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Energy Fluxes Over the Eastern Tropical Pacific Ocean, 1979-1982

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NOTICE

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ABSTRACT. Weather observations and measurements of insolation were made aboard the NOAA ships *Oceanographer* and *Discoverer* during the Equatorial Pacific Ocean Climate Studies (EPOCS) work in the eastern tropical Pacific from 1979 to 1982. These observations and computed fluxes of net longwave radiation, latent heat, and sensible heat are documented and presented. Insolation was the dominant heat flux, and latent heat loss was typically much greater than net longwave radiation or sensible heat loss. The largest values of net surface flux occurred during periods of minimal cloud cover and weak winds. Comparisons of net surface heat flux and changes in oceanic heat content in the region 4°-12°N showed an inexact balance, but the results indicate that the surface heat flux is an important variable during normal oceanic conditions. In contrast, observations over a 6-day period near the equator showed a change in heat content that was about 20 times the net surface flux, presumably as a result of lateral movement of a thermal front. The results near the equator suggest that in the initiation phase of an El Niño surface fluxes are not important.

1. INTRODUCTION

It has been known for many decades that the eastern equatorial Pacific Ocean is subject to large interannual changes. The most extreme type of event, called El Niño, occurs irregularly every several years and is characterized by abnormally warm ocean temperatures over large areas of the tropical Pacific, which in turn have significant effects on atmospheric circulation (see, for example, Bjerknes, 1966).

Gaining understanding of the influence of the equatorial ocean on interannual climate variations is the goal of NOAA's Equatorial Pacific Ocean Climate Studies (EPOCS) program, which is investigating the behavior of both the ocean and the atmosphere. Some aspects of the response of the ocean to varying wind stress are moderately well understood (Wyrtki, 1975; Busalacchi and O'Brien, 1981), but studies of the direct effect of heat flux variations on the upper ocean have been quite limited. This report presents determinations of air-sea energy exchange along tracklines of the NOAA ships *Oceanographer* and *Discoverer* during recent EPOCS work and examines the importance of these fluxes on the ocean heat budget.

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2. DETERMINATION OF FLUXES

Several assessments of air-sea heat exchange over the tropical Pacific have been carried out, but most of them suffer from serious errors in the formulas for computing one or more of the fluxes. A recent study that appears to be free from this problem is that of Weare et al. (1980), who used recently evaluated formulations for radiation (Reed, 1976, 1977; Simpson and Paulson, 1979) and for latent and sensible heat flux (Bunker, 1976). Weare et al. determined only long-term mean annual and monthly fluxes, however, and the data were averaged over 5° × 5° areas. Hence there is a need to examine the exchanges over other time and space scales.

The exchange of heat between the ocean and atmosphere may be expressed as

$$Q_t = Q_s - Q_b - Q_e - Q_h, \tag{1}$$

where Q_t is net heat gain or loss by the ocean, Q_s is the insolation (shortwave solar radiation) minus the shortwave radiation reflected from the ocean surface, Q_b is the net longwave radiation from the ocean surface, Q_e is the latent heat loss by the ocean, and Q_h is the sensible heat loss. The four terms on the right side of (1) were measured or assessed from environmental observations along the EPOCS tracklines of the *Oceanographer* and *Discoverer* as described below. Computational methods were similar to those of Weare et al. (1980) so that these data can be compared directly with theirs. The units used are watts per square meter (1 W m^{-2} = 2.06 cal cm^{-2} day^{-1}).

2.1 Insolation

The heat exchanges determined here have a major advantage over most other data sets because insolation, usually the largest flux in this region, was measured rather than computed. Insolation was routinely measured aboard the *Oceanographer* from 1975 through 1981 in an effort to derive computational methods for shortwave radiation over various oceanic regions (Reed, 1977, 1982), and the measurements were supported by *hourly* (rather than 3- or 6-hourly) weather observations. This observational program was not conceived as a part of EPOCS, but the data are available during nearly all of the EPOCS work prior to 1982. In 1982 the *Discoverer* conducted an identical program with EPOCS support.

On the *Oceanographer* insolation was measured with an Eppley model 8-48 pyranometer mounted atop a leveled post on the forepeak of the ship. (Details on methods and instrument calibrations are contained in Reed, 1982.) The data were recorded on an analog recorder, and the voltage was accumulated by an electronic integrator to derive daily total insolation values. The records were annotated by officers and technicians on the ship, who also inspected and cleaned the pyranometer dome each day when feasible. On the *Discoverer* in 1982 insolation was measured with an Eppley precision spectral pyranometer, calibrated by NOAA's Solar Radiation Facility in January 1982; other procedures were the same as those aboard the *Oceanographer*, except daily insolation was derived by manually digitizing the analog records.

2.2 Net Longwave Radiation

The net longwave radiation was computed with the formula

$$Q_b = \varepsilon\sigma T^4 (0.254 - 0.00495e)(1 - 0.7C), \qquad (2)$$

where ε is the emissivity of the sea surface (taken as 0.97), σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), T is the sea surface temperature in kelvins, e is the air vapor pressure in millibars, and C is cloud cover in tenths. This is the expression recommended by Reed (1976) for the middle-level clouds typical of the tropics; the clear-sky part of the formula was derived by N. A. Efimova (Budyko, 1974). On the other hand, Simpson and Paulson (1979) found better agreement of measurements with a more complex expression derived by M.E. and T. G. Berliand (Budyko, 1974); Weare et al. (1980) used the Berliand method. Additional, carefully controlled measurements at sea are needed to resolve these differences. The formula attributed to the Berliands gives clear-sky values about 15% greater than the formula developed by Efimova gives. However, the differences are usually insignificant under typical cloud cover, and the net longwave flux is normally only about 10%-20% of the insolation.

2.3 Latent and Sensible Flux

The latent and sensible heat fluxes were computed with bulk aerodynamic expressions using the exchange coefficients given by Bunker (1976). The coefficients are functions of windspeed and atmospheric stability. The values were derived from a review of numerous determinations and appear to have gained general acceptance. The methods used here were identical to those employed by Weare et al. (1980).

3. RESULTS

Figures 1-6 show the EPOCS tracklines south of 20°N and east of 130°W. Corresponding data and computations are contained in tables 1-6. The data in the tables were averaged from the 24 hourly observations (from 0000 to 2300 GMT), and the fluxes were computed from the averaged daily values. As noted previously, insolation was measured, not computed, and the daily totals were corrected for reflected radiation using an albedo of 0.06, after Payne (1972).

It is difficult to assess the errors associated with the flux determinations. Q_s was nearly always the largest flux and had the smallest error because it was actually measured; the values are probably reliable to ±3%. The computations of net longwave radiation (Q_b) are considerably less reliable, and the possibility of systematic errors in the formula cannot be entirely discounted. A random error estimate of ±10% will be assumed; the error is mainly a result of imperfect determination of mean cloud cover. The errors associated with the determination of latent and sensible fluxes (Q_e and Q_h respectively) by bulk aerodynamic formulas have not been precisely evaluated; a random error of ±20% will be assumed for Q_e, and the error in Q_h will be ignored because of its very small magnitude in this region (see tables 1-6). A crude estimate of the random error in total daily flux (Q_t) is about ±20%, using the values above.

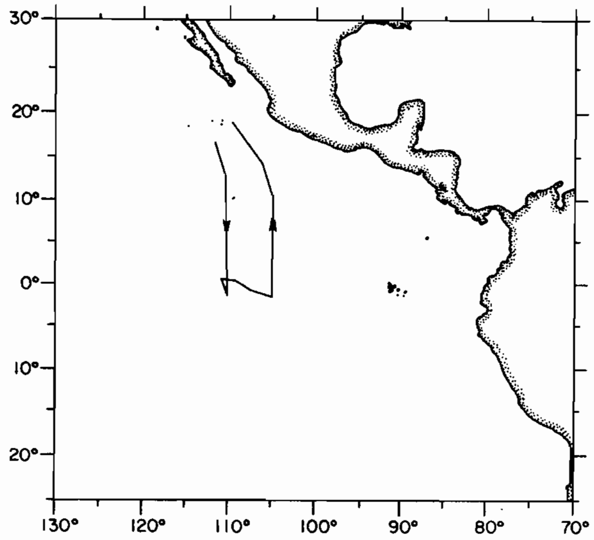

Figure 1.--Location of observations, NOAA ship *Oceanographer*, 18 October-3 November 1979.

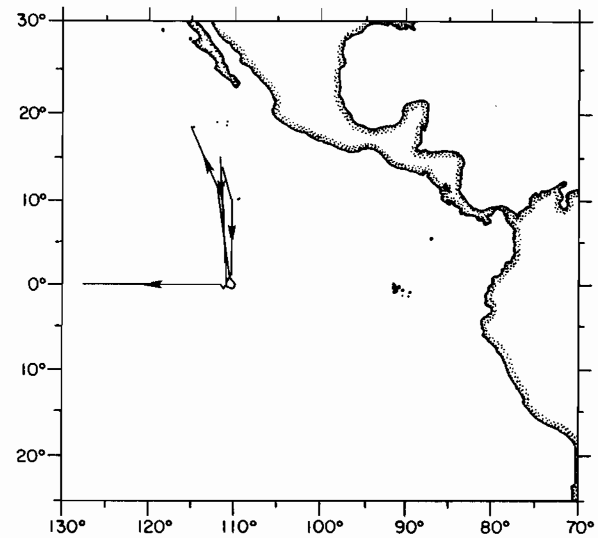

Figure 2.--Location of observations, NOAA ship *Oceanographer*, 29 February-4 April 1980.

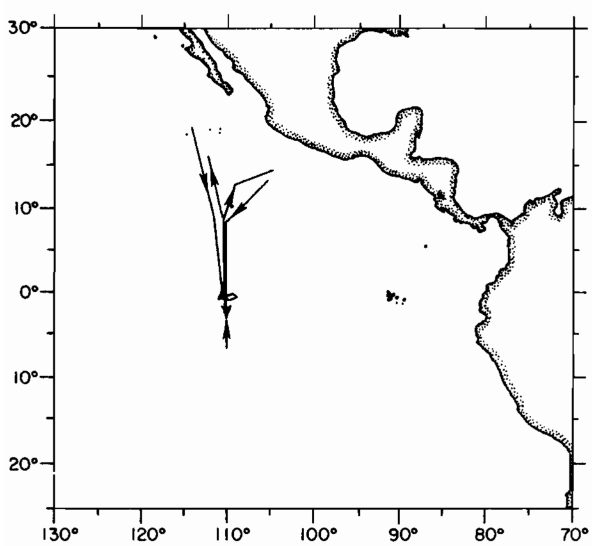

Figure 3.--Location of observations, NOAA ship *Oceanographer*, 28 January-21 March 1981.

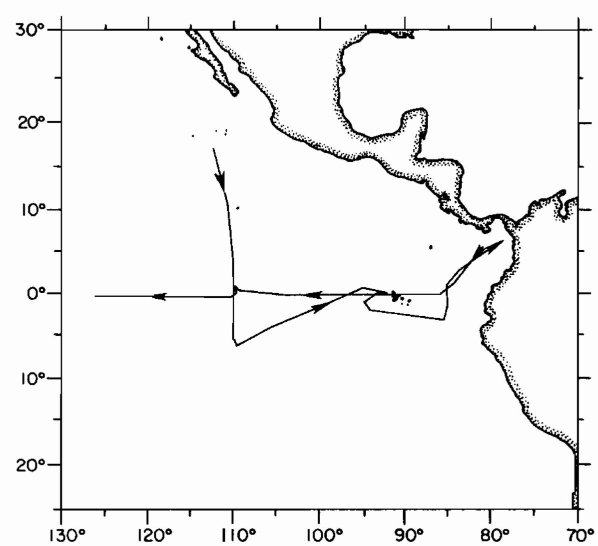

Figure 4.--Location of observations, NOAA ship *Oceanographer*, 28 May-14 July 1981.

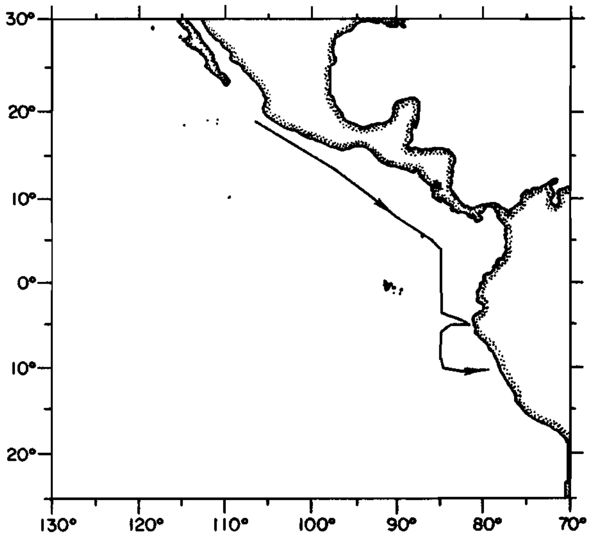

Figure 5.--Location of observations, NOAA ship *Discoverer*, 26 February-16 March 1982.

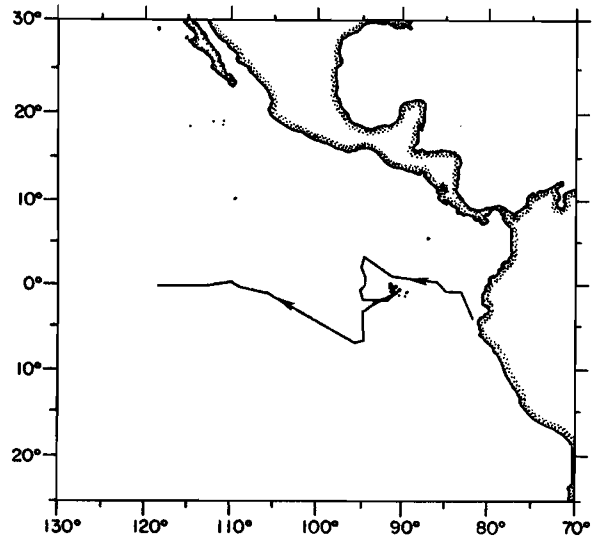

Figure 6.--Location of observations, NOAA ship *Discoverer*, 26 March-18 April 1982.

Table 1.--Daily mean heat fluxes and environmental data, 18 October-3 November 1979

Date	Lat. (°N,°S)	Long. (°W)	Sea sfc. temp. T_s (°C)	Air temp. T (°C)	Vapor press.(mb) sat. e_s	Vapor press.(mb) air e_a	Cloud amt.	Wind-speed (m s^{-1})	Heat flux* (W m^{-2}) Q_s	Q_b	Q_e	Q_h	Q_t
Oct.													
18	17.1	112.3	28.6	27.1	38.4	26.3	0.69	3.6	212	29	130	11	42
19	13.0	110.4	29.1	28.6	39.5	28.5	0.63	3.6	241	29	97	3	112
20	9.4	110.0	28.8	28.5	38.8	29.3	0.63	2.6	243	28	69	1	145
21	5.9	110.1	27.6	25.9	36.2	28.6	0.94	7.7	185	17	164	24	-20
22	2.6	110.0	25.1	24.5	31.2	23.8	0.75	8.8	240	28	171	9	32
23	0.4°S	110.0	23.3	23.9	28.0	23.4	0.38	7.7	270	43	87	-8	148
24	1.5°S	110.0	23.4	24.2	28.2	23.6	0.56	7.2	272	36	81	-9	164
25	0.3	110.2	23.6	24.3	28.6	24.7	0.88	8.2	196	22	79	-9	104
26	0.2	109.4	24.4	24.2	30.0	23.3	0.75	8.2	242	28	135	3	76
27	1.0°S	107.8	23.6	23.3	28.6	22.6	0.69	5.2	265	31	77	3	154
28	2.3°S	105.1	24.2	23.8	29.6	22.3	0.44	6.2	253	43	119	4	87
29	0.3	105.0	23.9	24.1	29.1	23.7	0.50	7.2	252	38	96	-2	120
30	3.4	105.0	26.7	25.9	34.3	25.7	0.88	7.2	148	22	163	10	-47
31	6.9	105.0	28.0	26.8	37.1	28.2	0.75	7.7	227	24	192	17	-6
Nov.													
1	10.4	105.0	28.7	26.8	38.6	29.7	1.00	4.6	135	15	122	17	-19
2	14.4	106.7	28.3	26.7	37.7	24.2	0.69	6.2	218	32	235	18	-67
3	18.9	110.0	26.4	25.5	33.7	22.7	0.50	6.2	202	41	180	10	-29

*Q_s = insolation minus reflected shortwave radiation; Q_b = net longwave radiation; Q_e = latent heat flux; Q_h = sensible heat flux; Q_t = net heat flux; ($Q_t = Q_s - Q_b - Q_e - Q_h$).

Table 2.--Daily mean heat fluxes and environmental data, 29 February-4 April 1980

Date	Lat. (°N,°S)	Long. (°W)	Sea sfc. temp. T_s (°C)	Air temp. T (°C)	Vapor press.(mb) sat. e_s	Vapor press.(mb) air e_a	Cloud amt.	Wind-speed (m s^{-1})	Heat flux* (W m^{-2}) Q_s	Q_b	Q_e	Q_h	Q_t
Feb.													
29	15.0	112.7	25.5	25.1	32.0	25.7	0.81	6.7	286	24	111	5	146
Mar.													
1	8.9	111.3	27.1	26.9	35.2	29.2	0.81	7.7	250	21	114	3	112
2	2.8	110.4	27.0	25.9	35.0	28.8	0.94	4.1	127	17	76	9	25
3	0.2°S	110.3	26.0	25.4	33.0	29.4	0.88	3.1	168	18	29	3	118
4	0.2°S	109.6	26.8	26.8	34.5	29.4	0.94	3.1	205	16	36	0	153
5	0.0	109.2	27.1	26.4	35.2	29.7	1.00	5.7	249	14	83	7	145
6	1.2	110.2	27.1	26.7	35.2	29.5	0.94	7.7	219	16	116	5	82
7	6.6	111.5	27.1	27.4	35.2	30.6	0.94	10.8	214	16	131	-6	73
8	12.2	112.7	26.7	26.7	34.3	28.5	0.88	11.3	257	19	173	0	65
9	17.5	113.8	24.8	23.2	30.7	23.1	0.88	7.2	212	23	154	21	14
Mar.													
25	13.8	111.3	27.5	26.2	36.0	25.7	0.69	5.2	253	30	160	13	50
26	9.0	110.0	27.2	27.7	35.4	30.8	0.88	6.7	182	18	76	-5	93
27	4.7	110.0	28.7	27.9	38.6	30.3	0.63	6.7	266	26	146	9	85
28	1.0	110.1	26.9	26.9	34.8	29.9	0.50	4.6	283	31	51	0	201
29	0.4°S	110.9	26.1	26.7	33.2	29.0	0.31	1.6	284	38	8	-1	239
30	0.0	111.7	25.8	26.7	32.6	29.3	0.44	1.6	284	33	6	-1	246
Apr.													
1	0.0	117.0	26.6	26.5	34.1	29.9	0.75	5.7	189	22	55	1	111
2	0.0	120.0	26.0	26.0	33.0	30.2	0.75	4.1	289	22	26	0	241
3	0.0	124.3	27.2	27.0	35.4	29.3	0.44	3.6	272	34	50	1	187
4	0.0	127.8	27.0	27.0	35.0	30.1	0.38	2.6	284	34	29	0	221

*See note, table 1.

Table 3.--Daily mean heat fluxes and environmental data, 28 January-21 March 1981

Date	Lat. (°N,°S)	Long. (°W)	Sea sfc. temp. T_s (°C)	Air temp. T (°C)	Vapor press.(mb) sat. e_s	Vapor press.(mb) air e_a	Cloud amt.	Wind-speed (m s^{-1})	Heat flux* (W m^{-2}) Q_s	Q_b	Q_e	Q_h	Q_t
Jan.													
28	19.7	114.3	21.8	21.8	25.6	17.5	0.25	6.2	222	57	132	0	33
29	13.8	113.0	25.5	25.3	32.0	26.1	0.69	9.3	181	28	144	3	6
30	8.8	111.8	26.6	25.1	34.1	27.1	0.94	4.6	101	18	90	13	-20
31	2.1	110.8	24.3	24.2	29.8	25.2	0.25	7.7	277	46	93	1	137

Table 3.--Daily mean heat fluxes and environmental data, 28 January-21 March 1981--Continued

Date	Lat. (°N,°S)	Long. (°W)	Sea sfc. temp. T_s (°C)	Air temp. T (°C)	Vapor press. (mb) sat. e_s	Vapor press. (mb) air e_a	Cloud amt.	Wind-speed (m s^{-1})	Heat flux* (W m^{-2}) Q_s	Q_b	Q_e	Q_h	Q_t
Feb.													
1	0.5	110.6	23.0	24.3	27.5	25.8	0.56	5.2	220	32	20	-10	178
2	0.0	110.9	22.9	23.8	27.4	25.9	0.25	6.2	280	44	23	-9	222
3	0.3°S	110.8	23.1	24.0	27.7	26.0	0.25	6.2	280	44	26	-9	219
4	0.2°S	110.3	23.1	23.8	27.7	25.7	0.13	5.7	289	49	28	-6	218
5	0.0	109.7	23.3	23.6	28.0	26.0	0.75	4.1	220	26	14	-1	181
6	0.1°S	109.3	23.3	24.4	28.0	27.2	0.44	3.6	275	30	3	-3	245
7	0.0	109.3	25.3	25.1	31.6	26.2	0.38	5.7	278	40	81	2	155
8	0.0	109.2	26.0	25.4	33.0	25.5	0.44	6.7	275	34	141	7	93
9	0.0	109.1	26.0	25.3	33.0	25.4	0.44	6.7	275	34	143	9	89
10	0.0	109.2	25.6	25.4	32.2	25.8	0.50	6.7	277	36	113	2	126
11	0.0	109.1	25.2	24.9	31.4	26.8	0.50	4.6	272	34	48	2	188
12	1.0°S	109.6	24.6	24.7	30.3	27.2	0.44	6.2	281	31	51	-1	200
13	0.5°S	110.4	25.2	25.2	31.4	27.6	0.44	5.7	274	31	57	0	186
14	3.8	110.4	26.3	26.1	33.5	28.6	0.75	7.7	165	24	99	3	39
15	8.5	110.2	26.8	26.8	34.5	28.2	0.38	10.8	251	37	227	0	-13
16	12.6	108.6	27.0	26.8	35.0	26.9	0.25	5.7	257	45	122	2	88
17	14.8	104.8	27.7	26.6	36.4	26.1	0.75	4.1	204	27	119	8	50
Feb.													
25	13.5	105.0	27.5	27.6	36.0	27.4	0.25	6.7	255	44	152	-1	60
27	8.5	110.0	26.8	26.8	34.5	28.4	0.38	9.8	258	37	157	0	64
Mar.													
1	5.9	110.0	26.8	27.2	34.5	30.8	0.75	8.2	213	22	75	-5	121
2	4.8	110.0	26.4	26.0	33.7	29.5	1.00	5.2	31	14	61	4	-48
3	4.7	110.0	26.3	26.5	33.5	30.4	0.63	2.6	248	26	16	-1	207
4	3.7	110.0	26.8	25.7	34.5	29.7	0.94	3.1	110	16	37	6	51
5	2.3	110.0	25.7	25.7	32.4	29.5	0.56	3.6	268	29	22	0	217
6	1.2	110.0	24.5	25.7	30.1	29.2	0.63	4.1	271	26	4	-3	244
7	0.1	109.9	24.1	26.0	29.4	29.2	0.50	1.6	273	30	0	-2	245
8	0.1	109.9	24.0	25.9	29.2	28.5	0.38	2.6	282	36	2	-3	247
9	0.4°S	110.0	23.4	25.7	28.2	29.5	0.38	2.6	281	34	-4	-4	255
10	1.5°S	110.0	25.0	26.1	31.1	29.7	0.31	4.6	287	36	7	-4	248
11	2.1°S	110.0	25.7	25.7	32.4	29.7	0.88	6.2	140	18	44	0	78
12	5.0°S	110.0	26.3	26.2	33.5	26.6	0.44	7.2	278	37	131	1	109
13	6.5°S	110.0	26.3	26.0	33.5	28.0	0.38	5.2	294	37	81	3	173
14	5.1°S	110.0	26.6	26.7	34.1	28.2	0.31	3.6	290	40	45	-1	206
15	2.9°S	110.0	26.3	25.9	33.5	27.8	0.25	2.1	294	42	27	1	224
16	0.1	110.1	25.5	26.1	32.0	28.9	0.25	2.6	290	40	14	-2	238
17	2.1	110.1	27.2	27.3	35.4	30.1	0.44	3.6	254	32	40	-1	183
18	4.6	110.0	27.4	27.0	35.8	30.9	0.75	5.2	172	22	72	-4	82
19	7.3	110.1	27.6	26.6	36.2	30.1	0.69	5.7	242	24	98	11	109
20	11.9	111.2	27.0	26.2	35.0	27.6	0.50	4.6	277	34	78	6	159
21	16.8	112.5	25.5	23.5	32.0	21.9	0.63	6.7	257	36	214	28	-21

*See note, table 1.

Table 4.--Daily mean heat fluxes and environmental data, 28 May-14 July 1981

Date	Lat. (°N,°S)	Long. (°W)	Sea sfc. temp. T_s (°C)	Air temp. T (°C)	Vapor press.(mb) sat. e_s	Vapor press.(mb) air e_a	Cloud amt.	Wind-speed (m s^{-1})	Heat flux* (W m^{-2}) Q_s	Q_b	Q_e	Q_h	Q_t
May													
28	17.4	112.5	25.4	22.7	31.8	22.4	0.69	5.2	213	32	155	29	-3
29	11.7	110.5	28.0	26.7	37.1	29.3	0.88	8.2	126	19	180	20	-93
June													
1	3.8	110.0	27.6	26.4	36.2	26.1	0.44	6.7	254	39	214	17	-16
2	2.4	110.0	27.0	25.4	35.0	25.1	0.31	5.7	252	51	179	19	3
3	1.1	110.0	26.2	25.0	33.4	24.9	0.56	6.2	252	35	167	16	34
4	0.3°S	110.0	24.8	25.1	30.7	24.6	0.31	5.7	251	45	86	-3	123
5	1.6°S	110.0	24.8	24.2	30.7	24.9	0.31	6.2	248	44	101	7	96
6	3.2°S	110.0	25.8	25.1	32.6	25.7	0.25	6.2	244	46	120	8	70
7	5.1°S	110.0	26.2	25.8	33.4	24.8	0.31	7.7	233	45	186	6	-4
8	6.1°S	109.5	26.3	25.5	33.5	24.6	0.44	8.2	203	40	206	12	-55
9	4.1°S	105.2	25.7	25.0	32.4	24.9	0.31	8.2	237	45	173	11	8
10	1.5°S	99.8	24.2	23.8	29.6	24.3	0.38	7.2	238	42	107	5	84
11	0.6	95.5	25.5	23.2	32.0	22.5	0.50	5.2	230	41	139	22	28
12	0.1	92.5	23.5	22.4	28.4	23.1	0.19	7.7	244	52	129	18	45
13	0.1	93.1	24.3	22.9	29.8	24.1	0.63	6.7	220	32	121	20	47
14	0.7°S	95.0	23.5	22.8	28.4	24.0	0.38	4.1	244	42	41	4	157
15	2.0°S	94.3	23.2	22.9	27.9	24.9	0.38	4.6	229	41	32	2	154
16	2.6°S	89.6	24.1	22.9	29.4	23.6	0.94	8.2	114	20	151	21	-78
17	3.1°S	85.4	24.2	22.0	29.6	20.4	0.81	7.7	141	28	224	35	-146
18	1.6°S	85.0	25.4	23.5	31.8	22.1	0.69	5.7	178	33	175	23	-53
19	0.1	85.0	25.6	23.9	32.2	23.5	0.63	6.2	209	34	171	22	-18
20	1.6	85.0	26.8	25.1	34.5	26.2	0.56	4.1	240	34	96	13	97
21	3.4	84.2	27.8	27.4	36.6	27.8	0.75	4.1	209	25	83	2	99
22	6.3	80.7	28.7	27.5	38.6	30.8	0.75	4.6	228	23	101	10	94
June													
29	5.4	81.2	27.7	25.6	36.4	29.0	0.94	8.8	58	17	206	39	-204
30	0.8	84.4	26.0	23.3	33.0	22.9	0.63	7.7	202	35	246	43	-122
July													
1	0.0	85.1	25.6	22.7	32.2	21.1	1.00	4.6	113	22	144	25	-78
3	0.0	93.1	22.6	22.0	26.9	21.6	0.56	6.2	247	38	93	7	109
4	0.0	95.1	23.3	22.7	28.0	22.0	0.88	4.6	162	24	63	4	71
5	0.0	99.0	23.0	24.1	27.5	21.2	0.50	6.7	230	41	97	-11	103
6	0.0	104.3	24.7	23.5	30.5	22.8	0.38	6.7	261	45	163	17	36
7	0.3	109.5	24.5	24.5	30.1	29.3	0.25	7.7	252	39	16	0	197
8	0.6	109.6	24.5	24.4	30.1	25.3	0.56	7.7	182	34	98	1	49
9	0.0	109.6	24.2	24.0	29.6	26.7	0.63	6.2	235	29	47	2	157
10	0.0	109.6	24.6	24.6	30.3	26.0	0.44	6.2	226	37	70	0	119
11	0.2°S	110.2	24.7	24.3	30.5	25.8	0.44	6.7	242	38	89	5	110
12	0.0	114.5	24.4	24.0	30.0	25.7	0.69	4.6	229	28	45	3	153
13	0.0	120.7	25.5	24.7	32.0	26.0	0.31	8.2	259	43	139	12	65
14	0.0	126.0	24.4	24.6	30.0	26.6	0.25	7.7	258	43	65	-3	153

*See note, table 1.

Table 5.--Daily mean heat fluxes and environmental data, 23 February-16 March 1982

Date	Lat. (°N,°S)	Long. (°W)	Sea sfc. temp. T_s (°C)	Air temp. T (°C)	Vapor press. (mb) sat. e_s	Vapor press. (mb) air e_a	Cloud amt.	Wind-speed ($m\ s^{-1}$)	Heat flux* ($W\ m^{-2}$) Q_s	Q_b	Q_e	Q_h	Q_t
Feb.													
23	18.7	106.6	24.8	24.2	30.7	23.3	0.06	3.2	255	58	58	3	136
24	15.8	102.0	29.8	27.2	41.1	26.9	0.13	3.6	258	51	153	18	36
25	13.0	97.8	28.4	27.5	37.9	27.3	0.13	5.3	264	49	138	8	69
26	10.2	93.9	27.5	27.0	36.0	27.3	0.31	8.1	286	42	186	7	51
27	7.6	90.2	27.8	27.2	36.6	29.1	0.19	5.4	296	43	100	5	148
28	5.0	86.2	28.8	28.6	38.8	30.2	0.38	2.8	284	35	55	1	193
Mar.													
1	3.7	85.0	29.0	28.3	39.2	30.0	0.75	5.8	260	24	131	7	98
2	1.8	85.0	26.9	26.3	34.7	28.5	0.69	7.4	298	26	121	8	143
3	0.0	85.0	25.0	25.1	31.0	26.7	0.31	3.5	299	42	34	-1	224
4	1.8°S	85.0	25.2	25.1	31.4	26.4	0.44	6.4	314	37	113	1	163
5	3.9°S	85.0	25.1	25.4	31.2	27.4	0.63	5.9	321	29	43	-2	251
6	4.9°S	82.8	22.0	22.6	25.9	24.3	0.38	7.2	306	41	28	-7	244
7	5.1°S	81.6	18.8	20.1	21.3	22.4	0.63	4.4	286	32	-6	-5	265
8	5.1°S	81.8	20.3	21.2	23.3	23.2	0.31	5.5	292	44	1	-6	253
9	5.0°S	82.3	22.3	22.2	26.4	23.2	0.56	6.8	307	35	53	1	218
10	5.0°S	83.9	24.3	24.0	29.8	25.3	0.44	5.6	300	38	62	3	197
11	6.2°S	85.0	27.1	25.6	35.1	26.1	0.50	6.8	287	36	172	19	60
12	8.4°S	85.0	27.0	25.9	34.9	25.7	0.44	8.6	328	39	222	18	49
13	10.3°S	84.8	26.3	25.4	33.5	24.1	0.44	10.0	301	41	264	17	-21
14	10.6°S	82.9	25.7	25.7	32.4	25.3	0.56	9.2	299	34	172	0	93
15	10.5°S	81.3	24.9	24.5	30.9	24.3	0.56	7.9	300	35	137	6	122
16	10.4°S	79.7	22.3	22.5	26.4	22.1	0.25	7.4	295	50	78	-2	169

*See note, table 1.

Table 6.--Daily mean heat fluxes and environmental data, 26 March-18 April 1982

Date	Lat. (°N,°S)	Long. (°W)	Sea sfc. temp. T_s (°C)	Air temp. T (°C)	Vapor press. (mb) sat. e_s	Vapor press. (mb) air e_a	Cloud amt.	Wind-speed ($m\ s^{-1}$)	Heat flux* ($W\ m^{-2}$) Q_s	Q_b	Q_e	Q_h	Q_t
Mar.													
26	4.4°S	81.9	22.5	22.8	26.7	24.3	0.08	4.7	293	53	22	-2	220
27	0.7°S	83.1	24.2	24.3	29.6	26.8	0.30	4.7	260	41	31	-1	189
28	0.5°S	85.0	24.4	25.0	30.0	27.0	0.32	4.8	286	40	28	-4	222
29	0.1	85.8	25.4	24.9	31.8	26.5	0.23	4.1	301	45	55	3	198
30	0.7	91.1	26.5	26.3	33.9	28.1	0.39	4.3	304	37	59	1	207
31	2.9	94.9	28.8	28.9	38.8	29.8	0.63	6.0	301	27	127	-1	148
Apr.													
1	2.2	95.1	27.9	26.9	36.8	29.1	0.39	6.9	301	36	136	12	117
2	0.8	94.9	25.4	25.5	31.8	29.1	0.33	5.1	283	37	32	-1	215

Table 6.--Daily mean heat fluxes and environmental data, 26 March-18 April 1982--Continued

Date	Lat. (°N,°S)	Long. (°W)	Sea sfc. temp. T_s (°C)	Air temp. T (°C)	Vapor press.(mb) sat. e_s	air e_a	Cloud amt.	Wind-speed (m s^{-1})	Heat flux* (W m^{-2}) Q_s	Q_b	Q_e	Q_h	Q_t
Apr.													
3	0.0	94.9	24.6	25.8	30.8	30.0	0.42	1.2	296	32	1	-1	264
4	0.2°S	95.1	25.3	25.6	31.6	28.7	0.38	2.3	290	36	8	-1	247
5	1.6°S	95.0	26.4	26.3	33.7	28.8	0.40	4.2	294	35	48	1	210
6	1.6°S	92.4	25.2	25.4	31.4	28.7	0.38	4.6	286	36	24	-1	227
7	0.4°S	90.3	24.6	25.0	30.8	28.2	0.21	5.2	294	42	27	-3	228
8	2.3°S	93.5	26.1	25.7	33.1	29.2	0.48	5.4	189	32	54	4	99
9	3.2°S	95.0	27.7	26.6	36.4	29.3	0.81	3.7	201	21	77	8	95
10	4.9°S	95.0	27.2	24.6	35.3	28.5	0.81	6.1	241	22	115	29	75
11	6.8°S	95.0	27.0	26.6	34.9	27.6	0.79	9.3	249	23	188	7	31
12	7.2°S	96.2	27.0	26.9	34.9	28.4	0.71	9.5	153	25	166	2	-40
13	4.2°S	101.3	27.0	26.6	34.9	29.1	0.67	6.5	244	26	97	4	117
14	1.1°S	106.1	27.4	27.0	35.8	30.1	0.39	4.2	244	34	61	3	146
15	0.0	109.0	27.5	26.6	36.0	29.3	0.79	1.8	274	22	35	3	214
16	0.1	110.0	27.6	27.5	36.2	29.7	0.38	2.9	276	35	44	0	197
17	0.0	112.7	26.7	26.9	34.3	30.1	0.49	5.0	205	30	41	-1	135
18	0.0	118.1	26.9	26.9	34.7	30.4	0.42	5.3	291	33	54	0	204

*See note, table 1.

In tables 1-6 it is apparent that sea surface temperature was usually greater than air temperature, although the difference was frequently less than 1°C. Consequently, Q_h was usually quite small but positive (that is, a heat loss from the sea surface). The vapor pressure difference was such that evaporation almost always occurred. Even with the moderate windspeeds that are usually present, however, Q_e was typically only about half the magnitude of Q_s. Q_b was often about 30 W m^{-2} compared with 200 W m^{-2} or more for Q_s. Cloud cover was highly variable, but Q_s was nearly always the dominant heat flux. Q_t was usually smaller than Q_s but varied from about -200 to 250 W m^{-2}. As expected, the larger values of net flux appear to occur consistently during times of small cloud cover and weak winds, and small or negative values are present during opposite conditions. The inferences drawn here about the relative magnitude of the various fluxes and their dependence on winds, cloud cover, etc., are quite similar to those in Weare et al. (1981), which are based on long-term mean annual distributions over this region. Only some of the net fluxes presented here are used in the next section to examine some aspects of the oceanic heat budget, but the complete data are given in tables 1-6 for other possible uses.

4. SOME ESTIMATES OF THE OCEANIC HEAT BUDGET

The flux estimates reported here can be used with temperature data from conductivity-temperature-depth (CTD) casts and expendable bathythermograph (XBT) drops to compare the degree of local heating of the water column with the net heat flux at the ocean surface. In winter 1980 and again in winter 1981, oceanographic sections along 110°W were repeated at intervals of a few weeks, and one can examine changes in heat content on these time scales. Also, a 6-day time series of data was obtained near the equator for seven days in February 1981. Comparisons will be made of terms in the following relation:

$$Q_t = \rho c_p \frac{\partial}{\partial t} \int_o^z T \, dz \quad , \tag{3}$$

where Q_t is the net heat flux at the surface as given in tables 1-6, ρ is seawater density, c_p is specific heat of seawater at constant pressure, t is time, T is water temperature, and z is the vertical coordinate (positive downward). If one performs the integration over layers without vertical temperature gradients at the bottom, the vertical advection and diffusion of heat can be neglected. Any imbalance in (3) would then be the result of horizontal advection and diffusion. The terms in (3) will be compared in sections 4.1 and 4.2.

4.1 Comparisons Along 110°W, 4°-12°N

Figures 7 and 8 show plots of the mean daily values of net surface heat flux, Q_t, along approximately 110°W during winter of 1980 and winter of 1981 (data from tables 2 and 3). The plots depict both spatial and temporal variability, but there is a tendency for an increase in Q_t from about 8°N, near the intertropical convergence zone (Ramage et al., 1980), to the equator. This increase appears to result mainly from a decrease in cloud cover, and a consequential increase of insolation, south of the convergence zone.

CTD or XBT data (provided by S. P. Hayes; NOAA/PMEL, Seattle, Wash.; 1982) were available near the start and end of both winter periods so that changes in heat content of the upper ocean over both intervals can be assessed. It was decided to determine changes in heat content ($\Delta H/\Delta t$, the right side of eq. 3) only over the latitude band 4°-12°N or within the region of the North Equatorial Countercurrent and the North Equatorial Current (see, for example, Tsuchiya, 1968). Data from as far south as the equator could have been used, but the extreme doming of isotherms apparent in vertical sections south of 4°N precluded choosing a layer for deriving heat content that did not have large vertical temperature gradients near the bottom. Considering only vertical thermal structure north of 4°N, an optimum choice for the lower depth limit for the integration of temperature would be about 25 m, but careful examination of the data indicated that fairly large changes occur at this level over a period of about a month. Consequently, 50 m was chosen as the limit even though it extends into the

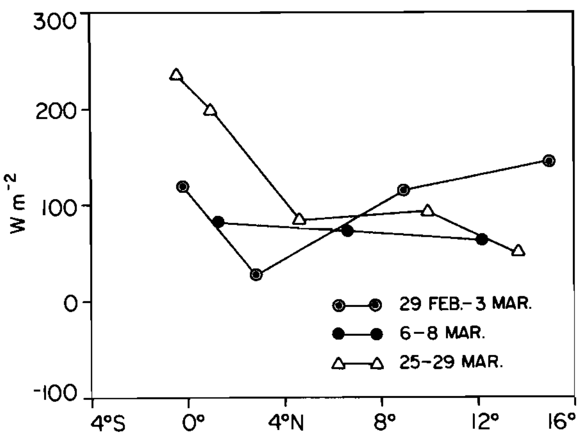

Figure 7.--Net surface heat flux, Q_t (W m^{-2}), along 111°W, 29 February-3 March 1980; 111°W, 6-8 March 1980; and 110°W, 25-29 March 1980.

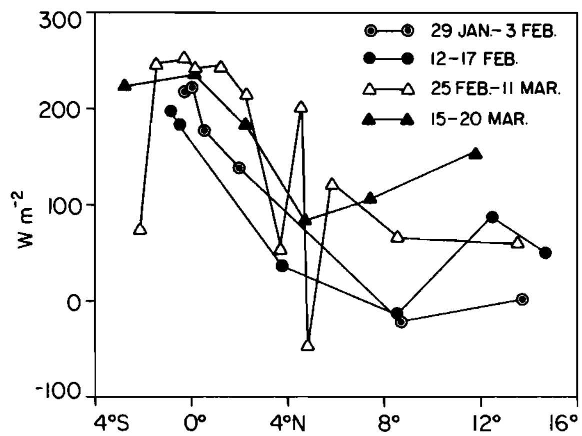

Figure 8.--Net surface heat flux, Q_t (W m^{-2}), along 111°W, 29 January-3 February 1981; 110°W, 12-17 February 1981; 110°W, 25 February-11 March 1981; and 110°W, 15-20 March 1981.

upper part of the thermocline in a few instances; all of the changes resulting from surface heating appear to occur above 50 m, however, and vertical advection and diffusion may approximately balance over the relatively short time scales used (Bathen, 1971; Halpern and Reed, 1976).

Hence heat contents were derived by integrating temperature over the upper 50 m of the ocean and averaging the values at 2° intervals between 4°N and 12°N; the average time differences between the sections were then used to derive changes in heat content. The net surface heat fluxes during the winter periods in 1980 and 1981 were estimated by averaging the values at 2° intervals from the plots in figs. 7 and 8. The results of these determinations are shown in table 7.

During March 1980, $\Delta H/\Delta t$ was fairly small--less than one-third of Q_t; during the winter 1981 period, however, the two values roughly balance each other. The greatest uncertainty in this comparison is probably the determination of Q_t. This is caused not so much by random errors in daily values of Q_t discussed previously as by lack of a continuous time series during the

Table 7.--Comparisons of net surface heat flux and changes in heat content of the upper 50 m of the ocean at approximately 110°W, 4°-12°N during March 1980 and January-March 1981

Period	Net heat flux Q_t (W m^{-2})	Change in heat content $\Delta H/\Delta t$ (W m^{-2})
1-26 March 1980	84	23
30 January-19 March 1981	64	42

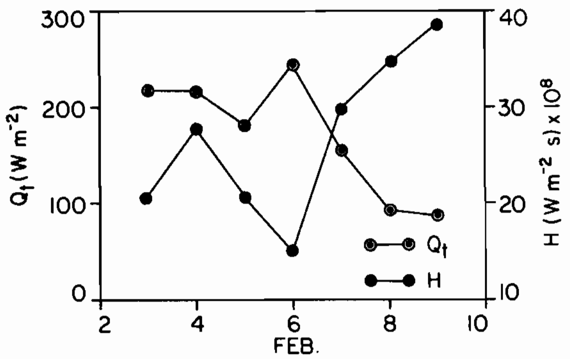

Figure 9.--Time series of net surface heat flux, Q_t (W m^{-2}), and upper-ocean heat content, H (W m^{-2} s), in the region bounded by 0.1°N-0.6°S and 109.1-111.2°W, 3-9 February 1981.

periods for which $\Delta H/\Delta t$ were derived. (Data between 4°N and 12°N in figs. 7 and 8 were for 10 and 19 days compared with total times of 25 and 48 days for the winter 1980 and winter 1981 periods respectively.) No reliable estimate of the error in Q_t can be given, but the values obtained (table 7) are in close agreement with the long-term monthly means for the area for February and March (65 and 85 W m^{-2}) from Weare et al. (1980).

The lack of balance between Q_t and $\Delta H/\Delta t$ is not surprising, especially in light of the uncertainty in Q_t; the general agreement for the 1981 period may reflect an approximate equality in net flux and change in heat content. The change in heat content for March 1980 appears to be unusually small, however, which suggests that horizontal advection or diffusion of heat was significant. The available data in the region are not adequate to allow reliable estimates of large-scale thermal gradients or flow, however. What is highlighted in the comparisons is that net surface heat exchange is quite significant to the oceanic heat content and cannot reasonably be ignored during typical "non-El Niño" conditions.

4.2 Comparison at 0°, 110°W

Quite a different comparison from those above, with markedly different results, has been carried out with data, contained in table 3, which were collected near the equator and 110°W during February 1981. XBT data are available from 3 through 9 February, and all of the observations are within the region bounded by 0.1°N-0.6°S and 109.1°-111.2°W. A comparison of net surface flux, Q_t, and heat content, H, is presented in fig. 9. Unlike data in the previous comparisons, estimates of Q_t here are continuous in time. The problem of obtaining a common depth surface without vertical temperature gradients near the equator was mentioned above. Consequently, H was obtained by integrating above the 22°C isotherm (depths 15-38 m), since significant amounts of heat were not likely to be transferred across the thermocline because of the short time span and the absence of storms (Leipper and Volgenau, 1972; Bowden et al., 1970).

The change in heat content over this 6-day period is striking (fig. 9). The temperature of the upper water column increased from about 23°C to 26°C during a time when the surface heat flux was decreasing. The mean Q_t during the 6-day period was 170 W m^{-2}, but $\Delta H/\Delta t$, obtained from the H values in fig. 9, was 3440 W m^{-2}. This huge change in heat content is comparable with changes that occur during El Niño events (Patzert, 1978) or hurricanes

(Leipper and Volgenau, 1972). The increase in heat content was undoubtedly a consequence of horizontal advection of heat; a composite of current measurements prepared by D. V. Hansen (NOAA/AOML, Miami, Fla.; 1982) showed a rapid shift from weak northward to strong southward flow at the time of this change. It is not obvious, however, whether this change represented a large-scale southward movement of warmer water or was possibly associated with wavelike thermal features as discussed by Legeckis (1977). If this event had been quite local in nature, its effects would have been much less widespread than those during an El Niño. The similarity in magnitudes of local change, however, would suggest that during the initiation phase of an El Niño the heat balance is dominated by advection, and effects of air-sea energy exchange could be neglected.

5. CONCLUSIONS

The dominant heat fluxes in this region of the eastern equatorial Pacific are insolation and latent heat loss, and the largest net surface flux occurs during periods of minimal cloud cover and weak winds. Conclusions from the daily fluxes examined here are quite similar to those from long-term monthly or annual means; this suggests that long-term distributions are not seriously distorted by short-term events in the surface energy flux. Comparisons of net surface flux and changes in oceanic heat content in the area 4°-12°N indicate that surface heat flux is an important component of the heat balance during normal conditions. A time series near the equator, however, revealed an extremely large change in heat content caused by advection; this change was comparable with those during the initiation or onset phase of an El Niño.

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