Marine Sciences Research Center, SUNY at Stony Brook

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THE THERMAL INERTIA OF THE SEA SURFACE

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1. INTRODUCTION

Given the state of the atmosphere, one can predict the change in the temperature distribution in the ocean (James 1966). The inverse problem, to predict the future state of the atmosphere from oceanic conditions has primarily been approached by correlating sea surface temperatures with the weather. The response of the atmosphere to changes in the surface ocean is important for studies of climatic variation because the effective time constants increase greatly as one progresses from the atmosphere to the surface ocean and the deep ocean. To gain a better understanding of the mechanisms by which the surface ocean stabilizes the climate, we need to understand the response of the ocean surface temperature to heat transfer to and from the ocean.

In this paper, I develop indices of the stability of sea surface temperature to heat loss, that are independent of atmospheric conditions. An examination of the variations of these indices with time and space will help us elucidate mechanisms that modify ocean - atmosphere interaction. The problem is complicated because the interactions between the two realms are non-linear. On the average, the ocean absorbs solar radiation and warms the bottom of the atmosphere. Changing the sign of the temperature difference ocean minus atmosphere from plus to minus, decreases the absolute magnitude of components of heat flux by an order of magnitude.

Cooling of the ocean generally results in a deepening of its convectively mixed surface layer. The process depends primarily on the physical state of the ocean. Warming of the surface layer reduces the depth of convection. The density instability results from the absorption of radiant energy in the upper 100 meters, while the loss of heat occurs at the sea surface. In the open ocean, the depth dependence of the absorption of solar radiation by seawater depends primarily on its biological characteristics. Here, I will limit myself to developing indices of the thermal inertia of the sea surface under conditions of cooling.

The surface ocean is not a passive thermal filter that reduces temperature fluctuations. Rather, it absorbs solar radiation and transfers heat to the bottom of the atmosphere. The following forms of thermal energy are exchanged:

1. Solar radiation is absorbed by the sea and reflected by the sea surface. The intensity of these terms depend on the location of the sun in the sky and on the state of the atmosphere, particularly on the distribution of clouds.

2. Infrared thermal radiation is radiated from the sea surface and thermal radiation from the atmosphere is absorbed by the sea.

3. Sensible heat is transferred between the sea and the air. The rate of sensible heat transfer depends on the temperature difference between the air and the water. Heat exchange increases rapidly with wind speed.

4. Latent heat is transferred by the evaporation of water from the sea sur-

face to saturate the moisture content of the air. The rate of transfer depends on the temperature of air and water and the relative humidity of the air. The rate increases rapidly with wind speed.

Whereas processes 1 through 3 only change the temperature of the sea, process 4, the transfer of latent heat also changes its salinity.

Of the heat flux terms listed above, only the rate of infrared radiation from the ocean to the atmosphere is approximately independent of atmospheric conditions. (Note that the net backradiation, the difference between the fluxes ocean-atmosphere and atmosphere-ocean does depend on atmospheric conditions.) I therefore introduce as an index of the thermal stability of the sea, the rate at which its surface temperature would drop, if its net rate of heat loss were equal to the rate of backradiation. The index has dimensions of degrees per unit time. A convenient time unit is the day. The value of the index depends on how the heat is lost. If the loss is exclusively by radiation and sensible transfer of heat, only the temperature of the sea is altered. If, instead, a portion of the heat is lost as latent heat, the salinity of the sea surface increases and its temperature decrease is reduced.

1.1 The Indices

I define the following two indices:

1. A Backradiation Index: This index assumes that the net heat transfer is equal to the rate of thermal backradiation from the ocean to the atmosphere and that there is no transfer of latent heat.

2. A Sensible and Latent Heat Index: This index assumes the same rate of heat loss, however, part of the heat is transferred as latent heat of evaporation. The partitioning between latent and sensible heat is set to equal a quasi-equilibrium process. The air in contact with the water remains saturated as the air is warmed. The fraction of latent heat transferred, due to the exponential increase of watervapor pressure with temperature, increases rapidly with increasing temperature.

Whereas the first index assumes that the surface ocean only loses heat, the second index also involves a loss of water and hence an increase in salinity. The indices ignore precipitation. On the average, the water evaporated from the ocean is balanced by precipitation and runoff. Precipitation, however, is generally separated in space and time from evaporation. Cooling and evaporation will cause local deepening of the mixed layer. Precipitation elsewhere in the open ocean, whether as water or ice will result in forming a less dense stable surface layer. Precipitation must be considered when developing indices for mechanisms that reduce the depth of the mixed layer.

2. CALCULATING THE INDICES

Conventional methods for computing the above indices from oceanographic data are difficult and time consuming. One could develop programs by which mainframe or minicomputers evaluate the indices. Recent developments of microcomputers with powerful spreadsheet applications programs provide a preferable alternative. They permit graphical analysis of the input data and allow the scientist to interactively explore the output using a variety of tabular and graphical displays.

2.1 Spreadsheet Analysis

The analysis here described was carried out using the Lotus Symphony applications program. It can readily be adapted to other electronic spreadsheet programs. A spreadsheet consists of a two dimensional array of fields organized into columns (labeled by capital letters) and rows (labeled by numbers). A field can contain numbers, formulas involving values in other fields and descriptive labels. Here, each row deals with hydrographic data from a single station. The process of calculation only has to be developed for a single row. To evaluate many rows, the formulas are copied with appropriate modifications, to simultaneously analyze data from many stations.

Table 1 list the sequences required to compute the indices of thermal inertia for the station data listed in row 8. The worksheet extends from column A through column AJ. Columns A through J contain the original station data and columns K through AJ contain the computations. The spreadsheet uses the following conventions:

- F8 The value located in column F row 8
- * The Multiplication sign
- \ Division
- ^ Raise to a power, $T\hat{}4 = T^4$

Table 1 Notes

1 N and E positive, S and W negative
2 All temperatures are potential temperatures.
3 Copied as values from SigmaT part of worksheet
4 Grams of water per kilocalorie of heat of total heat
5 Fraction of total heat that is sensible heat
6 Ratio of salinity increase temperature change
7 Heat loss in calories to deepen mixed layer by one meter

Table 1 Spreadsheet to determine the Thermal Inertia Indices.

Column	Attribute	Units	Note	Entry in Row 8
		DATA ENTRY		
A	Station #			287
B	Latitude	degrees	(1)	-69.0833
C	Longitude	degrees	(1)	-178.5
D	Date			@DATE(74,2,20)
E	z1	meters		21
F	T1	deg.Celsius	(2)	-1.49
G	S1	ppt.		33.384
H	z2	meters		32
I	T2	deg.Celsius		-1.2
J	S2	ppt.		33.761
		CALCULATED INITIAL CONDITIONS		
K	Radiation Loss at z1	Kcal/cm^2,day		(F8+273.2)^4*1.171 E-7
L	dT/dz	deg/m		(I8-F8)/($H8-$E8)
M	dS/dz	ppt/m		(J8-G8)/($H8-$E8)
N	sigmaT		(3)	26.882
O	dsigmaT/dT	per degree	(3)	-0.03376
P	dsigmaT/dS	per ppt	(3)	0.80932
Q	dS/dT:sigmaT	ppt/deg	(3)	0.04171
R	dsigmaT/dz at z1 + 1	per m		(O8*L8)+(P8*M8)
S	sigmaT			N8+R8
		AFTER MIXING TO DEPTH z1 + 1 meter		
T	T1	deg.Celsius		(F8*(E8+1)+L8*0.5)/(E8+1)
U	S1	ppt.		(G8*(E8+1)+(M8*0.5))/(E8+1)
V	dsigmaT mix			(T8-F8)*O8+(U8-G8)*P8
W	addtl dsigmaT needed			R8-V8
		COOLING ONLY		
X	dT	deg/m		W8/O8
Y	Heat loss	cal/cm2		-X8*100*(E8+1)
Z	final T1	deg.C		T8+X8
AA	Radiation Index	deg.C/day		-(Z8-F8)*K8/Y8
		SENSIBLE AND LATENT HEAT LOSS		
AB	gm evap/Kcal	cm/Kcal	(4)	0.56+0.034*T8-0.00024*T8*T8
AC	sensQ/total Q		(5)	0.67-0.022*T8+0.00020*T8*T8
AD	dS/dT	ppt/deg	(6)	-U8*AB8/1000*AC8
AE	dT	deg.		W8/(O8+P8*AD8)
AF	dS	ppt.		AD8*AE8
AG	final T	deg.		T8+AE8
AH	final S	ppt.		U8+AF8
AI	Heat loss	cal/cm2	(7)	-(AG8-T8)*100*(E8+1)/AC8
AJ	S & L Index	deg.C/day		-(AH8-F8)*K8/AI8

2.5 Cooling Only, Columns X-AA

To accomplish the density increase exclusively by cooling, the needed temperature decrease is calculated in column X by dividing the density change (column W) by the partial change of sigmaT with temperature (column O). The resultant temperature is calculated in column Z and the required heat loss in calories per cm^2 is found in column Y. The radiation index is computed in column AA.

2.6 Sensible and Latent Heat Loss (Columns AB-AJ)

To determine the index when heat is lost both as sensible and latent heat, the process is slightly more complex. First we use two empirical expressions that describe the characteristics of the quasi-equilibrium heating of moist air as a function of the temperature after mixing (Column T). Column AB estimates the grams of water evaporated per kilocalorie of total heat transfer. Column AC estimates the fraction of the heat loss that is in the form of sensible heat.

The derivative of salinity with temperature due to the quasi-equilibrium process, which depends on the salinity (column U) is calculated in column AD. Using this value, we can compute the required changes in T and S (columns AE and AF). The changes in T and S then give us the final values of T and S (columns AG and AH). The total heat loss in calories per cm^2 to mix the water column to a depth of z1 + 1 meters is calculated in column AI. This is then used to determine the sensible and latent heat index (column AJ).

3. THE INDICES FOR SELECTED HYDROGRAPHIC DATA

To examine the spatial variability of the indices of thermal inertia, I have determined them for the 38 stations comprising the Western Pacific Section of the GEOSECS Expedition (Broecker et al 1982). The stations data and the indices as computed using the spreadsheet are given in Table 2. Columns A through K as well as the indices, columns AA and AJ are shown. The data range in latitude from 69 degrees South to 53 degrees North near 180 degrees of Longitude. In time, the observations span the period from 25 September 1973 to 23 March 1974.

TABLE 2 INDICES for GEOSECS WEST PACIFIC SECTION

Stn.#	Lat	Long	Date	z1	T1	S1	z2	T2	S2	Radiation loss	INDICES deg/day Rad	S&L
A	B	C	D	E	F	G	H	⁝	J	·	AA	AJ
287	-69.08	-178.50	20-Feb-74	21	-1.49	33.38	32	-1.20	33.76	638	0.290	0.204
288	-67.70	-173.98	22-Feb-74	33	0.13	33.66	52	-1.35	34.18	654	0.193	0.129
289	-61.98	-174.00	24-Feb-74	82	2.15	33.85	104	1.54	33.97	673	0.081	0.051
290	-58.00	-174.00	25-Feb-74	93	4.49	33.96	124	3.74	34.04	696	0.074	0.043
298	-46.68	-166.83	18-Mar-74	42	13.41	34.81	77	12.61	34.82	790	0.186	0.077
297	-46.00	-166.75	18-Mar-74	77	13.40	34.85	106	11.24	34.86	790	0.102	0.042
296	-44.98	-166.70	16-Mar-74	53	12.43	34.70	82	11.46	34.94	779	0.145	0.062
299	-44.22	-166.77	19-Mar-74	29	14.53	34.67	54	11.72	34.76	803	0.272	0.107
300	-43.25	-166.77	20-Mar-74	3	15.64	34.80	74	12.36	35.00	815	2.281	0.885
301	-41.55	-166.83	21-Mar-74	52	14.44	34.82	112	11.49	34.94	802	0.153	0.060
302	-40.50	-166.70	22-Mar-74	29	16.94	35.01	44	15.38	34.99	830	0.281	0.100
303	-38.37	-170.07	23-Mar-74	43	18.22	34.93	62	14.82	35.03	845	0.194	0.065
273	-29.95	-175.70	22-Jan-74	32	23.20	35.57	51	20.96	35.71	904	0.278	0.075
269	-23.98	-174.43	18-Jan-74	6	27.26	35.42	41	25.87	35.51	954	1.454	0.328
268	-20.50	-172.80	17-Jan-74	5	27.94	35.41	71	24.10	35.75	963	1.726	0.378
267	-19.25	-171.42	16-Jan-74	20	28.33	34.94	30	28.24	34.97	968	0.467	0.098
266	-18.48	-168.05	15-Jan-74	28	28.23	34.71	68	25.23	35.77	967	0.337	0.070
263	-16.65	-167.07	09-Jan-74	37	28.34	34.79	77	26.43	35.68	968	0.256	0.053
255	-12.18	-169.90	03-Jan-74	36	28.44	34.72	50	28.30	34.78	969	0.264	0.055
257	-10.17	-169.97	05-Jan-74	11	28.30	34.77	51	28.00	35.41	968	0.812	0.169
252	-8.48	-178.08	26-Dec-73	51	28.65	34.55	61	28.73	34.90	972	0.187	0.038
251	-4.57	178.95	24-Dec-73	4	27.72	35.65	54	27.62	35.65	960	2.103	0.469
250	-2.98	178.98	23-Dec-73	79	27.80	35.59	113	27.39	35.75	961	0.121	0.026
249	-2.02	179.02	23-Dec-73	62	26.69	35.46	99	26.63	35.50	947	0.151	0.034
248	-1.03	179.03	22-Dec-73	58	26.08	35.39	88	26.07	35.40	939	0.160	0.037
246	0.00	178.98	21-Dec-73	85	25.71	35.24	129	25.22	35.38	935	0.109	0.026
243	2.00	178.93	19-Dec-73	50	26.26	35.10	91	25.44	35.08	942	0.187	0.043
242	3.07	178.92	19-Dec-73	50	26.54	35.09	90	26.08	35.18	945	0.187	0.042
241	4.55	179.00	17-Dec-73	49	27.16	35.13	99	26.77	35.18	953	0.192	0.042
229	12.88	173.47	18-Nov-73	73	27.95	34.56	92	27.20	34.84	963	0.131	0.028
228	19.02	169.35	15-Nov-73	80	27.71	34.96	111	25.02	35.15	960	0.119	0.026
227	25.00	170.08	12-Nov-73	51	26.60	35.21	77	24.32	35.16	946	0.184	0.042
214	32.02	-176.98	25-Sep-73	28	25.47	34.75	32	24.23	34.76	932	0.327	0.079
215	37.47	-177.32	28-Sep-73	33	20.05	34.33	48	16.94	34.62	866	0.258	0.080
216	40.77	-176.97	30-Sep-73	34	16.04	33.61	49	13.28	34.23	820	0.236	0.087
217	44.67	-177.05	02-Oct-73	46	10.40	33.07	54	8.98	33.25	757	0.162	0.075
218	50.43	-176.58	04-Oct-73	42	8.25	32.65	51	6.96	32.68	735	0.173	0.087
219	53.10	-177.28	08-Oct-73	51	7.22	33.07	63	5.59	33.23	724	0.140	0.073

The two indices are plotted as a function of latitude in figure 1. The figure shows a very large scatter of the indices. The rates of temperature loss vary from about 2.5 to 0.03 degrees per day. The rates of temperature loss tend to be higher in the summer hemisphere (South) than in the winter hemisphere (North).

The ratio of the radiation to the sensible and latent heat index (figure 2) increases with temperature. Deviations of the ratio from the average trend are relatively small. The increase in the ratio is directly related to the increasing transfer of latent heat, as the temperature rises.

The large fluctuations in the indices are primarily the result of variations in the depth of the mixed layer. This is brought out by figure 3, which is a log-log plot of the radiation index against the depth of the mixed layer. Deviations from an inverse relationship between the radiation index and the mixed layer depth range up to about 50 percent.

4. CONCLUSION

I have developed two indices that are a measure of the thermal stability of the surface ocean to cooling. The indices are readily determined from oceanographic data using a microcomputer implemented spreadsheet. Having the data in a spreadsheet format facilitates analysis and permits the interactive creation of a variety of output formats. The use of a spreadsheet also facilitates the development and verification of the mathematical manipulations required, by dividing the complex process into a number of simple consecutive steps. The intermediate results can be useful when analyzing the roles of various factors in determining the final index.

Much larger data sets, that involve time - space series will be needed, to map out the variability of the thermal inertia of the sea surface. This paper indicates that one can expect large variations that depend primarily, but not exclusively on the depth of the mixed layer.

5. REFERENCES

Broecker, W. S.; Spencer, D. W. and Craig C; 1982; GEOSECS Pacific Expedition, Volume 3 Hydrographic Data 1973-1974, IDOE, NSF Oct. 1982.

James, Richard W. 1966; Ocean Thermal Structure Forecasting, SP-105 ASWEPS Manual v.5, U.S. Naval Oceanographic Office.

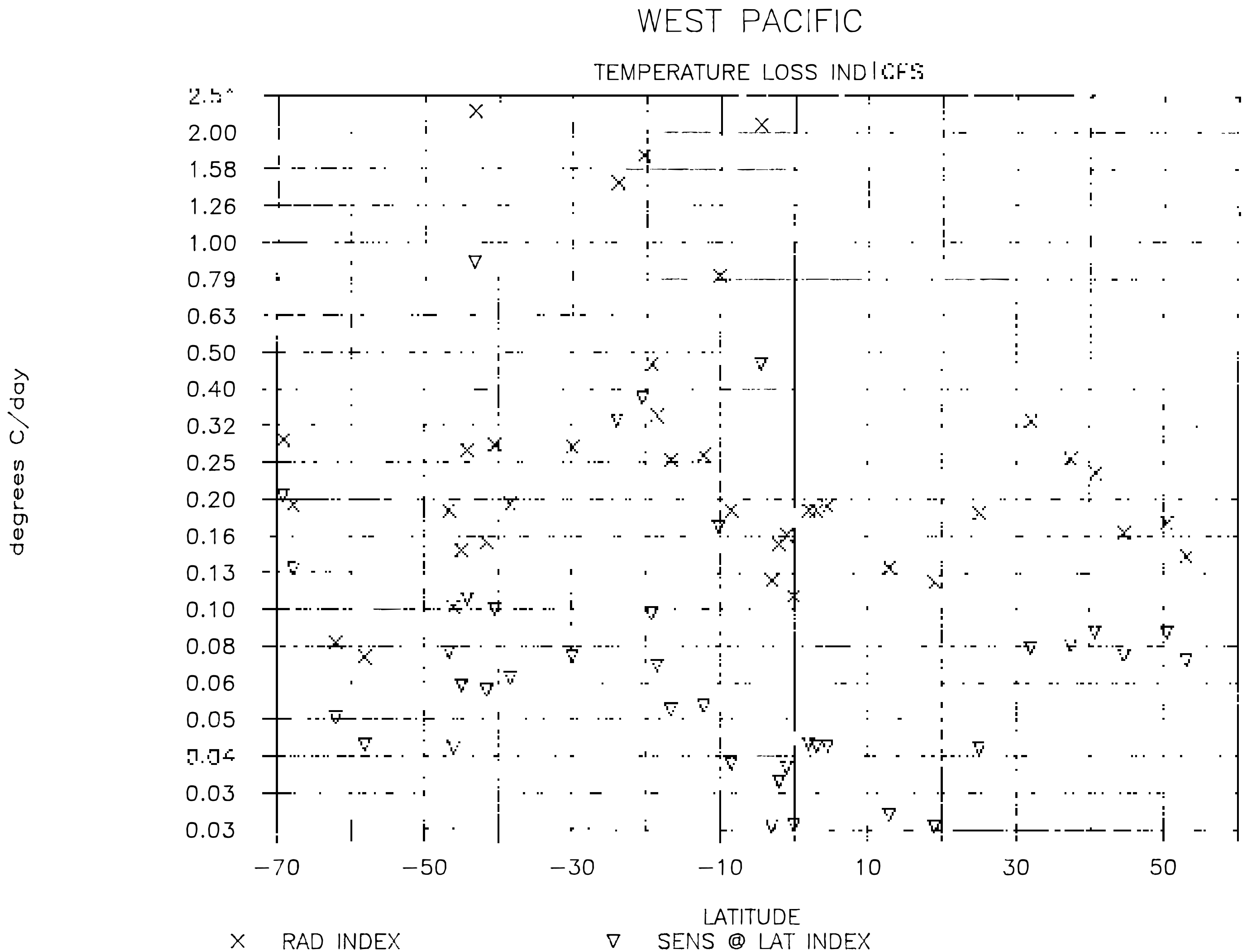

WEST PACIFIC
TEMPERATURE LOSS INDICES
degrees C/day
2.00
1.58
1.26
1.00
0.79
0.63
0.50
0.40
0.32
0.25
0.20
0.16
0.13
0.10
0.08
0.06
0.05
0.04
0.03
0.03
−70
−50
−30
−10
10
30
50
LATITUDE
× RAD INDEX
∇ SENS @ LAT INDEX

Figure 1

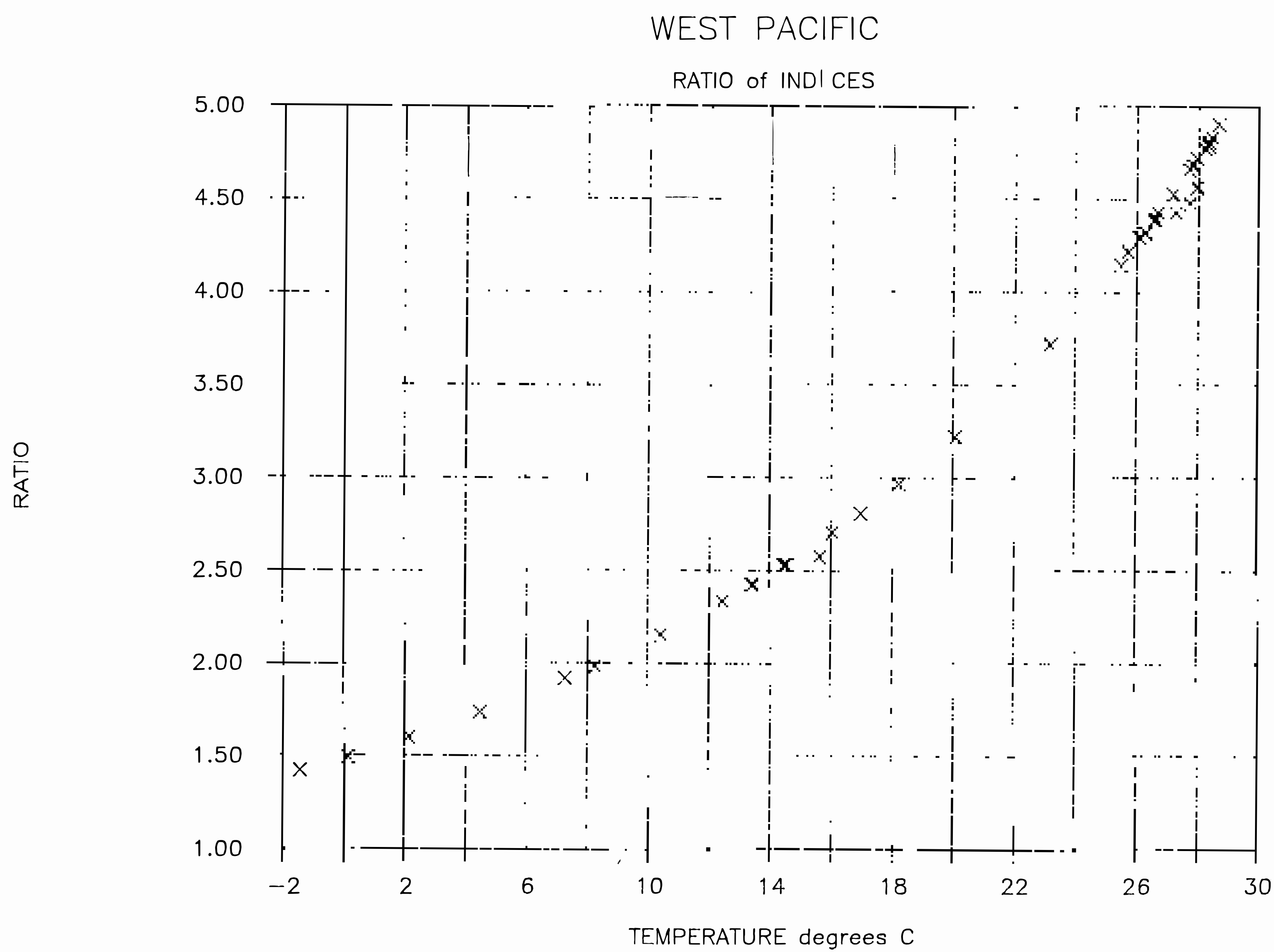
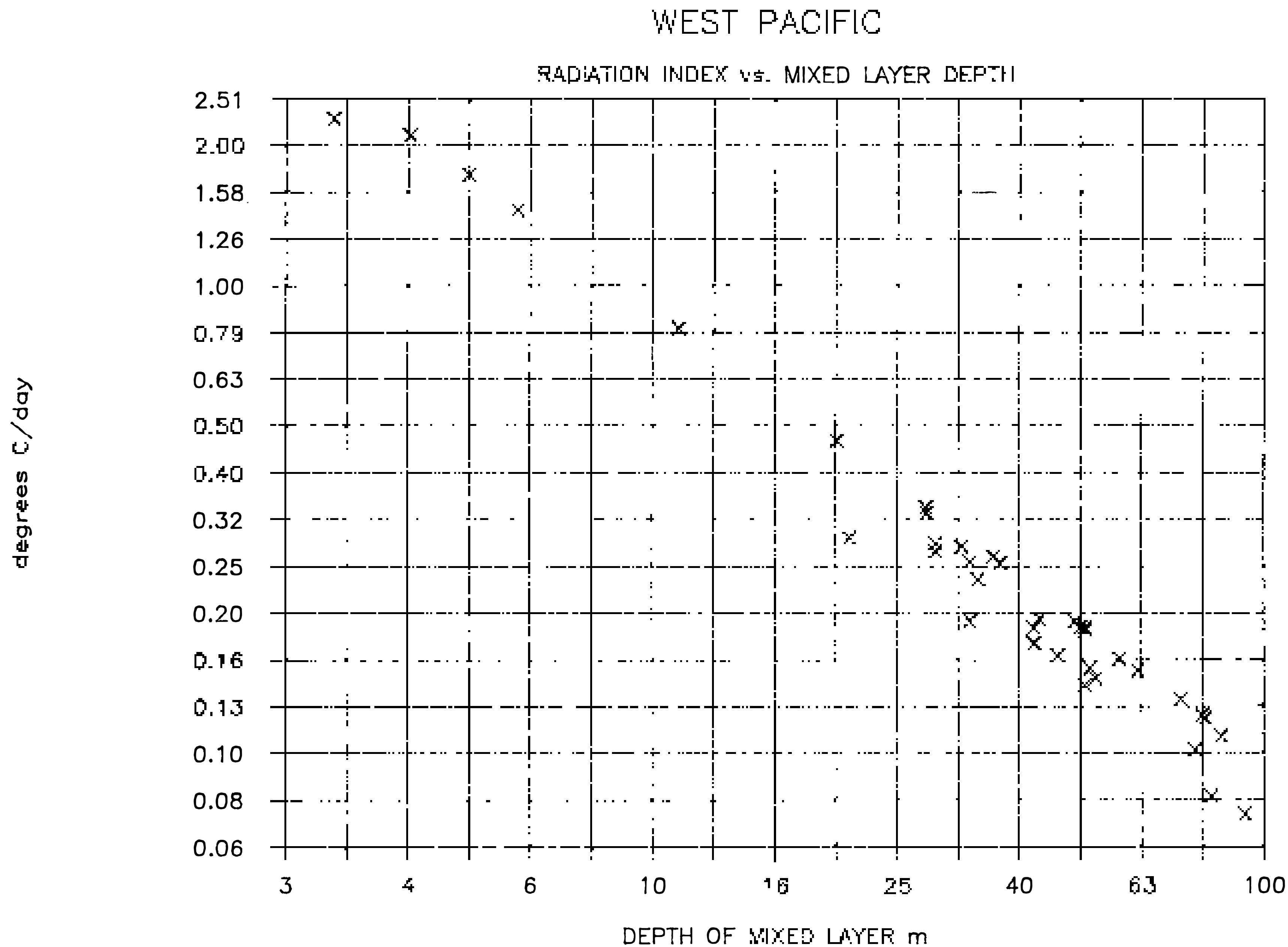

WEST PACIFIC
RATIO of INDICES
RATIO
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
−2
2
6
10
14
18
22
26
30
TEMPERATURE degrees C

Figure 2



WEST PACIFIC
RADIATION INDEX vs. MIXED LAYER DEPTH
degrees C/day
2.51
2.00
1.58
1.26
1.00
0.79
0.63
0.50
0.40
0.32
0.25
0.20
0.16
0.13
0.10
0.08
0.06
3
4
6
10
16
25
40
63
100
DEPTH OF MIXED LAYER m

Figure 3

DUE DATE