The Relationship between Convection and Sea Surface Temperature on Intraseasonal Timescales

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ABSTRACT

The relationship between tropical convection, surface fluxes, and sea surface temperature (SST) on intraseasonal timescales has been examined as part of an investigation of the possibility that the intraseasonal oscillation is a coupled atmosphere–ocean phenomenon. The unique feature of this study is that 15 yr of data and the whole region from the Indian Ocean to the Pacific Ocean have been analyzed using lag-correlation analysis and compositing techniques.

A coherent relationship between convection, surface fluxes, and SST has been found on intraseasonal timescales in the Indian Ocean, Maritime Continent, and west Pacific regions of the Tropics. Prior to the maximum in convection, there are positive shortwave and latent heat flux anomalies into the surface, followed by warm SST anomalies about 10 days before the convective maximum. Coincident with the convective maximum, there is a minimum in the shortwave flux, followed by a cooling due to increased evaporation associated with enhanced westerly wind stress, leading to negative SST anomalies about 10 days after the convection. The relationships are robust from year to year, including both phases of the El Niño–Southern Oscillation (ENSO) although the eastward extent of the region over which the relationship holds varies with the phase of ENSO, consistent with the variations in the eastward extent of the warm pool and westerly winds.

The spatial scale of the anomalies is about 60° longitude, consistent with the scale of the intraseasonal oscillation. The spatial and temporal characteristics of the surface flux and SST perturbations are consistent with the surface flux variations forcing the ocean, and the magnitudes of the anomalies are consistent with mixed-layer depths appropriate to the Indian Ocean and west Pacific.

1. Introduction

The Madden–Julian oscillation, or intraseasonal oscillation, is a dominant mode of variability in the Tropics (Madden and Julian 1971, 1972, 1994). It is manifested as large-scale eastward propagating circulation anomalies and associated convective anomalies with timescales of about 30–60 days. The convective anomalies associated with the intraseasonal oscillation are strongest over the Indian Ocean, the Maritime Continent, and the warm pool region of the west Pacific, extending out to the date line. Over the cooler waters of the eastern and central Pacific and Atlantic Oceans, there is very little convective signature of the intraseasonal oscillation, although there is a weak convective signal over the African and South American continents. The oscillation is strongest and most frequent in the boreal winter and spring. In the boreal summer the oscillation has a slightly different nature in its convective signal, with a northward expansion and contraction of the convective activity in the Indian Ocean associated with Indian summer monsoons.

Over the Eastern Hemisphere, where the convective signal is strong, the intraseasonal oscillation has a phase speed of around 5 m s⁻¹. Away from the convective signal, the oscillation has a phase speed of about 10 m s⁻¹ (e.g., Hendon and Salby 1994). There is a considerable amount of interannual variability in the activity of the intraseasonal oscillation in terms of both the strength of the anomalies in the circulation and convection and the number of events in the season (Slingo et al. 1999).

Theories and models of the intraseasonal oscillation need to be able to represent and predict these observed propagation characteristics. Comparisons of the intra-
seasonal oscillation in 15 general circulation models (GCMs) as part of the Atmospheric Model Intercomparison Project (AMIP; Slingo et al. 1996) indicated that most GCMs had weak intraseasonal activity compared to observations; they tended to simulate slightly shorter periods than observations and failed to capture the seasonality in the oscillation.

There have been many attempts to develop a theoretical framework to explain the propagation characteristics of the intraseasonal oscillation. Much of this work has centered around the modification of equatorially trapped waves by the consideration of moist processes, either through the wave–CISK (conditional instability of the second kind) mechanism (e.g., Lau and Peng 1987) or by considering the role of wind–evaporation feedbacks (Emmanuel 1987; Neelin et al. 1987). Both of these theories have their weaknesses. The wave–CISK mechanism typically produces disturbances with phase speeds of about 15 m s$^{-1}$ or greater, which are faster than observations. The mechanisms of Emmanuel (1987) and Neelin et al. (1987), variously known as air–sea interaction, evaporation–wind feedback, or wind-induced surface heat exchange (WISHE), can produce disturbances that propagate at phase speeds between about 4 and 20 m s$^{-1}$, depending on the choice of surface parameters, but further arguments have to be introduced to produce the scale selection required to explain the large spatial scales of the intraseasonal oscillation. However, the major weakness of the WISHE mechanism is the requirement for basic state easterlies in the Tropics. In the region where the convective signal of the intraseasonal oscillation is large, the climatological winds are westerly at the surface.

The poor representation of the intraseasonal oscillation in atmospheric GCMs and the lack of success in developing a theory of the intraseasonal oscillation that predicts its general propagation characteristics suggest that the theories of the intraseasonal oscillation and atmospheric GCMs may lack a vital part of the system that is responsible for the maintenance of the oscillation.

Krishnamurti et al. (1988) showed that there is large intraseasonal variance in the sea surface temperature (SST) in the west Pacific. Observations from the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE) have shown that SSTs in the warm pool are modulated by the passage of the intraseasonal oscillation (e.g., Weller and Anderson 1996; Hendon and Glick 1997; Lau and Sui 1997). The modulation of the SST is related to the change in surface fluxes associated with the passage of the intraseasonal oscillation.

Such observations have led to speculation that the intraseasonal oscillation may be a coupled mode of the atmosphere–ocean system (e.g., Flatau et al. 1997; Sperber et al. 1997). Flatau et al. (1997) developed a simple parameterization of SST change as a function of surface wind speed appropriate to the warm pool region of the west Pacific based on observations from and related to TOGA COARE. They included this parameterization in an aquaplanet integration of an atmospheric GCM and showed that the convection associated with the simulated intraseasonal oscillation became more coherent. Similarly, Waliser et al. (1999) investigated the effect of coupled SSTs on the intraseasonal oscillation in an atmospheric GCM. The control integration used a fixed annual cycle of SST, whereas the coupled integration used SSTs from a slab ocean model forced by the surface fluxes from the atmospheric model and relaxed back on intraseasonal timescales to the fixed annual cycle of the control integration. The coupled integration showed evidence of a stronger intraseasonal oscillation with increased seasonality and a slower phase speed over the Indian Ocean and west Pacific compared to the uncoupled integration.

Wang and Xie (1998) have developed a simple linear coupled model of the tropical atmosphere–ocean system. The atmosphere is represented by the lowest baroclinic mode (i.e., the atmospheric model of Gill 1980), with the heating rate proportional to the SST anomaly. The ocean model consists of an active upper ocean with an embedded mixed layer, both of variable depth. In addition to predicting these depths, the model predicts vertically averaged currents and the mixed layer temperature. The depth and temperature of the mixed layer are controlled by Ekman pumping, entrainment, solar radiation, and evaporative heat fluxes. The model can be modified to exclude the variations in the depth of the active ocean and the radiative forcing of the mixed layer temperature. For basic-state conditions that are consistent with those observed in the warm pool region, the model exhibits unstable eastward propagating modes with phase speeds under 10 m s$^{-1}$. The large-scale features of this mode compare well with the structure of the intraseasonal oscillation as observed during TOGA COARE.

The hypothesis that the intraseasonal oscillation is a coupled phenomenon is not tenable unless two questions can be answered in the affirmative. First, does the atmospheric intraseasonal oscillation impact on the ocean? Second, if it does, then is the atmospheric intraseasonal oscillation sensitive to this ocean response? It is the first of these questions that this paper will address; the second question will probably require detailed ocean–atmosphere modeling to address it. The general approach used in this paper is similar to that in the recent papers of Hendon and Glick (1997) and Shinoda et al. (1998); however, there are some major differences. In this paper, 15 yr of data have been used, allowing the interannual variability of the relationships between the convection and the surface to be studied, and the composing technique used here is different from that of Shinoda et al. (1998). The conclusions in this paper both support and extend the results of Hendon and Glick (1997) and Shinoda et al. (1998). In section 2, the data are described. Sections 3b and 3c use lag correlations and composites, respectively, to tackle the questions.
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Fig. 1. 20–100-day bandpass filtered equatorial (5°N–5°S) OLR (contour interval 20 W m⁻² from ±10 W m⁻²), SST (0.2°C from ±0.1°C), SWF (20 W m⁻² from ±10 W m⁻²), UST (0.02 N m⁻² from ±0.01 N m⁻²) and LHF (20 W m⁻² from ±10 W m⁻²). Negative values are shaded and negative contours are dashed.

raised by the preliminary analysis in section 3a. The results are discussed in section 4.

2. Data

Outgoing longwave radiation (OLR) from the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites is used as a proxy for tropical convection (e.g., Arkin and Ardanuy 1989). Surface fluxes of sensible heat, radiation and moisture, and the surface wind stresses were obtained from the initialized analyses of the European Centre for Medium-Range Weather Forecasting (ECMWF) reanalysis (ERA; Gibson et al. 1996, 1997) for the period of 1981–93 and ECMWF operational analysis for the period of 1993–97. SST data are obtained from the weekly analyses of Reynolds and Smith (1994). For compatibility with the OLR, surface fluxes, and surface stresses, the SST data are interpolated to daily values. The period analyzed runs from 1 January 1982 to 31 December 1997. The start of this period is determined by the availability of weekly SST data.

To isolate the intraseasonal variability in each of the fields, the data are filtered with a 20–100-day bandpass filter using a 180-point Lanczos filter. In view of the very different nature of the tropical circulation and the behavior of the intraseasonal oscillation during the boreal summer, the characteristics of any atmosphere ocean coupling may be very different during this season, and only the period of October to May will be analyzed.

The variance of the 20–100-day bandpassed sensible heat flux (SHF) and longwave flux (LWF) at the surface in the Tropics is much smaller than that of the latent heat flux (LHF) and shortwave flux (SWF). The climatological October–May values of the standard deviations within the bandpassed data for the 15 Oct–May seasons analyzed averaged over the sea points in the region 10°N–10°S, 30°E–180°, are approximately 1, 5, 20, and 25 W m⁻², respectively, for SHF, LWF, LHF, and SWF. In view of the dominance of the SWF and LHF variations, the relationship between the convection and the SHF and LWF will not be considered further.

3. Results

a. Preliminary analysis

Equatorial time series of the intraseasonal anomalies in the OLR and surface variables are constructed by
averaging the 20–100-day bandpassed fields between 5°N and 5°S. For the surface fields, that is, all except the OLR, only ocean points are included. Figure 1 shows these equatorial time series of filtered OLR, SST, SWF, LHF, and zonal wind stress (UST) for October 1987–May 1988.

Five eastward propagating convective events can be clearly seen in the OLR time series. Associated with these convective events are variations in the SST, SWF, LHF, and UST, with comparable spatial and temporal scales. This visual relationship raises the questions that will be addressed in this paper:

1) Is there a coherent relationship between convection, surface fluxes, and SST on intraseasonal timescales?
2) How robust is such a relationship from year to year and from region to region within the Tropics?
3) What is the spatial scale of the anomalies in the surface fields?
4) What are the magnitudes of the anomalies in the surface fields?

The first two questions will be addressed in section 3b by the use of lag correlations, and the second two questions will be addressed in section 3c using composites.

**b. Temporal relationships between convection, surface fluxes, and SST**

The temporal relationship between the convection, surface fluxes, and SST is investigated using lag correlations. As noted in section 2, the various parameters are on different longitudinal grids, depending on the source of the data. To calculate the lag correlations, an equatorial time series of each variable is calculated on a 5° longitude grid. The use of a 5° grid rather than a 2.5° grid (the smallest consistent grid that could be generated from the data) means that over the Maritime Continent, each of the grid points contains at least 50% ocean points and gives a better spread of Northern and Southern Hemisphere points, thus providing a more consistent surface coverage over these regions. These time series are calculated from the original gridded data to give the proper weight to each ocean point, where there is a mixture of land and sea.

The significance level of these correlation coefficients is calculated by assuming that the number of degrees of freedom is equal to the minimum number of points that would be required to resolve the 20-day period wave, which is the high-frequency cutoff. This is equal to one-tenth of the number of points used to calculate
FIG. 2. Lag correlations between OLR (convection) and surface fields (SST, SWF, LHF, UST). Negative lags indicate that the convection lags the surface field; positive lags indicate that the convection leads the surface fields. The sign convention is such that positive correlations indicate that enhanced convection (a negative OLR anomaly) is correlated with a negative SST anomaly, reduced SWF at the surface, a negative LHF anomaly at the surface (enhanced evaporation), or an easterly wind stress anomaly. Negative correlations are shaded; contour interval is 0.1, with negative contours dotted; and the zero contour is dashed. Correlation coefficients above 0.103 at zero lag and 0.116 at 50-day lag are significant at the 95% level based on \( N/10 \) degrees of freedom, the minimum number of points required to resolve variations with the largest retained frequency.

Figure 2 shows the lag correlations between the equatorial timeseries of the OLR and each of the surface fields. As expected, there are significant positive correlations between the OLR and SWF (Fig. 2b) at approximately zero lag across the whole region. Also, there are significant negative correlations between the OLR and SST (Fig. 2a) at lags of order \( \pm 15 \) days. In addition to the correlations with SWF, the OLR also exhibits significant correlations with SST, LHF, and UST at various lags over some regions. The significant correlations between the OLR and SST (Fig. 2a) are confined mainly to the region between the east coast of Africa and near the date line, with positive correlations at lags of order +10 days and negative correlations near lags of order −10 days. Remembering that a minimum in the OLR corresponds to a peak in convection, then this is indicative of above-normal SSTs preceding a maximum in convection and below-normal SSTs occurring afterward. In the eastern Pacific ocean, there is a region of negative correlation between the OLR and SST at lags close to zero.

Over the warm pool regions of the Indian Ocean, where there are small horizontal gradients in the mean SST (Fig. 3a), one might expect the SST to be driven mainly by local processes such as surface fluxes. However, over the central Pacific, where there are larger horizontal gradients in the SST, it is more likely that ocean dynamics plays a role in determining the intra-seasonal variability in the SST, and SST variations may be forced, at least partly, by nonlocal processes (e.g., Hendon et al. 1998). Near the South American coast, the thermocline is close to the surface so that internal ocean waves (e.g., Kelvin waves and instability waves) can have a large impact on the SST. In addition, coastal upwelling, driven by the local surface winds, also im-
pacts the SST, and so local variations in the surface winds, induced by the large-scale convection, may contribute to variations in the SST.

The significant correlations between the OLR and UST (Fig. 2c) and LHF (Fig. 2d) do extend beyond the date line, although the relationships tend to change in the Western Hemisphere. Between about 60°E and the date line, there are significant negative correlations between the OLR and UST, and positive correlations between the OLR and LHF at lags of about ±5 days, implying westerly wind anomalies and enhanced evaporation after the convective maximum. At lags of about ±10 days, there are significant positive correlations between the OLR and UST and negative correlations between the OLR and LHF, corresponding to easterly wind stress anomalies and reduced evaporation preceding the convection. The association of enhanced LHF with westerly wind stress anomalies and reduced LHF with easterly wind stress anomalies, implied by the correlations of each of these with the OLR, is consistent with the climatological westerly surface wind stress in the Indian Ocean and west Pacific (Fig. 3b).

The relationship between the OLR and UST extends beyond the date line to about 120°W, although the lags at which the extrema occur change slightly across the central Pacific. Close to the South American coast there are significant negative correlations between the OLR and UST at about zero lag. The significant positive correlations between the OLR and LHF extend only to the date line, and the negative correlations between the OLR and LHF in the central Pacific occur at lags closer to zero than in the Indian Ocean and west Pacific. The change in the correlations between the OLR and LHF in the central Pacific is consistent with the fact that the climatological wind stress changes from westerly to easterly there (Fig. 3b). Close to the South American coast, there are negative correlations between the OLR and LHF at lags of about ±5 days, with positive correlations at about ±15 days at either side, which is consistent with the correlations between the OLR and UST in the presence of a climatological easterly wind stress. All the lag-correlation maps are slightly weaker and less coherent around the location of the Maritime Continent and, with the exception of the SWF, are weaker close to the African coast.

The correlation coefficients calculated here give a picture of the mean relationship between the convection and the SST, and the surface fluxes and the surface stresses. However, there is considerable interannual variability in the tropical atmosphere–ocean system, of which the largest component is the El Niño–Southern Oscillation (ENSO). Figure 4 shows the lag-correlation maps for the OLR with SST and the OLR with LHF, constructed from the three El Niño seasons of 1982–83, 1986–87, and 1991–92 (Figs. 4a and 4b) and the three La Niña seasons of 1984–85, 1988–89, and 1995–96 (Figs. 4c and 4d). Comparing the lag-correlation maps in Fig. 4 with those in Fig. 2 shows that the general relationship between the convection, the SST, and the LHF does not vary much with the status of the El Niño, but the region over which this relationship holds does vary. In the time series constructed from the three El Niño seasons, the pattern of significant correlations of the OLR with SST and the OLR with LHF, which are observed in the Indian Ocean and the west Pacific in the complete record, extend beyond the date line to about 160°W. In La Niña years, the pattern does not extend as far as the date line, holding to about 160°E. These changes in the extent to which these patterns in correlation coefficient hold can be related to the changes in the regions of the warmest SST and westerly wind surface stresses between El Niño years and La Niña years (Fig. 5).

To investigate how the relationship between the convection and the surface fluxes varies from year to year and to produce a measure of the robustness of the relationships obtained from the single time series constructed from the 15 seasons, the lag-correlation maps have been calculated for each season individually.

Quantitative comparisons between these correlation maps are difficult to make, but year to year variations in the relationship between the convection and the surface fields can be summarized by the lags at which the extrema in the correlation coefficients occur. The significant (at the 90% level) extrema have been located as a function of longitude in the correlation maps for
Fig. 4. Lag-correlation maps for (a) OLR with SST in El Niño years, (b) OLR with LHF in El Niño years, (c) OLR with SST in La Niña years, and (d) OLR with LHF in La Niña years. Negative correlations are shaded; contour interval is 0.1, with negative contours dotted; and the zero contour is dashed. Correlation coefficients above 0.167 at zero lag and 0.187 at 50-day lag are significant at the 95% level.

Each season and in the 15 seasons treated as a single time series. As an example, Fig. 6 shows the lags at which the extrema in the correlation coefficient occur for the lag correlation between the OLR and SST. Figures 6a and 6c show the maxima and minima, respectively, that are significant at the 90% level for the 15 seasons treated as a single time series. They correspond to the timings of the maximum and minimum values seen in Fig. 2. Figures 6b and 6d show the lags at which the extrema occur for the 15 seasons treated individually. The lags at which the extrema in the correlation coefficients between the OLR and SST occur for the 15 seasons treated individually are clustered around the lag at which the extrema occur for the 15 seasons treated as one time series. For example, in each season, positive SST anomalies lead enhanced convection and negative SST anomalies follow enhanced convection. The spread of these lags for the individual seasons about the lag for the single 15-yr time series gives a measure of the robustness of the relationship between the OLR and SST that is deduced from the single 15 season time series.

The results shown in Figs. 2 and 6 suggest that there is some robustness in the lag-correlation maps for differing periods. This leads to the hypothesis that there is an underlying physical mechanism relating the convection to the SST, surface fluxes, and surface stresses. The coherent pattern of significant correlations is, in general, confined to the Indian Ocean and west Pacific, so the subsequent analysis will focus on this region. Because of the variations around the Maritime Continent, it is useful to divide the analysis region into three separate regions: the Indian Ocean (60°–100°E), the Maritime Continent (100°–140°E), and the west Pacific (140°E–180°). Each of these regions contains eight longitudes at which the correlation coefficients have been calculated.

The relationship between the convection and the surface fields can be summarized by interpreting the lags at which the extrema in the correlation coefficients between the OLR and each of the SST, SWF, LHF, and UST occur in terms of their timing relative to the convective maximum (OLR minimum). This representation implies a linear assumption that the signals associated
Fig. 5. Seasonal (Oct–May) mean (a) SST in El Niño years (contour interval 1°C, heavy contours are 20°C and 25°C, SST > 28°C shaded), (b) surface zonal wind stress in El Niño years (contour interval is 0.02 N m⁻², heavy contour is 0.1 N m⁻², positive values shaded), and (c) and (d) as for (a) and (b), except for La Niña years.

with enhanced convection are opposite to those associated with suppressed convection.

For each extremum in the surface fields, five parameters are used to describe the timing of the surface anomaly relative to the convection as well as the spatial coherence and interannual variability of this timing. These five parameters are the median lag within each region, the range of lags across the region, the interannual range of lags, the interannual standard deviation of lags, and the number of significant correlations in each region.

The first two parameters are obtained from the correlations calculated using the 15 seasons as a single time series. The median lag within the region is used to describe the mean relationship between the convection and surface field. The longest and shortest lags within the region are used to describe the spatial coherence of the relationship.

The other three parameters are obtained from the correlations calculated for each season individually and are used as measures of the interannual variability in the relationship between the convection and the surface fields. This is not straightforward, as the following example for the maxima in LHF illustrates (Fig. 7). First, a histogram is made of the lags at which either the maximum or minimum in correlation coefficient occurs (the bars in Fig. 7). The histogram is then smoothed using a three-point running mean (the solid line in Fig. 7), and the range of lags is defined by the points for which the smoothed histogram takes values of 1 or above (indicated by the outermost dotted lines and the shaded bars in Fig. 7). The second parameter is the mean plus or minus one standard deviation of the data within the range (indicated by the other dotted lines in Fig. 7). The third parameter is the total number of observations falling within the defined range (i.e., the sum of the shaded bars in Fig. 7). Both of the measures of interannual variability used here have their weaknesses. The range as it has been defined here is not a particularly robust statistic, but it has the advantage of being able to indicate a skewed frequency distribution. The standard deviation, while being more statistically robust, does not indicate any skewness. However, using both of these statistics gives an indication of the interannual variations in the relationship between the convection and the surface fields.

Figure 8 shows a summary of the relationship between the convection (OLR) and the surface fields based on the parameters described above. The positions of the dots indicate the median lags at which the extrema occur in each region from the correlations based on the single 15-yr time series. The sizes of the dots indicate the number of significant extrema in the correlation coefficients within the defined ranges. The vertical dotted lines indicate the ranges of the lags as defined above and illustrated in Fig. 7. The horizontal dotted error bars indicate one standard deviation on either side of the
mean. Thus, the observed lags that are most robust from year to year, are those with large dots and small error bars, and the least robust are those with large error bars and small dots. The solid error bars indicate the range of these lags across each of the three regions, a measure of the robustness within region.

Figure 8 shows that the general relationship between the convection and the SST, surface fluxes, and surface stresses is the same in each of the analyzed regions. The relationship is more robust from year to year in the Indian Ocean than in the west Pacific, which in turn is more robust than over the Maritime Continent. The convective signal of the intraseasonal oscillation is often disrupted in the region of the Maritime Continent. Here, the much less robust relationships between convection and the surface parameters may be a result of the weaker convective signal, but they may also point to an explanation for the weaker convective signal. Across all the regions, some relationships are more robust than others. In particular, the lags of the SWF minimum and the wind stress maximum and minimum are the most robust in each region, and the lags of the LHF anomalies are less robust. The robust relationship with the shortwave minimum and wind stress anomalies is consistent with the idea that they are driven directly by the convection. LHFs are influenced by the variations in the wind, but they depend on the absolute speed of the wind and are therefore dependent on interannual variability in the basic state that is not included in the filtered dataset. LHF is also related to low-level atmospheric humidity and SST. This dependence on a number of variables, some of which are not related only to intraseasonal timescales, probably explains the weaker relationship between the convection and the LHF.

The general relationship between the convection and the surface fields for the Indian Ocean, with lags given in days, is shortwave maximum (−17), easterly wind stress anomalies (−13), reduced evaporation (−12), SST maximum (−9), shortwave minimum (−1), enhanced convection (0), westerly wind stress anomaly

![Figure 6](image-url)
FIG. 7. Example of the way in which the parameters used to characterize the relationship between enhanced convection and the surface fields are determined; here based on the enhanced evaporation following the convection in the Indian Ocean. The vertical bars indicate the number of occurrences of a maxima in correlation coefficient between OLR and LHF at each lag from the 15 seasons treated individually at eight grid points across the Indian Ocean (60°–100°E). The solid line indicates the same distribution with a three-point running average applied to the data. The dotted vertical lines indicate the positions corresponding to the parameters used to describe the interannual variations and the shading of the bars indicates those cases that fall within the defined range and have therefore been used to determine the standard deviation (see text for further details).

(+4), enhanced evaporation (+5), SST minimum (+9), and shortwave maximum (+15). The timings in the other regions are slightly different, particularly in the lag between the easterly wind stress anomalies and the reduced evaporation before the convection and in the timing of the wind stress anomalies relative to the convection. In the west Pacific, both the easterly wind stress anomalies before the convection and the westerly wind stress anomalies after the convection occur 2–3 days earlier, relative to the convection than in the Indian Ocean.

c. Spatial relationships between convection, surface fluxes, and SST

The lag-correlation analysis gives no indication of the spatial structure or scale of the surface anomalies, or of the magnitude of the anomalies. Information on the spatial structure can be obtained from lag correlations in space rather than time; however, this still does not yield information on the magnitude of the anomalies. Composites give information on both the structure and magnitude of the surface anomaly fields and can also distinguish between the enhanced and suppressed convective phases of the oscillation.

Composites of the OLR, SST, and the surface fluxes and zonal stress were constructed for both enhanced and suppressed convection in the equatorial OLR time series at each longitude on the 5° grid. The selection of events was designed to include only propagating events of large magnitude and was based on two criteria. First, at each longitude, all the minima and maxima in the OLR with magnitudes greater than one standard deviation in OLR at that longitude were selected. Second, to test for propagation, each of the negative (positive) events must additionally satisfy at least one of the following: (i) the OLR 45° to the west must be negative (positive) for the entire period between 10 and 19 days earlier, or (ii) the OLR 45° to the east must be negative (positive) for the entire period between 10 and 19 days later, or (iii) the OLR 25° to the west, 3–14 days earlier, and the OLR 25° to the east, 3–14 days later, must be negative (positive).

For variations in the OLR with a period of 40 days, (i) and (ii) are equivalent to permitting waves with phase speeds between 3.3 and 5 m s⁻¹ while (iii) is equivalent to permitting waves with phase speeds between 2.9 and 6.5 m s⁻¹. For variations with longer periods, the range of phase speeds permitted is increased. The range of phase speeds that the propagation test allows might be considered to be too slow and slightly too narrow compared with observed phase speeds of around 5 m s⁻¹, where there is a strong convective signal, or up to 10 m s⁻¹, away from the convective signal. However, a comparison of the events that this criterion includes with those that it excludes shows that only a small proportion of those events that it excludes have eastward propagation characteristics that resemble those of the intraseasonal oscillation. It is successful in removing nearly all the OLR anomalies that are stationary or that propagate westward. Including the test for propagation reduces the number of events on which the composite is
F I G . 8. Summary of the temporal relationships between the convection and surface fields. The dots indicate the lags at which extrema in correlation coefficients occur when the 15 seasons are treated as one time series and the solid error bars indicate the range within each region. The extended dotted error bars indicate the range within that region when the 15 seasons are treated individually (see text for details of how this range is defined). The horizontal dotted bars indicate ±1 std dev from the mean of this distribution. The size of the dots indicates the number of significant extrema within this defined range. Within each region, the ordering of the events (relative to a convective maximum) from left to right is SWF max, UST min, LHF max, SST max, SWF min, UST max, LHF min, SST min, and SWF max. Here, SWF and LHF positive correspond to fluxes into the surface.

based from about 60 at each longitude over the Indian Ocean and west Pacific to about 35.

At each longitude, two types of composites were constructed for minima in the OLR: (i) longitude–time maps of the equatorially averaged values for time lags between ±30 days and (ii) latitude–longitude maps at zero lag. At each longitude, composites were produced for the OLR, SST, SWF, LHF, and UST.

Examination of the longitude–time OLR composites revealed that the spatial minimum in the OLR does not necessarily occur at the longitude at which the composite is based; that is, a composite based on the minimum values of the OLR at 57.5°E has its lowest OLR value at 67.5°E. Figure 9 shows the longitude of the spatial minimum in the OLR as a function of the longitude of the OLR time series on which the composite is based. In the western Indian Ocean, the spatial minima in the OLR occurs to the east of the longitude on which the composite is based, and in the eastern Indian Ocean, the spatial minima in the OLR occurs to the west of the longitude on which the composite is based. A similar, though less pronounced, pattern occurs in the warm pool region of the west Pacific. The displacement of the strongest convection away from the region on which the composite is based means that care must be taken in interpreting the location of the anomalies in the surface fields relative to the center of the convection. To account for this, composites based on the OLR time series at 82.5° and 162.5°E, where the longitude of the spatial minima in the OLR coincides with the longitude on which the composites are based, are chosen to represent the Indian Ocean and west Pacific regions.
Figures 10 and 11 show the time–longitude composites of the equatorially averaged values for propagating minima in the OLR at 82.5° and 162.5°E, respectively. By construction, the minima in the OLR in both cases have their largest amplitude at the location on which the composite is based, and they both demonstrate an eastward propagation of about 5 m s⁻¹ (Figs. 10a and 11a). The phase speed of the propagation will be determined partly by the test for propagation that has been applied, but the use of other slightly different filters barely altered the phase speed. Excluding the test for propagation altogether produced composites of OLR with phase speeds about 1 m s⁻¹ faster. At both locations, most of the composite fields show local temporal variability that tends to be stronger than the spatial variability (e.g., in Fig. 10a, the OLR anomalies at 82.5°E at ±15 days are at least as large as the OLR anomalies away from 82.5°E at day 0). This may indicate that the timescale of the intraseasonal oscillation is more strongly defined than the spatial scale.

At the two locations, there is a similarity in both timing and relative strengths between the OLR and SWF composites (Figs. 10b and 11b). The composites of zonal wind show that in both basins, the strongest surface westerly anomalies at day 0 are approximately collocated with the minima of the OLR anomalies (Figs. 10c and 11c). For convection at 82.5°E, there are westerly wind stress anomalies that are collocated with the convection and that lie to the west of the center of the enhanced convection and easterly wind stress anomalies to the east of the enhanced convection. These wind stress anomalies are associated with enhanced evaporation and cooling of the ocean surface. In the west Pacific, where the climatological winds are westerly, the easterly wind stress anomalies are associated with reduced evaporation. The reverse is found in the eastern and central Pacific, where the climatological winds are easterly. The sum of the LHF and SWF anomalies (Fig. 10e) has the effect of cooling the ocean coincident with, and to the west of, the convection, with a warming to the east of the convection. The SST composite (Fig. 10f) shows warm SST anomalies in the Indian Ocean prior to the convection and cold SST anomalies in the Indian Ocean after the convection. The convection in the Indian Ocean is also associated with warm SST anomalies in the west Pacific. These SST anomalies are consistent with the coupled mechanism for the intraseasonal oscillation proposed by Flatau et al. (1997). All the fields composited here show propagating signals with similar phase speeds to the convective signal.

There are some marked differences between the composites based on enhanced convection in the Indian Ocean versus those for enhanced convection in the west Pacific. First, the positive OLR anomaly in the Indian Ocean to the west of the enhanced convection in the west Pacific (Fig. 11a) is in excess of 20 W m⁻², whereas the positive OLR anomaly in the west Pacific to the east of the enhanced convection in the Indian Ocean is only about 10 W m⁻² (Fig. 10a). This asymmetry may indicate that the suppressed convection in the Indian Ocean is in part a local response to the previously enhanced convection in the Indian Ocean rather than a remote response to the enhanced convection in the west Pacific. This suggestion is supported by the fact that the
Fig. 10. Time–longitude composite based on 36 propagating OLR minima at 82.5°E. (a) OLR (contour interval 5 W m\(^{-2}\)), (b) SWF (contour interval 5 W m\(^{-2}\)), (c) UST (contour interval 0.005 N m\(^{-2}\)), (d) LHF (contour interval 5 W m\(^{-2}\)), (e) SWF + LHF (contour interval 5 W m\(^{-2}\)), and (f) SST (contour interval 0.05°C). In each plot, the light shading and dashed contours indicate negative values and the zero contour is suppressed. In (a)–(d) and (f), the dark shading indicates values that are significant at the 90% level under a local \(t\) test.
Fig. 11. As for Fig. 10, except based on 31 propagating OLR minima at 162.5$^\circ$E.
positive OLR anomalies in the Indian Ocean following the enhanced convection there are stronger than those preceding it (Fig. 10a). Second, the easterly wind stress anomalies to the east of the enhanced convection seen in the Indian Ocean composite (Fig. 10c) do not appear in the composite for the enhanced convection in the west Pacific (Fig. 11c). There are two possibilities for this difference. First, the variability in the central Pacific, not associated with the intraseasonal oscillation, may swamp the signal associated with the convection in the west Pacific. Second, the dynamical response to the convection in the west Pacific may not have as strong a response to the east of the convection as for the enhanced convection in the Indian Ocean, where the climatological winds are different.

The time–longitude composites in Figs. 10 and 11 are in agreement with the sequence of events described by the lag-correlation analysis shown in Fig. 8. They show a coherent link between the Indian Ocean and west Pacific and eastward propagation of both positive and negative anomalies.

In order to identify the spatial scale and coherence of the anomalies, latitude–longitude composites were constructed for the same locations as in Figs. 10 and 11 and are shown in Figs. 12 and 13.

The OLR composites (Figs. 12a and 13a) suggest that
the convective anomalies associated with the intraseasonal oscillation extend 15° on either side of the equator and have a longitudinal scale of about 60°. The suppressed convection in the west Pacific that is associated with the enhanced convection in the Indian Ocean (Fig. 12a) is centered off the equator at about 5°S. Associated with the enhanced convection are negative anomalies in the SWF (Figs. 12b and 13b), with a maximum of about 20 W m⁻², a slightly smaller longitudinal scale than the OLR anomalies and a smaller meridional scale, extending only 10° on either side of the maximum anomaly. Associated with the suppressed convection are positive anomalies in SWF, although these are smaller scale. Over the west Pacific, where the convection is only weakly suppressed during the enhanced convection in the Indian Ocean (Fig. 12b), the positive SWF anomaly is weaker, about 10 W m⁻², and barely significant at the 90% level.

Collocated with and to the west of the enhanced convection are westerly surface wind stress anomalies (Figs. 12c and 13c). As with the SWF anomalies, these anomalies have a slightly smaller longitudinal scale than the enhanced convection and a smaller meridional scale, extending about 10° of latitude on either side of the maximum anomaly. For enhanced convection in the Indian Ocean, there is a large region of easterly wind stress anomalies along the equator and down the South Pacific convergence zone (SPCZ), extending about 120° in longitude (Fig. 12c). The easterly anomalies have a larger meridional scale comparable to that of the negative OLR anomaly. There is also a region of easterly wind stress anomalies in the subtropical Pacific Ocean at about
25°N, which may be a manifestation of Rossby wave propagation in response to the heating anomalies in the Indian Ocean. For the enhanced convection in the west Pacific, there is no evidence of easterly wind stress anomalies to the east of the convection (Fig. 13c). There is a region of easterly wind stress anomalies to the west of the suppressed convection in the Indian Ocean.

Associated with the wind stress anomalies are anomalies in the LHF (Figs. 12d and 13d). For enhanced convection in the Indian Ocean, there are negative LHF anomalies with a maximum of about 10 W m$^{-2}$ (Fig. 12d) to the west of the convection associated with the westerly wind stress anomalies and positive LHF anomalies of 10 W m$^{-2}$ in the west Pacific associated with easterly wind stress anomalies. In the central Pacific, where the climatological winds are easterly, the easterly anomalies are associated with enhanced evaporation. For enhanced convection in the west Pacific, there are negative LHF anomalies, with a maximum of about 20 W m$^{-2}$ in the west Pacific (Fig. 13d) associated with the equatorial westerly wind stress anomalies. Away from the equator, in the west Pacific, there are easterly wind stress anomalies, and these occur where the climatological winds are easterly, leading to a broad region of enhanced evaporation. In the Indian Ocean, there is a small region of positive LHF anomalies with a maximum of about 10 W m$^{-2}$ associated with the easterly wind stress anomalies to the west of the suppressed convection. The LHF anomalies have a similar longitudinal scale to the shortwave anomalies, but occur slightly to the west, leading to a broadening in the zonal direction of the anomalies in the sum of the SWF and LHF anomalies (Figs. 12e and 13e). Because of the dominance of the LHF and SWF over the SHF and LWF, the sum of the LHF and SWF is an approximation to the net surface heat flux into the ocean.

The sum of the LHF and SWF leads to a net cooling of the surface, with a maximum flux of about 35 W m$^{-2}$ collocated with, and to the west of, the enhanced convection, extending over about 60° longitude. For enhanced convection in the Indian Ocean, there is a warming of the surface, with a maximum flux of about 20 W m$^{-2}$ in the west Pacific and down the SPCZ (Fig. 12e). For the enhanced convection in the west Pacific, there is no evidence of warming to the east of the convection, but there is a net surface warming, again with a maximum of about 20 W m$^{-2}$ in the Indian Ocean, associated with the suppressed convection there.

Figures 12f and 13f show the SST anomalies associated with the convective anomalies. For enhanced convection in the Indian Ocean, there is a positive SST anomaly over the Maritime Continent region and west Pacific, with a maximum of about 0.1°C, and a smaller region of negative SST anomalies in the eastern Indian Ocean. For enhanced convection in the west Pacific, there are negative SST anomalies to the west of the convection over the Maritime Continent of a similar magnitude to positive anomalies in the same region for the enhanced convection in the Indian Ocean. There is no region of positive SST anomalies to the east of the enhanced convection in the west Pacific.

The magnitude of the composite flux and SST anomalies are smaller than those observed in individual events; this reduction in amplitude arises from averaging together events with slightly different characteristics. In the Indian Ocean, the SWF is slightly larger than the LHF but because of the slightly different phases (e.g., Figs. 12b and 12c), they both contribute significantly to the net surface heat flux. Over the west Pacific, the SWF and LHF anomalies have comparable sizes. The magnitudes of the composite net surface heat flux anomalies and SST anomalies are consistent with a simple mixed-layer calculation, with depths between approximately 10 and 50 m. These depths are comparable with the range observed in the warm pool region (Anderson et al. 1996).

4. Discussion and conclusions

The results from the lag-correlation analysis in section 3b and the composites in section 3c have revealed a coherent temporal and spatial relationship between the enhanced and suppressed convection associated with the intraseasonal oscillation and SST, surface energy fluxes, and surface wind stress across the Indian Ocean and west Pacific warm pool.

The relationship between the convection and the surface fluxes, diagnosed from the lag-correlation analysis, can be summarized as a warming of SST by shortwave radiation and reduced LHF associated with an easterly wind stress anomaly prior to the convection, with the maximum in SST occurring about 10 days before the maximum in convection. Along with the enhanced convection, there is a cooling of the SST by reduced shortwave radiation and increased evaporation associated with a westerly wind stress anomaly. This is consistent with the appearance of a minimum in SST about 10 days after the convective maximum. There is very little spatial variability in the timing of these events relative to the convection except that in the west Pacific, the enhanced westerly wind stress, enhanced evaporation, and coldest SST occur slightly sooner after the convective maximum than in the Indian Ocean.

The order of the surface anomalies found in this paper is consistent with the observations during TOGA COARE (e.g., Weller and Anderson 1996; Hendon and Glick 1997) and with the mechanisms proposed by Flatau et al. (1997) and Wang and Xie (1998). The relationship between the convection and surface fluxes is inconsistent with the air–sea interaction mechanisms proposed by Emmanuel (1987) and Neelin et al. (1987), which require enhanced evaporation preceding the enhanced convection. Hendon and Glick (1997) found for the 7-yr period of 1986–93 a lag of 10–15 days between the convection and the SST maxima and minima in the Indian Ocean and west Pacific, which is slightly longer
than the typical lags seen here for the longer period. They also determined a lag of about 7 days and about 10 days between the enhanced convection and enhanced evaporation in the west Pacific and Indian Ocean, respectively, about 3 days longer than the lags found here. The time–longitude composites constructed in section 3c also support the phase relationships between the convection and surface fields determined from the lag-correlation analysis.

Comparison of the lag-correlation coefficients for three El Niño years and three La Niña years showed that the phase of ENSO affected the longitudinal region over which the relationships between the convection and the surface fluxes held rather than the timing of the surface anomalies relative to the convection. In El Niño years, the coherent relationship between the convection and the surface fields extends beyond the date line into the central Pacific, consistent with the extension of both the warm pool and the region of westerly surface winds in El Niño years. This provides further support for the proposed coupled mechanism for the intraseasonal oscillation.

Time–longitude and latitude–longitude composites have been constructed for minima in the time series of equatorial OLR, subject to a constraint that there is evidence of eastward propagation at phase speeds appropriate to the intraseasonal oscillation. The OLR composites showed that the temporal minima in the OLR at a particular grid point did not necessarily coincide with a spatial minima at the same grid point. This is consistent with the idea discussed by Zhang and Hendon (1997) that the magnitude of the convection associated with the intraseasonal oscillation is modulated by a zonally varying amplitude envelope. Because of this, composites representative of the Indian Ocean and the west Pacific were chosen at longitudes where the spatial minimum in the OLR is coincident with the longitude at which the composites were based. In the time–longitude composites, the local temporal anomalies are somewhat more coherent and have slightly larger magnitudes than the instantaneous remote responses, suggesting that the timescale of the intraseasonal oscillation may be better defined than the spatial scale.

The enhanced convection in the Indian Ocean and west Pacific is preceded by local warm SST anomalies and followed by local cold SST anomalies. At the time of the enhanced convection in the Indian Ocean, there are warm SST anomalies in the west Pacific. The location and sign of these anomalies are consistent with the proposed coupled mechanism for the intraseasonal oscillation; however, the magnitudes of these anomalies are smaller than those observed in individual events and in the composites of Shinoda et al. (1998). The composite surface flux anomalies are also smaller than those observed in individual events and the composite anomalies of Shinoda et al. (1998), who found SWF anomalies of 25 W m⁻², LHF anomalies of 40 W m⁻² in the west Pacific, and SST anomalies of between 0.2° and 0.35°C. The composites of Shinoda et al. (1998) are based on only 10 events, which may account for some of the discrepancies in the magnitude of the anomalies. Their composites also take account of the phase speed of each event, which will also tend to give larger anomalies.

In the west Pacific, the anomalous LHF and SWF contribute about equally to the warming of the SST prior to the enhanced convection and cooling of the SST following it. In the Indian Ocean, the largest component of the negative surface heat flux comes from the reduced shortwave radiation that is associated with the enhanced convection, but because of the different phases of the SWF anomalies and the LHF anomalies, both contribute significantly to the net surface heat flux. The relative strengths of these two components of the surface heat flux are slightly different from those determined by Shinoda et al. (1998), who found that the negative LHF and SWF anomalies in the Indian Ocean were comparable, whereas the LHF anomalies in the west Pacific were slightly larger than the SWF anomalies.

The composites have highlighted some differences between the convectively active phase of the intraseasonal oscillation in the Indian Ocean and west Pacific. For enhanced convection in the Indian Ocean, there is a large region of easterly wind stress anomalies to the east. However, for convection in the west Pacific, there is no such response to the east. The enhanced convection in the west Pacific is associated with suppressed convection in the Indian Ocean; however, for enhanced convection in the Indian Ocean, there is only weak suppression of the convection in the west Pacific. This asymmetry suggests that the suppression of the convection in the Indian Ocean may be partly a local thermodynamic response to the previously enhanced convection in the Indian Ocean rather than a dynamical response to the convection in the west Pacific.

The longitudinal scales of about 60° for the SST and surface flux anomalies are similar to those of the convection, as are the westerly wind stress anomalies. However, the easterly wind stress anomalies associated with the enhanced convection in the Indian Ocean extend for about 120° across the western and central Pacific. This asymmetry is also found by Shinoda et al. (1998) in their composites and also in studies of the atmospheric circulation associated with the intraseasonal oscillation (e.g., Hendon and Salby 1994). The meridional scale of the surface flux anomalies is slightly smaller than the scale of the OLR anomalies.

In summary, the results of this comprehensive analysis, using 15 years of data, have demonstrated that there is a robust relationship between the tropical atmosphere and the ocean on intraseasonal timescales. In particular, they have shown that coherent relationships between atmospheric convection, surface fluxes, and SST exist on intraseasonal timescales in the Indian Ocean, Maritime Continent, and west Pacific regions of the Tropics. Qualitatively, the relationship between the convection
and the surface fluxes is the same in the Indian Ocean and west Pacific, although there are small variations in the timing of the westerly wind stress anomalies in the two basins. The relationship is robust from year to year, including both phases of ENSO, although during the El Niño years, the region over which the relationship holds extends farther east into the central Pacific, consistent with the eastward extension of the warm pool and westerly winds. The spatial scale of the anomalies is large, about 60° of longitude, which is consistent with the scale of the intraseasonal oscillation. The magnitudes of the composite surface flux and SST anomalies are consistent with mixed-layer depths appropriate to the Indian Ocean and west Pacific regions, when applied over the timescale of the intraseasonal oscillation. Although the magnitude of the composite SST perturbations is small, on an individual basis, it can be as large as 0.5°–1°C, a significant departure when the background SST is 28°–29°C. The spatial and temporal characteristics of the surface flux and SST perturbations are consistent with the surface flux variations associated with the atmospheric convection forcing the ocean and are consistent with the coupled mechanism proposed by Flatau et al. (1997). The impact that such SST anomalies may have on the convection on intraseasonal timescales needs to be tested within a modeling framework, and this will form the next part of the research.

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REFERENCES


Gibson, J. K., P. Kalberg, and S. Uppala, 1996: The ECMWF ReAnalysis project. ECMWF Newsl. 73, ECMWF, Shinfield Park, Reading, United Kingdom, 7–17.


