NOTES AND CORRESPONDENCE

On Equatorial Pacific Surface Wind Changes around 1977: NCEP–NCAR Reanalysis versus COADS Observations*

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ABSTRACT

This note compares equatorial Pacific surface wind changes around 1977 in the NCEP–NCAR reanalysis and the Comprehensive Ocean–Atmosphere Data Set (COADS) observations. Significant discrepancies are found in wind changes over the equatorial central and eastern Pacific. In the NCEP–NCAR reanalysis, the easterlies weakened over the eastern equatorial Pacific, while the southerlies strengthened over the north equatorial central Pacific. As a result, the low-level convergence and precipitation decreased over the equatorial central Pacific. These wind and precipitation anomalies are opposite to those derived from the COADS observations. Independent observations of ocean heat content are used to validate the changes in equatorial zonal wind, and it is found that the zonal slope of the thermocline in an ocean model forced by the COADS wind is more consistent with ocean observations than forced by the reanalysis wind. The equatorial wind biases are also identified in the NCEP–NCAR reanalysis climatology, reaching a maximum in the cold season from August to October. This seasonality of wind biases calls for improved representation of atmospheric boundary layer processes in climate models.

1. Introduction

Much work has been done to document and study the so-called climate regime shift that took place around 1977 over the Pacific (e.g., Nitta and Yamada 1989; Trenberth 1990; Trenberth and Hurrell 1994; Graham 1994; Zhang et al. 1997; Xie et al. 2000). Associated with this regime shift are an increase in sea surface temperature (SST) and an enhancement of convection over the equatorial central Pacific (Nitta and Yamada 1989; Graham 1994). This enhanced convection is manifested as a decrease in outgoing longwave radiation (OLR; Nitta and Yamada 1989) and an increase in station rainfall near the equatorial central Pacific (Nitta and Kachi 1994; Kachi and Nitta 1997). While earlier work is mostly confined to surface variables because of a lack of long-term upper-air observations, there are several recent studies on the upper-level and vertical structure of circulation changes due to the 1970s regime shift (Garreaud and Battisti 1999; Krishnamurthy and Goswami 2000; Goswami and Thomas 2000), based on multidecade-long reanalysis products such as the one released by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR). There have been few studies, however, to evaluate the reliability of these reanalyses in describing the interdecadal change in the Tropics.

Deficiencies of the NCEP–NCAR reanalysis were identified for mean and interannual variation of tropical Pacific surface winds (e.g., Putman et al. 2000; World Climate Research Programme 1998, 2000, 2001). Spu-

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rious "climate" shifts were also found due to changes in the observing system, which imposes limitations of the reanalysis for climate studies (Trenberth et al. 2001; Kistler et al. 2001; World Climate Research Programme 2000). The main purpose of this note is to assess the capability of the NCEP–NCAR reanalysis of describing the climate regime shift around 1977 over the tropical Pacific by comparing surface wind changes between the NCEP–NCAR reanalysis and shipboard measurements based on the Comprehensive Ocean–Atmosphere Data Set (COADS). We focus on surface winds because of their important roles in driving ocean currents and thermocline changes, their strong coupling with SST variations, and their close link with atmospheric convection. The rest of the paper is organized as follows. Section 2 briefly describes data and methods. Section 3 compares interdecadal changes in the reanalysis and COADS. Section 4 uses independent observations to validate interdecadal wind changes based on the reanalysis and COADS. Section 5 is a summary.

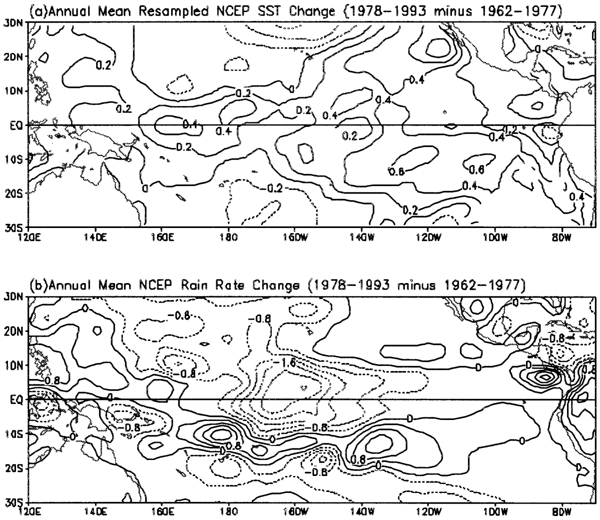

FIG. 1. (a) Difference of annual-mean SST and (b) rain rate from the NCEP–NCAR reanalysis between the periods of 1978–93 and 1962–77. The contour intervals are 0.2°C in (a) and 0.4 mm day^{-1} in (b).

2. Data and methods

The NCEP–NCAR reanalysis is based on a frozen state-of-the-art global data assimilation system (Kalnay et al. 1996), incorporating COADS surface marine data and other measurements. The variables used in this study include monthly mean surface wind velocity at 10 m, sea level pressure (SLP), SST, precipitation, and 500-hPa vertical *p* velocity, for the period from 1950 to 1997. Surface wind, SST, and precipitation are on a T62 grid with a latitude–longitude resolution of about 1.9° × 1.9°. SLP and 500-hPa vertical *p* velocity are on 2.5° × 2.5° grids.

We use the COADS (Woodruff et al. 1987) monthly mean surface winds, SLP, and SST to compare with the NCEP–NCAR reanalysis. The COADS data extend to 1997 on 2° × 2° grids. The COADS winds may include false trends toward higher wind speed introduced by gradual changes in the methods of wind measurement (Posmentier et al. 1989; Cardone et al. 1990; Ward 1992; Ward and Hoskins 1996; Clarke and Lebedev 1996, 1997). Ward (1992) suggested that, during the 40-yr period 1949–88, there is a global-mean increase in reported wind speed of about 16% that cannot be explained by trends in geostrophic winds derived from SLP. This wind speed bias varies from region to region. In the present analysis, the COADS winds are corrected using a uniform percent rate of 20% $(40\ \mathrm{yr})^{-1}$, a rate that is close to that derived by Ward (1992) in the central and eastern tropical Pacific.

In this study, difference fields between the two 16-yr periods of 1962–77 and 1978–93 are computed to describe the climate regime shift around 1977 in the Tropics. For COADS variables, the calculation for epochal means is restricted to those grid points where there are at least 48-month observations for the total of 192 months. Because the observations do not show obvious biases toward any specific calendar months or events (e.g., El Niño or La Niña), the obtained epochal means are considered to be representative of the 16-yr means. To avoid the possible effects of sampling, the NCEP–NCAR reanalysis has been resampled as follows before the calculation of epochal means. First, the reanalysis variables are interpolated to the same grid as the COADS using cubic spline. Then, at those grid points where there is no observation in the COADS, the corresponding reanalysis variable is reset as missing. This procedure is applied to monthly mean surface wind velocity, SLP, and SST. The resampled epochal difference fields are similar to those without resampling (not shown).

3. Comparison

a. SST and convection

SST shows an apparent increase after 1977 in the equatorial central Pacific and northeastern (southeastern) tropical Pacific off North (South) America (Fig. 1a), consistent with previous studies (e.g., Nitta and Yamada 1989; Graham 1994; Wang 1995; Zhang et al. 1997). The SST increase in the equatorial central Pacific is associated with enhanced convection near the date line as indicated by the decrease of OLR (Nitta and Yamada 1989). Analysis of radiosonde data showed evidence of a shift to higher values of the specific humidity in 1976/77 from the surface to 500 hPa in the equatorial belt (Gaffen et al. 1991). Rainfall at stations near the equatorial central Pacific displays an increase in the late 1970s (Nitta and Kachi 1994; Kachi and Nitta 1997). Analysis of tropical Pacific rain gauge measurements showed a trend toward increased precipitation near the

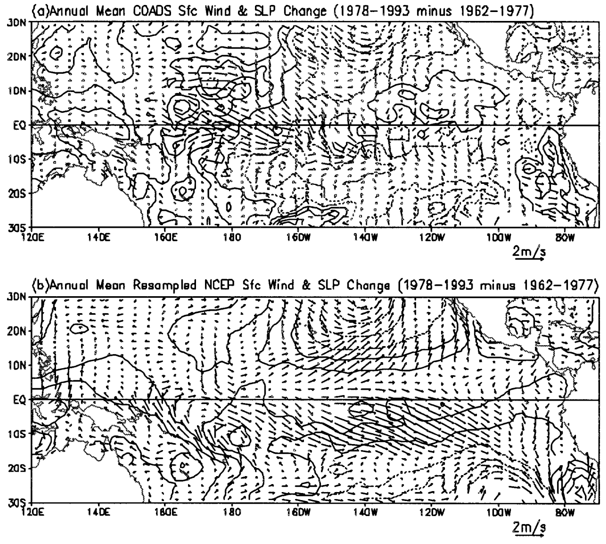

FIG. 2. Difference of annual-mean surface wind velocity and SLP (contours) from (a) COADS and (b) NCEP–NCAR reanalysis between the periods of 1978–93 and 1962–77. The scale for wind vectors is shown on the bottom of both (a) and (b). The contour intervals for SLP are 0.2 hPa.

equator and the date line during the period 1971–90 (Morrissey and Graham 1996). Graham (1994) consolidated various observations to support the notion of enhanced convection, including ocean island precipitation, high reflective clouds, and surface moisture convergence. All of these studies suggest that the convection enhancement over the equatorial central Pacific is not artificial.

In the NCEP–NCAR reanalysis, by contrast, the rain rate is reduced from 1962–77 to 1978–93 over the equatorial central Pacific (Fig. 1b), in association with a reduction of upward motion at 500 hPa (not shown). Thus, this equatorial central Pacific convection change in the NCEP–NCAR reanalysis is inconsistent with previous observations. It also appears to be in conflict with the SST increase in the equatorial central Pacific.

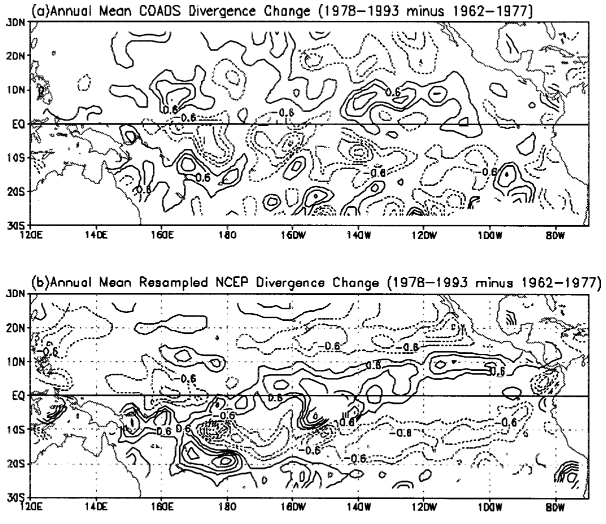

FIG. 3. Same as Fig. 2 except for surface wind divergence. The contour intervals are 0.3×10^{-6} s^{-1} with the zero contour omitted.

b. Wind and SLP

As a consistency check, we compare annual-mean surface wind and SLP changes in the corrected COADS and the NCEP–NCAR reanalysis (Fig. 2), in relation to convection changes. Over the southwestern equatorial Pacific (12°S, 180°) and northeastern tropical Pacific (30°N, 140°W), both the COADS and NCEP–NCAR reanalysis show cyclonic wind changes that are consistent with SLP change patterns. Marked discrepancies, however, are seen over the equatorial central and eastern Pacific. Over the eastern equatorial Pacific, the easterly wind increases in COADS (Fig. 2a) but decreases in the NCEP–NCAR reanalysis (Fig. 2b). Over the north equatorial central Pacific, the differential winds are northerly in COADS but southwesterly in the reanalysis.

In both COADS and reanalysis, SLP increases over the western equatorial Pacific. East of the date line, however, the SLP changes are very different between the two datasets. In COADS, the SLP decreases over the equatorial central Pacific with the largest decrease south of the equator (Fig. 2a). There are weak increases of SLP north of the eastern equatorial Pacific around 120°W. The differential pressure gradient induces anomalous westerlies (easterlies) over the equatorial central (eastern) Pacific. In the NCEP–NCAR reanalysis, SLP increases over the whole equatorial Pacific from the west to east and decreases over the subtropics in the east (Fig. 2b). This differential pressure pattern drives poleward winds over the equatorial central Pacific and westerlies over the eastern equatorial Pacific. This results in large discrepancies in eastern equatorial Pacific zonal wind changes between the reanalysis and COADS. We will discuss these zonal wind discrepancies in section 4a in more detail.

The above discrepancies in wind changes over the equatorial central and eastern Pacific lead to very different low-level convergence changes. In COADS, anomalous westerlies west of 130°W and anomalous easterlies to the east (Fig. 2a) lead to an enhanced convergence over the equatorial central Pacific (Fig. 3a), which is consistent with precipitation changes based on station observations (Gaffen et al. 1991; Nitta and Kachi 1994; Morrissey and Graham 1996; Kachi and Nitta 1997). In the NCEP–NCAR reanalysis, by contrast, the poleward anomalous winds (Fig. 2b) cause a divergence over the equatorial central Pacific (Fig. 3b) that reduces the precipitation (Fig. 1b). The decrease of convergence is also partly due to the eastward increase of anomalous westerlies up to 135°W (Fig. 2b).

4. Validation with independent observations

The wind divergence, reduced rainfall, and increased SLP over the equatorial central Pacific are mutually consistent within the NCEP–NCAR reanalysis. The same is true for COADS, except with the changes reversing signs. COADS consists of real measurements but may suffer from sampling problems. On the other hand, the NCEP–NCAR reanalysis is designed to interpolate observations in a self-consistent way but can be biased by the model errors in data-sparse regions. In this section, independent observations are used to verify the wind changes in the reanalysis and COADS. We focus on the zonal wind in the eastern equatorial Pacific (5°S–5°N, 150°–90°W) and the meridional wind in the north equatorial central Pacific (0°–10°N, 170°–130°W), which contribute to the discrepancies in divergence field between the two datasets.

a. Equatorial Pacific zonal wind

Low-frequency variations in the equatorial thermocline depth are governed to a large extent by linear wave dynamics and are very sensitive to changes in equatorial zonal wind stress (e.g., Philander 1990). Based on this consideration, we drive an ocean model with the two wind products and compare the equatorial thermocline depth changes with those of observed heat storage from the Joint Environmental Data Analysis Center (JEDAC) compilation based on ocean subsurface temperature measurements (White 1995).

We use a 2.5-layer ocean model (Wang et al. 1995) that covers the tropical Pacific from 30°S to 30°N with a horizontal resolution of 1° latitude × 2° longitude. In the control run, the model is driven by a wind climatology based on the annual mean of Sadler et al. (1987) and the NCEP–NCAR reanalysis seasonal cycle. We carry out two sensitivity experiments by adding interdecadal changes of annual-mean wind based on COADS and reanalysis, respectively. For each experiment, the model has been integrated for four years starting from initial conditions saved from a previous multiyear run. The annual-mean departure at the last year of the model integration from the control run is taken as the interdecadal oceanic response to wind changes. This quasi-steady assumption for interdecadal adjustment is valid since the equatorial Kelvin (Rossby) wave travels across the Pacific in three (nine) months.

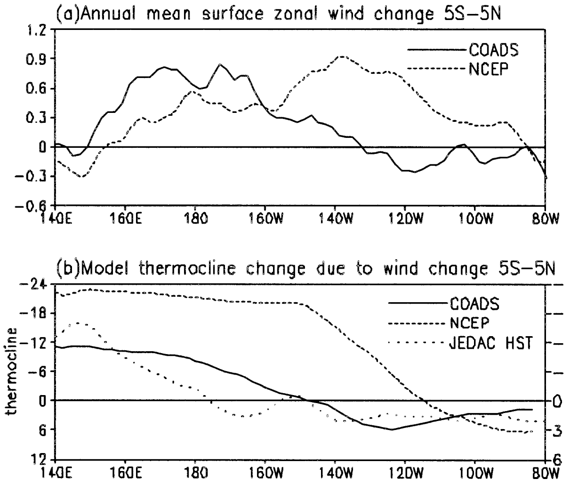

FIG. 4. (a) Annual-mean surface zonal wind change (m s^{-1}) averaged over 5°S–5°N from COADS (solid) and the NCEP–NCAR reanalysis (dashed). (b) Model annual-mean thermocline depth change (m) averaged over 5°S–5°N in response to COADS (solid) and NCEP–NCAR reanalysis (dashed) wind change and observed heat storage (HST) change (10^8 J m^{-2}) averaged over 5°S–5°N from JEDAC (dotted).

Figure 4 shows the zonal wind and thermocline depth anomalies averaged over 5°S–5°N. Both the COADS and reanalysis wind experiments reproduce the observed shoaling of the thermocline in the west (Fig. 4b), a result of zonal-mean westerly wind anomalies (Fig. 4a). In the steady response the tilt of the equatorial thermocline is tightly linked to the zonal wind stress τ_x by $g(\partial h/\partial x) = \tau_x/\rho H$, where g' is the reduced gravity, ρ is the water density, h and H are the perturbation and mean depth of the thermocline, respectively. Thus, large differences in zonal wind east of 130°W—weakly easterly in COADS versus strongly westerly in the reanalysis—lead to a large difference in the thermocline tilt there. While the experiment with the reanalysis wind forcing shows a transition from shoaling to deepening of the thermocline around 115°W, the positive thermocline perturbation levels off east of 125°W in the COADS wind experiment, in agreement with observed heat storage (dotted line in Fig. 4b). Since the ocean heat storage and surface wind observations are independent, this result suggests that westerly wind changes over the eastern equatorial Pacific in the reanalysis are probably spurious.

b. North equatorial Pacific meridional wind

In section 3b and Fig. 2, large discrepancies of meridional wind changes are found to the immediate south of the intertropical convergence zone (ITCZ). Since wind convergence in this region is tightly coupled with ITCZ convection, here we verify the COADS and reanalysis wind products against the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), which is derived from gauge observations and estimates from various satellite observations (Xie and Arkin 1997). Since CMAP data are available only after 1978, we start with a comparison of the climatological seasonal cycle based on a 21-yr period from 1979 to 1999.

Figure 5 compares the seasonal evolution of rain rate, surface convergence, and meridional wind averaged over 170°–130°W. The reanalysis rain rate and surface convergence in the ITCZ region are much weaker than in CMAP and COADS, respectively. This weakness of

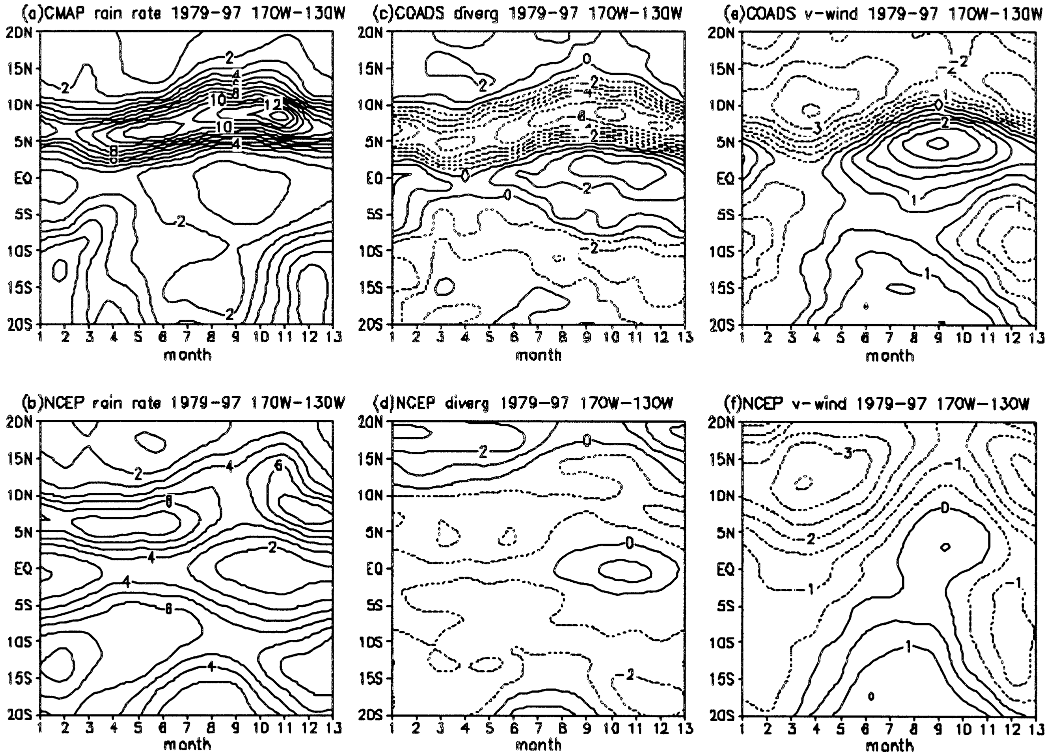

FIG. 5. Hovmöller diagrams for seasonal evolution of rain rate from (a) CMAP and (b) NCEP–NCAR reanalysis, (c) surface convergence from COADS and (d) NCEP–NCAR reanalysis, (e) surface meridional wind from COADS and (f) NCEP–NCAR reanalysis averaged over 170°–130°W for the period of 1979–97. The contour intervals are 1 mm day^{-1} for rain rate, 10^{-6} s^{-1} for divergence, and 0.5 m s^{-1} for wind.

the reanalysis was pointed out in previous studies. Through a comparison of precipitation from the NCEP–NCAR reanalysis and the Global Percipitation Climatology Project (GPCP) analysis for the period 1988–95, Janowiak et al. (1998) showed that the reanalysis ITCZ in the Pacific is too weak and not as sharply defined as in the GPCP analysis. Putman et al. (2000) indicated that the Pacific ITCZ is practically nonexistent in the reanalysis surface divergence field. We note here that the bias in the ITCZ convergence and precipitation is particularly large in the eastern Pacific cold season (August–October). While the CMAP shows intensified ITCZ rainfall in August–October, the reanalysis produces a seasonal minimum in precipitation, a result of spurious reduction in wind convergence. The COADS wind convergence, on the other hand, shows a seasonal cycle that is roughly consistent with CMAP rainfall. The discrepancies in meridional wind between the equator and ITCZ are responsible for those in wind convergence between the COADS and reanalysis. Whereas the meridional wind in this region is similar for the two products in other seasons, the cold season southerlies that converge onto the ITCZ are much stronger in the COADS than in the reanalysis (maximum speed: 3 versus 0.5 m s^{-1}) in the 170°–130°W mean.

The increased bias in the cold season in the reanalysis wind velocity and convergence may arise from the errors in the boundary layer treatment in the NCEP general circulation model (GCM), which is what the reanalysis is based on. Wallace et al. (1989) suggested that the cold-season southerly wind acceleration between the equator and 5°N is due to the enhanced vertical mixing of faster wind aloft as the air moves across the SST front from the equatorial cold tongue to the warmer water in the north. This vertical momentum mixing mechanism has been confirmed in SST-induced monthly wind variability by satellite and in situ measurements (Liu et al. 2000). In particular, based on radiosonde observations, Hashizume et al. (2002) concluded that the strong temperature inversion plays a key role in the dynamic adjustment of the equatorial boundary layer to SST changes. They show that in response to SST-induced vertical motion, the strong stratification at the inversion induces large temperature and, hence, pressure perturbations there. The realistic simulation of the inversion and vertical shear requires high vertical resolution and realistic representation of boundary layer physics, areas where climate models like the NCEP GCM are weak. It should be mentioned that version 2 of the NCEP–NCAR reanalysis provides a substantially improved representation of the Pacific ITCZ and meridional winds south of the ITCZ.

The bias of the reanalysis surface wind is present both before and after 1977. Comparatively, the bias is re-

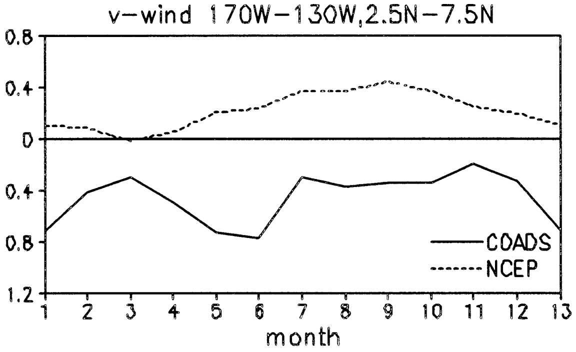

FIG. 6. Seasonal evolution of surface meridional wind difference averaged over 2.5°–7.5°N and 170°–130°W from COADS (solid) and NCEP–NCAR reanalysis (dashed) between the periods of 1978–93 and 1962–77.

duced in the recent period. Figure 6 shows differential meridional winds averaged over 2.5°–7.5°N, 170°–130°W as a function of calendar month in COADS and the NCEP–NCAR reanalysis. The reanalysis meridional wind changes are positive almost throughout the year, with the largest changes in the cold season. Thus, the cold-season southerly north of the equatorial central Pacific is enhanced after 1977. This improvement may be due to the increase of amount of data assimilated into the reanalysis because of available satellite observations. The reanalysis meridional wind changes, however, are of the opposite sign to those of COADS.

A human error was introduced in the reanalysis for the period of 1979–92 due to an incorrect assimilation of the Australian surface pressure observations (PAOS). According to estimates made at NCEP (Kistler et al. 2001), we feel this error does not affect our results.

5. Concluding remarks

Comparison of surface wind changes in the 1970s between the corrected COADS observations and the NCEP–NCAR reanalysis indicates large discrepancies in the zonal wind changes over the eastern equatorial Pacific and in the meridional wind changes over the north equatorial central Pacific. The easterlies over the eastern equatorial Pacific increase slightly in COADS, but decrease in the reanalysis. The southerlies over the north equatorial central Pacific weaken in COADS, but intensify in the reanalysis. As a result, surface wind convergence over the equatorial central Pacific decreases in the reanalysis, but increases in COADS.

We use independent measurements to verify interdecadal wind changes in the two datasets. In an ocean model, the zonal tilt of the equatorial thermocline east of 130°W is roughly consistent with independent ocean subsurface observations under the COADS wind forcing but much less so under the reanalysis forcing. By comparing the surface wind convergence field with independent CMAP precipitation, we show that the southerly winds that converge onto the ITCZ are too weak in the reanalysis over the north equatorial central Pacific, a bias that is strongest in August–October. Based on these validations and previous analyses of station rainfall and humidity measurements, we conclude that the surface divergence change in the central and the zonal wind change in the eastern equatorial Pacific in association with the 1970s climate regime shift in the reanalysis are probably spurious. The increased bias in the cold season suggests that these problems of the reanalysis may result from inadequate representation of the atmospheric boundary layer, which is stably stratified and capped by a temperature inversion, a weakness common to many atmospheric GCMs.

Surface winds are a driving force for ocean current and thermocline fluctuation, and are closely linked with atmospheric convection and circulation. Our study calls for caution in the study of tropical Pacific interdecadal variability based on the output of ocean general circulation models forced by the NCEP–NCAR reanalysis wind. Discretion is recommended for interpreting the interdecadal modulation of the monsoon–ENSO relationship based on the interdecadal changes of tropical convection and the Walker circulation derived from the NCEP–NCAR reanalysis.

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