POTENTIAL EVAPOTRANSPIRATION

ON SMALL PACIFIC ISLANDS

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ABBREVIATIONS, VARIABLES and SYMBOLS

symbol	definition
a	albedo
alt	solar altitude
alpha	Priestley-Taylor constant
C	cloudiness in hundredths
c	cloudiness in octavs
day	day of the year
dec	sun's declination
delta	slope of T versus saturation vp curve
ET	evapotranspiration (in mm)
gamma	psychometric constant
J_o	the solar constant (1.94 ly/min)
lambda	latent heat of vaporization of water
n/N	ratio of actual to possible sunshine hours
o	a variable used in computing R_{gc}
PE	potential evapotranspiration (in mm)
phi	latitude
Pi	3.1415926
R_a	Angot's value
R_{dc}	clear day direct beam radiation
R_g	global radiation
R_{gc}	clear day global radiation
R_n	net radiation
R_{no}	net outgoing longwave radiation
r	daily earth-sun distance
r_o	mean annual earth-sun distance
sigma	the Steven-Boltzman constant
T	temperature
t	time of day
tao	length of the day
vp	vapor pressure (in mb)
z	solar zenith angle

CHAPTER I

INTRODUCTION

In this study, potential evapotranspiration (PE) is calculated for small Pacific islands and used to compute the water balance for wet areas.

The results of this study will be useful as a reference for PE applications, such as computing the water balance for water resource studies (e.g. Peterson, 1980; Lloyd, 1980). The results are compared with radiation and pan evaporation data taken from stations around the Pacific, and are presented in a series of monthly and annual isoline maps for the region from 30^{0} North to 25^{0} South and 130^{0} East to 130^{0} West. One theme of this research is to make the results as widely applicable as possible. Therefore, all calculations are based on uniform assumptions and methods are derived or suggested for conversion to PE based on some variation of these assumptions, e.g. a different albedo or Priestley-Taylor constant.

A water balance is computed for wet areas, e.g. taro patches and other swampy areas, by subtracting calculated PE values from precipitation. The significance of the water balance to fresh water lens systems will be discussed as well as some suggestions for water management.

CHAPTER II

POTENTIAL EVAPOTRANSPIRATION

Many methods are available for computing potential evapotranspiration (PE); one of the most widely accepted is Penman's equation. Penman's (1956) formula incorporates the basic variables that affect PE: radiation, wind, humidity, and temperature. Priestley and Taylor (1972) simplified the Penman equation by including the aerodynamic term in a constant, and their method has been widely accepted and evaluated (de Bruin and Holtslay, 1982; Bailey and Davies, 1981; Williams and Broersma, 1978; Mukammal and Neuman, 1977; Stewart and Rouse, 1976; Thompson, 1975; Tanner and Jury, 1976). The Priestley-Taylor approach seems the most practical for computing PE in the Pacific region because of the scarcity of wind data (some wind data can be found in the Navy's Marine Climatic Atlas for the Pacific region, but readings are sparse and widely scattered). Temperature and humidity data are available for many Pacific stations in the World Meteorological Organization's (WMO) publication, "Monthly Climatic Data for the World." Actual radiation data are not available, but can be estimated using cloudiness data given for the Pacific by Sadler (1976). Sadler used nine years of satellite observations to estimate average monthly cloudiness on a 2-1/2 degree grid over the tropical Pacific ocean.

These calculations will be valid for islands or parts of islands that have similar cloudiness to that of the open ocean; i.e. atolls, barrier islands, cays, and other small, flat islands without large convective or orographic effects. PE is then computed for vegetated surfaces assuming an albedo of 0.25. The choice of 0.25 for an albedo is somewhat arbitrary, although suggested by de Bruin (1983) for tropical applications of the Priestley-Taylor equation, because actual albedo depends on field conditions, e.g. surface type. A formula is derived to facilitate conversion to PE for other types of surfaces.

Temperature and Humidity

To simplify the computations, temperature and vapor pressure are assumed constant at 27°C and 28.5 mb, as recommended by de Bruin (1983) for the humid tropics. Of course, temperature will not normally rise above about 30°C in the wet tropics because evaporation absorbs most of the available energy (Priestley, 1965; Hoffert, 1983).

Humidity is fairly constant throughout the region, being slightly lower on the average in the eastern Pacific and fluctuating during the sub-tropical winters. For this study, relative humidity is taken as an estimation of the precipitatible water in the atmosphere, i.e. the water vapor available to absorb outgoing longwave radiation. This is not strictly accurate as the amount of precipitatable water is higher in the western Pacific than in the eastern Pacific due to the rising trade wind inversion. However, a small change in atmospheric moisture has little effect on the results as it is important only in the computation of net outgoing longwave radiation (if there were an aerodynamic term, like the Penman equation, vapor pressure would be significant). For comparison: at $27^{\circ}C$, 70% relative humidity would decrease PE values by about 2%, 60% humidity would decrease PE by 5%, and 90% humidity would increase PE by 2%; these differences are due to the change in the radiation balance, i.e. the lower the atmospheric moisture (humidity), the greater the outgoing longwave radiation. The Penman equation would respond oppositely because of the increasing vapor pressure gradient in the aerodynamic term.

Temperature is more important than atmospheric moisture in the PE calculations as it is a factor in computing net outgoing longwave radiation, the psychometric constant (also dependent upon surface air pressure, Storr and Hartog, 1975; Ripley, 1976), and the slope of the saturation vapor pressure curve; all important factors in the Priestley-Taylor equation. Table 1 gives some idea of temperature variations on low Pacific islands at various latitudes (From WMO's, "World Weather Records: 1961-1970") It should also be noted that ocean surface temperature tends to increase from east to west in the tropical Pacific (Newall, 1979), which affects air temperature.

For the equatorial Pacific, where most of the relevant islands lie, temperature is fairly constant throughout the year, fluctuating slightly more in the drier eastern Pacific. For the higher latitudes, the annual temperature range is greater, from $18.5^{\circ}C$ in February to $26^{\circ}C$ in August for Midway. Midway's $22.1^{\circ}C$ annual average temperature would result in approximately 7% lower values of PE than those calculated using $27^{\circ}C$. However, since very few of the relevant islands (predominantly coral atolls) lie that far from the equator (coral cannot survive in cold water) where temperature is

Table 1

Temperature Data for Selected Stations

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Takaroa 14° 29' S 145° 2'W Elev=2m												
27.3	27.5	27.9	27.9	27.5	26.7	26.1	25.8	26.0	26.5	26.9	27.3	27.0
Tarawa 1° 21' N 172° 55'E Elev=2m												
27.7	27.7	27.6	27.7	28.0	27.9	27.6	27.9	28.0	28.0	27.9	27.9	27.8
Midway 28° 12' N 177° 23' W Elev=4m												
18.6	18.5	18.9	19.4	21.3	24.1	25.3	26.0	26.0	24.2	22.1	20.2	22.1
Johnston Island 16° 44' N 169° 31' W Elev=2m												
25.0	24.9	25.1	25.5	26.2	26.8	27.2	27.5	27.6	27.2	26.4	25.6	26.3
Kwajalein 8° 44' N 167° 44' E Elev=1m												
26.7	26.7	26.9	27.1	27.3	27.4	27.6	27.7	27.7	27.7	27.4	27.1	27.3
Penrhyn 9° 1' S 158° 4' W Elev=2m												
27.7	27.8	28.0	28.3	28.3	27.7	27.4	27.2	27.3	27.5	27.7	27.8	27.7
Falalop Is., Ulithi 10° 2' N 139° 48' E Elev=1m												
27.1	26.8	27.7	27.9	28.1	28.0	27.8	27.5	27.4	27.5	27.6	27.1	27.5

fairly uniform, it seems reasonable to simplify the equations by assuming that it remains constant.

The Priestley-Taylor Equation

The Priestley-Taylor equation can be written as:

$$PE = (1.26/\text{lambda})(\text{delta}/(\text{delta}+\text{gamma}))R_n \text{ (in mm)} \qquad \text{eqn (1)}$$

where:

gamma is the psychometric constant

lambda is the latent heat of vaporization of water

delta is the slope of the saturation vapor pressure versus temperature curve.

R_n is net radiation (in cal/cm^2/day)

Lambda is 58.2 $cal/cm^2/mm$ for 27^oC as given by List (1966).

Gamma can be calculated using an equation given by Jenson (1973):

gamma = .24(press in mb)/.622(lambda)

= 1008(.24)/.622(582) = 0.6683

Delta is found using another formula from Jenson:

$$delta = 33.864(.0594(.00738(T)+.8072)^7-.0000342)$$

$$= 2.1031 \text{ for } T=27^oC$$

Thus, the 1.26(delta/(delta + gamma)) term approximates 1/(1+Bowen ratio). The equation can then be evaluated:

$$PE= (1.26/58.2)(2.1031/(2.1031+.6683))R_n$$

$$PE = 0.01643R_n \qquad \text{eqn (2)}$$

Equation 2, then, suggests that for the tropical Pacific, approximately 96% of net radiation is available for PE (calculated by factoring the lambda term out of equation 2). Net Radiation calculations and formulae are given in the next section.

There has been some discussion concerning the constant 1.26 given by Priestley and Taylor (e.g. de Bruin and Keijman, 1979; Mukammal and Neuman, 1977; Shuttleworth and Cullen, 1979). The choice of a constant depends on estimated wind conditions, on surface wetness and type and soil characteristics. Since each of the aforementioned conditions depends upon the characteristics of each specific place and this study is intended as a baseline for the entire region, 1.26 is used as recommended by de Bruin (1983). Other values of the Priestley-Taylor constant can be incorporated simply by scaling the results.

Net Radiation

Global radiation is based on cloudiness data given by Sadler. He estimated average monthly values on a 2-1/2 degree grid (each square representing about 80,000 km^2) using satellite photos taken during a nine year period: 1965-1973. The data represent conditions for the open ocean and therefore my results will represent only those land areas that have cloudiness similar to that of the open ocean, i.e. islands without large convective, advective, or orographic effects. A discussion of representative areas is given later.

Net radiation (the energy available for evapotranspiration) is calculated using the formula:

$$R_n = (1-a)R_g - R_{no} \qquad (\text{in cal/cm}^2\text{/day}) \qquad \text{eqn (3)}$$

where:

a is the albedo (assumed 0.25 for vegetated surfaces)

R_g is global radiation (direct and diffuse)

R_{no} is net outgoing longwave radiation

Net outgoing longwave radiation is primarily dependent on cloud cover, temperature, and humidity. For this study, vapor pressure at the surface is used, although, strictly speaking, precipitatible water in the atmosphere should be used because of changing atmospheric moisture content with altitude (e.g. the trade wind inversion). Net outgoing radiation is normally calculated using the following formula (from Doorenbos and Pruitt, 1977):

$$R_{no} = \text{sigma}T^4(.34-.044vp^{1/2})(.1+.9(n/N))$$

where:

sigma = $11.71(10^{-8})$ given in cal-cm^{-2}-^{o}K^{-4}-day^{-1}

T is the temperature (300^{o}K)

vp is vapor pressure (28.5 mb at 80% humidity and 27^{o}C)

n/N is the ratio of actual sunshine hours to maximum possible sunshine hours given by the approximation:

$n/N = (.95 - c/10)$ (derived from Doorenbos and Pruitt)

where: c is cloudiness in octas.

Assuming that T=300^{o}K and vp=28.5mb, R_{no} is then:

$$R_{no} = 11.71E{-8}(300)^4(.34-.044(28.5^{1/2}))(.1+.9(.95-c/10))$$

$$R_{no} = 95.2063 - 8.9723c \quad \text{(in cal/cm}^2\text{/day)} \qquad \text{eqn (4)}$$

A typical value for R_{no} (assuming 50% sky cover; normal for most of the study area) would be about 91 cal/cm^2/day using equation (4). This compares favorably with the range of values given for the Hawaiian Islands by Charnell (1967) of 58 cal/cm^2/day for overcast skies to 173 cal/cm^2/day for clear skies. Assuming linearity, 1/2 sky cover would result in R_{no} = 115 cal/cm^2/day over the open ocean.

A formula for computing global radiation, R_g, has been empirically derived and confirmed by Reed (1977, 1978, 1982) using shipboard pyranometer readings in the central Pacific. His formula is:

$$R_g = R_{gc}(1 - .62C + .0019alt) \quad \text{(in cal/cm}^2\text{/day)} \qquad \text{eqn (5)}$$

where:

C is cloudiness in hundredths

alt is the noon solar altitude in degrees

R_{gc} is clear day global radiation

Combining Seckel and Beaudry's (1973) equations for calculating clear day global radiation (R_{gc}) with equation (5), average daily global radiation can be calculated for each month. Another method of calculating global radiation, the Brunt formula, is presented later for comparison. (A presentation of Seckel and Beaudry's equations is given in Appendix B.) Average annual values are given in Figure 1.

It should be noted that Reed's equation (eqn (4)) requires two daily independent variables as input and thus radiation must be computed for each day and then summed to obtain monthly averages. Reed (1977) reported that monthly mean values should be accurate to $\pm$ 13% at the 95% confidence limit and probably slightly underestimates global radiation for the central and western Pacific due to the prevalence of cirrus clouds as suggested by Quinn and Burke (1968).

Typical net/global radiation ratios are show in Figure 2 for all months at 30° N and all latitudes for January. Since longitude did not significantly affect results, the curves shown incorporate averages for all longitudes. Note that the ratio is lower when global radiation is low (i.e. during the winter) because the magnitude of net outgoing longwave radiation remains fairly constant throughout the year due to constant temperatures. The summer ratios correspond well with the 2/3 ratio found for Hawaii by Ekern (1965).

Note that net radiation totals can be found directly from PE values by combining data from Figures 3 through 15 with equation (2).

Radiation Comparison

For comparison, I have calculated global radiation using the crude, but popular, Brunt formula. It is given by:

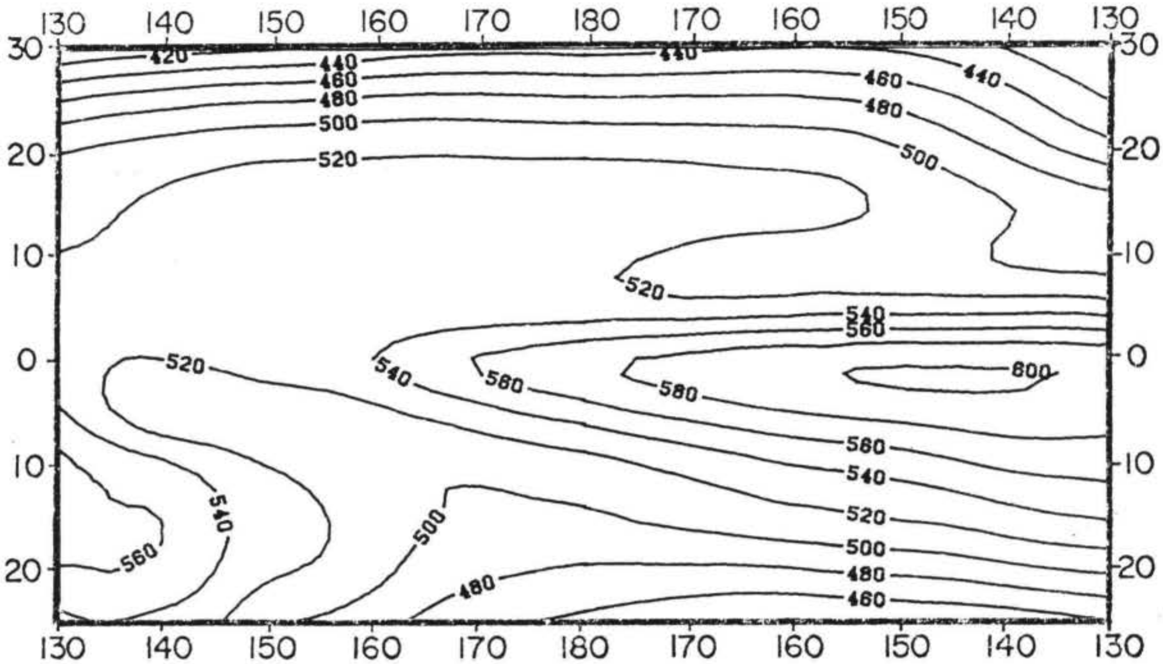

Figure 1. Mean Daily Global Radiation for the Year

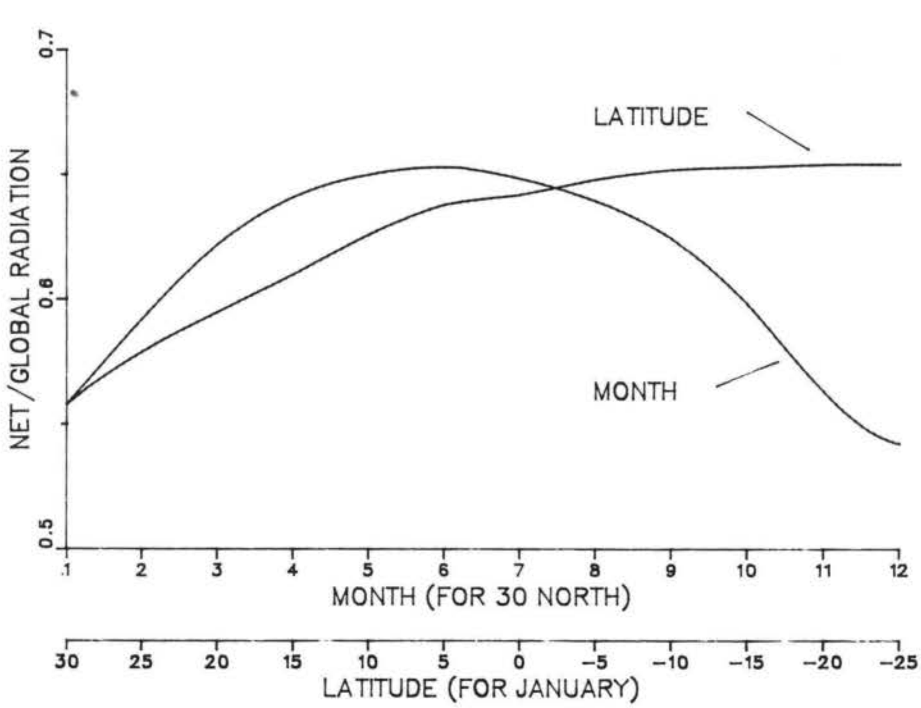

Figure 2. R_n/R_g Ratio

$$R_g=(.25 + .5(n/N))R_a$$

where:

n/N is the ratio of actual to possible hours of sunshine

R_a is Angot's value

The constants .25 and .5 in the Brunt formula are suggested by Doorenbos and Pruitt (1977) as appropriate for the tropics. Brunt's original constants were .18 and .55 respectively and Black (1954) suggests .23 and .48. n/N can be estimated from cloudiness data using the approximation given earlier. Angot's value, the amount of radiation that would reach the earth's surface in the absence of the atmosphere, is calculated using the equations given by List (1966). (A presentation of these equations, derivations, assumptions, a FORTRAN program, and average monthly Angot's values for all latitudes are given in Appendix A.) A comparison showing the ratio of radiation calculated using Reed's method to that calculated using the Brunt formula is given in Table 2 (longitude did not significantly influence the results):

Table 2

Comparison of R_g by Reed and Brunt Formulae

Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
30N	1.08	1.11	1.13	1.14	1.15	1.16	1.16	1.16	1.15	1.13	1.09	1.07
25N	1.11	1.14	1.15	1.16	1.17	1.17	1.18	1.18	1.17	1.15	1.13	1.10
20N	1.14	1.16	1.18	1.18	1.18	1.19	1.19	1.19	1.19	1.17	1.15	1.13
15N	1.17	1.18	1.19	1.20	1.20	1.20	1.20	1.20	1.20	1.19	1.18	1.16
10N	1.19	1.20	1.21	1.22	1.21	1.21	1.21	1.22	1.22	1.21	1.20	1.19
5N	1.21	1.22	1.23	1.24	1.23	1.22	1.22	1.23	1.23	1.23	1.22	1.21
0	1.23	1.23	1.24	1.24	1.23	1.22	1.22	1.23	1.24	1.24	1.23	1.22
5S	1.22	1.23	1.23	1.23	1.22	1.20	1.20	1.21	1.22	1.23	1.22	1.22
10S	1.20	1.21	1.22	1.21	1.20	1.19	1.18	1.19	1.21	1.21	1.21	1.21
15S	1.20	1.20	1.20	1.19	1.17	1.15	1.15	1.16	1.18	1.19	1.20	1.20
20S	1.18	1.18	1.18	1.17	1.15	1.12	1.11	1.14	1.16	1.18	1.18	1.19
25S	1.17	1.16	1.16	1.15	1.12	1.08	1.07	1.10	1.13	1.16	1.17	1.17

The average ratio is 1.18, i.e. the resulting values from the Brunt formula are somewhat lower than global radiation calculated using Reed's method. At the equator, Reed's equation gives R_g consistently higher at about 23%. The Brunt formula gives values closer to Reed's in the higher latitude winter due to the influence of the noon solar altitude term in the latter. One reason that global radiation might be higher in the Pacific than normally expected for similar cloudiness (e.g. if computed using the Brunt formula) is the predominance of high clouds (Reed, 1977; Quinn and Burt, 1968), i.e. high cirrus clouds admit more direct radiation than thick cumulus clouds, over the equatorial Pacific. While Reed's formula was derived using data taken in the central Pacific, and thus may not accurately estimate global radiation for the eastern and western Pacific, it seems prudent to calculate PE for the entire Pacific using the same method as a baseline for consistent comparison. Also, Quinn and Burke (1968 and 1967) suggest that cloud quality may be similar for the western and central Pacific along the equatorial trough.

Calculated global radiation values can also be compared with global radiation measurements recently collected from several Pacific stations. Table 3 is a compilation of Pacific island radiation data (HNEI, 1983) taken during the period from June 1982 to May 1983, except for the Hawaii (from Ekern and Yoshihara, 1977) and Canton Island (from Quinn and Burke, 1968) data.

Table 3
Average Daily R_g at Pacific Stations
($cal/cm^2/day$)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Canton 2° 49' S 171° 41' W Atoll (12 year mean)													
estimated	576	608	614	588	550	519	533	579	606	627	606	586	582
measured	590	630	631	598	560	538	543	595	636	649	513	585	597
% diff.	-2	-3	-3	-2	-2	-4	-2	-3	-5	-3	-1	0	-3
Honolulu, Hawaii 21° 20' N 157° 50' W High Island (50 year mean)													
estimated	367	426	505	553	603	605	601	593	549	471	387	349	502
measured	368	430	491	542	580	599	598	589	554	471	403	352	498
% diff.	0	-1	+3	+2	+4	+1	+1	+1	-1	0	-1	-1	+1

	1982 Jun	Jul	Aug	Sep	Oct	Nov	Dec	1983 Jan	Feb	Mar	Apr	May	Year
Majuro 7° 5' N 171° 20' E Atoll													
estimated	522	526	550	544	532	504	472	488	528	557	557	532	526
measured	393	422	430	456	444	-	438	469	510	552	562	527	473
% diff.	+33	+25	+28	+19	+20	-	+8	+4	+4	+1	-1	+1	+11
Truk 7° 30' N 151° 52' E High island													
estimated	528	526	553	542	533	495	475	486	520	540	557	547	525
measured	393	394	391	413	-	-	415	427	-	-	-	-	406
% diff.	+34	+34	+41	+31	-	-	+14	+14	-	-	-	-	+29
Ponape 6° 58' N 158° 13' E High island													
estimated	521	524	549	548	530	497	474	488	521	550	554	557	526
measured	393	405	410	393	-	443	372	416	458	516	567	-	436
% diff.	+33	+29	+34	+39	-	+12	+27	+31	+25	+20	+7	-	+21
Kosrae 5° 20' N 163° 2' E High island													
estimated	545	542	551	534	503	482	457	481	538	570	572	565	522
measured	-	386	380	367	-	413	383	-	-	-	-	-	386
% diff.	-	+40	+45	+46	-	+20	+19	-	-	-	-	-	+35
Yap 9° 28' N 138° 6' E High island													
estimated	545	532	540	524	522	473	457	476	514	555	588	602	527
measured	378	-	430	-	-	-	-	-	-	-	-	-	-
% diff.	+44	-	+26	-	-	-	-	-	-	-	-	-	-

Table 3 (continued)

	1982 Jun	Jul	Aug	Sep	Oct	Nov	Dec	1983 Jan	Feb	Mar	Apr	May	Year
	Palau 7° 20' N 134° 30' E High island												
estimated	523	511	537	542	533	498	473	486	520	546	581	559	525
measured	275	457	399	504	-	-	-	-	476	-	-	-	422
% diff.	+90	+12	+35	+8	-	-	-	-	+9	-	-	-	+24
	Saipan 14° 14' N 145° 45' E High island												
estimated	598	566	542	520	510	457	530	436	501	557	608	617	529
measured	450	485	480	453	358	410	380	422	485	519	539	574	463
% diff.	+33	+17	+13	+15	+42	+11	+13	+3	+3	+7	+13	+7	+14
	Am. Samoa 14° 20' S 174° 43' W High island												
estimated	382	386	445	520	542	584	569	566	567	553	481	418	525
measured	373	302	275	424	399	353	488	413	411	484	444	322	383
% diff.	+2	+28	+62	+23	+36	+65	+17	+37	+38	+14	+8	+30	+37

The data given for 1982 and 1983 may not represent long term mean conditions because of the unusual climatological situation existing during the period they were being gathered. First, the recent extreme El Nino event distorted weather patterns world wide. El Nino was accompanied by a rise in Pacific ocean surface temperature; this resulted in an increased cloud cover in some areas and hence less incoming solar radiation. Also, in Mexico, El Chichon erupted in March and April of 1982. The volcano lifted a cloud of fine dust particles, and sulfur dioxide, into the stratosphere at approximately the same latitude (17^{0} 20' North) as most of the Pacific radiation stations. It has been shown that the resulting dust cloud depleted incoming solar radiation (Pollack, Toon, Danielsen, Hoffman, Rosen, 1983; Dutton, DeLuisi, 1983) which further distorts data gathered during 1982 and 1983. The calculated global radiation values correspond better with the measured R_g values for the first half of 1983 when the effects of El Chichon and El Nino were weakening. Also, it should be noted that radiation for this period was the lowest on record for Hawaii stations (Ekern and Yoshihara, 1977).

The best correspondence is with the data of Canton Island, the only low island station given, and with Hawaii; both stations having long term records. Although, the Honolulu data is taken from a high island, the station is located on the lee side of the mountains of Oahu where rainfall is approximately the same as that of the open ocean. The differences between estimated values and Canton and Honolulu data are well within Reed's estimated accuracy ($\pm$ 13%) for monthly averages.

Radiation in the PE Equations

Average monthly global radiation values have been computed on a five degree grid from 30^{o}N to 25^{o}S and 130^{o}E to 130^{o}W by combining equations (2), (3), and (4):

$$PE = .01643(.75Rg-(95.2063-8.9723c)) \qquad \text{eqn (5)}$$

Note that an increase in cloudiness results in a decrease in net outgoing longwave radiation (increasing R_n) and a decrease in insolation (decreasing R_n).

The PE calculations, based on an albedo of .25, can be converted to PE based on other albedos by separating the shortwave and longwave terms in equation (2). It should be noted first, however, that the ratio of net R_g ($(1-a)R_g$) to R_{no} is not constant from month to month; it changes with the altitude of the sun, i.e. since the study area is always warm, outgoing longwave radiation is always high while global radiation depends on solar zenith and day length. This is illustrated by the following sample of monthly R_{no} to net R_g ratios for all months at 30^{o}N and for all latitudes during January. (The ratio is fairly constant at the equator because the solar altitude is always high.)

Table 4

R_{no}/net R_g for 30^{o}N for all Months

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
.25	.20	.16	.14	.13	.12	.14	.15	.17	.20	.25	.26

Table 5

R_{no}/net R_g for January at all Latitudes

30N	25N	20N	15N	10N	5N	0	5S	10S	15S	20S	25S
.25	.23	.21	.18	.17	.15	.14	.13	.13	.12	.14	.14

The average annual ratio of R_{no} to net R_n for all latitudes is 0.16, ranging from 0.18 at higher latitudes to 0.14 in equatorial areas. Note that the ratio rises sharply in the winter at high latitudes, thus decreasing net radiation available for PE, while it remains fairly constant throughout the year at the equator.

Since this ratio has already been included in the computation of PE for an albedo of 0.25, small adjustments in annual PE totals for different albedos using the 0.16 ratio will result in but a small error. In order to convert my calculations to PE values on surfaces having an albedo other than 0.25 (important only in computing net global radiation), one would use the equation:

$$PE_{new} = PE_{old}/.84((1\text{-albedo})/.75 - .16)$$

The error introduced will be small. For example, converting to an albedo of 0.10 at Tarawa (1^{0} 21' North) would result in virtually no error and an overestimation of only 1% at Midway (28^{0} 12' North).

Distribution

Figures 3 through 15 are monthly and annual isoline maps of PE for the Pacific using radiation cloudiness data compiled on a five degree grid. Annual totals are fairly uniform for all latitudes because the study area straddles the equator and thus most points are subjected to about the same total annual amount of radiation (see Figure 1). Although the isolines have no meaning for most of the area because it is open ocean, it does seem a convenient format to show the variations in PE for different months and locations. Also, notice that the maps include isolines for Australia. This is an artifact of the methodical compilation of cloudiness data, and by no means is intended to suggest that the numbers shown are accurate measures of PE for that continent. For an area as large and dry as Australia, there would be a huge increase in PE due to advection. In fact, advection is important on any large land mass such as the large islands of Melanesia and the high islands of the Polynesia.

The PE values shown on the maps are valid only for areas that have cloudiness similar to that of the open ocean and have no, or slight, advection effects; for example, Lavoie (1963) and Wiens (1962) suggest that atoll influence on cloudiness and precipitation is negligble. This may also be true for other small land masses such as barrier islands, cays, and flat, rocky islands. These would include:

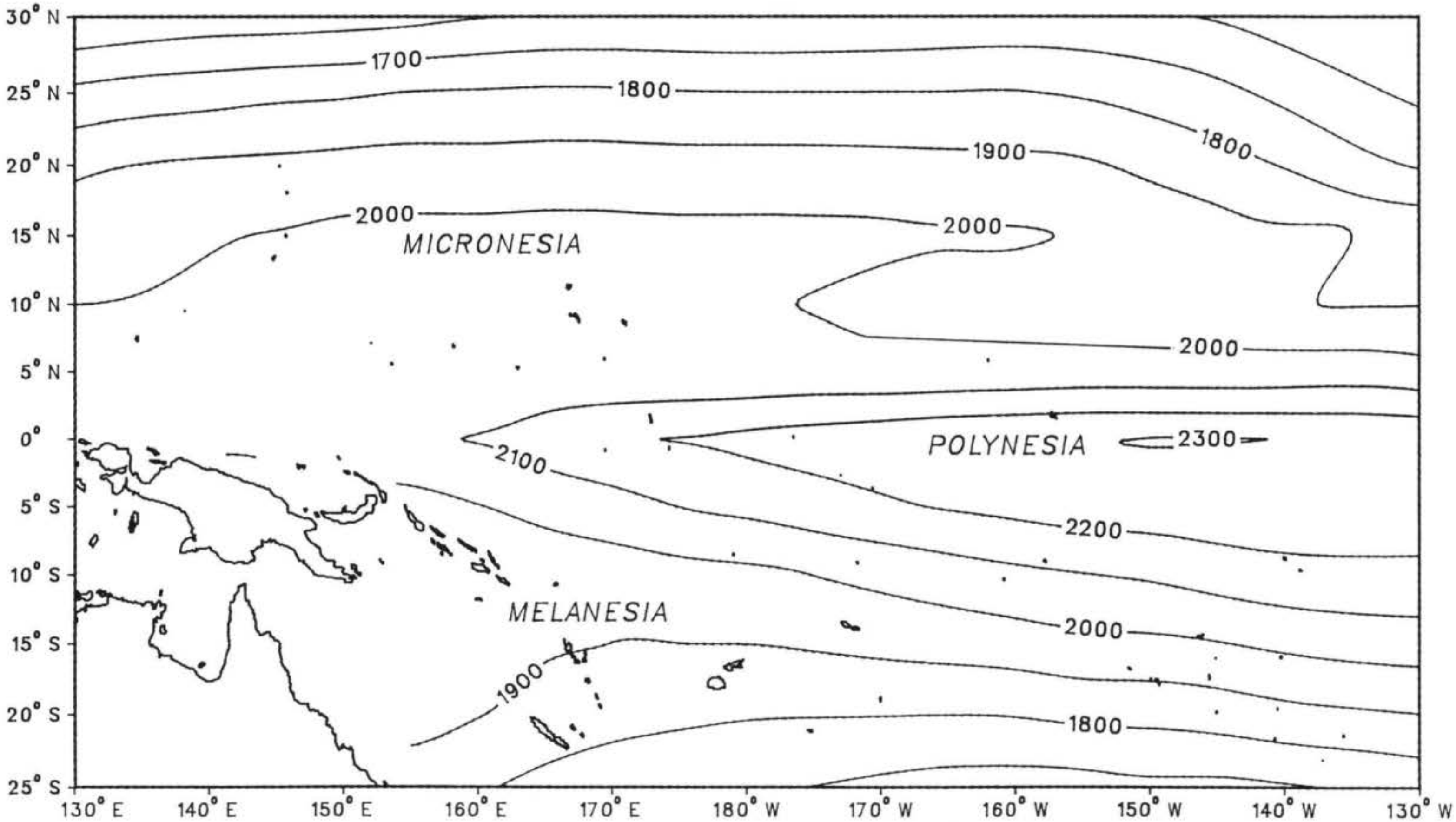

Figure 3. Annual PE for Small Pacific Islands

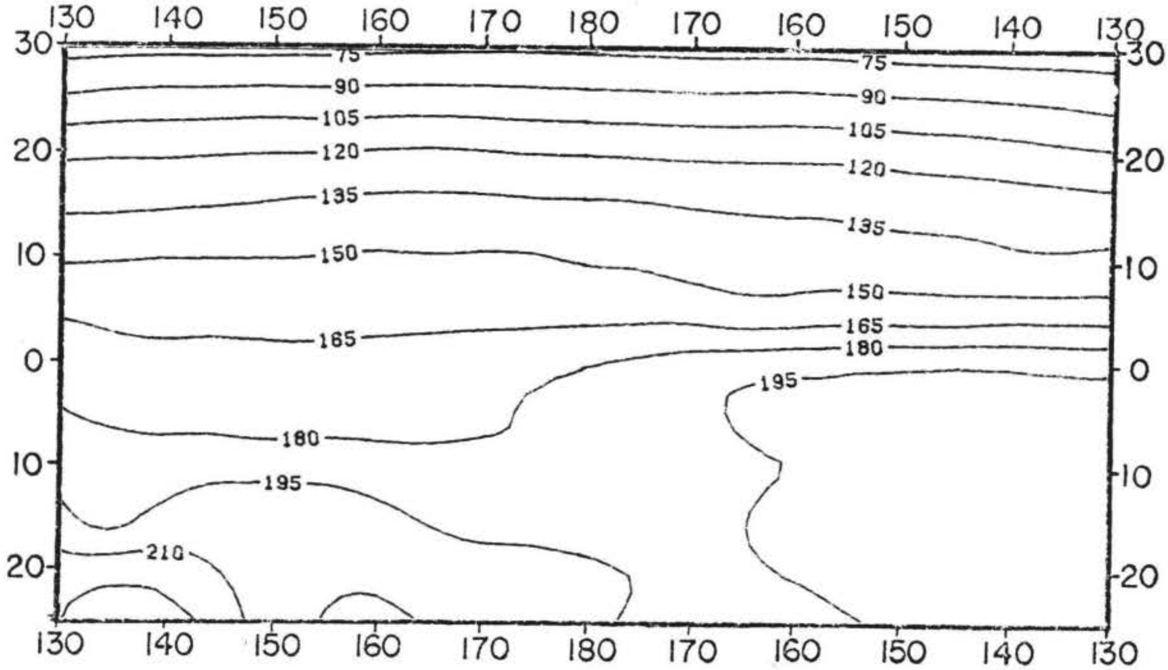

Figure 4. PE for January

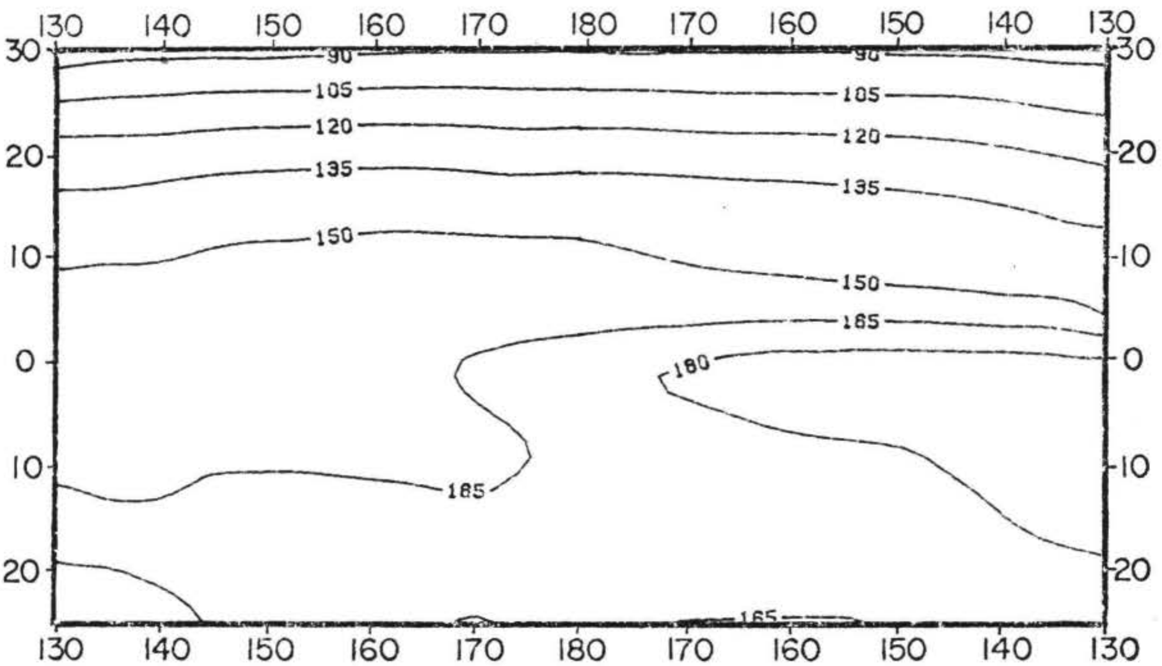

Figure 5. PE for February

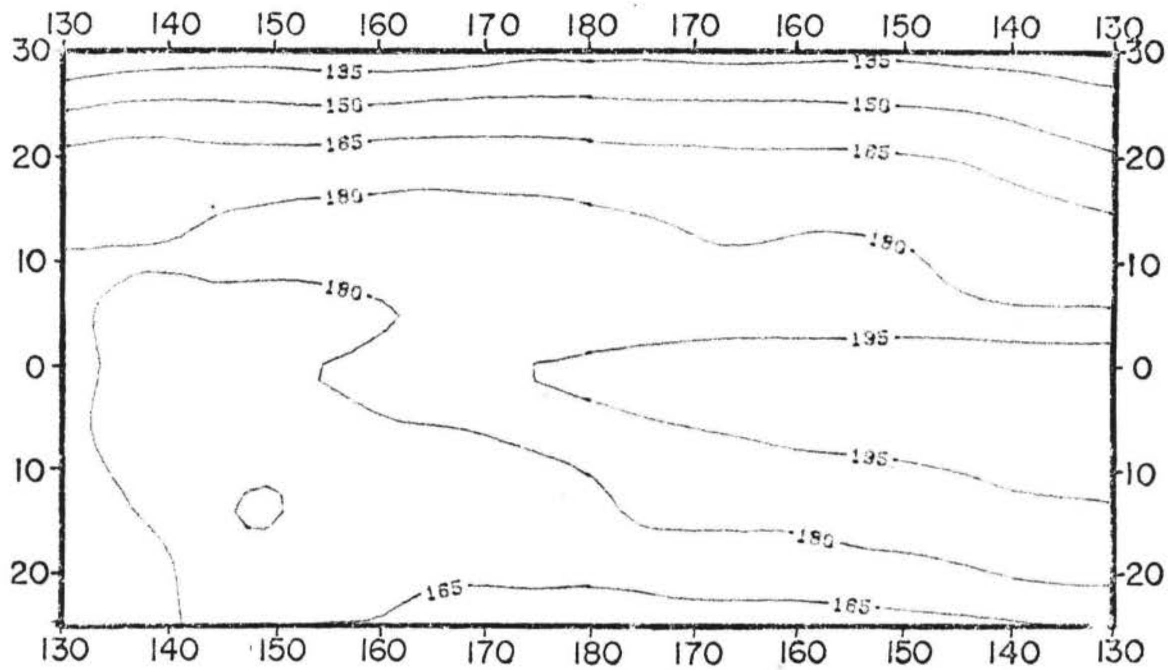

Figure 6. PE for March

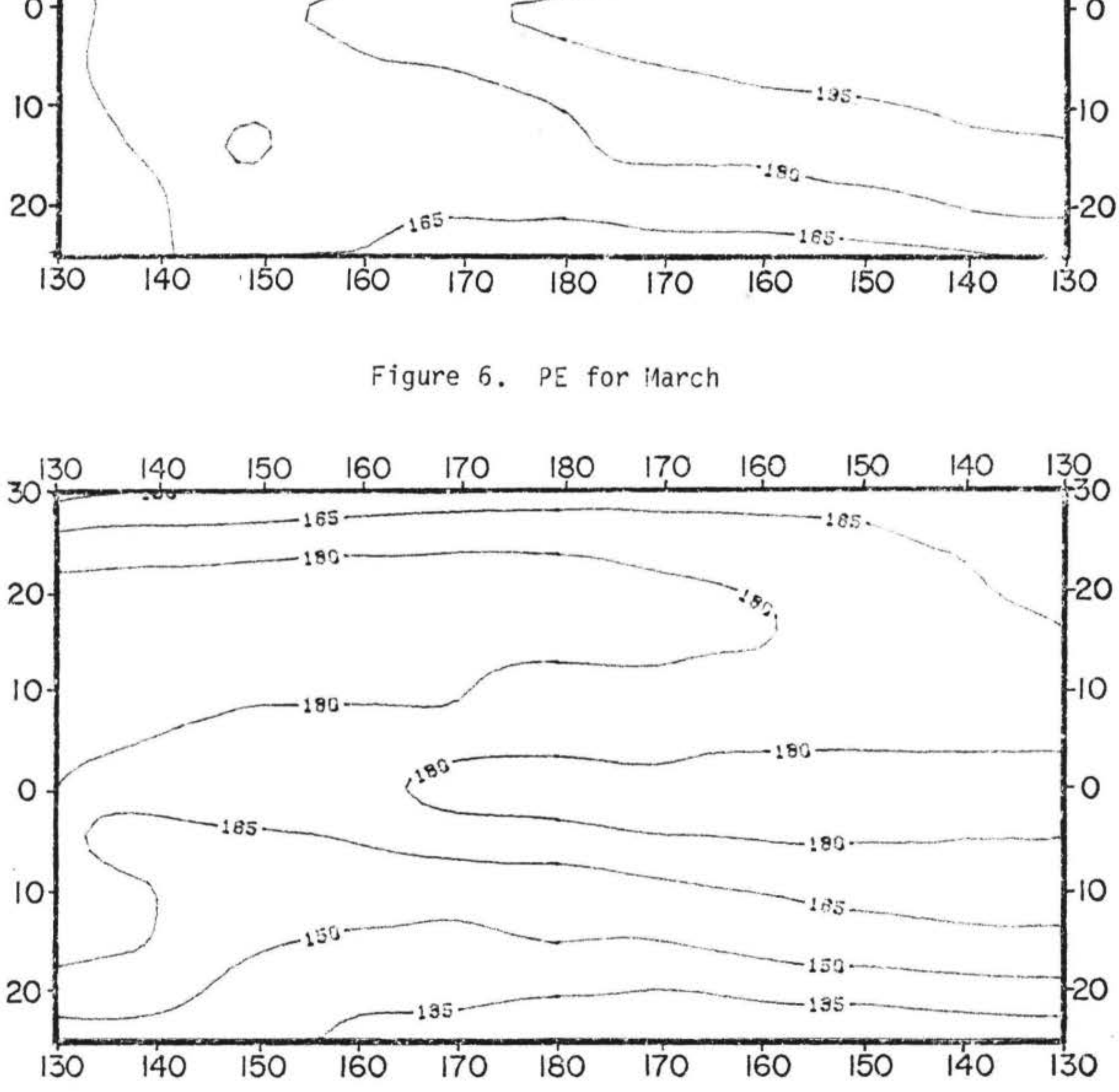

Figure 7. PE for April

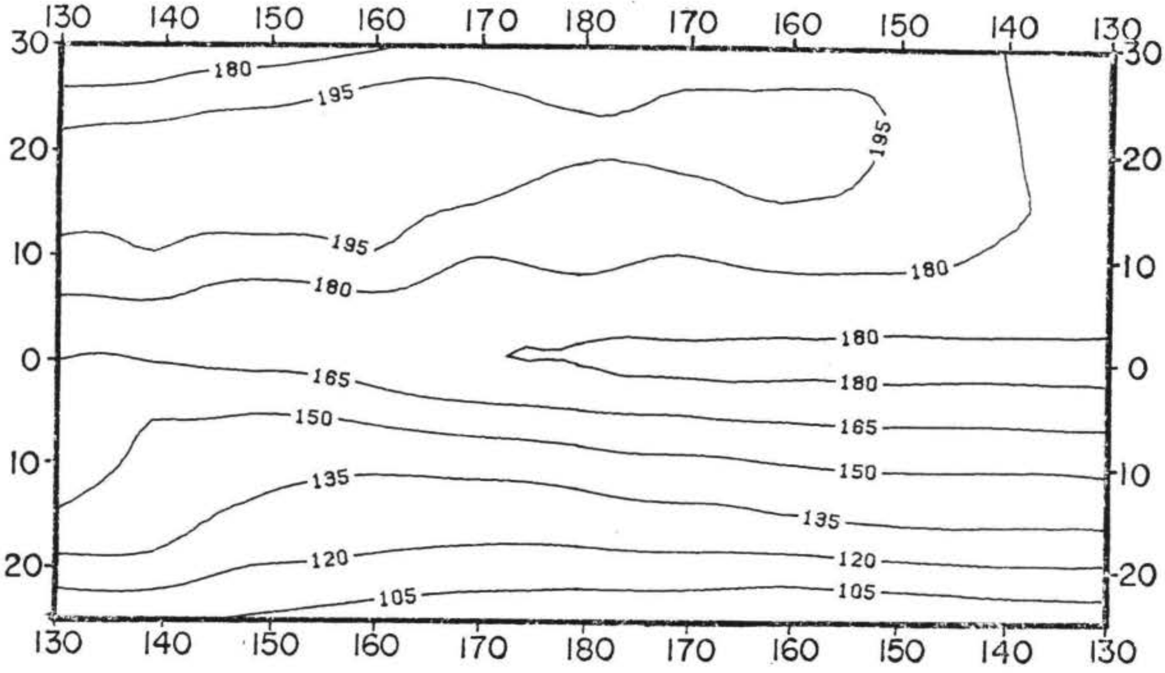

Figure 8. PE for May

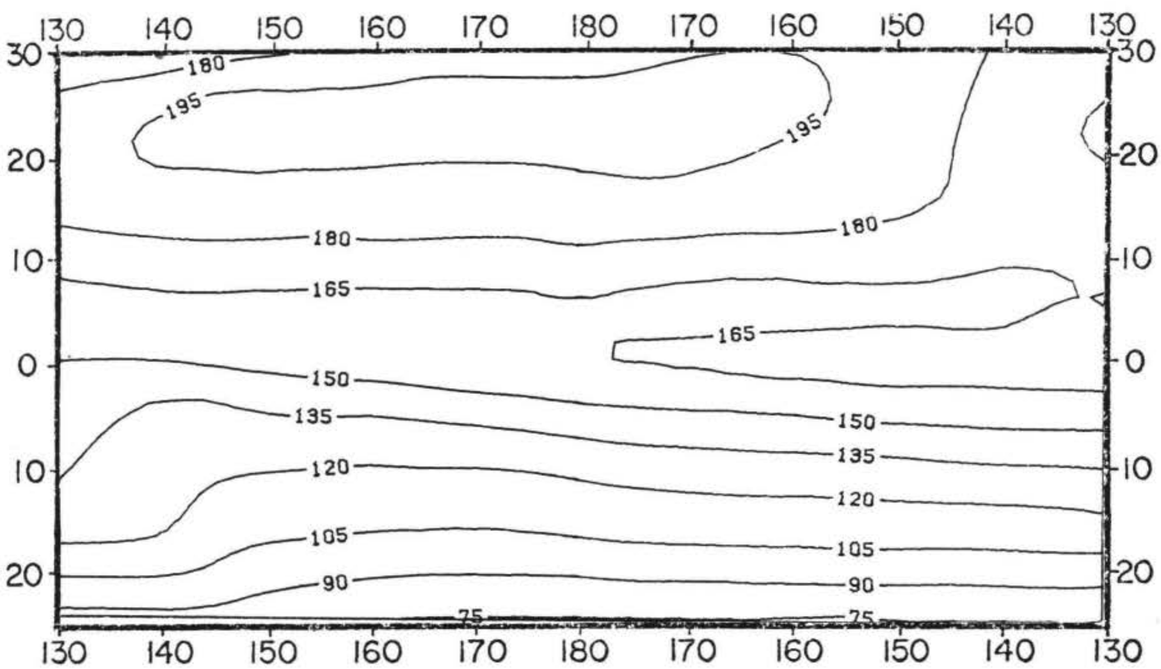

Figure 9. PE for June

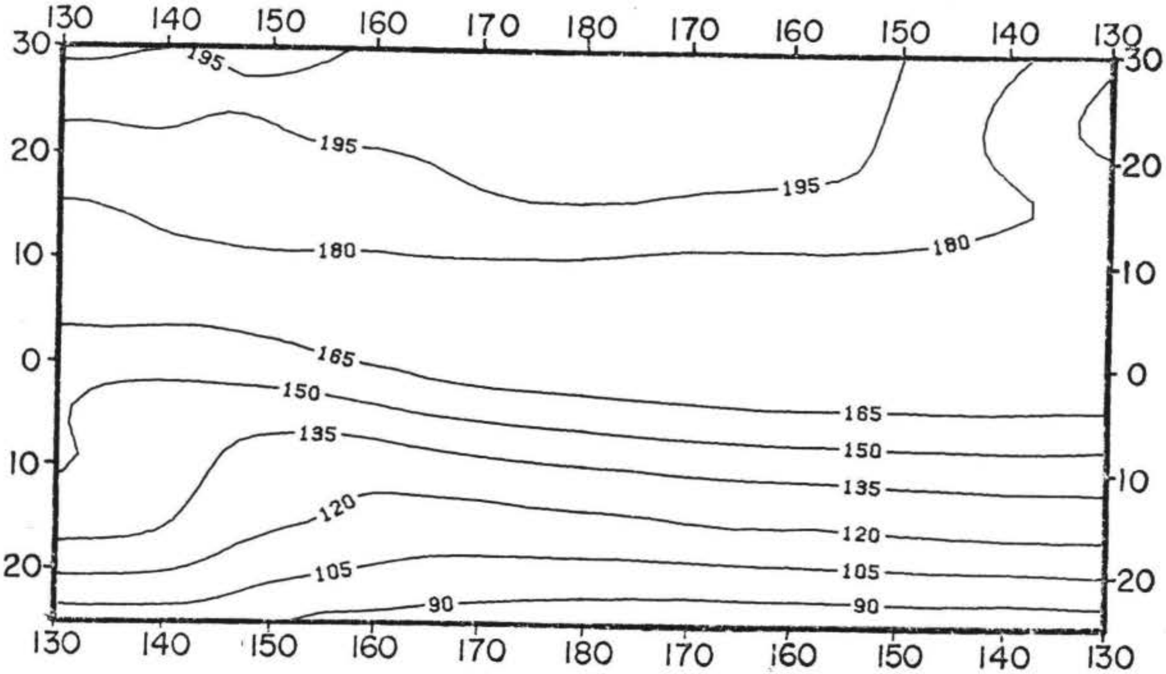

Figure 10. PE for July

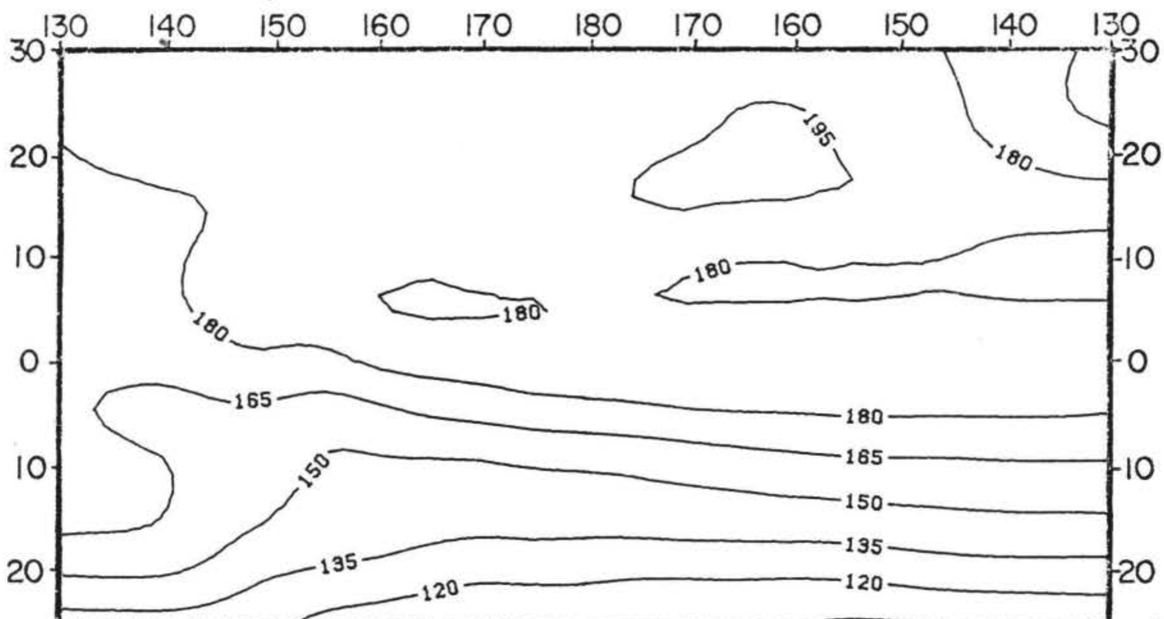

Figure 11. PE for August

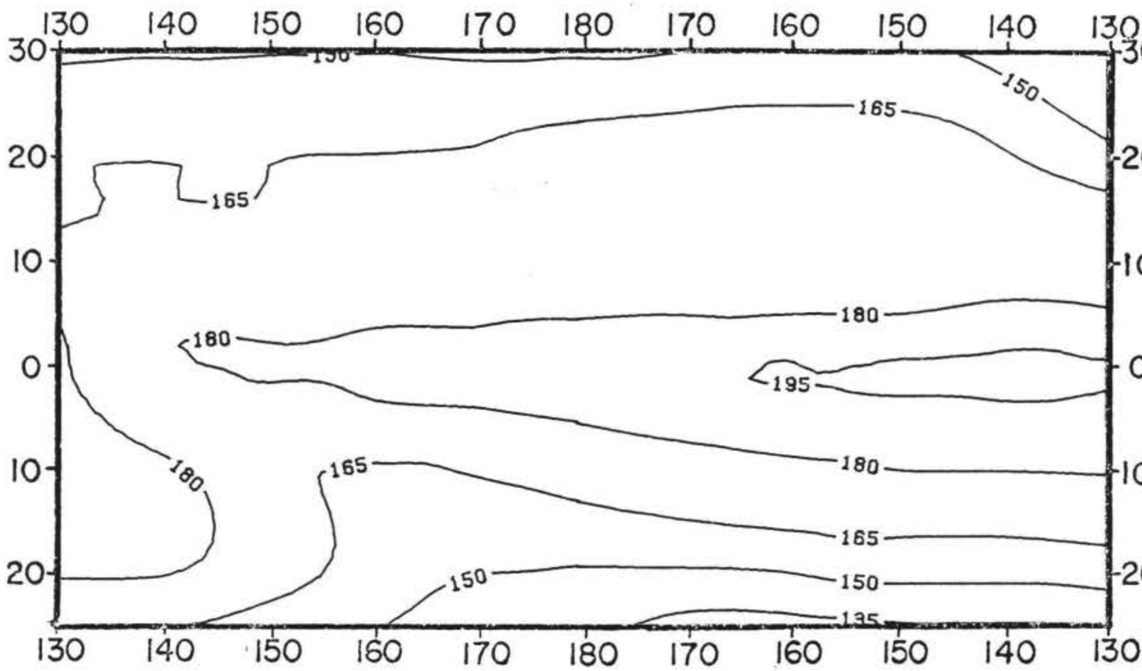

Figure 12. PE for September

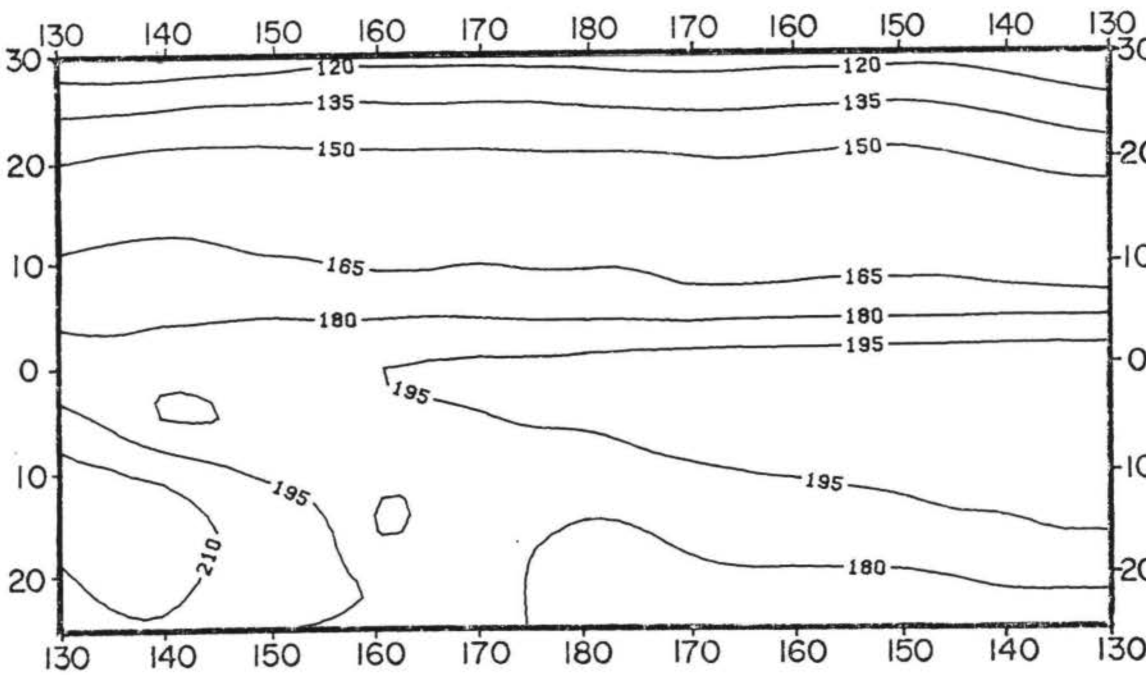

Figure 13. PE for October

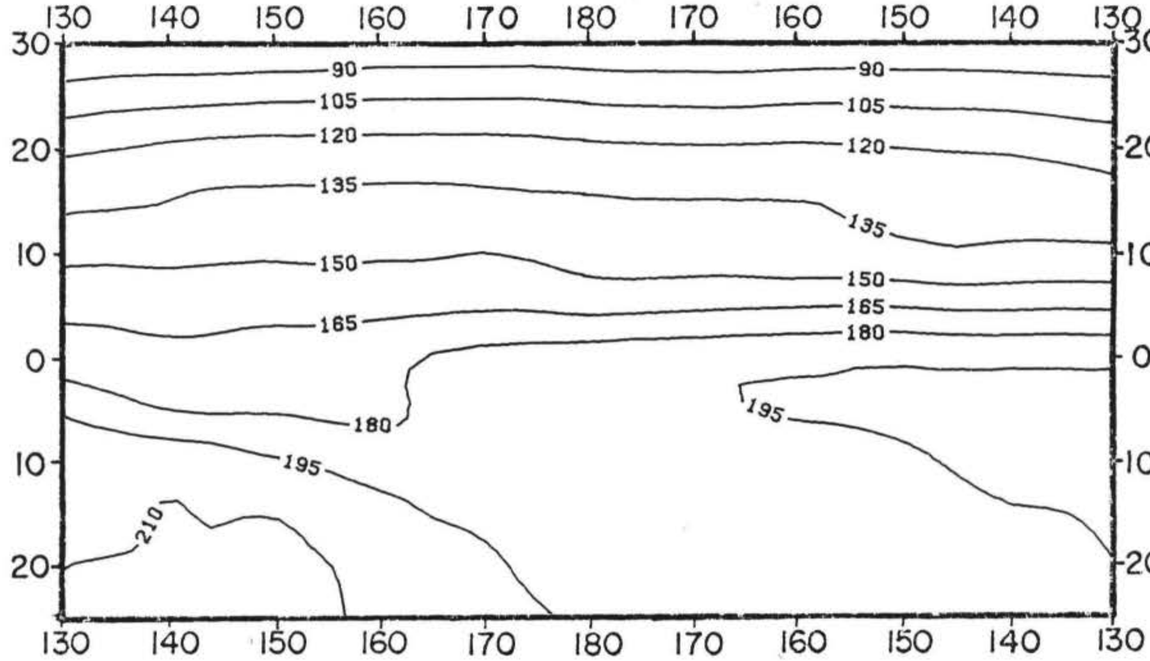

Figure 14. PE for November

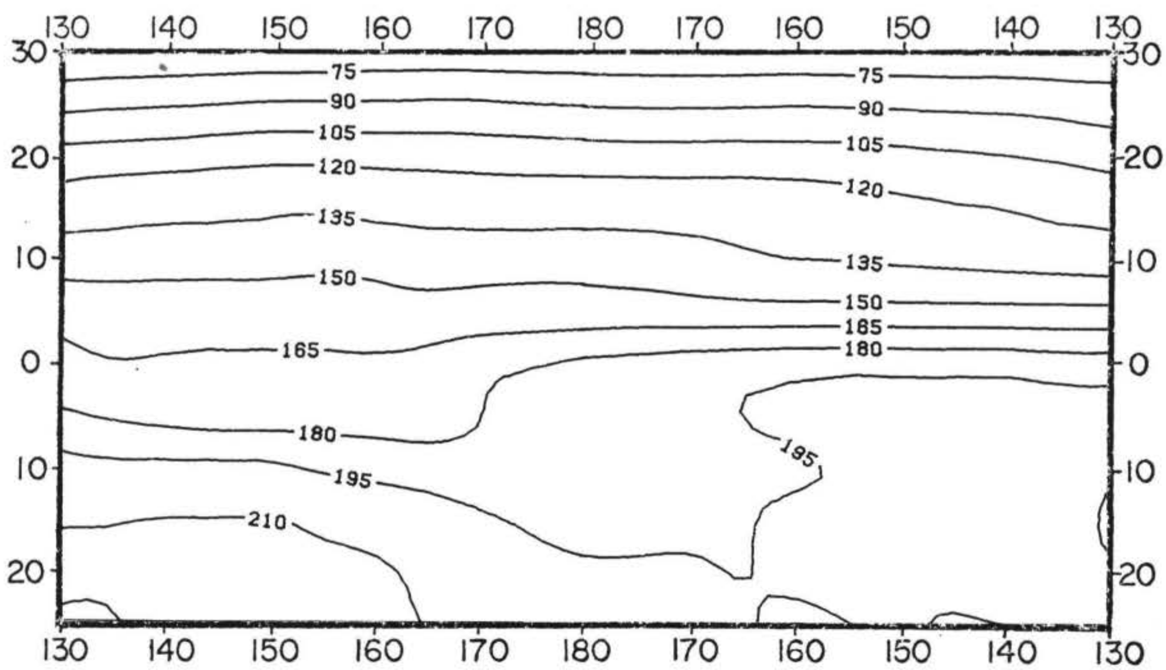

Figure 15. PE for December

the Marshall Islands, the atolls of the Federated States of Micronesia, the Tuamotu's, the Tokelau's, the Northern Cooks, Kiribati, Tuvalu, small islets (motus) such as those found on the reefs of Bora Bora and Truk, the barrier islands off the eastern coast of Australia, Nauru, and many of the small islands in the Solomons, Papua New Guinea, Vanuatu and New Caledonia.

How accurate are the PE calculations? Table 6 shows a comparison with Oçeanic-station pan evaporation data compiled by NOAA and published in the National Climatic Center's, "Monthly Climatic Data for Hawaii and the Pacific," along with my predicted values, standard deviations, and the percentage difference between pan evaporation and my calculated PE values.

The estimated annual totals correspond well with measured annual pan evaporation totals for three of the stations and the monthly data show a fair correspondence, except that PE is higher than pan data for the northern hemisphere stations during the summer and lower than pan data for the southern hemisphere station in winter. This corresponds with the wet and dry season respectively at those stations, and thus the change in composition of cloud cover may be responsible for this discrepancy. The values broken out for the 1965-73 period, the period during which the cloudiness data were accumulated, for Guam and Johnston Island are slightly higher than the long term average. Among other things, this could indicate that Sadler's cloudiness data underestimate long term cloud cover or that there was a higher fraction for cirrus clouds for the period.

Table 6

Pan Evaporation Comparison

(Data are given in millimeters)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Guam (13° 33' N and 144° 50' E)													
estimated	140	146	181	191	198	186	184	186	166	164	141	136	2019
1963-82	153	157	193	204	205	179	157	142	136	142	148	156	1972
st. dev.	23	17	27	24	23	26	19	21	20	19	18	14	
ratio	-8	-7	-6	-6	-3	+4	+17	+31	+22	+15	-5	-13	+2
1965-73	145	155	187	204	205	171	153	132	129	132	137	150	1900
st. dev.	20	13	32	28	15	24	20	20	14	12	16	15	
ratio	-3	-6	-3	-6	-3	+9	+20	+41	+29	+24	+3	-9	+6
Johnston Island (16° 44' N and 169° 31' W)													
estimated	130	137	175	185	194	194	196	196	175	158	130	123	1993
1963-82	225	223	266	265	276	289	299	285	260	251	217	237	3088
st. dev.	29	32	32	32	28	38	29	28	23	19	23	38	
% diff.	-42	-39	-34	-39	-39	-33	-34	-31	-33	-37	-40	-48	-35
1965-73	239	231	279	287	290	313	312	304	263	257	221	242	3238
st. dev.	26	41	37	30	26	42	34	30	28	22	27	15	
% diff.	-46	-41	-37	-36	-33	-38	-37	-36	-33	-39	-41	-49	-38
Yap (9° 31' N and 138° 08' E)													
estimated	151	150	181	186	195	172	174	179	168	171	148	146	2011
1979-82	143	154	185	193	164	141	153	170	152	169	140	149	1913
% diff.	+6	-3	-2	-4	+19	+22	+14	+5	+11	+1	+6	-2	+5
Pago Pago (14° 20' S and 170° 43' W)													
estimated	191	169	182	151	133	115	123	147	166	181	188	191	1937
1979-82	193	185	190	152	151	149	142	172	180	144	192	213	2063
% diff.	-1	-9	-4	-1	-12	-23	-13	-15	-8	+26	-2	-10	-6

Johnston Island evaporation is grossly underestimated, possibly because Johnston Island is a barren, windswept spit of rubble perched on a coral shelf in an area where advection and wind invalidate the Priestley-Taylor equation. It should be noted that pan evaporation at Johnston Island approximately equals global radiation which indicates that advection must be present, perhaps from the long runway there. Johnston Island does not represent the typical tropical island situation as it is situated at a higher latitude than most of the relevant islands, and is devoid of vegetation, and has a large percentage of its surface covered with concrete and asphalt.

It should be noted that all the pan stations (except Johnston Island) are located on high islands, and thus the resulting pan values should not necessarily correlate well with my estimates of PE which are based on cloudiness over the open ocean. Also, it is not really possible to conclude much on the basis of the small amount of pan data available. For example, two of the stations, Yap and Pago Pago, have only three years of data (interestingly, my estimates match them best). Also, the condition of the pans is unknown. For example, they could be partially shaded, or be downwind from a large windbreak; the pans may not be cleaned regularly which could alter the heat characteristics of the system; or they could be surrounded by asphalt pavement, especially those near airports, which could result in some advected energy being introduced into the system. Also, it is not know whether the data have been accurately screened for missing data, overflows, and the like. Despite the uncertainty involved in the above pan data, they seem to correspond fairly well with my computed

PE totals using Reed's method of calculating radiation. For Hawaii, PE is usually calculated as 1.1 times pan evaporation (Ekern, 1966) for continuously wetted surfaces. Disregarding the Johnston Island data, the average ratio of PE to pan evaporation would be 1.02. This seems remarkably consistent considering the scarcity of data and the diverse locations (and unknown conditions) of the pan evaporation stations.

This chapter has presented the principal research and results intended for this paper. There are many possible applications of PE for Pacific islands including, computing the water balance for wetlands, finding actual ET for drier areas, climate classification, determining irrigation requirements, and correlation studies. The follwing chapter discusses one of these applications: a water balance for wet areas.

CHAPTER III

A WATER BALANCE FOR WET AREAS

The water balance for constantly wet areas, e.g. swamps and taro patches, can be computed fairly easily by subtracting monthly PE from monthly rainfall (i.e. PE equals ET for wet conditions). This exercise may help illustrate the importance of water conservation measures in the drier areas of the Pacific.

Penman (1956) defines PE as "the amount of water transpired in unit time by a short, green crop, completely shading the ground, of uniform height and never short of water." This implies that water loss from wetted surfaces that are not short and green may be different. For example, wet soil or open water would have a higher water loss because of their lower albedo, i.e. net radition is higher and thus more energy would be available for PE. Likewise for a swamp with higher heat capacity and lower albedo (the sun is always overhead so albedo is always low). Tall vegetation could have a high surface roughness, which would enhance vapor removal, thus increasing the vapor gradient, which would increase the rate of evapotranspiration. The characteristics of the plant itself greatly affect ET. For example, the stomata of taro plants are found on the underside of the leaf where vapor movement is inhibited and where they are not subject to direct radiation. This should have the effect of decreasing PE. Thus, this study assumes a crop water use coefficient of 1.0. Also, although taro patches are always saturated, and usually contain

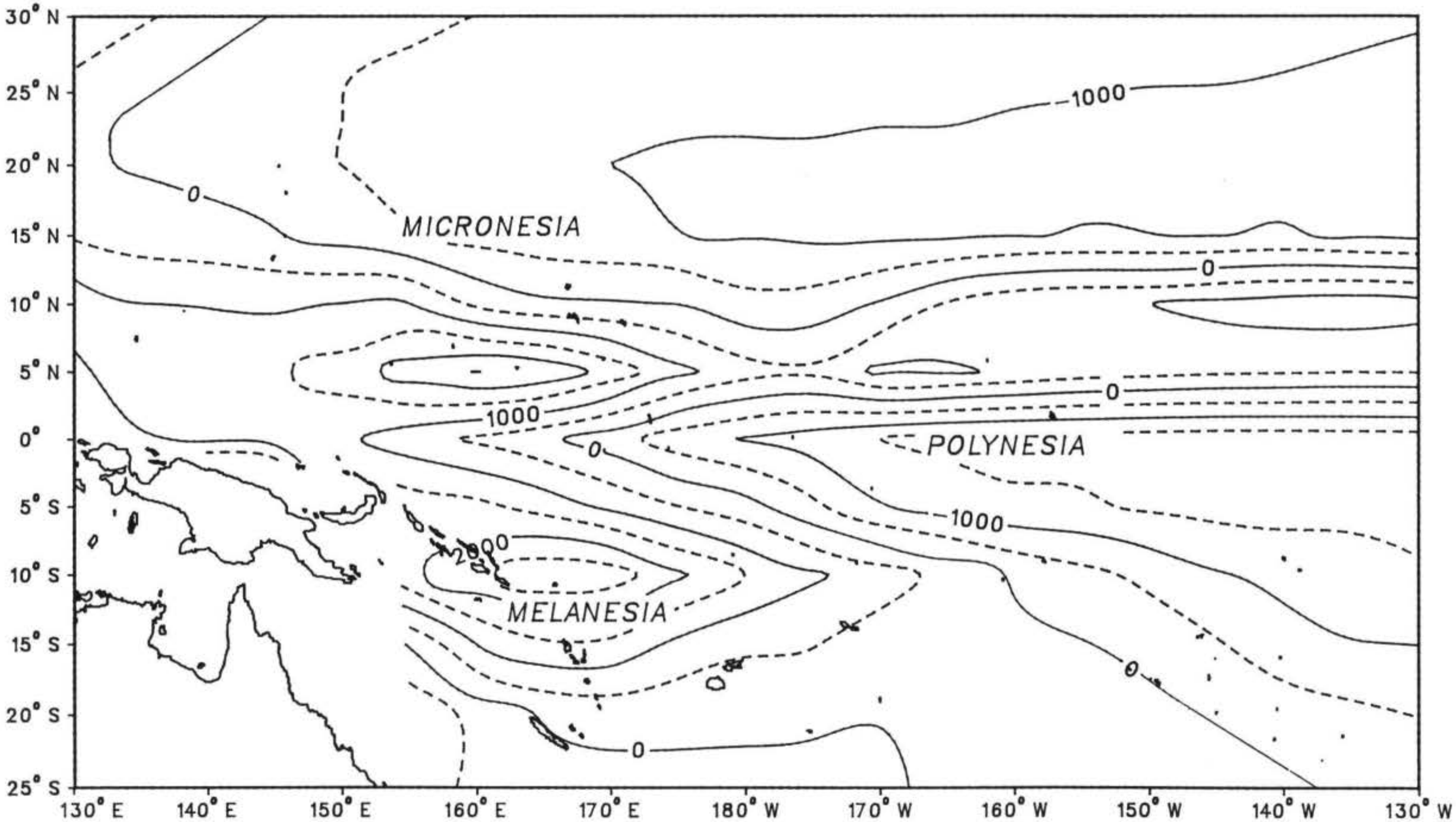

FIGURE 16. A WATER BALANCE FOR WET AREAS

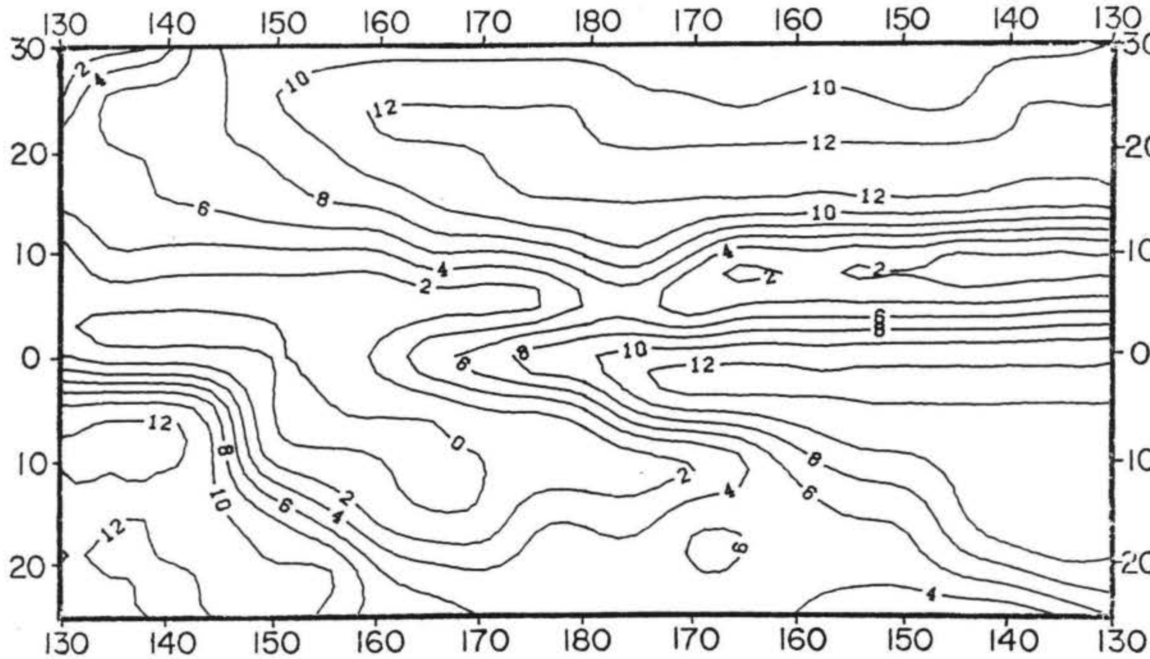

Figure 17. Number of Deficit Months

standing water, often much of the surface is covered with an organic mulch which can dry and prevent water loss. (This is not much help if the entire pit is overgrown with taro and the leaves intercept all the available radiation, however.) The size of the wetted area is important also; small taro patches may be shaded for part of the day, thus reducing direct radiation, although the principal shader, the coconut palm, attenuates insolation only slightly. None of the above considerations are considered in my calculations, as the importance and applicability of each factor is highly dependent on the individual site and its characteristics. My water balance estimates are for the ideal case only and are intended to illustrate somewhat quantitatively the importance of water conservation measures in dry regions.

As would be expected, the water balance pattern echoes the rainfall pattern rather closely; not surprising as annual PE totals for the entire study area are fairly uniform (see Figure 3). The highest deficit areas are south of the Inter Tropical Convergence Zone where rainfall is lowest, and in the northeastern Pacific, e.g., the Hawaiian Islands region. This points out the importance of the mountains in the Hawaiian Island chain; without orographic rainfall from moist trade winds, the islands would be dry (i.e. from Figure 16, Hawaii lies in an area of approximately 1000mm/year deficit for wet areas). Such conditions are, in fact, found on the atolls of the Northern Hawaiian chain, Midway, Laysan, and others.

Kiribati is the driest nation in the Pacific. (Ironically, western Kiribati also has one of the highest population densities.) Annual rainfall for Tarawa, for example, averages only 1800 mm while annual PE is near 2100. This would result in an average water loss of 300 cm (30,000 m^3) of fresh water per hectare of wetted area. This loss is particulary harmful in taro patches because they are generally located at the freshest part of the groundwater body. Other annual deficit areas are the northern Marshalls, and the Tuamotus.

The principal effect of high ET in wetlands is to drain the delicate Ghyben-Herzberg lens found on small islands. This convex body of fresh water floats on the heavier sea water and losses through mixing with sea water, exacerbated by fluctuations in response to tides, and ET can only be replenished by rainfall. Although mixing and flux are the major source of water loss, in dry areas or during drought, ET losses can be quite important. If losses are high and recharge is low, salt water will invade and contaminate the lens.

This affects crops which depend on a fresh groundwater source, such as breadfruit and taro, and reduces the domestic water supply, for drinking, washing, and other uses (Wentworth, 1947; Cox, 1951; Arno, 1954 and 1955). With increasing population pressure on Pacific nations and the stated goal of self-sufficiency, e.g. increased agricultural diversity, proper management of slender water resources is becoming less avoidable. Some possible measures would be:

Recovering taro pits. Taro is a favorite of Pacific islanders and eliminating it would not be a practical suggestion. However, old and unused pits could be recovered and a moratorium enacted on new pit construction and expansion. Existing taro pits could be covered with an organic mulch to slow water loss. Wet taro pits can be source of considerable fresh water drain (they are normally constructed in the freshest areas of the lens). For example, Ayers and Clayshulte (May, 1983) investigated salt water intrusion of Kuttu Island, Sakawan atoll, in Truk state of FSM. The pit that they examined had been expanded until it consumed 1/2 of the total 40ha of land area. Rainfall for the year preceeding their study totaled about 2400 mm (extrapolated from records on nearby Truk) which is 60% of normal. Annual PE for the area is 2000 mm, which would leave only 400mm of recharge for the entire year. This apparently was not enough to compensate for losses through the transition zone between salt and fresh water from mixing and flux resulting in salt water intrusion and dead taro. Ayers and Clayshulte's study points out the danger involved in relying on high rainfall and high water consumption crops to provide a regular food supply. The original purpose of the taro pit expansion was to increase the food supply, but due to salt water intrusion this became impossible. Ayers and Clayshulte concluded that, "In terms of a solution to the salt water intrusion problem, there appears to be none." This is undoubtedly true for the taro patch salt water intrusion problem but not necessarily for the expanding the food supply problem. A more dependable and less wasteful agricultural system could be installed by practicing water management and cultivating water efficient crops.

Taro has high water consumption and a low water use efficiency. Other crops, such as sweet potato and cassava, are better adapted to dry atoll conditions and have a much higher yield. These crops can be watered (when necessary) using water drawn by hand pumps from skimming galleries, such as those in use on Kwajalein (Walker, 1978) and in French Polynesia (Meyer, 1980). This would eliminate wasteful ET losses and reduce upconing.

Another way to recover taro pits would be to convert them to subirrigation. The procedure is outlined by the Department of Rural Works in French Polynesia (1982): Coconut husks are buried near the water table and covered with a thick layer of sand. Crops are then sown in the well drained sand (which acts also a dry mulch) and can put roots down to the coconut husks which remain wet by drawing water though capillary action. This would eliminate water loss when the pits were not in use and allow a greater diversity of agriculture as most crops cannot tolerate waterlogged condtions.

Filling swampy areas, if fill material is available, could also increase the size and freshness of the lens; perhaps some of these areas could be converted to subirrigation, increasing agricultural area and decreasing water loss. Also, since the freshness of the lens depends, in part, on the distance from a shoreline, filling swampy areas on the lagoon sides of atoll islets, where sediments are most likely to support a fresh water lens, would both increase the recharge area and the freshness of the lens.

For the most part, agriculture on Pacific atolls is limited to copra production and taro farming (somewhat more diverse on the wetter atolls). Islanders depend on revenues from copra to buy imported foodstuffs such as rice, flour, and canned fish and use taro as a supplement; although even the practice of taro farming is declining (Small, 1972). If imported food becomes less accessible (e.g. if copra prices fall, or economic aid declines), islanders will find it necessary to produce their own food supply once again. Given the increasing concentrations of islanders at a few administrative centers, e.g. Majuro and Tarawa, and the loss of agricultural traditions, the task of feeding themselves becomes more difficult than it was in the past. Indeed, in the more crowded areas, populations are far beyond the carrying capacity of the land.

Inevitably, the source of fresh water determines the land's ability to support a population. To best utilize available fresh water resources, some rural development, such as installing hand pumps and skimming wells to water small gardens, and cultural changes, such as recovering taro pits, seem essential. Until another source of inexpensive fresh water is found, islanders will have to depend on the slim resources of the Ghyben-Herzberg lens and water management to conserve it.

CHAPTER IV

SUMMARY

In this paper, potential evapotranspiration (PE) for small Pacific islands has been computed and one PE application, the water balance for wet areas, discussed.

Using cloudiness data to calculate global radiation, PE has been computed for small islands in the tropical Pacific, "small" referring to low islands without significant orographic, convective, or advective effects, such as atoll islets or barrier islands. Results have been compared with radiation and pan evaporation data from oceanic stations where they are available. Estimates have been presented in a series of maps; the isolines tend to follow parallels of latitude in response to the sun's declination, although there is some east-west variation due to cloud cover patterns.

The water balance for wet areas, swamps, taro patches, and irrigated land, was computed by subtracting PE from precipitation. As expected, the water balance pattern echoes the rainfall pattern rather closely as PE is fairly uniform throughout the region. This computation helps illustrate the need for water conservation measures in the drier areas of the Pacific.

The pressing need for further work in this kind of research is in gathering field data, specifically, global radiation data and PE data. Much of the available information for oceanic stations has been presented in this paper, and it obviously is too sparse and widely

scattered to provide a good data base for conclusions. Thus the methods I have used and conclusions I have drawn are, for the most part, based on current theories and empirical equations derived using data for stations in similar climates around the world. Such assumptions are not necessarily strictly valid for the equatorial Pacific and only a long term monitoring program can provide the solid data base required to accurately estimate PE.

Further research could be done on many of PE's applications, particularly in the water balance for areas that are not constantly wet, i.e. most land areas. This is an essential component of recharge calculations, which are necessary for determining sustainable yield from island aquifers. Before any development program, such as irrigating truck gardens, can begin, safe yield must be determined or the lens could be damaged by saltwater intrusion caused by over-exploitation. Also, there is a need to explore methods of efficient irrigation in atoll soils, such as burying coconut husks and subirrigation. The most important component in the PE equations is global radiation, yet using crude cloud cover data is the only method available for estimating it. More research needs to be done on the relationship between radiation and cloud cover, perhaps incorporating other factors, such as solar declination and season, to more accurately estimate its distribution and quantity.

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APPENDIX A

COMPUTATION OF ANGOT'S VALUE

Angot's value, the amount of radiation that would strike the earth's surface in the absence of atmosphere on a plane tangent to the earth's surface, can be calculated by evaluating the equations given by List (1966) with the aid of a computer. The basic equation is:

$R_a = 2J_o(r_o/r)^2\ {}^{tao}\cos(z)\ dt$ eqn (A1)

where:

R_a is Angot's value

J_o is the solar constant (1.94 cal/cm^2/minute)

r_o is the earth's mean annual distance from the sun

r is the daily average earth-sun distance

tao is the length of 1/2 of a day in radians

cos(z) is the ratio of the amount of radiation which would strike an area of the earth's surface to that which would strike the same area if it directly faced the sun.

The CRC Handbook (1982 edition) lists the semi-major axis of the earth as 1.4957(10^8)km, the minor axis at 1.4707(10^8)km for perihelion and the major axis at 1.5207(10^8)km for aphelion. The procession of the sun-earth distance (r) can be approximated by the equation:

$r = 1.4957(10^8) - .025\cos((day-2)/365(2Pi)))$ eqn (A2)

where:

day is the day of the year

Pi is 3.1415926

This is not strictly true because the earth's semi-major axis is not the mean annual earth-sun distance, but the error is small. The (day-2) term must be included because perihelion occurs approximately two days after the year begins.

Tao is given by the following equation (from Kubota,1967):

tao = arcos(-tan(delta)tan(phi)) in radians eqn (A3)

where:

delta is the sun's declination

phi is latitude

Tao can be converted to minutes by the ratio 720/Pi, and this constant must be included in the final equation as the solar constant is given in minutes.

Phi (noontime value) can be caculated for any day by:

phi = 23.45(Pi/180)cos((day+10)/365(2Pi)) eqn (A4)

23.45 is the sun's maximum declination. Also, the (day+10) term must be included because the beginning of the year follows winter solstice by about 10 days.

cos(z) is given by:

cos(z) = sin(delta)sin(phi) + cos(delta)cos(phi)cos(t) eqn (A5)

where:

t is the time of day

In other words, the integral sums the radiation from dawn till noon using the sun's angle and then multiplies the result by two, since the day is symmetric. Substituting equation (A5) into equation (A1) and integrating yields:

$$R_a = 1440/Pi(J_o(r_o/r)^2)(t\sin(tao)\sin(delta) + \cos(tao)\cos(delta)\sin(t) \qquad \text{eqn (A6)}$$

(Note that when the above equation is evaluated at zero, R_a becomes zero.) Equations (A2), (A3), (A4), and (A6) were then written into a computer program and Angot's value was computed for all days at every five degrees of latitude and averaged to get monthly values. Note that when (phi - delta) is less than 90^0 (i.e. during the 24 hour days of the polar summer), t is equal to Pi, and when (phi - delta) is less than 0^0 (i.e. during the polar winter), t equals zero and R_a equals zero.

The values below correspond well (when scaled) with those calculated by Kuboda who used a solar constant of 1.98 ly/min. (Note: there is an error in equation (5) in Kuboda's article. The cos(delta) term should be sin(delta) in the first line of the equation). Also, daily totals agree with the few values given by List in the Smithsonian Meteorological Tables.

Table Al

Average Daily Angot's Value

Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
90N	0	0	27	452	877	1061	975	630	131	0	0	0	348
85N	0	0	51	450	874	1057	972	627	155	0	0	0	351
80N	0	0	110	461	864	1045	961	621	214	14	0	0	360
75N	1	16	182	494	847	1025	942	626	284	54	0	0	375
70N	1	62	255	545	834	997	918	653	353	116	9	0	397
65N	28	126	328	599	844	970	908	692	421	185	48	9	431
60N	82	196	398	651	866	970	919	733	486	256	107	54	478
55N	146	267	466	700	889	976	933	771	547	327	174	114	527
50N	216	339	531	744	910	983	946	806	605	397	244	181	576
45N	288	410	592	784	927	987	956	837	658	465	316	252	624
40N	361	479	648	819	939	988	962	862	706	530	388	325	668
35N	433	546	700	848	945	983	962	882	749	591	458	398	709
30N	504	608	746	870	946	973	957	895	786	648	527	471	745
25N	572	667	786	887	941	957	946	902	818	701	593	542	776
20N	638	721	820	895	929	935	929	904	844	749	656	610	803
15N	700	771	850	900	912	908	906	898	862	791	714	675	824
10N	757	815	872	896	888	875	877	886	874	827	767	736	839
5N	810	853	887	886	859	837	843	868	880	857	816	793	849
0	858	885	896	870	823	793	803	843	879	881	860	844	853
5S	900	911	898	847	782	744	758	813	871	899	897	891	851
10S	936	930	893	818	736	691	708	777	857	910	929	932	843
15S	966	943	881	783	685	634	654	735	836	914	954	967	829
20S	989	948	862	741	629	573	595	689	810	912	973	997	809
25S	1007	948	838	696	570	509	534	636	775	904	987	1020	784
30S	1018	940	807	644	507	442	469	580	736	887	992	1036	753
35S	1023	926	770	588	442	374	402	520	692	885	992	1047	719
40S	1022	906	727	528	375	306	334	457	642	836	985	1052	680
45S	1015	879	679	465	306	237	266	392	587	802	973	1052	637
50S	1004	847	625	398	238	171	199	324	528	763	957	1048	591
55S	989	811	567	330	170	107	134	256	465	718	936	1041	542
60S	973	770	505	260	106	51	74	187	399	669	913	1033	494
65S	960	727	439	189	49	8	24	121	330	618	891	1034	447
70S	968	686	371	121	10	0	1	61	259	565	882	1063	414
75S	994	657	301	58	0	0	0	17	187	515	898	1092	393
80S	1013	654	231	16	0	0	0	1	116	484	916	1114	378
85S	1025	661	174	0	0	0	0	0	56	476	926	1127	369
90S	1029	663	150	0	0	0	0	0	31	477	930	1131	367

```
C
C     FORTRAN SUBROUTINE TO COMPUTE DAILY ANGOT'S VALUE FOR ALL LATITUDES
C
      DIMENSION QD(370,40)
      PI=3.1415926
      RO=1.4957
      FIVE=5.*PI/180.
C
C     FILL ARRAY QD(I,L) WITH DAILY VALUES ON A FIVE DEGREE GRID.
C     I IS THE DAY OF THE YEAR AND L IS THE LATITUDE.
C     NEGATIVE LATITUDE VALUES ARE IN THE SOUTHERN HEMISPHERE.
C
      DO 1 L=1,37
         RLAT=(PI/2.+FIVE)-L*1.*FIVE
         DO 2 I=1,365
            R=RO-.025*COS((I-2)/365.*2.*PI)
            DEC=23.45/180.*PI*(-COS((I*1.+10.)/365.*PI*2.))
            IF(ABS(RLAT-DEC).GT.PI/2.) THEN
               QD(I,L)=0.
               GO TO 2
               ENDIF
            IF(ABS(RLAT+DEC).GE.PI/2.) TIME=PI
            IF(ABS(RLAT+DEC).LT.PI/2.) TIME=ARCOS(-TAN(RLAT)*TAN(DEC))
            QD(I,L)=1440./PI*1.94*((RO/R)**2.)*(SIN(RLAT)*SIN(DEC)*
     &         TIME+COS(RLAT)*COS(DEC)*SIN(TIME))
 2          CONTINUE
 1       CONTINUE
      RETURN
      END
```

APPENDIX B

COMPUTATION OF Rg

Seckel and Beaudry (1973) suggested the following equations for calculating clear day global radiation, R_{gc}, over the Pacific and their validity has been investigated by Reed (1982):

$$A0 = -32.65 + 674.76\cos(phi)$$

$$A1 = 19.88 + 397.26\cos(phi+90)$$

$$B1 = -6.75 + 224.38\sin(phi)$$

$$A2 = -1.32 + 16.10\sin2(phi-45)$$

$$B2 = -1.04 + 29.76\cos2(phi-5)$$

$$R_{gc} = A0 + A1\cos(o) + B1\sin(o) + A2\cos(2o) + B2\sin(2o)$$

where:

phi is the latitude

o = 2Pi/365(day - 21) where day is the day of the year

(Note that the A0 term in equation (1) is missing in Seckel and Beaudry's article. Note further that Seckel and Beaudry use both radians and degrees in their equations.)

Average global radiation under normal cloudy conditions is then calculated from clear day radiation by equation (1) using Reed's formula:

$$R_g = R_{gc}(1 - .62C + .0019alt)$$

where:

C is cloudiness in hundredths

alt is the noon solar altitude

Since there are two independent variables whose value changes daily, the equation must be evaluated on a daily basis and then summed to obtain monthly averages.

The following are calculated daily averages of R_{gc} and the FORTRAN program used to calculate global radiation for latitudes from 30N to 25S, longitudes from 130W to 130E and for each month.

Table B1

Daily Average R_{gc}

Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
30N	355	440	549	647	711	737	726	677	590	478	377	328	552
25N	411	489	584	664	709	725	718	685	617	522	431	386	579
20N	464	534	615	675	702	708	705	687	639	561	482	441	601
15N	514	575	639	680	689	686	686	683	655	596	529	494	619
10N	561	610	659	679	671	659	662	673	665	626	573	543	632
5N	603	641	672	673	648	628	633	657	669	650	612	589	640
0	641	667	679	660	620	592	600	636	667	668	647	631	642
5S	675	686	680	642	587	551	561	609	659	681	677	669	639
10S	704	701	675	618	549	507	519	577	645	688	702	702	632
15S	728	710	664	588	507	459	473	540	625	689	722	731	619
20S	746	713	648	554	461	408	423	499	599	684	736	754	601
25S	759	710	625	515	411	354	369	453	568	674	744	772	579

APPENDIX C

COMPUTATION OF Rdc

It turned out that I did not need to compute clear day direct radiation, but since I have not seen the data available elsewhere and it cost a great deal to assemble it, I have decided to include it here.

Average monthly clear day direct radiation can be caluclated using the following formula given by List:

$$R_{dc} = 2J_o(r_o/r)^2 \; tao_a{}^{sec(z)} cos(z) \; dt$$

where:

R_{dc} = clear day direct beam radiation

a is the transmissivity of the atmosphere (.7 here)

sec(z) is the optical path (not strictly accurate for solar altitudes less than 10^o, but the error is small)

The other terms are defined in the previous section.

This integral is not soluble by conventional integration, and rather than tackle the unconventional, I have calculated R_{dc} for each minute of daylight of each day at each latitude and summed the result to derive monthly averages. This involves an incredible volume of calculations and the following computer time estimates may be of help to anyone wishing to use this program for other transmissivities and other latitudes. For monthly averages from 30^oN to 25^oS computer time is:

IBM 3081 . . . . 120 seconds

HP 2649G (18K memory) . . . . 36 hours

HP 41CV (2.2K memory) . . . . 45 days

The program executed about eight million lines in calculating the following table:

Table C1

Average Daily R_{dc} for Transmissivity = .7

Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
30N	235	311	415	510	567	586	576	532	450	344	253	212	416
25N	286	357	450	527	568	579	572	542	477	386	302	263	443
20N	335	400	479	539	563	566	563	546	500	425	350	314	465
15N	382	440	504	544	552	548	548	545	517	459	395	363	483
10N	426	475	523	543	535	524	528	538	529	488	437	409	496
5N	467	505	536	537	514	496	502	524	534	513	475	453	505
0	504	530	543	524	487	462	472	506	534	532	509	493	508
5S	536	550	544	506	455	425	437	482	527	545	537	528	506
10S	563	564	539	483	419	384	398	453	515	553	561	559	499
15S	584	571	528	454	379	340	356	420	497	554	578	584	487
20S	599	573	512	421	336	294	312	382	474	549	590	603	470
25S	609	568	489	383	291	247	265	341	445	539	596	617	449

```
C
C    FORTRAN SUBROUTINE TO COMPUTE DAILY CLEAR DAY DIRECT BEAM RADIATION
C    USING AN ATMOSPHERIC TRANSMISSIVITY OF 0.7.
C
      DIMENSION QD(370,40)
      PI=3.1415926
      RO=1.4957
      FIVE=5.*PI/180.
C
C   FILL ARRAY QD(I,L) WITH DAILY VALUES ON A FIVE DEGREE GRID FROM
C   25 DEGREES SOUTH TO 30 DEGREES NORTH.
C   L IS THE LATITUDE AND I IS THE DAY OF THE YEAR.
C   SOUTHERN HEMISPHERE LATITUDES ARE CONSIDERED NEGATIVE.
C   (DAILY TOTALS ARE COMPUTED BY SUMMING VALUE FOR EACH MINUTE.)
C
      DO 1 L=1,12
         RLAT=(PI/6+FIVE)-L*FIVE
         DO 2 I=1,365
            R=RO-.025*COS((I-2)/365.*2.*PI)
            DEC=23.45/180.*PI*(-COS((I*1.+10.)/365.*PI*2.))
            TIME=ARCOS(-TAN(RLAT)*TAN(DEC))
            MTS=INT(720/PI*TIME)
            QD(I,L)=0.
            X=SIN(DEC)*SIN(RLAT)
            X1=COS(DEC)*COS(RLAT)
            Y=2*1.94*RO*RO/R/R
            DO 3 K=1,MTS
               TIME=K*PI/720.
               Z=X+X1*COS(TIME)
               IF(ABS(Z).LT.(.01)) GO TO 3
               QD(I,L)=QD(I,L)+Y*Z*.7**(1/Z)
    3          CONTINUE
    2       CONTINUE
    1    CONTINUE
      RETURN
      END
```