Interannual Variation in Net Heating at the Surface of the Tropical Pacific Ocean

BRYAN C. WEARE

Department of Land, Air and Water Resources, University of California, Davis 95616

(Manuscript received 30 September 1982, in final form 15 February 1983)

ABSTRACT

Interannual variations of net surface heating of the tropical Pacific Ocean are analyzed for the period 1957–76. Special emphasis is given to exploring the relationship between these variations and those in sea temperature associated with El Niño/Southern Oscillation. The analyses include eigenvector analysis, composites of the net heating for various phases of El Niño, and time series analysis of various measures of the variability. The results indicate large-scale patterns of variability dominated by time scales greater than one year. A link between the large-scale variations of sea temperature and net surface heating is evident from each set of analyses. In general, anomalously high heating appears to be associated with cold water. However, it also seems apparent that greater than average heating of the ocean persists for several months into the periods of El Niño when sea temperatures are rising rapidly. Thus it is hypothesized that net surface heating contributes to the development of the early stages of an El Niño warm period.

1. Introduction

Recently there has been an increase in the number of studies attempting to use data analyses to discern the important modes of interannual variability of both the ocean and atmosphere in the region of the tropical Pacific Ocean. For instance, Bjerknes (1972) attempted to relate observed ocean surface temperatures in the eastern region with station measurements of temperature and geopotential. Wyrtki (1975) has described the apparent relationship between sea-level variations in the western ocean and surface wind changes in the western and central ocean with sea surface temperature (SST) departures in the eastern ocean. More recently, both Weare (1982) and Rasmussen and Carpenter (1982) have shown that interannual SST variations in the eastern equatorial Pacific are quite strongly coupled to SST variations over most of the tropical Pacific Ocean. White and Hasunuma (1980) have also suggested that large-scale variations in subsurface temperature in the western Pacific are related to eastern Pacific SST's.

Until this time little work has been reported describing the relationship of variations in net surface heating to these phenomena. The net surface heating is extremely important in the ocean because it is one of the primary ways in which a water column may be heated or cooled. For instance following Behringer and Stommel (1981), if one assumes a region of constant mixed layer depth $h$, conservation of heat for that mixed layer requires that

$$Q_N = \rho C_p h \frac{\partial T_s}{\partial t} - \rho C_p \left[ \frac{\partial T_s}{\partial x} \int_{-h}^{0} udz + \frac{\partial T_s}{\partial y} \int_{-h}^{0} vdz + \frac{1}{2} W_\Delta T \right],$$

where $Q_N$ is the net heat flux into the ocean, $\partial T_s/\partial t$ the rate of change of surface temperature, and the terms in the brackets are the effects on temperature of zonal and meridional advection and upwelling, respectively. An understanding of variations in $Q_N$ is also important to understanding the atmospheric heat balance. For instance, the energy available for transport to or from a region is given by the difference between the net radiant energy received at the top of the atmosphere and the net surface heating (Hastenrath, 1980; Weare et al., 1981).

The work, which has been published describing the net surface heating for the tropical Pacific region, has concentrated upon illustrating long-term means. Wyrtki (1965), Hastenrath (1977) and Weare et al. (1981) display estimated long-term annual means of $Q_N$. Weare et al. (1980) show similar analyses of long-term monthly mean values. Ramage and Hori (1981) and Weare (1983a) have briefly discussed interannual variations in $Q_N$ and their relation to El Niño. Ramage and Hori compare the El Niño year of 1972 with some months just before and after 1972. They conclude that "the ocean gains maximum heat where the SST is lowest and much less where the SST is highest. . .". Weare describes two studies relating the
net heating in the eastern equatorial Pacific and SST changes in the same region during 1957–76. He concludes that local net surface heating is an important factor in the development of El Niño (warm water) events early in their life histories, whereas dynamical factors dominate later.

One reason that there are so few published reports concerning the interannual variability of net surface heating is that it is a relatively difficult property to estimate from observations. Since no direct measurements are regularly made it must be calculated as a residual from

$$Q_N = Q_S - Q_L - Q_I - Q_H,$$  \hspace{1cm} (1)

where $S$, $L$, $I$, $H$ refer to the net surface fluxes of solar energy, latent heat, infrared radiation and sensible heat, respectively. Unfortunately, none of these terms is regularly measured and so must be estimated by using empirical relations, usually called the bulk formulas, and meteorological parameters reported as part of regular marine weather reports taken by commercial and military ships. The variables of primary concern are cloudiness, wind speed, and air, sea and dew point temperatures. Thus there are compound difficulties in calculating a record of $Q_N$ for short-term climate studies. The desired quantity is a residual of generally much larger magnitude quantities. Those quantities themselves must be estimated from empirical formulas which are subject to considerable uncertainties (see, e.g., Bunker, 1976; Simpson and Paulson, 1979). Finally, and most importantly, in order to estimate monthly means for some area one requires sufficient numbers of observations to give representative estimates. In the tropical Pacific Ocean there are often less than 10 observations per month for a $5^\circ \times 5^\circ$ latitude-longitude grid which is often insufficient to give truly representative values of cloudiness and wind speed (Weare and Strub, 1981a) thus contributing to much uncertainty.

In this paper an attempt will be made to clarify the nature of the modes of interannual variability of net surface heating in the tropical Pacific Ocean. Since the El Niño/Southern Oscillation phenomena are known to be dominant in this region, emphasis will be placed on understanding what relation, if any, variations in $Q_N$ have to El Niño. In order to as much as possible remove problems related to uncertainties in the specification of the bulk formulas, most of the following analyses will deal with departures such that long-term means have been removed. In order to suppress as much as possible the inherent noisiness in $Q_N$ estimates due to the problems of inadequate sampling and errors in the marine observation, several different analysis methods will be employed which smooth in space and/or time and thus diminish the influence of what one expects to be the nearly random errors. These analysis methods will include a composite analysis similar to those of Weare (1982) and Rasmussen and Carpenter (1982) in which “like” months of major El Niño events will be averaged together. The pattern of $Q_N$ changes of this “average” El Niño will be compared with the pattern of variation identified by the dominant functions of an eigenvector analysis of $Q_N$. The time evolution of various subregions of the tropical Pacific will be investigated by spectral analyses. Despite the smoothing inherent in all of these techniques, care must still be used in interpreting the following results since fairly large “random” variations still exist in many of the results. Nevertheless, from the several analyses taken as a whole it is believed that a number of general conclusions may be derived.

2. Data processing

The bulk formulas to calculate the terms on the right side of Eq. (1) are those used by Weare et al. (1981):

$$Q_S = Q_{S0}(1 - 0.62 C + 0.0019 \alpha),$$  \hspace{1cm} (2)

$$Q_L = \rho_d L C_E (q_s - q_a),$$  \hspace{1cm} (3)

$$Q_I = [e \sigma T_s^4(0.39 - 0.05 e^{1/2}) + e \sigma T_s^4 (T_s - T_a)] \times (1 - BC),$$  \hspace{1cm} (4)

$$Q_H = \rho_d C_p C_E (T_s - T_a).$$  \hspace{1cm} (5)

Most symbols in Eqs. (2)–(5) follow the usual meteorological conventions. In addition, $Q_{S0}$ is the clear sky solar flux at the surface, adjusted for the surface albedo; $C$ is the fractional cloud cover, $\alpha$ the noon sun angle, $B$ a factor depending on cloud type, and $C_E$ a turbulent exchange coefficient which is weakly a function of wind speed and air-sea temperature difference (Bunker, 1976).

The surface data used in Eqs. (2)–(5) are individual marine weather reports for the tropical Pacific Ocean between $30^\circ$N and $40^\circ$S and from the American coasts to $110^\circ$E for the period 1957–76. The sources and duplicate and error deletion procedures involved in the basic processing are described in Weare et al. (1981) and Weare and Strub (1981b). The final products are individual monthly mean values of $Q_S$, $Q_L$, $Q_I$, $Q_H$ and $Q_N$ for each $5^\circ \times 5^\circ$ latitude longitude grid in the tropical Pacific.

The quality of these estimates is a strong function of space and time because of large variations in the number of observations available in each $5^\circ$ grid. Fig. 1, taken from Weare and Strub (1981b) indicates that less than 10 observations per month were available for more than half of the period of record in a broad region in the central and western Pacific from about $5^\circ$N to $20^\circ$S as well as a large triangular shaped region offshore of South America near $110^\circ$W. The number of observations increases moderately from 1957

Unauthenticated | Downloaded 09/27/23 09:11 AM UTC
through 1968, declines slightly through 1973, and then more severely through 1976.

Pilot studies indicate that not all the meteorological variables in Eq. (2)–(5) require the same number of observations for a representative monthly mean. Cloudiness in particular appears to require a relatively large number of observations (perhaps >20) for reasonable estimates of $Q_S$. Fewer estimates of wind speed are probably necessary outside of the infrequent tropical storms and fewer still of the more conservative quantities of the temperatures. Thus, estimates of $Q_S$ and $Q_T$ are least certain in data-sparse areas, whereas those of $Q_L$ and $Q_H$ are more certain. Over much of the tropical ocean $Q_S$ and $Q_T$ are 5–10 times larger than $Q_L$ or $Q_H$.

Weare et al. (1981) estimate that the standard deviation of mean annual average $Q_N$ due to uncertainties in bulk formula parameterizations, sampling errors and gross data errors is about 25 W m$^{-2}$. The sampling and data errors are inversely related to the number of observations which have been averaged and thus should be more important to individual monthly mean estimates of $Q_N$. On the other hand, if one considers variations in monthly departures from long-term means rather than the fluxes themselves, the part of the standard deviation due to uncertainties in bulk formulations should be minimized. It is very difficult to estimate what the net result of these competing effects would be, but it seems that uncertainties in the following analyses of 25 W m$^{-2}$ and greater are likely.

Fig. 2 shows the 20-year mean net surface heating for three sample months. These were chosen because they are the central months in the seasonal composites to be discussed later. Values of net heating range from less than $-280$ W m$^{-2}$ in the northwestern corner in December to greater than $120$ W m$^{-2}$ over broad regions of the eastern ocean in both April and December. Fig. 2 illustrates the large degree of annual variability which is superimposed on the interannual variation which will be discussed. It also highlights those regions in the southeastern and western equatorial oceans where a lack of observations seems to contribute to a rather spatially incoherent picture. Fig. 2 also shows that especially for April and August $Q_N$ is often in the rather narrow range of ±50 W m$^{-2}$.

3. Eigenvector analysis

A common method in meteorology and oceanography to illustrate the dominant spatial patterns of variability of a data field is to employ eigenvector analysis (see, e.g. Kutzbach, 1967). This method produces sets of functions which are the best linear predictors of the total variance in a least-squares sense. Eigenvectors of net surface heating were calculated for the individual monthly mean $5^\circ \times 5^\circ$ data averaged into eighty-five $10^\circ \times 10^\circ$ regions for the area between $30^\circ$N and $30^\circ$S. Since the $10^\circ$ grids were formed by a simple averaging, the resultant values in very sparse data regions may be only due to the data for a single $5^\circ$ region, which in turn may be the result of only a very few actual observations. Eigenvectors were calculated for the departures of the $10^\circ$ data from the 20-year means and also for those departures normalized by the interannual standard deviations. The spatial patterns of the dominant unnormalized eigenvectors (not shown) seem to be overly influenced by the large variances in the poor data regions of the western Pacific where there are interannual standard deviations of up to $\sim 150$ W m$^{-2}$ over small regions (Weare et al., 1980).

The dominant functions depicting the normalized data show larger scale patterns which seem less biased by data uncertainties. The first five functions explain a modest 7.4, 5.3, 4.6, 3.8 and 3.4% of the variance, respectively. The rather low total of 24.5% for the first five functions is probably not surprising given the very noisy nature of this rather poorly inferred variable. Despite the low explained variance the first
few functions do show rather uniform broad-scale features (see Fig. 3). The first function illustrates an east-west asymmetry such that one would expect that positive net heating departures in the eastern ocean to be accompanied by slightly larger magnitude negative departures west of 180°. This east-west asym-
Fig. 3. Dominant eigenvectors of normalized departures of $Q_n$ from the 1957–76 monthly means. $EQ_A$, the most important function explaining $\sim 7.4\%$ of the variance; $EQ_B$, the second function explaining $\sim 5.3\%$ of the variance.

Symmetry is quite similar to that in sea surface temperature for the same region and period found by Weare (1982). The second most important function shows a pattern of nearly all one sign with the greatest weights given to the northwestern region. The negative region near $180^\circ$ is in a poor data area and that near the Latin American coast probably has too small a weighting to be significant (see Barnett and Preisendorfer, 1978). Both of these eigenfunctions suggest large-scale coherence which may be related to the large-scale SST changes associated with El Niño.

4. Composite analysis

A major question to be answered is how the ocean-scale variations of $Q_n$ are associated with the El Niño/Southern Oscillation phenomena. As previously mentioned the data are probably much too sparse to produce individual anomaly maps which are useful. Therefore, following the works of Weare (1982) and Rasmusson and Carpenter (1982), composite maps were formed. The method averages together data during the same phases of each moderate and strong El Niño during 1957–76. These “base” years were chosen as the calendar years 1957–58, 1965, 1972 and 1976. Composites were formed as the three-month means and average departures for the months corresponding to the same phase of each El Niño. For instance all available departures from the 20-year means for July, August and September for 1964, 1971 and 1975 were averaged together to form the average June–July–August departure preceding an El Niño.

Such composites were calculated for each three-month group from June–July–August preceding the base years to April–May–June following the base years and will generally be referred to as “El Niño” means.

Fig. 4 illustrates six composites of El Niño departures. The hatched regions indicate those $5^\circ$ grids in which the El Niño departures are more than two standard deviations from the 20-year means. These standard deviations were calculated from the variance of
Fig. 4. Net surface heating ($Q_s$) departures of the "average" El Niño periods indicated from the corresponding 1957–76 means. The time periods are relative to the base El Niño years of 1957, 1965, 1972 and 1976. Only departures which are either greater than 25 W m$^{-2}$ or less than −25 W m$^{-2}$ are shown. The contour intervals are 25 W m$^{-2}$ with positive departures denoted by solid lines and negative departures by dashed lines. The hatching indicates regions whose departures are more than two standard deviations from the mean.
the departures making up an El Niño average departure minus that average. For instance, for July–August–September preceding El Niño, the variance is given by
\[ \sum_{i=1}^{3} \sum_{j=1}^{3} (Q_{ij} - Q)^2 / 8, \]
where \( i \) is the index over July (1), August (2) and...
September (3) and \( j \) is the index over 1964 (1), 1971 (2) and 1975 (3) and
\[
Q_i = \sum_{j=1}^{3} Q_{ij}/3.
\]

The sum of the squares is divided by eight, the number of samples minus one, to give an unbiased estimate. If the departures belong to normal populations, then the hatched regions of Fig. 4 indicate the relatively few places in which El Niño years have average departures which are significantly different from the 20-year means at approximately the 95% level.

Fig. 4 will be discussed in reference to the four El Niño stages described by Weare (1982). The spatial pattern of all maps, especially in the western Pacific near the equator, is quite noisy. This is related to the low density of observations and the convective nature of weather in this region.

1) JUly–SEPTEMBER: PRIOR STAGE
During this period sea temperatures are lower than normal over most of the basin except west of about 150°E and south of about 20°S. The heating departure pattern for this period indicates moderate positive departures over much of the southern basin except a region near the equator and 180°. This pattern is strongly suggestive of far less cooling in the Southern Pacific than is typical for this season (see Fig. 2).

2) NOVEMBER–JANUARY: BUILDUP STAGE
During this period sea temperatures remain cool over most of the basin with increasing temperatures evident only south of 10°S. The El Niño heating departure pattern indicates moderate positive departures in much of the eastern ocean. The magnitudes are largest in the southeastern ocean. A small region of negative departures is evident off the coast of China and near the equator and 170°E.

3) MARCH–MAY: BUILDUP STAGE
During this period sea temperatures are rising quite rapidly over much of the eastern ocean. Positive heating departures are still evident over most of the ocean, with +25 W m⁻² departures quite common in the central region. Small regions of moderate negative departures are now, however, apparent near the South American coast.

4) JULY–SEPTEMBER: MATURE STAGE
Sea temperatures have large positive departures over most of the eastern region extending along the equator to near the dateline. The heating departure map shows moderate positive departures just north of the equator. South of the equator the pattern indicates generally negative departures near the South American coast.

5) NOVEMBER–JANUARY: DISSIPATION STAGE
Large positive sea temperature departures still exist over most of the eastern ocean north of 20°S.
Negative temperature departures are evident south of 20°S. The heating departure pattern is now weakly negative over most of the eastern ocean. However, the westernmost regions of both the Northern and Southern Hemispheres have moderate positive departures.

6) MARCH–MAY: DISSIPATION STAGE
Positive sea temperature departures are reduced and are replaced in the southeastern and south equatorial oceans by weak negative departures. The heating departure map suggests that the positive heating anomalies in the west have spread eastward. However, small regions of moderate negative departures are still evident over much of the eastern ocean. The equatorial region west of 140°W is even noisier than on other maps.

Overall, despite considerable small-scale noise spatially coherent changes in net surface heating are evident during all phases of the “average” El Niño. In the eastern ocean it appears that positive departures dominate in the Prior and Buildup Stages and near zero or negative departures in the Dissipation Stage. Although the changes in the western basin seem less distinct there is the suggestion of near zero or negative departures in the Buildup Stage and positive departures during the Dissipation Stage. At any given point the nature of the departures is generally quite uncertain as indicated by the lack of hatching.

5. Time series analyses

In order to better understand the temporal evolution of the \( Q_N \) field and its possible link to El Niño/Southern Oscillation, a number of time series have been formulated. Two of these, shown in Fig. 5, are the time coefficients associated with the two eigenvectors of \( Q_N \) shown in Fig. 3. These are referred to as \( EQ_A \) and \( EQ_B \) and illustrate how the patterns in Fig. 5 change in time. For instance, when \( EQ_A \) is positive the eastern ocean has anomalously high net heating and the western ocean anomalously low \( Q_N \) in this mode. It must be emphasized that these eigenvectors explain only a relatively small fraction of the variance and thus these time coefficients cannot be expected to represent but a small portion of the variability. Also shown in Fig. 5 is the variation of the SST for region X (see Fig. 6), whose variations were shown by Weare (1982) to strongly reflect changes associated with El Niño. All of the time series have been smoothed with a seven point binomial filter.

The time coefficients \( EQ_A \) and \( EQ_B \) both have much of their variability in time scales greater than one year. In addition \( EQ_A \) often changes in the opposite direction to the SST variations for region X. The phase is such that decreases in \( EQ_A \) seem to lag the increases in sea temperature by a few months. As should be expected given the orthogonality require-
ments, the time variations of EQB seem to have little relation to the sea temperature of region X. They do, however, seem to indicate a period during 1961–63 in which Q, is diminished especially in the northwestern region and perhaps a period after 1973 when the net heating over much of the ocean is increased. The significance of the latter period is somewhat more questionable since the density of available data declines substantially after 1972.

Coherence spectra were calculated between EQA and EQB and the SST departures from the 1957–76 mean for region X. The coherence squares between EQA and the region X temperatures are greater than 0.6 for most frequencies less than 0.5 year⁻¹. The phases are such that increasing temperatures tend to lead the decreasing Q, associated with EQA by 20–45°. This phase relation would imply that an aspect of most El Niños is a period of increased eastern basin heating while temperatures in the core region are low, which continues into the early stages of the temperature rise. Similar coherence squares and phase relationships hold for the temperature data for regions H, I, J, N, P and R.

The maximum coherence squares between EQB and the temperatures of region X are generally less than 0.55 for a rather narrow spectral interval about 0.6 year⁻¹. At this frequency the variations in EQB and the sea temperatures are nearly 180° out of phase. Comparable results are evident for cross-spectra between EQB and temperatures for regions B and C. Both sets of coherence spectra suggest that there are very significant (>99% level) relationships between the time coefficients of the two dominant eigenvectors of normalized Q, departures and sea temperature variations in and near the El Niño core region and in the western Pacific in the case of EQB.

To augment EQA and EQB, which are indicative of basinwide variations, average departures of Q, have been calculated for the regions whose centers are indicated in Fig. 6. Fig. 7 shows the time series

---

**Fig. 5.** Time coefficients of the dominant eigenvectors of net surface heating (heavy lines) of EQA and EQB. Light lines on both frames indicate the departures of SST for region X shown in Fig. 6. All curves have been slightly smoothed with a seven-point binomial filter.

**Fig. 6.** The locations of the centers of the averaging regions mentioned in the text and in Fig. 5, 7 and 8. For regions A–Q and X these average departures were calculated from the mean of the monthly departures from the 20-year normals of each of the 5° grids in a region covering 10° of latitude and ~40–50° of longitude. Region R, which is meant to represent the coastal waters, is composed of six 5° grids extending along the South American coast southward from the equator.
of the monthly departure of \( Q_N \) for regions H, N, I and X, the core area of El Niño sea temperature changes. Also plotted on Fig. 7 are the estimates for each of the regions of the rate of change of sea temperature \( \frac{\partial T_s}{\partial t} \) after the seasonal cycle has been removed. The latter were calculated as the difference between the average departure of sea temperature for month \( i \) from that for month \( i + 1 \). There is a moderate correspondence between the \( \frac{\partial T_s}{\partial t} \) and \( Q_N \) curves, with the closest fit for regions H and X. Coherence spectral analysis (see Table 1) shows that for these latter two regions the maximum coherence squares are about 0.90 with phases such that variations in \( Q_N \) tend to lead those in \( \frac{\partial T_s}{\partial t} \) by \( \sim 2-6 \) months. In a further analysis of the data for region X Weare (1983a) shows evidence which strongly suggests that \( Q_N \) variations are especially important in the Buildup Stage of El Niño and is much less important during the Mature Stage as was implied in the previous discussion of \( EQ_A \). Given an amplitude of the \( Q_N \) departures in region X of \( 25 \) W m\(^{-2}\) and given a mixed-layer depth in this region of \( 25 \) m, the variations shown in Fig. 7 imply a \( \frac{\partial T_s}{\partial t} \) of \( \sim 0.6^\circ \) C per month, which is actually larger than observed. Thus the variations in \( Q_N \) are of a sufficient magnitude to be "potential" causes of some of the SST variations.

Fig. 8 shows the \( Q_N \) variations for regions A, B and C. The changes for these three regions are quite similar to each other, especially for the 1961–63 period.
TABLE 1. Results of the coherence analysis of $Q_N$ with $\partial T_s/\partial t$.

<table>
<thead>
<tr>
<th>Region</th>
<th>Approximate maximum frequency (year$^{-1}$)</th>
<th>Approximate phase (deg)</th>
<th>Variable leading</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.6</td>
<td>45</td>
<td>$\partial T_s/\partial t$</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>10</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>B</td>
<td>0.6</td>
<td>45-65</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>C</td>
<td>0.4</td>
<td>60</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>D</td>
<td>0.5</td>
<td>80</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>E</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>F</td>
<td>&gt;0.5</td>
<td>10</td>
<td>$\partial T_s/\partial t$</td>
</tr>
<tr>
<td>G</td>
<td>0.5</td>
<td>40</td>
<td>$\partial T_s/\partial t$</td>
</tr>
<tr>
<td>H</td>
<td>&gt;0.7</td>
<td>30-45</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>I</td>
<td>0.3</td>
<td>60-90</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>J</td>
<td>&gt;0.5</td>
<td>30-45</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>K</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>L</td>
<td>0.5</td>
<td>20</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>M</td>
<td>0.3</td>
<td>45</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>N</td>
<td>&gt;0.5</td>
<td>10-45</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>X</td>
<td>&gt;0.7</td>
<td>60</td>
<td>$Q_N$</td>
</tr>
<tr>
<td>P</td>
<td>0.3</td>
<td>0-20</td>
<td>$\partial T_s/\partial t$</td>
</tr>
<tr>
<td>Q</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>R</td>
<td>&gt;0.6</td>
<td>90</td>
<td>$Q_N$</td>
</tr>
</tbody>
</table>

* The > signs indicate fairly broad spectral peaks including a number of spectral points.

** The < and > signs indicate frequencies less than and greater than the printed values, respectively.

In addition, the variations illustrated in Fig. 8 for region B strongly resemble those of the second most important eigenvector ($\text{EQ}_B$) shown in Fig. 5. Coherence spectra analysis (see Table 1) shows a rather modest link between $Q_N$ variations for regions A, B, C and the corresponding estimates of variations in $\partial T_s/\partial t$. Coherence squares are less than 0.6 for periods longer than two years, where $Q_N$ tends to lead by 10–60°. The rather small magnitude of the coherence and large range of angles of lead may be related to the great depth of the permanent thermocline in this region. Unfortunately the variations in $Q_N$ do not seem to be better related to the rather sparse measurements of heat storage (steric sea level) in this region given by White and Hasumuma, (1980).

Space limitations do not allow the display or detailed discussion of the time variations of $Q_N$ for the other lettered regions. However, Table 1 attempts to convey a summary of the significant results of the coherence spectral analyses between $Q_N$ and $\partial T_s/\partial t$ for all regions. The 95% significance level for the coherence squares is ~0.23. That of the phases depends upon the corresponding value of the coherence and are between approximately 28° and 13° for coherence squares of 0.4 and 0.8, respectively (Jenkins and Watts, 1968). The most important results not previously discussed include those for regions F, J and R. For the latter two cases there seems to be a moderate link between $Q_N$ and $\partial T_s/\partial t$ over a broad range of low frequencies for which the $Q_N$ leads by ~3–12 months. The reasons for such large phase angles are difficult to understand. The coherence for region F is one of the few for which the variations in $\partial T_s/\partial t$ may slightly lead those in $Q_N$, although the 95% confidence region overlaps zero lead. The possibility of this relationship being true is strengthened by the fact that the spectra for the adjacent region G exhibits a similar pattern.

![Fig. 8. Monthly departures of net surface heating for western Pacific regions A, B and C. All curves have been smoothed as in Fig. 5.](image-url)
6. Discussion

Although the presently available estimates of net surface heating are subject to rather large uncertainties, the previously discussed analyses in toto suggest several basic conclusions. First, spatially and temporally coherent basin-wide variations of $Q_N$ do exist at the surface of the tropical Pacific Ocean over interannual time scales. This conclusion may be drawn from all three of the analyses: eigenvector, compositing and time series. One important question concerning this conclusion is whether or not the magnitude is sufficient to have an impact on ocean temperatures as described by Eq. (1). If one assumes standard values of $\rho$ and $C_p$ for water and that net heating is the only important process, then Eq. (1) becomes

$$Q_N \approx \frac{\partial T_S}{\partial t},$$

where the units are °C per month. Many of the analyses show typical $Q_N$ departures of 25 W m$^{-2}$. If the temperature were to change 1°C per month (probably nearly an upper limit) this would require a very shallow mixed layer of about 15 m. On the other hand, if the temperature change were a more realistic 0.1°C per month, then the required mixed layer depth is about 150 m. Bather (1972) diagnosed mixed-layer depths for the Pacific north of the equator and found annual average values of less than 40 m in the eastern equatorial region and between 65 and 102 m in the western equatorial region. Thus the observed heating departures are quite consistent with observed surface temperature heating or cooling rates and the measured mixed-layer depths. On the other hand, dynamical effects [those terms in brackets in Eq. (1)] are known to be important in many parts of the tropical ocean and certainly cannot be ignored.

The typical departures of ~25 W m$^{-2}$ are of the same magnitude as the uncertainties in $Q_N$ departure estimates discussed in Section 1. This means that very little confidence can be put in an observed departure of 25 W m$^{-2}$ for any specific 5° grid and month. On the other hand, the spatial and temporal averaging incorporated in all of the aforementioned analyses reduces the impact of the presumably random estimation errors (see, e.g., Leith, 1973).

The three analyses also show that variations in $Q_N$ are linked to those of SST associated with El Niño/Southern Oscillation. One piece of evidence for this statement is that the dominant heating eigenvalue $E_{N}$ is morphologically quite similar to the dominant eigenvector of sea temperature shown by Were (1982). The primary difference is that the temperature vector is most strongly weighted in the eastern equatorial region whereas $E_{N}$ has weights of rather equal magnitude across the entire basin. Fig. 5 indicates that there is a tendency for a cold eastern ocean to be associated with anomalously high heating in the east and low in the west. In the eastern ocean this would correspond to the conclusion of Ramage and Hori (1981) that "the ocean gains maximum heat where the SST is lowest". However, Fig. 5 suggests a very important phase lag in this relation such that anomalously high heating continues some months after the eastern ocean begins to warm. This is especially true early in 1972 and 1976. This phase relation is also confirmed by the coherence spectra analyses.

The composite analysis seems to imply a similar picture. Overall positive heating departures occur in the eastern ocean during the Prior Stage when the temperatures are below average and negative anomalies are most evident in the latter stages of El Niño when temperatures are still warmer than normal. Again, however, an important phase lag seems evident. Positive heating in the eastern ocean continues into the Buildup Stage, a period when sea temperatures are rising dramatically. Similarly negative departures are most evident in the latter phase of the Dissipation Stage rather than during the Mature Stage when sea temperatures are highest.

The time series in Fig. 7 further point to this conclusion. For region X, for instance, positive heating $Q_N$ tends to lead variations in temperature $\partial T_S/\partial t$ by several months, especially in 1964–65, 1971–72, 1975–76. Furthermore, negative departures in $Q_N$ tend to lead negative $\partial T_S/\partial t$ in the years 1963, 1965–66 and 1972. These general impressions are verified by the coherence analysis implying that heating changes lead temperature variations by several months.

Although these conclusions must be considered tentative, they do suggest several attributes of El Niño which have not been fully explored. During the Buildup Stage, when Wyrtki (1975) indicates there are stronger than average easterlies and high eastern Pacific sea levels, anomalously high net surface heating exists in the eastern ocean. This heating seems to continue for some months into the primary El Niño year during the period in which Wyrtki has hypothesized a dynamical response in sea temperatures due to a relaxation of the easterlies. During much of the primary El Niño year (Mature Stage) heating changes appear to have little effect or even retard the warming of the eastern ocean. Toward the end of the primary El Niño year (Dissipation Stage) negative heating anomalies contribute to the cooling of the ocean surface waters. Unfortunately, even if this scenario is verified by further studies, it still leaves several important questions. Perhaps most important is why there is an apparent lag between changes in net surface temperatures. Undoubtedly, any answer would require a further clarification of the dynamical components of El Niño and the relation of El Niño to the even larger scale Southern Oscillation.

A third conclusion is that for a broad part of the western Pacific, encompassing regions A, B and C,
nearly coherent interannual variations in \( Q_N \) are evident. Unfortunately, the reasons for or consequences of such large-scale variations are not known.

Very little has been said in this paper as to what induces the \( Q_N \) changes. Correlation studies for the data for the regions identified in Fig. 6 indicate that about 90% of the variability in \( Q_N \) is due to \( Q_L \), the latent heat loss. The \( Q_L \) changes are due to both changes in the air-sea humidity difference and wind speed (see Weare, 1983b). This result would imply that the hypothesis proposed by Bjerknes (1966) that warmer seas induce greater air-sea humidity differences and hence greater \( Q_L \) can only be partially correct.

Finally it was felt premature to speculate on the exact role of net surface heating changes in El Niño/Southern Oscillation. These results are undoubtedly enlightening and intriguing, but much more work is necessary to understand how they fit along with the myriad other observations now known to be related to these phenomena.

Acknowledgments. I wish to thank P. Ted Strub and Michael D. Samuel who were involved in much of the processing of the original data. This work was supported by the Climate Dynamics Section of the National Science Foundation under Grants ATM-8017049 and ATM-8041336.

REFERENCES


