Interannual moisture variations near the surface of the tropical Pacific Ocean

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SUMMARY

Interannual variations of surface specific humidity, surface latent heat flux out of the ocean and surface layer moisture divergence are analysed for the period 1957–76. Special emphasis is given to understanding the relationship between variations in these quantities and the El Niño/Southern Oscillation phenomenon. The analyses include eigenvectors, composites and time series. The results indicate spatially coherent temporally persistent variations, some of which are clearly linked to El Niño. The composite and time series analyses both suggest that during El Niño in the eastern Pacific moisture convergence changes precede those of sea surface temperature by one or more months, which in turn precede those of surface latent heat flux by a further one or more months. A hypothesis is suggested to relate these changes to variations of the South Pacific high.

1. INTRODUCTION

The oceanography and meteorology of the tropical Pacific Ocean has recently been the subject of a number of theoretical and diagnostic studies. Much of this work has attempted to define better and to clarify the complex set of interrelated phenomena now often given the name El Niño/Southern Oscillation. For instance Weare (1982) and Rasmusson and Carpenter (1982) display the morphological features of sea surface temperature (s.s.t.) variations which are common to the more recent El Niño events. Rasmusson and Carpenter also show the corresponding variations in surface winds and wind divergences. All these analyses suggest that El Niño is a basin-scale phenomenon with variations which are both temporally and spatially coherent. More recently Weare (1983a) has discussed the similar analyses of the net surface heating of the ocean across the tropical Pacific. He concludes that coherent large-scale variations exist and that certain aspects of those variations are related to El Niño s.s.t. changes. Also, in a preliminary analysis, Weare (1983b) discusses the evolution of moisture variations during El Niño events.

Bjerknes (1966) proposed an important role for atmospheric moisture variations in a hypothetical response to an El Niño warm water event. He suggested that the higher s.s.t.s give rise to greater evaporation (surface latent heat flux from ocean to atmosphere) and greater lower layer specific humidities. He went on to hypothesize that these higher humidities would lead to greater instability, more cumulus convection and greater latent heat release. The general circulation model results of Rowntree (1972) and Julian and Chervin (1978) partially confirm these suggestions.

Ramage and Hori (1981) investigated some of these links in an analysis of surface data for the 1972 El Niño (Ramage et al. 1980). They calculated zonal averages in the Pacific region east of the dateline of s.s.t., wind speed, surface sensible and latent heat loss, surface wind divergence and highly reflective cloud frequency. The latter is a measure of convective rainfall (Kilonsky and Ramage 1976). In contrasting the 'El Niño year' April 1972–March 1973 with the 'non-El Niño months' January–March 1972, April–December 1973, they conclude that the "largest heat losses do not coincide with the maximum s.s.t. but with the maximum upstream gradient." In addition they find that convergence in the near-equatorial zone is slightly less during El Niño whereas rainfall is significantly more.

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Recently Khalsa (1983) has continued the Ramage and Hori analysis by illustrating maps of s.s.t., surface heat flux, moisture divergence and highly-reflective-cloud estimates of rainfall for the ‘non-El Niño’ period and the difference between ‘El Niño’ and ‘non-El Niño’. He concludes that ‘the maximum s.s.t. anomaly is not correlated spatially or temporally in any consistent manner with the sum of latent and sensible heat fluxes or rainfall’. While both these works are useful, their conclusions are hampered by the fact that they apply only to one El Niño event and that they mainly choose to look only at 12-month averages.

Rasmusson and Carpenter (1982) discuss possible moisture changes based upon inferences derived from wind divergence patterns and data from several island rainfall stations, but an understanding of moisture changes is clearly not the main focus of their work.

The aim of this work is to illustrate the temporal and spatial modes of variability of several surface moisture variables in the tropical Pacific Ocean region for the years 1957–76. Special attention will be given to the surface latent heat flux \( Q_L \) and the divergence of surface layer moisture (DIV \( Q \)), since these are direct links in the Bjerknes hypothesis. Furthermore, emphasis will be given to relating variations in the moisture terms to s.s.t. variations identified with El Niño perturbations.

2. DATA PROCESSING

The basic data were approximately five million individual marine weather reports for 1957–76. The sources and duplicate and error deletion procedures used are described in Weare et al. (1981). From these individual observations individual monthly means for each 5° latitude by 5° longitude region between 30°N and 40°S were calculated for a number of variables. These include s.s.t., wind components, specific humidity and surface latent heat flux. The long-term monthly means of each of these quantities are illustrated in Weare et al. (1980).

\( Q_L \) has been computed from the bulk formula (Bunker 1976)

\[
Q_L = \rho_a L C_E V (q_s - q_a)
\]

for each observation. The required data are wind speed \( V \), saturation specific humidity at the sea surface temperature \( q_s \) and the specific humidity \( q_a \) of the air at the height at which the dew point temperature observation is taken (~10 m). \( \rho_a \) and \( L \) are constant and \( C_E \) is a weak function of wind speed and stability (Bunker 1976). Figure 1 illustrates analyses of the long term mean \( Q_L \) for three sample months, March, July and November. Maximum \( Q_L \) (losses of energy from the ocean surface) are ~250 W m\(^{-2}\) with typical values between 100 and 200 W m\(^{-2}\). Major morphological features are common to all three months. These include relative minima in the eastern and western equatorial basin and maxima in the central ocean trade wind zones between 10 and 20°N and 10 and 30°S. The largest seasonal variations are evident near 35°S. The contours are relatively noisy in the data-poor areas just south of the equator in the western Pacific and in the south-eastern ocean near 30°S 100°W.

Monthly estimates of surface layer moisture flux divergence (DIV \( Q \)) were calculated from the monthly estimates of specific humidity and wind components for the region 25°N–35°S. These DIV \( Q \) estimates were calculated as a simple finite difference of the flux values at each 5° grid. Figure 2 illustrates long-term monthly means of DIV \( Q \) for the sample months March, July and November. The North Pacific Convergence Zone (NPCZ) in the eastern ocean and South Pacific Convergence Zone (SPCZ) in the western
Figure 1. 1957-76 monthly means of surface latent heat flux out of the ocean (W m\(^{-2}\)) for March, July and November.
Figure 2. 1957–76 monthly means of the divergence of surface moisture flux, $\nabla \cdot V q_s (10^{-8} \text{kg kg}^{-1} \text{s}^{-1})$ for March, July and November.
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ocean are quite evident in all three months. The relatively strong divergences in the regions of the North and South Pacific highs show distinct seasonal variations such that in the north the divergence region is farthest south in March, whereas that of the South Pacific is most extensive in July. It should be noted that in Fig. 2 regions without contours in the western equatorial and south-eastern areas have insufficient observations.

3. Eigenvector Analysis

Eigenvector analysis (see e.g. Kutzbach 1967) was carried out on fields of surface specific humidity \( (q_s) \), surface latent heat flux \( (Q_L) \) and surface layer moisture flux divergence \( (\text{DIV} \ Q) \) in order to determine the primary modes of variability of each. The eigenvectors were calculated from the individual monthly 5° estimates averaged into eighty-five \( 10^0 \times 10^0 \) regions for the area between 30°N and 30°S. For each 10° region the long-term means were removed and the difference was divided by the inter-annual standard deviation. This normalization minimizes the influence of data-poor regions of the ocean which have unrealistically large inter-annual standard deviations. The dominant \( q_s \), \( Q_L \) and \( \text{DIV} \ Q \) eigenvectors explain 15-9, 7-4 and 4-4 percent of the total variance, respectively. The cumulative variances explained by the first ten vectors are 49-3, 37-8 and 27-7 percent. The rather low values of explained variance illustrate the very noisy nature of monthly mean estimates for these fields, especially \( \text{DIV} \ Q \).

Figure 3 illustrates the dominant functions for \( q_s \), \( Q_L \) and \( \text{DIV} \ Q \). The pattern for \( q_s \) suggests variability which is greatest in a broad region of the eastern equatorial Pacific. This pattern is quite similar to that of the dominant eigenvector of tropical Pacific s.s.t. shown by Weare (1982). The pattern of the dominant eigenvector of \( Q_L \) is also similar to that of s.s.t. except that it is spatially less coherent. Despite the low fraction of variance explained, the spatial pattern of variability of \( \text{DIV} \ Q \) is clearly interpretable in the eastern Pacific. When the associated time coefficient is positive there is greater convergence in the 0–10°N zone and more divergence both south of the equator and north of 10°N. Little coherent variation seems to be identifiable west of 180°.

Figure 4 illustrates the time coefficients of these dominant eigenvectors of \( q_s \), \( Q_L \) and \( \text{DIV} \ Q \). These are shown together with the time coefficients of the dominant s.s.t. eigenvector which Weare (1982) identified as a measure of El Niño. The coefficients of \( q_s \) and \( Q_L \) are quite strongly related to those of s.s.t.; those of \( \text{DIV} \ Q \) are moderately related to s.s.t. The correlation coefficients of the \( q_s \), \( Q_L \), \( \text{DIV} \ Q \) time coefficients with those of s.s.t. are 0-79, 0-65 and 0-49, respectively. Since these are all highly significant, these results imply that the dominant basin-wide mode of variation of the moisture fields is that associated with El Niño. However, the small amount of variance explained by these eigenvectors, especially those of \( Q_L \) and \( \text{DIV} \ Q \), implies that other basin-wide modes of variation may be possible. Nevertheless, these correlations, together with the patterns illustrated in Fig. 3, suggest that El Niño is generally associated with increased surface specific humidity, increased latent heat fluxes in the eastern ocean together with a southward shift of the North Pacific Convergence Zone (see Fig. 2).

4. Composite Analyses

A major question to be answered is how are ocean-scale changes in the moisture parameters related to the El Niño/Southern Oscillation phenomena. To help clarify these relations, if they exist, composite maps of \( q_s \), \( Q_L \) and \( \text{DIV} \ Q \) were formed for each phase of an ‘average’ El Niño. This method averages together data during each moderate
Figure 3. Dominant eigenvectors of the normalized departures of $q_a$, $Q_L$ and DIVQ, explaining 15.9, 7.4 and 4.4 percent of the variance, respectively. A normalized departure is the difference of a monthly value from the 1957-76 mean divided by the 1957-76 inter-annual standard deviation.
Figure 4. Time coefficients of the dominant eigenvectors of $q_a$, $Q_L$, $\text{DIV} Q$ (see Fig. 3). The bottom panel shows the time coefficients of the dominant s.s.t. eigenvector illustrated in Weare (1982). All curves have been smoothed with a seven-point binomial filter. $\text{DIV} Q$ coefficients have been multiplied by $10^2$.

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 June, July and August for 1964, 1971 and 1975 were averaged together to form the average June–July–August departure preceding El Niño. Such composites were calculated for each three-month group from June–July–August preceding the base years to April–May–June following and will generally be referred to as 'El Niño means'.

Selected composite maps of $Q_L$ and $\text{DIV} Q$ will be discussed in terms of the four El Niño stages described by Weare (1982). Since these maps are quite 'noisy' they have been contoured so as to exclude departures near zero. Nevertheless, care must be taken in interpreting the maps, especially in the sparse-data areas near the equator west of the dateline and in the eastern ocean south of $\sim 10–20^\circ S$. 
Figure 5. Surface latent heat flux ($Q_l$) departures of the 'average' El Niño periods indicated from the 1957–76 means. The time periods are related to the base El Niño years 1957–8, 1965, 1972 and 1976. Only departures which are either greater than 25 W m$^{-2}$ (solid lines) or less than −25 W m$^{-2}$ (dashed lines) are contoured. The large plus and minus signs indicate regions where departures are largely 10 to 25 W m$^{-2}$ or −10 to −25 W m$^{-2}$, respectively.
Figure 5 shows the $Q_L$ composite departure maps for four 'seasons'. Each plate of Fig. 5 will be described separately.

A. October–December: Prior stage

During this period the s.s.t. in most of the Pacific is below average except for much of the ocean south of 20°S. The corresponding $Q_L$ is somewhat less than average over most of the ocean except near 5°S and 180°.

B. February–April: Buildup phase

During this period s.s.t.s in the eastern equatorial Pacific are rising rapidly. South of 10°N and east of 160°W s.s.t.s are generally slightly above average. The latent heat flux for this period is again slightly less than normal over much of the ocean. No increase in $Q_L$ in the eastern Pacific, as might be suggested by the Bjerknes hypothesis, is evident.

C. October–December: Mature phase

Sea surface temperature departures are near their maximum along a broad swath of the eastern and central ocean between about 20°N and 20°S. Generally $Q_L$ departures in the eastern ocean are slightly positive especially along the equator between 165°W and 100°W. Thus weakly increased latent fluxes seem to be associated with high s.s.t.

D. February–April: Dissipation stage

Sea surface temperatures remain somewhat above average over much of the eastern ocean, especially near the equator and 140°W. Slightly higher than average $Q_L$ are still evident over much of the central equatorial region and near 20°S 100°W. Negative departures dominate elsewhere. As in the mature phase higher s.s.t.s seem to be associated with a greater flux of latent heat (and thus moisture) out of the ocean.

In general the composite analyses show a fairly weak relationship between $Q_L$ and the various phases of El Niño. This may be in part due to the noisiness of the data, but also it may be due to the fact that the $Q_L$ is related to wind speed and dew point temperature as well as s.s.t. Rasmussen and Carpenter (1982) have shown with similar composite maps that departures of wind speed are often less than 0.5 m s$^{-1}$ and rarely greater than 1.5 m s$^{-1}$ over most of the equatorial ocean. The relation between s.s.t. and $Q_L$ which does seem to display itself is that warm water is associated with higher latent fluxes, as suggested by Ramage and Hori (1981). However, Fig. 4 and the intervening composite maps (not shown) also suggest that increases in $Q_L$ follow by several months increases in s.s.t.

Figure 6 shows four sample composite 'seasons' of the surface layer moisture flux divergence departures. Although these maps also illustrate a great deal of small-scale detail, coherent variations, especially in the eastern ocean near 10°N, are evident.

A. October–December: Prior phase

During this period of generally low s.s.t. over most of the eastern ocean, little coherent variation in DIV $Q$ seems evident.

B. February–April: Buildup phase

During this period, in which eastern equatorial Pacific s.s.t. is rising rapidly, there are indications in the eastern ocean of more moisture convergence just south of the equator accompanied by less just to the north (see Fig. 2). There is also the suggestion that in the southern hemisphere near 150°W there is less divergence to the east and more to the west. Changes in both these regions seem to be indicative of a contracted and weaker South Pacific high.

C. October–December: Mature phase

During this period of large positive s.s.t. departures in the equatorial region significant variations in the moisture flux divergence patterns seem evident. Over most of the ocean east of 160°E there is greater convergence between 0 and 10°N and greater
Figure 6. Surface moisture divergence (DIVQ) departures indicated from the 1957–76 means ($10^{-8}$ kg kg$^{-1}$ s$^{-1}$). Only departures which are greater than $1 \times 10^{-8}$ s$^{-1}$ (solid lines) or less than $-1 \times 10^{-8}$ s$^{-1}$ (dashed lines) are contoured.
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divergence between 10 and 20°N. In the southern hemisphere along a diagonal line from about 0° 180° to 30°S 120°W there appears to be greater convergence to the east and divergence to the west. These changes are suggestive of a southward and eastward shift in the positions of the normal convergence zones shown in Fig. 2. This would seem to indicate a continued contraction of the South Pacific high.

D. February–April: Dissipation stage

The DIV Q patterns in the eastern ocean for this period are qualitatively similar to those just discussed. However, the systematic variations in the regions of the North and South Pacific Convergence Zones are not as evident. In the western Pacific there appears to be greater divergence near 10°N from 120°E to about 180°.

Rasmusson and Carpenter (1982) have shown composites of surface wind divergence. They suggest that the surface moisture convergence may be estimated by multiplying their wind divergence estimates by a mean specific humidity of 14 g kg⁻¹. A comparison of Fig. 6 with their Figs. 20c, 23c, 24c, 25c and 26c suggests that there is a relation between the wind and moisture flux divergence patterns as expected. However, that comparison also suggests that positive moisture divergence departures are generally poorly estimated, if one follows Rasmusson and Carpenter's suggestion, by as much as a factor of two. This is likely to be due to the fact that, as was shown in section 3, moisture as well as wind changes are taking place during El Niño events.

5. Time series analysis

The eigenvector and composite analyses have given an indication of the space and time scales of moisture variations and their relation to El Niño. However, in order to understand better the temporal variations of the moisture fields and the links to El Niño, a number of time series, in addition to the eigenvector coefficients, have been formulated. Spatial averages of \( q_a, Q_L \) and DIV Q departures from the 20-year monthly means have been calculated for each month of 1957–1976 for the 18 regions identified in Fig. 7. All these regions except R are 10° of latitude and 40°–50° of longitude. The averages of region R are derived from the six 5° grids running along the South American coast from the equator to 15°S. Only selected averages for \( Q_L \) and DIV Q will be discussed.

Figure 8 shows the average latent heat flux departures for regions B, N, X and P.
Figure 8. Monthly departures of surface latent heat flux (heavy lines, left scale) for regions B, N, X and P (see Fig. 7) and the departures of sea surface temperature (light lines, right scales) for region X. All curves have been filtered with a seven-point binomial filter.

These are all plotted together with the s.s.t. departures for region X, which is strongly related to the dominant s.s.t. eigenvector and hence the temporal evolution of El Niño events (Weare 1982). The variations in $Q_L$ in regions N, X and P are fairly similar to each other and to s.s.t. departures. The maximum amplitude of the variations is about 30 W m$^{-2}$. The zero-lag correlations between the region X s.s.t. and the $Q_L$ departures are 0.18, 0.69 and 0.15 for regions N, X and P, respectively. Only that for region X is significant at the 99% confidence level.

Coherence spectra have been calculated between region X temperature departures and $Q_L$ departures for regions A–R. The coherence squares between the s.s.t. and $Q_L$ of regions N, X and P have maxima of about 0.6, 0.8 and 0.5, respectively, at frequencies less than 0.8 cycles/year. The coherence squares greater than 0.23 are significant at the 95% confidence level (Jenkins and Watts 1968). The phases associated with these maximum coherence squares indicate that s.s.t. changes in region X lead the $Q_L$ variations in region X by about 0–2 months (95% confidence interval of ±1 month) and those in regions N and P by 2–6 months (±2 months). These lags are quite apparent in Fig. 8.

Figure 8 also includes a plot of $Q_L$ variations of region B, which is very representative of regions A, B and C. The correlation between $Q_L$ and region X s.s.t. is −0.12, which is insignificant at the 95% level. The dominant feature in the variations of region B is
the nearly three-year period centred on 1962 with increased latent flux from ocean to atmosphere of 30–40 W m\(^{-2}\). This feature seems unrelated to El Niño.

Reviewing the variations of \(Q_L\) for all the regions shown in Fig. 7 results in several conclusions. Regions G, H, I, J, M, N, X, P have similar longer period (longer than one year) variability. In general latent losses in these regions increase during El Niño and are decreased after El Niño events. Spectral analysis shows moderate correspondence between \(Q_L\) in these regions (excepting I and J) and s.s.t. variations in region X. The s.s.t. variations lead the \(Q_L\) changes by 0–12 months.

Figure 9. Monthly departures of surface moisture divergence: heavy lines, left scale (10\(^{-8}\) kg kg\(^{-1}\) s\(^{-1}\)). Light lines, right scale, as in Fig. 8.

Figure 9 illustrates the departures in the divergence of surface layer moisture flux for regions M and N. Again these plots also include a tracing of s.s.t. departures for region X. It is quite obvious that the longer period variations of DIV \(Q\) for N and M tend to be out of phase with each other and that both are moderately related to s.s.t. departures. The correlation between DIV \(Q\) departures for M and N is \(-0.49\), and for G and H \(-0.23\). Correlations with magnitudes greater than about \(-0.20\) are significant at the 95% confidence level. Correlations between DIV \(Q\) for regions G, H, M and N and s.s.t. for region X are \(-0.44\), \(-0.20\), \(-0.46\) and \(-0.54\), respectively. Coherence analyses of the DIV \(Q\) for regions G, H, K, M, N and X with the s.s.t. for region X (representing El Niño changes) all show maximum coherence squares greater than 0.5 for periods longer than two years. The phase spectra suggest that variations of DIV \(Q\) in regions M and N lead s.s.t. variations by about 1–6 months. The 95% uncertainty levels for the phases are about \pm 2 months (Jenkins and Watts 1968). DIV \(Q\) variations of regions G, H and K tend to follow s.s.t. changes by 1–6 months. These results suggest that El Niño is preceded by a change in the position or latitudinal extent of the North Pacific Convergence Zone in the eastern ocean and that the changes in the convergence–divergence patterns expand westward as El Niño develops.

The relationship of specific humidity to El Niño has only been shown in the discussion of the eigenvectors. Composite analyses similar to those illustrated for \(Q_L\) and DIV \(Q\) have also been carried out. The patterns of variations are very similar to those of s.s.t. shown by Weare (1982) and Rasmusson and Carpenter (1982).
6. Discussion

These three sets of analyses indicate that spatially coherent temporally persistent variations in moisture parameters take place near the surface of the tropical Pacific Ocean. Many of the observed changes are related to s.s.t. variations in the eastern equatorial ocean indicative of El Niño events. In addition, however, large-scale variations, especially in the western ocean, are evident which are not easily related to El Niño.

The analyses strongly suggest that $Q_L$ variations are often not directly nor simultaneously related to those of s.s.t., as Bjerknes (1966) seemed to have assumed. Figure 10 further illustrates this point. It shows the fractions of the variance of departures of $Q_L$ for each region shown in Fig. 7 which are independently explained by the departures of the regional average s.s.t. and wind speed (Weisberg 1980). As may be seen in the eastern equatorial ocean the influences of both are quite comparable. However, in many other regions wind speed changes are much more important. This is in part because wind speed is a direct component of the bulk formula (1) used to calculate the latent heat of evaporation, whereas s.s.t. enters indirectly through specific humidities.

The previous analyses indicate that moisture divergence variations in the regions of the North and South Pacific Convergence Zones are moderately related to El Niño. This is especially strongly suggested by the time series analyses of regions M and N near the NPCZ. In this case there is evidence that variations in the moisture divergence precede by one or more months s.s.t. changes in the El Niño core region X. This would suggest that moisture divergence changes and the associated variations in precipitation and mid-troposphere latent heat release may be more related to the causes of, rather than the effects of, s.s.t. changes.

The suggestion that moisture convergence variations precede those of s.s.t. is consistent with observations of changes in the strength of the South Pacific high (SPH). Rasmussen and Carpenter (1982) show that pressure variations at Rapa and Easter Islands, which are indicative of variations in the strength of the SPH, lead the earliest
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El Niño s.s.t. variations by about one month. This is also suggested by the analyses of
island data of Quinn and Burt (1972) and Trenberth (1976) and of ship-derived data of
Weare (1983b).

The apparent temporal relationships between the large-scale variations in sea level
pressure, moisture divergence, latent heat flux, and sea surface temperature suggest a
possible working hypothesis of the origin of El Niño events. Initially, the SPH may
weaken; this seems to be associated with decreased latent heat fluxes along its perimeter
and an equatorward movement of the NPCZ. Eastern Pacific s.s.t. may decline because
of greater net surface heating (Weare 1983a, c) and as a dynamic response to weaker
ekasterly winds (Wyrki 1975). The weaker easterlies may be the result of a combination
of a direct response to the weaker SPH and an indirect response to the movement of
the NPCZ giving rise to anomalous westerly winds along the equator (Gill 1980).

This hypothesis rests heavily upon the observations implying that changes in sea
level pressure and moisture divergence precede those of s.s.t. To investigate the latter
more fully, coherence spectra were calculated between the s.s.t. for the coastal region
R (thought to be the region of the initial s.s.t. changes; see Weare (1982) and Rasmusson
and Carpenter (1982)) and moisture divergence for regions M and N. Highly significant
coherence squares of 0.7 and 0.6, respectively, are apparent at frequencies of about 0.3
cycles per year. In both cases the s.s.t. variations are nearly simultaneous with those of
the moisture divergence. This evidence might tend to negate the above hypothesis if it
were not for the fact that the zonal scale of region R is so small. The linear response
of the atmosphere to a s.s.t.-induced heating (Gill 1980) decays rapidly to the west of
the heating such that a 1 m s\(^{-1}\) anomaly in region R near 80°W would be expected to be
less than 0.1 m s\(^{-1}\) at longitudes only 15 to 30° to the west. Thus it would seem improbable
that the observed moisture divergence variations could be a result of s.s.t. departures
in region R alone.

While it is believed that this hypothesis synthesizes many of the rather sketchy
observations discussed in this and other papers, it is quite speculative. Nevertheless, it
is put forward because it presents a line of thinking not previously emphasized in the
literature and because the several links involving the response of the atmosphere to the
surface moisture convergence variations may be tested in models similar to that of Gill
(1980). On the other hand, it is also recognized that the hypothesis is incomplete because,
for example, it ignores variations in most of the north and west Pacific and because it
does not suggest why El Niño tends to have phases which are quite fixed relative to the
seasons.

Reemphasis must be given to the fact that a great many uncertainties exist in the
analyses discussed. Not least are the uncertainties in the estimates of the basic quantities
discussed, \(q_a\), \(\Omega_L\), and DIV \(\Omega\). Over much of the tropical ocean measurements leading
to these quantities are so sparse as to make 5° monthly means highly uncertain. It is
quite apparent that interpretable results may be derived only from fields which are
smoothed spatially and/or temporally. However, a great deal of uncertainty still remains,
for instance as to how representative of 'average' El Niño conditions is a composite
map. As has been emphasized by Rasmusson and Carpenter (1982) such composites are
likely to represent the stronger events better. Also the sample of four events making up
the composites may not represent the total realm of changes possible during El Niño.
Similarly, uncertainties exist as to how representative are spatial averages defined by the
regions designated in Fig. 7. Nevertheless, it is believed that the analyses taken as a
whole give a reasonably complete qualitative picture of the interannual surface moisture
variations and their relation to the El Niño/Southern Oscillation.
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