main character, appear in these fables. Sea ice in these fables is, moreover, very much grounded in scientific knowledge. The apparent literalness with which I approach sea ice risks collapsing the very space of possibility that fables produce—a metaphorical space that is neither true or false, here nor there—and slipping into a mere report on science that takes sea ice for granted. Let me emphasize that 'sea ice' as constructed by scientific knowledge is no more literal or 'really real' than the animal characters in La Fontaine's Fables. As much as La Fontaine drew on well-known animal types, "they were also creatures of fantasy, bearing only a distant resemblance to the animals the naturalist observes" (Sykes 1999). Similarly, 'sea ice' is neither a literal object *or* a metaphor but constituted through scientific knowledge, historically contingent, and open to change.

It is this contingency of scientific knowledge that I want to reintroduce into my explorations sea ice worlding. I do not want to take 'sea ice' or scientific knowledge of this object literally, any more than the animal characters in fables. What if scientific arguments could be read *as if* they were fables? Again, not in the sense of classic fables that seek to anthropomorphize nonhumans and convey a moral message from human life. Nor do I mean to suggest reading scientific arguments as fables in order to assert the moral authority of sea ice. This *'as if'* is meant to suggest a different mode of reading science than that found in STS or history of science, which make the contingency of scientific knowledge production the object of analysis rather than a method. I want to bring to scientific knowledge the readerly sensibilities that one assumes when reading fables or science fiction—that is, to suspend one's belief in the finality or absoluteness of scientific knowledge, but to also take it seriously as historically contingent. *What if* we were to treat scientific knowledge of sea ice as a self-conscious and provisionally stabilized epistemic space that is fragile and subject to change? This goes for scientific knowledge accepted as textbook as well as more speculative hypotheses.

Lastly, to read scientific knowledge '*as if*' they were fables—that is, to bear in mind its own contingencies and fragility in the present—is also an attempt to introduce some critical distance from scientific knowledge when mobilizing it as the substrate for derivative claims. Sea ice worlds *'what if'* and '*as if'* wedge open a space that is neither here nor there. These are not-fables. This is neither a genre or a category.

Three fables follow: "Salts-in-solution," "The Great Salinity Anomaly," and "Snowball Earth." While each fable introduces its own argument, they are variations on one another.

Salts-in-solution

Consider lake ice.

Cracked ice of an Arctic lake. Photograph by Claude Duguay, University of Waterloo.

In the image, lake ice is dark—effectively black in colour. Thin, bright lines reveal flaws running deep into its interior.

Lake ice is remarkable for its clarity. In her quest to understand ice, journalist Mariana Gosnell overwintered in a cabin near a lake in New Hampshire. There, she patiently waited for the first lake ice. When it finally formed, Gosnell drew comparisons of the ice with glass, describing it to be "as thin as a windowpane, about the size of a windowpane, and as clear as a windowpane" (Gosnell 2005: 17-18). "People have compared being on clear lake ice," she wrote, "to standing on air or riding in a glass-bottomed boat" (Gosnell 2005: 18). And, like glass, when dropped from high enough lake ice will shatter.

By contrast, there is sea ice.

Sea ice in McMurdo Sound. Note area of bare sea ice cleared of 3 mm crust of salty snow. Instrument shown is an ASD radiometer to take spectral albedo measures. September 2009. Photograph courtesy of Regina Carns, reprinted from Carns et al. 2015.

It is milky in colour and translucent. When handled, sea ice is relatively soft and porous. What explains the differences between lake ice and sea ice?

The key, scientists note, is salt. When sea water freezes, impurities such as dissolved salts are excluded from the ice crystal lattice. The presence of salts lowers the freezing point of water from 0 degrees Celsius to -1.8 degrees Celsius, allowing liquid brine to persist at sub-zero temperatures.

As sea water freezes, the interface between solid ice and liquid sea water advances down the water column. Salt builds up ahead of this moving interface, resulting in a saltier layer just a few millimetres to centimetres in thickness. This saltier, cooler, and heavier layer sits above the slightly warmer ocean below, creating a chemical and physical instability. In one direction, heat travels upwards from the slightly warmer ocean towards the salt-enriched layer; in the other direction, salt molecules diffuse from the salt-enriched layer into the slightly fresher ocean below. The rate of flux of heat and salts is unequal: heat travels upwards faster than the downwarddiffusing salts. The result is a 'constitutionally supercooled' layer just below the ice-water interface, which is, crucially, below the freezing point of brine.

The supercooled layer gives any small (submillimetre) protrusion from the ice-water interface a growth advantage. In this zone, delicate ice lamellae form: that is, thin plates or scales like those that coat the surface of a shell, or the gills on the underside of a mushroom's cap. The lamellar morphology results from the geometric self-selection of crystals to grow faster in one axial orientation over another. Salts rejected from the ice crystal lattice concentrate along the protrusion boundaries. In this way, narrow films of brine form in between the submillimetre-thick ice platelets, which eventually close off as temperatures drop and ice lamellae join up to form low-porosity sea ice. Pores of heterogeneous sizes and shapes, as well as brine tubes and channels become integral features of the sea ice microstructure. Together, the array of ice blades and brine layers at the bottom of sea ice is called the skeletal layer. This layer is a dynamic zone of exchange of salts, gases, and nutrients between the ocean water and brine from the sea ice's interior, which in turn contributes to an extraordinarily rich and productive site for microbiological life.

The skeletal layer, and the constitutionally supercooled layer that drives its formation, are unique to sea ice. The skeletal layer traps brine between lamellae at the bottom of sea ice, resulting in the retention of 10 to 40 percent of ions. Lake ice, by comparison, grows in a different direction. Its ice-water interface is oriented in a planar rather than lamellar direction, and as a result more than 99.9 percent of impurities such as dissolved salts are expelled (Petrich and Eicken 2010).

The qualitative difference that salts-in-ice can make is visible at the human scale of observation. The influence of salts-in-ice can be seen as variations in the hue and brightness of sea ice. Inclusions in the ice microstructure, such as brine, air bubbles, precipitated salt crystals, and other impurities scatter light—like shining a flashlight into fog—giving sea ice its milky white colour. Sea ice's variability in colour, from bright white to translucent gray, deep blue to emerald green can be accounted for by the way in which inclusions in sea ice interact with sunlight. Salts-in-ice also accounts for the relativeness softness of sea ice; it is more porous and contains liquid brine inclusions that make it more 'slushy.'[62]

"All properties of sea ice are related to salt."[63] The statement, though penned by an individual scientist, grows out of a collective understanding within the sea ice community. Contained in this statement is a dazzling possibility: salts-in-solution offers a basic unit of understanding out of which knowledge of all other properties and behaviours of sea ice can emerge.

It is seen as a unifying principle that keys into the patterns of sea ice at a variety of length-scales. In sea ice textbooks, scientific reports, and journal articles, following the pathways of salts-in-solution during freeze-up and melt is both a mode of instruction and a pathway to understanding sea ice at varying length-scales (see Dieckmann and Thomas 2009; Weeks 2010; Wettlaufer et al. 1999).

Sea ice, in turn, structures polar ecosystems (Eicken 1992). The freezing of seawater partitions microbiological life into communities that reside within the ice itself or in the water column below. In the water column, the "sea ice canopy" controls the amount of light into its depths and favours shade-adapted phytoplankton. The skeletal layer provides a substrate for phytoplankton to attach to, on which krill graze, which in turn feed warm-blooded mammals, from seals to penguins (in the Antarctic). On its upper surface, sea ice offers a place for mammals to rest and breed. The spatial variability of sea ice—its geographic extent, topographical features, snow cover, and proximity to open water—further patterns interactions between different groups of organisms and their environment. The life cycles of species may be synchronized with the prevailing circulation of sea ice through the polar ocean. Krill juveniles may associate with growing sea ice in one part of the sea during autumn, feed under the ice during winter, and then release into the water column during spring when the ice melts (Smetacek et al. 1990; Siegel et al. 1990 [cited in Eicken 1992]). Growth, drift, and decay of sea ice thus shapes the spatial and temporal division of polar ecosystems.

This picture begins to sketch the faintest traces of a world-in-the-making—one produced, moreover, not by sea ice *per se* but by the freezing of salts-in-solution in conjunction with winds and waves, the geographic configuration of land and ocean. Sea ice-worlding of this kind has little, if anything, in common with orderings as anthropologists and philosophers conceive them. According to the framework that emerged out of the Enlightenment, it was ridiculous to suggest that non-human things could world. The patterns and behaviours they gave rise to were merely mechanical and deterministic reactions, entirely void of meaning. Let me linger a while on this question of meaning, the making of which comprises a sorting principle for what counts as 'worlding' or not.

"Countless worlds made from nothing by use of symbols," writes philosopher Nelson Goodman, adding, "so might a satirist summarize some major themes in the work of Ernst Cassirer" (Goodman 1978:1). Goodman's statement, which simultaneously satirizes with worlds-as-symbols, diagnosed a shift in thinking in the late 20th century. In modern philosophy, thinking had shifted from trying to locate the World in the singular, as fixed, unique, and accessible through the physical sciences, towards the existence of many worlds. These worlds, Goodman notes, are not mere alternatives to a single actual world but *multiple actual worlds*, "of independent interest and importance, without any requirement or presumption of reducibility to a single base" (Goodman 1978: 4).

If there is no singular world-in-itself, no firm foundation on which to stand, then in what do worlds consist? "Not from nothing, after all," Goodman claims, "but *from other worlds*" (Goodman 1978: 6). That is, worlds are made through composing and decomposing, emphasizing and de-emphasizing, ordering and reordering, substituting and deleting, deforming and reforming worlds already made by use of words and other symbols. "World making as we know it always starts from worlds already on hand," argues Goodman, "the making is a remaking" (Goodman 1978: 6). There is meaning-making all the way down.

Goodman's argument about 'worlds' as countless makings and remakings with symbols recalls the figure of 'Man' or 'the Human' as sole meaning producer. Writing about the emergence of 'the Human' in the abstract, Tobias Rees (2018) relates Diderot and d'Alembert's ambitious project to compile all existing knowledge into what would become *Encyclopédie*. Immediately, they were confronted with a problem: How, exactly, should they organize such knowledge? According to what principle does this vast array of knowledge become intelligible? The authors self-consciously turned away from using a God-given order. But organizing knowledge according to a natural order posed problems as well, for nature was "nothing but a long, confusing list of individual things." "We would face," remarks Rees (2018) with respect to the dilemma facing Diderot and d'Alembert, "an infinite ocean of things, endless, boundless, never to be exhausted. Any sense of order that one would establish would be haunted by the arbitrary." Diderot's conclusion was that only humans could make meaning out of this multitude. That is, human meaning granted order to the world where there was none, and humans were singular—but by the same token, lonely—in their ability to make meaning (Rees 2018).

Putting Goodman, Diderot, and Rees into conversation outlines a basic assumption that relates worlds and meaning-making: worlds come into being through meaning-making, and since only humans make meaning, only humans can produce worlds. Conversely, for some*thing* or some*one* to world, one must demonstrate its ability to produce meaning. This is the task that several scholars have undertaken to demonstrate that other nonhuman living beings are also capable of semiosis but in non-symbolic ways (Kohn 2013).

In other social scientific and humanities scholarship, there is an implicit understanding of 'worlds' and 'worlding' as emergent through situated material-semiotic-affective relationships rather than general theories of semiosis (e.g., Haraway 2008; Tsing 2010, 2015). Worlds are constitutively relational and collective, their constituent members not discrete and bounded individuals that preexist encounters, but 'become-with' only in relation to one another. Emergent from 'becomings-with' are figures, or "material-semiotic nodes or knots in which diverse bodies and meanings coshape one another" (Haraway 2008: 4). Figures can be cyborgs or companion species, plants or mushrooms. The potential to *re*figure the *con*figurations out of which worlds emerge. They are, in short, "signs of possible worlds" (Haraway 1991: 2). Although figures and figurations enlarge meaning-production beyond the purely symbolic and human beings, they are still embedded in contexts of meaning-making.

Insofar as such efforts hinge on meaning-making as central to worlding, do they not reinscribe nonhumans within a humanist framework? Can there be worlds without meaning? If meaning is not produced, can there be a 'world' as such? In what would 'worlds' consist if they do not ground in meaning-production?

I have promised no morals, no claims about how things really are or should be. For the moment, let me close with some reflections from Gosnell as she waits for Lake Pleasant to ice over. One chilly December morning while walking by Lake Pleasant, something on the lake surface catches Gosnell's attention. Stepping down to have a closer look, she catches sight of an ice formation that brings her thoughts to a halt, then launches them into wild flight. Unlike the lake ice she first saw that was as "smooth and blank and plain" as a windowpane, this ice is "highly textured, with lines running all over it, helter-skelter, a frenzy of very fine lines, some raised, some indented, some bent, some dagger straight, some branching like feathers,… some outlining four- and five-sided polygons, the edges beveled as if gouged out of metal,… Something that looks like a knot of wood, something that looks like a clam shell, like a boomerang, like the lobes of a broken heart" (Gosnell 2005: 20).

Metaphors leap over one another in rapid succession, but the cacophony of similes and figures-of-speech cannot keep up with the patterns of freezing she sees. Gosnell's next thoughts are provoking: "I am dumbfounded. What I'm looking at seems too wild, too rich, too weird to be natural. Why *this* shape, I keep wondering, and not *that*? Why *here,* and not *there*?" (Gosnell 2005: 20).

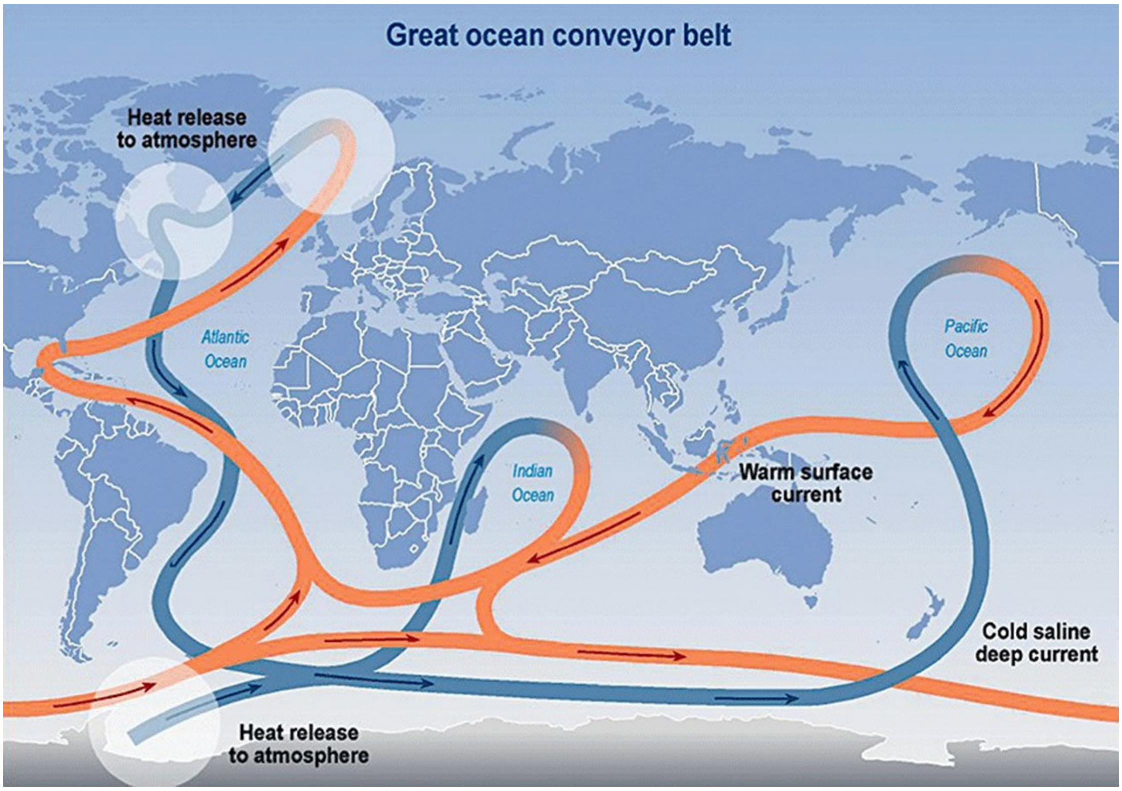
Too weird to be natural. The thought is revealing. It points towards a tendency to look for meaning in things, and if meaning is found to attribute it to something other than nature. But even more poignant is the impulse to search for meaning at all; to ask in what the difference between *this* or *that* consists, instead of considering that it is nothing at all.

The Great Salinity Anomaly

The Great Salinity Anomaly is a wonderful fable of how sea ice worlds. It is a tale that takes place in contemporary times and in which humans enter the field of view but in an unfamiliar way. Its protagonist is a salinity anomaly—that is, a slight *freshening* of the upper ocean in the North Atlantic. Freshwater is another way of seeing sea ice: during freezing, two thirds or more of salt is rejected from the ice structure, and any remaining salt in the ice is flushed out over time through summer melt and drainage (Aagard and Carmack 1989). Sea ice, in other words, is solid freshwater. To follow a 'freshening,' then, is to trace sea ice in another mode—not as a discrete, self-contained unit, but sea ice in terms of its formation and dissolution.

Let me begin this fable in the early 1970s. Scientists at the time had started to notice a freshening of the upper layer of the ocean in the Iceland and Labrador Seas. The salt deficit could be tracked as it moved from the Iceland Sea westwards to the Labrador Sea, then east across the North Atlantic into the Greenland, Iceland, and Norwegian (GIN) Seas, and then north through the Faroe-Shetland channel. It took two to three years for the anomaly to complete its circuit. By the late 1980s, scientists could draw together these observations into a picture that became known in the polar scientific community as the "Great Salinity Anomaly" (Dickson et al. 1988).

Attending to differences in salt is of no small consequence. In fact, a slight excess of salt is understood to drive global ocean circulation. As water evaporates from the ocean surface, it leaves behind saltier and denser waters, which sink to form deep waters of the ocean. Salt—and, by implication, freshwater—plays a major role in deep water formation and global ocean circulation. Salt enrichment creates contrasts in salinity and temperature, which set in motion global-scale dynamics that work to erase these differences. In scientific terms, this is called the 'thermohaline circulation' of the ocean, popularized in a cartoon known as the "global ocean conveyor belt" (Broecker 1987). The effect of salts on circulation is even more pronounced in the cold polar regions: one extra gram of salt per litre of seawater increases the density of seawater by the same amount as cooling it by 3 to 4 degrees Celsius. In short, the effect of salts on density literally outweighs that of temperature.

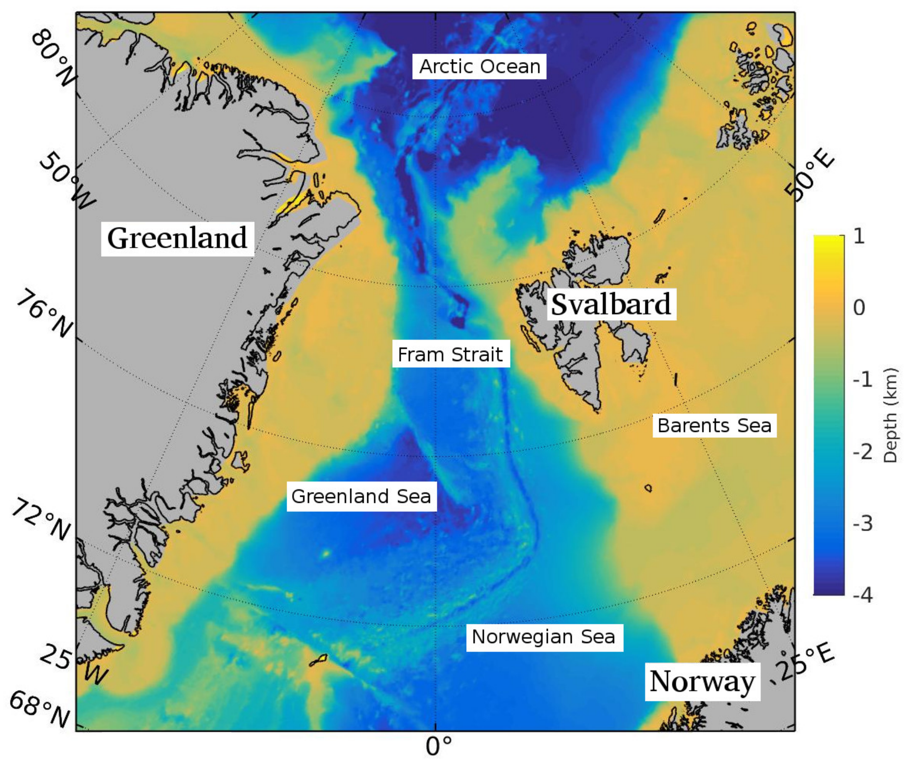


Great Ocean Conveyor Belt. Figure by IPCC.

The role of salts in global ocean circulation gains significance in light of the fact that the sites of global deep water production happen to be located in the cold north Atlantic, just south of Greenland.[64] In this region there are 'convective gyres,' or chimneys of violently mixed waters that bring to the surface dense, salty waters from the ocean deeps while mixing downwards lighter and fresher surface waters. As surface waters are converted into deep water, the heat released to the atmosphere is responsible for Europe's surprisingly mild winters. Deep water production is only possible at these locations because the ocean layers are not so strongly stratified; vertical mixing can occur from surface-to-bottom, a characteristic that makes these gyres "windows to the deep ocean" (Aagard and Carmack 1989: 14492).

In the 1980s, scientists had become keenly aware of the sensitivity of these gyres to a freshening of the upper ocean. Model studies suggested a slight influx of freshwater into the vicinity of these gyres could slow down, or even 'kill,' vertical mixing (Manabe and Stauffer 1988). If this happened, freshwater would pool at the surface and create a barrier to deep water formation.[65] Besides model studies, large and abrupt swings legible in deep ice cores from Greenland suggested that the ocean conveyor belt could turn off—and on again—on millennial time scales.[66] If global climate models showed that such conveyor belt shutdowns were possible, paleoclimate studies suggested that it had actually occurred thousands of years ago.

Scientists hypothesized that ice sheets and glaciers controlled operation of the global ocean conveyor. Land ice contains a tremendous amount of freshwater, which, if released can dilute the northern Atlantic sufficiently to stop the global ocean conveyor. But what if such catastrophes were not controlled solely by land ice and, moreover, had already been witnessed in contemporary times?



Location of Fram Strait between Greenland and Svalbard. The Greenland Sea is to the south of Fram Strait, while the Arctic Ocean is to the north. Fram Strait is the only deep passage between the Arctic and World Oceans. Azimuthal Equal Area projection. 24 October 2015. Figure by Bdushaw, Wikimedia Commons.

Sea ice, two oceanographers noted, floats out of the Arctic Ocean via Fram Strait, between Greenland's west coast and west of Svalbard (Aagard and Carmack 1989). The volume of water that exits the Arctic is second only to that of the Amazon (Holland 1978). This river of solid freshwater passes "perilously close" to the convective gyres that produce deep water in the North Atlantic. What if, these scientists argued, the source of freshwater during the Great Salinity Anomaly was neither meltwater from continental ice sheets or increased precipitation in a warmed world, *but sea ice drifting out of the Arctic*?

The claim was provocative. It suggested that the stability of global ocean overturning was not just an event of the distant past, or a result of dramatic influxes of freshwater associated with deglaciation. Rather, the stream of sea ice that regularly leaves the Arctic is sufficient to produce a world of difference, and on time scales commensurate with an individual human life span. Telltale signs of freshening included heavier than usual ice conditions in the Icelandic and Labrador Seas during the 1970s, as well as the temporary halt of deep water formation in the Labrador Sea (Lazier 1988).

The sensitivity of global ocean circulation to a minute different in salt or to slight perturbations in freshwater fluxes brings into sharp focus its contingency.[67] To what extent, then, does the ice-covered Arctic Ocean of today produce the world as we know it? On the flip side, what other worlds are possible if the Arctic Ocean could be otherwise—that is, ice-free? Simply put, exactly how stable is the Arctic sea ice cover?

These questions prompted Arctic oceanographers, Knut Aagard and Eddy Carmack (1994)—the same pair that argued Arctic sea ice had caused the great salinity anomaly (Aagard and Carmack 1989)—to undertake a journey beyond the familiar territory of classic oceanography in the present day with its focus on describing the structure and circulation of the ocean. To peer into the past, they ventured not only into paleoclimate studies but cross over into the human sciences.

"On occasion," Aagard and Carmack write, "human history may provide an insight into the workings of the climate machinery, and perhaps that is the case in this manner" (Aagard and Carmack 1994: 18). Drawing on archaeological arguments, they fashion a window out of human culture to peer into past sea ice-worlds. According to archaeologists, about a thousand years ago a whale-hunting people known as the Thule people began to spread eastward from northern Alaska to Greenland. Humans chased bowhead whales who in turn followed open water conditions in the summer where they could feed (McGhee 1984). But over the course of several hundred years, open water conditions in the summer began to give way to increasing ice cover. People shifted from hunting whales to hunting seals; winter homes switched from structures built around whale bones to snow houses (McCartney and Savelle 1993). About 500 years ago, this whale hunting period came to an end. The very same open water conditions that favoured whale hunting, Aagard and Carmack speculated, had also conditioned the shallow continental shelves for extensive freezing in fall and early winter, ending this period of favourable whale hunting conditions.

Aagard and Carmack admit at the end of their article on the Arctic Ocean and climate that their scenario is “highly conjectural” (1994: 18). But Aagard and Carmack also take refuge in this speculative space that is neither right or wrong. In doing so, their thoughts turn to “the message of change that Nansen himself preached on numerous occasions” (Nansen 1897 [cited in Aaagard and Carmack 1994]). Addressing an audience in 1897 after he had finally returned from his three-year Arctic drift, Nansen ended with these words: “Everything is drifting, the whole ocean moves ceaselessly…a link in…Nature’s never ending cycle…just as shifting and transitory as the human theories.” Scientific knowledge is rarely final. It is continually on the move, restless, and ephemeral—as changeable and variable as the ocean or sea ice. Aagard and Carmack’s attitude gestures to an open-endedness to knowing. The production of scientific knowledge is creative, underdetermined, and capable of novelty. ‘Salts-in-solution’ provides just as contingent an organizing principle as ‘sea ice’ or ‘the human’; it is just as transitory an entity as a ‘marine lung’ or ‘rotten ice.’

From a salinity anomaly of contemporary times to whale-hunting humans one thousand years ago, this fable follows the distillation of freshwater from the ocean surface, salt enrichment, deep water formation, thermohaline circulation, the flow of solid freshwater out Fram Strait, the rapid efflorescence of human activity in high latitudes, and its equally swift disappearance. Where has ‘sea ice’ gone in this fable? What has happened to ‘sea ice’ in the form of discrete ice floes or, alternatively, a unified pack?

The continual unravelling of ‘sea ice’ indicates the difficulty of finding any singular, discrete, and all-encompassing unit of analysis. Freezing of salts-in-solution transmutes sea ice into forms of life—algal, whale, seal, human; it deforms and transforms human ways of living in the present and the past. Sea ice becomes the condition of possibility of human forms of living, both near and far. ‘Sea ice’ is merely a departure point that undoes itself as soon as one alights upon it. To follow sea ice, then, one must develop a sensitivity to dynamism and underdeterminism; an attentiveness to salt and temperature, heat and momentum. As several anthropologists have noted, it is precisely by attending to process, flux, and phase shifts, rather than final forms as discrete, bounded, and stable, that the nonhuman production of worlds comes into focus (Simonetti and Ingold 2018; McLean 2011).[68] "Far from being the inanimate stuff typically envisioned by modern thought," writes Tim Ingold, "materials… are the active constituents of a world-in-formation" (Ingold 2011: 28).

The mutability of things such as sea ice, but also atmospheres, peat bogs, and even stones, has invited anthropologists to develop different analytic and aesthetic sensibilities in order to take seriously the nonhuman production of worlds—and, through these sensibilities, to consider how 'the human' is being unmade and remade. Drawing on their anthropological studies of air, Timothy Choy and Jeremey Zee (2015) articulate a form of attention that they call "suspension-condition." This is a "manner of attunement to the potentials of substances to shift from states of settlement or condensation to ones of airborne agitation, to settle again in time, or to reactivate, somewhere else" (Choy and Zee 2015: 211). This applies as much to air, their object of study, as to 'the human' as a disciplinary organizing principle of anthropology. In reference to the Anthropocene, Choy and Zee (2015) ask:

> "*What* and *who* are becoming in such an air condition? (…) At this place where geology and history converge, to respond grandly to the epochal gesture, we endeavour to witness *a vaporizing of the human*. Not an obliteration, but a shifting of phase, a distribution into concentrations, burgeoning spheres of sensitivity." (Choy and Zee 2015: 217)

To see 'sea ice' as a temporarily stabilized effect brings into view the contingency of what we accept as stable, permanent features in the world—including human beings. Humans, in Aagard and Carmack's rendering, are decentered and rescaled. They only come into view if one squints hard enough, and looks in the right places. They transform with the sea ice conditions, acquire new definition in relation with the sea ice. They are radically de-centered. This is how Aagard and Carmack close their journey: with the end of Thule culture, which, also, is the beginning of the world today with its ice-covered Arctic Ocean.

One could say that salts-in-solution contains their own differential principle, grounded in physical properties and independent of meaning-making, which gives rise to form and pattern.

Differentiations—of brine from freshwater, heat from cold, light from heavy—produce sea ice, the spatial organization of phytoplankton, the migration of whales, the flourishing and human ways of living. Sea ice is neither the beginning or end of worlds. The worlds that emerge from the freezing salts-in-solution are centreless and continually in motion. What kind of worlding is this? It is non-essentialist: it does not seek closure in an *a priori* form. It is not guided by final ends, or, even underdetermined, relational 'becomings-with.' The differentiations of salts-in-solution through freezing may not be a 'becoming-with' or a 'becoming' at all—at least, not in any recognizable sense as the concept is currently used. As the term suggests, built into 'becomings' is a 'coming into *being'* that the freezing of salts-in-solution as a non-teleological principle continually undoes. Can there be worlds without 'becomings'?

Snowball Earth

The Ice Ages are perhaps one of the most popularly known ice fables for the strange worlds that glaciers give rise to, as well as for the human drama and personalities that shaped this idea in the first place. Icy worlds can be glimpsed today in the shape of the land: the crisp geometry of pyramidal peaks; the distinctive curves of U-shaped valleys; and the inexplicable appearance of enormous boulders in the middle of fields or high on mountain slopes.

U-shaped valley (Leh Valley, Indian Himalaya)
Photograph by Dan Hobley, Wikimedia Commons

Pyramidal peak (Matterhorn, Swiss Alps).
Photograph by Zacharie Grossen, Wikimedia Commons

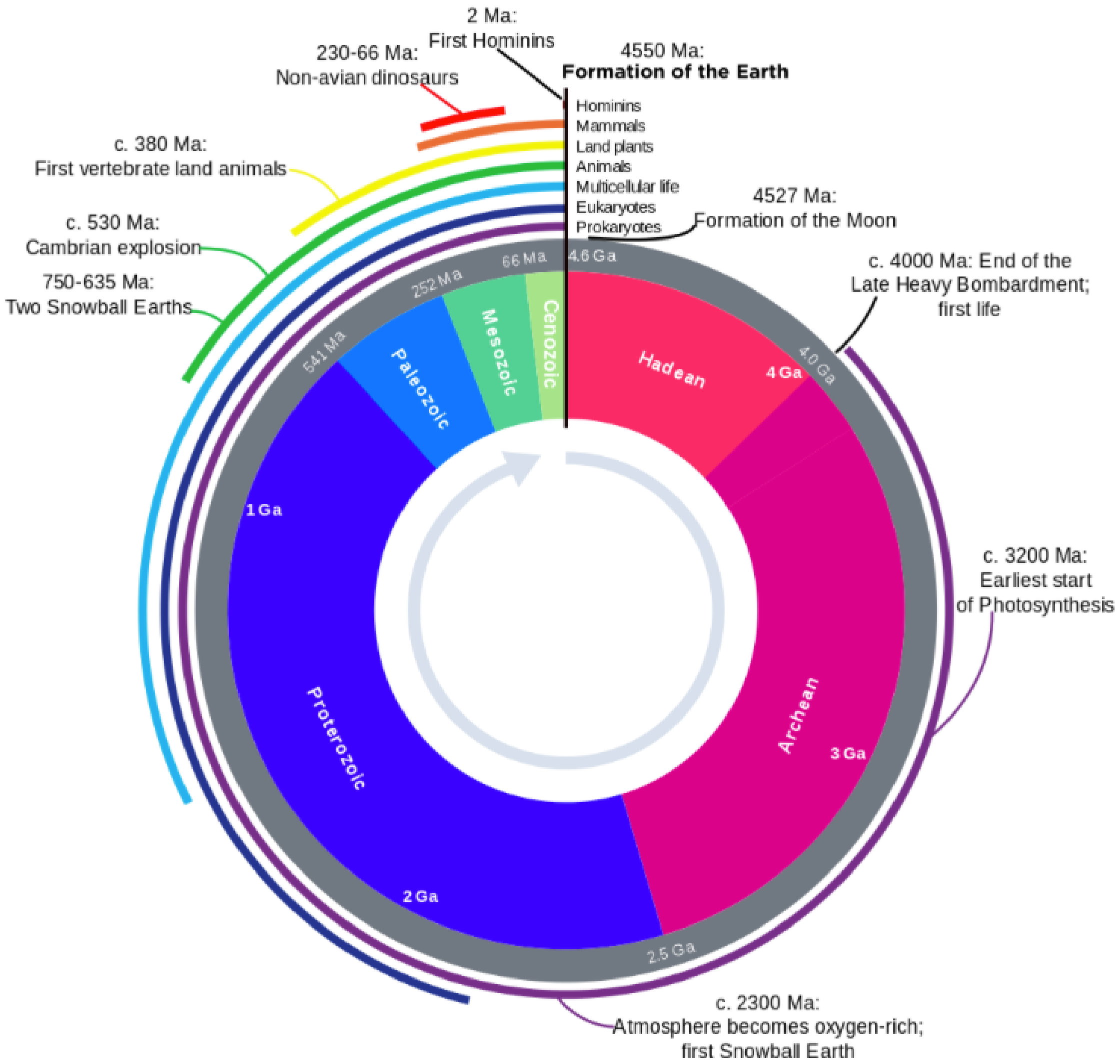
Like mineralized shadows, these landforms gained contour from something apart. This formative 'something' is no longer present in the contemporary field of view. It is an imaginative act to see in the contours of what is left behind continental sheets of ice, hard as rock, flowing under their own weight. It is a leap in understanding to grasp how a solid fluid—ice—can sculpt vast tracts of the Earth's surface into its current form.

The landforms we see are positivities that anchor life today. In Seattle, bicycling is easier in the north-south direction, parallel with the movement of the Cordilleran ice sheet that once covered the Northwest region of Washington state. Iconic hikes in Banff, Albera take one up and along ridges of debris that once paralleled the edges of moving glaciers. The lakes that make Northern Ontario so beloved as cottage country are the legacies of the retreat of the Laurentide Ice Sheet, which gouged out pockets in the ground that filled with water from springs, rain, and waterways. Today, the faint outline of ancient icy worlds is visible in the negative; an otherwise to the forms life assumes today.

But this practice of seeing a former ice-world in the lie of the land is relatively young. Until the late 18th century in Western Europe and North America, ice was not permitted world-shaping powers of the scope and magnitude taken-for-granted today. That a moving sea of ice might have at one time covered large parts of the globe—and transported enormous boulders long distances—remained in the margins for over half a century after it was first proposed.

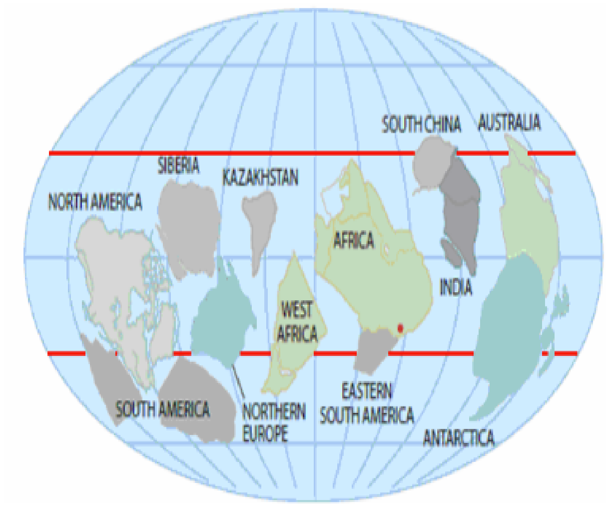
That sea ice *itself*—and not flowing sheets of land ice—might have ushered in an ice age unlike anything glaciers could produce is not as well known. One such glimpse of bygone icy worlds is the Snowball Earth hypothesis, which posits that there were multiple episodes of global glaciation 650 million years ago, during the late Precambrian (Neoproterozoic era) known as the Cryogenian period.

Whether or not the Snowball Earth hypothesis is true or false is incidental to the line of thought I wish to explore. What interests me is the *possibility* that ice gives rise to a different world order. One, moreover, produced by *sea* ice. Let me invite you onto this threshold, not to finally pass on to a 'here' or 'there,' but to dwell in a non-place that resists true or false.



Clock representation of major units of geological time and definitive events of Earth history. The Hadean eon represents the time before the fossil record of life on Earth (~4.0 billion years ago). The three million-year Quaternary period to which humans belong is too small to be visible at this scale. Figure by Woudloper, Wikimedia Commons.

Snowball Earth occurs when the tropical ocean freezes over, and ends when the equatorial ice shelf finally divides and collapses (Hoffman et al. 2017: 15). It is, essentially, an oceanographic phenomenon.



The (rough) positions of the Earth's continents 700 million years ago. The red lines are at ±30 degrees latitude. Figure and caption by Banik 2016, based on figure by Heidi Noland printed in Hoffman and Schrag 2000.

Imagine a radically reconfigured Earth 650 million years ago. Near the equator there is a preponderance of land masses and a distinct absence of land near the poles—the result of the breakup and redistribution of the Rodinia supercontinent around this time. The tectonic reorganization of Earth's surface into its current positions helps set the stage for global glaciation. The higher albedo of land surfaces, combined with their clustering near the equator where sunlight strikes Earth's surface at a more direct angle, raises the overall planetary albedo of Earth. At the same time, the reduced intensity of the younger Sun further conditions the Earth towards cooler temperatures. As will be explained later, once oceanic ice (sea ice plus ice shelves) forms in the land-free poles, it alone is sufficient to drive global glaciation.

In the presence of globally extensive sea ice cover, the hydrological cycle bifurcates into two loops. Below, seawater freezes to the bottom of ice and returns to the ocean as meltwater. Above, sea ice sublimates into the atmosphere and falls as snow and frost depositions onto the surface of the ice sheet. The bestiary of ice expands as ice forms proliferate, hybridize, and mutate on Snowball Earth. There is 'marine ice,' formed from seawater like 'sea ice,' but distinct insofar as it freezes onto ice cover from the ocean below and, as a result, produces relatively clear, dark blue ice free of bubbles and brine inclusions. 'Meteoric ice,' by contrast, comes from the sky. It is full of bubbles and, hence, white in colour. On an ice-covered planet, nothing is more relevant than knowing the colour, or albedo—and hence, its susceptibility to melt—of ice sub-species.

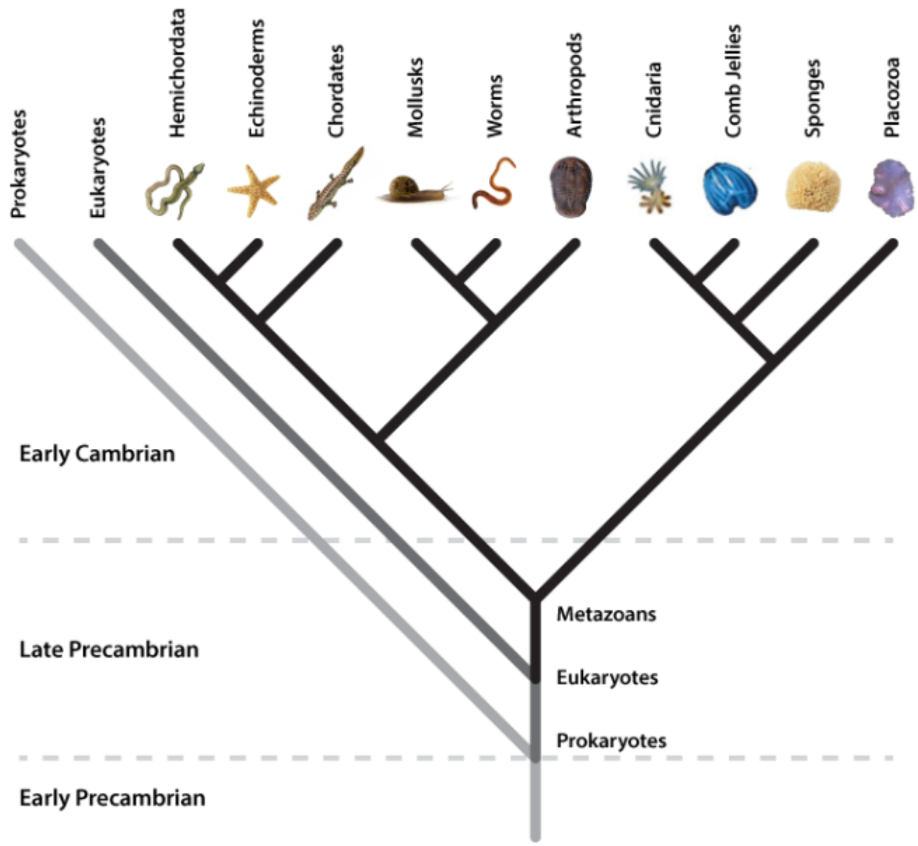
Iceberg at 68.25°S, 78.27°E, 36 km north of Davis Station, on 31 October 1996. There are five kinds of ice in this picture: sea ice, snow, glacier ice, marine ice, and ice cloud. Photograph and caption courtesy of Stephen Warren, reprinted from Warren et al. 2019.

Perhaps the most fantastic ice formation is the ‘sea glacier.’ Over several millennia, oceanic ice thickens—from above by meteoric ice, and from below by marine ice—to reach depths of several hundred metres. Ice of this thickness moves under its own weight, flowing gravitationally towards the equator. These sea glaciers are sustained by a weak hydrological cycle: at the equator, a sublimative desert of sea ice supplies water vapour to snow belts in the subtropics where sea glaciers build up over millennia.

Atmospheric circulation and the carbon cycle gain new contour in the presence of global sea glaciers. Global temperatures on Snowball Earth average -50 degrees Celsius and the atmosphere is extraordinarily dry. Without the moderating influence of a liquid ocean, surface temperatures closely track changes in solar radiation, with large temperature swings from day to night, and from summer to winter. The surface of Snowball Earth resembles Mars more than modern-day Earth.

Ice sheets covering the continents literally freezes out a major carbon sink from the carbon cycle. On modern-day Earth, carbon dioxide precipitates out of the atmosphere as acid rain. This rain dissolves silicate rocks into aqueous minerals—calcium, bicarbonate, and silica—which wash into the sea where they either form carbonate sediments, or combine to make up the shells of marine microorganisms. When these organisms die, their shells fall to the ocean floor, which subducts into the Earth's solid mantle. Volcanic eruptions release this carbon back into the atmosphere. On Snowball Earth, however, the ice-capped continents experience little chemical weathering. Atmospheric carbon dioxide therefore builds up, slowly but steadily over millions of years, through volcanic activity. The increase in carbon dioxide would drive surface temperatures up to 50 degrees Celsius, initiating a large greenhouse effect. The ice-albedo feedback in reverse—melting that exposes low-albedo seawater, which enhances melting—would lead to the rapid melt out of Snowball Earth.

Curiously, the Snowball Earth episodes of the Neoproterozoic would have reordered not only geophysical phenomena of the world at the time, but might have shaped the course of evolution itself. It is a long-standing mystery why it took so long for multicellular organisms to diversify, from a relatively few and simple organisms (i.e., filamentous algae and unicellular protozoa), into 11 different animal body plans—an event known as the Cambrian explosion. This is visible in the fossil record and phylogenetic trees, which show the emergence of diverse metazoans, or early animals, "as a delayed radiation crowning a long, unbranched stem" (Hoffman and Schrag 2000: 74).



Cambrian Explosion. Fossil record indicates that all major phyla were established around 540 Mya in the Cambrian period. Figure courtesy of Chen and Ruffini 2018.

The timing of this biological radiation and the first appearances of early animals coincides with the end of the Neoproterozoic glaciation in the late Precambrian. Could Snowball Earth episodes have exerted exactly the kind of selective pressure for body plans to differentiate into an array of possibilities? That is, the Snowball Earth catastrophe would have put the evolution of life through an environmental filter, the termination of which would open up "a variety of favourable but biologically empty environments" that allowed for radical evolutionary changes (Harland and Rudwick 1964: 36). In other words, the geologically sudden appearance of animals in the fossil record might have occurred *because*, rather than *in spite*, of the Snowball Earth episodes. This is a question that remains hotly debated.

In the shadow of this fantastical picture of Snowball Earth, it is easy to forget the means of its making for the final world that emerges, which is just as marvelous—not least because this mechanism is contained in sea ice itself.

Since the late 18th century, scientists had begun to look for cosmic mechanisms to explain glacial epochs on earth: variability in solar output, the wobble and migration of earth's axis, as well as variations in the shape of earth's orbit. But as several scientists noted, none of these mechanisms on their own, or even in combination, were sufficient to produce glacial epochs as observed in the geologic record. Perhaps, several scientists remarked, contained in processes on Earth were the conditions of possibility for glacial epochs.

"The important fact… was overlooked," wrote James Croll, the Scottish scientist who examined the compound influence of earth's axial wobble and orbital eccentricity on climate in 1875, "that although the glacial epoch could not result *directly* from an increase of eccentricity, it might nevertheless do so *indirectly*" through the activation of other "physical agents." Croll argued, based on the observations of polar explorers, including William Scoresby, James Ross, and Captain Cook, that snow and ice tended to lower temperatures. Even though summer temperatures in the high latitudes were normally low, "it is so only in consequence of the perpetual presence of snow and ice" (Croll 1875: 56-60). Thus, Croll reasoned, any changes *however small* in solar radiation would be amplified by the snowfields themselves (Imbrie and Imbrie 1979). When Serbian scientist, Milutin Milanković, further developed astronomical theories of ice ages in the 1920s (to mathematically predict the onset and end of ice ages), he gave greater weight to the summertime ice-albedo feedback in the high latitudes. This was based on the logic that reductions in summer heat would allow glaciers to persist when they would otherwise melt and, due to their increased albedo, continue to expand (Köppen and Wegener 1924). What these various authors were describing is known in modern scientific terms as the 'positive ice-albedo feedback,' a process whereby the growth of sea ice reflects more sunlight, cooling temperatures and making conditions favourable to the formation of more ice, which in turn reflects more sunlight, and so on.

If I linger on these theories of ice ages, it is because *ice*—specifically the ice-albedo feedback—emerges as a curious mechanism in the various theories of ice ages. Glaciation began as the phenomenon to be explained and, yet, it contains within itself its own conditions of possibility. "With their high albedo," note Peter Hoffman and Daniel Schrag, "snow and ice cool the atmosphere and thus stabilize their own existence" (Hoffman and Schrag 2000). This slight shift in emphasis recasts the genealogy of ice age theories in a different light (e.g., see Imbrie and Imbrie 1979): instead of looking for directs mechanism of glaciation, scientists began to investigate what circumstances would trigger an ice-albedo feedback; the ice-albedo feedback would take care of the rest.

It did not become apparent until the 1960s, however, with the advent of early climate models just how far-reaching the effects of the ice-albedo feedback could be. In 1969, two climate scientists Mikhail Budyko and William Sellers, each working independently observed a peculiar phenomenon in their energy balance models: if sea ice reached 30-degrees latitude north or south of the equator, the planet's albedo would rise at a faster rate because sunlight was striking a larger surface area of ice per degree of latitude. The ice-albedo feedback would run out of control, and the entire planet would freeze over. Such a 'runaway greenhouse' effect is observable on Venus, and explains its extremely hot surface temperatures. Here, however, models showed the opposite in an 'runaway icehouse' effect (Kirschivink 1992).

That sea ice might totalize the world was initially seen as a mistake. If such a 'white Earth' disaster occurred, as observed in these models, scientists presumed it would be permanent. The simple existence of *the world today,* free of ice at its equator, was proof that such an event was impossible. But beyond the lack of a physical mechanism at the time of its proposal, and perhaps most definitively for skeptics, the Snowball Earth hypothesis seemed to contradict the geologic record, which suggested a continuity of life, rather than a sudden extinction—or complete termination—incurred by a Snowball Earth episode. In rocks up to one billion years old, geologists had found microscopic algae that closely resemble modern forms. How could these organisms have survived a Snowball Earth catastrophe? The thickness of sea glaciers would have eliminated oceanic photosynthesis. Decoupled from the atmosphere, the ocean underlying sea ice would be deprived of oxygen. In these circumstances, all eukaryotic life would be eliminated. Only bacteria (prokaryotes) would survive.

A de-glaciation mechanism only became apparent in modelling studies in the early 1980s. These models suggested that a 'white Earth' disaster might be rescued through volcanic activity, which would gradually increase the concentration of atmospheric greenhouse gases and thaw planet out of its frozen state. As such, the possibility of a Snowball Earth episode "could not be ruled out on grounds of irreversibility" (Hoffman 2009: 2).

The survival of microscopic algae has led scientists to hypothesize a 'soft' rather than 'hard' Snowball Earth (e.g., Hoffman et al. 1998). Based on modelling studies, different scientists have shown that glaciation may have been incomplete, positing that a layer of either *thin ice* (e.g., McKay 2000; Pollard and Kasting 2005), *slush* (e.g., Cowen 2001; Hyde et al. 2000), or *water belt* (e.g., Abbott et al. 2011; Pierrehumbert et al 2011; Rose 2015) encircled the equator (see Bechstädt et al. 2018 for a review of Snowball Earth theories).[69] In effect, scientists worked out ways in which photosynthetic organisms could somehow escape the smothering effects of snowball earth, to capture sunlight and survive long periods of extreme cold.

But as Paul Hoffman, geologist and champion of today's Snowball Earth hypothesis, writes, the discovery of microorganisms living in extreme conditions—near geothermal vents, in sub-glacial lakes, and sea ice—makes it plausible that eukaryotic life would have found refugia on Snowball Earth. In other words, the world today—and more precisely, life as we know it—cannot be used as an endpoint, inevitable conclusion of what came before and what is possible. Today does not define the limits of the possible, for either what is yet to come or what has already passed. There exist radically other forms of life, which, furthermore, are not human, and which can displace those we know today.[70] Even livability itself may not be the organizing principle or final ends of worlds.

Let me dwell a little longer on this relationship of livability to 'worlding,' as it bears directly on the high stakes of contemporary times: that is, what it means to live and die in the Anthropocene. As Elizabeth Kolbert (2014) has reported, we are in the midst of the Earth's sixth mass extinction. In jeopardy are not only human and nonhuman lives, but, as Kohn (n.d.) has put it, "life *as* a form."

At stake in Tsing's (2015) mushroom 'worldings' is "the possibility of common life on a human disturbed earth" (Tsing 2015: 163) or what she calls *livability*. Livability, Tsing argues, is more than just the survival of individual organisms or species, or even survival in a strictly biological sense. It refers to social and cultural forms of livability important for collective survival, as well as to the often ignored or neglected conditions of possibility that generate livability in the first place. Mushroom worlds are contingent upon other world-building activities, such as pine trees, human cultivation practices, cultural valorization, and economic valuation. Mushrooms give contour to shared livability by bringing into focus a more-than-mushroom worlding. This '*more than*,' which mushrooms depend upon, and which they inadvertently generate through their own world-building activities, make worlds possible. In Tsing's account of mushrooms, then, 'to world' is to produce the possibility of life-in-common. Life-in-common refers not just to a gathering of many individual lives, but coming into being itself in relation to, and with, others. Life-in-common gives worlds their significance. It is in terms of livability that Tsing analyzes the threat of extinction.

Celia Lowe's (2010, 2017) ethnography of viruses touches on the possibility of death at stake in the making of worlds alongside companion species. While viruses have reworked human and other life in newly discovered and subtle ways—from their role in allowing a mammalian fetus to draw nutrients from its mother, to the "uncertain reassortment of identity" inherent in viral clouds that transform animal hosts, human institutions, and social relations (see Lowe 2010)—Lowe notes that "viruses arguably play their most expansive social role when they are on a rampage" (Lowe 2017: 94). As Lowe points out, "relations with companion species and human commensals are recently described through love, care, desire, sensuousness, affection, curiosity, pleasure, even sexuality in multispecies work. But multispecies relationships are also about predation, encroaching, poaching, infection, and pathogenicity" (Lowe 2017: 94). More to the point, Lowe notes: "Flourishing always involves a constitutive violence; flourishing does not imply an 'anything goes' free-for-all, but requires that some collectives prosper at the expense of others" (Lowe 2017, quoting Ginn, Biesel, and Barua 2014). It is from this perspective—of the undesirable forms of life that 'we' do *not* wish to cultivate—the forms of which take shape within the interconnected lives of viruses, humans, and other nonhuman animals—that Lowe conducts her ethnography of viruses (see Low 2010; Lowe and Münster 2016).

Life, then, remains the contrastive background against which death gains definition. But part of the analytic challenge that viruses present with respect to worlds and worlding lies precisely in its positioning on the threshold between life and nonlife. By definition, viruses do not properly belong to either domain. In the absence of 'life' or 'death' as conceptual referents, how to make intelligible the 'worlds' that viruses produce? The liminality of viruses displaces 'worlding' from the sphere of livability into another realm altogether.

From the perspective of livability, salts-in-solution and sea ice are also limit cases. On one side, and as observed on modern Earth, salts-in-solution can generate worlds as we know them today. But on the other, and as inferred from studies of Snowball Earth episodes, and the Great Salinity Anomaly, salts-in-solution can reorganize geophysical patterns that usher in entirely different worlds. Life has little to do with these possibilities. More unsettling is the radical contingency or, fundamental indifference, of sea ice. That salts-in-solution and sea ice "make worlds for others" is an accidental and underdetermined side effect. Even sea ice *itself* is an incidental side effect that salts-in-solution did not set out to produce, and which is not a final form. Under different circumstances, sea ice—and the worlds it supports—may not have come into being at all. Sea ice—and, by extension, salts-in-solution—has an arbitrariness that challenges conceptions of worlding understood as the making of significance, not just in the narrow sense of symbolic meaning-making, but in the broader sense of worlds as systems of relations through which life-in-common comes into being and comes to *matter*. Without the significance supplied by life-in-common, radical contingency and indifference is an unrecognizable, even antithetical, form of worlding.

Can there be 'worlds' without biological life, let alone life-in-common? How to describe worlds without reference to life (survivability, conviviality, commensality) *or* death (violence, disease, extinction)? Maybe these questions can be put a different way: Absent life, does ice *not* world at all? Is is it merely the background against which microbial, fungal, or human 'worlding' occurs? Although my focus is sea ice, these questions direct attention to the possibility of worlding by weather and climate, oceans and tectonic plates. Their ability to shape the environment and, to some extent, modify their own conditions of occurrence through positive or negative feedbacks, suggests that these abiotic processes cannot be discounted from producing worlds on the assumption that they can enable—but also destroy—livability. If we admit that sea ice (and land ice) can 'world' but perhaps in directions other than livability, how must we re-think 'worlding' as a concept?

The indifference of sea ice echoes that of the peat bogs central to McLean's (2011) argument about other-than-human worldings, which shaped European settlement and cultivation, human health and disease. While bogs have played a crucial role in defining 'Europe' as a historical entity, and as such can be understood within the framework of human history, bogs exceed any version of the story of modernity: "its temporality is one that encompasses, rather than being encompassed by that of history" (McLean 2011: 591). This is cast into sharp relief, McLean notes, by the recent activity of today's sub-Arctic western Siberia, where the world's largest frozen peat bog is beginning to thaw and releasing billions of tons of trapped methane frozen 10 000 years ago, which would likely accelerate global warming.[71] Bogs, but also sea ice, are neither companionable or unsociable. As McLean notes: "If [bogs] reminds us of human beings' inextricable embeddedness within an active and dynamic material universe, such a reminder carries with it too the threat of dispossession, evisceration, loss, of the dissolution of human agency and subjectivity into the amorphous and protean black good of matter's inhuman self-transformation. (McLean 2011: 611).

A perspective from the discipline of history offers another view on this provocation of 'worlding' that does not ground in life-in-common. In his effort to find a form of history that can grapple with geological time, Dipesh Chakrabarty (2009, 2018) finds himself in the company of planetary scientists. The retreat of the last Ice Age was the result of axial tilt and orbital relationships between the Earth and the Sun, which stabilized the temperature of the planet within a zone that allowed barley and wheat to grow. "Without this lucky 'long summer' or what one climate scientist has called an 'extraordinary' 'fluke' of nature in the history of the planet," Chakrabarty poignantly notes, "our industrial-agricultural way of life would not have been possible" (Chakrabarty 2009: 218). These are, moreover, the boundary conditions for the existence of institutions, such as capitalism and socialism, that are "central to our idea of modernity and the meanings we derive from them" (Chakrabarty 2009: 218). Such conditions are independent of human institutions, and could very well have been otherwise. Geological processes sit outside the limits of history, then, not because they involve much longer time scales, but because they are alien—indifferent—to history as a meaning-making endeavour.[72] Human 'worlds' and 'worlding' are not just historically contingent, but *geologically* contingent as well.

The contingency of human and nonhuman life on geological (and astronomical) phenomena brings into focus not only the worlds that geophysical processes produce, but worlding as non-teleological. To the extent that life-in-common today could have been radically otherwise— or simply not at all—puts this reference frame into perspective. Life-in-common is not the ultimate ends of geophysical processes, and to make it the vanishing point for 'worlds' as they arise out of geophysical processes is to ignore the contingency of life. Life-in-common, then, is certainly one of many possible worlds but it cannot be the measure of them all. Geophysical processes can world but in non-teleological ways.

What are the implications of letting go of livability and life-in-common as guiding frameworks for making worlds? A non-teleological argument runs the risk, as some analysts have argued, "to anaesthetize politics" (Bonneuil and Fressoz 2016: 80), for what can one do if the current crisis is still 'worlding' but in a different direction, away from life-in-common? This kind of fatalism, whether in the form of "it's too late" or "the climate has always changed, so what?" is exactly what Haraway (2016) wants to refuse. In "staying with the trouble," she seeks to find ways of cultivating "response-ability," of not abandoning hope or succumbing to despair. Haraway argues against turning away from the onrushing disaster and finding refuge in some "salvific future" or "edenic past," but to have the courage to acknowledge the uncomfortable entanglements of today and respond by learning to live in the present. "Whether we asked for it or not, the pattern is in our hands. The answer to the trust of the held-out hand: think we must" (Haraway 2016: 34).

Think we must. This is the injunction that Haraway puts to thinkers of all kinds, whether inside or outside academia. It is a call for intellectual openness and creativity, not only in generating alternate conceptual apparatuses, but to cultivate different aesthetic sensibilities, ethical orientations, emotional sensitivities, modes and forms of storytelling in this time of multispecies urgency. "It matters what thoughts think thoughts. It matters what relations relate relations. It matters what worlds world worlds. It matters what stories tell stories" (Haraway 2016: 35). In many ways, Haraway argues, autonomous Man/the Human as distinct from Nature and over which it has control is a master story that has gotten us into today's mess. But this story can be told differently, she argues, as well as pluralized—and in finding alternate ways to narrate the world it is possible to re-pattern thinking and relationships. Learning to listen for other stories, then, and finding ways to tell stories differently, offer key tools to navigate these urgent times. In this light, what kind of stories can salt-ice worlds offer? What kind of storytelling emerges from attending to sea ice?

I am afraid that I have no stories to share from sea ice. I have shared some fables above, which are certainly stories, but they are not made by sea ice. They are an analytic device I have constructed to make sea worlds and scientific knowledge accessible. Insofar as stories produce meaning, or, more broadly, life-in-common, sea ice does not 'story'; it worlds, however, in non-teleological ways. Let me close this chapter—this dissertation—with a couple of reflections.

Considering worlds apart from livability does not deny the importance of "learning to be truly present…as mortal critters entwined in myriad unfinished configurations of places, times, matters, meanings" (Haraway 2016: 1), nor is it an escape into "a world without us."[73] But as I explored the ways in which salt-ice worlds, I found myself estranged from familiar coordinates. Sea ice worlds were unrecognizable from the perspective of livability or life-in-common. These were not the premises on which salt-ice worlds rest, whether in the past, present, or future. To stay with the worlds produced by sea ice required withholding from 'becoming' or 'becoming-with' as analytics, not as a denial of relationality or collaboration, but because sea ice worlds exceed the frame of view they offer. Sea ice offers a glimpse onto endless worlds-in-the-making, open-ended, underdetermined, and not always livable. This non-teleological worlding required fostering a different ethical orientation that can take seriously the non-necessity of life as-we-know-it. Indifference is productive as an attitude insofar as it seeks to create some distance but not transcendence; that it can be sensitive but not unresponsive. In these urgent times, then, this dissertation tries to articulate a different sensibility as another way of facing these urgent times alongside new forms of storytelling and "arts of noticing." Thinking with the ethic and aesthetic in the photographs of Edward Burtynsky, the Canadian artist known for his depictions of 'manufactured landscapes,' helps me bring into focus the kind of sensibility I have in mind.

"Manufactured Landscapes" is a documentary (2006) and retrospective exhibit (2004), comprised of Burtynsky's photographic renderings of industrial landscapes since the mid-1980s: quarries, recycling yards, railcuts, factories, mines, and dams.[74] The photos are visually stunning in their choice of subject matter—places and processes that most people ordinarily do not get to see—but most of all in their manner of presentation. Perspective is flattened by the relentless repetition of identical discarded materials, not only because they are shot close-up but because they are so numerous they overflow the frame.[75] Scenes of quarrying without boundaries or reference points, without markers to suggest scale or horizon line, and only minimal shadows, generate an ambiguity of scale and perspective. In the images spatial relationships lose their self-evidence and ways of seeing unravel.[76] When photographed at great heights, things lose their taken-for-granted identity as houses or logs, tailing ponds or salt pans, and come into view as form and pattern, colour and contrast.[77] As Kenneth Baker notes about the plays with scale in Burtynsky's photos, "at no point of enlargement does it suddenly become newly explanatory of what it encodes" (Baker 2003: 44). In fact, Burtynsky's aerial photographs effect a curious scalar dislocation. Aerial photographs, rather than aggrandize the scale of collective human activities seems to diminishes them. Scenes of human terraforming and megaprojects appear as if seen under a microscope—an impression that is further emphasized by photographs that mimic the form of photomicrographs showing *in vitro* fertilization. For instance, a long, narrow road puncturing a circular phosphor tailing pond.[78] The disorientation that the photographs produce simultaneously reworks our senses.

The dislocating effects of the photographs are heightened by the tension between their subject matter (content) and its style of presentation (form), as well as between styles of art as a frame of reference and as phenomena in their own right within the world. Burtynsky's photographs are reminiscent of abstract modernism and surrealism, except that these art forms are 'found,' so to speak, in the unintentional figures left by human terraforming and ecological destruction.[79] Also recognizable in these images are technological ruins, toxic wastelands, extractive sites, manufactured landscapes, ecological dead zones. In short, scenes of environmental devastation. But their composition in the photographs imbues them with an unexpected aesthetic quality. Their formal beauty has such visual force that it can arrests viewers' thoughts. For a split second, one is compelled to reconsider what is being presented, and *how*. "Burtynsky thus alternates between the photograph as visual record of disaster," writes Jonathan Bordo, "and the photograph as intense, charged and abstracted colour field" (Bordo 2006).

Critics are suspicious of precisely this vacillation. In their commentaries, criticisms consist two broadly identifiable, but overlapping, kinds. One kind of criticisms is largely aesthetic. Burtynsky's artistic ambitions in composing a photograph runs the risk of aestheticizing ecological destruction or monumentalizing industrial transformations. Critics have also expressed concern that Burtinsky's ambitions to produce visually striking photos cultivates detachment from extreme ecological damage, and an apathy that discourages people from taking action or caring (Vaughn 2011). In response to these concerns, Burtynsky's curator Paul Roth quipped: "Maybe these people are a bit immune to the sublime—being terribly anxious while also being attracted to the beauty of an image" (Roth quoted in Khatchadourian 2016).

The other kind of criticism is political. Industrialists see in Burtynsky's photographs an indictment of their activities. Environmentalists, by contrast, condemn Burtynsky's photos for their moral ambiguity. It is clear to environmentalists that his photographs, by virtue of being mechanically produced, show something *in* the world and this is clearly environmental destruction (e.g., Bordo 2006). To present these objects as something other than an environmental disaster, i.e., to *not* see it as such, is a moral failing. As various commentators have noted, it can be difficult for viewers to appreciate the photograph's aesthetic qualities for the environmental disaster that it represents (Pauli 2003; Haworth-Booth 2003). Both industrial and environmentalist critiques hinge on the assumption that photographs are not just depictions but representations of what they show, and therefore share an identity with their referents (Bordo 2006). They argue that one knows *what* to see and how, which are determined in advance of any photographic or artistic rendering.

Burtynsky's photographic renderings, however, seek precisely to work against this self-certainty of seeing. "Burtynsky does not see these facilities as a capitalist's dream or as an environmentalist's nightmare," writes curator Lori Pauli, "what interests him is getting beyond the automatic response that equates manufacturing with ugliness and pollution. He compels us to think of these landscapes as inevitable products of our times" (Pauli 2003: 24-5). His goal, as his collaborator and filmmaker Jennifer Baichwal notes, is to present complexity without simplistic judgments or reductive resolutions. The visual force of his work resists closure; it seeks to create an opening that allows one to look at things differently. In other words, Burtynsky not only brings to ordinary people images of things outside our normal range of experience, but he also provokes viewers to develop a different practice of seeing, and to thereby expand their range of understanding. The space that Burtynsky's photographs create can be freeing in that it does not dictate to viewers the different possible ways to relate, and respond, to his photographs. But for the same reason, this openness can be disorienting, even disturbing, as people are left to find their own ways of coming to terms with his photographs.

Ambivalence, indifference, neutrality, non-attachment. These are ways to characterize Burtinsky's positioning (or lack thereof), which is central to his artistic practice. Allowing for indifference is one way to stay with the worlds that sea ice produces, to let it reorder how one sees the world, even if means suspending certainty. For months, Mount Rainier left me in this suspended time of uncertainty. And I let it do so. I wanted to keep this tension alive rather than square it away and thereby put it out of sight and out of mind. The incoherence it produced was thought-provoking and productive. Things are not always what they seem. As sea ice scientist Willy Weeks writes in the introduction to a textbook on the topic, sea ice dynamics are "high-speed plate tectonics" (Weeks 2010: 5) in which mountain building and breakdown occurs in the span of hours. Or, as Cecilia once heard from her colleague, Peter Lemke: "Sea ice are the clouds of the ocean."

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Notes

[1] See Cambrosio et al. (2006) for arguments about 'regulatory objectivity' and the disciplinary standards that regulate the production of scientific knowledge. See Knorr-Cetina (1979), Fujimura (1987) for arguments about how science is constrained by material and institutional requirements.

[2] *La Mer de Glace*, or 'Sea of Ice,' is a glacier in Chamonix, France. It is where several glaciologists (e.g., John Tyndall who studied glacier motion) had their beginnings in the scientific study of glaciers. As such, it was a model glacier. It is also the birthplace of Frankenstein the novel. In 1816, Mary Shelley, Percy Bysse Shelly and Lord Byron spent a few days at the Temple of Nature, which overlooks the glacier. The weather was wet and dreary—due, in part, to the 1816 eruption of Krakatoa, which spewed volcanic ash around the world causing global cooling Eighteen-sixteen became known as the 'Year Without a Summer.' Cooped inside, the group of friends had challenged each to write horror stories. Frankenstein was one of its outcomes.

[3] The SWIPA assessment is a periodic update to the Arctic Climate Impact Assessment, which was published in 2005 by the Arctic Monitoring and Assessment Proramme (AMAP), the Conservation of Arctic Flora and Fauna (CAFF), and the Interantional Arctic Science Committee (IASC). The first SWIPA assessment was conducted between 2008 and 2010, and was published in 2011.

[4] For an overview of historical sources that provide historical accounts on defined periods of Arctic activity, including the search for the Northwest Passage, the heroic age of Arctic exploration, the International Polar Years, see Roger D. Launius (2001).

[5] A naval tradition of scientific work in Britain was first introduced with Captain Cook's voyages to Tahiti to observe the transit of Venus across the Sun (1761) (Levere 1993).

[6] The scientific mandate of the Royal Navy became a model for subsequent naval arctic expeditions until the last quarter of the 19th century (Levere 1993).

[7] Wilson Bentley, born in 1865 in Jericho, Vermont, is also known for his work with snowflakes. Like Scoresby, Bentley was introduced to the miniature world of snowflakes after receiving a microscope as a gift from his mother at age 15. To capture their ephemeral forms, Bentley made sketches of the snow crystals. When Bentley's father gave him a camera, he learned how to affix it to the microscope to take photos of the snowflakes. Over his career, Bentley captured over 5000 snow crystals on film (Gosnell 2005).

[8] Another example of early international scientific cooperation could be extended to include the coordinated expeditions made to catch the 1761 transit of Venus, though this was different in scope and purpose compared to the IPY proposed by Weyprecht.

[9] The second Congress was supposed to be held in Rome in September 1877; however, due to the Balkan War, it was postponed until April 1879 (Tammiksaar et al. 2010).

[10] The IPY expeditions generated a great deal of data, but the lack of a central data repository, incomplete data sets, patchy distribution, and delayed published made utilization of the data less smooth than its collection. See Baker (1982), Elzinga (2010).

[11] The *Fram* never exceeded 86 degrees North, so Nansen and Frederick Hjalmar Johansen, an army reserve lieutenant and experienced dog driver, set out on skis with kayaks, sleds, and provisions to reach the North Pole. After reaching slightly further north than their starting latitude, heavy pressure ridges forced Nansen and Johansen to turn around and head to Franz Josef land where they overwintered (see Nansen 1837).

[12] Though far outside the walls of a modern scientific laboratory, the *Fram* resembles the Bachelard's (1937) 'phenomenotechnique'
[13] The first Soviet ice station, North Pole-1 (NP-1), was launched in 1937. Beginning in 1950 during the Cold War, a succession of Soviet drifting stations were deployed, sometimes one or two per year, until 1991 with the termination of NP-31. Similar to the *Fram* expedition, each of these stations lasted an average of two to three years before drifting out into the Greenland Sea where they disintegrated. Out of the 31 stations, only NP-19 passed over the North Pole. For a vivid account of life on the ice, see Papanin (1937) "Life on an Ice Floe."
[14] As Paul Edwards (2010) notes, 'better' can mean that results agree more closely with observations, but it can also refer to better agreement with a modeller's judgements, or what one interviewee of Edwards' called "physical plausibility."
[15] Paramaterizations are quantities that stand in for those processes that cannot be modelled directly because: they are very small-scale; there is inadequate empirical data; or their calculation exacts high computational costs. The values of parameterizations are determined based on empirical observations and their ability to scale from the sub-grid scale and large-scale processes in models (Edwards 2010). Radiative transfer, or the partitioning of solar energy within the atmosphere and the amount of solar energy that reaches the Earth's surface, is often parameterized in sea ice models and global climate models.
[16] Satellite sensors 'see' sea ice in different ways. To detect sea ice, satellites sensors take measurements in the visible, infrared, and microwave radiation regions of the electromagnetic spectrum. Visible light sensors on satellites 'see' objects like the human eye does; that is, they pick up the radiation reflected off objects. Thus, 'whiter' objects (i.e., those with a high albedo) reflect more light than 'darker' ones. Visible sensors, however, are blind at night when there is no light to see by—a shortcoming that is especially problematic during the long polar night. In addition, visible light sensors can mistake white clouds for sea ice. Infrared sensors measure the amount of heat emitted from the Earth's surface. Relatively cold sea ice is easy to distinguish from the warmer surrounding ocean. But the heat from clouds can also interfere with these readings. And during the summer when the Arctic Ocean is a giant ice bath sitting at zero degrees Celsius, sea ice becomes effectively indistinguishable from the ocean (see NSIDC 2018c for more details).
[17] Sea ice scientist, Willy Weeks, makes comparisons of sea ice to "plate tectonics at high speed" (Weeks 2010: 5).
[18] See Shoemaker, Brian. 2000. Untersteiner Transcript.
[19] University of Washington Applied Physics Laboratory Interview http://www.apl.washington.edu/project/project.php?id=rotten_ice
[20] Scientifically speaking, polymer gels are elastic fluid-filled networks of polymers, which give them hybrid solid-liquid properties and behaviours.
[21] On October 4, 2016, voters narrowly approved changing the name of the town from 'Barrow' to 'Utqiagvik,' meaning 'place to gather wild roots' in Inupiaq (Demer 2016). The town acquired its colonial name after Frederick William Beechy of the British Admiralty 'discovered' the town in 1825 and named the location after his patron, Sir John Barrow. Based on archaeological evidence, the settlement's origins go back much further. Archaeological sites indicate that the Inupiat lived in Barrow as early as AD 500, making it one of the oldest permanent settlements in the US (Daley 2016). A court complaint has since been filed to block the name change, stating that the community's ancient name should be Ukpeagvik, or 'place to hunt snowy owls' (Demer 2016). The town is still in transition after the name change was voted on (Koenig 2018).

[22] Scientific research arguably began even earlier than 1947 when the US Army established a meteorological and magnetic research station at Barrow in 1881 for the first International Polar Year. See Greely 1886, "Three Years of Arctic Service."

[23] For the purposes of this dissertation, I use the term 'Iñupiat' to refer to the indigenous people living in Utqiagvik, specifically. The choice of terminology is based on different terminology conventions between different countries for the Inuit and Yupik people who live in the circumpolar Arctic. 'Inuvialut' is the preferred term in the western portion of the Northwest Territories of Canada, whereas eastwards towards Labrador, the preferred term is 'Inuit.' The indigenous people of Greenland refer to themselves as 'Greenlanders' or 'Kalaallit,' while in Alaska, the preferred term is 'Inupiat' or 'Alaska Native' (Alaska Native Language Centre 2011). Although the term 'Native' is seen as derogatory and outdated, in the United Sates this term is still frequently used, particularly because it has particular legal usage related to the 1971 Alaska Native Claims Settlement Act. 'Alaska Natives' is inclusive of indigenous groups through the whole state: Iñupiat, Yupik, Aleut, Eyak, Tlingit, Haida, Tsinshian, and several other Northern Athabaskan cultures.

[24] See Charles Wohlforth's (2004) "The Whale and the Supercomputer" for an in-depth journalistic account of how scientists and Native Utqiagvik residents have forged relationships through the study of climate change.

[25] As Rheinberger notes: "In scientific thought the subject's meditation upon the object always take the form of a project. The project is a draft, and science is realized in drafting. The draft, however, only exists in the form of alterantives with possible experimental realizations" (Rheinberger 2010: 23).

[26] See Cambrosio et al. 2006 on 'regulatory objectivity.'

[27] The laboratory was, and is, not the only privileged site of scientific experimentation. Historians have shown how scientific experiments were performed in other sites, and how the laboratory was the site for other kinds of work (e.g., Shapin 1988; Smith 2008). Karin Knorr-Cetina (1999) also shows how experiment and laboratory are de-coupled.

[28] Recognizable in this configuration of lab-to-field in the rotten ice project is the hierarchy of epistemic sites that Robert Kohler (2013) describes in his cultural history of the 'field' in ecology. Kohler argues that the 'field' (and 'lab') are cultural practices rather than physical locations, per se. His, analysis, however, places the lab and field in an economy of cultural credibility through the borrowing or mixing of practices, or the creation of novel epistemic practices as cultural products. What if the configuration of lab-to-field is part of a practice of objectivity, rather than a competition for cultural credibility?

[29] Lab/field divisions often map onto other dualisms: artificial/natural, universal/particular, human/nonhuman. However, the 'field' as an epistemic site and rotten ice as collected in the field are no less *produced* than those scientific objects made in a laboratory. On the flip side, the laboratory is not a space of total human control but one open to contingency and the idiosyncracies of experimental systems (e.g., Rheinberger 1992).

[30] For instance, in Susan Leigh Star and James Greisemer's (1998) classic study on the creation of the Museum of Vertebrate Zoology at the University of California, Berkeley, they developed the concept of 'boundary objects,' or "objects which are both plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites" (Star and Greisemer 1998: 393). Boundary objects, Star and Greisemer add, "are often internally heterogeneous" (Star and Greisemer 1998: 408). Notably, Peter Galison (1997) describes what he calls 'trading zones' to make sense of the interactions

between theorists and experimentalists in high energy physics. Rather than come to a single understanding of reality, these two groups engaged in a selective coordination of action, developing a rudimentary but functional 'in-between' language, similar to what culturally disparate communities develop to trade goods.

[31] See Hacking (1983), Rheinberger (1992, 1997), Rees (2016)

[32] The differential reproduction described by Rheinberger (1992) occurs through a displacing dynamic in which technological objects define the boundary conditions for the emergence of scientific objects, which in turn become sufficiently stabilized to constitute the technical conditions for the making of yet other scientific objects beyond the original goals for which a technological object was designed. As such, scientific objects and technological objects are not so much fixed parts of an experimental system so much as "places" within it, and they are able to change places (Rheinberger 1992: 310).

[33] Stains are made using molecules called fluorophores. Fluorophores can be synthetic chemicals, proteins, or antibodies. There are a variety of different fluorophores, each of which has a distinctive absorption and emission spectra and appears as a specific colour to human viewers. In addition, fluorophores can be designed to isolate biological molecules of interest. For interest, DAPI (4′,6-diamidino-2-phenylindole) is a synthetic chemical that binds to nucleic acids (DNA, RNA), thus labelling the nuclei of cells. Other fluorophores will bind to other cellular structures, such as mitochondria, chloroplasts, or the cell membrane, allowing for differentiation of organisms (e.g., bacteria vs. algae). To image a specimen, filters must be chosen to match the excitation and emission spectra of the flourophore used to label the specimen. Due to these technical constraints, it is only possible to image the distribution of a single fluorophores, or colour, at a time. To produce multi-colour images of several fluorophores, several single-colour images must be combined. For the cells, the team chose DAPI stain (blue); for the algae, autoflourescence (red); for the bacteria, CTC (orange-red); and for the polymer gels, chlorotetracycline (green).

[34] According to Robert Kohler, "practices of place" in scientific fieldwork involved "recognizing the places where observation and comparison can reveal how nature works" (Kohler 2013: 212). Such practices requires an intimate knowledge of the locale, which enables the selection of an appropriate field site for one's scientific questions, as well as the ability to make sense of . "Places are to the field what experimental setups are to laboratories" (Kohler 2013: 212).

[35] See NSIDC Press Release "Arctic Sea Ice Shatters All Previous Record Lows" October 1, 2007 (https://nsidc.org/news/newsroom/2007_seaiceminimum/20071001_pressrelease.html); Stroeve et al. 2014.

[36] That said, the North Sea Route was blocked by a band of ice for the summer of 2007.

[37] Today, the Arctic sea-ice minimum is listed by NASA as one of the "Vital Signs" for global climate change (www.climate.nasa.gov), alongside carbon dioxide concentrations, global temperature, changes in land ice and sea level.

[38] See, for example, Deweaver, Bitz and Tremblay, eds. (2008)

[39] For studies on the role of environmental predictions in social life, see Hastrup and Skrydstrup (2013), Heymann et al. (2017), Mathews and Barnes (2016), Sarewitz and Pielke (1999)

[40] At its inception, the Outlook was a "response by the scientific community to the need for better understandings of the Arctic sea ice system, given the drastic and unexpected sea ice decline witnessed in 2007." When it began, it was seen as an "exploratory exercise" that would help the scientific community understand and anticipate complex phenomena in a way that could also serve the public and stakeholders. Crucially, the intent was not to issue *predictions,* but to

summarize findings from models and observations to provide the best available information for the scientific community, stakeholders, and the public (SIPN 2013). Each year over the last decade, beginning in June, organizers distributed an open call for estimates of the Arctic sea-ice extent for each month in summer through September. Participants volunteer estimates of the September sea ice extent based on late spring (June) conditions, which a core team then analyzes and synthesizes into monthly reports. These reports describe current observations of sea ice conditions and, based on submissions, their expected evolution into September. A post-season summary provides a retrospective overview of how the whole summer season unfolded and evaluates the performance of observations against predictions. Over the last decade, the Outlook has expanded its focus, producing regional as well as pan-Arctic outlooks of sea ice conditions, experimenting with the prediction of different metrics (e.g., sea ice area and thickness), and more recently, broadening its horizons beyond the Arctic to include Antarctic sea ice extent.
[41] See, for example, Aporta (2011), Laidler (2006), Krupnik et al. (2010) for excellent studies on the effects of melting sea-ice on northern Indigenous communities. Laidler (2006) has further pointed out that differences in attitude among different groups of people can be attributed to their relative proximity to living out the consequences of anthropogenic climate change.
[42] To be clear, the epistemological gap Petryna refers to is *not* a first-order opposition between what is known and unknown, or even a second-order argument about things-as-we-know-them and things-in-themselves, but an argument about the difference between the *knowable* and *realizable*—or, even, the knowable and fundamentally unknowable. To specify this distinction, Petryna draws on Bachelard's concept of the 'phenomenotechnique' to specify how technical instruments do not just describe pre-existing phenomena but actually bring them about. In this light, the epistemological gap she wants to make visible is between the techniques we have available
[43] Anomalies can vary depending on the time interval over which they are averaged.
[44] 'Heat capacity' is defined as the amount of energy required to raise a unit mass of sea ice by 1 degree Celsius.
[45] Significantly, the heat capacity of sea ice includes not only the energy required to warm pure ice and liquid brine, but the energy to melt ice at the brine-ice interface. This gives sea ice an unusually high heat capacity compared to pure ice.
[46] The concept of memory has been crucial to anthropological critiques of human exceptionalism. For example, 'memory' is a fundamental tenet of Eduardo Kohn's (2013) theory of biosemiosis. Only living things, which have a self, can 'remember.' Snowflakes and whirlpools, by contrast, although they are self-organizing do not selectively remember or forget in generating a form that shapes a future, an embodied self. In his meditation on bodies from the bog, Stuart McLean (2008) examines the crucial role of non-humans (e.g., modern imaging technologies, chemical processes) in the creation of collective memory that is not produced or maintained by humans. My purpose in posing the question, 'can sea ice remember?', is less about making a case for the extension of 'memory' to nonhumans, than I am interested in following scientists and their re-tooling of this concept for their purposes.
[47] More specifically, scientists noted that these pairs of months shared a similar mean sea ice cover from melt to growth season.
[48] Edward clarified that these mnemonic 'limbs' are not related to the limbic system in the human brain, which is associated with long-term memory.
[49] According to Peixoto and Oort (1992): "The feedback mechanisms act as internal controls of the system and result from the coupling or mutual adjustment among two or more subsystems.

Part of the output returns to serve as an input, so that the net response of the system is altered; the feedback mechanism may act either to amplify the final output (positive feedback) or dampen it (negative feedback)."

[50] The dynamical heart of El Nino is a sea surface temperature gradient along the equator in the tropical Pacific: cold water off the coast of Peru and warm water in the western tropical Pacific. The temperature difference sets up a pressure difference that drives the westward-flowing trade winds. As dry air sinks over the cold water in the eastern tropical Pacific, winds flow westward. Travelling over the progressively warmer ocean, the air warms and moistens until it reaches the western tropical Pacific where it builds up into towering rain clouds. The westward blowing winds pile up warm shallow waters in the west Pacific, which brings up cold, nutrient-rich waters from the deep on the east side of the Pacific. Return flow occurs in the upper troposphere. This describes the 'normal' state of affairs, or La Niña phase. During an El Niño episode, warmer than usual sea surface temperatures in the east tropical Pacific weakens the east-west temperature difference and the westward winds (trade winds) slacken. Warm ocean surface waters slosh eastwards and the convective heavy rainclouds shift eastward from their position over Indonesia into the central and eastern tropical Pacific. Scientists have sometimes combined El Niño with the Southern Oscillation, to identify the oscillation's oceanic and atmospheric components, respectively. But as Philander (2004) notes, it is difficult to separate the two. A change in winds alters surface temperature patterns in the tropics, but the reverse could also be said: changes in temperature patterns change the winds. "The two coupled together form an inseparable unit" (Philander 2004: 21). El Niño, then, refers less to a strictly oceanic phenomenon (as it was formerly known) than to a temporal phase of an alternating weather pattern. Based on this reasoning, one can refer to the whole phenomenon as El Niño alone.

[51] One of the World Research Climate Programme's Climate and Ocean: Variability, Predictability, and Change (CLIVAR) projects is working on understanding how global warming could impact the processes that contribute to El Nino's variability. It is not yet possible to say whether El Nino's activity will be enhanced or damped, or if the frequency or character of events will change in coming decades. For more details, see: http://www.clivar.org/research-foci/enso

[52] See Wanner et al. (2001) and Hurrell et al. (2003) for reviews of current knowledge on the temporal variability of the NAO/AO.

[53] The NAO also has the potential to shape collective time by inflecting the *timing* of living patterns. In ecology, this is called 'phenology,' or seasonal activity driven by environmental factors (Drinkwater et al. 2003). For instance, it is well known that interannual variability of phytoplankton and zooplankton reflect changes in winds and ocean temperatures (Colebrook 1982). As well, temperature determines the rate at which phytoplankton cells divide and wind mixing is important in controlling the onset of spring phytoplankton blooms (Sverdrup 1953). By influencing atmospheric variables (wind speed and direction, air temperatures, heat and moisture transports, precipitation), the NAO can modify the temperature and salinity characteristics of the ocean, which the influence the temporal unfolding of marine biology.

[54] There is no unique way to define the NAO (Wallace 2000). There are different techniques to decompose the spatial-temporal variability of atmospheric data into coherent spatial patterns and time series (Wanner et al. 2001). Which statistical method is used leads to different dynamical mechanisms. The classic method of decomposition relies on *a priori* knowledge, such as the pressure difference between Iceland and the Azores. Taking the Iceland/Azores are the main centres of action, scientists have looked for possible driving factors in the North Atlantic region involving ocean and sea ice dynamics (Wanner et al. 2001). Other decompositions are entirely

statistical. This is the case of the AO. Instead of using station-based indices over the North Atlantic to produce one-point correlation maps, scientists have sought to analyze statistically sea level pressure over the entire Northern Hemisphere and extract leading modes of variability (Thompson et al. 2003). The pattern that arises bears striking resemblance to the NAO in the Atlantic sector, but shows a centre of action over the Arctic surrounded by a ring opposite in sign at the mid-latitudes. In other words, instead of an exchange of atmospheric mass between Iceland and the Azores, there is an opposing pressure pattern between the Arctic and middle latitudes in the Northern Hemisphere. With the AO, the main actors are the zonal circulation and troposphere-stratosphere couplings are implicated. As Wallace (2000) points out, the difference between the AO and NAO lies not so much in the spatial pattern but in their interpretation.

[55] 'Recent' is relative. For paleo-historical reconstructions of Arctic sea ice cover, see Polyak et al. (2010)

[56] Since 1980, the NAO has been in a strongly positive phase with an upward trend, so that by the end of the 20th century winters have exhibited the most pronounced positive indices every recorded (with the exception of 1996). The AO has also increased over the past 30 years, which may represent a trend or a modal shift (Marshall et al. 2001).

[57] For sound pieces on the Arctic and ice more generally, see Jane Winderens' piece on the spring bloom in the marginal ice zone of the Arctic Ocean: https://workofwind.ca/project/spring-bloom-in-the-marginal-ice-zone-from-the-barents-sea-to-lake-ontario/; several sound pieces are listed in Stefan Helmreich's essay on "Melt": https://culanth.org/fieldsights/801-melt

[58] You can listen to Judy's "Sonification of Sea Ice" here: https://www.judytwedt.com/the-sounds-of-climate-change.html

[59] For an anthropology of waves, see Helmreich (2014)

[60] In everyday life, sublimation can be observed in one's freezer as the shrinking of old ice in ice-cube trays, or as 'freezer burn' on meat.

[61] In his attempt to make peat bogs tractable to anthropological thought, Stuart McLean (2011) casts around for a mode of presentation, an "idiom" that can make palpable the other-than-human worlding of peat bogs that, on one hand, resists reducing matter to "the dynamics of human history or the assignment of cultural meaning," and on the other, escapes science communication as the explanation of why wetlands matter for ecosystems and natural habitats. McLean draws on multiple sources in an act of *poesis* as an act of making. These efforts are nothing *but* poetry as a serious intellectual endeavour. These experiments in writing are intellectually rigorous and scientific. He finds that Seamus Heaney's poetry might better able capture the "inherent volatility" of peat bogs as they release vapours "yet there remains arguably the need for a diferent kind of register, as much evocative as descritipve, one capable of making manifest a quality largely unarticulated in scientific accounts butat appears, nonetheless, quintessential both to the material being and to the cultural and historical efficiacy of the spaces commonly grouped together as wetlands." That finds expression more readily perhaps in Heaney's bog poems. Bogs, fens, marshes, and swamps—what

[62] An earlier version of this section appeared in Episode 2 of the Periscope Podcast produced by Raad Fadaak; co-written by Raad Fadaak, Julianne Yip, and Olivier Bollengier: https://soundcloud.com/periscope_podcast

[63] Untersteiner, Norbert. 1969. "Sea Ice and Heat Budget." *Arctic*: Vol 22 (3): 195-99.

[64] The fresher surface waters in the north Pacific, when cooled to their freezing point (-1.8 degrees Celsius), cannot sink to the same depths as those in the Atlantic.

[65] Such an arrangement describes the modern-day northern Pacific. The Pacific is relatively fresh compared to the Atlantic. Thus, even when surface waters are cooled to -1.8 degrees Celsius, they do not sink to the ocean bottom (Broecker 1991).
[66] See Broecker et al (1985) for an argument about how the ocean-atmosphere system probably has more than one stable mode of operation. See Broecker et al. (1990) for the "salt oscillator hypothesis" that suggests a mechanism explaining how deepwater production can 'switch' on and off. Broecker (1991) provides an easy-to-read explanation of these scientific arguments for lay audiences.
[67] If the Great Salinity Anomaly follows the path of relatively fresh, frozen sea ice, then another fable would follow the other component of sea ice—brine—in the formation of deep water in Antarctica.
[68] See Tim Ingold's (2011) 'Prologue' to "Being Alive: Essays on movement" for some insights on the role of 'production' as a key analytic in worlding, both human and nohuman.
[69] See Bëchstadt et al. (2018) for a review of modifications to the Snowball Earth hypothesis. There are critics of the hypothesis who argue that there are alternative ways to account for the puzzling geological observations that precipitated the Snowball Earth hypothesis without invoking global glaciation (Eyles and Januszczak 2004, 2007; Eyles 2008). Snowball Earth was, at the time of its articulation in the early 1990s, as speculative as other competing theories, though the provision of several testable hypotheses made it amenable to scientific testing (see Kirschivink 1992; Hoffman and Schrag 2002).
[70] For an anthropological exploration of extremophiles, see Helmreich (2009, 2010)
[71] See https://nsidc.org/cryosphere/frozenground/methane.html
[72] Chakrabarty cites Kosselleck's (2004) argument about the specificity of historical time. A concept of History in the singular, and as a human science, emerged out of the late 18th century as a plane of existence unique to human beings. What made historical time distinct from that of natural, physical, or astronomical phenomena, and which granted historical time its specificity, was the production of meaning; history emerged out of making sense of the relation between a given past to a given future, "or (in anthropological terms) experience and expectation (Kosselleck 2004: 3). This concept of 'history' as a meaning-making endeavour, Chakrabarty (2018) notes, cannot be applied to geological events, such as the Great Oxygenation Event of 2.5 billion years ago, or the Ordovician-Silurian great extinction event from 440 million years ago. Geological time sits outside the limits of history, then, not because it involves much longer time scales, but because it is alien—indifferent—to meaning-making.
[73] See Weisman (2017)
[74] Although Burtynsky uses photography as his medium, his preference is for view cameras, or large format cameras, requires more time to produce an image. As Burtynsky notes: "The view camera hit a direct chord in me. I liked it because it slowed me down, it made me more methodical. It compelled me to study the subject intensely as I attempted to find a way to translate it through this ground glass." This choice opens a time for contemplation, to compose a photograph. Since 2010, Burtynsky has switched to digital photography, which allows for new kinds of scalar distortions (see Khatchadourian 2016).
[75] For example, see Edward Burtynsky, "Ferrous Bushling #6, #7, Hamilton, Ontario"
[76] For example, see "Rock of Ages, #4, #17, #26, E. L. Smith Quarry, Barre, Vermont"; "Carrara Marble Quarries #24, #25, Carrara, Italy"

[77] For example, see "Saw Mills #1, Lagos, Nigeria"; "Verona Walk, Naples, Florida"; "Silver Lake operations #15, Lake Lefroy, Western Australia"; "Salt Pan #25, Little Rann of Kutch, Gujarat, India"

[78] Phosphor Tailings #5, Near Lakeland, Florida, USA, 2012

[79] Burtynsky's work has drawn comparison to Jackson Pollock, Jean Dubuffet, and Gerard Richter. Also identifiable in Burtinsky's photographs is the 'sublime,' an aesthetic category codified by Edmund Burke in 1756 as "whatever is fitted in any sort to excite the ideas of pain and danger," and which strongly shaped Romantic painting in the 18th century. Burtynsky's work can be situated within the tradition of painting "the industrial landscape sublime," which turned to manmade sites (e.g., coal pits, quarries, ironworks) as examples of the sublime (Haworth-Booth 2003).