Satellite and Buoy Observations of Boreal Summer Intraseasonal Variability in the Tropical Northeast Pacific

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ABSTRACT

Tropical intraseasonal variability in the eastern North Pacific during June–September of 2000–03 is analyzed using satellite and buoy observations. Quick Scatterometer ocean vector winds and the Tropical Rainfall Measuring Mission (TRMM) precipitation indicate that periods of anomalous surface westerly flow over the east Pacific warm pool during a summertime intraseasonal oscillation (ISO) life cycle are generally associated with an enhancement of convection to the east of 120°W. An exception is a narrow band of suppressed precipitation along 8°N that is associated with negative column-integrated precipitable water anomalies and anticyclonic vorticity anomalies. Periods of surface easterly anomalies are generally associated with suppressed convection to the east of 120°W. Summertime wind jets in the Gulfs of Tehuantepec and Papagayo exhibit heightened activity during periods of ISO easterly anomalies and suppressed convection. Strong variations in east Pacific warm pool wind speed occur in association with the summertime ISO. Anomalous ISO westerly flow is generally accompanied by enhanced wind speed to the east of 120°W, while anomalous easterly flow is associated with suppressed wind speed. Intraseasonal vector wind anomalies added to the climatological flow account for the bulk of the wind speed enhancement in the warm pool during the westerly phase, while the easterly phase shows strong contributions to the negative wind speed anomaly from both intraseasonal vector wind anomalies and suppressed synoptic-scale eddy activity. An analysis using Tropical Atmosphere Ocean buoys and TRMM precipitation suggests that wind–evaporation feedback is important for supporting summertime intraseasonal convection over the east Pacific warm pool. A statistically significant correlation of 0.6 between intraseasonal latent heat flux and precipitation occurs at the 12°N, 95°W buoy. Correlations between precipitation and latent heat flux at the 10°N, 95°W and 8°N, 95°W buoys are positive (0.4), but not statistically significant. Intraseasonal latent heat flux anomalies at all buoys are primarily wind induced. Consistent with the suppressed convection there during the ISO westerly phase, a negative but not statistically significant correlation (~0.3) occurs between precipitation and latent heat flux at the 8°N, 110°W buoy.

1. Introduction

It has been well documented that the tropical intraseasonal oscillation (ISO) forces coherent variations in wind and convection over the eastern North Pacific warm pool during boreal summer (e.g., Knutson and Weickmann 1987; Kayano and Kousky 1999; Maloney and Hartmann 2000; Higgins and Shi 2001; Maloney and Esbensen 2003, hereafter ME03; de Szoeke and Bretherton 2005; Raymond et al. 2006). Periods of anomalous westerly flow at 850 hPa are associated with enhanced convection over the warm pool, whereas anomalous easterly flow is associated with suppressed convection (e.g., ME03). These convection and flow variations are associated with a strong modulation of tropical cyclones and synoptic-scale wave activity (e.g., Molinari et al. 1997; Molinari and Vollaro 2000; Maloney and Hartmann 2000, 2001; Higgins and Shi 2001). The anomalous surface flow has a notable southerly component during ISO convectively enhanced phases that may be at least partially explained through Ekman balance associated with anomalous low pressure over the warm pool (ME03; de Szoeke and Bretherton 2005). The large-scale ISO circulation in the east Pacific appears to be amplified through interactions with east
Pacific warm pool convection, as is suggested by an energy budget analysis using gridded reanalysis fields (e.g., ME03).

How convection is enhanced during periods of anomalous southwesterly flow over the warm pool (and suppressed during periods of anomalous northeasterly flow) remains a topic of intense investigation. Using reanalysis fields ME03 showed that ISO surface southwesterly anomalies accompany enhanced latent heat fluxes and convection, suggesting that wind–evaporation feedback may support east Pacific ISO convection. Surface moisture convergence anomalies, which are to a large extent fractionally induced, also accompany periods of enhanced convection, and may be another important moist static energy source (ME03). Maloney and Esbensen (2005, hereafter ME05) used a general circulation model that produces realistic east Pacific intraseasonal variability to examine the influence of wind–evaporation feedback on the ISO. When surface fluxes were fixed at their climatological seasonal cycle, effectively removing wind–evaporation feedback, east Pacific intraseasonal convective variability became significantly weaker and less realistic. Data collected during the East Pacific Investigation of Climate (EPIC2001; Raymond et al. 2004) field program also suggest that enhanced surface entropy fluxes associated with periods of southwesterly flow provide a major energy source for east Pacific convection (Raymond et al. 2003, 2006). Lateral entropy flux variations during EPIC2001, which were indicative of boundary layer moisture convergence, appeared to be less important than evaporative fluxes for forcing the boundary layer moist energy budget and convection. Back and Bretherton (2005) did a more general study of the relationship between satellite-derived surface wind speed and precipitation for the Pacific intertropical convergence zone (ITCZ) and found a strong correlation between the two, particularly in regions of sufficiently high free-tropospheric relative humidity. Back and Bretherton (2005) suggest that moisture convergence forced by convection acts to augment column moist static energy above that initially provided by anomalous surface fluxes.

We will use Tropical Atmosphere Ocean (TAO; McPhaden et al. 1998) buoy data and satellite vector wind, precipitation, and column precipitable water fields to analyze the east Pacific boreal summer variability associated with the ISO. Up to now, most analyses of east Pacific ISO variability have come through use of reanalysis data (e.g., ME03), or have been derived using the relatively short data records of field campaigns such as EPIC2001 (e.g., Raymond et al. 2006). We will study the east Pacific ISO using 4 yr of satellite and buoy data during 2000–03. This is the period during which the 95°W TAO buoy line was augmented by warm pool buoys at 10°N and 12°N for the enhanced monitoring phase of EPIC2001. The buoys along 95°W were also augmented during 2000–03 with instrument enhancements, including radiometers to measure shortwave and longwave radiation (Cronin et al. 2002). Cronin et al. (2006) recently showed that reanalysis surface radiative fluxes have significant biases in the east Pacific relative to buoy data.

This study examines whether wind–evaporation feedback contributes to convective variability during summertime ISO events in the east Pacific warm pool. Wind speed and precipitation derived from satellite observations are used in conjunction with buoy latent heat fluxes to quantify the wind–evaporation feedback and its relationship to ISO convection. We also assess the contributions of surface divergence and tropospheric dryness to ISO convective variability, particularly where wind–evaporation feedback breaks down. Finally, high-resolution scatterometer ocean vector wind fields suggest a possible role for the ISO in modulating Central American wind jets, an analysis that is more difficult when using relatively coarse-resolution model analysis products (particularly reanalysis fields, e.g., ME03). Recent studies have found strong ISO variability signals in global and east Pacific scatterometer winds (Arguez et al. 2005; Searcy and Raymond 2005).

Section 2 describes the buoy and satellite data products used in the study and the ISO index used for regression and composite analysis. Section 3 presents an analysis of summertime wind–evaporation feedback in the east Pacific warm pool using satellite and buoy observations. Section 4 examines the roles of convergence and free-tropospheric water vapor in modulating boreal summer east Pacific ISO convection. Section 5 discusses modulation of the Tehuantepec and Papagayo jets of coastal Mexico and Central America by the boreal summer ISO. Section 6 provides conclusions.

2. Data and ISO index

a. Global ISO index

We use a global ISO index to conduct a regression and composite analysis of June–September east Pacific ISO variability. This index was previously developed by Maloney and Hartmann (1998) and Maloney and Kiehl (2002) (and described in ME03), and we provide only a brief description of it here. Equatorial (5°N–5°S averaged) 850-hPa zonal winds from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kalnay et al.
reanalysis are bandpass filtered to 30–90 days during 1979–2004 at all equatorial longitudes. An empirical orthogonal function (EOF) analysis is then conducted that produces a leading quadrature pair of EOFs that explains eastward-propagating ISO variability. These leading EOFs explain over 50% of the variance of intraseasonal 850-hPa equatorial zonal wind. The principal components of the two leading EOFs are linearly combined to form a time series that describes global ISO variability, and results in the index we use here for the regression and composite analysis. Regression onto local east Pacific intraseasonal precipitation and wind time series produces very similar results to those derived using this global ISO index, and so our analysis does not appear to be sensitive to the ISO index used.

b. TAO buoy data

We use TAO (McPhaden et al. 1998) moored buoy data at four locations: three buoys along 95°W at 8°, 10°, and 12°N, and the buoy at 8°N, 110°W. These buoy locations are the best-suited TAO mooring sites for studying intraseasonal precipitation and flux variability in the east Pacific warm pool. The buoys at 10°N, 95°W and 12°N, 95°W were deployed during 2000–03 for use in the enhanced monitoring phase of EPIC2001. All buoys along 95°W were also equipped with enhanced instrument packages for EPIC2001 (Cronin et al. 2002). In addition to the standard measurements of wind speed, direction, air temperature, relative humidity, 1-m ocean temperature, and other subsurface ocean data, radiometers were added to the buoys along the 95°W line to measure shortwave and longwave radiation. Rainfall measurements were also part of the enhancements made at 95°W, although the rainfall records have too many gaps to be useful for the analysis presented here.

Surface latent heat and sensible heat fluxes are calculated using version 3.0 of the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment flux bulk algorithm (Fairall et al. 2003). We use 10-min-averaged wind speed, air temperature, relative humidity, and 1-m ocean temperature to compute latent and sensible heat fluxes. Daily averaged flux fields were then created from these 10-min-averaged fields. When shortwave and longwave radiometer data are available for a buoy, we include cool skin and warm layer calculations in our estimates of sensible heat flux and evaporation. The buoy at 12°N, 95°W has the most extensive June–September radiometer data of the sites we analyze (about three summers worth). We did a sensitivity test to determine whether exclusion of the cool skin/warm layer calculation significantly alters our estimates of intraseasonal flux variability there, and we found very little sensitivity. Thus, we feel comfortable comparing intraseasonal flux variability along the 95°W line to that at 8°N, 110°W, a buoy location with no radiometer data to enable a cool skin/warm layer calculation in the estimation of sensible and latent heat fluxes.

c. Satellite fields

1) Quick Scatterometer Ocean Vector Winds

The SeaWinds scatterometer on the National Aeronautics and Space Administration (NASA) Quick Scatterometer (QuikSCAT) satellite retrieves surface wind stress using the backscatter of microwave radiation from the ocean surface from multiple azimuth and incidence angles (Chelton and Freilich 2005). Surface wind is estimated as the “equivalent neutral stability wind vector,” the wind vector that would produce the observed wind stress if the atmospheric boundary layer were neutrally stratified. The effective resolution of the retrieved surface wind estimates is approximately 25 km. For the analysis presented here, the QuikSCAT vector winds were downloaded on a 0.25° × 0.25° grid in daily ascending and descending swaths from Remote Sensing Systems of Santa Rosa, California (more information available online at http://www.remss.com). Because rain contamination of the backscatter signal can occur, we label QuikSCAT data as missing when radiometer data indicate that rain is occurring within, or adjacent to, the 0.25° × 0.25° scatterometer grid cell.

Wind speed, divergence, and vorticity were calculated in swath from the vector wind components before further processing. Three-day mean fields were then constructed for the vector wind, wind speed, divergence, and vorticity. Linear interpolation was used to fill any remaining data gaps. One exception is that in the analysis of synoptic wind speed variance described below, the unfiltered daily fields were retained in lieu of 3-day averages in order to derive synoptic eddy wind components before further filtering. Further application-dependent processing of scatterometer data in the spatial and temporal domains is described below.

We use scatterometer data during June–September of 2000–03 to coincide with the period of EPIC2001 enhanced monitoring associated with the 95°W TAO array. An analysis that includes scatterometer data from the summer of 2004 was also conducted, but produced very similar results to those presented here for the 2000–03 period. These 2004 results will therefore not be further discussed.
2) Tropical Rainfall Measuring Mission precipitation

Daily averaged precipitation fields from the Tropical Rainfall Measuring Mission (TRMM) level 3B-42, version 5, product were downloaded on a 1° x 1° grid from the Goddard Space Flight Center Distributed Access Archive System (available online at http://trmm.gsfc.nasa.gov/). Data during 2000–03 are used to coincide with the period of EPIC2001 enhanced monitoring. The TRMM product is derived from a merged microwave and infrared precipitation retrieval designed for tropical rainfall studies (e.g., Huffman et al. 2001). Given the predominance of convective processes for driving ISO-related precipitation variability, we will use the terms “convection” and “precipitation” interchangeably throughout this study.

3) Special Sensor Microwave Imager column-integrated water vapor data

We use Special Sensor Microwave Imager (SSM/I) column-integrated water vapor data during 2000–03 that are obtained on a 0.25° x 0.25° grid from Remote Sensing Systems (available online at http://www.ssmi.com/). Data were downloaded in 3-day-average format. The algorithm used to retrieve precipitable water data from SSM/I is documented by Wentz and Spencer (1998).

3. Analysis of wind speed and latent heat flux

a. Mean June–September wind and precipitation

We will briefly discuss satellite-derived climatological June–September surface wind and precipitation fields over the east Pacific. A more in-depth analysis of summertime east Pacific climatological wind and precipitation fields can be found in a recent analysis by Xie et al. (2005).

Figure 1 shows mean TRMM precipitation and QuikSCAT surface vector winds for June–September of 2000–03. As has been extensively documented in previous studies, the main axis of the ITCZ occurs near 9°N except in the far eastern Pacific, where the region of convection flares toward the Mexican and Central American coasts between 110° and 90°W. This northward expansion of ITCZ convection between 90° and 110°W is a center of strong summertime intraseasonal convective variability in the east Pacific, as will be described below. The strong maximum in mean precipitation near Panama has also been well documented in previous studies (e.g., Mapes et al. 2003), and is associated with strong diurnal variability caused by orographic forcing. A minimum in precipitation is also apparent over the cold waters of the oceanic Costa Rica Dome near 10°N, 90°W, a feature associated with the substantial wind stress curl caused by the Papagayo jet (Chelton et al. 2000a; Xie et al. 2005).

QuikSCAT vector winds indicate that the average June–September cross-equatorial flow between 120°W and the coast becomes an east–west band of surface southwesterly flow that is centered near 8°N. It has been suggested that this band of mean southwesterlies is important for producing the strong relationship between latent heat flux and convective variability over the east Pacific warm pool region (ME03). The collocation of a southwesterly anomaly with this basic-state flow can lead to enhanced wind speed. If latent heat flux variability in this region is dominated by wind-induced variations (which appears to be the case), then increased surface latent heat flux can result from the enhanced southwesterly flow (e.g., ME03). Mean easterly flow generally dominates to the west of 120°W and...
over the Caribbean Sea, where imposition of a southwesterly wind anomaly would imply decreased surface wind speed and suppressed latent heat flux.

b. ISO precipitation, wind, and wind speed

We now analyze wind and precipitation anomalies over the east Pacific warm pool during an ISO life cycle. QuikSCAT vector wind, wind speed, and TRMM precipitation fields were first bandpass filtered to 20–100 days using a linear nonrecursive filter before lag regression onto the global ISO index. Regressed fields were scaled by a one standard deviation value of the ISO index, representing a typical amplitude for an ISO event. The results presented here exhibit little sensitivity to reasonable variations in the size of the bandpass window used to filter data. For example, a 30–90-day bandpass filter produces very similar results to those shown here.

Results from the linear regression analysis are displayed in Fig. 2. Day −15 approximately corresponds to the peak suppressed phase of convection (and easterly anomalies) over the east Pacific warm pool, and day +10 corresponds to the peak phase of enhanced convection (and westerly anomalies). Days +15 through +30 resemble days −10 through +5 but with anomalies of opposite sign, and are therefore not shown here.

Northeasterly wind anomalies are generally associated with suppressed convection over the east Pacific...
warm pool, with enhanced convection to the west of 110°W (day −15). This enhanced convection moves eastward as time progresses (days −10 to +5), and eventually results in the enhanced phase of ISO convection over the warm pool at day +10, accompanied by southwesterly surface wind anomalies. Interestingly, a narrow band of suppressed convection occurs along 8°N during periods of strong southwesterly anomalies, and this narrow band of suppressed convection is out of phase with positive convective anomalies to the north. Possible reasons for this band of suppressed convection will be discussed below, as will the statistical significance of warm pool precipitation anomalies (Fig. 6).

The satellite-derived precipitation and wind anomalies during a boreal summer ISO life cycle are broadly consistent with those derived using reanalysis data and coarser-resolution precipitation and outgoing longwave radiation products (e.g., ME03). Here, as in previous analyses, enhanced precipitation over the east Pacific warm pool is generally associated with westerly anomalies, and suppressed convection is associated with easterly anomalies. However, the high-resolution products we use allow interesting features on small spatial scales to become evident. The band of suppressed convection along 8°N extending eastward from 120°W at day +10 is not apparent in other studies, and will be shown below to be associated with narrow features in the divergence and vorticity fields. We will also show that this narrow region of suppressed precipitation provides an interesting counterexample to previous findings that suggest wind–evaporation feedback supports ISO convection in the east Pacific warm pool (e.g., ME03; Raymond et al. 2006; ME05). Apparently, such a relationship may not hold everywhere in the warm pool.

QuikSCAT wind speed anomalies regressed onto the ISO index are shown in Fig. 3. During periods of suppressed convection and anomalous east-northeasterly flow (e.g., day −15), wind speed is generally suppressed to the east of 120°W, and enhanced to the west of 120°W. Convectively enhanced phases (e.g., day +10) are associated with an enhancement of wind speed to the east of 120°W, and a suppression of wind speed to the west of 120°W. If latent heat flux variability is primarily controlled by variations in wind speed during east Pacific ISO events, as suggested by previous studies (e.g., ME03), then enhanced wind speed over the warm pool during westerly phases suggests increased latent heat flux (e.g., day +10). Suppressed latent heat fluxes would occur to the west of 120°W during the westerly phase. These relationships are thus qualitatively consistent with the pattern of latent heat flux variability during ISO events obtained in previous work using the NCEP–NCAR reanalysis (ME03).

Closer scrutiny of the wind speed anomalies during peak enhanced and suppressed phases in Fig. 3 indicates more complex structure than has been previously suggested. A striking feature at day +10 is the double maximum in positive wind speed anomalies with one maximum centered along 10°N between 90° and 120°W, and another secondary maximum closer to the Mexican coast.

To explain the double maximum in ISO wind speed variability, we will take a phenomenological approach, focusing on the relative importance of ISO vector wind changes and the modulations due to changes in synoptic-scale eddy activity. In particular, we will determine the portion of the wind speed anomaly that is due solely to ISO vector wind anomalies, and the portion to which intraseasonal anomalies in eddy wind variance provide some contribution.

We begin with the daily averaged wind components from QuikSCAT, and do three distinct calculations. 1) We derive a total intraseasonal wind speed anomaly by applying a 20–100-day bandpass filter to the magnitude of the daily averaged wind vector. 2) We then derive the intraseasonal wind speed anomaly due solely to ISO vector wind anomalies. A low-pass filter is applied to the daily averaged wind components to retain periods of greater than 20 days, effectively removing eddy variability. A 20–100-day bandpass filter is then applied to the magnitude of these filtered vector components. 3) The difference between wind speed anomalies in 1) and 2) is computed. This third calculation indicates the portion of the ISO wind speed anomaly to which anomalies in eddy variance provide some contribution. The analysis shows that most of the eddy variance contribution comes from eddies with time scales of 10 days or less, a period band associated with easterly waves, tropical depression–type disturbances, and tropical cyclones. We attempted several other methods of partitioning the wind speed field into eddy and ISO vector wind components as well. Each partition depends upon assumptions that are difficult to justify in general, but they produce results consistent with the three-part method described above.

After decomposing the wind speed anomalies into ISO vector wind and eddy-related portions, we examine their relative contributions during the convectively suppressed and enhanced phases of the ISO by composite analysis. A primary motivation for doing a composite analysis here as opposed to a regression analysis is to determine how well the linear regression in Fig. 3 characterizes anomalies during both the positive and negative phases (i.e., the linearity of the ISO events). For the convectively suppressed phase, we first isolate minima in the ISO index that exceed one standard de-
violation from zero, for a total of eight events during June–September of 2000–03. Then, fields 10 days after the minima are averaged across all events to form a composite for the convectively suppressed phase. A related composite analysis can be done for the enhanced phase of the ISO using strong positive deviations of the index, consisting of a total of 10 events.

Composites of the total wind speed anomaly (Fig. 4a), the wind speed anomaly due to ISO vector wind anomalies (Fig. 4b), and the wind speed anomaly related to eddy variability (Fig. 4c) are displayed for the convectively suppressed phase. A prominent spatial separation exists between the local wind speed minimum near the Mexican coast (14°–18°N) and that between 8° and 10°N (Fig. 4a). Examination of Figs. 4b,c indicate that ISO vector wind anomalies dominate wind speed anomalies along 10°N, whereas suppression of synoptic eddy variance appears necessary to explain the negative wind speed anomalies along the Mexican coast. Previous studies have suggested that this suppression of eddy activity during the ISO easterly phase may be due to weakened barotropic energy conversion and suppressed convection (e.g., Maloney and Hartmann 2001).

Our results show that the ISO easterly phase is primarily responsible for the double maxima in wind speed anomalies shown in the linear regression in Fig. 3. Strong easterly anomalies along 12°–14°N and east of 120°W result in vector winds of larger magnitude than in climatology (Fig. 4b), because the easterly anomalies...
are collocated with weak westerly climatological winds (see Fig. 1b). Suppressed eddy variance is still large enough to produce negative wind speed anomalies between 12° and 14°N. This nevertheless results in dual extrema in suppressed wind speed during the easterly phase, with one center of suppressed wind speed located near 10°N, and another near the coast of Mexico.

A comparable composite analysis for periods of ISO westerly flow and enhanced convective activity is shown in Fig. 5. Our analysis suggests that ISO vector wind anomalies dominate the enhancement of wind speed that occurs during ISO westerly/convectively enhanced phase. An enhancement of surface wind speed due to ISO vector wind anomalies occurs in a band centered between about 8° and 10°N (Fig. 5b), approximately coincident with the band of mean surface westerly flow shown in Fig. 1b. When the influence of eddies on time scales less than 20 days is considered, an increase in wind speed occurs over the warm pool just to the south of Mexico (Fig. 5c). The increase in eddy activity over the warm pool is consistent with the increase in synoptic-scale wave and tropical cyclone activity that occurs there during ISO westerly phases (e.g., Molinari and Vollaro 2000; Maloney and Hartmann 2000, 2001). However, the enhancement in east Pacific wind speed due to eddies during the ISO westerly phase appears to be relatively modest compared

**Fig. 4.** (a) Composite intraseasonal wind speed anomaly for the ISO easterly (convectively suppressed) phase. (b) The wind speed anomaly due to ISO vector wind anomalies. (c) The difference between (a) and (b), representing the portion of the wind speed anomaly that is related to intraseasonal variations in eddy variance. Composite ISO vector wind anomalies are also shown in (a)–(c). The reference wind vector (m s⁻¹) is shown at the bottom right. Units of the color bar are in m s⁻¹.

**Fig. 5.** Same as in Fig. 4, but for the ISO westerly (convectively active) phase.
with that associated with ISO vector winds. Furthermore, the magnitude of wind speed anomalies due to suppressed eddy activity over the warm pool during the ISO easterly phase (Fig. 4c) is higher than that associated with eddy enhancement during the ISO westerly phase (Fig. 5c). A comparison of eddy variance also verifies that the magnitude of eddy suppression during the ISO easterly phase is significantly higher than the eddy enhancement during the ISO westerly phase (not shown here).

Because we remove QuikSCAT data when rain is detected, we performed additional analysis to ensure that the smaller-amplitude eddy variance anomalies during the ISO westerly phase as compared with the ISO easterly phase are not simply due to preferential data removal during the westerly phase. First, we applied the analysis described above to winds from the TAO buoys, and obtained a similar result to that derived using QuikSCAT. Because eddies over the warm pool likely exhibit strong convective coupling, we also examined eddy precipitation variance using TRMM. These data also indicate greater suppression of eddy variance during the ISO easterly phase than eddy enhancement during the ISO westerly phase, confirming the QuikSCAT results described above.

c. TAO buoy latent heat fluxes

The TAO buoys at 8°N, 95°W; 10°N, 95°W; 12°N, 95°W; and 8°N, 110°W are relatively well suited to help characterize the relationship between east Pacific latent heat flux and precipitation anomalies associated with the ISO. While not in the heart of the strongest convection anomalies in the east Pacific warm pool region during ISO events, these buoys are found within regions of significant TRMM precipitation anomalies (Fig. 6). Figure 6 shows the locations of buoys we use in this study, regressed 20–100-day precipitation anomalies for days 0, +5, +10 of an ISO event, and regions where regressed precipitation anomalies are significantly different from zero at the 90% confidence level assuming three independent samples per summer (~40 days or one ISO event per independent sample). The correlation coefficient was used in conjunction with the t statistic to determine statistical significance. Precipitation anomalies at the 95°W buoys appear to peak in time slightly before those just off the Mexican coast. Positive wind speed anomalies occur at these 95°W buoy locations at the time of the maximum in precipitation there (not shown).

Interestingly, at the same phase lags (0, +5, and +10 days) associated with anomalous southwesterly flow and enhanced wind speed to the east of 120°W, the 8°N, 110°W buoy is associated with suppressed convection. This relationship suggests a negative correlation between intraseasonal precipitation and latent heat flux there, opposite to the relationship observed over most of the warm pool. We now analyze the relationship between intraseasonal latent heat flux and precipitation anomalies at the buoy locations shown in Fig. 6 to infer the importance of wind–evaporation feedback for supporting east Pacific intraseasonal convective variability.

Figure 7 shows daily averaged latent and sensible
heat fluxes derived from the four buoys shown in Fig. 6. The summertime period we analyze is indicated in white. The time series at the buoys indicate that latent heat flux anomalies clearly dominate the total surface flux variability at these four locations, and thus sensible heat fluxes will not be discussed further in this paper. Figure 7 also shows that long data gaps often occur at the buoys. The 12° N, 95° W buoy has the most extensive June–September data coverage of the four buoys during 2000–03, with approximately three summers of usable flux data (2001, 2002, and 2003). Approximately two summers of data exist at the 10° N, 95° W and 8° N, 110° W buoys, with a somewhat shorter record at the 8° N, 95° W buoy. Results derived below will not be statistically significant at these later three buoys, and will merely be suggestive of the relationship between latent heat flux and precipitation at those sites. However, the wind speed anomalies from QuikSCAT when compared with TRMM precipitation support the correlations found there (Fig. 3). The 12° N, 95° W buoy provides a statistically significant result, however. It is interesting that flux variability at the 12° N, 95° W buoy appears to be somewhat more vigorous than at the other sites. One possible reason for this behavior is that the 12° N, 95° W buoy often falls under the influence of the Tehuantepec jet (e.g., Chelton et al. 2000a,b). The relationship between the Central American wind jets and the boreal summer ISO is explored further in section 5.

Daily averaged TRMM gridded precipitation was interpolated to the four buoy sites and then converted to an equivalent energy flux in watts per meters squared. A bandpass filter of 10–100 days was then applied to both precipitation and the buoy latent heat fluxes. After filtering, both fields are approximately normally distributed about zero. Because the buoy record is relatively data sparse, we use a broader 10–100-day filter here in order to maximize degrees of freedom, although we use a relatively conservative method to determine the statistical significance of the relationship between precipitation and latent heat flux (as discussed below). The correlation between latent heat flux and precipitation is higher when using a more narrowly defined 20–100-day bandpass filter.

Scatterplots of 10–100-day precipitation versus latent heat during June–September are shown for the 95° W buoys in Fig. 8. The linear least squares fit is shown, that was constructed using all available filtered data points. Binned averages and 90% confidence limits on those averages are also shown. Bins are constructed of width 20 W m$^{-2}$ and centered on −30, −10, +10, and +30 W m$^{-2}$. Every fourth day is plotted in gray, although the number of independent samples for each bin is somewhat less than shown. Independent samples are determined by assuming that each ISO event spans 40 days. As done in ME03, an individual ISO event is broken into eight phases that spans the entire range of latent heat flux anomalies shown in Fig. 8. Each event in our ISO index has duration of one wavelength (≈40 days). Phase 5 is assigned to the peak of the index. Phases 3 and 7 are assigned to the zero crossings before and after phase 5, respectively. Phase 1 is assigned to
the minimum before phase 5, and phase 9 (phase 1 of
the next event) is the minimum after phase 5. Phases 2,
4, 6, and 8 fill in halfway between these other points.
Adjacent ISO phases are thus approximately 5 days
apart. We assume in the calculation of degrees of free-
dom that each bin cannot contain more than one
sample from the same ISO phase, or from adjacent ISO
phases. In practice, this method mandates that indepen-
dent samples within each bin must be more than 10
days apart.

The slope of the least squares fit and the correlation
coefficient are shown on the lower-right corner of the
plot. Degrees of freedom for correlation statistics were
calculated by assuming three independent samples per
summer, for a total of nine independent samples at the
12°N, 95°W buoy.

A significant correlation (0.59) at the 90% confi-
dence level exists between intraseasonal precipitation
and latent heat flux at the 12°N, 95°W buoy (Fig. 8a).
Binned averages at 12°N, 95°W also appear to be statis-
tically different from zero for all four of the bins we
analyzed. To determine whether the flux anomalies
were primarily wind induced, we recalculated the latent
heat fluxes used in Fig. 8b by fixing SST and boundary
layer relative humidity and temperature at their June
–September averages. Scatterplots look nearly identical
to those in Fig. 8, indicating that wind speed variations
primarily control the flux anomalies shown. These re-
sults support previous observations derived from NCEP–NCAR reanalysis fields (ME03) and the
EPIC2001 field program (Raymond et al. 2006), which
indicate a strong relationship exists between sum-
mer-time wind-induced latent heat flux variations and in-
traseasonal precipitation over the east Pacific warm
pool. The enhancement of mesoscale circulations
forced by convection itself may contribute to the posi-
tive correlation between intraseasonal latent heat flux
and precipitation (e.g., Esbensen and McPhaden 1996).
However, a calculation in which the mesoscale com-
ponent of the flow is minimized by using the magnitude
of the daily averaged vector wind as a proxy for wind
speed still indicates a comparable relationship between
intraseasonal latent heat flux and precipitation at the
12°N, 95°W buoy (correlation = 0.51, regression coef-
ficient = 4.2). Modeling results also strongly suggest
that the latent heat flux anomalies shown here have an
important role in supporting intraseasonal precipitation
variations over the east Pacific (ME05). Mesoscale en-
hancement of surface fluxes not represented by the
model in ME05 could make the wind–evaporation feed-
back even stronger.

The slope of the regression line in Fig. 8a indicates
that for each unit of latent heat flux at 12°N, 95°W,
about five units of precipitation are generated. Thus, if the ISO moisture balance is dominated by evaporation, precipitation, and moisture convergence, our results support the conclusion of Bretherton et al. (2004) that moisture convergence strongly augments the amount of precipitable water available for precipitation, even with significant forcing by surface fluxes.

The correlation between intraseasonal precipitation and latent heat flux at the 8°N, 95°W, and 10°N, 95°W buoys are 0.37 and 0.44, respectively. While these positive correlations are consistent with the relationship observed at the 12°N, 95°W buoy, the results at the 8°N, 95°W, and 10°N, 95°W buoys are not statistically significant.

Interestingly, the relationship between intraseasonal precipitation and latent heat flux anomalies at the 8°N, 110°W buoy appears to be different than that along the 95°W line (Fig. 9). While not statistically significant, the correlation at 8°N, 110°W is negative (−0.34). This relationship is consistent with that between regressed precipitation (Fig. 2) and wind speed anomalies (Fig. 3). If wind–evaporation feedback is important for supporting east Pacific ISO convection, it may not be doing so universally across the east Pacific. This does not necessarily rule out wind–evaporation feedback being a primary driver of east Pacific ISO convection; however. It was suggested by ME03 that the strongest energy conversions that amplify the large-scale anomalous ISO circulation over the east Pacific are associated with convection to the north of 12°N, between 95° and 115°W. Thus, the 8°N, 110°W buoy appears to be outside of the region of convection that is most important for the energy budget of the boreal summer east Pacific ISO. Below we will discuss possible reasons for this negative correlation between intraseasonal latent heat flux and precipitation at 8°N, 110°W.

4. Convergence and column water vapor

To provide clues as to why the intraseasonal precipitation–latent heat flux relationship varies across the east Pacific, we now examine the surface divergence and vorticity anomaly fields derived by regression onto the ISO index. Regressed vorticity and divergence anomaly fields are displayed at day +10, the enhanced convective phase of the ISO (Fig. 10). These fields can be directly compared to day +10 precipitation, wind, and wind speed anomalies shown in Figs. 2 and 3. Anomalous cyclonic vorticity occurs to the north of the axis of strongest wind anomalies, and is approximately coincident with the area of enhanced precipitation (Fig. 2). A narrow band of anticyclonic vorticity anomalies occurs to the south of the axis of maximum winds, nearly coincident with the narrow band of suppressed convection there (between 8° and 10°N).

Regions of anomalous surface convergence occur to the north of the axis of strongest wind anomalies, coincident with positive precipitation anomalies (cf. Figs. 2 and 10b). Anomalous surface convergence would suggest anomalous low pressure there, consistent with the analysis of de Szoeke and Bretherton (2005), who showed that periods of intraseasonal westerly anomalies are accompanied by anomalous low pressure to the north of 10°N. Anomalous divergence occurs to the south of the maximum wind anomalies in association with anticyclonic vorticity anomalies and suppressed convection. These results suggest that frictional divergence may help to suppress convection to the south of the axis of maximum winds during westerly phase of the ISO. ME03 used a simple Ekman layer model with the NCEP–NCAR reanalysis surface pressure field to show that frictional effects could explain most of the ISO-induced surface divergent flow in the east Pacific, although their analysis could not fully resolve some of the narrow divergence features shown here. Frictional divergence could presumably force downward motion in the lower troposphere along 8°N and cause drying, contributing to suppression of convection there. Surface divergence may thus be one contributing factor to the negative correlation between intraseasonal surface latent heat flux and precipitation at the 8°N, 110°W buoy, although anomalous surface divergence could also be a
result of suppressed convection rather than a cause. The depth of the vertical motion induced by the surface divergence anomalies cannot be determined from satellite data. Such vertical motion could presumably be relatively shallow. Raymond et al. (2006) also suggest using EPIC2001 observations that moisture convergence variations are relatively less important than surface entropy fluxes in forcing precipitation variations in the east Pacific warm pool.

Another reason for the suppression of convection at 8°N, 110°W during periods of enhanced latent heat fluxes could be a dry free troposphere. Back and Bretherton (2005) suggest that the coupling between wind speed and precipitation variations in the Pacific
tures in the Tropics are uniform to first order (e.g., Sobel and Bretherton 2000), these negative column water vapor anomalies likely correspond to negative tropospheric relative humidity anomalies. Tropospheric relative humidity was determined by Back and Bretherton (2005) to regulate the strength of the wind speed–precipitation feedback.

5. Central American wind jets

Lower-tropospheric wind jets along the Central American coast occur in association with stable planetary boundary layers. A comprehensive analysis of these jets for October 1996–June 1997 was conducted by Chelton et al. (2000a,b) using scatterometer vector winds. Wintertime cold air surges and associated high pressure over the Gulf of Mexico can trigger flow through Chivela Pass that causes a wind jet in the Gulf of Tehuantepec (e.g., Schultz et al. 1998; Steenburgh et al. 1998). Wind jets in the Gulf of Papagayo tend to occur when trade winds and accompanying meridional pressure gradients are enhanced across the Caribbean Sea and east Pacific, and appear to generally be triggered by mechanisms distinct from the Tehuantepec jet (Chelton et al. 2000a,b). However, cold fronts that penetrate sufficiently far south can trigger both the Tehuantepec and Papagayo jets in short succession (e.g., Shultz et al. 1997). Although Chelton et al. (2000a,b) suggest that the Tehuantepec and Papagayo jets are most active during boreal winter, summertime wind variability in association with these jets has not been extensively examined using scatterometer winds.

We will show here that significant boreal summer ISO events appear to modulate jets in the Gulfs of Papagayo and Tehuantepec, with the jets being preferentially active during the easterly/convectively suppressed phase of the summertime ISO. Interestingly, Waliser et al. (2005) indicate that strong chlorophyll anomalies occur in the Gulfs of Papagayo and Tehuantepec during boreal summer ISO events, signatures consistent with strong turbulent mixing by wind jets.

Figure 2 suggests that strong wind anomalies occur near the location of the Tehuantepec and Papagayo wind jets during summertime ISO events. Because anomaly fields in Fig. 2 were derived via linear regression, they provide no information on whether these wind anomalies occur preferentially during westerly (enhanced convection) or easterly (suppressed convection) ISO phases. We conduct a composite analysis during easterly and westerly ISO phases to determine whether wind jets are preferentially active during one phase versus the other. The same suppressed and enhanced ISO events used to construct Figs. 4 and 5 are used here to construct composites of averaged unfiltered winds for the 8 suppressed phase events and the 10 enhanced phase events.

Composite wind fields in Fig. 12 indicate that surface wind flow into the Gulfs of Tehuantepec and Papagayo occurs preferentially during periods of easterly flow and suppressed ISO convection. Winds in those regions during periods of westerly flow and enhanced convection are close to the June–September mean. ISO easterly phases are presumably associated with a stable boundary layer as reflected by the suppression of convection across the warm pool during those times. Anticyclonic vorticity anomalies over the Gulf of Mexico during the ISO easterly phase suggest anomalously high pressure, a condition favorable for producing a Tehuantepec jet. Trades are also enhanced across the Caribbean (not shown) and to the west of Central America during ISO easterly periods, conditions that are favorable for the Papagayo jet. The composite Tehuantepec and Papagayo jets merge with the strong easterly flow that continues to the west of 100°W.

Because Fig. 12 is a composite, it provides little information on the interdependence of the Papagayo and Tehuantepec jets during summertime ISO events. We have examined each of the eight summertime ISO events on which the suppressed phase composite is based, and its appears that six of eight ISO events are characterized by Tehuantepec and Papagayo jets being both active, one event has an active Papagayo jet, and the last event has activity in neither jet. These results suggest that the Papagayo and Tehuantepec jets may be forced by mechanisms that are more interdependent during boreal summer than during the rest of the year (e.g., Chelton et al. 2000a,b). However, our analysis of interdependence of the jets is limited because our wind fields represent 3-day averages. Because our wind jet analysis focuses specifically on the boreal summer ISO, a more comprehensive analysis of jet triggering during summertime and the interrelatedness of the Papagayo and Tehuantepec jets will need to be conducted in future work.

Figure 12 also provides some general characteristics of the unfiltered flow field during summertime ISO easterly and westerly phases. During easterly phases, the cross-equatorial flow is cut off at about 8°N, and is replaced by strong easterlies to the north of 10°N. During westerly phases, cross-equatorial flow penetrates across 10°N, with generally weak flow from 11°N to the Central American coast. Westerlies penetrate farther northward to the west of 100°W (not shown here).

6. Conclusions

Eastern North Pacific intraseasonal variability during June–September of 2000–03 is analyzed using satellite
and buoy observations. An analysis using QuikSCAT
ocean vector winds and TRMM precipitation demon-
strates that ISO westerly flow anomalies are associated
with an enhancement of summertime convection over
most of the east Pacific warm pool. A notable exception
is a narrow band of suppressed precipitation that occurs
along 8°N just to the south of the strongest westerly
wind anomalies. This precipitation minimum was not
resolved in previous ISO studies that relied on lower-
resolution data products such as outgoing longwave ra-
diation or Microwave Sounding Unit precipitation to
diagnose convective variability (e.g., Maloney and
Hartmann 2000; ME03). Widespread suppressed con-
vection occurs to the west of 120°W during the westerly
phase. Periods of ISO easterly anomalies are generally
associated with suppressed convection over the warm
pool to the east of 120°W.

Strong variations in wind speed occur over the east
Pacific warm pool in association with the summertime
ISO. Periods of anomalous ISO westerly flow are gen-
erally accompanied by enhanced wind speed to the east
of 120°W, while periods of anomalous easterly flow are
associated with suppressed wind speed. During the
westerly phase, southwesterly intraseasonal vector
wind anomalies combined with climatological south-
westerly flow account for the bulk of the wind speed
enhancement in the warm pool, with a much weaker
contribution from enhanced eddy variance. Suppres-
sion of wind speed during the ISO easterly phase has
strong contributions from both northeasterly intrasea-
sonal vector wind anomalies and suppression of eddy
activity on time scales of less than 20 days. Previous
studies have suggested that this suppression of eddy
activity may be due to weakened barotropic conversion
and suppressed convection during periods of anoma-
lous low-level easterly flow (e.g., Maloney and Hart-
mann 2001).

An analysis using TAO buoys and TRMM precipita-
tion suggests that wind–evaporation feedback is impor-
tant for supporting summertime intraseasonal convec-
tion over the east Pacific warm pool. The increase in
wind speed during periods of ISO westerly anomalies
and enhanced convection implies an increase in the
wind-induced component of latent heat flux. TAO
buoys along the 95°W line at 8°N, 10°N, and 12°N, and
the 8°N, 110°W buoy are used to examine the relation-
ship between intraseasonal precipitation and latent
heat flux in the east Pacific warm pool. A sensitivity
study indicates that the intraseasonal flux anomalies at
these buoys are primarily wind induced. A statistically
significant correlation of 0.59 between intraseasonal la-
tent heat flux and precipitation occurs at the 12°N,
95°W buoy, consistent with previous studies suggesting

![Composite Total Wind Vectors](image)

Fig. 12. Composite unfiltered wind vectors for (a) easterly and
(b) westerly ISO events. (c) June–September 2000–03 mean wind
vectors. The reference wind vector (m s⁻¹) is shown at the bottom
right.
a role for wind–evaporation feedback in supporting intraseasonal convection over the east Pacific warm pool. Correlations between precipitation and latent heat flux at the 10°N, 95°W (0.44) and 8°N, 95°W (0.37) buoys are positive, but not statistically significant.

A negative, but not statistically significant, correlation exists between summertime intraseasonal precipitation and latent heat flux at the 8°N, 110°W buoy (−0.34). QuikSCAT wind speed and TRMM precipitation fields support the negative correlation, indicating a statistically significant suppression of precipitation there during periods of enhanced ISO wind speed. This result was somewhat unexpected, given that previous results using outgoing longwave radiation and NCEP–NCAR reanalysis surface fluxes suggested a positive correlation between latent heat flux and precipitation everywhere over the warm pool to the east of 120°W (e.g., ME03). An analysis of possible reasons for the suppression of convection at 8°N, 110°W shows that periods of enhanced wind speed associated with the ISO westerly phase are associated with anomalous frictional divergence along 8°N (and implied anomalous downward motion), and anomalously low column-integrated water vapor as determined from SSM/I data. Reanalysis wind fields previously used to analyze the boreal summer ISO in the east Pacific are not able to resolve the narrow divergence and vorticity anomalies shown here in QuikSCAT data (e.g., Maloney and Hartmann 2001). Surface convergence and cyclonic vorticity anomalies occur over the warm pool to the north of 10°N during ISO westerly phases in association with enhanced convection.

Summertime wind jets in the Gulf of Tehuantepec and Gulf of Papagayo appear to be active in association with ISO easterly anomalies and suppressed convection. ISO easterly periods are characterized by enhanced trade winds across the east Pacific warm pool and Caribbean Sea, as well as anomalous surface anticyclonic vorticity over the Gulf of Mexico. The composite total wind vector in the Gulf of Papagayo and Gulf of Tehuantepec during ISO westerly phases is close to that of the June–September mean.

The slope of the intraseasonal precipitation versus evaporation relationship, as demonstrated for the east Pacific buoys in Fig. 8, may be a good diagnostic against which to test climate model parameterizations of convection. The climate model used in ME05 produces realistic intraseasonal variability across the Tropics, variability that appears to be attributable in large part to wind–evaporation feedback. Other models produce very weak intraseasonal variability across the Tropics (e.g., Slingo et al. 1996), including the standard version of the NCAR Community Atmosphere Model, version 2 (e.g., Sperber 2004), of which the ME05 model is a modified version. We intend to examine whether models that produce weak tropical intraseasonal variability are characterized by a weakened coupling (regression slope) between precipitation and latent heat flux.

Bacmeister et al. (2006) suggest that the strength of the moisture convergence feedback in a particular model can be tuned by altering the amount of convective rainfall available for reevaporation into unsaturated environmental air. More rain reevaporation cools the lower troposphere, which adjusts hydrostatically and leads to a rise in surface pressure that weakens lower-tropospheric moisture convergence. Less precipitation is thus generated per unit surface forcing. Initial experiments with the model used in ME05 indicate that the slope of the intraseasonal precipitation versus heat flux relationship can indeed be changed significantly by altering the rain reevaporation parameter (not shown here). The strength of wind–evaporation feedback on intraseasonal time scales may therefore be somewhat tunable in this model. We intend to pursue these model sensitivity experiments in future work, with possible extension to other general circulation models.

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