

Double ITCZs

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Abstract. This study examines where and when double InterTropical Convergence Zones (ITCZs) exist and whether double ITCZs, defined in terms of monthly precipitation distributions, are significant climatological features in the tropics. The most identifiable double ITCZ is found over the eastern Pacific during boreal spring, mainly in March and April. Weak signals of a double ITCZ exist over the Indian Ocean during November, but only infrequently. Over the western and central Pacific, signatures of a double ITCZ can often be found, but mostly during June through September. No double ITCZ is found over the Atlantic Ocean. The boreal - spring double ITCZ over the eastern Pacific fails to exist only during El Niño - Southern Oscillation warm phases, when it is replaced by a single ITCZ at the equator as the cold tongue disappears and the maximum sea surface temperature emerges at the equator. It is therefore concluded that double ITCZs are significant features of the tropical climate even though they undergo spatial and temporal variations. Simple composites of double ITCZs and associated surface conditions indicate that double ITCZs, at least over the Pacific Ocean, exist when there are local minima in surface humidity and temperature along the equator. On the basis of the limited observations, it is proposed that double ITCZs in the Pacific are more causally related to surface thermal conditions than atmospheric internal dynamics alone. During boreal spring a special distribution in sea surface temperature with its local minimum at the equator (i.e., the cold tongue) and two maxima at each side is necessary for the double ITCZ over the eastern Pacific. The westward advection of cold and dry surface air by the easterlies from the cold - tongue region is instrumental in the double ITCZ over the central and western Pacific.

1. Introduction

A double InterTropical Convergence Zone (ITCZ) is a phenomenon featured with two ITCZs, one at each side of the equator. Using a year of satellite observations, *Hubert et al.* [1969] examined seasonal mean distributions of cloudiness in the tropics. They found a double ITCZ only infrequently over the eastern Pacific during boreal spring when sea surface temperature (SST) south of the equator reaches a temporary maximum. They concluded that it is a misconception to treat the double ITCZ as a characteristic feature of the tropical circulation. Since their study, hardly any published observational analysis has focused exclusively on the double ITCZ. Nevertheless, the double ITCZ has been a topic frequently discussed in studies examining simulations of general circulation models (GCMs). It has been well documented that a too strong double ITCZ in the Pacific is a common problem in coupled GCMs [*Mechoso et al.*, 1995] as well as atmospheric GCMs [e.g., *Meehl and Arblaster*, 1998]. It is also an unsettled issue whether atmospheric internal dynamics alone would generate a double ITCZ when the surface temperature is equatorially symmetric on an aqua planet [e.g., *Sumi*, 1992; *Hess et al.*, 1993]. Documenting the existence of double ITCZs using observations collected since the study of *Hubert et al.* [1969] would provide useful information for addressing these issues. This is the purpose of the present study.

In this study, double ITCZs are documented using monthly mean precipitation data instead of surface wind data, which should be used by definition. The reason for this is given in section 2 where the data and method used are described. Section 3 presents the results. Discussions are given in section 4 where based on limited observations presented, a hypothesis on the cause of double ITCZs is proposed.

2. Data and Method

Double ITCZs are defined in terms of the spatial distribution of monthly mean precipitation instead of surface wind convergence. This is mainly to benefit from precipitation data whose records are longer than reliable surface wind data. Monthly mean Climate Prediction Center Merged Analysis of Precipitation (CMAP) data [*Xie and Arkin*, 1997] from 1979 through 1999 were used. In addition, observations of surface meteorology from the Tropical Atmosphere-Ocean (TAO) mooring array [*Hayes et al.*, 1991] were also used to explore surface conditions associated with double ITCZs. The TAO array covers an area of 135°E to 95°W and 8°N to 8°S. The TAO data include hourly measurements of surface temperature, relative humidity, wind vectors, and SST. Specific humidity and equivalent potential temperature were derived from these hourly data. Monthly means were then calculated. The availability of TAO observations varies among the buoys. For most buoys, the data start from the early 1990s. The TAO array deployment was completed in 1995 [*McPhaden et al.*, 1998].

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Paper number 2001JD900046.
0148-0227/01/2001JD900046\$09.00

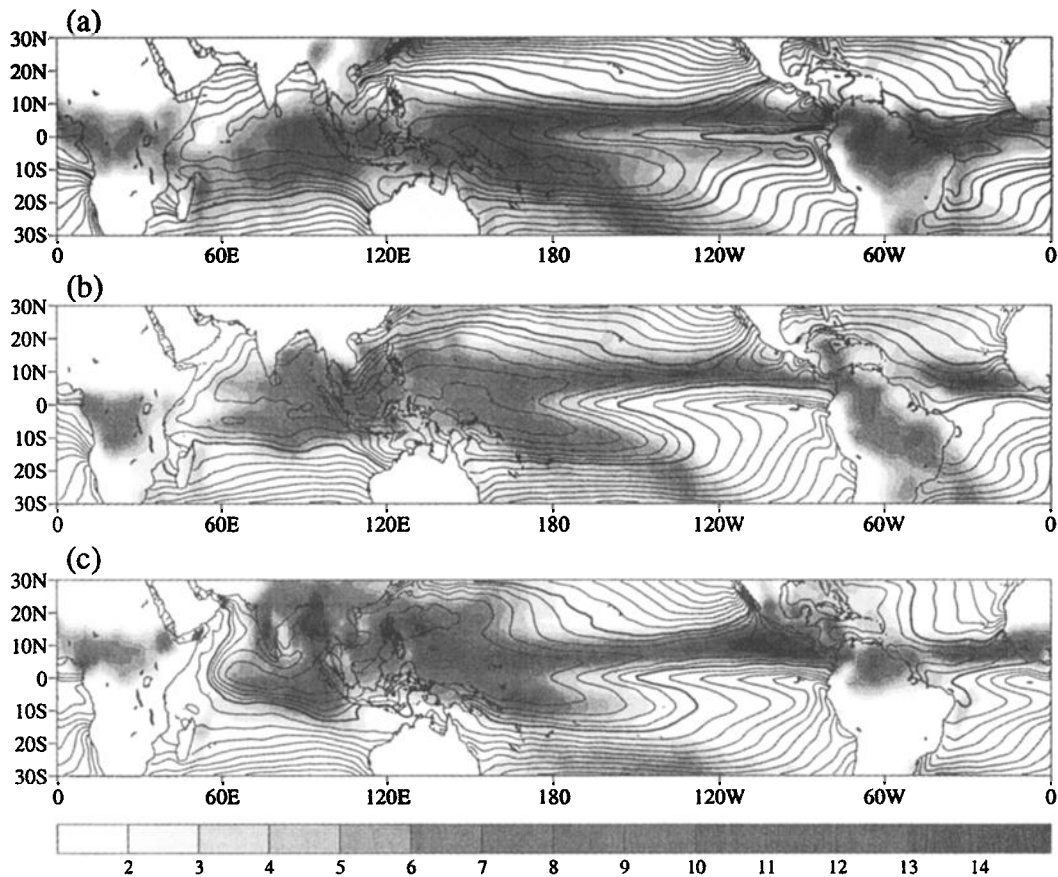


Figure 1. Climatological monthly means of precipitation (mm d^{-1} , shading) and sea surface temperature (SST, $^{\circ}\text{C}$, contour) for (a) April, (b) November, and (c) July. Contour intervals are 1°C and 0.5°C below and above 27°C (thick lines), respectively.

An ITCZ in this study is defined as a precipitation band that is confined in latitude and elongated in longitude. In other words, the ITCZ is distinguished from other tropical convective zones by its narrowness in the meridional direction as well as by its zonal orientation. A double ITCZ, therefore, is identified by the coexistence of two such precipitation bands at each side of the equator, both parallel to the equator. Formally, a double ITCZ must satisfy the following criteria based on monthly mean data: (1) a precipitation minimum at the equator is flanked by precipitation maxima within 15° latitude at each side of the equator, (2) the difference between the maxima and minimum is greater than 1.5 mm d^{-1} , (3) both precipitation bands extend zonally for at least 20° , and (4) latitudinal displacements in the precipitation maxima are less than 5° .

These criteria for a double ITCZ are defined subjectively. However, once they are defined, a double ITCZ can be identified objectively and its location and time determined quantitatively. The last criterion is included to distinguish an ITCZ from the Southern Pacific Convergence Zone (SPCZ), which is oriented northwest to southeast. Notice that there is no requirement for the intensity of the two precipitation bands to be similar. The total number of double ITCZ occurrences selected using these criteria tends to be less than what one might estimate by a completely

subjective inspection of mean precipitation for individual months.

3. Results

We first examine climatological mean distributions of precipitation and subjectively judge when and where double ITCZs might exist. As observed by *Hubert et al.* [1969], a double ITCZ occurs over the eastern Pacific, normally during boreal spring. An example is given in Figure 1a where climatology mean precipitation for April is plotted. The normal ITCZ north of the equator is accompanied by a zonally elongated precipitation band south of the equator; both are almost perfectly parallel to the equator. The southern precipitation band extends from about 150°W to the South American coast but is weaker than its northern counterpart by approximately a factor of 5. These two precipitation bands construct a clear signature of a double ITCZ. This double ITCZ in April has been observed using other satellite observations, such as outgoing longwave radiation and the highly reflective cloud [e.g., *Mitchell and Wallace, 1992; Waliser and Gautier, 1993*].

A double ITCZ also exists over the Indian Ocean in boreal fall and winter (Figure 1b). There, two precipitation maxima are found at both sides of the equator. The south-

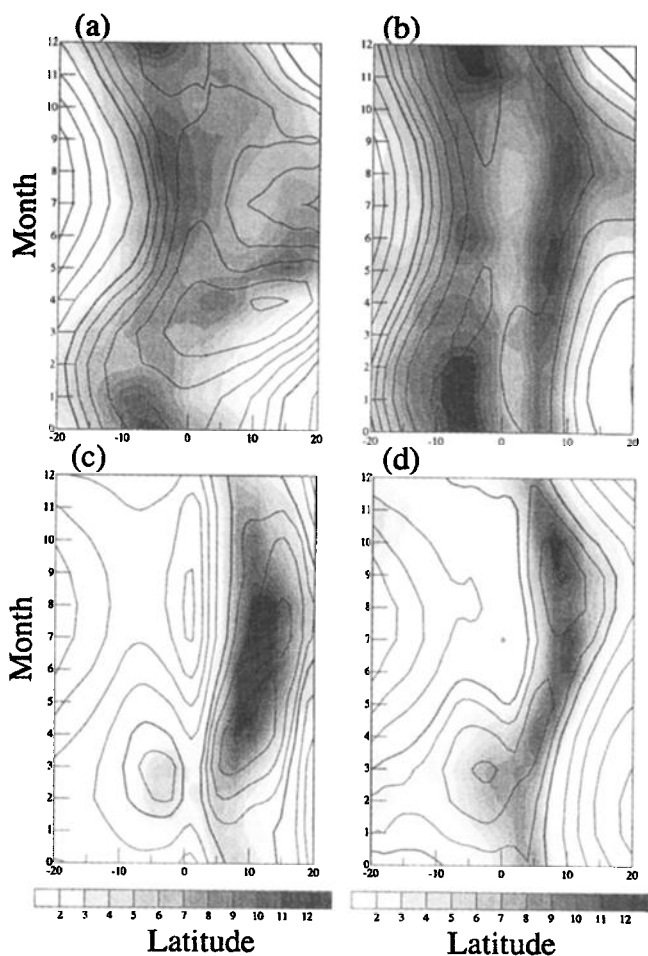


Figure 2. Time-latitude diagrams of climatological mean precipitation (mm d^{-1} , shading) and SST ($^{\circ}\text{C}$, contours) zonally averaged over (a) the Indian Ocean ($60^{\circ} - 90^{\circ}\text{E}$), (b) the western Pacific ($150^{\circ} - 180^{\circ}\text{E}$), (c) the eastern Pacific ($90^{\circ} - 120^{\circ}\text{W}$), and (d) the Atlantic Ocean ($20^{\circ} - 40^{\circ}\text{W}$). Contour intervals are 1°C and 0.5°C below and above 27°C (thick lines), respectively.

ern maximum is stronger than the northern one. Neither of them, however, shows distinct zonally elongated structure as seen over the eastern Pacific. They are separated only in the western part and merge together to the east. This precipitation pattern is viewed as a weak signal of a double ITCZ.

Over the western and central Pacific, a precipitation minimum near the equator and maxima at both sides of the equator are constantly observed. However, this is not necessarily associated with a double ITCZ. More often than otherwise, the southern precipitation maximum is part of the SPCZ, which is oriented northwest to southeast and extends into the subtropics (e.g., Figure 1b). Here, the co-existence of an ITCZ north of the equator and the SPCZ south of the equator is not considered as a signature of a double ITCZ. A double ITCZ, nevertheless, does appear when the precipitation maximum south of the equator becomes more zonally oriented than usual, confined to the tropics, and somewhat separated from the precipitation zone further to the south. An example is given in Figure

1c. In this case the precipitation maximum south of the equator over the western Pacific bears more characteristics of an ITCZ than the SPCZ. No double ITCZ can be identified over the Atlantic Ocean.

As mentioned earlier, a precipitation minimum at the equator with maxima on both sides is considered to be an essential feature of a double ITCZ. This feature can be observed only in certain regions at certain times of year as shown in Figure 2, where latitude-time diagrams of climatological monthly mean precipitation are plotted for the Indian Ocean ($60^{\circ} - 90^{\circ}\text{E}$), western and central Pacific ($150^{\circ} - 180^{\circ}\text{E}$), eastern Pacific ($90^{\circ} - 120^{\circ}\text{W}$), and Atlantic Ocean ($20^{\circ} - 40^{\circ}\text{W}$). Over the Indian Ocean (Figure 2a), the precipitation maximum stays south of the equator most of the time except during the onset of the Indian summer monsoon (April - June). Only during November can a vague hint of a double ITCZ be found when a short-lived precipitation minimum occurs near the equator with maxima at both sides.

Over the western and central Pacific (Figure 2b), precipitation maxima at both sides of the equator and a local precipitation minimum in between can be seen most of the time. This two-peak precipitation or cloud distribution is more pronounced in the central Pacific than to the west [Waliser and Gautier, 1993]. From November to May the southern precipitation maximum extends southward to 20°S , which is a manifestation of the SPCZ. During these months it is unclear when the precipitation distribution there can be characterized as a double ITCZ. From June to October the southern precipitation region is confined to the tropics ($0^{\circ} - 10^{\circ}\text{S}$), while the equatorial precipitation reaches its minimum. This precipitation distribution is likely to meet the double ITCZ criteria given in section 2. How often a double ITCZ can be objectively identified in this region will be determined later.

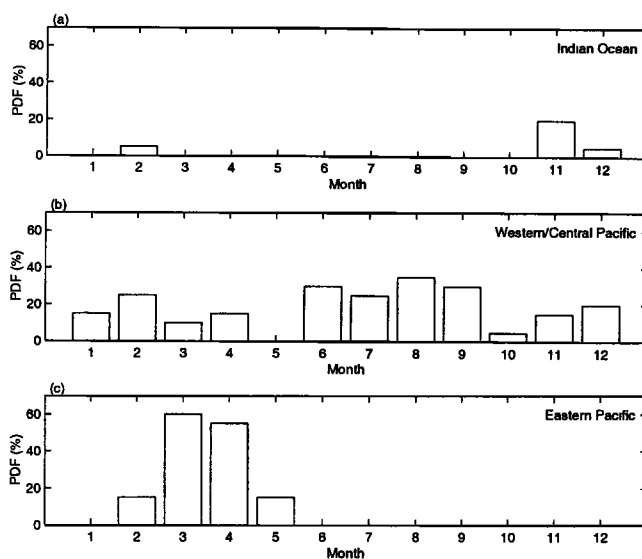
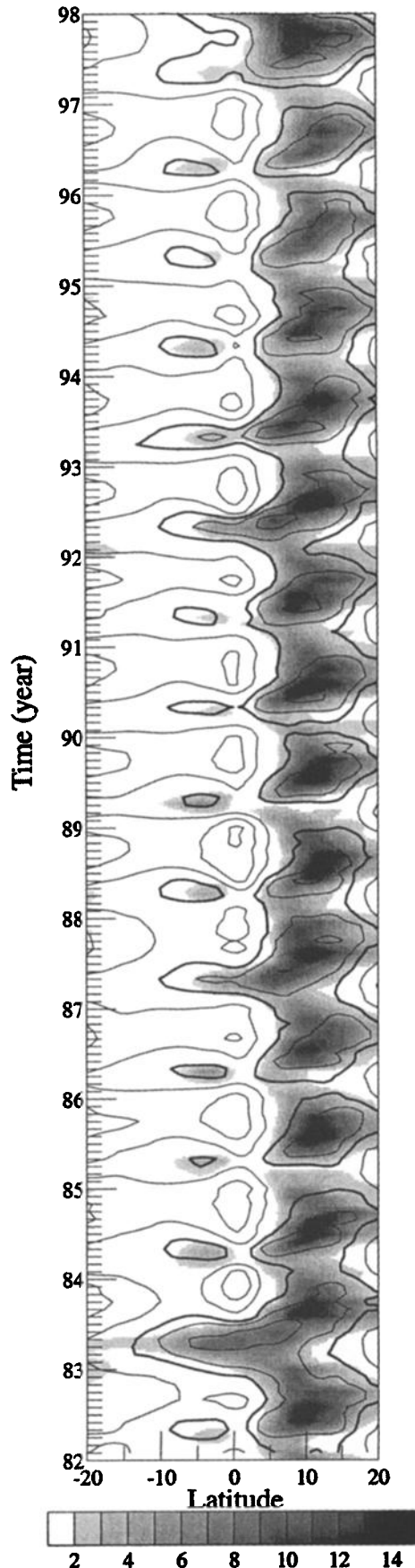


Figure 3. Probability distribution functions (PDFs) of double ITCZs over (a) the Indian Ocean, (b) the western and central Pacific, and (c) the eastern Pacific, defined for each month as the ratio of the number of years with double ITCZs and the total number of years.



The double ITCZ over the eastern Pacific emerges without ambiguity as a robust climatological feature during boreal spring (Figure 2c). Over the Atlantic Ocean the seasonal migration of the ITCZ in latitude is clearly seen (Figure 2d), but there is no sign of a double ITCZ.

The above discussion provides a general description of the existence of double ITCZs. When and where a double ITCZ actually occurs can be further quantified using the criteria described in section 2. These criteria were applied to the precipitation data to select months and longitudes of double ITCZs. Composite precipitation distributions were then made for months during which double ITCZs occur over the Indian, western and central, and eastern Pacific Oceans, respectively. Double ITCZs in these regions in the composites are almost the same as those in Figure 1 (see Figures 6 and 7 later). Again, no double ITCZ was identified over the Atlantic Ocean based on these criteria.

Double ITCZs in the different regions exhibit quite different seasonality. The probability distribution functions of double ITCZs in the three regions are shown in Figure 3. Over the Indian Ocean, double ITCZs infrequently occur only in boreal fall or winter, mainly in November (Figure 3a). Double ITCZs over the eastern Pacific mainly occur in March and April (Figure 3c). Over the western and central Pacific, double ITCZs can possibly be found in all seasons, but more frequently during June through September (Figure 3b). These results, which are not very sensitive to small variations in the criteria, are consistent to those seen from the simple latitude-time diagrams in Figure 2.

Interested readers are encouraged to examine precipitation distributions in individual months during the prominent seasons for double ITCZs as suggested by Figure 3. They would find signatures of double ITCZs clearer than seen in Figure 1 and more frequent than indicated by Figure 3. Even more evident signatures of double ITCZs can be found from monthly mean plots of cloud liquid water (see, for example, such plots in the Climate Diagnostics Bulletins). There is little doubt that double ITCZs are significant climatological phenomena of the tropics because of their frequent, if not constant, appearance in their due seasons at certain longitudes. The sole reason a different conclusion is obtained here from that by *Hubert et al.* [1969] is that they used only one year of data.

The double ITCZ over the eastern Pacific presents a very interesting problem. There, it occurs during boreal spring only when SSTs near the equator are lower than SSTs on both sides of the equator or, in other words, only when SSTs south of the equator reach a temporal maximum while the cold tongue remains (e.g., Figures 1a, 2e, and 4), as described by *Hubert et al.* [1969]. When this equatorial SST minimum is absent or very weak, the double ITCZ would fail to occur. This happens during warm phases of El Niño - Southern Oscillation (ENSO) when the equatorial cold tongue disappears (e.g., 1983, 1987, 1992, 1997, as shown in Figure 4, and 1998, not shown). At cer-

Figure 4. Time-latitude diagrams of SST ($^{\circ}\text{C}$, contour) and precipitation (mm d^{-1} , shading) zonally averaged over the eastern Pacific (90° - 120°W). Contour intervals are 2°C and 1°C below and above 27°C (thick lines), respectively.

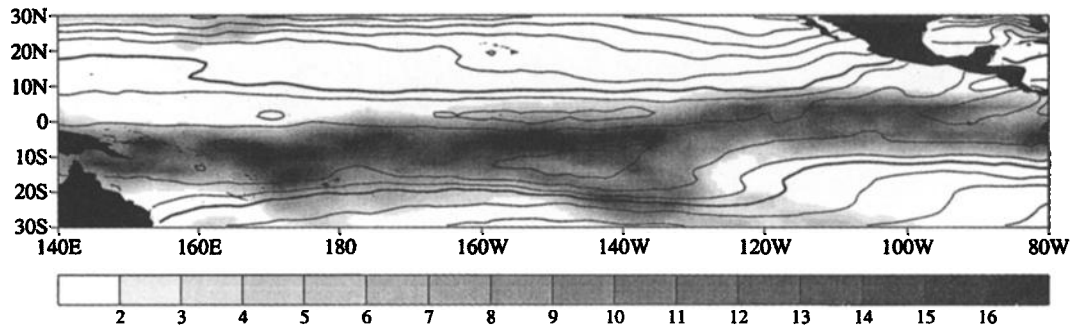


Figure 5. Monthly mean precipitation (mm d^{-1} , shading) and SST ($^{\circ}\text{C}$, contour) for February 1998. Contour intervals are 1°C and 0.5°C below and above 27°C (thick lines), respectively.

tain stages of ENSO warm events, the meridional SST distribution in the eastern Pacific is almost equatorially symmetric, with its maximum at the equator. In such an unusual situation, maximum precipitation always occurs at the equator, resulting in a single ITCZ centered near the equator. An example of this is given in Figure 5, where signatures of a double ITCZ over the eastern Pacific, if they exist at all, are extremely weak. The implications of this observation are discussed in section 4.

4. Discussion

The existence of double ITCZs is nothing new. Those who follow closely tropical weather and climate have long recognized that a double ITCZ occurs frequently over the eastern Pacific during boreal spring. Some features of double ITCZs shown in this study can also be found from others [e.g., Mitchell and Wallace, 1992; Waliser and Gautier, 1993; Meehl and Arblaster, 1998]. This study merely summarizes the signatures of double ITCZs using formally although subjectively defined criteria. Some information provided here is known to many, but has seldom been systematically documented.

The double ITCZs (or their secondary southern branches) may not have the same dynamic effects on the tropical circulation and climate as the regular single ITCZ, but they warrant further investigation because of their implications to our understanding of tropical dynamics and thermodynamics. It is not apparent why a double ITCZ (or its weaker, southern branch) should not exist because of the same physical mechanisms as for the regular single ITCZ. Many theories and hypotheses have been proposed to explain the regular single ITCZ. None of them has been applied directly to the double ITCZ. A complete theory of the ITCZ should explain with equal success both the single and double ITCZs. In this sense, the double ITCZ presents a challenge for all theories and hypotheses of the ITCZ.

It has been shown that double ITCZs often exist in climate simulations, but too frequently and with too much strength in comparison to observations [e.g., Mechoso et al., 1995; Meehl and Arblaster, 1998]. It is controversial whether a GCM, especially in a hypothetical aqua-planet setting with an equatorially symmetric distribution of SST (i.e., maximum SST at the equator), should produce a

double ITCZ, a single ITCZ centered at the equator, or a single ITCZ off the equator [Hayashi and Sumi, 1986]. The current understanding is that simulated characteristics of the ITCZ, namely, double or single, at or off the equator, can be sensitive to physical parameterizations [Miller et al., 1992; Hess et al., 1993] and model resolutions [Sumi, 1992]. Central to the controversy is what type of ITCZ atmospheric internal dynamics tend to produce in the absence of other factors. The existence or absence of the double ITCZ in observations might provide some insights.

In the eastern Pacific, where the equatorial cold tongue reigns most of the time, a distribution of SST that is almost equatorially symmetric with its maximum at the equator can be found near the peak phase of ENSO warm events, as discussed briefly in section 3 (Figure 5). What makes this interesting is the question as why the double ITCZ there ceases to exist during that time if it is caused primarily by atmospheric internal dynamics. The absence of the double ITCZ in the observations during warm phases of ENSO challenges one to consider whether a double ITCZ produced by GCMs in an aqua-planet setting with equatorially symmetric SST is physically correct. In reality, if the atmospheric internal dynamics tend to produce a double ITCZ, it might constantly face competition from the influence of the distribution of SST. The limited observations presented here suggest that the capability of atmospheric internal dynamics to produce a double ITCZ is so weak that it can easily be dominated by the influence of SST and it alone is insufficient in generating a distinct double ITCZ as observed over the eastern Pacific during boreal spring. This argument is supported by the observations of the weak signals of the double ITCZ over the tropical Indian Ocean, where SST can be symmetric about the equator or at least quite uniform, and by the absence of a double ITCZ over the Atlantic Ocean, where SST is nearly symmetric about the equator during boreal spring (Figures 1 and 2).

If atmospheric internal dynamics are not primarily responsible for the double ITCZ observed, then what is? The strongest, if not the only, candidate is SST. As discussed previously, the double ITCZ in the eastern Pacific exists only when SST south of the equator increases during boreal spring to a certain degree that it is roughly equatorial symmetric but with a minimum centered at the equator (Figure 4). Related to this rare SST distribution are those

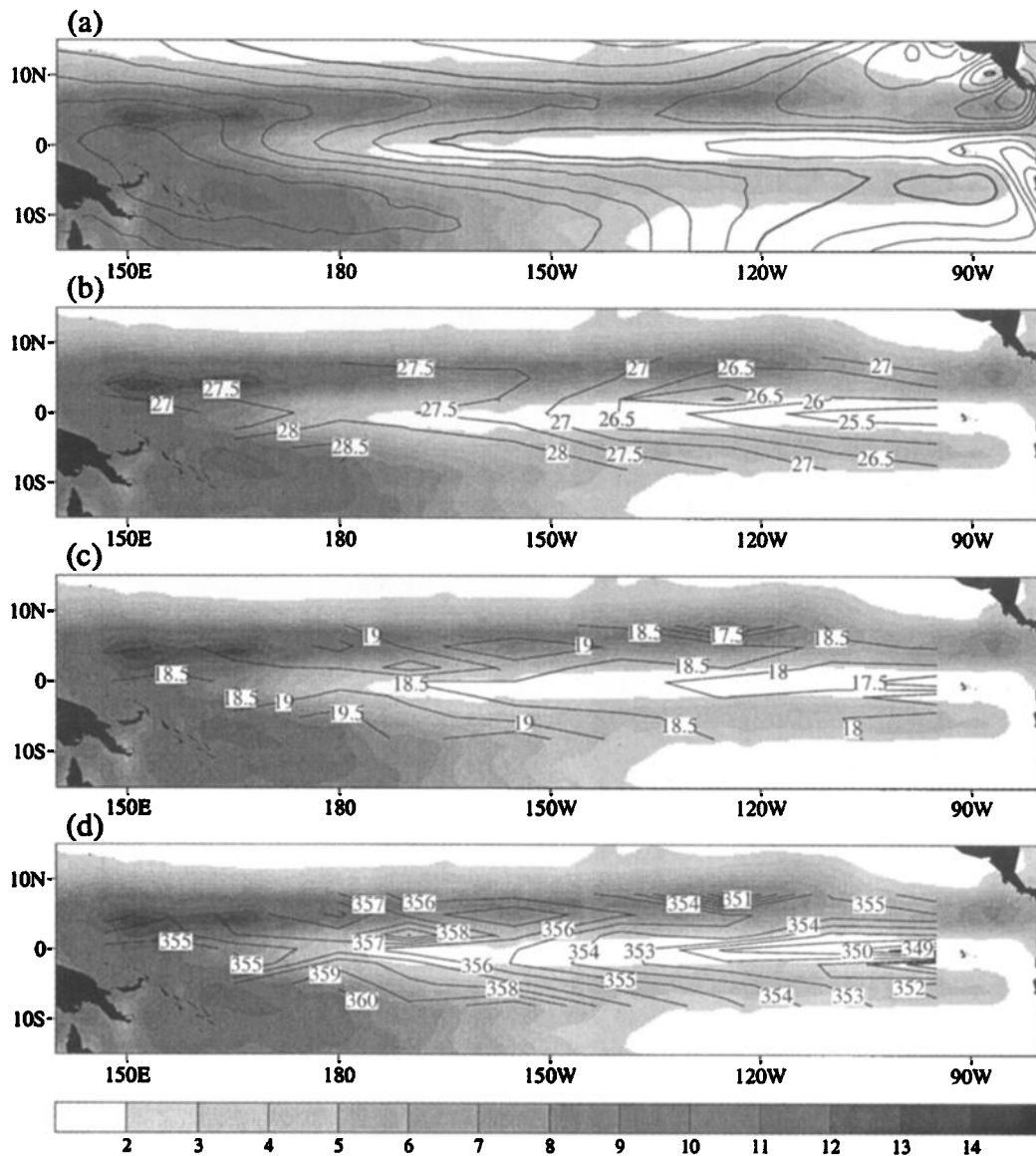


Figure 6. Composites of the double ITCZ over the eastern Pacific and its surface conditions during March and April. Shading is precipitation (mm d^{-1}). Contours are (a) SST ($^{\circ}\text{C}$, same intervals as in Figure 5), (b) surface air temperature T ($^{\circ}\text{C}$), (c) surface specific humidity q (g kg^{-1}), and (d) surface equivalent potential temperature θ_e (K).

in surface air temperature T , humidity q , and equivalent potential temperature θ_e , which all exhibit a local minimum along the equator (Figure 6). To what extent such atmospheric thermodynamic conditions at the surface are actually responsible for the existence of the double ITCZ there has yet to be quantified. This probably must be done through numerical experiments. However, their observed coincidence provides a strong hint that they are causally related.

This above speculation can be further extended to the western Pacific, where precipitation is usually less at the equator than away from it and this precipitation distribution can sometimes be labeled as a double ITCZ (Figures 2b and 3b). The western Pacific warm pool is featured of a rather uniform SST distribution, at least without any obvious SST minimum at the equator (Figures 1c and 7a). Nevertheless, T , q , and θ_e reach their local minima near

the equator (Figures 7b, c, and d). Cold and possibly dry advection by surface easterlies from over the equatorial cold tongue to the east (Figure 7e) is a suspect for causing the equatorial minima in these surface variables over the western Pacific warm pool.

If double ITCZs are indeed causally related to the surface thermal conditions (and possibly their vertical extension into the atmospheric boundary layer), then the probability distribution of double ITCZs shown in Figure 3 would not be hard to explain. The mechanisms for the specific surface condition for double ITCZs, namely, an equatorial symmetric distribution of SST with its local minimum (or cold zonal advection) at the equator and local maxima at both sides of the equator, never exist in the Indian and Atlantic Oceans, where double ITCZs are rarely or completely absent. In the Pacific region the existence of the cold tongue and its related westward near-surface cold advection

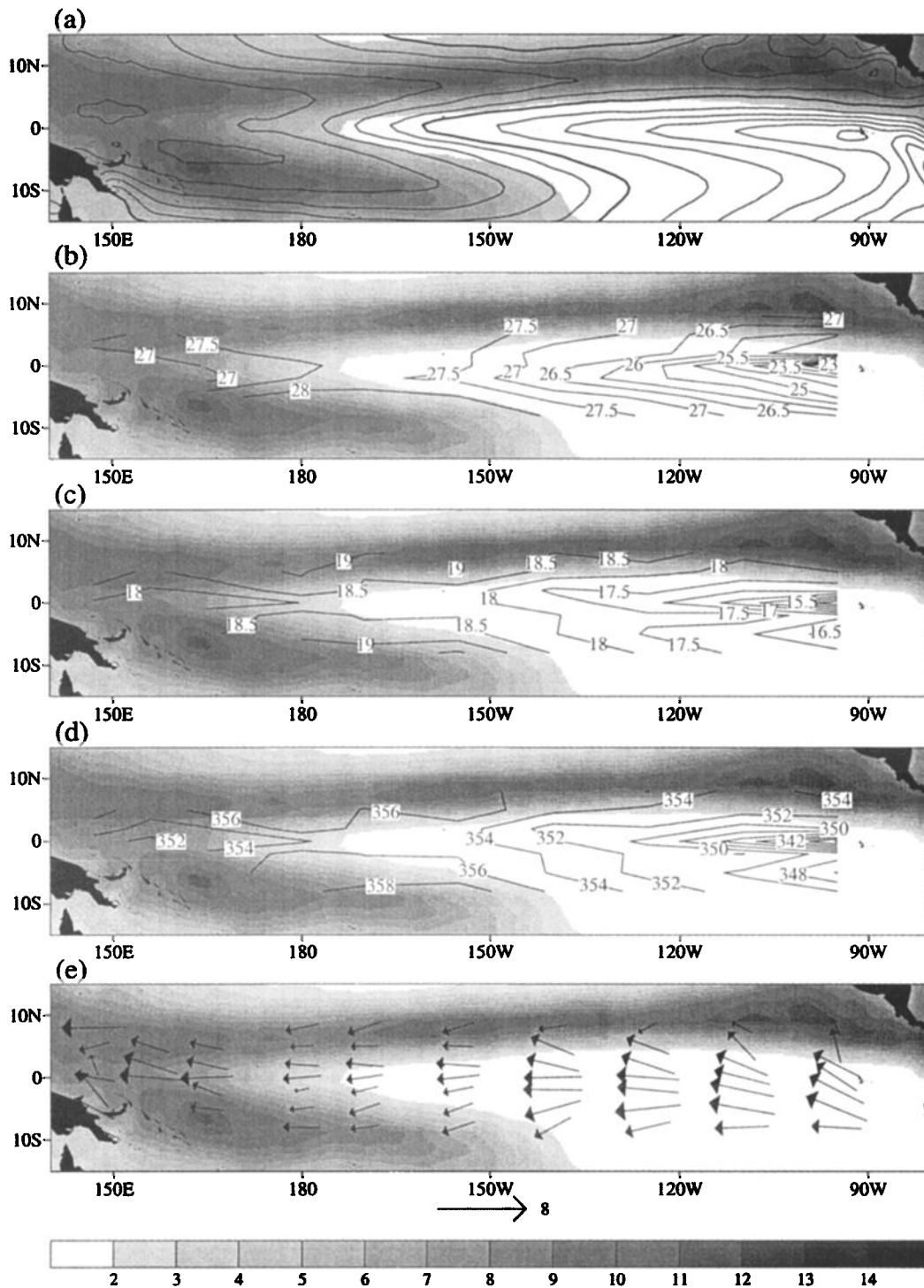


Figure 7. Same as Figure 6, except for the double ITCZ over the western and central Pacific and its surface conditions during June through September.

into the western Pacific is much more common than the equatorial symmetric distribution of SST in the eastern Pacific. Double ITCZs therefore appear to be much more frequent over the western than eastern Pacific.

Recently a detailed analysis on the southern branch of the double ITCZ over the eastern Pacific was conducted by D. Halpern and C.-W. Hung (Satellite Observations of the Southeast Pacific InterTropical Convergence Zone During

1993 - 1999, submitted to *Journal of Geophysical Research*, 2001). They observed surface wind convergence at the latitude of the Southern Hemispheric ITCZ and they attributed this convergence to the meridional gradient of SST whose minimum is at the equator and maximum underneath the southern ITCZ. Their observations are completely consistent with this study. While they focused on the cause of the southern branch of the double ITCZ, this

study emphasizes why precipitation regions in the two branches are separated. Surface warming south of the equator after the maximum insolation during boreal winter is a necessary but insufficient condition for the southern branch of the double ITCZ. Similar warming also occurs in the Indian and Atlantic Oceans. However, no equatorial cold tongue exists in the Indian Ocean and the cold tongue in the Atlantic Ocean is weak and disappears during boreal spring (Figure 2). The cold tongue persists only in the eastern Pacific, while the upper ocean to the south is warmed during boreal spring of normal years. When the cold tongue disappears during warm phases of ENSO, so does the double ITCZ.

In summary, the results from this study clearly indicate that double ITCZs are significant climatological features of the tropics because of their repeating occurrence at certain longitudes and during certain seasons. Limited observations suggest that their primary causes are surface thermal conditions rather than atmospheric internal dynamics. Double ITCZs deserve more research attention than they have received, especially in the context of interpreting climate simulations of GCMs and theoretically understanding the ITCZ.

Acknowledgments. The CMAP data were downloaded from NCEP web site <ftp://ftp.ncep.noaa.gov/pub/precip/cmap/>, courtesy of Ping-Ping Xie. The TAO data were made available by the TAO Project Office, Michael McPhaden, director. This study was supported by the NOAA PACS Program through awards under Cooperative Agreement #NA67RJD49 through CIMAS.

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(Received August 30, 2000; revised January 4, 2001; accepted January 17, 2001.)