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Potential evapotranspiration in Guyana

POTENTIAL EVAPOTRANSPIRATION IN DIFFERENT CLIMATIC REGIONS OF GUYANA

by

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ABSTRACT

Climatological and radiation data from Guyana observed at Botanic Gardens, Ebini, and St. Ignatius, are used to estimate potential evapotranspiration by various methods.

The climate of Guyana is also analysed for the purpose of determining representative sites for evapotranspiration experiments, and for analysing the climatic influences on potential evapotranspiration.

The Penman energy budget approach is adopted as control. The results of the study show that the pan coefficients (EP/Epan) increase from the coast towards the savannah region, or from humid to dry conditions. The equilibrium model cannot be used in the savannah region during the dry season; while evapotranspirometers are unreliable over 5-day periods, during the wet seasons because of heavy rainfall and during the dry seasons because of the oasis effect. The semi-empirical energy budget formula gives fairly reasonable 5-day estimates of potential evapotranspiration. However, when shortwave radiation data are available, the Penman energy budget method should be used since a high correlation is found between net radiation and incoming shortwave radiation.

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RESUME

Des données climatologiques et radiatives de Guyanne, observées aux Jardins Botaniques, Ebini et St. Ignatius, sont utilisées pour estimer l'évapotranspiration potentielle par différentes méthodes.

Le climat de Guyanne est aussi analysé dans le but de déterminer des sites représentatifs pour des expériences d'évapotranspiration et pour analyser les influences climatiques sur l'évapotranspiration potentielle.

Le bilan énergétique de Penman est employé comme contrôle. Les résultats de l'étude montrent que le "Pan" coefficient (EP/E_{pan}) augmente, allant de la côte vers la savane, ou changeant d'un climat humide à un climat sec. Le modèle à l'équilibre ne peut pas être utilisé dans la savane pendant la saison sèche; tandis que les évapotranspiromètres ne sont pas fiables pour une période de cinq jours, pendant les saisons humides à cause des fortes pluies et pendant les saisons sèches à cause de l'effet oasis.

Le bilan énergétique semi-empirique donne des estimés de cinq jours, d'évapotranspiration potentielle, passablement bons. Cependant, quand les données de rayonnement de courtes longueurs d'onde sont disponibles, la méthode du bilan énergétique de Penman devrait être utilisée car il y a une bonne corrélation entre le rayonnement net et le rayonnement descendant de courtes longueurs d'onde.

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CHAPTER ONE

INTRODUCTION

Most of the population of Guyana lives on the fertile coastal plains along the Atlantic Ocean and flooding of towns, villages, and fields is a regular occurrence in the rainy seasons; on the other hand, severe droughts occur in some years when the wet seasons begin one or two months later than expected, or terminate earlier. To prevent the resultant agricultural failures and other tragedies, and also to improve water resources planning, the Government of Guyana is improving the drainage and irrigation network of the coastlands. The success of this scheme depends on proper estimates of rainfall, evapotranspiration, soil water storage, subsurface and river runoff, and the water requirements for domestic and agricultural use. During the dry season there is insufficient rainfall, and the fields must be irrigated such that the amount of stored water is equal to the evapotranspiration and subsurface runoff. However, during the rainy seasons, the fields must be drained, where the drainage is such that there are no floods in the rainy seasons and no water shortage in the dry seasons. The excess water in wet seasons and the water shortage in dry seasons are both dependent on soil moisture content before rainfall, which to a large extent depends on moisture loss by evapotranspiration.

However, the coastland is a few feet below sea level; therefore its water budget is influenced by surface and subsurface runoff from the interior regions and thus indirectly by evapotranspiration in the interior regions. Consequently, an evapotranspiration study of the

Guyana coastland must include all parts of the country. On the other hand, a method developed for estimating evapotranspiration in one climatic region may not necessarily be valid in another region.

The importance of actual evapotranspiration in water balance analysis must be stressed. This quantity is extremely difficult and costly to measure directly. However, it can be obtained from potential evapotranspiration. Thornthwaite, Budyko, and Penman all showed that the actual evapotranspiration is equal or proportional to potential evapotranspiration, depending on the availability of soil moisture. The problem in Guyana may therefore in the first instance be reduced to that of estimating potential evapotranspiration (EP).

Besides its practical applications, EP is a useful climatological index and its determination would provide additional information about the climatic regions of Guyana. It is a combined effect of many meteorological parameters: wind, atmospheric dryness, net radiation, etc. It is also the opposite process to rainfall, since it involves returning water vapour to the atmosphere. Climatologically it is just as important as rainfall. However, energy is required for evapotranspiration and the climate of a region is somewhat an effect of the energy that remains to heat the surface and the atmosphere after evapotranspiration has taken place. Thus, latent evaporation is one term in the energy budget equation. For these reasons, Thornthwaite (1948) used potential evapotranspiration in his climatic classification or climatic-subdivisions of the world.

The Chief Hydrometeorological Officer of Guyana, in a personal letter (1972), said: "Last year we started computing Penman evaporation at Georgetown, Botanic Gardens. We found that the Penman estimates of open water evaporation were substantially higher than measured pan evaporation. These preliminary investigations seem to indicate that the Penman formula used was not appropriate and may well require modification for Guyana conditions. However, there is no possibility in the near future of setting up any large scale evaporation experiments such as was done in the U.S.A. in Lake Heffner and Lake Mead." (Potter, 1972). A reliable means of estimating EP in this tropical region would be a big step forward in local climatology and related disciplines. To find and test such a means is the objective of this thesis.

1.1 Summary of work

In Guyana, potential evaporation has usually been estimated from pan measurements which, unfortunately, do not yield reliable results in the tropics because the pan coefficients developed in mid-latitudes do not hold in the humid tropical climate. However, pan evaporation may not be totally useless; provided a suitable correction is worked out for tropical conditions. This is attained if a reliable method of calculating EP is used to obtain suitable pan coefficients. Such a method, however, must be both reliable and practical under Guyana conditions, taking into consideration limited finances, a general lack of instruments, recorders, electrical facilities, and the absence of a climatological laboratory.

In order to compute potential evaporation more accurately, the Penman energy budget formula (Penman, 1948) is used in this thesis as the necessary basic measurements simply include: net radiation, wind run and vapour pressure deficit.

Wind run and vapour pressure deficit are already measured by the Guyana Hydrometeorological Service, while soil heat storage is found to be negligible and not necessary for EP. A net radiometer, two solarimeters, two actinographs, and two psychrometers were loaned by Prof. B. J. Garnier, Geography Department, McGill University. Accordingly, an actinograph was installed in each climatic region of Guyana during the period July 1972 - February 1973, to provide daily incoming shortwave radiation. The actinographs were calibrated using the solarimeters, and the net radiation is obtained from incoming shortwave radiation (actinographs) after a relationship is established between net radiation and incoming shortwave radiation. Each climatic region requires its own linear regression, as the soil, vegetation, and cloud characteristics are slightly different. The Penman method, based on the actual physical process of EP, is here used to obtain control data for testing other methods.

The Penman method (1948) uses radiation which, unfortunately, is measured only at one first order climatological station since January 1972. For practical applications in remote areas, another method must be found that uses ordinary climatological data in place of radiation. Accordingly, the semi-empirical Penman formula, using bright sunshine, temperature and vapour pressure data to estimate net radiation was tested, and the constants suitably modified.

In order to verify the estimation of EP by the Penman formula (1948) two drainage lysimeters or evapotranspirometers were installed at Botanic Gardens along the Atlantic Coast, at Ebini in the inland forests, and at St. Ignatius in the Rupununi Savannahs. With the measurement of soil moisture content at two places, actual evapotranspiration can eventually be estimated.

1.2 Outline of the thesis

The thesis is presented in six chapters. The present introductory chapter is followed by one in which various methods of measuring and evaluating potential evapotranspiration are reviewed, including evaporation instruments, aerodynamic formulae, energy budget approach, and empirical formulae. Emphasis is given to those methods that are suitable and practical for Guyana conditions. The controlling factors that influence the methods selected are (a) the tropical nature of Guyana's climate, (b) the limited facilities of climatological stations and (c) the practical usage of the methods which should be valid over areas of land and not only for specific sites.

Chapter Three is presented as a review of the Guyana climate, illustrating the main characteristics of each region and the climatic influences on evapotranspiration in each region, and to show that the climatic regions are sufficiently different so that each region requires special modification of the evapotranspiration methods selected. The most accessible and developed climatological station in each region is selected for experiments during the period July 1972-February 1973, which is found to be slightly drier than the mean climate of the July-February period.

Chapter four: After positively deciding on the methods to be used and the location of sites, the author spent the summer of 1972 doing field work in Guyana. Two evapotranspirometers, constructed from pipes and standard oil drums, were installed at each station together with an actinograph. The latter was calibrated using two solarimeters, while a linear regression between net radiation and incoming short-wave radiation was established, using measurements from the net radiometer and solarimeters taken over a period of 15 days at each site. This thesis is based primarily on climatological, evapotranspirometer and radiation measurements taken by observers of the Guyana Hydrometeorological Service during the period July 1972-February 1973. Other data, but less significant for the thesis, include 20 years of climatological data.

In chapter five, EP is determined by various methods which are tested, treating the energy budget method as a control. Suitable monthly pan coefficients are evaluated and the relative contribution of net radiation to EP determined. The EP results are used in a water balance scheme, yielding the daily actual evapotranspiration and other components of the water balance.

In this research considerable attention is given to previous climatological work done in tropical regions. In Guyana, the McGill Savannah Research Group has been investigating the savannah-forest delimitation and work done on the savannah climate, in the form of graduate theses, include: the influence of climate on the Rupununi vegetation (Frost, 1966), and the weather conditions and the climate of the Rupununi (Atwoki, 1968). For the water balance, both authors used Thornthwaite's formula for EP but emphasised that it was chosen as being the best method possible at the time, rather than because of it's intrinsic accuracy.

In Barbados, the earlier evapotranspiration results of Rouse (1966) and Watts (1966) are still relevant to Guyana. The more advanced research employs the equilibrium model where EP depends on temperature and net radiation (Garnier, 1972a). The latter can be reasonably estimated from incoming solar radiation. Given incoming solar radiation, it is possible to map the topographic variation of incoming solar radiation (Basnayake, 1971) by considering the changes of the sun's zenith angle and the slope with topography (Garnier and Ohmura, 1968). Garnier (1972b) believes that "topographic variations in net radiation can be rationally evaluated by means of observations taken at a single representative site." In spite of the difficulty of mapping topographic variations of temperature in Barbados, it is possible to map the variations of EP as it takes quite large temperature variations to cause large changes in EP. The equilibrium model is therefore attractive for estimating EP in Guyana for small scale agricultural and large scale hydrological uses.

Evapotranspiration research in Nigeria was inaugurated by Garnier (1956, 1960) using evapotranspirometers and Thornthwaite's formula. Davies (1965) found that the Penman formula, "using empirical net radiation and aerodynamic terms," was too high in Nigeria but recommended a new approach by measuring the net radiative flux over vegetated surface. His new approach (1966) "proved valuable in estimating EP and in delineating moisture availability on a broad scale" in Nigeria. This approach is essentially used in this thesis, principally because instruments for other methods are unavailable in Guyana.

CHAPTER TWO

THEORY OF POTENTIAL EVAPOTRANSPIRATION

Evaporation, the change of state from liquid to vapour, occurs if there is an input of energy at the moist surface and a negative vertical gradient of vapour pressure above the surface. The amount of evaporation depends on the available moisture within the soil and on the rate of diffusion of water vapour away from the surface. It is, therefore, a complex physical process.

Although evapotranspiration, the total water loss by evaporation from the ground and transpiration from plants, can be measured by the use of lysimeters, there is no simple formula, using easily available data, to compute the evapotranspiration rate. With this difficulty in mind scientists, notably Thornthwaite (1948) and Penman (1948), developed formulae to compute evapotranspiration under certain ideal conditions: (a) an unlimited water supply, which eliminates soil moisture influences on evapotranspiration, (b) the crop being short and of even height, to reduce atmospheric turbulence, (c) the crop covering an extended area, so there is no "oasis effect", and (d) the crop covering the ground completely, to reduce ground evaporation. Potential evapotranspiration takes place under such conditions and is often realised in nature.

Methods used for determining evaporation and evapotranspiration include various instruments, the water budget approach, empirical formulae, aerodynamic formulae, and the energy budget method. In spite of all these methods for evaluating evapotranspiration, there is no exact solution to the complex processes involved. Much work has been done on the theory of evapotranspiration by scientists whose works have been reviewed by several authors including Munn (1961), King (1961), Konstantinov (1963), Rose (1966), Sellers (1967), Chang (1968) and Gray et al (1971). Some of these methods are reviewed here, but emphasis has been given to those that are suitable, reasonably accurate, and practical under Guyana conditions.

2.1 Measuring Instruments

(a) Class "A" Pan: The most widely used instrument for measuring evaporation is the pan, of which the U.S.W.B. Class "A" Pan has been adopted by W.M.O. as standard. It is cylindrical in shape with dimensions 47.5 x 10 inches, being exposed just above the ground on a wooden frame support. Kohler (1955) suggests a formula to obtain shallow lake evaporation by correcting for advected energy through the sides of the pan. His equation is:

$$E_L = 0.70 \left[Epan + 0.00051\, p\, \alpha_p (0.37 + 0.0041U)(T_a - T_o)^{0.88} \right] \quad (2\text{-}1)$$

where E_L is lake evaporation, Epan is pan evaporation, p is atmospheric pressure in inches of mercury, α_p is advected energy used for evaporation, U is pan wind run in miles/day, T_o is surface water temperature, and T_a is air temperature in ^oF. Kohler provides a nomogram for the advected energy but over the range of water temperatures and pan wind run found in Guyana it can be approximated by:

$$\alpha_p = 0.24 + 0.0047\, T_o + (\log_{10} U - 1.1)/10.0 \quad (2\text{-}2)$$

Although evaporation pans are inexpensive and simple instruments to operate, their measurements depend on size, exposure, colour, splash-out of rainfall, turbulence, and many other processes for which there are uncertain corrections. Mukammal(1961) and Chang (1968) concluded that evaporation pans are by no means ideal evaporation instruments.

(b) Atmometer: This consists of a porous procelain disc, which is the evaporating surface, drawing water from a reservoir by capillary tension. However, the instrument measures the "drying power" of the air and the results are difficult to interpret since the latent evaporation is very responsive to wind and less so to net radiation, which is the dominant factor influencing evaporation over natural surfaces. Watts (1966), from readings taken in Barbados, states that atmometers "are unadjusted to the tropical trade wind environment."

(c) Lysimeter: The lysimeter utilises a weighing mechanism for accurate determination of surface water loss from a large block of undisturbed soil contained within the instrument. Pelton (1961) found that "the most carefully installed lysimeter may still not provide data which accurately represents the average evapotranspiration of the surrounding area." For representative data the accuracy should be to a water equivalent of 0.01 inch, necessitating a weighing device. A hydraulic weighing mechanism will reduce the cost considerably. Percolation, soil moisture retention, and root distribution should be indistinguishable from the surrounding soil, thus requiring an undisturbed soil block with a tensioning device at the bottom.

Because of its immobility, high cost of installation, and maintenance the lysimeter remains a research tool for checking the accuracy of other methods, and for comparing variations of evapotranspiration due to differences in crop morphology, soil, and meteorological conditions over short periods of time.

(d) Evapotranspirometer: The evapotranspirometer will be described later in more detail but basically consists of a drum of soil maintained at field capacity by the application of a known volume of water. By monitoring the moisture input and drainage of the soil within the drum, the EP can be measured over long periods, more than 5 days (Garnier, 1956). The instrument is rather attractive for use in Guyana as it is simple to instal and requires little maintenance.

2.2 Water Budget

The water budget approach can also be used in the determination of actual evapotranspiration (EA), based on the following equation (Rouse and Wilson, 1972):

$$EA = R - \Delta S_m - V_z - V_x - S_r \qquad (2\text{-}3)$$

where R is rainfall, S_r is surface runoff, and V_x is horizontal subsurface runoff. ΔS_m is the volumetric change in soil moisture, as determined by the gravitational change in weight of daily soil samples or by a neutron scattering device. V_z, the subsurface drainage, is given by

$$V_z = r\ K_z \frac{d\phi}{dz}$$
$$= K_z \frac{d\Psi}{dz} + K_z \qquad (2\text{-}4)$$

where K_z is the capillary conductivity, ϕ is the hydraulic head given by the sum of the matric suction, ψ , and the gravitational potential, z. The conductivity, K_z, can be determined in the laboratory, while ψ is measured by soil moisture tensiometers.

Rouse and Wilson (1972), using a neutron scattering device, have shown that this method is unreliable over daily periods because of unavoidably large errors in measuring soil moisture profile, capillary conductivity, and matric suction due to considerable soil variability over short distances. Consequently, the determination of drainage and change of soil moisture was not realistic, especially during periods of rainfall.

The water balance method can also be applied over a river basin where all the quantities in equation 2-3 are constantly monitored. However, none of Guyana's river basins are sufficiently instrumented to allow such a method to be executed (Potter, 1972, personal communication).

2.3 Empirical Formulae

Numerous empirical formulae have been devised for estimating potential evaporation, but only a few of the most popular will be mentioned here.

(a) Blaney and Criddle developed a simple formula for estimating monthly consumptive use in inches:

$$U=KT_m p \tag{2-5}$$

where K is the crop coefficient that depends on length of growing season, height and completeness of vegetation, T_m is the mean monthly air temperature in ^oF, and p is the number of daylight hours in the year. The formula does not work outside semi-arid regions (Chang, 1968) and therefore may not work in Guyana.

(b) Thornthwaite's formula is based on easily obtainable climatic data and reads:

$$EP = C\,(10\,\frac{Tm}{I})^{a} \qquad (2\text{-}6)$$

where EP is in centimeters, C is a coefficient depending on location, Tm is mean monthly temperature in ^{o}C, I is annual heat index or

$$I = \sum_{m=1}^{12} \left[\frac{Tm}{5}\right]^{1.514} \qquad (2\text{-}7)$$

and $a = 0.000000675\ I^{3} - 0.0000771\ I^{2} + 0.01792\ I + 0.49239$

The monthly EP is next corrected by the actual duration of daylight in the month to give the adjusted EP.

Pelton et al (1960) report that "the Thornthwaite method was found unreliable for daily, 3-day, and 6-day period estimates, because mean temperature is not a suitable physical measure of energy available for evapotranspiration."

(c) Makkink's formula, considering solar radiation as the prime cause of evaporation, is based on the fact that with high temperatures more solar radiation is used for evapotranspiration. The formula reads:

$$E = 0.61\ (Q+q)\downarrow\ \frac{s}{s+\gamma} - 0.12 \qquad (2\text{-}8)$$

where $(Q+q)\downarrow$ is the incoming short wave radiation expressed in mm/day by dividing by 59.0 (the energy in calories used to evaporate 0.1 c.c. at $10^{o}C$), s is the slope of the saturation vapour pressure curve at mean air temperature in mm Hg/^{o}C, and γ is the psychrometric constant 0.49 mm Hg/^{o}C.

(d) Turc gave a complex formula to estimate evapotranspiration over 10 day periods, by taking into consideration the effects of soil moisture. It reads:

$$E = \frac{R + E_{10} + K}{\left[1 + \left(\frac{R + E}{I} + \frac{K}{2I}\right)^2\right]^{1/2}} \qquad (2\text{-}9)$$

where

E= evapotranspiration over a 10 day period (mm)

R= precipitation over a 10 day period (mm)

E_{10}= estimated evaporation from bare soil, assuming no precipitation, and is not greater than 10 mm.

K= additional soil moisture available for evaporation (through vegetation) from cultivated soil

$= 25\sqrt{\frac{MC}{z}}$ where M = total dry matter yield in 100 kg/hectare
10_z = length of growing season in days
C = crop factor given by Turc

I = "evaporation capacity" of air

$= \frac{(T+2)\sqrt{(Q+q)L}}{16}$ where T is mean temperature over 10 days.

However, Turc's method is so complicated that it is rarely used.

2.4 Aerodynamic Method

(a) Dalton: This approach to evapotranspiration measures the rate of water vapour diffusion by turbulent motion in the lower boundary layer. Dalton first used a simple aerodynamic formula to estimate free water evaporation:

$$E_o = k\ f(u)\ (e_s - e_a) \qquad (2\text{-}10)$$

where e_a is the vapour pressure of the air, e_s is the vapour pressure at the evaporating surface, K is a constant, and f(u) is the wind speed profile. However, the surface vapour pressure, estimated from surface temperature, is difficult to estimate.

(b) Thornthwaite and Holtzman (1942) regarded evaporation as the diffusion of water vapour, i. e.

$$E = - \rho k \frac{\delta q}{\delta z} \qquad (2\text{-}11)$$

where ρ is the air density, z is the height, q the specific humidity, and k is von Karman's constant. For adiabatic conditions only, they assumed a logarithmic wind profile and that the eddy diffusivity, k, is the same for momentum and water vapour. Consequently

$$E = - \rho \frac{k^2 \quad u_1}{\log \frac{z_1}{z_2}} \quad z \frac{du}{dz} \qquad (2\text{-}12)$$

where u_1 is the wind velocity at height z_1. Integrating between two heights z_1 and z_2

$$E = \frac{\rho k^2 (u_2 - u_1)(q_1 - q_2)}{(\log \frac{z_2}{z_1})^2} \qquad (2\text{-}13)$$

Holtzman modified equation (2-13) for any condition of stability while Pasquill (1949) expressed it in a more convenient form for all heights of vegetation.

However, the aerodynamic method cannot be very accurate under unstable conditions and cannot be adopted as a field method in Guyana, because instantaneous and accurate measurements of wind speed and specific humidity are required. In Pasquill's equation, the zero plane displacement varies in a complicated manner with different wind speeds.

(c) Eddy Fluctuation: The eddy correlation method first devised by Swinbank (1951) is much more complicated although the idea is fundamental:

$$E = \rho \, \overline{w'q'} \qquad (2\text{-}14)$$

which means that evaporation is proportional to the instantaneous fluctuations of vertical velocity, w', and water vapour, q'. The instrumentation makes this method prohibitive for use in Guyana.

2.5 Energy Budget

(a) Bowen Ratio: From the principle of conservation of energy, the difference between incoming and outgoing radiation, Rn, is equal to the sum of the flux of heat into the ground, G, the sensible heat transfer to the atmosphere, H, and the latent heat used in evaporation, LE; i.e.

$$Rn = G + LE + H \qquad (2\text{-}15)$$

Bowen (1926) introduced the ratio

$$\beta = \frac{H}{LE} = \frac{-\rho c_p K_H \frac{\Delta T}{\Delta z}}{-\rho L K_E \frac{\Delta e}{\Delta z}} = \gamma \frac{K_H}{K_E} \frac{\Delta T}{\Delta e} \approx \gamma \frac{\Delta T}{\Delta e} \qquad (2\text{-}16)$$

$$\therefore \quad Rn - G = \beta \cdot LE + LE = LE(\beta + 1)$$

$$\therefore \quad E = \frac{Rn - G}{L(\beta + 1)} \qquad (2\text{-}17)$$

The above equation means that evaporation can be estimated provided net radiation, ground heat flux, and the Bowen ratio are known. The latter, obtained from measurements of vapour pressure and temperature at two heights above the ground, when used in equation 2-17 gives valid results for periods as short as 30 minutes. However, it is essentially an experimental method since fast response instruments are required.

(b) Penman approach: To overcome the difficulty of surface measurements, Penman (1948) combined the aerodynamic equation and the energy budget equation. He assumed that evaporation is proportional to vapour difference between surface and air, while sensible heat transfer is proportional to temperature difference between surface and air. That is

$$E = f(u) \quad (e_o - e_a) \tag{2-18}$$

$$H = \gamma f(u) \quad (T_o - T_a) \tag{2-19}$$

where f(u) is the wind profile equation which Penman assumed to be the same for heat and water vapour, γ = psychrometric constant = 0.66 mb/^oC, T_o is the temperature of surface, e_o is the saturation vapour pressure of water at temperature T_o, T_a is the air temperature, and e_a is the vapour pressure of air. Substituting equation 2-18 and equation 2-19 into equation 2-15 gives

$$Rn - G - E = \gamma f(u) \quad (T_o - T_a) \tag{2-20}$$

The slope of saturation vapour pressure curve is

$$s = \frac{de}{dT} \approx \frac{e_o - e_s}{T_o - T_a} \tag{2-21}$$

where e_s is the saturation vapour pressure of water at temperature T_a.

Equation 2-21 can be substituted into equation 2-20 to give

$$Rn\text{-}G\text{-}E = \frac{\gamma}{s} f(u) (e_o - e_s)$$

$$(Rn\text{-}G) \frac{s}{\gamma} - E \frac{s}{\gamma} = f(u) (e_o - e_a - e_s + e_a)$$

$$= f(u) (e_o - e_a) - f(u) (e_s - e_a)$$

$$= E - f(u) (e_s - e_a)$$

$$\therefore \quad E = \frac{s}{s+\gamma} (Rn\text{-}G) + \frac{\gamma}{s+\gamma} f(u) (e_s - e_a) \qquad (2\text{-}22)$$

So potential evaporation can be estimated, provided the above quantities can be determined.

In the derivation of the energy budget formula, there is made only one assumption, namely that H and LE are proportional to f(u). Whatever errors this assumption may introduce, the errors in EP would be small in the humid tropics as the second term in the equation only contributes 10 - 20 percent to EP.

The Penman equation, based on sound physical principles, has been tested and used with success in many parts of the world. It works best when the aerodynamic term is small, as in Guyana. With the availability of a net radiometer, this method is used to obtain control data against which other EP methods are compared in the present study.

(e) Semi-Empirical Penman Formula: Since radiation is not measured routinely in many places, particularly in tropical areas, Penman's energy budget method is in some respects reserved for field experiments. To remedy this deficiency, Penman incorporated ordinary climatological data to estimate Rn for use in his equation, as follows: Assuming that all net radiation at the surface is used to obtain maximum evapotranspiration, then G can be neglected, and therefore:

$$E = \frac{s}{s+\gamma} Rn + \frac{\gamma}{s+\gamma} f(u) (e_s - e_a) \qquad (2\text{-}23)$$

The net radiation, Rn, is composed of net shortwave radiation and net long wave radiation, Rnl, where the latter is generally negative. Therefore

$$Rn = (Q+q)\downarrow (1 - \alpha) - Rnl \qquad (2\text{-}24)$$

Incoming shortwave radiation is a function of the shortwave radiation reaching the top of the atmosphere, Q_o, and the cloud cover, n, above the station:

$$(Q+q)\downarrow = Q_o (a + b \frac{n}{N}) \qquad (2\text{-}25)$$

and the constants are obtained by regression analysis between $(Q+q)\downarrow / Q_o$ and n/N . The net longwave radiation under clear sky conditions, Rnl′, is the difference between the upward and downward components; that is

$$Rnl' = R_{ld} - R_{lu} \qquad (2\text{-}26)$$

According to Brunt (1932, 1944) and Gray et al (1971)

$$\frac{R_{ld}}{R_{lu}} = \varepsilon \text{ (emissivity)} = a_o + b_o \sqrt{e_a}$$

where e_a is the mean vapour pressure of the air at 2m, and a_o and b_o are regression constants. Therefore

$$\begin{aligned} Rnl' &= R_{lu} (\varepsilon - 1) \\ &= 0.96 \, \sigma T_a^4 (\varepsilon - 1) \\ &= 0.96 \, \sigma T_a^4 (0.56 - 0.09 \sqrt{e_a}) \end{aligned} \qquad (2\text{-}27)$$

since $R_{lu} = 0.96\ \sigma T_a^4$ is the black body radiation from the surface. The daily mean surface temperature is approximated by the daily mean air temperature at 2 m, and the infrared emissivity of grass is approximated by 0.96. The empirical constants 0.56 and 0.09 are taken from Penman (1950, 1949) and although they must be different in Guyana, no modification is possible since the downward and upward components of longwave radiation are not known with sufficient accuracy. Penman showed that

$$\frac{Rnl}{Rnl'} = (a_1 + b_1 \frac{n}{N}) \tag{2-28}$$

$$\therefore \quad Rnl = 0.96\,\sigma T_a^4\ (0.56 - 0.09\sqrt{e})\ (a_1 + b_1 \frac{n}{N}) \tag{2-29}$$

For the wind function many wind profile equations have been proposed but Davies and McCaughey (1968) suggested

$$f(u) = 1.2\ u \left[\frac{k}{\ln \frac{z + z_o}{z_o}} \right]^2 \tag{2-30}$$

which they found to be accurate for hourly periods if needed. Substituting equation (2-29) into equation 2-24, and the result together with equation 2-30 into equation 2-23 gives

$$E = \frac{s}{s+\gamma}\left[(1-\alpha)Q_o(a + b\frac{n}{N}) - 0.96\sigma T_a^4\ (0.56 - 0.09\sqrt{e_a})\ (a_1 + b_1\frac{n}{N})\right] + \frac{\gamma}{s+\gamma}\left[1.2\ u\left(\frac{k}{\ln\frac{z + z_o}{z_o}}\right)^2 \ (e_s - e_a)\right] \tag{2-31}$$

This equation is not as precise as the unmodified equation, but it is certainly better than any evaporation pan or empirical formula. It could well be adopted for routine use in Guyana as only climatological data are required.

2.6 Potential Evapotranspiration of Forests

Potential evapotranspiration takes place over short, uniform and extended vegetation having an unlimited water supply. For water balance and agricultural needs in Guyana, the EP of crops, tall rainforests, and savannah grasses will be required.

An extended and uniform forest should transpire at the same rate as the above vegetation for EP conditions, since both receive equal radiation. In spite of the large volume of forest per unit area the upper leaves, averaging 8-10°C above air temperature, transpire at a higher rate than the unexposed lower leaves that average 2.4°C below air temperature (Munn, 1966). Work done in Equatorial Africa indicates that "Direct measurements of water use from 10 feet depth of soil showed equal consumption by 120 ft high, twenty-six year old Radiata Pine; 50 feet high, sixteen year old Monterey cypress; 30 feet high, ten year old 'shamba' planted Patual pine, and from undisturbed indigenous thicket" (Pereira quoted in Penman, 1963). The height and age of forests are unimportant in the EP rate.

There is some scattered experimental evidence to support nearly equal daily EP rate from different plant species. Thornthwaite (1951) states that "the type of vegetation growing on the surface is of secondary importance in determining the combined evaporation and transpiration from a moist soil." Other published results, contrary to this, may be due to unequal spacing between different crops, unequal length of growing seasons, etc.

Leaves of different species have different chemical compositions and therefore absorb different wavelengths of solar radiation. Nevertheless, less than 5 percent of net radiation (or an average close to 1 percent of (Q+q)↓) is used for photosynthesis and respiration (Lemon quoted in Hillel, 1971). Differences in plant growth make no difference to the EP rate as the required energy is very small.

The measured albedo in Guyana is: 0.28 over short grass at Botanic Gardens, 0.26 over short grass at Ebini, and 0.26 over dry bunch grass in the savannahs during the dry season. However, the visually darker forests may have lower effective albedo since multiple scattering below the forest canopy may result in greater absorption of incoming radiation. Sellers (1967) gives albedo of 10-20 percent for deciduous forest in mid-latitudes.

The evapotranspiration/transpiration ratio depends on the leaf area index. However, the tropical forests are usually very dense. A change in this above ratio may take place during floods or in areas of swamp vegetation. With a strong competition between species to occupy as much space as possible, transpiration would be the predominant process in EP, as only a small fraction of solar radiation (0.1 percent) reaches the ground surface under a tropical rainforest (Glesinger quoted in Munn, 1966).

The EP rate does not depend on soil type. Thornthwaite (1955) notes that for any soil "when the soil moisture content is near field capacity the rate of evapotranspiration will approximate the potential rate." Under the same conditions, the root depths of plants will not affect the EP rate (Kramer, 1949). The effect of soil types, root depths, and plant-soil-water relations on actual evapotranspiration will be discussed later.

The wind function f(u) over crops or forests is an uncertain term in Penman's equation. Although, Davies and McCaughie (1968) found equation 2-30 to be satisfactory over short grass, it cannot be used over forests as z_o = antilog (-1.385 + 1.417 log h) becomes extremely large when h is over 50 feet. To date no satisfactory wind profile equation has been found.

In summary, the following characteristics of forests should be taken into account: albedo and wind function. It will be shown later than Rn is a function of (Q+q)↓ with the albedo having little effect on the regression constants (Davies, 1967). To eliminate the uncertainty of the aerodynamic term in EP, the equilibrium model is proposed.

2.7 Equilibrium Model

In the natural evaporation process illustrated in Fig. 1, consider the heat exchange when unsaturated air at (T_1, e_1) is raised to a different state (T_2, e_2) by the addition of radiative energy. Slatyer and McIllroy, and Montieth (quoted by Wilson, 1971) have shown that the change of state can be approximated by three different processes: (1) the air first reaches saturation by the addition of water vapour from the surface where the latent heat flow from the air to surface is $LE_1 = \rho c_p D/r_a$ where ρ is the air density, c_p is the specific heat of air at constant pressure, D is the wet bulb depression of initial air, and r_a is the time required for one unit volume of air to ex-

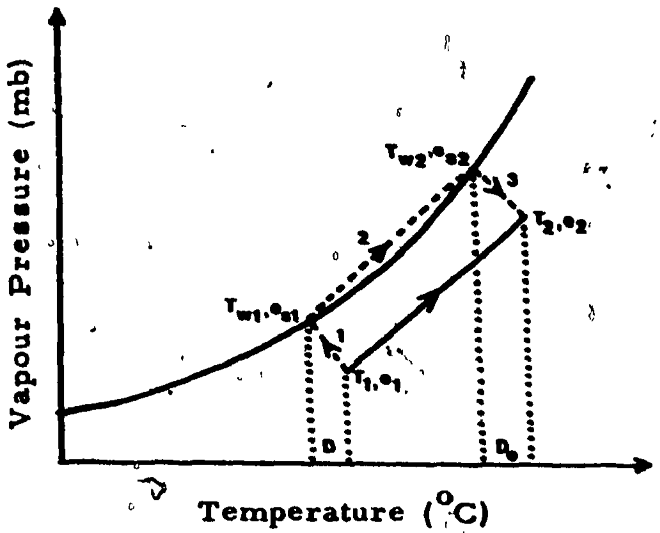


Fig. 2-1 Natural Evaporation Process (Wilson, 1971)

change heat with unit area of surface but is referred to as the dynamic resistance to the diffusion of water vapour from surface to air; (2) the addition of radiation to the saturated parcel and is given by $LE_2 = \frac{s}{s+\gamma}$ (Rn - G); and (3) the extraction of latent energy from the saturated air until (T_2, e_2) is reached and is given by $-LE_3 = \rho c_p D_o / r_a$. Therefore the total heat flux is

$$LE = \frac{s}{s+\gamma}(Rn - G) + \frac{\rho c_p (D - D_o)}{r_a} \qquad (2-32)$$

When the wet bulb depressions of the overlying air and the surface are equal, equation 2-32 reduces to the equilibrium model or equilibrium evapotranspiration, EQ. Hence

$$EQ = \frac{s}{s+\gamma}(Rn - G) \qquad (2-33)$$

Rouse and Wilson (1972) have drawn attention to the fact that the equilibrium model can be applied when the soil is not very wet or very dry and "appears to be more reliable for a vegetated surface." It should work well over a forest where most transpiration takes place at the upper branches that are not very wet or very dry, but works best in an advection free environment as in the humid tropics.

Priestley and Taylor (1972) showed that EP is proportional to EQ given by

$$EP = \bar{\alpha} \ EQ = 1.26 \ EQ \tag{2-34}$$

where $\bar{\alpha}$ has an overall mean of 1.26. Recently Davies and Allen (1973) treated α' as a variable, depending on soil moisture content where $\alpha' = \bar{\alpha} \left[1\text{-}\exp(-b \cdot ssm/ssmf)\right]$ where ssm/ssmf is the soil moisture content over moisture of field capacity. Although this relationship needs further testing, it destroys the simplicity of equation 2-34.

Penman's energy budget method (equation 2-22) is, in fact, composed of a radiation term, Erad, and an aerodynamic term, Eady, expressed as

$$EP = Erad + Eady \tag{2-35}$$

while the equilibrium model only consists of a radiation term, Erad. Therefore

$$\alpha = \frac{EP}{EQ} \tag{2-36}$$

$$= \frac{Erad + Eady}{Erad}$$

$$= \frac{EP}{EP - Eady}$$

$$= \frac{1}{1 - \frac{Eady}{EP}} \tag{2-37}$$

$\bar{\alpha}$ consequently depends on the contribution of the aerodynamic term to the total EP, for when Eady = 0 then α = 1.0 and when Eady = 0.5 EP then α = 2.0. The use of α =1.26 is only justified when Eady = 0.21 EP, as in mid-latitudes areas, producing 10 percent error when Eady = 0.13 EP to 0.28 EP. The use of α =1.26 could very well overestimate EP in a humid climate and underestimate EP in a dry climate.

For time periods such as one day, when G → 0, equation 2-34 is attractive as it only requires temperature and net radiation. It also eliminates any reason to calculate the aerodynamic term and can, therefore, be used over any surface of any aerodynamic roughness.

2.8 Methods used in Guyana

Many factors influence the choice of EP methods used in Guyana. The country lies in the humid tropics while most evapotranspiration research has been done in mid-latitudes; there are limited climatological research facilities in Guyana, making it impossible to implement a very reliable method; the present requirement is for 5-day totals of EP over large areas for agricultural and hydrological uses, while some methods are only applicable at a single site.

Of primary importance is the selection of a control method from the following techniques: lysimeter, water balance, eddy correlation, and energy balance. While the lysimeter and eddy correlation methods are out of question, the water balance is difficult over long periods and the necessary instruments are unavailable. However, the loan of 2 solarimeters, 1 net radiometer, and 3 actinographs from McGill University enabled the implementation of the energy balance scheme at 3 stations over a six month period.

The disadvantages of atmometers, empirical formulae, and aerodynamic formulae are already described, and these methods are ignored in the present study. Since pan evaporation is measured on a routine basis at many places by the Guyana Hydrometeorological Service it is useful to include these measurements. Evapotranspirometers, being inexpensive, were constructed at each station and are expected to give measurements of EP. Semi-empirical expressions for incoming shortwave radiation and net longwave radiation can now be derived in Guyana from the measurement of these quantities over 15 day periods; therefore, the semi-empirical Penman equation can be developed in Guyana. Considerable attention is also given to the equilibrium model.

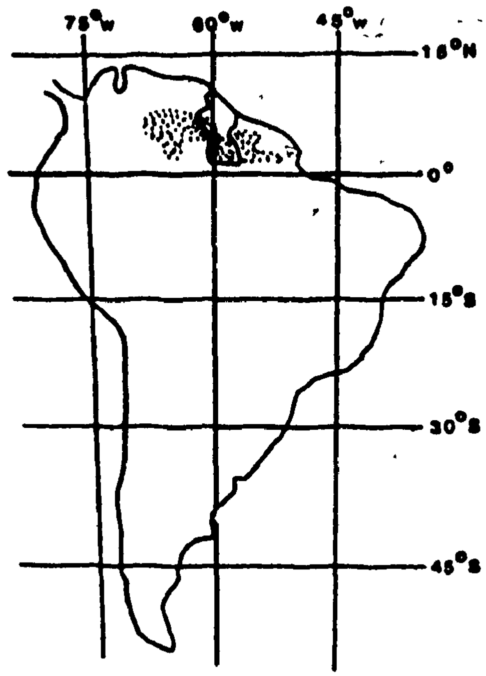
CHAPTER THREE

THE CLIMATE OF GUYANA

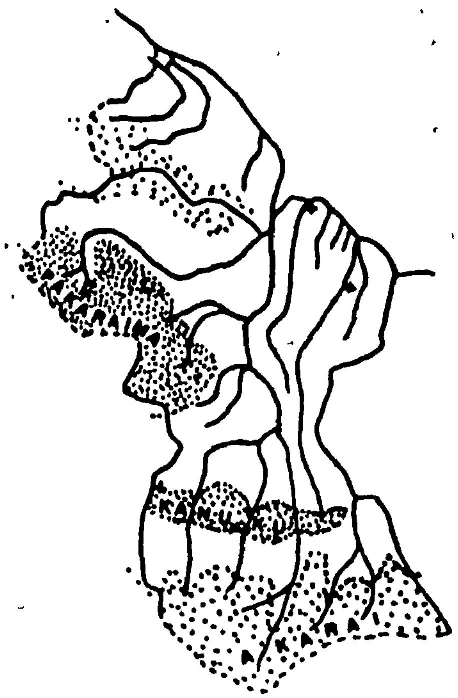
The vast proportion of Guyanese live on the coastland, along the Atlantic Coast, for which a water balance study would be of much economic and agricultural importance. Such a study must include the whole land mass of Guyana as the low coastland is exposed to river, surface, and underground water flow from the interior. Therefore, evapotranspiration should be determined from the low coastland and the interior hills and mountains, i.e., for each climatic region.

The preceeding chapter concluded with a description of a few evapotranspiration methods that can presently be used in Guyana. However, before these methods are applied, or the data analysed, a general review of Guyana's climate is presented in this chapter, for the following reasons: (a) Potential evapotranspiration occurs when soil and plant influences are treated as constants and therefore reflects meteorological factors. An analysis of climatological controls on EP is unavoidable in this study. (b) It was mentioned that some evapotranspiration methods work best in specific climatic regions (for example the evapotranspirometer is unreliable in a dry climate). A climatological analysis will expose limitations of the chosen methods. Garnier (1968) mentions that shortwave radiation income, and therefore EP, is influenced by topography; there are many topographical variations in Guyana. (c) From each climatological region a suitable site must be selected for field work on evapotranspiration.

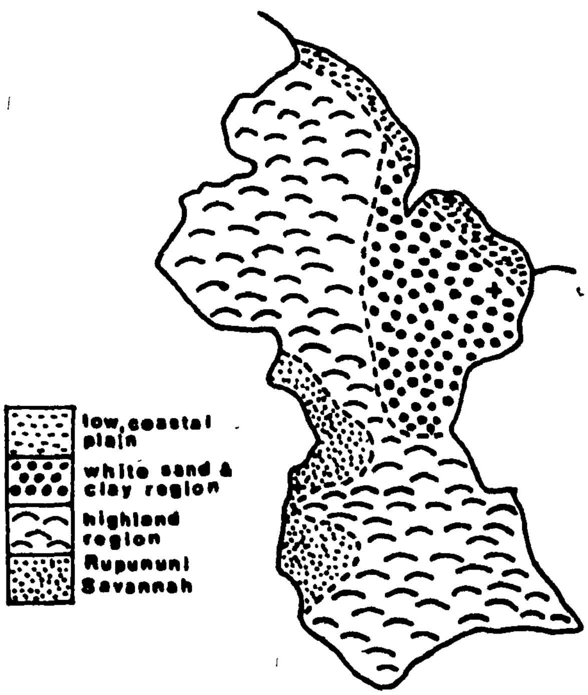
Fig. 3-1 Position of Guyana, and the physical, natural, and vegetation landscapes of Guyana (Cummings, 1965)



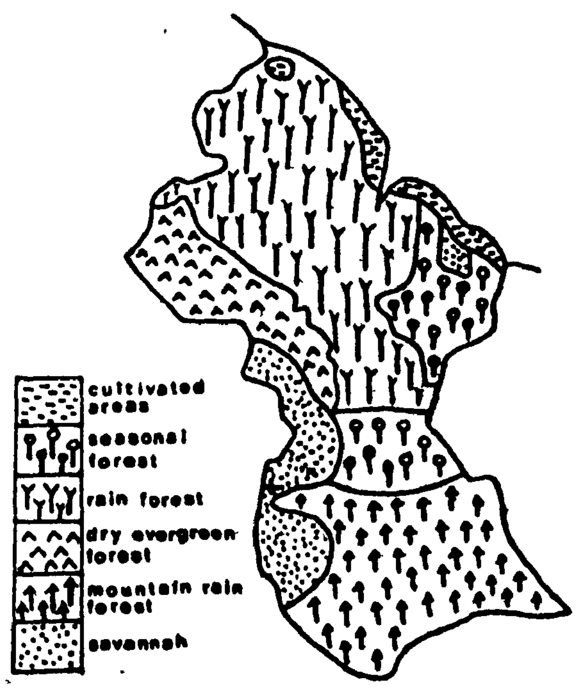
(a) Position of Guyana, showing Guiana Highlands (shaded area)



(b) Physical landscapes

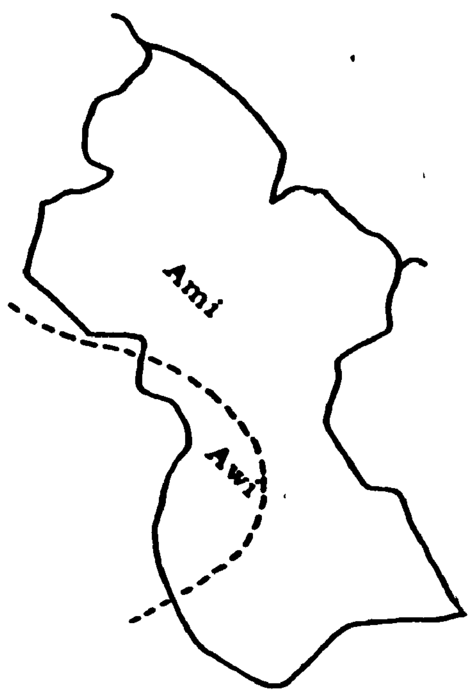


(c) Natural regions

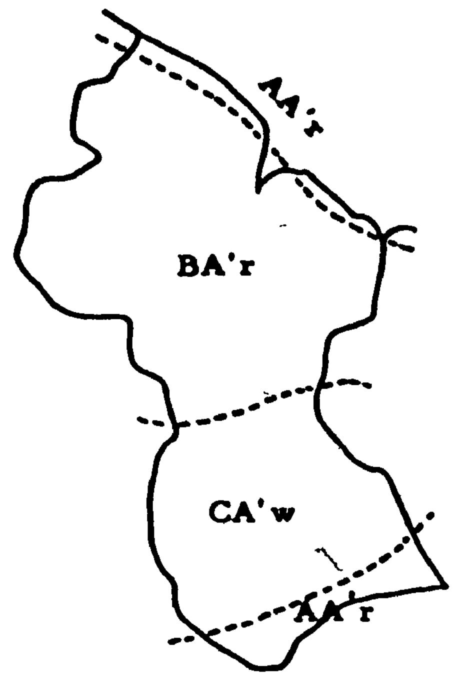


(d) Vegetation

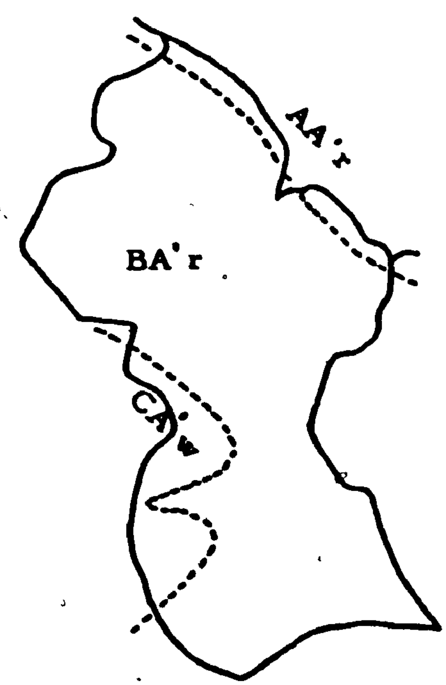
Fig. 3-2 Climatic classification of Guyana



(a) Köppen (Trewartha, 1943)



(b) Thornthwaite (Trewartha, 1943)



(c) Modified

3.1 Geography of Guyana

Guyana lies in the northern part of South America, between latitudes 1^{o}N - 9^{o}N and between 56.5^{o}W - 61.5^{o}W as shown in figure 3-la. The total area is 89,000 square miles.

Figures 3-lb, 3-lc, and 3-ld show the three main geographical regions: (a) the coastal plain characterised by silty clay soil and high population density; the land is a few feet below high tide and is protected by an earth dam. With high annual rainfall of 80-100 inches, drainage is quite a problem. The vegetation originally comprised mangrove swamps and bushes but the region now forms the principal agricultural region of Guyana with sugar plantations, rice fields, etc. (b) The hilly and mountainous region characterised by tropical rain and evergreen forests, sandy or rocky soils which are agriculturally poor, mountain ranges varying between 600'-7000', and a low population density consisting of a few small river settlements and 2 mining towns. (c) The Rupununi Savannahs with tall grasses and scattered trees, gravel and sandy soil, and a few small Amerindian settlements.

3.2 Climatic Classification

Köppen's and Thornthwaite's systems of climatic classification are used here as they are based on quantitative analysis. Köppen's system, based on annual and monthly means of temperature and rainfall, recognises two climatic regions in Guyana - figure 3-2a - which are symbolically designated as: (1) Ami-tropical rainy climate, and (2) Awi-tropical savannah climate. Some geographers have criticised Köppen's classification which often "leads to pronounced discrepancies between climatic subdivisions and the features of the cultural and natural landscapes" (Trewartha, 1943). This criticism is true for the coastal and forest landscapes.

Thornthwaite's classification identifies three climatic regions designated as: (1) AA'r - wet tropical, (2) BA'r - humid tropical, and (3) CA'w - subhumid tropical savannah (Figure 3-2b). This classification quite rightly recognises wet tropical climate over large tropical estuaries, tropical peninsulae, and tropical isthmuses. But this system includes mountainous rainforests in the Rupununi savannahs.

Both systems have their merits in world climatic classification but should be modified for climatic subdivisions, using human judgement when data are lacking. Accordingly, the coastal climate as emphasised by Thornthwaite is maintained here while the mountainous rainforests are excluded from the savannah region using the savannah - forest boundary to guide the exact delimitation. The resulting climatic regions are shown in figure 3-2c and for convenience designated as: (a) coastal climate, (b) forest climate, and (c) savannah climate.

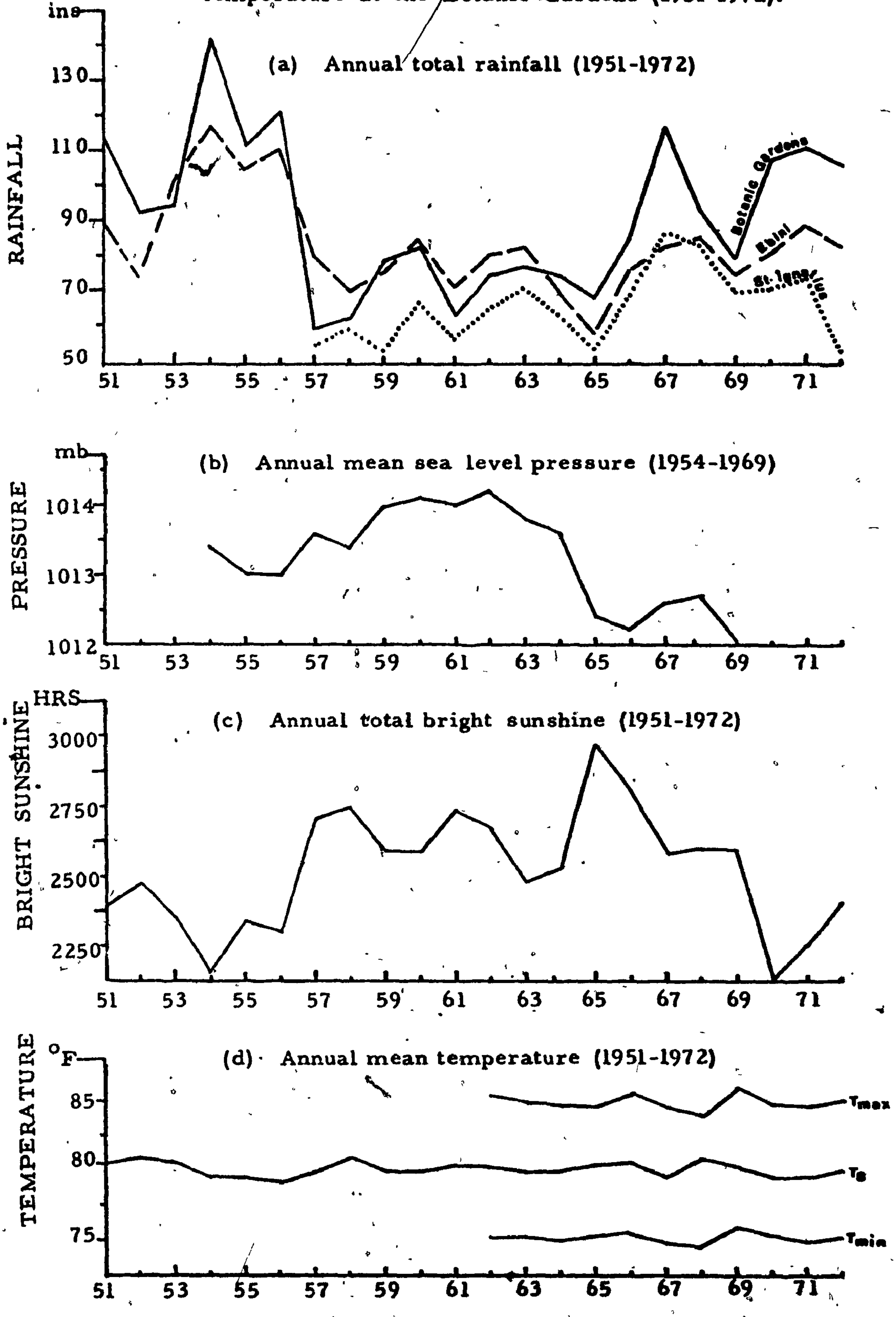
Sukanto (quoted by Arakawa, 1969), however, believes that in equatorial rainfall areas "the climate type will depend on the number of wet and dry months."

3.3 The Coastal Climate

Botanic Gardens: The climatological station in the Botanic Gardens is situated in Georgetown, the capital of Guyana. Being the best instrumented station with the longest record, and lying only 2 miles from the Atlantic, it is certainly an ideal station for analysing the coastal climate and for evapotranspiration experiments.

Rainfall: Rainfall is the most important climatological parameter

Fig. 3-3 Annual rainfall, annual mean sea level pressure, annual total bright sunshine, and annual mean temperature at the Botanic Gardens (1951-1972).



in tropical climates, and it influences the actual rate of evapotranspiration. Along the coastland average annual rainfall varies from 80 inches along the Berbice Coast to 100 inches on the Essequibo Coast. At Botanic Gardens, the average long term rainfall is 100 inches but varies between 147-57 inches.

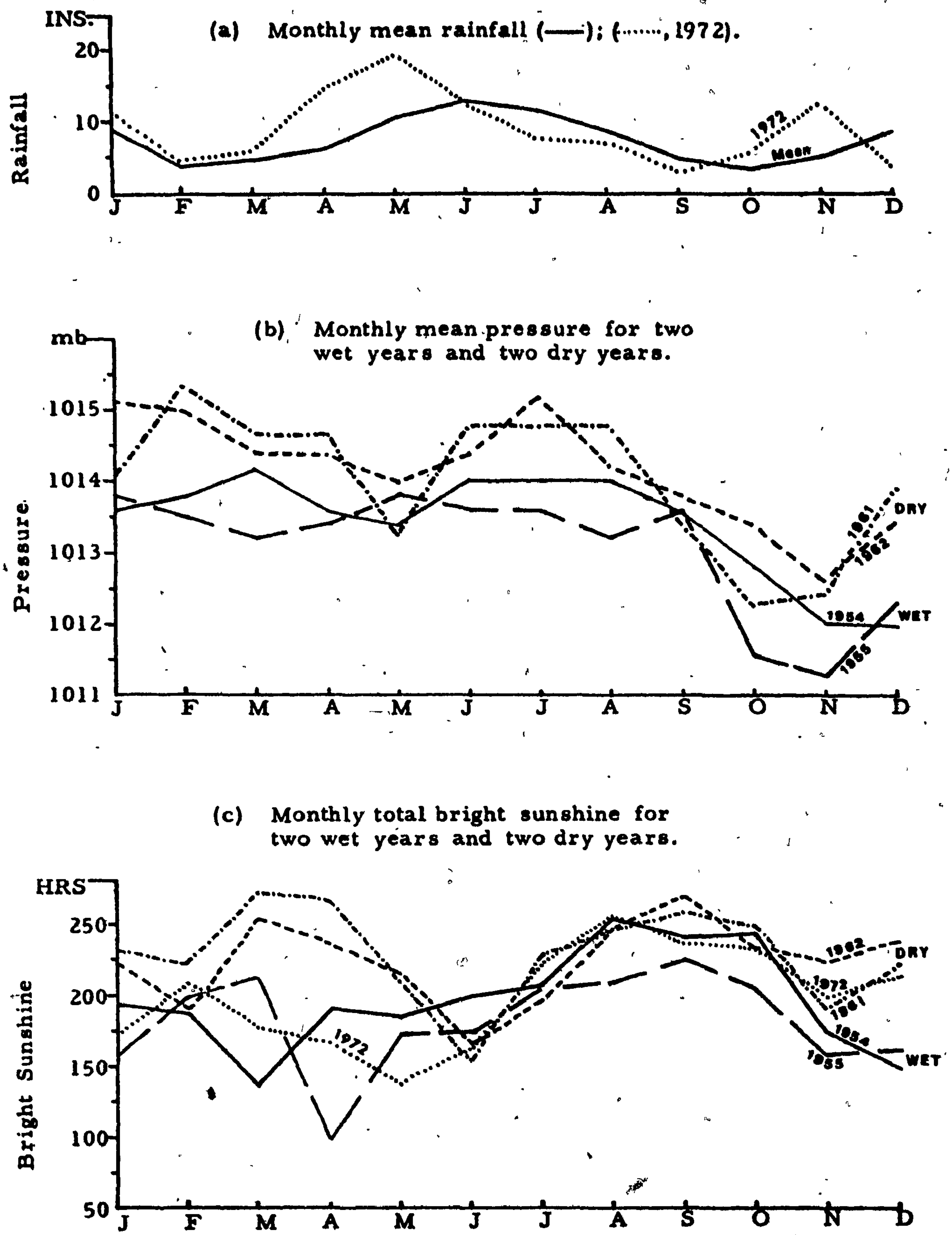
Based on 100 years of rainfall data, Potter (1970) noticed complete 45 year cycles of annual rainfall. Figure 3-3a, covering a half cycle 1951-1971, definitely indicates short cycles of 4 years superimposed on the longer cycle. These year-to-year variations of precipitation cause droughts in some years and floods in others. By coincidence, 1972 with 107 inches of rainfall should portray the average rainfall conditions although there were some floods. It is important that an evapotranspiration formula should be developed under average conditions.

The coastland experiences two wet seasons and two dry seasons, figure 3-4a, which are associated with the north-south movements of the Intertropical Convergence Zone (ITCZ). October, the driest month, has an average of 3.5 inches of rainfall so that half the plant water requirements should be satisfied but, unfortunately, monthly rainfall is quite variable.

In 1972 the first wet season began abruptly on April 18 and ended early but slowly as shown in figure 3-4a. The second dry season was extremely dry. The second wet season began abruptly on October 27, one month ahead of average time; its short duration produced extremely low rainfall from December 1972 to April 1973, resulting in a serious drought. The evapotranspiration experiment, July 1972 to February 1973, was therefore conducted under conditions drier than average.

Daily wet season rainfall indicates heavy rainfall every 5-6 days

Fig. 3-4 Monthly mean rainfall, pressure, and bright sunshine at the Botanic Gardens.

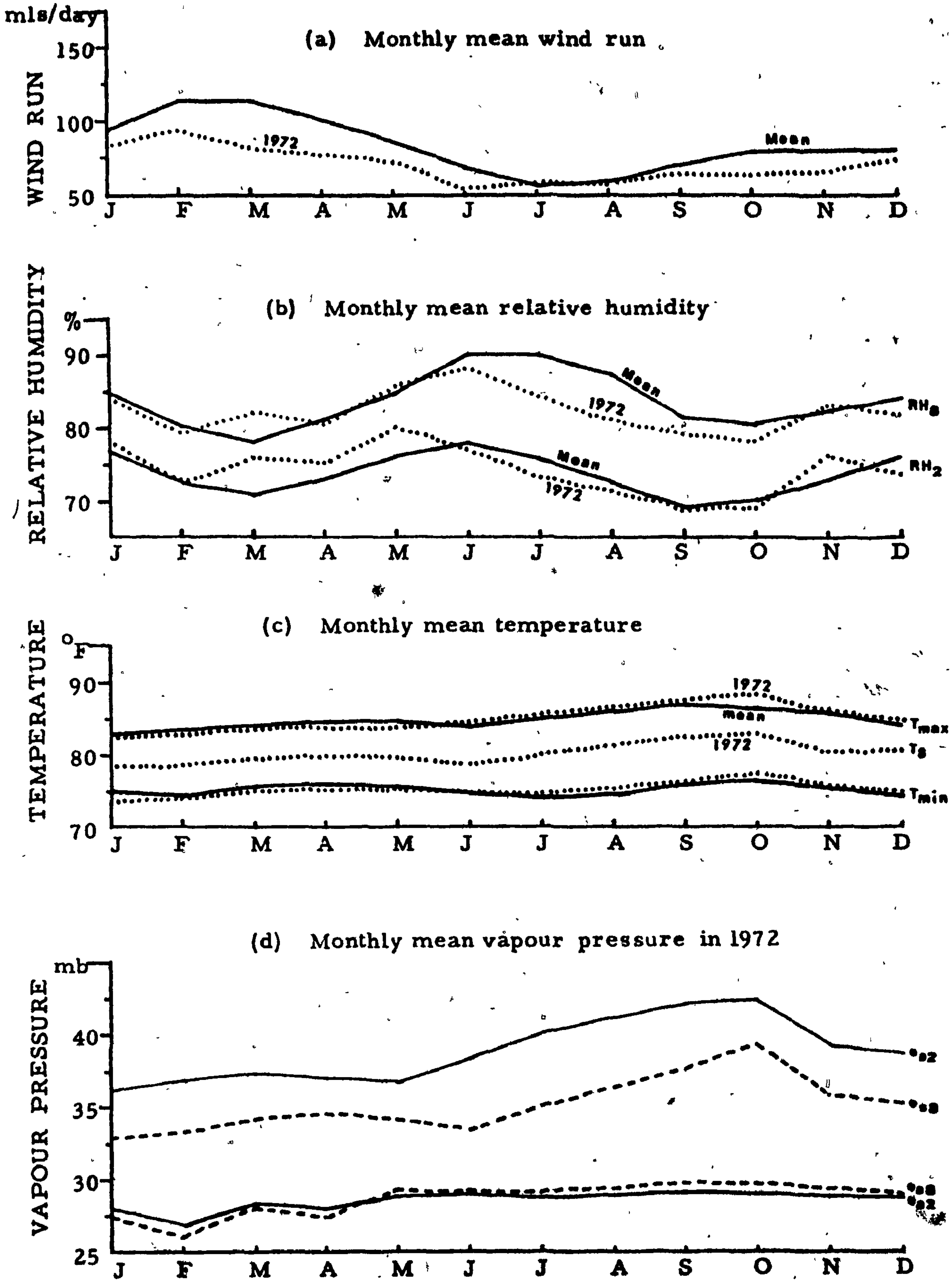


coinciding with the passage of tropical disturbances along the ITCZ. Between disturbances rainfall is low. Similarly, all other climatological parameters, even EP, show 5 to 6 day periodicities.

Bright Sunshine: Bright sunshine is a rough indicator of cloud cover and solar radiation; it is an important quantity in the semi-empirical evapotranspiration formula. 1972, with 2375 hours of bright sunshine, had slightly below average annual incoming radiation as seen in figure 3-3c. In figure 3-4c, the total monthly bright sunshine is plotted for two wet and two dry years. 1972 was rather peculiar, as bright sunshine in the earlier half was similar to that in wet years, but similar to dry years in the later part when the evapotranspiration experiment was carried out. Daily bright sunshine varies from 0-10 hours per day in the wet season resulting in large variations of EP, but less variations of sunshine (or EP) take place in the dry months.

Atmospheric Pressure: Atmospheric pressure has little effects on EP although it is highly related to the weather. Kohler (1955) used pressure as a measure of height for correcting pan evaporation. The mean annual sea-level pressure is 1013.2 mb. with a tendency for low annual pressure in wet years and high annual pressure in dry years - figure 3-4b. There is one cycle of annual pressure with high monthly mean values in the January-March period, when the Azore high moves near to the equator from its mean position, and lowest pressure in November when the ITCZ is just north of Guyana. Low monthly pressure rather occurs just before the onset of the wet seasons. On the other hand, low daily pressure occurs on wet days.

Fig. 3-5 Monthly mean wind run, relative humidity, temperature, and vapour pressure at the Botanic Gardens. The 1972 data are denoted by dotted lines.



Wind Run: Wind run to a large extent determines the contribution of the aerodynamic term in Penman's equation. But due to scattered trees at the Botanic Gardens, the measured wind run may not be representative. Monthly mean wind run, in figure 3-5a, has one cycle per annum like the monthly pressure; and it varies between 110 miles per day in March to 55 miles in July. The rate of removal of water vapour from the surface can be extremely large in the first dry season.

The land and sea breeze phenomena along the coastland are markedly noticeable. Daily wind run fluctuates considerably in the wet season, reaching 100 miles per day on dry days and decreasing to 20 miles per day on wet days. Daytime wind direction varies from 5-10^{O}E of N throughout the year; or daytime wind always blow from the sea. It is therefore a humid sea breeze and the aerodynamic term produces only a small contribution to EP.

Temperature: The daily mean dry bulb temperature at 2 metres is used to find the slope of the saturation vapour pressure curve in Penman's equation. Figure 3-5c shows the small seasonal variation in temperature which is typical of a tropical climate reinforced by maritime influences. With the exception of October, the temperature of 1972 was average. The diurnal range of temperature was 10-12 ^{O}F, much greater than the seasonal range. 8a.m. dry bulb temperature approximately equals the mean daily temperature, on a monthly basis, but daily values depend on the 8 a.m. cloud conditions.

Relative Humidity: The 8 a.m. relative humidity is often treated as the daily mean value and can be used to estimate the daily mean vapour pressure at coastal stations. Unlike pressure and wind, two cycles of relative humidity are observed in figure 3-5b, indicating that it is influenced by rainfall. In the wet seasons, 8 a.m. relative humidity above 97 percent are rare indicating the absence of fogs.

The coastland with daytime sea breeze experiences the highest daytime relative humidity (2 p.m.) in Guyana, being only 10-14 percent lower than 8 a.m. values. The drier atmospheric conditions during the June-August period of 1972 was very noticeable.

Vapour Pressure: Relative humidity does not give the drying power of the air, but the vapour pressure deficit does. The saturation vapour pressure (e_s), entirely a function of temperature, is about 32-40 mb. at 8 a.m. and approximately 4-5 mb. higher at 2 p.m: see figure 3-5d.

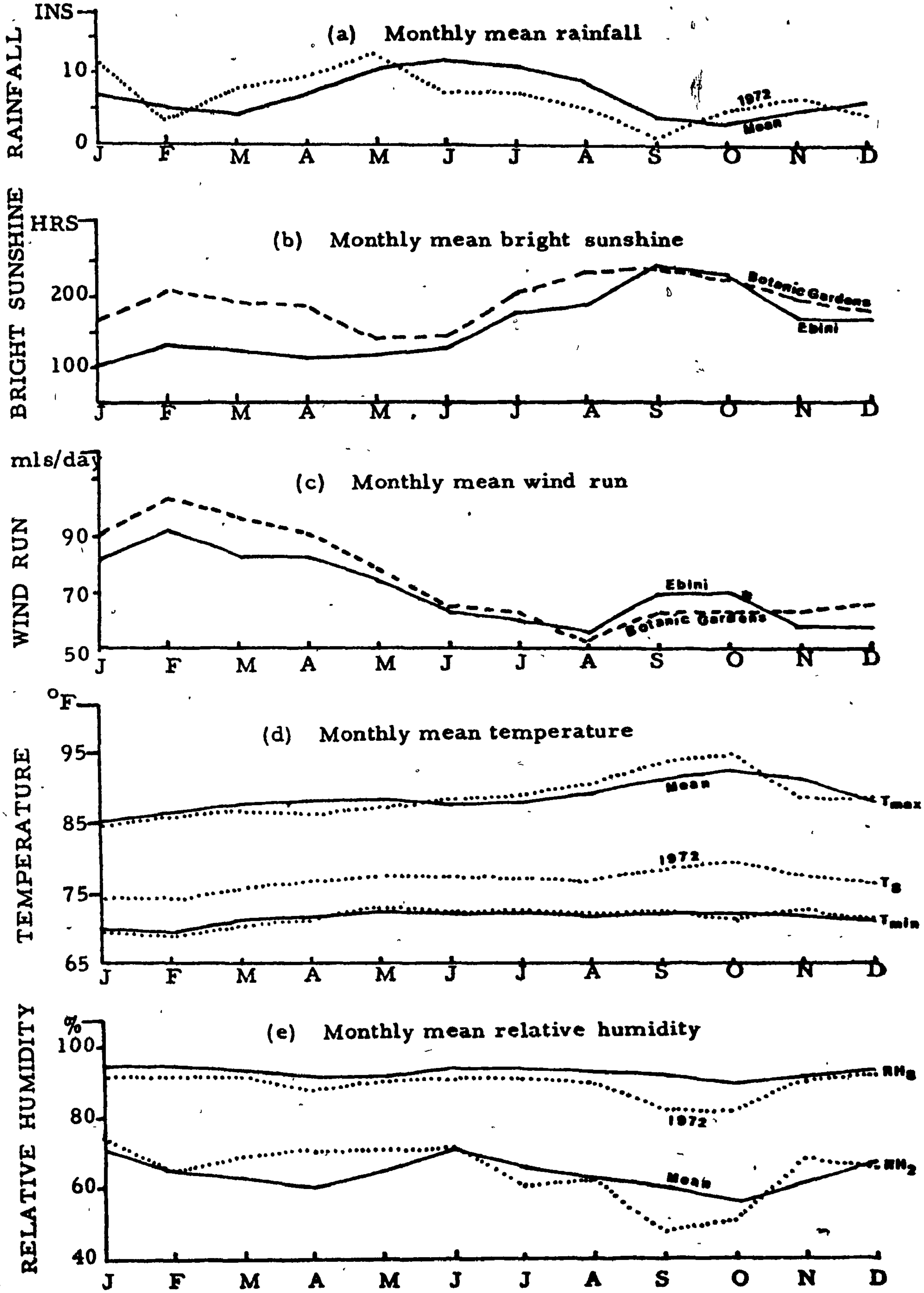
The actual vapour pressure (e_a), unlike relative humidity, exhibits one annual cycle with lowest values in January to April. It is surprising that the moisture content in the lower atmosphere is the same in June and October. There is also little diurnal variations of vapour pressure as the moisture content does not vary with temperature. Nevertheless, by 2 p.m. monthly mean vapour pressure increases by 0.3 mb. in the first dry season, due to high actual evapotranspiration, and decreases by 0.5 mb. in the second dry season due to low actual evapotranspiration.

The vapour pressure deficit is the difference of e_s and e_a as shown in figure 3-5d which is self-explanatory.

3.4 The Forest Climate

The forest climate, shown in figure 3-2c, stretches over the greater part of Guyana; numerous rivers that originate in the mountains traverse the forest region.

Fig. 3-6 Monthly mean rainfall, bright sunshine, wind run, temperature, and relative humidity at Ebini.



Ebini: Ebini, 60 miles from the Atlantic Ocean, was chosen for evapotranspiration experiments in the forest climate. The station, also a dairy and agricultural research station, is spacious and well equipped. There is a pit gauge and in July 1972 two evapotranspirometers and an actinograph were installed. The grass at the site is, however, affected by disease causing partial drying of the leaves and this may affect evapotranspiration.

Rainfall: The annual mean rainfall is 86 inches, fourteen inches less than Botanic Gardens, and shows the same 45-year and 4-year periodicities. With less rainfall, floods pose less problems at Ebini.

There are two wet seasons and two dry seasons, but the second wet season receives less rainfall than the Botanic Gardens. The close similarity in monthly and daily rainfall suggests that rainfall is due to synoptic scale disturbances. Each disturbance deposits heavy rainfall (> 1.0 inch) for one or two days and low rainfall (1-0.2 inch) for several days at Botanic Gardens; but Ebini receives moderate rainfall for several days while heavy rainfall is rare. While Ebini has about 4 days per annum with rainfall above 2.0 inches, Botanic Gardens has about 9 days and this accounts for its higher annual rainfall of 14.0 inches. In some dry years, when heavy rainfall above 2.0 inches are absent, Ebini may receive more annual rainfall as in 1957 to 1963 (see figure 3-3a). Figure 3-6a shows that the latter part of 1972 was drier than average.

Bright Sunshine: There are less hours of bright sunshine at Ebini than at the Botanic Gardens, especially in the early part of the year as shown in figure 3-6b. Why more cloud cover but less rainfall at Ebini? Daytime heating over the forest region causes the development of a local thermal low pressure area, favouring low cumulus clouds. Perhaps less radiation reaches the surface at Ebini so causing, perhaps, a lower EP.

Wind Run: Wind run is 7 miles per day less at Ebini than at the Botanic Gardens and is partially due to the absence of winds at night, which is a necessary condition for fog formation.

Temperature: Annual mean minimum temperature is 71.0 °F or 5.0 °F lower than at Botanic Gardens. In spite of the small monthly changes, large day-to-day variations take place depending on the night-time cloud cover. However, the minimum temperature and the night-time climate seem to have little relationship with the daytime climate. February has the lowest monthly mean minimum temperature, sometimes dropping to 66 °F on cloudless nights. The low nightly temperatures, with the resulting fogs, signify a net longwave radiation balance and this has been confirmed by measurements.

An annual mean maximum temperature of 89 °F gives rise to the already mentioned daytime thermal low, causing increased convection and much low clouds. January has lowest mean maximum temperature of 85 °F, while October records 93.5 °F. Air temperature at 2 metres rarely rises above 100.0 °F. The diurnal range of temperature is 16-20 °F, compared to 10-12 °F at Botanic Gardens, and indicates little maritime influence. In 1972, maximum temperature was 2 °F above average in the second dry season. Figure 3-6d shows that the 8 a.m. temperature, being near to the minimum temperature, cannot be used as the daily mean temperature.

Relative Humidity: Mean 8 a.m. relative humidity is usually above 90 percent, as shown in figure 3-6e; morning fogs are regular phenomena in both wet and dry seasons. Night-time cooling produces low temperature, a high pressure cell, little wind, no maritime heating, and a peculiar night-time climate over the forest region. Consequently, the aerodynamic sink strength for water vapour must be negligible at nights.

From a near saturation point at 8 a.m., relative humidity drops to 65 percent by 2 p.m., a direct result of high daytime temperature and a reduced maritime effect. The diurnal range of more than 27 percent far exceeds the seasonal range. In 1972, extremely dry air prevailed from September to October.

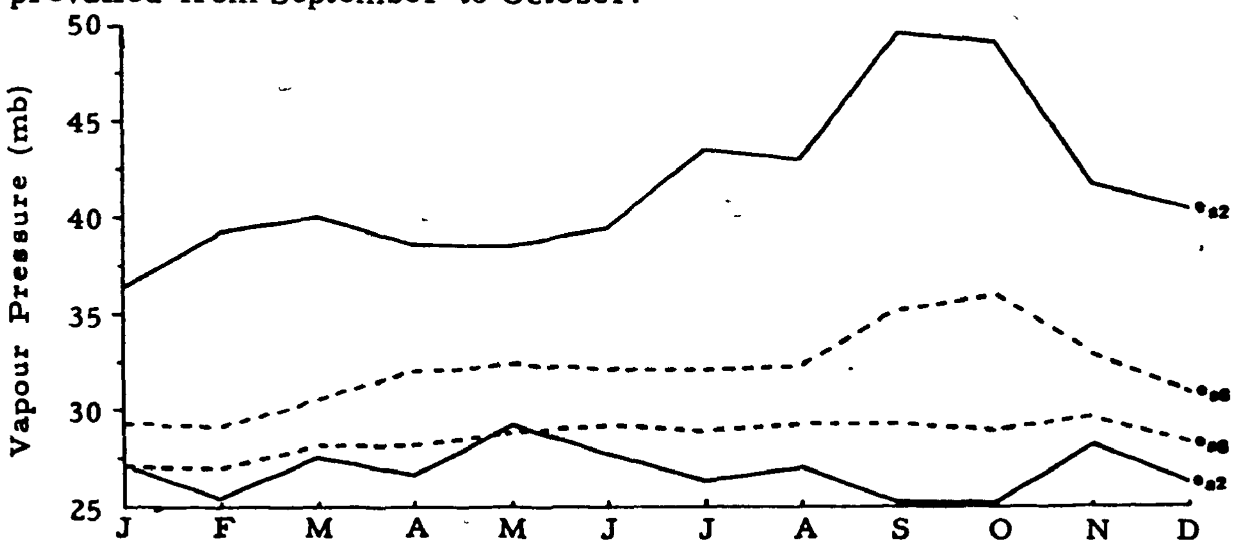
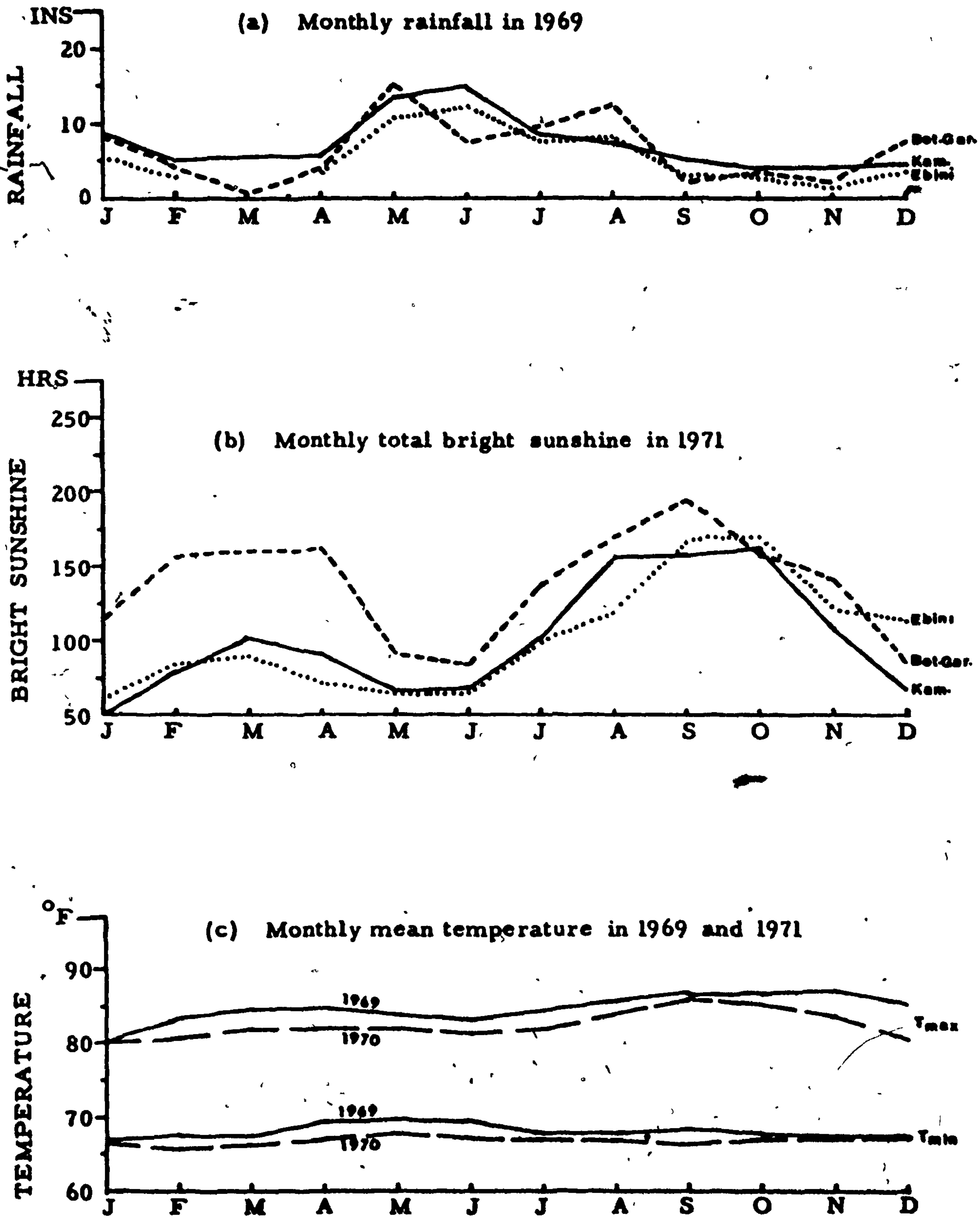


Fig. 3-7 Monthly Mean Vapour Pressure at Ebini in 1972.

Vapour Pressure: Figure 3-7 shows the saturation vapour pressure at 8 a.m. and 2 p.m., es8 and es2, and the actual vapour pressure, ea8 and ea2, in 1972.

The vapour pressure deficit at 8 a.m. varies from 2 to 7 millibars. The very high saturation vapour pressure at 2 p.m. is naturally a result of high temperature; however, the actual vapour pressure only

Fig. 3-8 Monthly rainfall, bright sunshine, mean temperature at Kamarang (——), Ebini (·······), and Botanic Gardens (– – –).



drops slightly from its 8 a.m. values. Consequently, the vapour pressure deficit is 8-25 millibars at 2 p.m. With an average daytime value of about 5-15 mb, the aerodynamic term should be the same as at Botanic Gardens.

Kamarang: The forest climate stretches over a wide range of topography. Therefore the climate of Kamarang will be examined to show the similarity in climate at two vastly different places, both within the forest region.

	Kamarang	Ebini
1.	190 miles from Atlantic	60 miles from Atlantic
2.	Forests	Forests and savannahs
3.	Mountainous landscape	Hilly landscape
4.	Rocky soil	Sandy soil
5.	1,200 feet above sea level	100 feet above sea level

The climatological station at Kamarang lies on the upper Mazaruni River valley within the Pakaraima Mountains. Forest covered mountains rise on both sides of Kamarang while Mt. Roraima, 9094 feet, lies 50 miles to the South. Only two years of climatological data are available.

The northern slope of the Pakaraima mountains record the highest rainfall in Guyana (Potter, 1970) of 140 inches. But in 1969, Kamarang received 83.36 inches. Figure 3-8a displays the large monthly variability of rainfall at Botanic Gardens in contrast to the smooth seasonal change at Kamarang and Ebini. The table below shows that Kamarang's rainfall, like Ebini's, occurs primarily on moderate rainy days (0.2-1.0 inch) in contrast to that at Botanic Gardens. Rainfall above 2.0 inches is unknown at Kamarang.

Range (ins)	.01	.01-.09	.10-.19	.20-.49	.50-.99	1.00-1.99	2.00
Botanic Gardens	184	56	34	51	14	22	6
Kamarang	126	72	38	67	42	16	0

Bright Sunshine: In figure 3-6b it is shown that Ebini records less bright sunshine than Botanic Gardens while figure 3-8b also verifies that lower sunshine is common to all stations throughout the forest region. The very close similarity between Ebini and Kamarang is striking.

Temperature: Figure 3-8c shows that Kamarang has lower maximum and minimum temperatures than Ebini, but this is a direct result of Kamarang's higher elevation. However, the seasonal variation and diurnal variation (16 ^{o}F) are very much greater than at Botanic Gardens.

In conclusion, rainfall, sunshine or cloud cover, and temperature characteristics bear much similarity throughout the forest region, in spite of topographical variations. It can be assumed that evapotranspiration results based on field work at Ebini should be representative of the whole forest region.

3.5 Savannah Climate

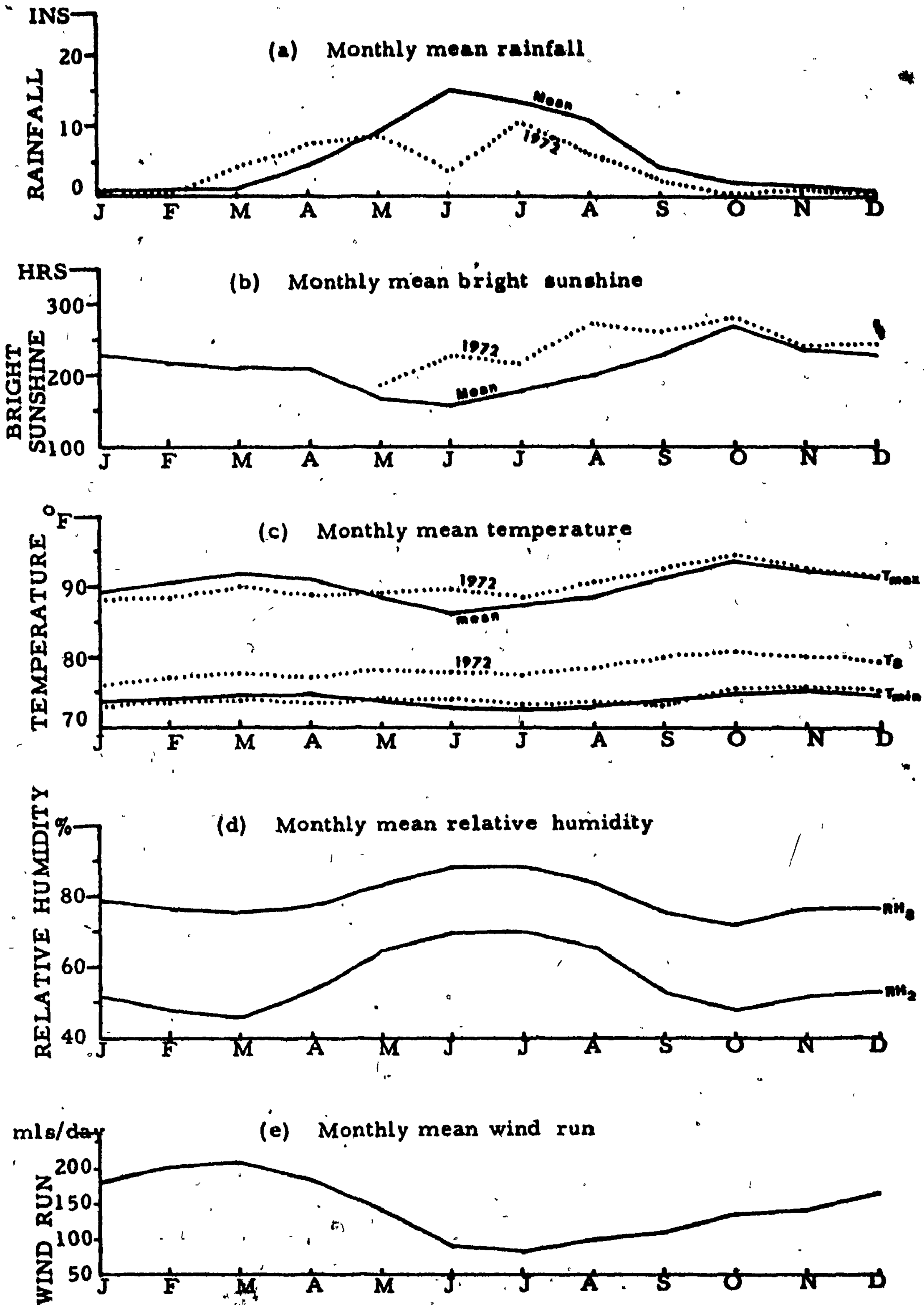
The Rupununi Savannah has received considerable attention by the McGill Savannah Research Group and some notable research, in the form of graduate theses, have been produced: Waddel (1963), Eden (1964), Frost (1966) and Atwoki (1968). Frost and Atwoki have thoroughly investigated the savannah climate. Although much use is made of their research in the present study, attention is particularly given to the climatic differences between the savannah and other climatic regions of Guyana as far as the effects on evapotranspiration are concerned.

Geography: The Rupununi Savannahs, lying in the south-east of the country, adjoins the Rio-Branco savannahs of Brazil. The Pakaraima Mountains lie to the north while the forest covered Kanuku mountains run east-west across the Rupununi savannahs. Although 500 feet above mean sea level, natural drainage is inadequate because of the very fine sandy soil that hardens to an impermeable layer after long exposure both to sun and rain. Numerous wet season swamps appear in the low valleys. Vegetation consists of tall tough grasses with scattered trees in some places and riverine bushes along the creeks and rivers. The cultural landscape is dotted with a few Amerindian settlements of 100-200 people. St. Ignatius, 8 miles north of the Kanuku Mountains, is very representative of the savannah climate (Atwoki, 1968). Two evapotranspirometers and an actinograph were installed in July 1972.

Rainfall: The Rupununi Savannahs comprise the driest region of Guyana, and St. Ignatius has a long term average of 62.7 inches per year. Unlike other regions, there is only one wet season, April - August, that records nearly 75 percent of the annual precipitation. EP conditions are only satisfied for 5 months in the year.

The rest of the year is one long dry season, or drought, lasting 7-8 months as the second wet season, that occurs in other parts of Guyana, is totally absent as seen in figure 3-9a. From November-May, the average monthly precipitation is 1.0 inches. It is obvious that forests cannot survive the long dry season as the minimum plant-water requirements cannot be satisfied.

Fig. 3-9 Monthly rainfall, bright sunshine, temperature, relative humidity, and wind run at St. Ignatius.



Although most precipitation is received from large cumulonimbus clouds that seem to originate from the Kanuku Mountains (Atwoki, 1968), the development of these clouds are associated with synoptic scale disturbances of the ITCZ as it usually rains at St. Ignatius about 12 hours after raining at Ebini. Wet season rainfall occurs at pre-morning hours, but dry season rainfall at late afternoon hours. In 1972, twelve major storms accounted for about 50 percent of annual rainfall. Figure 3-9a shows the very low rainfall throughout 1972, especially in June when a couple of intense disturbances missed the station.

There is much controversy about the absence of the second wet season, which prevents the survival of forests. Frost (1966) attributes this to the rainshadow effects of the Pakaraima Mountains while Atwoki (1968) believes that the Venezuela High pressure system produces stable and subsident atmosphere in December. However, an inspection of photographs from ESSA 1970 reveal large cloud clusters entering the Rupununi Savannahs every 4-5 days during the first wet season, producing heavy rainfall over the Savannah , and every 8-10 days during the second wet season producing no rainfall over the Savannah . The absence of rain during the latter period cannot be explained, and further research is recommended at all levels of the atmosphere. The possibility of successful cloud seeding experiments in December, just in the middle of the long dry season, is high.

Bright Sunshine: Bright Sunshine is 150 hours in July and 270 hours in October, i.e., 20 hours less and 30 hours more than Botanic Gardens, respectively. From this it can be deduced that there are larger cloud formations over the savannahs than over the coastland during the wet season and less cloud formations during the dry season.

The decrease in bright sunshine hours during December coincides with the passage of the above mentioned disturbances that produce no rainfall. The large seasonal variation of sunshine hours should cause a large seasonal variation of EP; but radiation is not the predominant contributor to EP over the savannahs. Bright sunshine in 1972 was far above average.

Wind Run: St. Ignatius records nearly twice as much daily wind run as Botanic Gardens or Ebini, but this is attributed to the absence of obstructions far around the site and the wind acceleration between the Pakaraima and Kanuku mountains. The daily mean value is 140 miles per day but reaches 210 miles per day at the end of the dry season. Wind direction is east-north-east, somewhat parallel to the alignment of the Kanuku Mountains. The strong dry winds over the savannahs have tremendous effects on EP during the dry season.

Temperature: A mean minimum temperature of 73.8°F at St. Ignatius is 1.2°F lower than Botanic Gardens but 2.3°F higher than Ebini. The forest region is definitely the coldest part of Guyana at nights, and the nighttime high pressure is centered over the forest region but does not extend over the savannahs.

With an average maximum temperature of 90.0°F, the Rupununi is the hottest region of Guyana. The dry season is especially hot; particularly October when temperature very often reaches 97°F but never exceeded 100°F. Absence of forest vegetation, distance from the sea, and low dry season rainfall account for such high temperatures. Seasonal variation is 8°F, but the diurnal variation of 14-18°F is larger. Temperature at 8 a.m. does not represent the daily mean value.

Relative Humidity: The savannahs naturally form the driest area in Guyana, with mean annual 8 a.m. relative humidity of 79 percent - figure 3-9d. Fogs occur only in some mornings during the wet season. From 8 a.m. to 2 p.m., relative humidity decreases by 17-26 percent, or nearly twice the diurnal range at Botanic Gardens. An increase in humidity is observed in December, in spite of the absence of rainfall.

Vapour Pressure: Saturation vapour pressure at 8 a.m. varies between 31 to 37 millibars while the actual vapour pressure is 25-27 mb. Vapour pressure deficit is 6-10 mb. at 8 a.m. Because of high daytime temperature at 2 p.m. saturation vapour pressure is then 40-50 mb but actual vapour pressure is 25-24 mb, slightly less than 8 a.m. values; a large vapour pressure deficit of 15-25 mb is produced. Daily mean deficit, being about 11-18 mb, is somewhat greater than in other parts of the country.

3.6 Conclusions

Maritime climatic influences are strong at the Botanic Gardens, with sea breeze by day and calm land breeze at night. Diurnal temperature variations are not large; humid conditions prevail throughout the year, but fogs are rare. The aerodynamic contribution to EP must remain small. Heavy daily rainfalls ($>$ 2.0 inches) are frequent, resulting in disastrous floods. With rainfall occuring in the pre-8 a.m. hours, clear sky conditions develop and much incoming radiation reaches the surface. EP should be high regardless of the humid conditions.

A maritime influence is not noticed at Ebini which experiences a peculiar nighttime climate of low temperature, with regular pre-morning fogs, as a result of a thermal high pressure cell. By noon, high temperature and low relative humidity increase the aerodynamic term; but the average daily contribution is just the same as at Botanic Gardens. A daytime land low, with the resulting convective clouds, reduces incoming radiation and thus energy for evapotranspiration. In spite of geographical differences, the climate at Kamarang shows marked similarity to that at Ebini, and an evapotranspiration experiment at Ebini should be representative of the whole forest region.

Evapotranspiration measurements, inaugurated following the termination of the wet season at St. Ignatius, encountered very dry conditions. Winds of 100-200 miles per day, in conjunction with large vapour pressure deficit, should cause extremely high aerodynamic contribution to EP.

The period July 1972-February 1973, when the evapotranspiration measurements were taken, is found to have been drier than average, but it is sufficiently long for a representative evapotranspiration study.

CHAPTER FOUR

METHODS OF MEASURING AND EVALUATING POTENTIAL EVAPOTRANSPIRATION IN GUYANA

Having decided on the methods of measuring and evaluating EP and on the most suitable site for each region, as described in the two previous chapters, the necessary instruments were installed in July 1972. Two evapotranspirometers were installed at each site to provide measurements of EP, and an actinograph was used to provide several months of continuous record of incoming shortwave radiation. Net radiation, incoming shortwave radiation, and reflected shortwave radiation were also measured, using a portable net radiometer and two solarimeters. The 15 day data from the latter were used to calibrate the actinographs, to measure surface albedo, and to establish a linear regression between incoming shortwave radiation and net radiation.

4.1 Instrumentation and Data

Climatological: For the analysis of the climate of Guyana all available data from each site were used, but the data of 1972 were found most useful as readings were then taken twice per day, at 8 a.m. and 2 p.m. Climatological instruments, installed and operated by the Hydrometeorological Service, included: 10-inch raingauge at standard height, mercury barometer, U.S.W.B. class A pan, pan anemometer, maximum and minimum thermometers, dry and wet bulb thermometers, thermohydrograph, grass minimum thermometer, soil thermometers at 4 inches and 12 inches, sunshine recorder, anemometer at 2 metres, and an anemograph at 70 feet. Readings from most of the above instruments are indispensable for estimating EP.

Fig. 4-1 The Evapotranspirometer (Garnier, 1952)

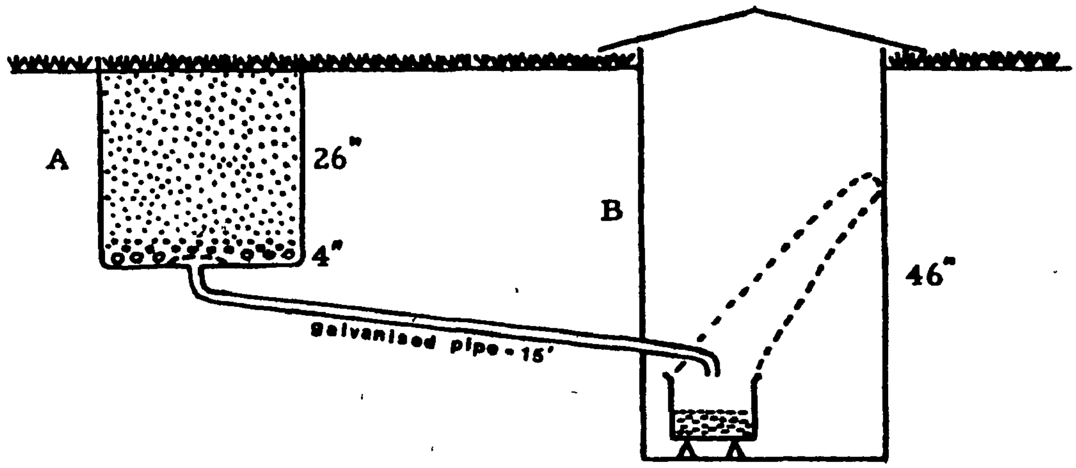
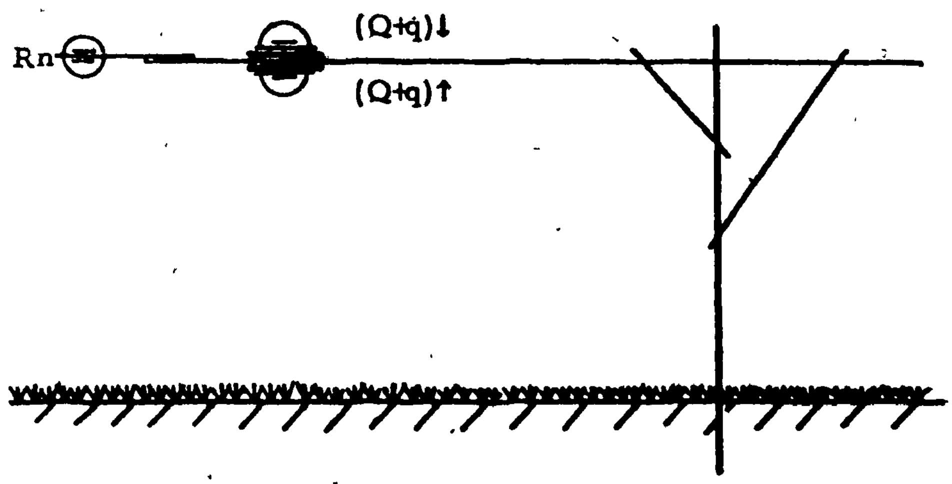


Fig. 4-2 The Net Radiometer and Solarimeters' Stand



Evapotranspirometer: The evapotranspirometer or drainage lysimeter (standard Thornthwaite type) was made from two steel drums (standard oil drums) and other easily available materials. A strip of about 10 inches of drum A was removed and welded thoroughly to the other drum, B. A 3/4-inch diameter hole was made at the bottom of drum A and the two drums connected by a 15 feet long galvanised pipe, as illustrated in figure 4-1. Both drums were then placed in the ground, leaving the rims 2 inches above the surface in order to prevent water from the surroundings from draining into the evapotranspirometer during heavy rainfalls. At the bottom of drum A was placed an aluminum filter directly over the hole, and a layer of graded stones 4 inches deep. Brown sand filled the rest of the tank to the level of the ground, and grass was planted at the surface.

Every afternoon at 5 p. m. an amount of water corresponding to 0. 5 inch of rainfall was poured over the grass to maintain the soil at field capacity. Twenty four hours later, the drainage into a collecting can inside tank B was measured and later reused for watering the evapotranspirometer to maintain the fertility of the soil. It was not practical to measure runoff at 8 a.m., as suggested by Garnier (1952), because rainfall generally occurred during pre-morning hours. Only two evapotranspirometers were installed at each site, although Garnier recommended three, because of simple problems that arose in welding and constructing the instruments at three different sites over a limited time. However, the two sets of EP measurements were quite comparable, as special care was taken to use similar soil and grass concentration.

The evapotranspirometers basically require little maintenance but, unless special care is taken, the measurements like many other evaporation measurements may become unrepresentative. Periodic clipping of the grass was necessary to maintain a height even with the surroundings. To reduce the "oasis effect", Thornthwaite (1955) recommended watering the surrounding grass to a radius of 40 metres, but only five feet was practical in Guyana. This was unnecessary at the Botanic Gardens since watering is done throughout the year, making it an ideal evapotranspiration site. One month was allowed for the soil to settle in the tank.

Radiation Instruments: A portable Thornthwaite hand-held net radiometer was used for net radiation. The instrument, consisting of an upper and lower thermopile, generates a small voltage that deflects a millivoltmeter calibrated directly into cal/cm^2, min and having maximum deflection of $\pm$ 2 cal/cm^2, min. No calibration was done except a periodic adjustment to zero by placing the sensor in a dark room with radiative equilibrium.

Two Lintronic Dome Solarimeters, one upward and one downward, were used to measure incoming shortwave and reflected shortwave radiation. Calibration was done in May 1972 at Shefferville, Quebec, when the instruments were used simultaneously with 2 Eppley Black and White Pyranometers. With no electrical recorder available in Guyana, readings were taken manually over a period of 15 days using a millivoltmeter (Comark, type 1221, Ser. No. 14104). Readings were taken every 5 minutes by day and every 15 minutes by night since there were rapid fluctuations of radiation caused by the convective nature of tropical clouds. Good comparison was noticed between manual readings and actinograph charts as the cumulus clouds usually take more than 5 minutes to pass across the sun. As this observational programme was an extremely monotonous and continuous 15 day undertaking, the Hydrometeorological Service provided three assistants.

The radiation stand for the three instruments, shown in figure 4-2, consisted of an aluminum pipe rigidly sunk in the ground and a horizontal pipe attached to it. The net radiometer and solarimeters were screwed on to wooden supports of the horizontal pipe and periodically levelled in the horizontal plane. A dark string tied to the horizontal pipe prevented swinging of the stand. Before sunrise, it was necessary to remove moths' eggs from the lower surface and condensation from the upper surface, for the instruments were not ventilated.

Measurements from the above radiation instruments were taken at each site for 15 days. At other times during the period July 1972-February 1973, three actinographs measured incoming solar radiation.

Data Obtained: For a representative study of evapotranspiration, at least six months of data are required, considering that this period should cover one dry season and one wet season in Guyana. For each site, data include:

a) Climatological -1.1.72 to 28.2.73

b) Evapotranspirometer -1.7.72 to 28.2.73

c) Solar radiation by actinograph -1.7.72 to 28.2.73

d) Net radiation and solar radiation -15 days at each site

The complete set of these data was unfortunately difficult to obtain to the degree of detail wished. The evapotranspirometers overflowed on days with heavy rainfall; at Ebini, the new observer intuitively applied excess fertilizer and killed the grass within the evapotranspirometers. However, the remainder of this thesis is based on these data.

4.2 Methods of Analysis of Climatological Data

Rainfall at ground level: Two raingauges, a 5 inch raingauge at two feet and a pit gauge at ground level, were installed at Ebini by the Hydrometeorological Service. Splashing of droplets into the pit gauge was prevented by a cubical mesh, one metre square. Measurements indicate that the standard raingauge underestimates rainfall by about 5 percent as shown in figure 4-3. Therefore, reported daily rainfall, R_s, must be adjusted accordingly to obtain rainfall at the level of the evapotranspirometer R_o, and is given by

$$R_o = 1.05\ R_s \tag{4-1}$$

During rainfalls high winds with strong gusts occur while calm winds prevail after the passage of storms. Raindrops should approach the rim of the standard raingauge at some angle to the vertical, thus presenting a reduced collecting area for the descending rainfall. But with reduced wind and gusts near the surface, raindrops enter the pit gauge in a more vertical direction, and this accounts for its greater collection.

If A is the collecting area of each raingauge and the rainfall is assumed to reach the pit gauge from a vertical direction, then $A \cos \phi$ is the collecting area of the standard raingauge where ϕ is the angle from the vertical of the rainfall. Therefore $A/A \cos \phi = 1.00/0.95$ or $\cos \phi = 0.95$ giving $\phi = 18^{\circ}$. This is the mean maximum angle of the descending rainfall and, from the author's experience, is not unreasonable. It is possible that the Rupununi Savannahs, with twice

Fig. 4-3 Relationship between rainfall at standard height (R_s) and rainfall at ground level (R_o) at Ebini.

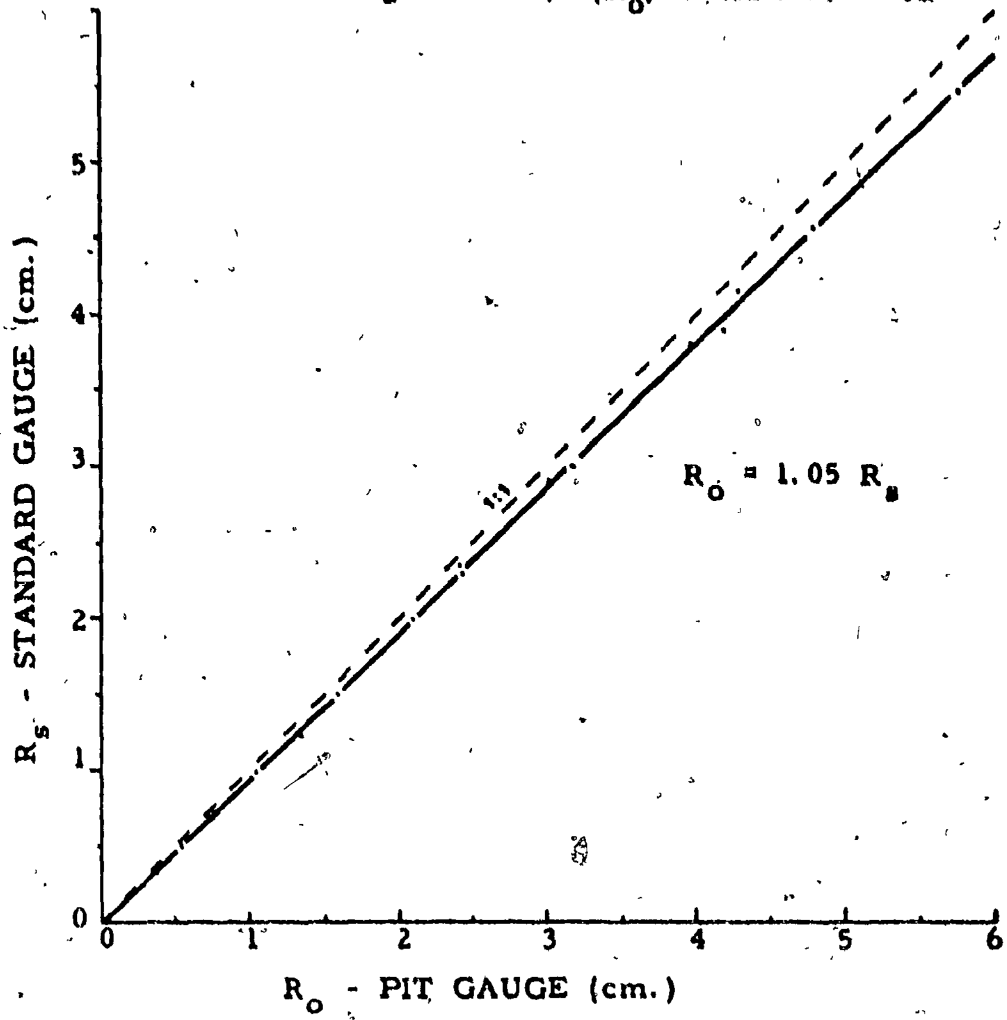
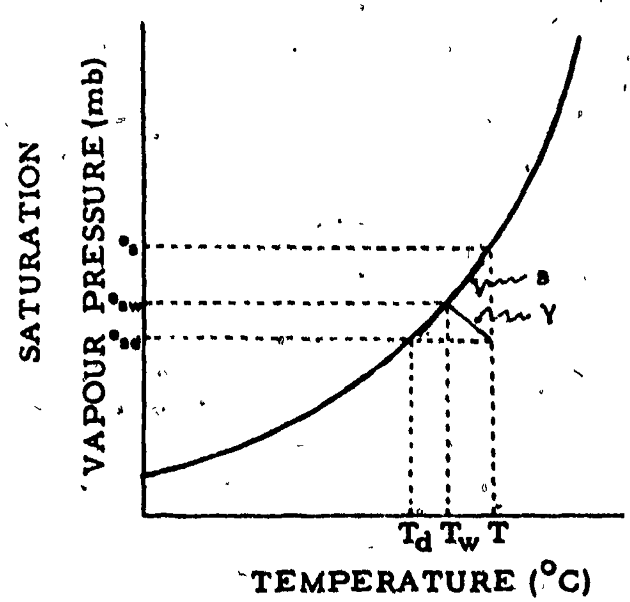


Fig. 4-4 Saturation vapour pressure vs temperature curve.



as much daily wind run as Ebini, actually receives a far higher rainfall than measured amounts.

Vapour Pressure: The saturation vapour pressure, in the pure phase over pure water, is entirely dependent on the temperature of the water at the surface and is given by the Goff-Gratch formula (List, 1968, p. 350). The slope of the saturation vapour pressure vs temperature curve, s, is obtained by differentiating the lengthy Goff-Gratch formula (List, 1968, p. 372). Both formulae are lengthy for accuracy but are quite simple to compute.

The psychrometric constant is given by

$$\gamma = -\frac{c_p p}{L\varepsilon} \tag{4-2}$$

where p is atmospheric pressure which has an average value of 1013.0 mb. in Guyana and only exhibits small daily and seasonal variations; c_p is the specific heat of dry air at constant pressure = 0.24 cal/gm, ^oK, $\varepsilon = 0.622$, and L is the latent heat of evaporation of water at wet bulb temperature given by

$$L = L_o + (c_{pv} - c_v)(T_w - T_o)$$

where L_o is the latent heat at 0^oC = 597.2 cal/gm; c_{pv} is the specific heat of water vapour at constant pressure = 0.456 cal/gm, ^oK; and c_v is the specific heat of water = 1.007 cal/gm, ^oK. Therefore

$$L = 597.2 - 0.551\,(T_w - 273.16) \tag{4-3}$$

To find the actual vapour pressure of the air, given the wet and dry bulb temperatures, consider figure 4-4 where the line with slope γ, passes through the points (T_w, e_{sw}) and (T, e_{sd}). Therefore, its equation is

$$-\gamma = \frac{e_{sd} - e_{sw}}{T - T_w}$$

or $e_{sd} = e_{sw} - \gamma (T - T_w)$ (4-4)

where e_{sd} and e_{sw} are the saturation vapour pressure at dew point and wet bulb temperature, respectively.

Daily mean temperature and vapour pressure: In the energy balance equation the required climatological data are best approximated by the mean of 24 hourly observations. But only two observations are available in Guyana. Outgoing longwave radiation and the slope, s, are both functions of mean daily temperature which can be approximated by

$$\overline{T} \approx 0.5 \ (T_{max} + T_{min}) \qquad (4\text{-}5)$$

Similarly, the mean daily relative humidity can be approximated by $\overline{RH} \approx 0.5 \ (RH_{max} + RH_{min})$. Thermohydrograph charts show that $RH_8 < RHmax < 100$ and that $RHmin \approx RH_2$. Therefore $\overline{RH} > 0.5 \ (RH_8 + RH_2)$ and $\overline{RH} < 0.5 \ (100 + RH_2)$, so that the average of these two expressions should give the mean daily relative humidity. That is

$$\overline{RH} \approx 0.5 \ (RH_2 + \frac{RH_8 + 100}{2}) \qquad (4\text{-}6)$$

Since $RHmin \approx RH_2$, then the above means that $RHmax \approx \frac{RH_8 + 100}{2}$ which is not an unreasonable assumption. The mean error introduced is 4 percent and the equation is suited for the Botanic Gardens where relative humidity drops from 90 percent to 77-84 percent by 8 a.m., and for the interior stations where 8 a.m. relative humidity drops from 90 percent to 80 percent on clear mornings, or 98 to 92 percent on foggy mornings. Equation 4-6 is not suited for foggy nights, with

RH = 100 percent, that clear up by 8 a.m. when RH_8 = 84 percent, thus introducing 5 percent error. Such conditions are rare.

The mean daily relative humidity can then be used to give the mean daily vapour pressure

$$e_a = e_s \frac{RH}{100} \tag{4-7}$$

where e_s is the s.v.p. at T.

Wind Function: The wind function, f(u), is perhaps the most uncertain quantity in Penman's equation, for the dynamics of the boundary layer are not fully understood. Most formulae apply only to the stable boundary layer conditions under which they were derived. Penman (1948) suggested an empirical formula

$$f(u) = 0.35 \ (0.5 + \frac{u_2}{100}) \tag{4-8}$$

where u_2 is the wind at 2 metres in miles per day. Numerous unsuccessful attempts have been made to improve Penman's formula and Davies and McCaughey (1968), using Businger's equation, have suggested

$$f(u) = 1.2 \ u_2 \left(\frac{k}{\ln \frac{z + z_o}{z_o}} \right)^2 \tag{4-9}$$

which they found to be accurate for hourly periods. z is the anemometer height and z_o is the roughness length (cm), given by Tanner and Pelton (1960)

$$\log z_o = -1.385 + 1.417 \log h \tag{4-10}$$

where h is the roughness element (cms).

4.3 Evaluation of Net Radiation

Linear Regression between Rn and $(Q+q)\downarrow$: Net radiation is required in Penman's equation but, since measurements of Rn require the use of electrical recorders and electricity is not always available in remote places, other techniques are used to estimate Rn. One method, proposed by Shaw (1956) and Orvig (1961), makes use of a linear relationship between Rn and $(Q+q)\downarrow$. From the radiation balance equation

$$Rn = (1 - \alpha)(Q+q)\downarrow - Rnl \quad (4\text{-}11)$$

Monteith and Szeicz (1961), assuming an approximate relationship between Rn and $(1 - \alpha)(Q+q)\downarrow$, showed that

$$Rn = \frac{1 - \alpha}{1 + \beta}(Q+q)\downarrow + a \quad (4\text{-}12)$$

where $\beta = -\frac{d(Rnl)}{d(Rn)}$ is a surface "heating coefficient". Stanhill et al (1966) found the definition of β rather misleading, while Davies and Buttimor (1969) concluded that "a knowledge of the albedo and the heating coefficient is not essential to the task of predicting net radiation from solar radiation." In other words,

$$Rn = a(Q+q)\downarrow + b \quad (4\text{-}13)$$

where a and b are regression coefficients. Using hourly data, Ekern (1965) and Linacre (1968) tested equation 4-13; while Davies (1966, 1967), using radiation data from 14 stations over the world, found little difference between the different regression constants in spite of the large differences in climate and surface cover. Polvarapu (1970) used equation 4-13 to estimate Rn from $(Q+q)\downarrow$ to within $\pm$ 10 percent of measured values. Holmes and Watson (1967) observed a 10 percent difference in Rn from two instruments exposed side by side. Therefore, the use of equation 4-13 to estimate Rn produces errors of the same order of magnitude as measured values.

In equation 4-11, $Rn = f(\alpha, (Q+q)\downarrow, Rnl)$. Mean five day albedo values in table 4-1 show little variations with time and place in Guyana and can be treated as constant. Therefore, $Rn = f((Q+q)\downarrow, Rnl))$. With small seasonal variations of temperature, Rnl should not have large seasonal variations. Table 4-1 shows the 5 day mean measurements of Rnl which, if considered as one record by ignoring the different sites, has a mean value of 87 ly./day with a standard deviation of 14 ly./day. Treating Rnl as a constant makes $Rn = f((Q+q)\downarrow)$, with Rnl introducing a mean error of 14 ly./day or about 4.3 percent of Rn. However, if $Rnl = f((Q+q)\downarrow)$, as showed by Davies and Buttimore (1969) and also noticed in Guyana, then the error is less than 4.8 percent while Rn is statistically a function of $(Q+q)\downarrow$. This linear relationship should estimate 5 day mean Rn to within $\pm$ 5 percent in Guyana, provided $(Q+q)\downarrow$ is known precisely.

Net radiation is plotted against incoming short wave radiation in figure 4-5a using 15 days data from the Botanic Gardens. The computed linear regression, by the method of least squares, is

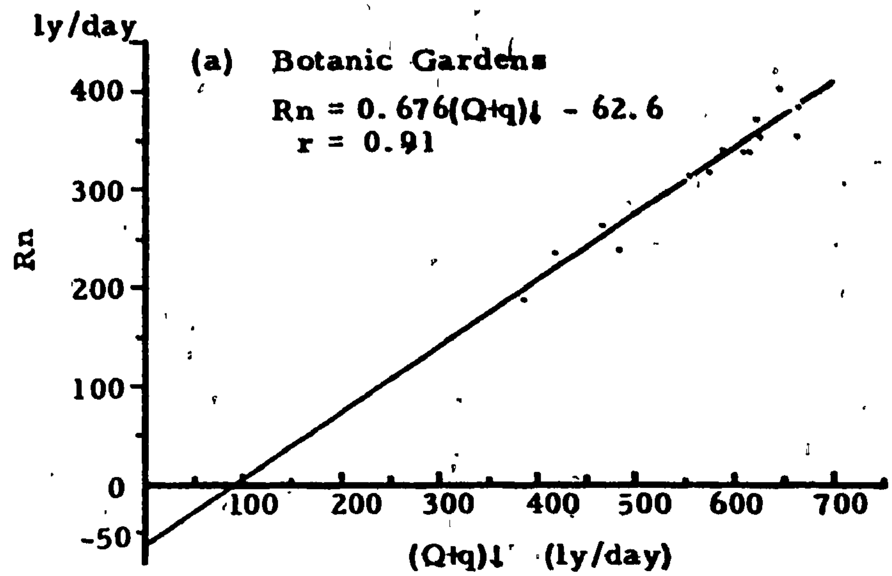
$$Rn = 0.676\ (Q+q)\downarrow - 62.6 \qquad (4\text{-}14)$$

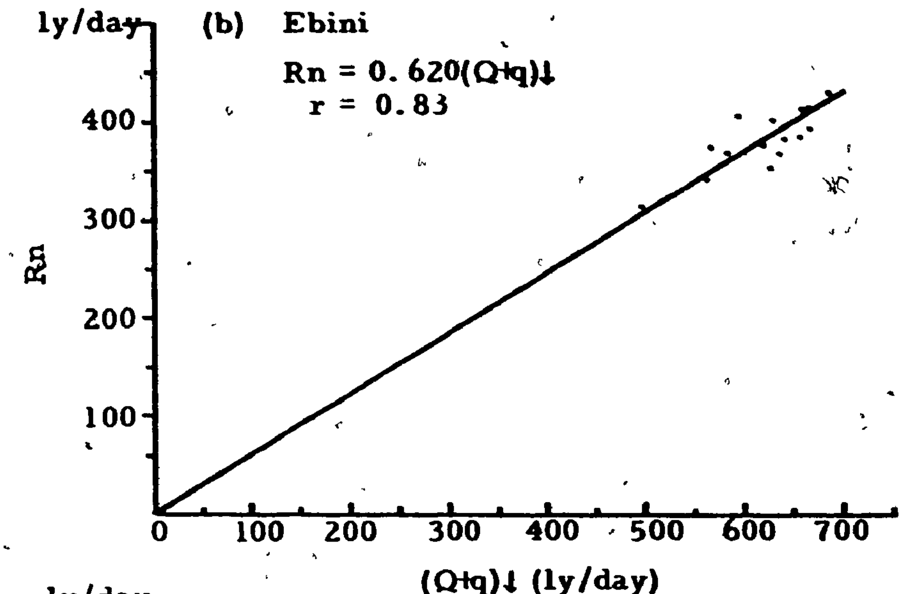
with a high positive correlation of 0.91. For zero incoming shortwave radiation, equation 4-14 gives a net radiation of -62.6 ly./day at the surface, and this is approximately twice the net radiation at night. When $(Q+q)\downarrow$ is less than 94 ly./day, as recorded on a few days during 1972, Rn is negative and consequently EP, which could be negative, must be regarded as zero. Such days usually record continuous precipitation.

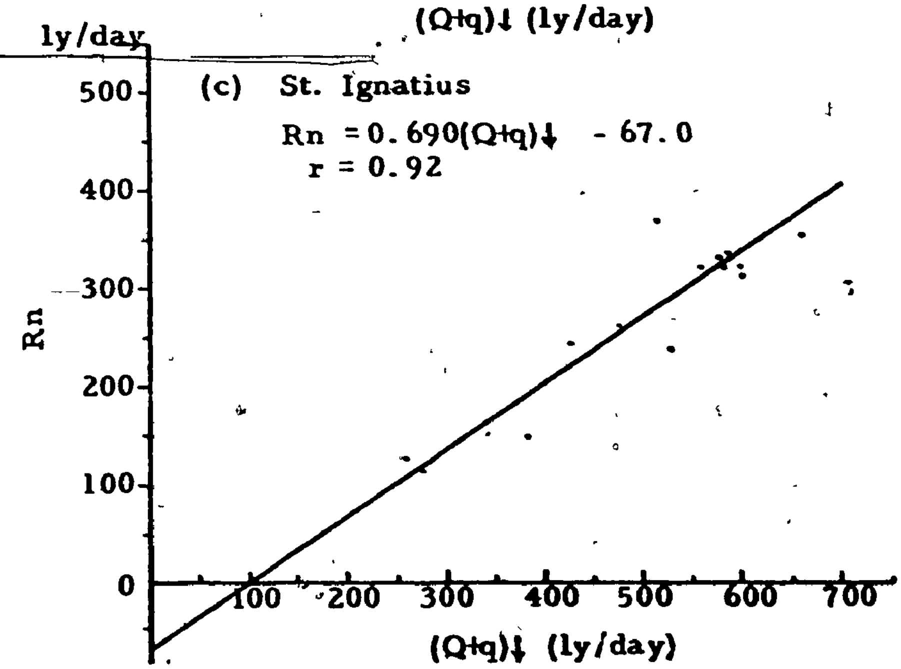
Table 4-1 Five-day mean albedo and five-day mean net longwave radiation at the Botanic Gardens, Ebini, and St. Ignatius.

Station	Month	Date	Season	Rnl (ly/day)	Albedo
Botanic Gardens	August	17-21	Wet	98	27
		22-26		88	28
		27-31		76	29
Ebini	September	6-10	Intermediate	98	26
		11-15		56	27
		16-20		72	26
St. Ignatius	October-November	28-1	Dry	103	27
		2-6		82	25
		6-10		108	26

Fig. 4-5 Rn as a function of (Q+q)↓







A similar analysis for Ebini, figure 4-5b, gives

$$Rn = 0.620\ (Q+q)\downarrow \qquad (4\text{-}15)$$

with a positive correlation of 0.83. A higher correlation would have been obtained if a wider range of daily radiation had been encountered over the 15 day experiment at Ebini, but only sunny days occurred. The above equation means that $Rn = 0.0$ for $(Q+q)\downarrow = 0.0$, quite unlike the situation at Botanic Gardens. On such unusual days with very high cloud cover, $Rn \rightarrow 0.0$ during the day and $Rn \approx 0.0$ during the night, as a result of fog.

At St. Ignatius

$$Rn = 0.690\ (Q+q)\downarrow - 67.0 \qquad (4\text{-}16)$$

with a positive correlation of 0.92. Like Botanic Gardens, St. Ignatius radiates considerably at night. Fogs are not prevalent. The regression constants are very similar at Botanic Gardens and St. Ignatius, in spite of climatic and surface differences.

The three regression equations above are expected to give reasonably accurate estimates of Rn for use in the control method for EP. The question must be asked if these equations, based on 15 days of data, are valid throughout the year. Davies (1965) obtained $Rn = 0.612\ (Q+q)\downarrow - 28$, using three Nigerian Stations over three different years, and if his equation is used in Guyana to estimate Rn on a typical day when $(Q+q)\downarrow = 600$ ly./day, then Rn is underestimated by 1 percent at Botanic Gardens, 9 percent at Ebini, and 1 percent at St. Ignatius.

Ebini data lack low points as no disturbance passed the station during the Rn measurements, and the entirely different equation is a result of local and diurnal climatic influences on radiation. The Botanic

Gardens regression equation, obtained over green grass at a coastal climate during the wet season in August, is very similar to that obtained over dry grass at St. Ignatius at a savannah climate during the middle of the dry season in November. The regression equations do not vary significantly with climate, site, and season.

The correlation coefficient of Rn and (Q+q)↓ is far greater than that between Rn and n/N, as will be shown later. Consequently, Rn can be more accurately estimated from (Q+q)↓ than from climatological data.

Figure 4-9 shows the 5 day moving average of net radiation, estimated from (Q+q)↓ as measured by actinograph. The mean 5 day error of Rn is governed by errors in actinograph measurements ($\pm$ 10 percent over daily periods but certainly less over 5 day periods).

4.4 Estimation of Radiation from Climatological Data

The absence of actinograph data is a common problem in many parts of the world, including Guyana. For such cases Penman (1948) proposed that net radiation can be estimated from astronomical quantities, bright sunshine, and vapour pressure. His method is repeated here, using Guyana data to derive regional semi-empirical EP equations.

Solar Radiation at top of the atmosphere, Q_o: This is basically an astronomical quantity. Sellers (1967) provided an equation to compute Q_o; Smart (1965) described a method for calculating the earth-sun distance and the orbital angle, while Chidley et al (1970) illustrated a programme to compute the sun's hour angle and the daylight hours. Russo (personal communication, 1973) developed a computer programme for estimating Q_o at any latitude. The maximum error of computed

Q_o was only 3 percent from May to August in comparison with values given by List (1968).

(a) Botanic Gardens: Incoming solar radiation can be estimated from bright sunshine, equation 2-31, by a linear regression between $(Q+q)\downarrow / Q_o$ and n/N. The monthly regression coefficients, a and b, at the Botanic Gardens are given in table 4-2 and the analyses illustrated in figure 4-6. The November - February coefficients are not given since it is believed that the actinograph's calibration changed drastically on 30th October 1972; presumably the heavy rainfall on that day entered the instrument.

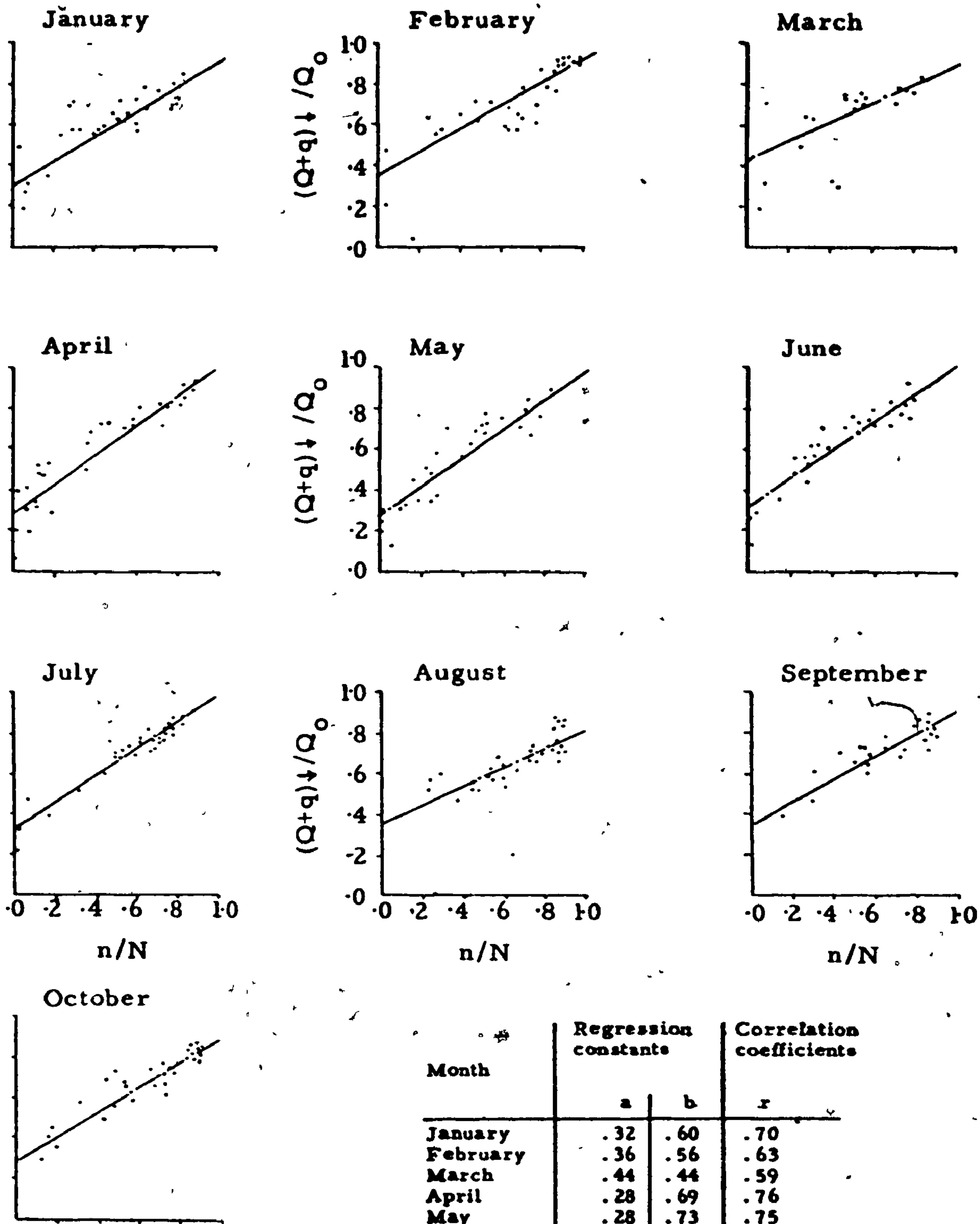
Table 4-2 indicates that $a < 0.35$ and $b > 0.60$ during the wet months (January; April - July; and October which recorded heavy rainfall on the last few days of the month) while $a > 0.35$ and $b < 0.60$ during dry months. It may seem desirable to use two separate equations to estimate incoming solar radiation but, since wet and dry months have rather elusive definitions with irregular durations from year to year, one equation is used. With the January - October data, the linear regression is

$$(Q+q)\downarrow = Q_o (0.34 + 0.58 \frac{n}{N}) \tag{4-17}$$

which is shown in figure 4-7.

This equation has some limitations. On an overcast day, when $n \rightarrow 0$, then $(Q+q)\downarrow \approx 250$ ly./day; but since $(Q+q)\downarrow < 250$ ly./day occurred on an average of two days per month, then equation 4-17 would not considerably overestimate $(Q+q)\downarrow$ over 5 day periods. In figure 4-7, some odd points at low bright sunshine and low $(Q+q)\downarrow$ would have altered the regression equation. However, low points are

Fig. 4-6 Monthly relationship between $(Q+q)\downarrow/Q_o$ and n/N at the Botanic Gardens - 1972.



Month	Regression constants a	Regression constants b	Correlation coefficients r
January	.32	.60	.70
February	.36	.56	.63
March	.44	.44	.59
April	.28	.69	.76
May	.28	.73	.75
June	.34	.66	.84
July	.34	.62	.90
August	.35	.45	.74
September	.38	.53	.81
October	.27	.63	.78
Year 1972	.34	.58	.78

Fig. 4-7 (Q+q)↓ as a function of bright sunshine at the Botanic Gardens in Jan. - Oct. 1972.

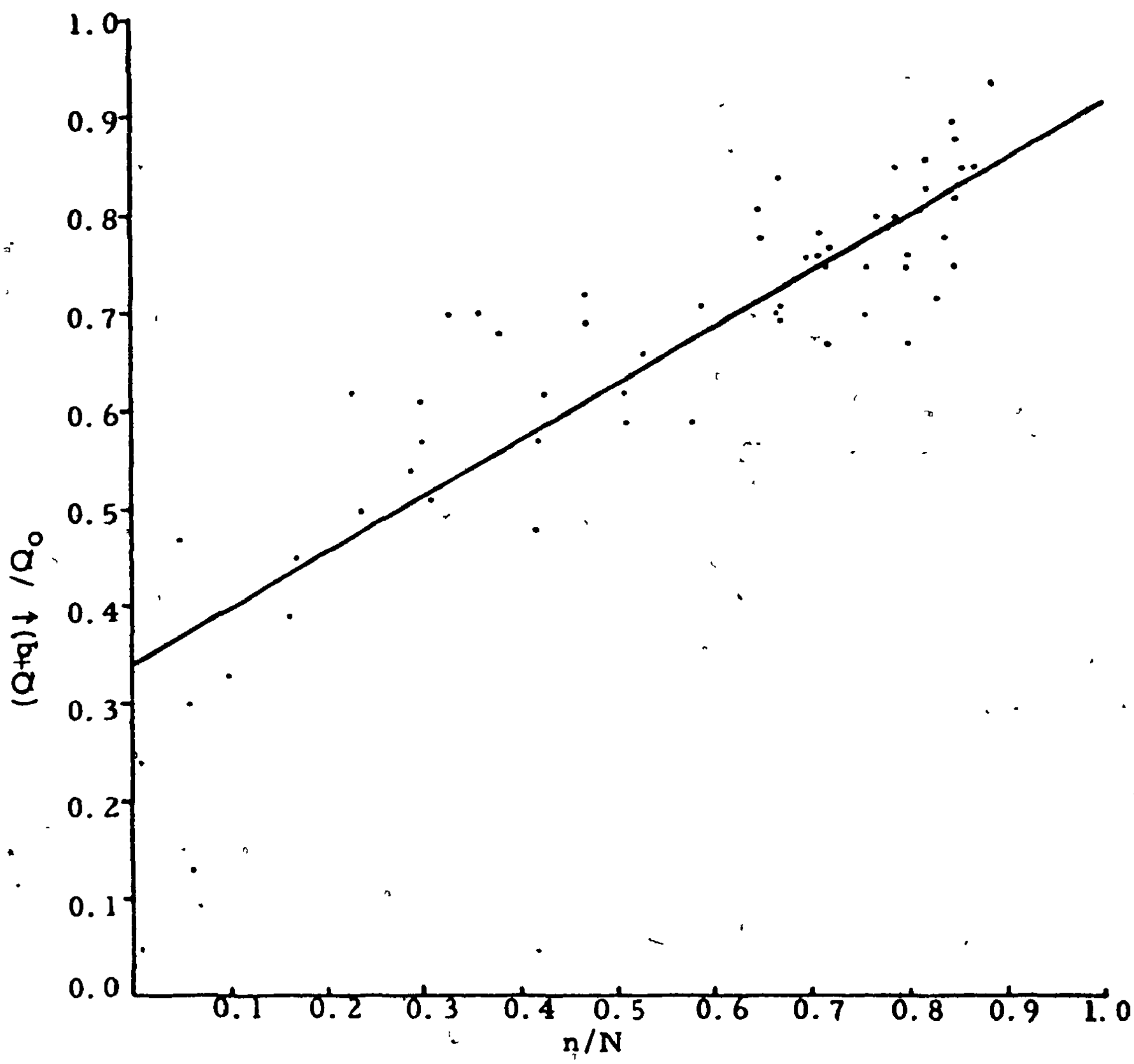


Fig. 4-8 Rnl as a function of bright sunshine.

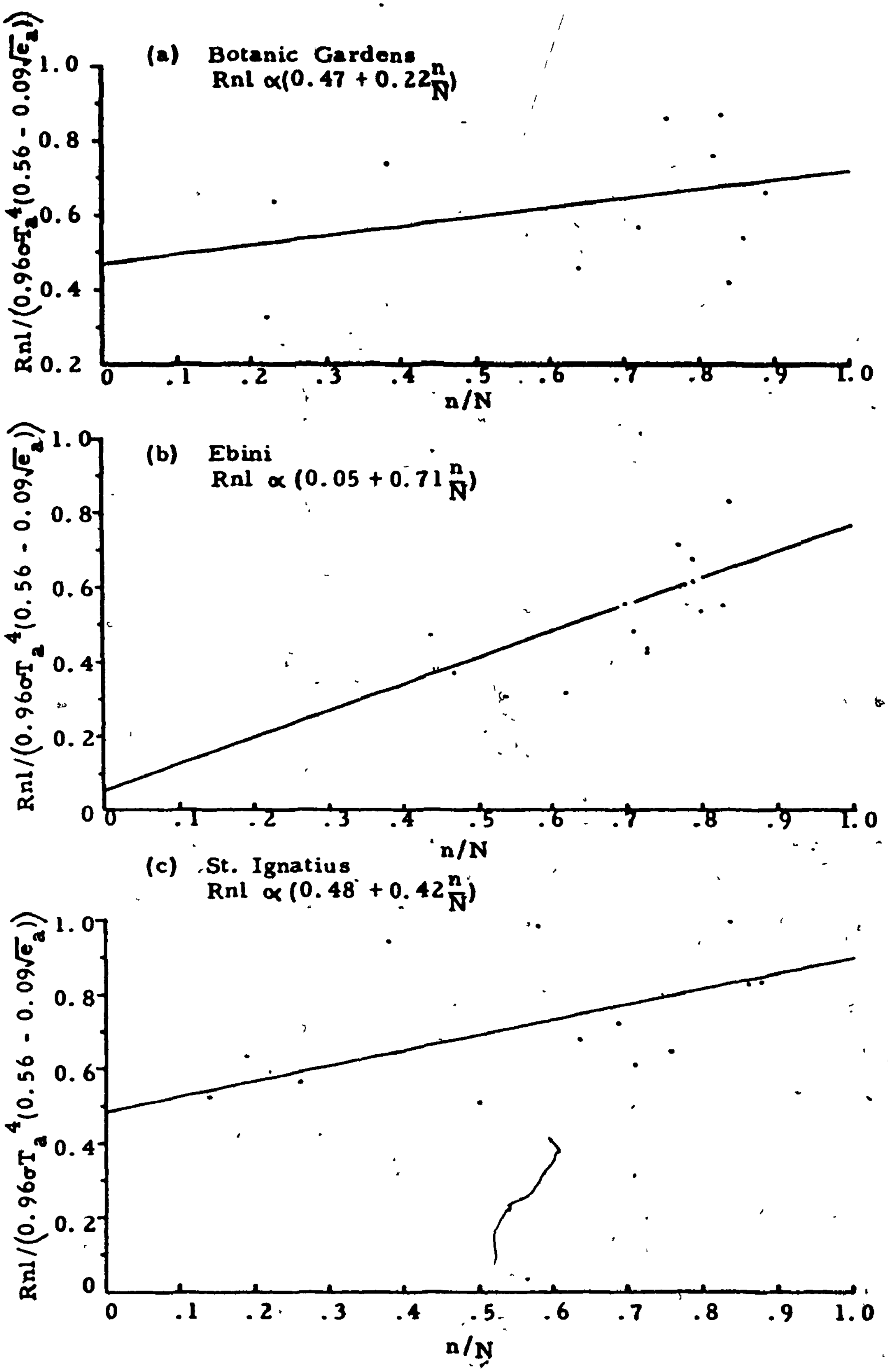
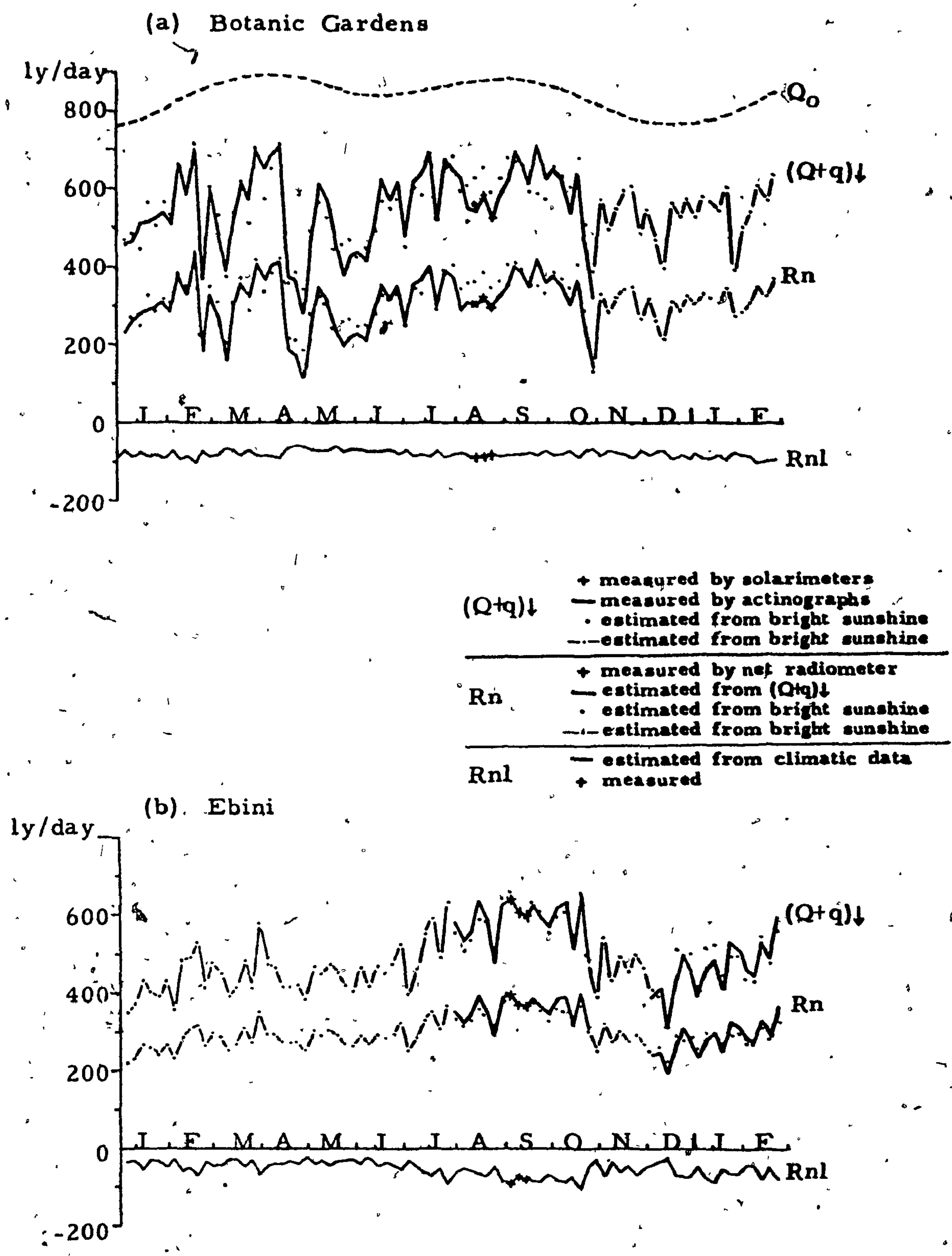


Table 4-2 Regression and correlation constants between Rn v $(Q+q)\downarrow$, Rnl v n/N, and $(Q+q)\downarrow$ v n/N at the Botanic Gardens, Ebini and St. Ignatius.

Form of regression equation	Month	Monthly regression constants (a, b) and correlation r											
		Botanic Garden 1972			Ebini Aug. 1972-Feb. 1973			St. Ignatius Aug. 1972-Feb. 1973			St. Ignatius 1965		
		a	b	r	a	b	r	a	b	r	a	b	r
$Rn = a(Q+q)\downarrow - b$	August	.676	62.6	.91									
	September				.62	0	.83						
	November							.69	67	.92			
$Rnl \propto (a+b\frac{n}{N})$	August	.47	.22	.41									
	September				.05	.71	.45						
	November							.48	.42	.59			
$\frac{(Q+q)\downarrow}{Q_o} = a+b\frac{n}{N}$	January	.32	.60	.70							.42	.26	.72
	February	.36	.56	.63							.41	.29	.68
	March	.44	.44	.59							.35	.39	.59
	April	.28	.69	.76							.34	.35	.65
	May	.28	.73	.75							.28	.45	.53
	June	.34	.66	.84							.26	.50	.84
	July	.34	.62	.90							.26	.48	.82
	August	.35	.45	.74	.35	.57	.58	.34	.48	.68	.30	.41	.77
	September	.38	.53	.81	.35	.50	.81	.20	.68	.71	.31	.43	.71
	October	.27	.63	.78	.35	.50	.84	.25	.55	.80	.28	.42	.58
	November							.30	.55	.67	.37	.31	.56
	December				.33	.48	.77	.38	.45	.79	.42	.26	.70
	January				.37	.42	.72	.45	.33	.43			
	February				.39	.45	.80	.35	.40	.45			
	Total	.34	.58	.78	.36	.49	.76	.33	.49	.72	.33	.38	.77

Fig. 4-9 Five day m[illegible]g average of measured and estimated radiation.



in a minority over the year and were ignored in order to give more representation at moderate and high $(Q+q)\downarrow$ values. The equation would also underestimate $(Q+q)\downarrow$ on extremely clear days.

The net shortwave radiation is given by $(1-\alpha)$ $(Q+q)\downarrow$, where α is the albedo. Five day mean albedo over grass are given in table 4-1, and the 15-day mean is 0.28. Daily albedo varies between 0.24 to 0.34, decreasing with increasing radiation or decrease in the ratio $q/(Q+q)\downarrow$.

The net longwave radiation, Rnl, is a function of temperature, vapour pressure, and cloud cover (equation 2-29). The regression constants in the vapour pressure factor in the equation can be determined from measurements of upward and downward longwave fluxes. These measurements are not known with sufficient accuracy for the present study, and Penman's constants must be adopted. This would introduce some errors in estimated Rnl but, as mentioned before, Rnl can be treated as a constant in Guyana without seriously affecting estimates of Rn. A linear regression between $Rnl / \left(0.96\sigma T_a^4 (0.56 - 0.09\sqrt{e_a})\right)$ and n/N, shown in figure 4-8a, gives

$$Rnl = 0.96\sigma T_a^4 (0.56 - 0.09\sqrt{e_a})\ (0.47 + 0.22 \frac{n}{N}) \qquad (4\text{-}18)$$

The points are widely scattered. The above equation is based on 15 days of data in August, and the regression constants may be different in other months. The validity of the equation at other times of the year must be assessed.

Seasonal variations of Rnl, or of the coefficients a and b, may not be large. This consideration is based on the fact that Rnl depends on temperature, vapour pressure and bright sunshine. Neither temperature or vapour pressure has large seasonal variations in Guyana. The regression constants in equation 4-18 indicates a weak correlation between Rnl and bright sunshine. This is realistic, for Rnl over 24 hours depends on net longwave radiation at night which in turn has little relationship with bright sunshine during the day, due to the diurnal variation of climate.

Finally, by combining the two regression equations to obtain net radiation, the semi-empirical energy budget equation at Botanic Gardens is given by:

$$EP = \frac{s}{s+\gamma}\left[(1-0.28)Q_o(0.34+0.58\frac{n}{N}) - 0.96\sigma T_a^4(0.56-0.09\sqrt{e_a})(0.47+0.22\frac{n}{N})\right]$$

$$+ \frac{s}{s+\gamma}\left[f(u)(e_s - e_a)\right] \qquad (4\text{-}19)$$

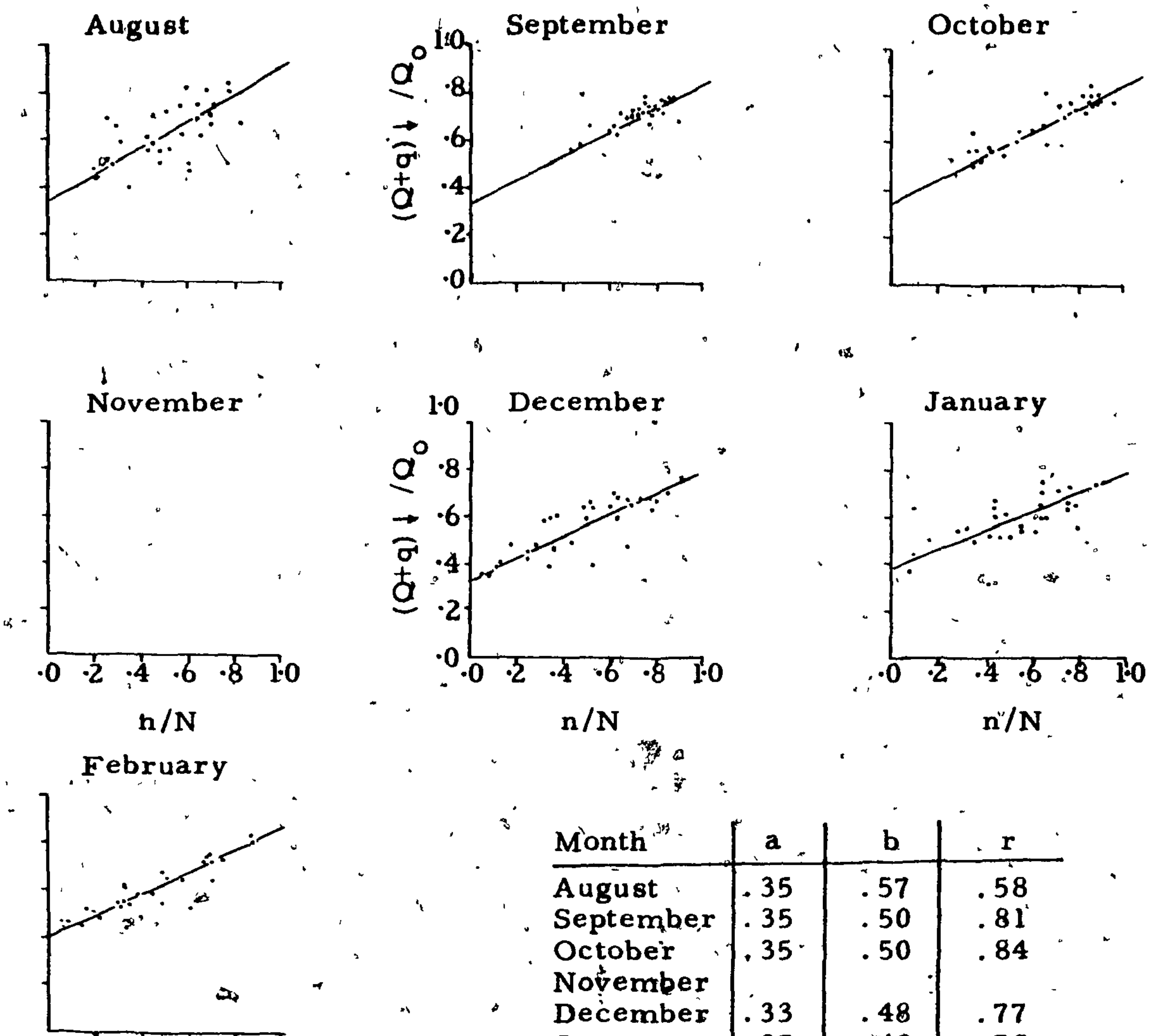
The accuracy of this equation depends on the accuracy of Rn estimates. The solid line in figure 4-9a shows actinograph measurements of (Q+q)↓ while the dots are the estimated (Q+q)↓ using climatological data in equation 4-17. The mean 5-day error is 6 percent. The errors in estimated Rnl are unknown but correspond well with measurements in August. 5-day mean Rnl varies from -60 to -105 ly/day over the year. Rn estimated from climatological data is within ± 7 percent of Rn estimated from actinograph data. Climatological data probably give a value for Rn that is within 10-15 percent of actual Rn, and this is acceptable in the present study.

(b) Ebini: A similar analysis at Ebini to adjust the constants of the semi-empirical EP equation gives for (Q+q)↓ :

$$(Q+q)\downarrow = Q_o(0.36 + 0.49\frac{n}{N}) \qquad (4\text{-}20)$$

which is based on the August-February data. The monthly regressions are shown in figure 4-10 and table 4-2. This period is, however, the drier part of 1972 with very high sunshine in January-February 1973,

Fig. 4-10 Monthly relationship between $(Q+q)\downarrow/Q_o$ and n/N at Ebini from August 1972-February 1973.



Month	a	b	r
August	.35	.57	.58
September	.35	.50	.81
October	.35	.50	.84
November			
December	.33	.48	.77
January	.37	.42	.72
February	.39	.45	.80
Aug. - Feb.	.36	.49	.76

and with only 3 days having $n < 2$ hours. Figure 3-6b shows the monthly bright sunshine at Ebini with low values in January-June 1972. Equation 4-20 is not representative for wet months, when it may overestimate (Q+q)↓ .

Table 4-1 gives the 5-day mean albedo over short grass fully covering the surface, in early September. The mean value is 0.26 and can be used to estimate net shortwave radiation.

Rnl can be expressed in terms of n/N as:

$$Rnl = 0.96\sigma T_a^{\ 4}\ (0.56 - 0.09\sqrt{e_a})\ (0.05 + 0.71\frac{n}{N}) \qquad (4\text{-}21)$$

where the regression is shown in figure 4-8b. From the above constants, which are far different from those at Botanic Gardens, it seems that Rnl at Ebini has a large dependence on daytime cloud cover. The occurrence of fog considerably reduces nighttime Rnl. Therefore, the magnitude of Rnl over 24 hours depends strongly on the daytime amount. This explains its high dependence on daytime cloud cover.

The semi-empirical EP equation at Ebini is expressed as

$$EP = \frac{s}{s+\gamma}\left[(1-0.26)Q_o(0.36+0.49\frac{n}{N}) - 0.96\sigma T_a^{\ 4}(0.56-0.09\sqrt{e_a})(0.05+0.71\frac{n}{N})\right] + \frac{s}{s+\gamma}\left[f(u)(e_s - e_a)\right] \qquad (4\text{-}22)$$

being most representative for the dry season.

Figure 4-9b gives the (Q+q)↓ obtained from actinograph data (full line) and (Q+q)↓ estimated from climatological data (dots). The mean 5-day error is 5 percent. In comparison with measured (Q+q)↓ at Botanic Gardens during the early half of 1972, the regression equation at Ebini does not overestimate (Q+q)↓ as was feared; since the Botanic

Gardens recorded an average of 520 ly./day in early 1972 while Ebini had an average $(Q+q)\downarrow$ of 445 ly./day. Rnl was about -40 ly/day in the early half of 1972 and about -75 ly/day in the later half. Rn, estimated from climatological data, has an average error of ± 6 percent in comparison with Rn estimated from actinograph data. The estimated radiation compares very well with solarimeters and net radiometer measurements (denoted by +).

(c) St. Ignatius: At St. Ignatius, incoming radiation data are available in 1972 as well as for 1965. The regression coefficients for the two years are shown in table 4-2. There are consistently lower coefficients in 1965 as a result of low radiation measurements. In 1965, 13 days recorded $(Q+q)\downarrow > 575$ ly/day as compared to 87 days during the recent period August 1972 - February 1973. Clearly the actinograph underestimated $(Q+q)\downarrow$ in 1965; but the data nevertheless give the relative seasonal trends of the a and b regression coefficients. Using the more recent data, incoming shortwave radiation is given by

$$(Q+q)\downarrow = Q_o(0.33 + 0.49 \frac{n}{N}) \qquad (4\text{-}23)$$

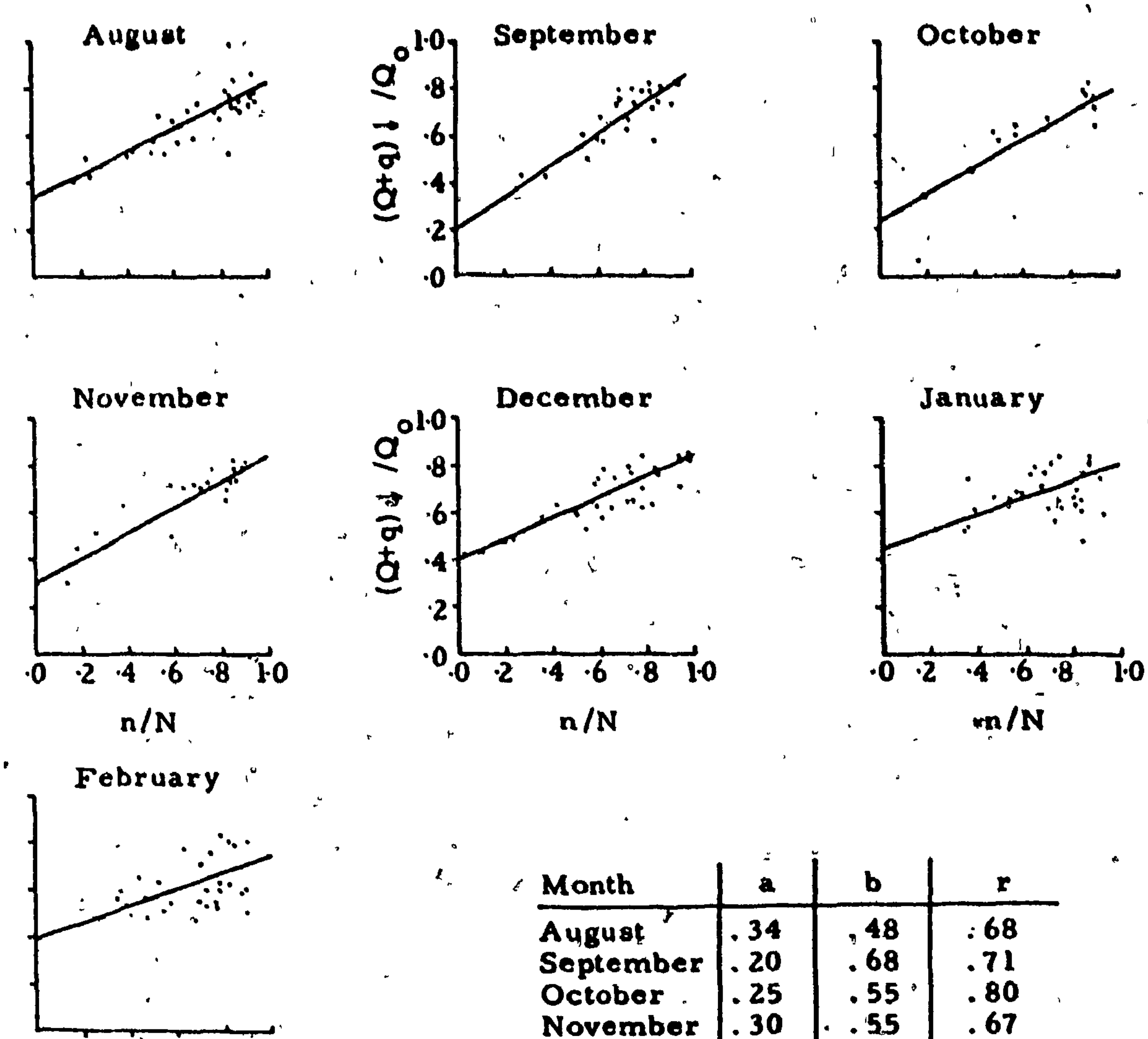
which only represents the dry season. Nearly the same coefficients are obtained at Ebini, and this is an indication that cloud influences on solar radiation are the same at interior stations.

Five-day mean albedo over bunch grass partially covering the ground in November during the dry season is given in table 4-1. The 15 day mean is 0.26 which is near the mean albedo at the other two stations.

Net longwave radiation is given by

$$Rnl = 0.96\sigma T_a^4(0.56 - 0.09\sqrt{e_a})(0.48 + 0.42\frac{n}{N}) \qquad (4\text{-}24)$$

Fig. 4-11 Monthly relationship between $(Q+q)\downarrow /Q_o$ and n/N at St. Ignatius Aug. 1972-Feb. 1973.



Month	a	b	r
August	.34	.48	.68
September	.20	.68	.71
October	.25	.55	.80
November	.30	.55	.67
December	.38	.45	.79
January	.45	.33	.43
February	.35	.40	.45
Aug.-Feb.	.33	.49	.72

as illustrated in figure 4-8c. EP at St. Ignatius is given by

$$EP = \frac{s}{s+\gamma}\left[(1-0.26)Q_o(0.33+0.49\frac{n}{N}) - 0.96\sigma T_a^4(0.56-0.09\sqrt{e_a})(0.48+0.42\frac{n}{N})\right]$$
$$+\frac{s}{s+\gamma}\left[f(u)\,(e_s - e_a)\right] \qquad (4\text{-}25)$$

4.5 General Equation and its limitation.

The use of three equations for EP in Guyana is inconvenient although climatically justified, and an attempt is made to obtain one equation by combining all relevant data irrespective of location and time. From figure 4-12a, Rn is given by

$$Rn = 0.76\,(Q+q)\!\downarrow - 96.0 \qquad (4\text{-}26)$$

where the two regression coefficients increase simultaneously above the regional coefficients. Combining all $(Q+q)\!\downarrow /Q_o$ and n/N data does not give satisfactory regression coefficients, for a few extreme values predominate by the use of the least squares method. A hand plotted regression, using all data, gives

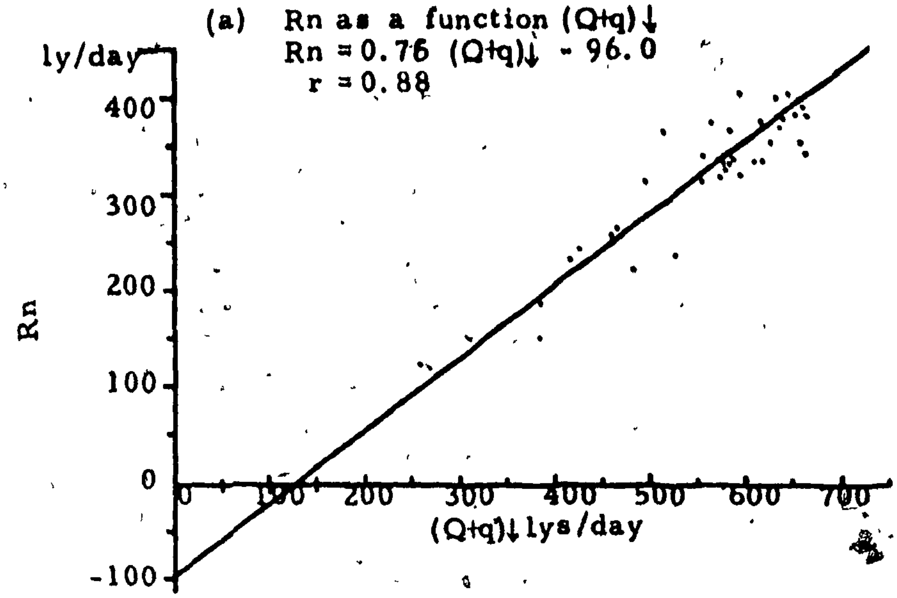
$$(Q+q)\!\downarrow = Q_o(0.35 + 0.50\frac{n}{N}) \qquad (4\text{-}27)$$

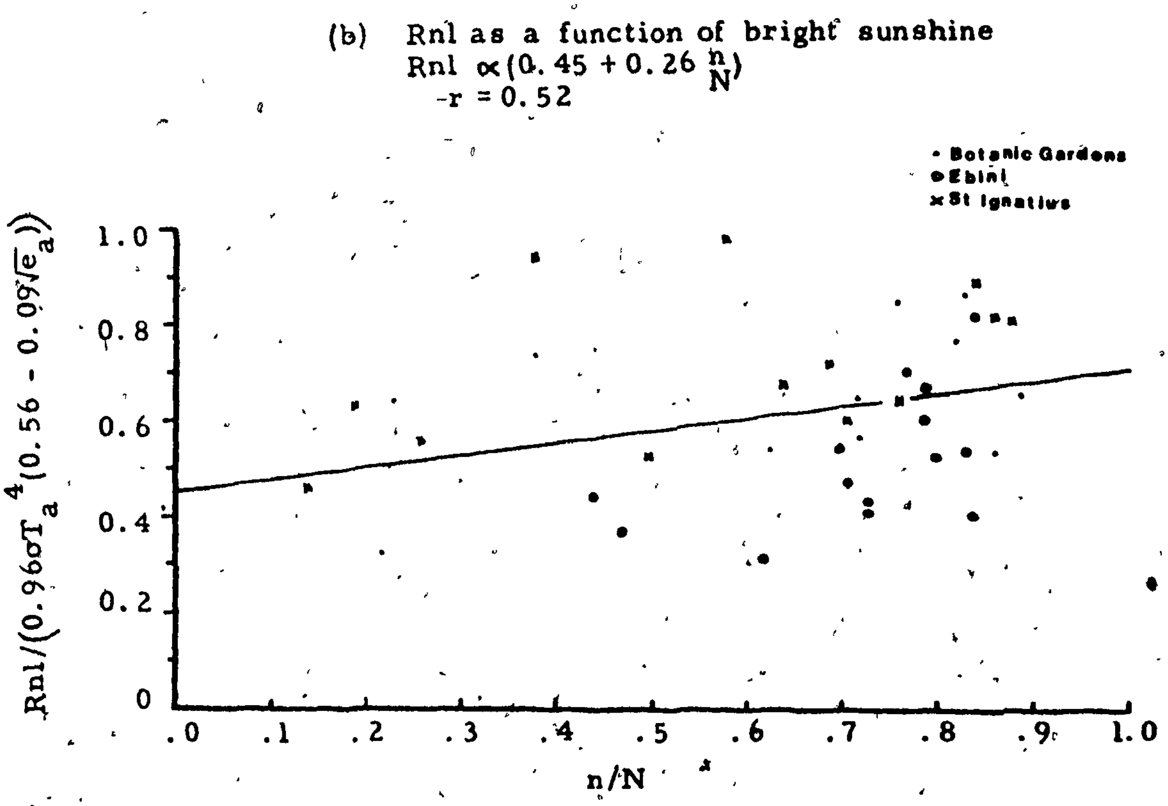
A linear regression of all Rnl and n/N data, shown in figure 4-12b, is

$$Rnl = 0.96\sigma T_a^4\,(0.56 - 0.09\sqrt{e_a})\,(0.45 + 0.26\frac{n}{N}) \qquad (4\text{-}28)$$

where the Ebini data do not predominate in the regression. A general EP equation for all regions of Guyana is

Fig. 4-12 (a) Rn as a function of $(Q+q)\downarrow$ and
(b) Rnl as a function of bright sunshine
using data from all three stations.





$$EP = \frac{s}{s+\gamma}\left[(1-0.27)Q_o(0.35+0.50\frac{n}{N}) - 0.96\sigma T_a^4(0.56-0.09\sqrt{e_a})(0.45+0.26\frac{n}{N})\right]$$

$$+\frac{s}{s+\gamma}\left[f(u)(e_s - e_a)\right] \quad (4\text{-}29)$$

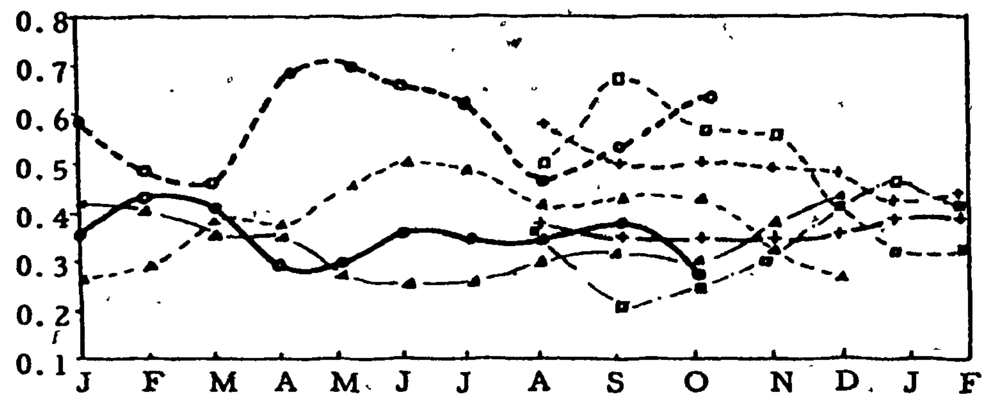
Limitations: The regional and general equations have some limitations. In the first instance, bright sunshine is only a rough measure of incoming radiation and cannot precisely estimate $(Q+q)\downarrow$ over a daily period when errors may reach 30 percent. But their reliability over five-day periods has already been established.

At low values of bright sunshine when $n < 2.0$ hours, $(Q+q)\downarrow$ is extremely variable depending on whether the bright sunshine occurs at mid-day, early morning, or in late afternoon hours. Some low radiation points in figure 4-7 have been ignored. The equations therefore overestimate $(Q+q)\downarrow$ on overcast days.

When $n/N = 1.0$, then $(Q+q)\downarrow = 0.85\ Q_o$; which means that a fraction of 0.85 of extra-terrestial solar radiation reaches the surface on clear days. However, cloudless days are rare occurrences in Guyana since low convective clouds usually develop. In figure 4-6, figure 4-10, and figure 4-11, n/N exceeds 0.9 on an average 0.8, 0.5, and 2.5 times per month at Botanic Gardens, Ebini and St. Ignatius respectively.

There are large seasonal variations of the regression constants plotted in figure 4-13. At Botanic Gardens, $b > a$ in the wet seasons, but $b \rightarrow a$ during the dry seasons (as in February, March and August). At Ebini, $b \rightarrow a$ only when it becomes exceedingly dry as in January-

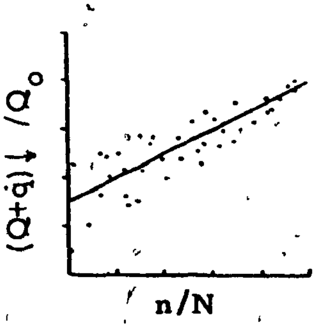
Fig. 4-13 Monthly regression coefficients between $(Q+q)\downarrow/Q_o$ and n/N at the Botanic Gardens, Ebini, and St. Ignatius.



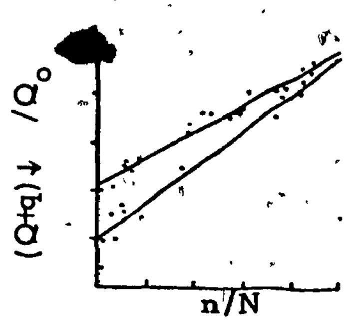
Station	Period	Indication
Botanic Gardens	Jan. 1972 - Oct. 1972	—o— a, ---o--- b
Ebini	Aug. 1972 - Feb. 1973	—+— a, ---+--- b
St. Ignatius	Aug. 1972 - Feb. 1973	—□— a, ---□--- b
St. Ignatius	Jan. 1965 - Dec. 1965	—▲— a, ---▲--- b

Fig. 4-14 The effects of (a) time of occurrence of bright sunshine and (b) synoptic disturbances on the relationship between $(Q+q)\downarrow$ and bright sunshine.

(a)



(b)



February 1973. At St. Ignatius, however, $b > a$ in the wet seasons but $b < a$ in the mid-dry season period. The 1965 data, with $(Q+q)\downarrow$ underestimated, nevertheless gives an indication of the seasonal trends of the regression coefficients.

It may appear that one regression equation cannot estimate $(Q+q)\downarrow$ throughout the year. However, a decrease of the monthly a coefficient is accompanied by an increase in the b coefficient, as shown in figure 4-13. But all the monthly regression lines for any station seem to pass through the same point at moderate radiation values. For example, when $n/N = 0.6$ at Botanic Gardens $(Q+q)\downarrow = (0.44 + 0.44 \frac{n}{N})\, Q_o = 0.70\, Q_o$ in March, and $(Q+q)\downarrow = (0.28 + 0.73 \frac{n}{N}) Q_o = 0.72\, Q_o$ in May; but the regional equation gives $(Q+q)\downarrow = (0.34 + 0.58 \frac{n}{N}) Q_o = 0.69\, Q_o$. However, the regional equations overestimate $(Q+q)\downarrow$ on wet days and underestimate $(Q+q)\downarrow$ on clear days. Since such days are a minority in any month the regional equations give reliable 5-day estimates of $(Q+q)\downarrow$.

On comparison with other research, Penman (1952) suggested $(Q+q)\downarrow = Q(0.18 + 0.55 \frac{n}{N})$ for S. E. England; equation 4-27 is justified for Guyana. On an overcast day when $n = 0$, then $(Q+q)\downarrow = 0.18\, Q_o$ in S. E. England and $(Q+q)\downarrow = 0.35\, Q_o$ in Guyana. However, the direct path length for incoming solar radiation is far greater in mid-latitudes than in the tropics and the a coefficient must increase towards low latitudes.

The fraction of extraterrestrial radiation reaching the surface does not simply depend on the du[illegible] of cloud cover but also on cloud type, cloud thickness, cloud drop size distribution, and atmospheric moisture. Atmospheric air has high relative humidity behind disturbances since it is rising (Riehl, 1959), and $(Q+q)\downarrow$ is much reduced for moderate cloud cover. Ahead of disturbances, the atmosphere is dry since it is descending so that (Q+q)↓ is less reduced for moderate cloud cover as compared to the previous case. There seems to be two families of cloud - solar radiation characteristics which should require two regression equations. This phenomenon can be noticed in the monthly regression figures (4-6, 4-10, 4-11) where some of the regression lines actually pass between two groups of points. With disturbances entering Guyana every 5-6 days, these two effects will, on the whole, cancel each other.

On a clear day with n = 10 hours, (Q+q)↓ is 600-700 ly./day. On a cloudy day with n = 3 hours, (Q+q)↓ is 200 - 450 ly./day depending on whether it is clear at morning or midday hours. Consequently the time of occurrence of bright sunshine does not affect (Q+q)↓ when n is large, since bright sunshine occurs during most of the daytime hours, but does affect (Q+q)↓ when n is small. (Q+q)↓ is more variable for small n than for large n as sketched in figure 4-14a. This effect in combination with the synoptic effect described in the previous paragraph produces two regression lines that intercept at high n values as illustrated in figure 4-14b which is based on April 1972 for the Botanic Gardens.

4.6 Actual Evapotranspiration and the Water Balance

The evaluation of EP is the first step towards the evaluation of the actual evapotranspiration (EA). As the second step, Budyko (1956), Thornthwaite (1955), and Penman (1955), agreed that EA can be obtained from PE by considering the physiology of plant cover and available soil moisture. Their methods and relationships varied, but they succeeded in estimating EA over larger areas on a continental scale.

Moisture for evapotranspiration comes from the root zone and plants cannot utilise moisture below the roots since the upward vapour flux is extremely small (Kramer, 1949). Thornthwaite and Mather (1957) provided tables for rough estimation of root depth and moisture holding capacity. For the present study these are adjusted by the use of soil profiles and root depths from the FAO soil survey of Guyana (1966), as shown in table 4-3.

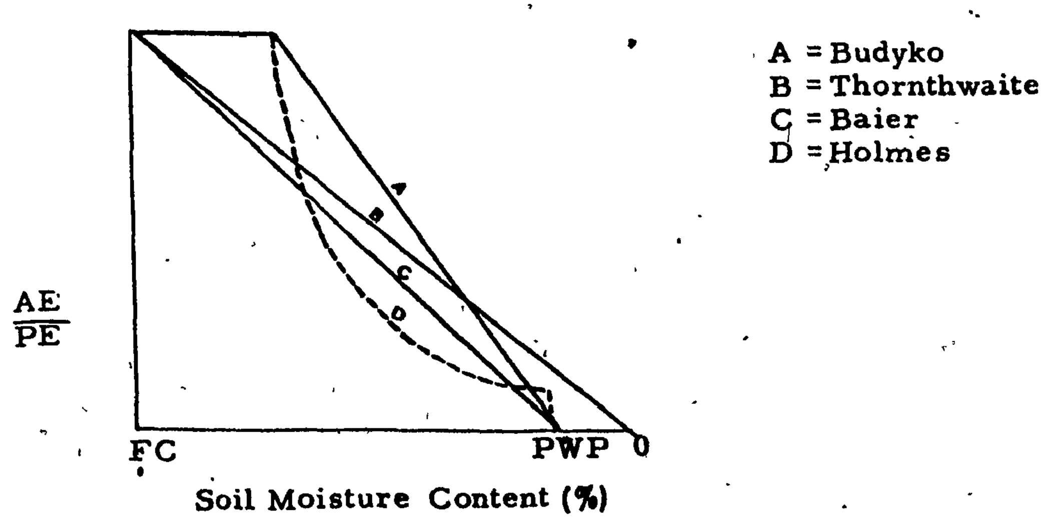
Below the permanent wilting point (PWP), soil moisture is held so tightly by the soil particles that it is unavailable for evapotranspiration. The PWP varies with soil texture and may be 3 percent of moisture holding capacity for sandy soil or 30 percent for clay soil (Chang, 1968, p 198). In Guyana, 20,12, and 8 percent are used for clay, fine sand, and coarse sand respectively.

Viehmeyer and Hendrickson proposed that EA = EP until the wilting point is reached but Thornthwaite and Mather (1955) proposed EA/EP is linearly dependent on soil moisture content. Other workers (Pierce, 1958 and Holmes, 1961) suggested a compromise between the two extremes. However, Baier (1969) found close agreement between estimated and measured soil moisture content by using Thornthwaite's relation. In view of such unresolved disagreement both Thornthwaite's and Holmes's proposals were tried in Guyana without significant effects on the monthly EA amounts. For Guyana soil types, EA = EP when soil moisture content is above 70, 80, 90 percent of field capacity for clay, fine sand, and coarse sand respectively. These figures are based on Holme's drying curve, for which he remarked that EA = EP over a large part of the available moisture range on the heavier soil,

Table 4-3 Plant-water characteristics of soil at the Botanic Gardens, Ebini, and St. Ignatius.

Station	Botanic Gardens	Ebini	St. Ignatius
Vegetation	Grass	Grass	Bunch Grass
Soil	Clay	Coarse Sand	Fine Sand
Root Depth	4.2	4.0	5.0
FC	10.0"	5.0"	6.0"
CS	70%	90%	80%
PWP	20%	8%	12%

Fig. 4-15 Drying Curves



but for coarse sand EA fell short of EP early in the drying cycle. Denmead and Shaw (1962) cautioned that under high EP rates EA fell short of EP at soil moisture content close to field capacity, but at low EP rates EA = EP close to the wilting point; this view has recently been supported by Linacre (1973).

Between the two extremes of low and high soil moisture content, Budyko (1956) used a linear relationship while Holmes (1961) used an exponential decrease shown in figure 4-15. Holmes (1961) found that the exponential drying curve is a "considerable improvement over Thornthwaite's method to estimate soil moisture status in Ottawa," but Baier (1969) found that his linear relationship, also for Ottawa, "gave results closely related to observations" as opposed to the exponential drying curve. Thornthwaite's relation is quite similar to Baier's, while Budyko's relation is similar to that recommended by Linacre. Thornthwaite's and Budyko's relationships are adopted here since both have been used successfully for worldwide estimates of EA.

The Water Balance: Thornthwaite and Mather (1957) have proposed a scheme to estimate the components of the water balance. This scheme is used here, but with the adjustment that monthly runoff is approximately 0.7 times the surplus water (Garnier, 1960).

Several assumptions are made in the water balance. There is no soil moisture storage unless rainfall exceeds EP, and no surplus water unless soil moisture content is at field capacity. Budyko (quoted by Sellers, 1967), however, assumed that surplus, S, is proportional to rainfall, R, and soil moisture content, w, where $S = \left(\frac{0.8R}{EP+R}\right) R \frac{\overline{w}}{w_{FC}}$. This relationship is not used here for there is uncertainty in the coefficient 0.8. Subsurface and surface runoff are not separated. Seventy percent of monthly surplus water runs off while 30 percent is kept as ground water storage (Garnier, 1960). No consideration has been given to lateral or horizontal flow of water which is certainly important along the coastland that is below the level of the interior water table. Evaporation from soil and transpiration of plants are treated as one process; this is acceptable for grass completely covering the surface. Interception of rainfall is not considered since all intercepted water eventually evaporates; but interception does increase the storage. The water stored in the litter layer is included in the total moisture holding capacity.

The water balance is determined here because EA and the water balance are interactive processes, and neither can be estimated independently using mere climatological data. The uncertainty of EP estimates in Guyana has been a serious obstacle in assessments of the water balance, and it is demonstrated here that this obstacle is removed. It is now possible to obtain the water balance of Guyana, using climatological data. This technique has been advocated by Thornthwaite; recently Lee (1972) used "readily available basic meteorological data as input for water balance calculations" over a watershed and concluded that these data were more representative than the available hydrological parameters.

CHAPTER FIVE

COMPARISON OF POTENTIAL EVAPOTRANSPIRATION METHODS

The results of several evapotranspiration methods are presented in this chapter. Penman method denoted by EP was used as control. However, Rn could not be measured for more than fifteen days and was therefore estimated from (Q+q)↓ . The regional semi-empirical energy budget formula is denoted by EPsemi and the general semi-empirical energy budget equation by EPguy. Pan coefficient refers to the ratio of potential evapotranspiration/pan evaporation and is not exactly the same as the ratio potential evaporation/pan evaporation. The actual evapotranspiration, EA, was obtained from the water balance.

5.1 Potential Evapotranspiration at Botanic Gardens

Penman: The highest daily EP in 1972 was 0.31 inch. Daily EP rarely exceeded 0.25 inch or fell below 0.05 inch. To be precise, EP exceeded 0.25 inch on 21 days in 1972 and was less than 0.05 inch on 16 days. Extreme values occurred 10 percent of the year.

It should not be thought that EP is always uniform in the tropics, for dramatic daily and seasonal changes take place. In May 1972, the wettest month of the year, five cycles of daily EP can be detected in figure 5-la. Six disturbances passed over the Botanic Gardens reducing incoming radiation, temperature, wind speed, and vapour pressure deficit; EP was accordingly reduced. Between disturbances the reverse climatological effects were felt, including high EP. In September, the driest month of 1972, intense disturbances were absent and EP remained high but, nevertheless, five or six cycles can be barely detected.

Fig. 5-1 Potential evapotranspiration at the Botanic Gardens in 1972

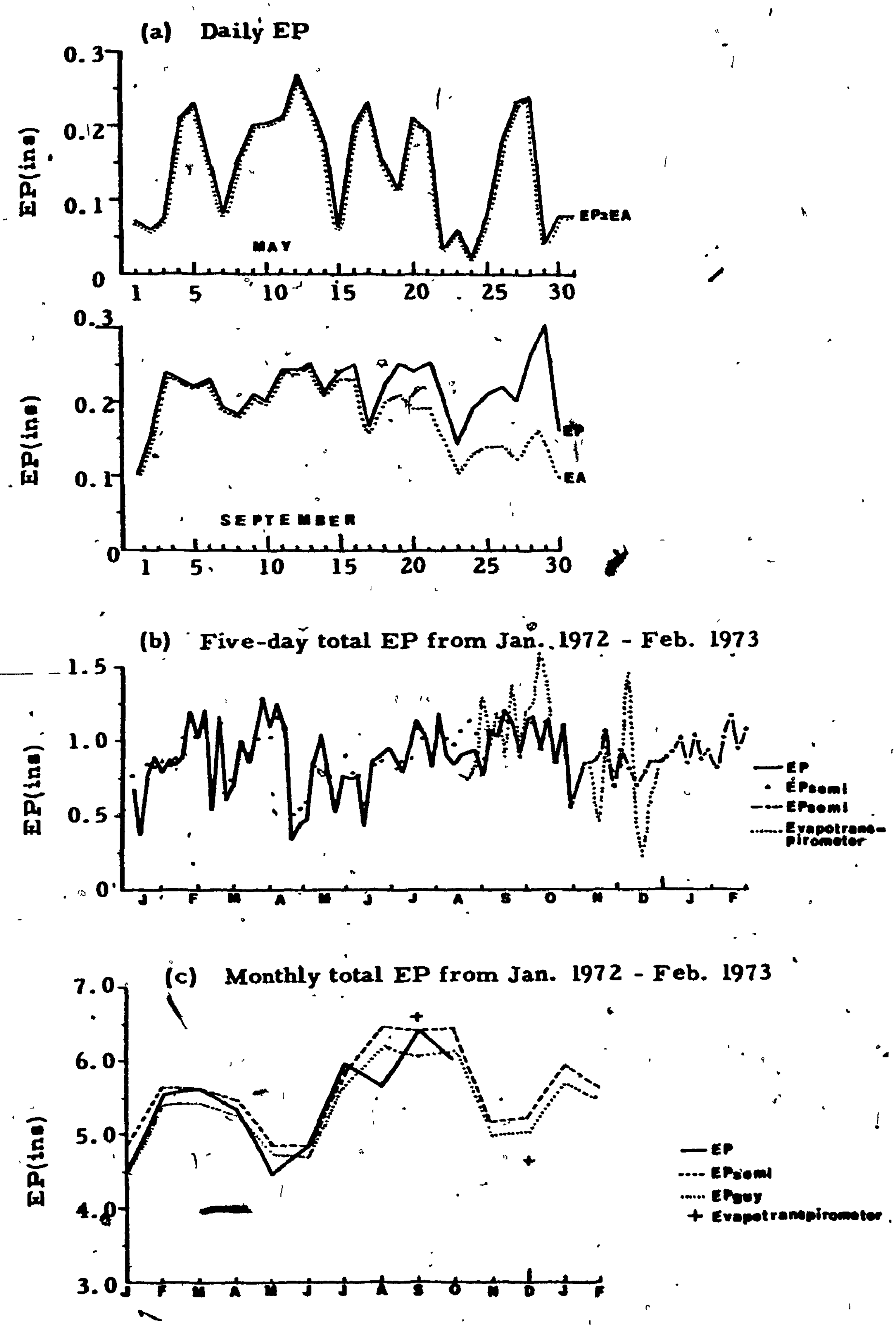


Table 5-1 Monthly EP at the Botanic Gardens from January 1972 to February 1973

	J	F	M	A	M	J	J	A	S	O	N	D	J	F	1972	TOTAL
EP	4.54	5.54	5.57	5.32	4.47	4.86	5.99	5.69	6.40	5.98	(4.91)	(5.19)	(5.81)	(5.57)	64.46	75.84
EPsemi	4.76	5.62	5.55	5.39	4.80	4.77	5.82	6.44	6.34	6.38	5.15	5.22	5.93	5.64	66.24	77.81
EPguy	4.65	5.42	5.42	5.28	4.75	4.68	5.61	6.16	6.07	6.12	4.98	5.03	5.70	5.46	64.17	75.33
Epan	4.75	5.15	5.83	5.11	4.47	4.43	5.09	6.45	6.75	6.27	4.90	5.80	5.94	6.08	65.00	77.02
EA	4.54	5.40	5.57	4.55	4.47	4.85	5.99	5.58	5.56	3.14	4.91	5.19	4.87	2.73	59.75	67.35
1.26 EQ	4.64	5.58	5.50	5.46	4.71	5.33	6.52	6.10	6.85	6.27						
1.19 EQ	4.38	5.27	5.19	5.15	4.45	5.04	6.16	5.76	6.47	5.92						
Erad	3.89	4.68	4.91	4.59	3.93	4.44	5.47	5.11	5.74	5.23	4.31	4.56	4.81	4.48	56.86	66.15
Eady	.65	.86	.66	.73	.54	.42	.52	.58	.66	.75	.60	.63	1.00	1.09	7.60	9.69
Eady/EP	.14	.16	.12	.14	.12	.09	.09	.10	.10	.13	.12	.12	.17	.20	.12	.13
EA/EP	1.00	0.97	1.00	0.86	1.00	1.00	1.00	0.98	0.87	0.53	1.00	1.00	0.84	0.49	0.93	.90
EP/Epan	.96	1.08	.96	1.04	1.00	1.10	1.18	.88	.95	.95	1.00	.89	.98	.92	1.00	.99
$\bar{a}$ = EP/EQ	1.22	1.24	1.24	1.20	[illegible]19	1.15	1.16	1.17	1.18	1.19					(1.19)	
1.26EQ/EP	1.02	1.01	.99	1.03	1.05	1.10	1.09	1.07	1.07	1.05					(1.05)	
1.19EQ/EP	.96	.95	.93	.97	1.00	1.04	1.03	1.01	1.01	.99					(0.99)	
EPsemi/EP	1.05	1.01	1.00	1.01	1.07	.98	.97	1.13	.99	1.07					([illegible].03)	
EPguy/EP	1.02	0.98	0.97	.99	1.06	.96	.94	1.08	.95	1.02					(1.00)	

In figure 5-1b five-day totals, hiding the five day cycles, show abrupt seasonal changes with the onset of the wet seasons in mid-April and late October. The wet seasons of 1972 began abruptly with a sudden drop in EP, in contrast to the gradual change from wet to dry season with constantly increasing EP in January-February and June-July. When the rains began, the soil and air changed from dry to humid but, with the cessation of the rainy season, the soil remained moist for some time afterwards and the upward vapour flux kept the boundary layer humid.

The monthly totals, shown in figure 5-1c, indicate two seasonal cycles of EP over the year. Monthly EP was approximately 5.5 inches in the first dry season, 6.2 inches in the second dry season, and 4.75 inches in the wet seasons. The second dry season was undoubtedly drier than the first both in terms of its longer duration and its higher EP rate.

Table 5-1 shows the contribution of the aerodynamic term, Eady, to the monthly EP amounts. In the dry seasons, Eady $\approx$ 0.70 inch per month, and in the wet seasons Eady $\approx$ 0.50 inch per month. Maximum daily Eady = 0.05 inch on a few windy days in February. Because of the very high EP in the second dry season, the ratio Eady/EP has only one cycle per annum. That is, Eady/EP $\approx$ 16 percent in the first dry season and Eady/EP $\approx$ 10-12 percent over the rest of the year. To explain the fact of only one cycle, it should be stressed that EP is mainly a function of radiation while Eady is a function of wind run and vapour pressure deficit. Therefore

$$\frac{\text{Eady}}{\text{EP}} \approx f\left(\frac{\text{wind run, vapour pressure deficit}}{\text{radiation}}\right)$$

As incoming radiation increases towards the dry seasons, so does the vapour pressure deficit. Consequently, Eady/EP is mainly a function of wind run, as verified in figure 5-2a. Figure 3-5a and table 5-1 also verify one cycle of wind run and Eady/EP over the year. In conclusion, Erad contributed 83-90 percent towards EP at the Botanic Gardens.

When 8 a.m. relative humidity and temperature were assumed as mean daily values in Penman's equation, the monthly EP was underestimated by 0.20 inch in dry months and 0.14 inch in wet months. The total annual underestimation was 1.90 inches or 3.2 percent. Therefore, at coastal climatological stations taking one daily 8 a.m. observation, the readings are sufficient for EP computations.

Evapotranspirometer: The evapotranspirometers functioned unreliably over most of the period of operation. The July-August data were disregarded since the soil had not fully settled and the grass had not reached the same maturity as that of the surroundings. Measurements were lower than computed EP values, as in late August (see figure 5-1b). The October period was the driest part of the year and measurements were 13 percent higher than the computed EP. The late October - mid-November period was the onset of the second wet season, producing overflowing of the evapotranspirometers. The January-February data are not available.

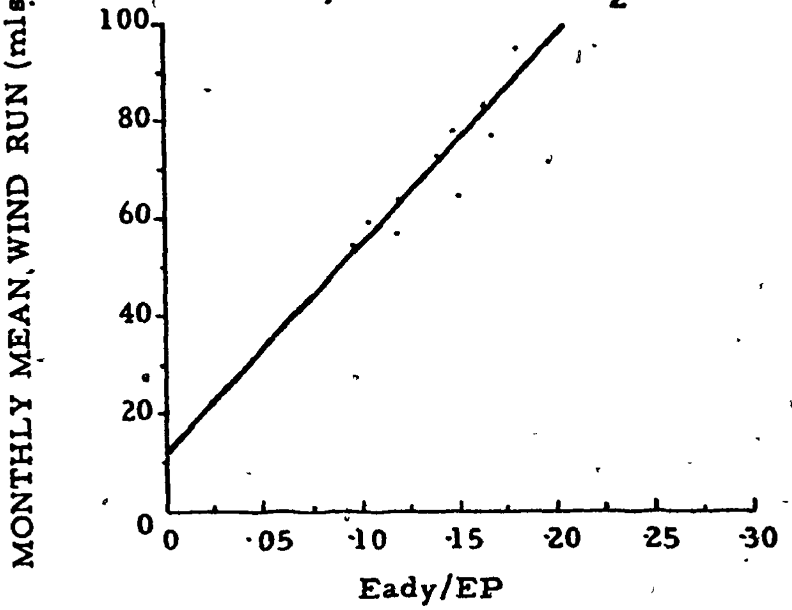
Period	No. of days	EP	Evapotranspirometer
13 Aug. -21 Oct.	70	14.07"	16.63"
11 Nov. -31 Dec.	51	8.64"	7.52"
Total	121	22.71"	24.15"

Best agreement and best EP conditions were obtained after the end of the wet seasons, in September with 4 percent overestimation and in mid-November to mid-December with 6 percent underestimation,

Fig. 5-2 Eady and α as functions of mean wind run at the Botanic Gardens

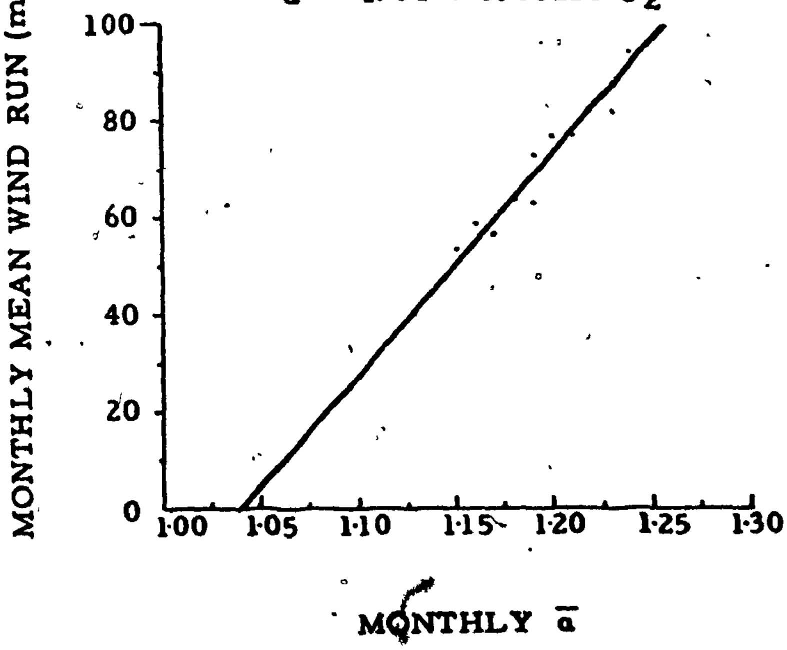
(a) Eady/EP as a function of monthly mean wind run

$$\text{Eady/EP} = 0.0023\,U_2 - 0.028$$



(b) Monthly mean α as a function of monthly mean wind run

$$\bar{\alpha} = 1.04 + 0.00223\,U_2$$



when heavy rainfall and dry conditions were absent but the soil was still near to field capacity. During the August-December period, excluding the late-October to mid-November rainy period, measurements over 121 days were 6 percent higher than computed EP. Since this period included dry conditions in early-October, it can be assumed that the computed EP was near to the true values.

Unfortunately, the evapotranspirometers cannot measure EP with sufficient accuracy over 5-day periods for the immediate requirements in Guyana. Monthly measurements should be accepted with caution and, for example, measurements over December were 0.6 inch or 12 percent below computed EP because 3.11 inches of rain fell during the last three days of November. Linsley (1958) recommended that evapotranspirometer results should not be employed in water-resources survey unless the results had been compared with estimates of EP by some other independent method. The evapotranspirometer results cannot be used as control.

Semi-empirical formulae: The regional semi-empirical formula, denoted by EPsemi in table 5-1 and figure 5-1c, overestimated EP by an average of 3 percent during the January-October period. This, however, is acceptable. Large overestimates, especially in the wet months (January, May, October, and August), were attributed to intense disturbances that drastically reduced incoming shortwave radiation; but the EPsemi formula cannot be adjusted to estimate accurately EP on overcast days without affecting EP on moderately cloudy days. For the other months during the January-October period, monthly EPsemi were within 1-2 percent of monthly EP. Five-day totals of EPsemi, denoted by dots in figure 5-1b, were sufficiently near to five-day totals of EP to recommend its use. At low EP rate, however, EPsemi overestimated by about 15-20 percent over five-day periods.

The general semi-empirical equation, EPguy in table 5-1 and figure 5-1c, improved the annual estimation of EP because it underestimated by 4 percent in dry months and overestimated by 4 percent in wet months. EPguy was therefore just as good as EPsemi, even over five-day periods.

Equilibrium model: Since Eady only contributed 13 percent to the total EP, net radiation could be used to estimate evapotranspiration or equilibrium evapotranspiration. EQ must be increased by at least 13 percent in order to equal EP. Table 5-1 shows that the monthly α varied between 1.15 to 1.24 with a 10 month average of $\bar{\alpha} = 1.19$. There was no systematic variation with the seasons. It seems that $\bar{\alpha} < 1.26$ in a humid climate.

As described in section 2-7 and equation 2-37, $\alpha = f(\text{Eady/EP})$. It was just shown that Eady/EP $\approx$ f(wind run). Therefore, $\alpha \approx$ f(wind run) and this is verified in figure 5-2b where $\alpha = 1.04 + 0.00223\ U_2$ with a high correlation of 0.93. From figure 3-5a and table 5-1, highest wind run and α occur in February while lowest values occur in June. To examine what this implies, note that the synoptic scale circulation controls the incoming solar radiation which determines the dry bulb temperature and, therefore, the vapour pressure deficit seeing that the actual vapour pressure changes little from day to day. The synoptic scale circulation controls the day to day changes of wind run while the large scale circulation controls the seasonal changes of wind run. Consequently, incoming solar radiation can be used to determine EP provided the influences of the large scale circulation on wind run are taken into account.

However, monthly α had a mean deviation of 0.024 and the use of α = 1.19 underestimated EP by 1 percent. Using the mid-latitude value of α = 1.26 gave a 5 percent overestimation of EP, which is an acceptable error. The equilibrium model can be used confidently at the coastal region, and it is particularly attractive since only air temperature and (Q+q)↓ from the actinograph are required. The model can, therefore, be used in wet conditions, provided the coefficient α is less than 1.26.

Pan Evaporation: Pan coefficients to estimate lake evaporation in Guyana cannot be determined here; the pan coefficient as used in the present study is the ratio of potential evapotranspiration over pan evaporation.

The corrections for heat advection through the sides of the class 'A' pan were usually less than +0.03 inch per day, since the mean surface water temperature was slightly higher than mean air temperature. Kohler (1955) stated that some incoming radiation is used to warm a lake to considerable depths and is not immediately available for evaporation. Therefore lake evaporation should be less than pan evaporation. In the tropics, with small seasonal temperature variations, the heat storage of lakes should vary little over the year and pan coefficient must be higher than that in mid-latitudes.

At the Botanic Gardens the pan coefficient is 1.00. Monthly pan evaporation and monthly pan coefficients are given in table 5-1. In the wet season, pan coefficients were usually greater than 1.00 and in the dry seasons they were less than 0.98. The use of the mean annual pan coefficient can estimate daily EP with good accuracy along the coastland.

The Water Balance for Botanic Gardens: The water balance was computed on a day-to-day basis and the total monthly components of the water balance are given in table 5-2 and figure 5-3. The computations began in June 1971, while EP after October 1972 was obtained from EPsemi.

Rainfall was the most variable quantity in the water balance. In the driest month at least half the plant water requirements were satisfied; floods caused many problems in 1972 but not in 1973. Forty-five percent of annual rainfall occurred in the long wet season of April - June and a large fraction of wet season rainfall did not remain in the soil. The second wet season began unusually early in 1972, on 27 October, but ended quickly in mid-December. January 1973, with 2.16 inches of rainfall, was far drier than January 1972 so that the first dry season of 1973 was exceedingly dry. The second dry season ended with a long dry spell of 55 days that recorded 2.66 inches of rainfall, which was 8 inches short of EP. The high annual rainfall of 105.71 inches in 1972, nearly twice the annual EP, did not prevent a long dry period of 55 days.

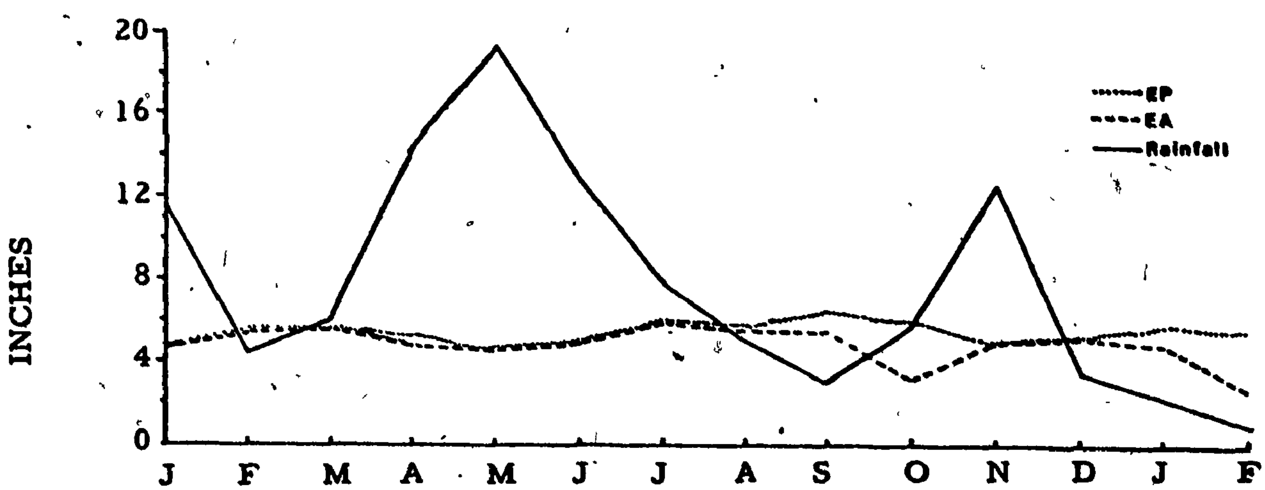
EP has been described above in detail. The seasonal variation of EP was far less variable than rainfall, since EP stayed within 4-6 inches per month. Low EP in rainy months and high EP in dry months are the restrictions to plant growth imposed by atmospheric processes producing heat and precipitation.

Soil moisture storage is 10.0 inches and remained above 70 percent

Table 5-2 Water balance at Botanic Gardens - 1972

Month	J	F	M	A	M	J	J	A	S	O	N	D	J	F	1972	Total
EP	4.55	5.55	5.57	5.33	4.48	4.85	5.99	5.68	6.39	5.99	4.91	5.19	5.81	5.57	64.48	75.86
Rainfall	11.57	4.40	5.98	14.43	19.43	12.59	7.76	5.00	2.90	5.65	12.47	3.53	2.17	0.90	105.71	108.78
R - EP	7.02	-1.15	0.41	9.10	14.95	7.74	1.77	-0.68	-3.49	-0.34	7.56	-1.66	-3.64	-4.67		
Accumulated Deficit		-1.15						-0.68	-4.17	-4.51		-1.66	-5.30	-9.97		
Storage	9.62	8.62	7.75	10.00	10.00	9.48	8.21	7.63	4.97	7.49	9.93	7.74	5.04	3.21		
Change in Storage	-0.38	-1.00	-0.87	2.25	0.0	-0.52	-1.27	-0.58	-2.66	2.51	2.44	-2.19	-2.70	-1.83		
EA	4.55	5.40	5.57	4.55	4.48	4.85	5.99	5.58	5.56	3.14	4.91	5.19	4.87	2.73	59.77	67.37
Deficit	0.0	0.15	0.0	0.78	0.0	0.0	0.0	0.10	0.83	2.85	0.0	0.0	0.94	2.84	4.71	8.49
Surplus	7.40	0.0	1.28	7.63	14.95	8.26	3.04	0.0	0.0	0.0	5.12	0.53	0.0	0.0	48.21	48.21
Runoff	8.68	2.60	1.68	5.84	12.21	9.45	4.96	1.49	0.45	0.13	3.62	1.46	0.44	0.13	55.57	53.14

Fig. 5-3 Water balance at the Botanic Gardens from Jan. 1972 to Feb. 1973



from January-August 1972 when evapotranspiration proceeded at the potential rate. Soil moisture content (SMC) above field capacity (FC) poses a danger to agriculture.. Floods along the coastal region depend on drainage, tides, etc., but can only take place if the moisture content exceeds FC and if a heavy shower occurs after FC is reached. The table below shows the number of times that FC was exceeded for 1-10 consecutive days in 1972.

Consecutive days	1	2	3	4	5	6	7	8	9	10
No. of consecutive days that FC was exceeded in 1972	7	3	3	1	2	0	2	1	0	0

Most heavy showers in 1972 temporarily raised the moisture content above FC for one day, but floods were likely on five occasions. At the beginning of the first wet season, 24 April - 1 May, heavy rainfall was recorded. This heavy rainfall raised SMC from 46 percent to 100 percent; during those 7 days, 10.46 inches of rainfall was recorded including 3.88 inches on 29 April. Floods resulted. At the beginning of the second wet season, 9.16 inches was recorded over the 7 day period 27 October - 2 November. SMC was raised from 60 percent to FC, but floods did not occur although 3.60 inches fell on 1 day, since heavy rainfall ceased after FC was reached. Therefore, rainfall data by itself gave no idea of flood occurrences. Floods were also likely on two other occasions: May 21-25 with 9.03 inches of rain over 4 days after FC was reached, and 8-12 June. SMC, as determined here, may not be precise but is undoubtedly a useful hydrological and agricultural parameter.

1972 was basically a wet year at the Botanic Gardens, but plant water requirements could not be satisfied in some months (February, April, September, and October) when SMC fell below 70 percent. The most severe drought, 2 September - 26 October, recorded only 2.66 inches of rainfall over 55 days so that SMC fell to 36 percent - its lowest value in 1972. For successful rice cultivation the ideal weather is heavy rainfall in April - August for good growth, and a dry period afterwards for harvesting. Therefore, the September -October drought was acceptable for rice cultivation but rather unsuitable for other crops. The early beginning of the second wet season, however, destroyed rice crops that were not harvested by October 27, 1972. In retrospect floods, rather than droughts, caused some problems in 1972 but conditions were reversed in 1973.

Actual Evapotranspiration proceeded near to the EP rate for most of the year since EA = 0.93 EP. Table 5-1 gives the monthly EA/EP ratio. Even in December, with 3.53 inches of rainfall, EA/EP = 1.0 by the utilisation of soil moisture. However, in April with 14.34 inches of rainfall, EA/EP = 0.86, since the heavy rainfall began towards the end of the month.

The daily picture of EA was different. Figure 5-la shows that EA=EP throughout May. On the first day of September 1.43 inch of rainfall raised SMC to FC and, although little rain fell during the rest of September, EA=EP for two weeks afterwards. For the rest of September, EP $\approx$ 0.22 inch per day but SMC < 70 percent; therefore EP continued at a reduced rate. By the end of the first dry season EA = 0.57 EP, but by the end of the second dry season EA = 0.47 EP.

Moisture deficit was 4.71 inches in 1972, in spite of the large surplus water of 48.21 inches. October experienced the largest deficit of 2.85 inches. The next year began differently with little rainfall in January and February 1973. While little or no deficit occurred in January - February 1972, a substantial deficit was experienced in the same period of the following year. The earlier half of 1973 was a severe drought in Guyana, and also in many parts of tropical Africa and Asia.

5.2 Potential Evapotranspiration at Ebini

Penman: Table 5.3 shows the monthly EP from August 1972 - February 1973, using Penman's formula. Because of the close similarity of EP and EPsemi, the latter will be used to analyse potential evapotranspiration at Ebini in early 1972. Ebini had approximately the same total annual EP as the Botanic Gardens, but in the first half of 1972 EP was less at Ebini and was more in the later half of 1972. Ebini did not experience 2 seasonal cycles of EP - a fact which can be inferred from the bright sunshine data in Figure 3-6b. The first dry season, apparently, was very mild over the forest region.

Five-day totals in figure 5-4b show the seasonal changes which occurred. Although the beginning and the ending of the first wet season were quite gradual, there was a sharp drop of EP in November as the ITCZ passed over Ebini. Variations of EP due to synoptic disturbances were smaller at Ebini, figure 5-4a. In the wet season, daily EP was less than 0.20 inch but greater than 0.20 inch in the dry season. The variations are less at Ebini because, between disturbances, there is reduced cloud cover over oceanic and coastal areas, but over continental areas convective clouds due to heating are always present. Thus, EP is not considerably increased.

The aerodynamic term, Eady, accounted for 0.50 inch of evapotranspiration per month in the early half of 1972 and 1.00 inch per month during the long dry season. However, the ratio Eady/EP, being 8-10 percent in the wet seasons and 13-15 percent in the dry seasons, did not have 2 cycles as in the case of Eady. Higher contribution from Eady is to be anticipated at Ebini where it is usually very hot during the day. However, Eady was lower at Ebini than at the Botanic Gardens as a combined effect of lower wind run and fogs or high humidity from 6 pm to 9 am. Eady was negligible at nights. In figure 5-5a, a linear relationship is also noticed between wind run and Eady/EP.

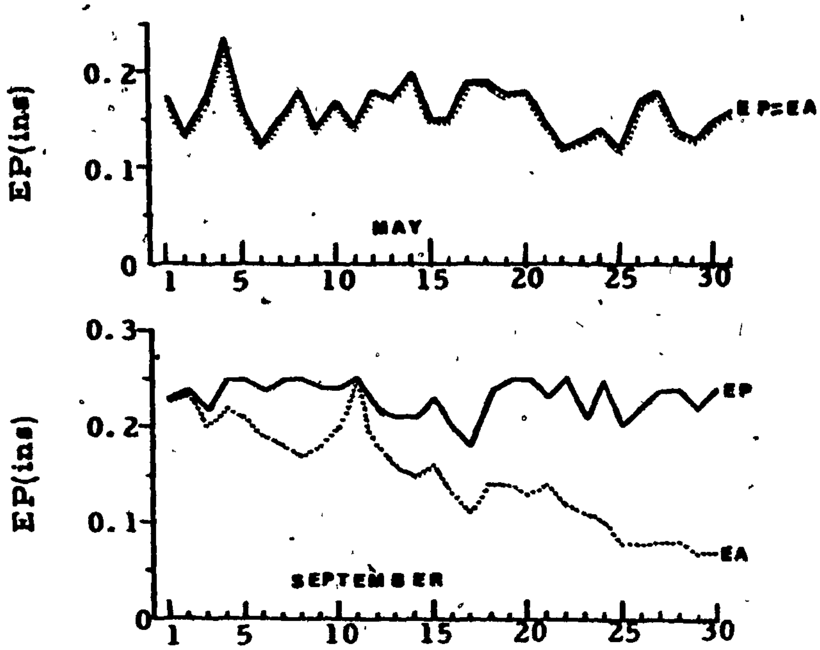
EPsemi: EPsemi gave monthly values to within $\pm$ 4 percent of EP with a mean error of one percent. Therefore, EPsemi should be near to the true EP during the early part of 1972. The five-day mean EP-semi show good agreement with EP in figure 5-4b.

However, the general semi-empirical formula consistently underestimated EP by about 9 percent. The underlying cause for this was that the general equation 4-29 overestimated Rnl and so reduced EP. In figure 4-12b, the Ebini points do not predominate and equation 4-28 for Rnl gives no consideration to the low Rnl at Ebini. Consequently, the general equation cannot be used over the forest region.

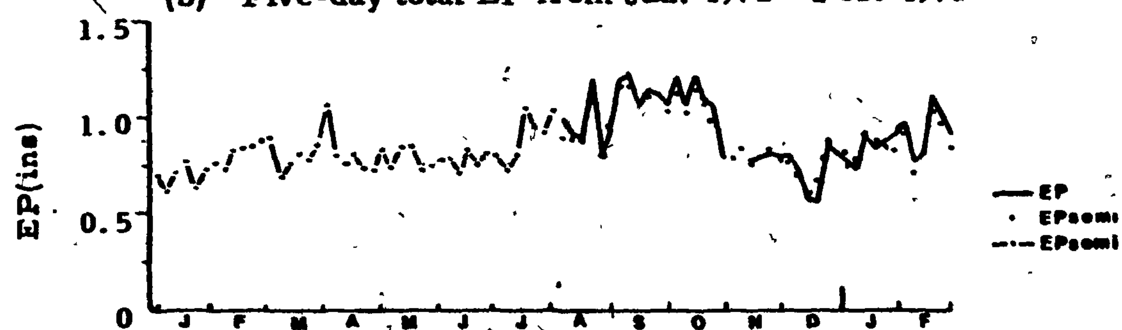
Evapotranspirometers: Measured values of EP exceeded 10.0 inches per month. The observer had killed the evapotranspirometer grass by applying excess fertilizer.

Fig. 5-4 Potential evapotranspiration at Ebini in 1972

(a) Daily EP



(b) Five-day total EP from Jan. 1972 - Feb. 1973



(c) Monthly total EP from Jan. 1972 - Feb. 1973

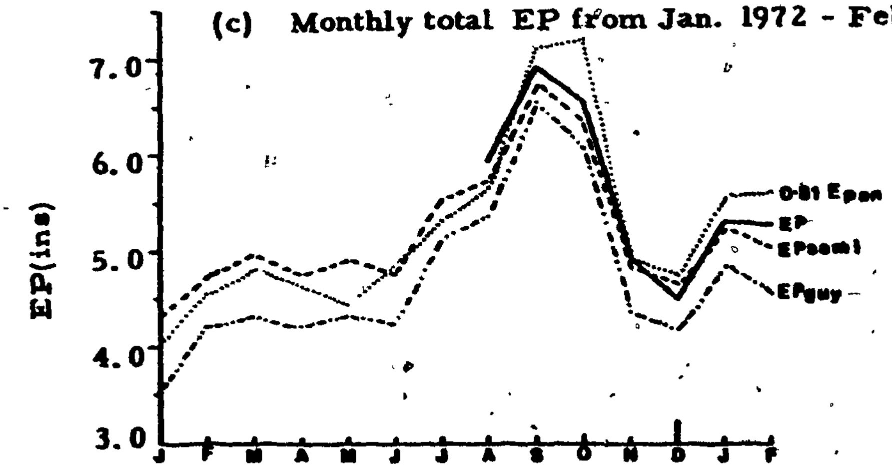


Table 5-3 Monthly EP at Ebini from January 1972 to February 1973

	J	F	M	A	M	J	J	A	S	O	N	D	J	F	1972	TOTAL
EP								5.95	6.96	6.59	(4.76)	4.50	5.31	5.27		
EPsemi	4.33	4.73	4.98	4.84	4.91	4.76	5.56	5.74	6.74	6.36	4.81	4.65	5.28	5.05	62.41	72.74
EPguy	3.61	4.30	4.43	4.31	4.42	4.33	5.25	5.47	6.65	6.18	4.47	4.29	4.96	4.68	57.71	67.35
Epan	5.00	5.62	5.95	(5.63)	5.51	5.98	6.59	7.02	8.80	8.90	6.10	5.85	6.88	6.97	76.95	90.80
0.81 Epan	4.05	4.55	4.82	(4.56)	4.46	4.84	5.34	5.69	7.13	7.21	4.94	4.74	5.57	5.65	62.33	73.55
EA	4.33	4.28	4.83	4.69	4.91	4.76	5.30	4.78	4.49	2.70	4.76	4.31	3.49	1.64	54.16	59.29
1.26 EQ								6.56	7.11	6.71	(5.14)	4.84	5.36	5.24		
1.22 EQ								6.36	6.90	6.50	(4.98)	4.68	5.20	5.08		
Erad	(3.88)	(4.12)	(4.44)	(4.28)	(4.50)	(4.45)	(5.02)	5.48	5.96	5.59	(4.33)	4.03	4.48	4.40	56.08	64.96
Eady	0.45	0.61	0.54	0.56	0.41	0.31	0.54	0.47	1.00	1.00	0.43	0.47	0.83	0.87	6.79	8.49
Eady/EP	(0.10)	(0.13)	(0.11)	(0.12)	(0.08)	(0.07)	(0.10)	0.08	0.14	0.15	(0.09)	0.10	0.16	0.17	.10	.11
EA/EP	1.00	0.90	0.97	0.97	1.00	1.00	0.95	0.80	0.65	0.41	(1.00)	0.96	0.66	0.31	0.87	0.83
EP/Epan	(0.87)	(0.84)	(0.84)	(0.86)	(0.89)	(0.80)	(0.85)	0.85	0.79	0.74	(0.77)	0.78	0.77	0.76	0.81	0.81
$\bar{a}$ = EP/EQ								1.14	1.25	1.24	(1.16)	1.17	1.25	1.27		(1.22)
1.22EQ/EP								1.07	0.99	0.99	(1.05)	1.04	0.98	0.96		(1.01)
EPsemi/EP								0.96	0.97	0.97	(1.01)	1.03	1.00	0.96		(0.99)
EPguy/EP	(0.83)	(0.91)	(0.89)	(0.89)	(0.90)	(0.91)	(0.94)	0.92	0.96	0.94	(0.94)	0.95	0.93	0.89	0.91	0.91

Fig. 5-5 Eady and α as functions of mean wind run at Ebini

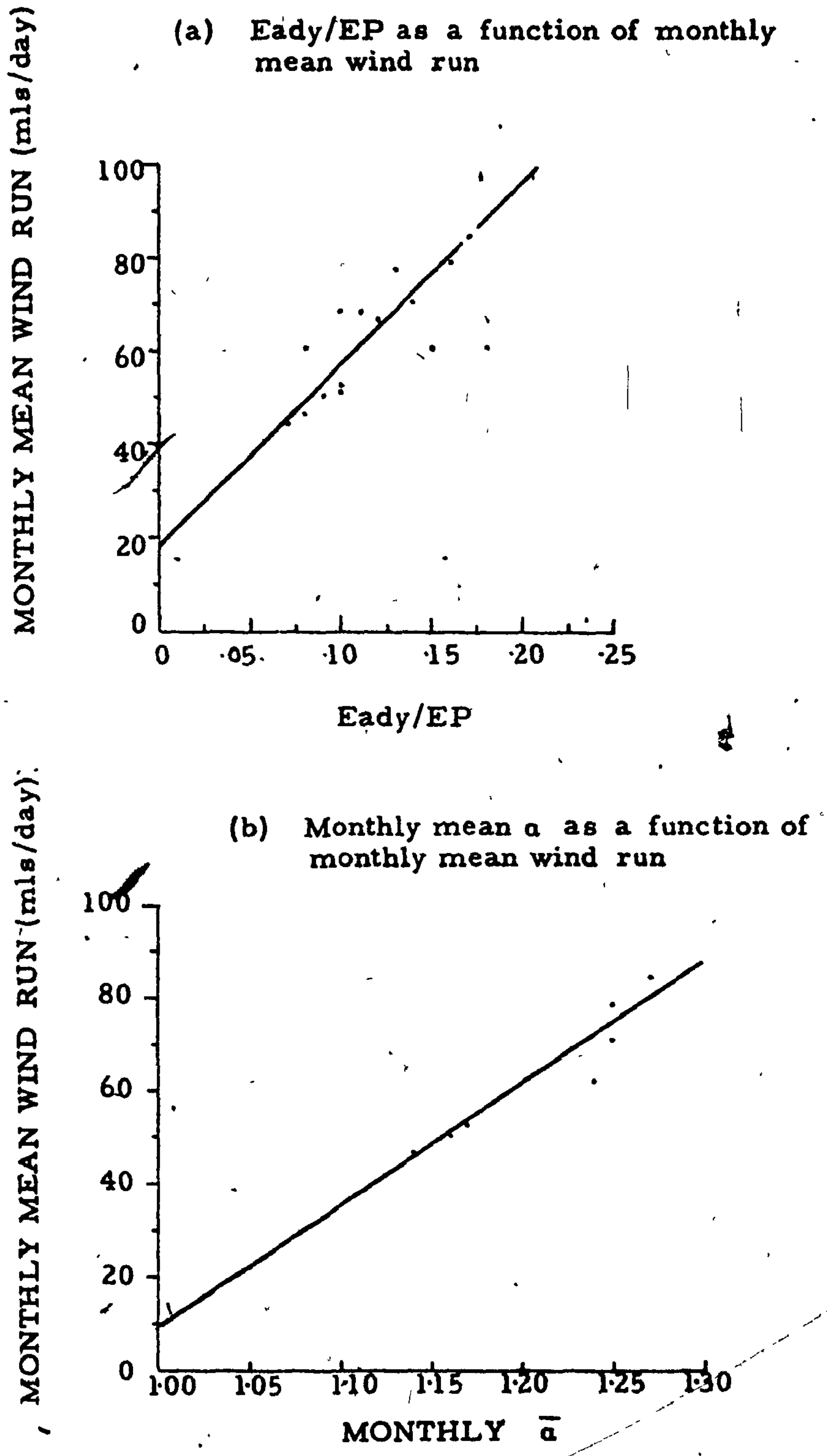
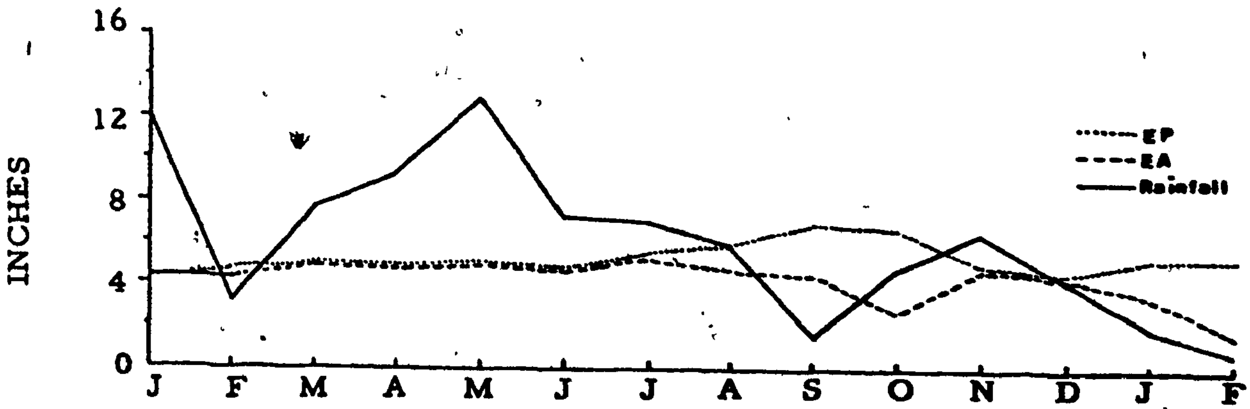


Table 5-4 Water balance at Ebini - 1972

Month	J	F	M	A	M	J	J	A	S	O	N	D	J	F	1972	Total
EP	4.32	4.74	4.98	4.85	4.93	4.77	5.55	5.91	6.95	6.61	4.80	4.48	5.29	5.28	62.89	73.46
Rainfall	11.86	3.09	7.65	9.36	12.99	7.28	7.04	5.84	1.48	4.80	6.54	4.10	1.99	0.72	83.03	84.74
R - EP	7.54	-1.65	2.67	4.51	8.06	2.51	1.49	-0.07	-5.47	-1.81	1.74	-0.38	-3.30	-4.56		
Accumulated Deficit		-1.65						-0.07	-5.54	-7.35		-0.38	-3.68	-8.24		
Storage	5.00	3.78	4.82	5.00	5.00	4.31	3.49	4.55	1.54	3.64	4.83	3.46	1.96	1.04		
Change in Storage	0.38	-1.22	1.04	0.18	0.0	-0.69	-0.82	1.06	-3.01	2.10	1.19	-1.37	-1.50	-0.92		
EA	4.33	4.28	4.83	4.69	4.92	4.77	5.30	4.78	4.49	2.70	4.76	4.31	3.49	1.64	54.16	59.29
Deficit	0.0	0.46	0.15	0.16	0.01	0.0	0.25	1.13	2.46	3.91	0.04	0.17	1.80	3.64	8.74	14.18
Surplus	7.15	0.03	1.78	4.49	8.07	3.20	2.56	0.0	0.0	0.0	0.59	1.16	0	0	29.02	29.02
Runoff	5.13	1.56	1.71	3.66	6.75	4.26	3.07	0.92	0.28	0.08	0.44	0.94	0.28	0.08	28.80	29.16

Fig. 5-6 Water balance at Ebini from Jan. 1972 to Feb. 1973



Equilibrium Model: The model overestimated EP by about 4 percent when $\alpha = 1.26$. This is an acceptable error. However, the computed coefficient is 1.22 and is based on 6 months data shown in table 5-3. Using $\alpha = 1.22$ gave good five-day estimates of EP. Once again the monthly mean α is related to wind run, as shown in figure 5-5b.

In section 2-7, the equilibrium model was proposed for estimating EP over forests. It was just shown that the model indeed gave good estimates of five-day EP and is therefore recommended. In figure 4-9b it was shown that (Q+q)↓ at Ebini can be reasonably estimated from bright sunshine data. Therefore, Rn can be reasonably estimated from bright sunshine. When actinograph data are not available, then EQ and EP can be estimated from bright sunshine and dry bulb temperature. However, it may be necessary to improve the Rn v (Q+q)↓ relationship by taking some radiation measurements over the forest rather that above the Ebini climatological station.

Pan Evaporation: During the first half of 1972, pan evaporation remained within 5-6 inches but increased to 8.9 inches by October. The high dry season evaporation was not due to high advected energy from air to pan, since corrections for this averaged 0.01 inch per day with a maximum correction 0.02 inch. Pan coefficients vary between 0.73 to 0.89 with an annual mean value of 0.81. The use of a mean coefficient of 0.81 throughout the year gave an underestimation of EP in the wet seasons and an overestimation in the dry season.

It was remarked in section 4-4 that the semi-empirical energy budget equation may only be valid for dry months. However two independent estimates of EP, namely EPsemi and 0.81 Epan, gave monthly values that are within 4 percent of each other during the early half of 1972 as shown in figure 5-4c. The monthly EPsemi and 0.81 Epan values were also well below the September - October EP amounts. Therefore EPsemi did not overestimate EP in wet months as was feared.

Water Balance at Ebini: The water balance at Ebini is given in table 5-4 and illustrated in figure 5-6. The annual rainfall, 20 inches in excess of EP, was well distributed throughout the year since the wet months received 7-13 inches of rain. The wet seasons began and ended gradually, unlike the abrupt beginning at the coastal and savannah regions. The second wet season of 1972 was barely noticeable, so that a serious drought took place in early 1973. The ground was parched dry by the end of February 1973.

The annual EP was 62.89 inches, about 2 inches lower than that of the Botanic Gardens. January and February 1973 recorded far higher EP than the corresponding months of the previous year.

Ebini, being on high ground, did not experience floods but when FC was reached heavy rainfall and surface runoff from hills caused floods in nearby valleys and river areas. Most heavy rainfall in 1972 temporarily raised SMC above FC for one or two days. Although floods were likely on several occasions, the heavy rainfall that occurred along the coastland or the savannahs did not prevail in the forest region. For example, daily rainfall in 1972 exceeded 2.0 inches on 3 days as compared to 11 days at the Botanic Gardens. Floods along the coastland were more often the result of coastal hydrometeorological events.

Unfortunately, the low moisture holding capacity of the sandy soil at Ebini favoured the existence of droughts. These were more severe than at the coastland which has a high soil moisture holding capacity. All that was necessary was 2 months of dry weather, as in September and October 1972. SMC reached 18 percent as compared to 47 percent at Botanic Gardens over the same dry spell. The second wet season, being a month and a half earlier, resulted in an exceptionally dry period in 1973. SMC decreased to 20 percent by the end of February compared to 60 percent at the Botanic Gardens; the moisture deficit was 3.64 inches in February. Because root depth is taken to be 5.0 feet, it is possible that trees have access to moisture in deeper layers. Further research is needed to determine how forests survive the severe droughts. Kramer (1949) reported that as SMC is reduced at the upper layers of the soil, the main roots grow downwards towards higher SMC at a rate of 0.1-2.5 inches per day, until a depth of 15-30 feet is reached.

Actual Evapotranspiration was approximately 0.87 of the potential rate. EA ≈ 0.97 EP in the early half of 1972; from a near potential rate in July, EA decreased to 0.41 EP in October. In November, EA= EP but by February 1973, EA=0.31 EP.

The annual EA of 1972 was 54.16 inches when Budyko's drying curve was used, and was 53.56 inches by using Thornthwaite's drying curve. The monthly EA are given below:

Month	J	F	M	A	M	J	J	A	S	O	N	D	1972
EA(THO)	4.3	4.1	4.8	4.5	4.9	4.7	5.1	4.7	4.6	2.9	4.6	4.1	53.6
EA(BUD)	4.3	4.3	4.8	4.7	4.9	4.8	5.3	4.8	4.5	2.7	4.8	4.3	54.2

Thornthwaite's relation overestimated EA in dry months and underestimated EA in wet months, but the monthly discrepancies were very small. The annual EA was also the same when evapotranspiration was assumed to proceed at the EP rate until wilting point was reached; for EA = EP during the wet months, while the total EA over the dry season was the same irrespective of the rate at which it was removed. When the root depth was increased to 10 feet in the dry seasons, then EA was the same in wet months but one to two inches greater in October, January, and February; the annual EA was four inches greater. Consequently, the root depth and the EA-EP relationships had no effect on the wet season water balance, much effects on the forest survival, some effects on the dry season water balance, and little effect on the annual water balance.

5.3 Potential Evapotranspiration at St. Ignatius

Penman: EP was approximately 5-6 inches in wet months and 7-8 inches in dry months. The Penman's method overestimates EP under non-potential evapotranspiration conditions; although incoming solar radiation remains unchanged, the surface temperature under non-EP conditions is greater than that under EP condition, so that Rn is reduced and $s/(s+\gamma)$ is increased. However, since Erad produced the same contribution in all parts of the country during the dry months, this disadvantage of Penman's method is removed at St. Ignatius.

The high EP was the result of large contribution from Eady which is seen, in table 5-5, to be 1.2 inches in wet months and 3.0 inches in dry months; the ratio Eady/EP being 0.20 and 0.40 respectively. The high Eady was the result of high wind run of 200-85 miles per day and large vapour pressure deficit of 11-18 millibars. Consequently, Eady was nearly 3-4 times the corresponding values in other parts of the country, and was an important contribution to high EP. The strong and dry savannah winds should not be ignored in future agricultural projects utilising the abundant ground water resources. It is an important cause of high EP and the savannah climate.

The daily EP in May showed five distinct cycles. The wet season variations of daily EP were very great at St. Ignatius and the Botanic Gardens but not at Ebini. Each disturbance reduced EP to about 0.10 inch, wind run to 70 miles per day, vapour pressure deficit to 4 mb., and Eady to 0.01 inch for 2-3 days. Net radiation increased between disturbances. EP increased, wind run increased to 120 miles per day, vapour pressure deficit increased to 10 mb., and therefore Eady increased to 0.05 inch. In the dry season, intense disturbances were absent from September to March but 5-6 cycles of EP were still observed.

The period 26 October - 27 November, of unique meteorological interest, recorded 1.45 inches of rainfall compared to 14 inches at the Botanic Gardens and 8 inches at Ebini. It marked the initial phase of the second wet season at the coastal and forest regions. From figure 5-7a, there is no question but that two intense disturbances passed over St. Ignatius on 30 October and 2 November since EP, Eady, wind run, and vapour pressure deficit decreased markedly. Both disturbances were responsible for very heavy rainfall at Botanic Gardens and Ebini but only very light rainfall at St. Ignatius. Large cloud formations passed over the Rupununi Savannahs during the middle of the long dry season.

Five day totals of EP are shown in figure 5-7b and monthly totals in figure 5-7c.

Fig. 5-7 Potential evapotranspiration at St. Ignatius in 1972

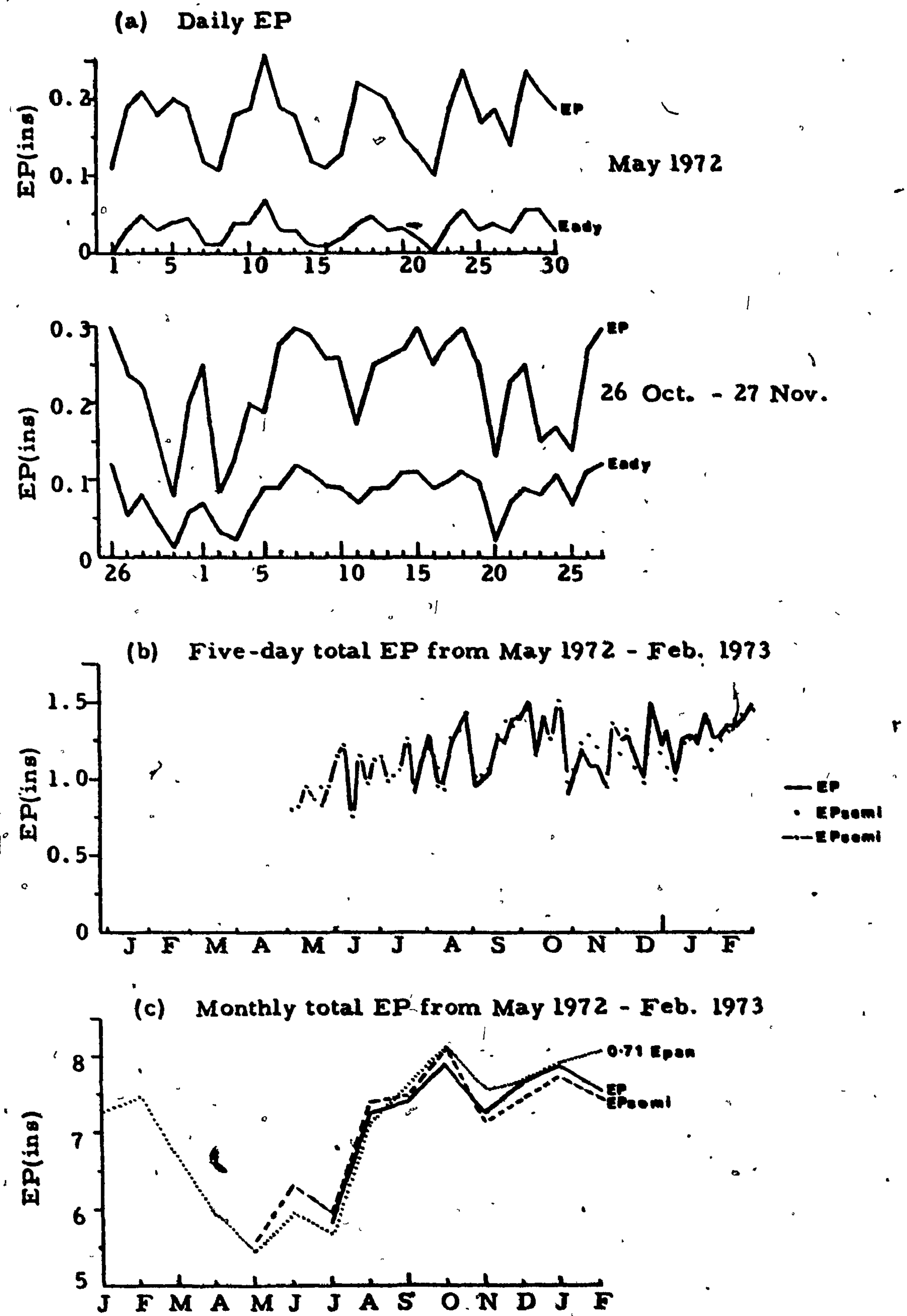


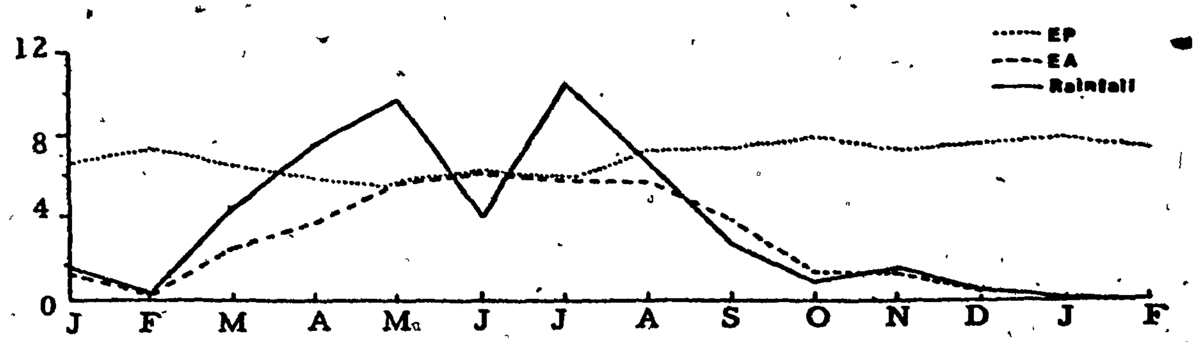
Table 5-5 Monthly EP at St. Ignatius 1972

	J	F	M	A	M	J	J	A	S	O	N	D	J	F	1972	TOTAL
EP							(5.85)	7.23	7.45	(7.91)	7.34	7.67	7.94	7.59		
EPsemi					5.53	6.32	5.96	7.40	7.49	8.07	7.13	7.41	7.82	7.49	(82.65)	(97.96)
EPguy					5.50	6.37	(6.05)	7.50	7.58	(8.19)	7.21	7.53	7.94	7.59		
Epan	10.25	10.53	9.38	8.34	7.66	8.35	7.97	10.06	10.74	11.45	10.61	10.81	11.18	11.32	116.15	138.65
0.71 Epan	7.27	7.47	6.65	5.91	5.44	5.92	5.65	7.14	7.62	8.12	7.54	7.67	7.93	8.04	82.40	98.37
EA					5.35	5.56	5.51	5.28	3.97	1.72	1.35	0.61	0.15	0.02		
1.26 EQ							(5.53)	6.45	6.60	(6.59)	5.69	5.59	5.89	5.03		
Erad							(4.61)	5.39	5.50	(5.50)	4.79	4.70	4.89	4.20		
Eady	2.49	2.63	2.32	1.61	1.07	1.35	1.24	1.87	1.95	2.41	2.55	2.97	3.05	3.39	24.46	30.90
Eady/EP					(0.20)	(0.21)	(0.21)	0.26	0.26	(0.31)	0.35	0.39	0.38	0.45	(0.30)	
EA/EP							0.94	0.73	0.53	0.22	0.18	0.08	0.02	0.00		
EP/Epan					(0.72)	(0.76)	(0.74)	0.72	0.69	(0.69)	0.69	0.71	0.71	0.67	(0.71)	
$\bar{a}$ = EP/EQ							(1.33)	1.40	1.42	(1.51)	1.61	1.75	1.73	1.93	(1.59)	
EPsemi/EP							(1.02)	1.02	1.01	(1.02)	0.98	0.97	0.98	0.99	(1.00)	
EPguy/EP							(1.03)	1.03	1.02	(1.04)	0.99	0.98	1.00	1.00	(1.02)	

Table 5-6 Water balance of St. Ignatius - 1972

Month	J	F	M	A	M	J	J	A	S	O	N	D	J	F	Year	Total
EP	6.66	7.36	6.60	5.85	5.51	6.32	5.85	7.23	7.45	7.91	7.34	7.67	7.94	7.59	81.75	97.28
Rainfall	1.06	0.20	4.49	7.65	9.75	3.98	10.53	6.58	2.56	0.80	1.04	0.38	0.07	0.0	49.02	49.09
R - EP	-5.60	-7.16	-2.11	1.80	4.24	-2.34	4.68	-0.65	-4.89	-7.11	-6.30	-7.29	-7.87	-7.59		
Accumulated Deficit	-17.29	-24.45	-26.56			-2.34		-0.65	-5.54	-12.65	-18.95	-26.24	-34.11	-41.70		
Storage	0.83	0.74	2.68	6.00	5.94	3.84	4.51	2.71	1.46	1.04	0.87	0.74	0.72	0.72		
Change in Storage	-0.17	-0.09	1.94	3.32	-0.06	-2.05	0.63	-1.80	-1.25	-0.42	-0.17	-0.12	-0.02	-0.00		
EA	1.23	0.29	2.55	3.69	5.51	6.03	5.83	5.70	3.81	1.22	1.21	0.50	0.09	0.0	37.57	37.66
Deficit	5.43	7.07	4.05	2.16	0.0	0.29	0.02	1.53	3.64	6.69	6.13	7.17	7.85	7.59	44.18	59.62
Surplus	0.0	0.0	0.0	0.64	4.30	0.0	4.08	2.68	0.0	0.0	0.0	0.0	0.0	0.0	11.70	11.70
Runoff	0.0	0.0	0.0	0.45	3.14	0.94	3.14	2.82	0.85	0.25	0.08	0.02	0.01	0.0	11.69	11.70

Fig. 5-8 Water balance at St. Ignatius from Jan. 1972 - Feb. 1973



Evapotranspirometers: In the Penman formula, Rn and Erad can be estimated to within 10 percent at St. Ignatius. However, there is a possibility that Eady was much too high or too low, in which case EP would have had large errors of 10-20 percent. The evapotranspirometers were expected to give measurements of EP; and the Penman method must be near to those measurements. However, the evapotranspirometers were operated from August - February, which was the long dry season, and measurements exceeded 10 inches per month due to the 'oasis' effect. Evapotranspirometer measurements taken by McGill in 1965 were 5.1-5.4 inches in wet months and 9-18 inches in dry months. The wet season measurements in 1965 were of the same magnitude as wet season computed EPsemi in wet months of 1972 (5.53 inches in May, and 6.00 inches in July) Therefore EPsemi or Eady are reliable in wet months.

Frost (1967) conceded that the evapotranspirometers at St. Ignatius read "unduly high during the dry season" and that readings from evapotranspirometers have, therefore, to be used with considerable caution. For his water balance, Frost used pan measurements instead of evapotranspirometer data. It will be shown later that very high EP errors in dry seasons make no difference in EA estimates for water balance studies. However, further research will be necessary to improve the Eady term at St. Ignatius.

The uncertainty of EP and EPsemi estimates during the dry season still remains but can be assessed by comparison with the Ebini data. In dry months at St. Ignatius, EP < Epan(max) < 11.0 inches and EP > Erad > 5.0 inches. Therefore monthly EP should be 5-11 inches. Since pan coefficients decreased from 1.0 at the coastland to 0.81 at Ebini, then the pan coefficient at St. Ignatius < 0.81 and EP < 0.81 Epan(max) $< 0.81 \times 11$ inches < 8.9 inches. The Penman method with EP $\simeq 7.75$ inches in dry months at St. Ignatius is not far from the real values.

Semi-empirical formulae: EPsemi estimated monthly EP to within 3 percent. Five-day totals show good agreement with the Penman method in figure 5-7b. Table 5-4 illustrates that EPguy overestimated EP by 2 percent and was, therefore, just as good as the regional formula.

Equilibrium Model: In the event of a large Eady contribution to EP, the equilibrium model vastly underestimated EP, as verified in table 5-4. Theoretically the model should not be applied under dry conditions and cannot be used in the Rupununi Savannhas. Mean α varied between 1.40 and 1.93, which was far above 1.26.

Class 'A' Pan: Daily mean air temperature at 2 metres was usually greater than daily mean pan surface temperature, resulting in air to pan heat transfer. Corrections for this process reduced pan meansurements by 0.01 inch in wet season, 0.02-0.03 inch in August-December, and 0.03-0.07 inch in January - March. Corrections often reached 0.10 inch in the January - March period, having winds of 200 miles per day or 8 miles per hour. However, such a mean value did not reveal the high wind speeds during gusts, which must be far above average daily values. Certainly there must be splashing of waves on the sides of the pan with subsequent non-evaporative loss of water; but no corrections were made for this. During the long, dry season birds, lizards, snakes, and rats probably consumed water from the evaporation pan, although a small pond 20 feet away was available to the thirsty animals.

Surprisingly, the 10-month mean pan coefficient, 0.71, fell close to that envisaged by Kohler (1955). Wet months had pan coefficients of 0.72 - 0.80, but dry months had 0.66 - 0.71.

The water balance at St. Ignatius: The water balance could only be evaluated by using pan evaporation during the early part of 1972, since bright sunshine data were absent. Pan evaporation are sometimes indispensible. The water balance for the pre-wet season was not reliable as compared to the period during and after the wet season.

Below average rainfall in June 1972 was the most unusual aspect of the water balance, as shown in figure 5-8. June, the wettest month of the year, has a 20-year average rainfall of 15 inches. Considering the sporadic nature of the savannah rainfall, it was possible that one or two heavy showers missed the raingauge. In spite of the below average rainfall of 1972, the regular wet season swamps were present.

EA proceeded close to the EP rate during the wet season, even in July, and at a reduced rate during the dry seasons. Soil moisture was utilised for evapotranspiration for 2-3 months after the heavy rains. By December all available soil moisture was depleted, and EA = 0.0 in February 1973. The possibility of survival of forest vegetation is negligible, bearing in mind that all available soil moisture was never totally depleted at Ebini or Botanic Gardens.

Since annual EP= 81.75 inches > annual Rainfall = 49.02 inches and annual Deficit = 44.18 inches > annual Surplus = 11.70 inches, then the Rupununi Savannah is a natural climatic phenomenon The savannahs north of Ebini cannot be a natural climatic phenomenon because EP= 62.89 inches < Rainfall = 83.03 inches while deficit = 8.74 inches < surplus = 29.02 inches.

Month	J	F	M	A	M	J	J	A	S	O	N	D	J	F	1972
EA(THO)	1.5	0.5	2.2	3.5	5.4	5.6	5.5	5.3	4.0	1.7	1.3	0.6	0.2	0.0	37.0
EA(BUD)	1.2	0.3	2.6	3.7	5.5	6.0	5.8	5.7	3.8	1.2	1.2	0.5	0.1	0.0	37.6

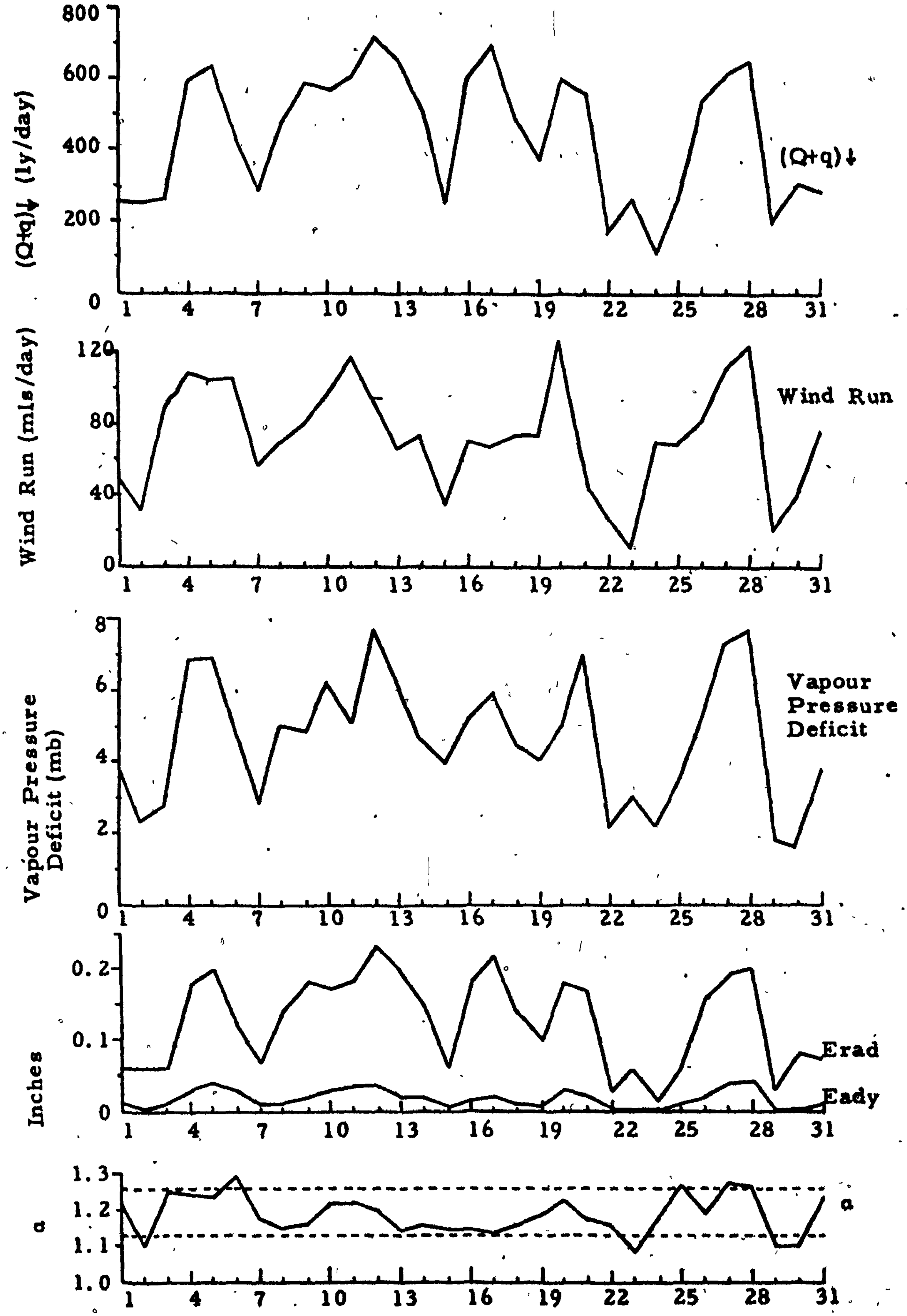
Using Thornthwaite's drying curve, EA was reduced by 0.4 inch in wet months and increased by 0.2 inch in dry months. The annual total EA was more or less unchanged for, given enough time, all soil moisture is eventually depleted irrespective of drying curve. If EP in dry months only were estimated with large errors greater than 10 percent, the total annual EA was unchanged and the water balance was not affected, since EA is very small in dry months.

5.4 Conclusions

The Equilibrium Model can be applied in a saturated atmosphere, or when the wet bulb depressions of the overlying air and the surface have adjusted to one another. Priestley and Taylor (1972) found that EP= $\bar{a}$ EQ where a =1.26. Davies and Allen (1973) claimed a' to be a function of soil moisture, while Rouse and Wilson (1972) found that the model was less applicable under very wet or very dry conditions. The results of this study show that the model, in fact, can be applied under very wet conditions at Botanic Gardens and Ebini provided $a <$ 1.26.

The model was treated in this study in terms of its simplicity and general application rather than its physical interpretation. This was because it eliminated the need of knowing, over a forest, the wind run

Fig. 5-9 Daily variations of (Q+q)↓, wind run, vapour pressure deficit, Erad, Eady, and α in May 1972 at the Botanic Gardens.



and the vapour pressure deficit which were only responsible for an annual average of 10 and 12 percent of EP at Botanic Gardens and Ebini, respectively. The high contribution of Erad towards EP meant that a knowledge of Erad alone was adequate for estimating EP with sufficient accuracy, which increased if Erad and Eady vary together, as seen in figure 5-9. In May, the wettest month of 1972 at Botanic Gardens, figure 5-9 shows that $(Q+q)\downarrow$, wind run and vapour pressure deficit all increased and decreased simultaneously. The knowledge of wind run and vapour pressure deficit were not absolutely essential for estimating EP within reasonable accuracy. Now

$$\alpha = \frac{EP'}{EQ}$$

$$= \frac{Erad + Eady}{Erad}$$

$$= 1 + \frac{Eady}{Erad}$$

$$= 1 + \frac{f(\text{wind run})\, f(\text{vapour pressure deficit})}{f\ (\text{radiation})}$$

In a tropical humid climate where the actual vapour pressure has little variation, $(Q+q)\downarrow$ determines the dry bulb temperature and, therefore, the vapour pressure deficit. Consequently, $(Q+q)\downarrow$ and vapour pressure deficit are highly related as illustrated in figure 5-9 so that

$$\alpha \approx 1 + \text{constant} \cdot f(\text{wind run})$$

This can be verified from figure 5-2b and figure 5-5b. When wind run = 0.0, then α = 1.0. Since the "constant" was very small, variations of α were not very large although wind run varied from 20 to 100 miles per day. As wind run decreased during disturbances, $\alpha = 1.10$, but as wind run increased during disturbances, $\alpha = 1.25$.

Although Erad varied by 90 percent from the mean monthly value in May at the Botanic Gardens, as shown in figure 5-9, the daily α varied by only 10 percent from the mean. Daily α changed from day to day according to the synoptic situation but was far less variable when compared to EP, Erad, Eady and climatological data from which α was determined. The dotted lines in figure 5-9 are the limits of α ($\alpha = 1.26$ and $\alpha = 1.13$) that produced $\pm$ 5 percent error when EP was estimated from $\bar{\alpha} \cdot$ Erad. Using $\bar{\alpha} = 1.19$ overestimated EP by 0.0054 inch on a cloudy day and underestimated EP by 0.018 inch on a sunny day. On cloudy days the errors were very small in quantity. Consequently, there were only 4 days in May at the Botanic Gardens when EP = 1.19 Erad produced daily errors greater than 0.02 inch. Using different monthly α coefficients EP can be estimated from Erad with a mean error of 2 percent. Using a mean annual coefficient of $\bar{\alpha} = 1.19$ throughout the year can estimate daily EP, five-day EP, and monthly EP with mean errors of 8, 5, and 1 percent at the Botanic Gardens.

A necessary condition for justifying the use of the equilibrium model is that Eady must be far smaller than Erad, as at the Botanic Gardens and Ebini. The main reason why the model could not be used in the dry savannah climate was that Eady became nearly as large as Erad. Eady was still highly related to Erad, figure 5-7a, and α was still related to wind run. With monthly α varying between 1.40 in wet months and 1.93 in dry months, the estimation of EP from Erad and a mean α was very unreliable in view of the fact that radiation was not the only primary contributor to EP.

CHAPTER SIX

CONCLUSIONS

The purpose of this study was to find a method of reliably estimating EP in Guyana over 5-day periods, using easily available climatological data.

The regional climatic influences on EP were found to be: maritime climatic influences at Botanic Gardens; restricted outgoing longwave radiation and negligible EP at night due to fogs at Ebini; and strong, dry winds at St. Ignatius.

The linear relationship between Rn and (Q+q)↓ was found to have little variations with changes of climate, surface cover, and seasons. Since albedo and net longwave radiation also had little variations, it was shown that (Q+q)↓ can be used to give reliable estimates of Rn for use in the Penman energy budget method. The regression coefficients between (Q+q)↓ /Qo and n/N had large month-to-month variations but, by using the annual regression coefficients, $(\hat{Q}+q)\downarrow$ could be estimated from bright sunshine to within $\pm$ 6 percent over 5-day periods. Net longwave radiation was not highly related to bright sunshine, or daytime cloud cover, because of the diurnal variations of climate.

Synoptic disturbances produce very large daily changes of EP, especially in the wet seasons. Monthly EP were 4.5 to 6.5 inches from wet to dry seasons; but were 5.5 to 8.0 inches at St. Ignatius.

The contributions of Eady towards EP were 12 percent, 10 percent, and 30 percent at the Botanic Gardens, Ebini, and St. Ignatius respectively; but the contributions of Erad were quantitatively the same in all regions. Consequently, the very high EP at St. Ignatius was a result of very high Eady. The strong dry winds have serious influences on the savannah climate, EP, and water balance.

The mean α coefficient were 1.19, 1.22, and 1.70 at the Botanic Gardens, Ebini, and St. Ignatius. It was shown to be linearly dependent on wind run. When Eady was much smaller than Erad, as at Botanic Gardens and Ebini, then the equilibrium model gave reasonable estimates of 5-day EP but when Eady $\approx$ Erad, as at St. Ignatius, the model was unreliable. The model is recommended for estimating EP over the forest region.

The evapotranspirometers, unfortunately, were unreliable over 5-day periods as a result of heavy rainfall in wet seasons and high heat advection in dry seasons. Over a short period at the Botanic Gardens when such conditions were absent, measured EP was slightly higher than that estimated from Penman formula. This suggests that the latter gave EP to the right order of magnitude.

Pan coefficients were 1.00, 0.81, and 0.71 at the Botanic Gardens, Ebini, and St. Ignatius. The coefficient decreased towards dry climate and dry seasons. The large variation of pan coefficient with climate suggest that pan evaporation cannot be used in a water balance scheme since it is difficult to know what the representative pan coefficients are in places between the three stations. However, the pan coefficient at Botanic Gardens should remain the same along the coastland, and it is recommended for agricultural uses.

The regional semi-empirical formulae gave fairly good estimates of EP and were the best substitute for the unmodified energy balance formulae. The general formula estimated annual EP with no difference at Botanic Gardens, underestimated EP by 9 percent at Ebini, and overestimated by 2 percent at St. Ignatius. The error at Ebini was reduced to 4 percent by using equation 4-21 to estimate Rnl separately.

Realistic estimates of the water balance were also made, using merely climatological data, in order to determine actual evapotranspiration. EA proceeded at the potential rate over most of the year at Botanic Gardens and Ebini. The annual water balance was the same for Thornthwaite's and Budyko's drying curves. Coastal floods were found to be the result of coastal hydrometeorological events. The forest vegetation, in order to survive, must extract moisture from the deeper soil layers, but the Rupununi vegetation cannot do this since annual EP was found to be far above annual rainfall.

This study has shown that EP can be estimated with reasonable accuracy over five-day periods, using ordinary climatological data, and the values so obtained are sufficiently reliable for agricultural and hydrometeorological uses. Most important, calculations of the water balance of Guyana can be undertaken since rainfall and river runoff are known while EP can easily be determined.

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