A Proposed Mechanism for the Intrusion of Dry Air into the Tropical Western Pacific Region

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ABSTRACT

Recent studies using data from the Tropical Ocean and Global Atmosphere program’s Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) have shown that synoptic-scale areas of extremely dry air can occur in the troposphere over the equatorial western Pacific. These layers of extremely dry air modify convective activity and the vertical profile of radiation in clear air. At the present time there is some disagreement as to the dynamic mechanism responsible for these events and a number of their characteristics are relatively unknown. In this study, the origin and characteristics of the dry air events were investigated through analysis of TOGA COARE rawinsonde data and examination of global analyses from two different forecast centers. These drying events were found to be very common and evidence was presented that their intensity was underestimated in the global analyses. These dry events were shown to most often originate in the Northern (winter) Hemisphere as troughs associated with baroclinic waves intensified and expanded equatorward, leading to a process analogous to Rossby wave breaking. In these cases, the dry air at the edge of the westerlies at upper levels was incorporated into the equatorward extension of thin NE–SW tropospheric troughs, where it subsided and was subsequently advected equatorward. If sufficient subsidence took place, the dry air continued equatorward on the eastern edge of well-defined anticyclones in the lower troposphere. The dry air in one case originated in a Southern (summer) Hemisphere trough that was associated with midlatitude baroclinic waves that propagated equatorward and developed into a series of distinct disturbances along a subtropical jet. In both the Northern and Southern Hemisphere events, the subsiding dry air in the midtroposphere was injected into the fringes of the Tropics, where it was able to reach equatorial regions if it interacted with favorable meridional flow in the Tropics. Past studies have proposed that these intrusions of dry air could induce droughts in the Tropics through decreasing deep convective activity. The implication of this study is that these droughts are actually induced by midlatitude processes.

1. Introduction

The Coupled Ocean–Atmosphere Response Experiment of the Tropical Ocean and Global Atmosphere program (TOGA COARE) was designed to improve the understanding of the interactions between oceanic and atmospheric processes over the warm ocean surface of the tropical western Pacific. A summary of the scientific goals of TOGA COARE can be found in Webster and Lukas (1992). The project included a four-month intensive observing period (IOP) between 1 November 1992 and 28 February 1993. One atmospheric phenomenon that has attracted substantial research interest in the COARE IOP dataset is the frequent appearance of extremely dry air in the lower and midtroposphere over this equatorial region (Parsons et al. 1994; Numaguti et al. 1995; Yoneyama and Fujitani 1995; Sheu and Liu 1995; Mapes and Zuidema 1996; Johnson et al. 1996). Evidence suggests that the dry air covers synoptic scales as Numaguti et al. (1995) noted a zonal extent of 1000 km, while Mapes and Zuidema (1996) found a typical width of a few hundred kilometers and proposed life cycles of 3–4 days.

Some of the interest in these dry events is due to their potential impact on convection. For example, in mesoscale convective systems, it is well known that once convection is initiated, dry midlevel air can be entrained into the system and enhance the strength of surface cool outflows that in turn enhance or disrupt the formation of
of new convective cells (Zipser 1977; Houze and Betts 1981; Rotunno et al. 1988). However, radar analysis indicates that dry layers and deep convective precipitation are negatively correlated over the convectively active warm water pool (Rickenbach 1995). Satellite data also reinforce that deep convection is reduced during dry air events so that Brown and Zhang (1997) termed these periods as tropical droughts. Parsons et al. (1994) noted that dry events tend to be associated with strong inversion near the top of the boundary layer, significantly inhibiting deep convection. A similar situation occurs with warm, dry air at the trade inversion over the central and eastern equatorial Pacific (Betts and Albrecht 1987; Kloesel and Albrecht 1989). According to the Mapes and Zuidema (1996) study, these stable layers are generated at the base of dry layers through radiative and dynamic processes interacting with the intense vertical gradients of humidity in a dry layer of finite width. In addition to the impact of the thermal inversion on deep convection, it is possible that the dry air itself could be responsible for the reduction in convective activity through entrainment (Mapes and Zuidema 1996; Brown and Zhang 1997). Dry air layers may also affect cloud distributions through detrainment at midlevel stable layers (Mapes and Zuidema 1996; Johnson et al. 1996). An additional reason to study these dry events is the recent hypothesis proposed by Emanuel and Bister (1996) that the amount of convective instability present over the Tropics may depend on the distribution of midlevel moisture. Earlier, Parsons et al. (1994) noted a dramatic increase in convective instability during a dry event.

An example of a dry air layer observed aloft at Kapingamarangi (1°N, 155°E) at 1200 UTC 13 November 1992 is shown in Fig. 1. In this skew T diagram, extremely dry air is present between 900 and 680 hPa as the mixing ratio decreases from 11.8 g kg$^{-1}$ at 900 hPa to 3.3 g kg$^{-1}$ at 880 hPa. The minimum value of the mixing ratio, 1.1 g kg$^{-1}$, is found at 760 hPa. From comparisons with previous studies of dry air events in TOGA COARE, we note that this minimum value and these vertical gradients are typical of these events but do not represent the most extreme soundings. In this skew T, a strong temperature inversion exists near 900 hPa, consistent with the Mapes and Zuidema hypothesis (1996).

Vertical displacements of air near the trailing edge of mesoscale convective systems have successfully explained the presence of weaker and smaller-scale dry events associated with mesoscale convective systems, resulting in so-called onion soundings (e.g., Zipser 1977; Houze and Betts 1981). However, after noting the presence of such extreme vertical gradients of water vapor mixing ratio, many studies have reported that these extensive dry air layers, such as shown in Fig. 1, cannot be explained by vertical adiabatic displacements. Instead, the horizontal advection of air from the subtropics has been shown to account for the origins of
these air masses over the tropical western Pacific (Numaguti et al. 1995; Yoneyama and Fujitani 1995; Sheu and Liu 1995; Mapes and Zuidema 1996; Johnson et al. 1996). Perhaps the strongest direct evidence for the advective nature of these dry events was the trajectory analysis by Numaguti et al. (1995) of two cases observed during TOGA COARE in November 1992. From these two events, they concluded that 4–5-day mixed Rossby–gravity waves played an important role in the advection of dry air over the COARE domain. A different causal mechanism for dry air events was proposed by Sheu and Liu (1995), who stressed the importance of circulations associated with cold pressure surges in midlatitudes and the subsequent development of westerly wind bursts over the tropical Pacific. Hendon and Liebmann (1990) also showed humidity decreases after convectively active periods of the intraseasonal oscillation. In contrast with these studies linking dry events with organized circulations, Mapes and Zuidema (1996) proposed that dry air arrived from chaotic advection in the presence of intense subtropical–tropical humidity gradients. Hence, while there is agreement that horizontal advection explains the appearance of extremely dry air over the tropical western Pacific, there appears to be no consensus on what dynamical mechanism causes these drying events. The issue of the cause and life cycle is further complicated by many previous studies that have focused on different aspects of one or two events, rather than investigating all of the extreme drying events observed during TOGA COARE.

2. Data

In this study, we utilized the rawinsonde sounding datasets obtained during the TOGA COARE IOP at four observation sites: Kapingamarangi, Kavieng (2.5°S, 151°E), R/V Shiyan #3 (2.5°S, 158°E), and R/V Kexue #1 (4°S, 156°E). These sondes were launched every 6 h from integrated sounding systems (ISS) (Parsons et al. 1994) installed as part of the intensive flux array (IFA) area (Fig. 2). In this study, reference to the IFA mean indicates the average of these four sites plus any additional soundings taken from R/V Moana Wave (2°S, 156°E) and R/V Xiangyanghong #5 (2°S, 156°E). In this dataset, the sounding data for all available sites was interpolated to 5-hPa vertical intervals. The humidity errors due to sensor-arm heating were corrected by procedures developed at the National Center for Atmospheric Research/Atmospheric Technology Division/Surface and Sounding Systems Facility (Miller and Riddle 1994; Cole and Miller 1995). While other humidity biases exist in the TOGA COARE soundings, the extreme departures in humidity associated with the dry intrusions make these biases basically irrelevant for our purposes. The reader should also be aware that during the IOP the number of sites varied as various research vessels went on- and off-station.

To investigate the relationship between the dry air events and larger-scale circulations, we also utilized the global analysis dataset (GANAL) of the Japan Meteorological Agency. The parameters used were horizontal wind, temperature, and dewpoint. Their horizontal grid spacing is 1.875° and conventional levels (surface, 1000, 850, 700, 500, 400, 300, 200, 150, 100 hPa) were used in the vertical. In this dataset there are no dewpoint data for levels above 200 hPa and the time resolution is twice daily (0000 and 1200 UTC). The area analyzed in GANAL generally ranged in longitude from 120°E to the dateline, and in latitude from 20°S to 20°N. When we refer to the 750-hPa level in the GANAL datasets, linear interpolation was used between the 700- and 850-hPa levels. The three-dimensional trajectories were calculated using the GANAL datasets, employing techniques that will be explained later. These trajectories were calculated to ±30° from the equator, allowing us to understand the relative role of advection and subsidence over the life cycle of the event.

We also utilized the global analysis provided by the European Centre for Medium-Range Weather Forecasting (ECMWF) for qualitatively verifying the trajectories derived from GANAL and for the synoptic analysis of the large-scale flow over the Pacific and Indian Oceans. The products were used at 0000 and 1200 UTC, when more data from the special TOGA COARE observations were incorporated, increasing the likelihood of a higher quality analysis (Pires et al. 1997). The analysis had a 2.5° by 2.5° grid spacing at conventional levels. Initially, the ECMWF analysis was selected to investigate whether our trajectory results were dependent upon our choice of a global data system. Later, as our research led us to investigate higher-latitude circulations and regions more distant from the tropical western Pacific, we also used the ECMWF analysis for synoptic analysis. Our decision to use the ECMWF data was based on the ease of access.
to relatively larger spatial domains through the data products distributed to TOGA COARE investigators and well-developed visualization tools (Corbet et al. 1994), rather than any perceived difference in the quality between the two datasets. We believe that our use of two different global analysis products and general consistency between the two provides further support for our hypothesis. Additional evidence for the general consistency between the two products can be found from comparison of the results of the Numaguti (1995) and Pires et al. (1997) studies of tropical waves.

3. Basic characteristics of the dry intrusions

In section 3a, we begin with rawinsonde data used to determine the frequency, duration, and intensity of the dry air events over the TOGA COARE area during the IOP. We will also describe the four events that subsequently discussed in greater detail. In section 3b, a series of “forward and backward” three-dimensional trajectories and some horizontal cross sections based on the GANAL data show the spatial origins of the dry air mass for these four cases.

a. Defining the dry air periods

The frequency and duration of the dry air events averaged over the TOGA COARE IFA during the four-month IOP are shown in Fig. 3a. In this figure, the dots indicate times when the IFA mean mixing ratio \( (Q_m) \) is between one and two standard deviations less than the IOP average \( \overline{Q_m} \) calculated over the same area, while the diamonds indicate that \( Q_m \) is less than \( \overline{Q_m} \) by two or more standard deviations. Although standard deviations are used as a threshold to define dry periods, it should be noted that the humidity is not normally distributed (e.g., see Fig. 4a). Although our threshold is different from that used by Mapes and Zuidema (1996), both thresholds reveal similar patterns of drying. It is evident in Fig. 3a that the dry periods are well defined, relatively common, and can be subjectively divided into two types of events. One type of event is mainly found in the lower levels (below \( \sim 500 \) hPa) with the drying sometimes extending into the boundary layer. This type of event is extremely dry (greater than two standard deviations from the mean) and the arrival of the dry air is relatively sudden. For example, examination of Fig. 3a shows that the region defined by a departure of more than two standard deviations (diamonds) is seldom surrounded by large areas with departures of one standard deviation (dots). The duration of these extreme events over the IFA is generally less than 3–7 days. Our study will concentrate on this type of event with more extreme drying. The second type of event is often found above 500 hPa and is relatively less dry, with the fluctuations generally not reaching two standard deviations. These less extreme upper-level events are often marked by more gradual drying, as any regions with departures exceeding two standard deviations are often preceded and followed by relatively lengthy departures of between one and two standard deviations. The maximum duration of this second type of event exceeds 7 days. The lifetimes of both events over the IFA are generally longer than the 3–4-day lifecycle proposed by Mapes and Zuidema (1996). Brown and Zhang (1997) proposed that the periods of relative drought last up to 10 days.

An analogous plot of the frequency and duration of the dry air events at Kapingamarangi, which is the closest to the equator of the four ISS sites, is shown in Fig. 3b. At a single site, the distinction between the two types of dry air events is also evident, perhaps even more clearly than in the IFA mean data. From comparison of Figs. 3a and 3b, it can be seen that some events that appear at a single site (e.g., the event near day 26 at Kapingamarangi) are not evident in the IFA mean dataset, while some events are better defined in the IFA mean (e.g., the event near day 85 in the IFA mean). This difference partly results from the size and location of the dry air masses causing some of the dry events to impact only a portion of the IFA sounding sites at a given time. At Kapingamarangi, it appears that there were six distinct dry events during the IOP. In November there were three events, with the weakest event occurring near the start of the IOP; in late December and early January there was a prolonged period of drying with some suggestion of multiple events; and two events were evident during February. With the exception of the late December–early January case, the duration of the events at a single site was less than in the IFA mean conditions. From examination of Figs. 3a and 3b and the humidity fields at other sites, we estimate that during the IOP the dry events were present over the IFA for 9%–17% of the time period, depending on how they are defined.

A corresponding plot for the GANAL dataset at the grid point (2°N, 156°E) located nearest to Kapingamarangi is shown in Fig. 3c. In this figure, the thresholds are still defined as standard deviations at each level based on the distribution of the in situ dataset at Kapingamarangi. Namely, the squares indicate the mixing ratio in the GANAL data at 2°N, 156°E is less than the mean by departures larger than two or more standard deviations (as defined from data taken at Kapingamarangi in Fig. 3b), while the pluses show when the GANAL data are between one and two deviations. Dry events are found in the GANAL datasets in mid-November, late November–early December, early January, and to some degree in early February. Comparing Fig. 3c with Fig. 3b, the GANAL dataset shows smaller variations in magnitude than the in situ data. This difference is consistent with the fact that the mean conditions in the GANAL dataset are biased moist with deviations smaller than in the in situ dataset as examination of the IOP mean mixing ratio and its standard deviations at 700 hPa are 7.7 ± 1.1 g kg\(^{-1}\) for GANAL and 7.1 ± 1.3 g kg\(^{-1}\) for the in situ dataset.
FIG. 3. Time–altitude section of departures in water vapor constructed from (a) IFA mean soundings, (b) Kapingamarangi soundings, and (c) the data point at 2°N, 156°E in the GANAL analysis. See the text for the definitions of each symbol.

The time series of water vapor mixing ratio, wind speed, zonal wind component, and meridional wind component in the 700–800-hPa layer constructed from the Kapingamarangi rawinsonde data are shown in the four panels of Fig. 4. A 1–2–1 time filter was applied in order to reduce the impact of smaller-scale features such as convection. From the humidity time series (Fig. 4a), we found four major dry air periods over Kapingamarangi in mid-November, in late November, in late December–early January with significant substructure, and in early February. The weaker events in early November and late February (near days 2 and 118, respectively) had humidity departures of less than 1.5 standard deviations and are not clearly defined in the GANAL data (Fig. 3c). Defining moist air periods in a similar way (i.e., exceeding the IOP mean \( Q_m \) by at least 1.5 standard deviations), we also found three very moist periods: early November, mid-December, and late January. The latter two periods apparently correspond to the passage of the intraseasonal oscillation over the IFA area (Velden and Young 1994; Gutzler et al. 1994; Nakazawa 1995). The mean wind speed in the 700–800-hPa layer and the corresponding zonal winds show that the strongest winds generally correspond to westerly flow
The winds in early January and early February correspond to the periods of westerly bursts (Velden and Young 1994; Chen et al. 1996) with a weaker westerly event during November (Lin and Johnson 1996). The departures in the meridional wind (Fig. 4d) are generally much weaker, with the strongest departures occurring in November. Examination of humidity and zonal winds (Figs. 4a and 4c) suggests that the four strong and two weak dry air events correspond to or closely follow periods of westerly winds over Kapingamarangi. Comparison of the zonal wind analysis by Lin and Johnson (1996) (see their Fig. 3a) with the dry air events in this study (Fig. 3a) reveals a similar correspondence between dry air events and westerlies. The cross correlation was calculated between the mixing ratio and wind speed, with the coefficient reaching a maximum value (0.5) with a time lag of 1.75 days (wind speed precedes drying). This lag indicates that at a single point the arrival of the dry air is associated with a prior acceleration of the flow over the equatorial western Pacific.

Our result for the extreme dry events differs from that of Sheu and Liu (1995), who noted drops in precipitable water both before and after westerly wind bursts in association with equatorward winds during the transitions between westerly and easterly flow. In our analysis, not all the periods of westerly winds periods that occurred near the dry air events could be termed westerly bursts, as the drying noted at Kapingamarangi in late November (Fig. 3b) corresponds to a period of very weak and shallow westerly winds over the IFA (see Fig. 3a of Lin and Johnson 1996). It is also evident that not all westerly periods are linked with dry events, as illustrated by data taken at the R/V *Kexue* #1 located to the south of Kapingamarangi, where no dry event can be found to correspond to the early January period of strong westerlies. Instead, at this site the early January period is rather moist with drying in late January during easterly winds. The westerly winds at the R/V *Kexue* #1 are far stronger, reflecting the observation that the bursts in early January and early February were located to the south of the equator in the vicinity of the IFA.

**b. Defining the origins of the dry air masses**

The horizontal distribution of the mixing ratio and horizontal wind vectors at 750 hPa is shown in Fig. 6. The results of the three-dimensional trajectory analysis are shown in Figs. 7 and 8 for the four strongest dry air events. Before we discuss the wind fields and tr-
Fig. 6. Mixing ratio and horizontal wind vectors at 750 hPa at (a) 0000 UTC 13 Nov 1992, (b) 1200 UTC 25 Nov 1992, (c) 0000 UTC 2 Jan 1993, (d) 0000 UTC 2 Feb 1993, and (e) 0000 UTC 4 Feb 1993. Contour interval is 1 g kg\(^{-1}\). Areas of more than 9 g kg\(^{-1}\) are shaded.

jectories, the issue must first be raised as to the accuracy of the GANAL winds and whether they can be used to determine the origin of these events through trajectories. Fortunately, the strong similarities between the GANAL and in situ horizontal winds of IFA suggest some confidence in using GANAL for the trajectories, as the correlation coefficients between these fields are 0.94 with an rms of 2.2 m s\(^{-1}\) for the zonal wind component and 0.76 with an rms of 2.1 m s\(^{-1}\) for meridional wind component at 700 hPa. These numbers are similar to the 2–3 m s\(^{-1}\) rms difference values derived from the observed winds and the ECMWF analysis (Nuret and Chong 1996). Since the accuracy of the Omega sonde wind measurements is thought to be near 2 m s\(^{-1}\) and the soundings represent the impact of subgrid-scale processes in GANAL, one can conclude that the wind fields are generally quite close to the in situ values and that the observed horizontal flow should be well represented. While the vertical motions are more problematic in global analysis in the Tropics due to the influence of con-
Fig. 7. Backward (solid) and forward (dotted) air parcel trajectories calculated from 18°N, 155°E, 800 hPa for 1200 UTC 13 Nov 1992 (plus), 0000 UTC 26 Nov 1992 (asterisk), 0000 UTC 28 Dec 1992 (solid circle), 1200 UTC 2 Jan 1993 (diamond), 1200 UTC 6 Jan 1993 (triangle), 0000 UTC 2 Feb 1993 (square), and 0000 UTC 4 Feb 1993 (cross). Horizontal location of the trajectories with each symbol indicating 1-day intervals with “S” and “E” indicating starting and ending points within this domain.

Fig. 8. Vertical locations of the air parcels along the trajectories shown in Fig. 7. The symbols are also defined in Fig. 7.

convection, these events are generally associated with an absence of convection that makes the construction of reasonable trajectories less difficult. With these points in mind, three-dimensional trajectory analysis was employed to investigate the origins of the dry events. We calculated backward (maximum 10 days before) and forward (maximum 5 days after) air parcel trajectories for each case following the work of Numaguti et al. (1995). In this analysis, we calculated the vertical velocity from the continuity equation with a linear adjustment applied to obtain the vertical velocity = 0 at 100 hPa according to O’Brien (1970) (cf. a constant adjustment was applied in Numaguti et al. 1995). The trajectories were calculated starting from 18°N, 155°E, 800 hPa.

1) MID-NOVEMBER 1992

The dry event of 13 November is shown in Fig. 6a. In this figure, dry air (<3–4 g kg⁻¹) is present over the IFA and at the southern boundary of the domain near Australia (15°–20°S, 120°–160°E). In this analysis, the minimum mixing ratio in the vicinity of the IFA in Fig. 6a is only <4 g kg⁻¹. The observed value, in contrast, is less than 0.4 g kg⁻¹ at 750 hPa (see Fig. 5a of Parsons et al. 1994). This local difference is consistent with our earlier finding that the analysis generally underpredicts the local extreme magnitude of the drying partly due to a moist bias in the analysis, but it could also be due to the vertical resolution in the analysis, which is coarse relative to that of the rawinsonde data. Even though the analysis underpredicts the drying, the analysis does produce a very localized dry area over the IFA region. We strongly suspect that the localized nature of the minimum in the mixing ratio over the IFA is the result of assimilation of the sounding data from TOGA COARE into the analysis, since previous studies that employed satellite images of vertically integrated water vapor discuss the dry events as having the appearance of tongues of reduced moisture (Mapes and Zuidema 1996) rather than local minimum over the Tropics. The appearance of the local minimum over the sounding domain suggests that the model output and observations outside of sounding regions have difficulty reproducing the extreme drying. For example, satellite estimates of vertically integrated water vapor may be useful for determining the location of a dry event but lack the information necessary to properly correct the vertical distribution of water vapor.

The pattern of winds in the Tropics over the GANAL domain at this time is dominated by weak gyres resulting in regions of enhanced zonal and meridional flows. The dry air and the southerly winds between 150° and 160°E are suggestive of dry air being advected from the subtropics into the equatorial regions, although the driest region over the IFA is located to the east of the strongest southerly winds. The southerly winds are part of strong east-western flow from the Southern to the Northern Hemisphere. A corresponding cross-equatorial northerly flow is evident to the east of the IFA near the dateline. The horizontal projection of the trajectory for this case shows that the dry air that passed over the IFA was located at 30°S (over southern Australia) 6 days earlier (Fig. 7). The trajectory was initially southwesterly and became more southerly as the air moved into the Tropics. The large latitudinal displacement is surprising considering that some previous studies have discussed these dry intrusions in terms of tropical dynamics or displacement from the subtropics. From the daily progression of the dry air, it is evident that the air decelerated as it moved equatorward toward 10°S but then accelerated as it moved yet closer to the equator. After it arrived over the equatorial area, the wind advecting the dry air changed to weak westerlies and eventually had a north-
erly component. The vertical projection of the trajectory, shown in Fig. 8, indicates that consistent subsidence occurred as the air moved to the Tropics with the air initially located near the 570-hPa level. After the air passed over the IFA the GANAL analysis indicates the air moved rapidly upward in association with convective activity. Considering the extreme dryness, this aspect of the trajectory seems unlikely.

2) Late November 1992

In the 25 November case (Fig. 6b), the flow pattern has some similarities to the earlier event with westerlies to the west of the IFA and cross-equatorial flow associated with a large-scale gyre in the Tropics. The flow and mixing ratio field, however, suggest an intrusion of dry air from the Northern Hemisphere between 150° and 160°E. The accompanying trajectory in Fig. 7 shows that the air was rapidly advected from the northeast of the IFA with the flow originating near 30°N. Although the flow originated in an opposite hemisphere, the higher-latitude origin and initial westerly component are consistent with the 13 November case. In this case, however, there is a larger easterly component at lower latitudes. Another similarity to the 13 November case is that the initial origin is near the 570-hPa level, with generally weak subsidence when averaged along the entire trajectory (Fig. 8). In addition to the equatorward dry air transport, the poleward transport of moist tropical air is also evident in Fig. 6b, indicating an energy exchange between the Tropics and higher latitudes. For example, a typhoon existed near 17°N, 133°E associated with strong poleward winds and high mixing ratio between 160° and 170°E in the Northern Hemisphere. Areas of moist air being advected out of the Tropics can also be found near 17°N, 158°E and 10°S, 160°E.

3) Late December 1992–early January 1993

Some aspects of the 2 January (Fig. 6c) event are different from the previous two cases. In this event, for example, there are westerlies across most of the domain, with the strongest westerlies located south of the equator. To the north of the equator, the flow has generally a northerly component into the equatorial Tropics with significant variation with longitude. Strong equatorward flow is also present in the Southern Hemisphere to the south of the strong westerlies. In this figure an area of very low mixing ratio is not readily apparent across the IFA region but is clearly evident just to the north of the IFA, which is consistent with Figs. 3a and 3b (e.g., dry air over Kapingamarangi but not in the IFA mean value). From the wind field, it is again likely that the dry air at Kapingamarangi was advected with northerly winds as is evident from this dry northerly flow to the north of the site.

The January event was very long lived with a suggestion of multiple pulses of dry air, as was noted in the discussion of Fig. 3a. For this reason we constructed three different trajectories for this case: for 28 December at 0000 UTC, 2 January at 1200 UTC, and 6 January at 1200 UTC (Figs. 7 and 8). The earliest trajectory shows the flow again could be traced back to the edge of our analysis domain at 30°N in the westerly flow. In the second and third trajectories there is the same general flow pattern, but with the air tending to originate at lower latitudes. All the trajectories indicate a similar vertical location with mean subsidence along the trajectory as the air moved toward the IFA. In these trajectories and in the trajectories for the two November cases, the subsidence is greater when the parcel is at higher latitudes in the westerly flow poleward of 20°.

4) Early February 1993

Since the winds evolved during the February dry air event, horizontal cross sections from both 2 and 4 February (Figs. 6d and 6e, respectively) are presented for the dry event observed at Kapingamarangi. On both days there are strong westerlies to the south of the equator, however, in the earlier cross section, strong westerly flow is also evident north of the equator, west of approximately 150°E. Conditions are very moist east of 165°E and within 10° of the equator for this case. From examination of Fig. 6d, it appears that on 2 February the dry air over the IFA came from tropical areas to the west (120°–130°E) accompanying the strong westerlies. Later during this dry event (Fig. 6e) the dry air advected from the Northern Hemisphere with southward winds associated with counterclockwise wind pattern. The trajectories for this event in Fig. 7 are consistent with the described flow, with the 2 February trajectory starting from tropical latitudes just north of the equator and the 4 February case originating at higher latitudes to the east-northeast of the site. The origins of both trajectories are from relatively lower latitudes than the other events, which is perhaps expected since the entire flow pattern shifted significantly southward for this event, with westerlies south of equator. The change in the location of the origin of the air in this case is quite different from the January event, which indicated a prolonged period when dry air was advected from the northeast of the IFA. The vertical motions are also different with very strong subsidence on 2 February and only very slight mean subsidence in the equatorward flow in the later trajectory (Fig. 8).

c. Some general characteristics

In the previous analysis there is a general consistency between the different trajectories in both the horizontal and vertical displacements with the dry flow most frequently originating near the fringes of the westerly flow within or poleward of the subtropics and subsidence taking place as the air moves equatorward. While past studies did not generally investigate such high-latitude
origins in detail, some aspects of our trajectory analysis can be expected from earlier work. For example, our trajectories within the Tropics for the two November cases are almost the same as the trajectories shown in Figs. 20 and 21 of Numaguti et al. (1995), in spite of the different adjustment methods for deriving the vertical motions. In addition, the January and February trajectories show that air parcels often move rapidly eastward after they reach the equatorial region, in agreement with the work of Sheu and Liu (1995) relating the drying to strong westerlies. Finally, past studies have indicated subsidence associated with these dry events. The subsidence of air from higher latitudes moving toward the equator can be expected from conservation of potential vorticity. From Fig. 6, the trajectories in Figs. 7 and 8 and past studies, it is clear that the driest air near the equator arises from advection of air from higher latitudes in the westerly flow together with subsidence, rather than simply subsidence of tropical air alone. The mean value of the subsidence of six higher-latitude trajectories (except 2 February case) in our case is only about 200 m day$^{-1}$ prior to the air reaching the equator, with stronger values evident on the poleward portions of the trajectories. Although this value is smaller than that of previous studies [300–500 m day$^{-1}$ Numaguti et al. (1995) and Yoneyama and Fujitani (1995)], it can be regarded as consistent with estimates from radiative cooling (Mapes and Zuidema 1996). Since the values of subsidence discussed in the previous studies were often estimated indirectly from the observations, it is possible that the smaller values of subsidence found from using GANAL may be the cause of the moist bias in the GANAL data discussed earlier in this section.

The mean horizontal wind speed of the seven trajectories when the flow was within the Tropics and sub-tropics was about 8 m s$^{-1}$, which was significantly faster than the mean wind speed of 4 m s$^{-1}$ in the lower levels (1–4 km) averaged over the IOP in the vicinity of the IFA. This finding is consistent with the rapid advection of air from higher latitudes and the presence of strong westerlies after some of these parcels reached the equatorial latitudes. In general, these high speeds indicate that the advection pattern is associated with general disturbed conditions in the flow field.

To this point our discussion has largely ignored the forward portion of these time-dependent trajectories, in which a westerly component to the flow often developed after the dry air entered the equatorial areas. The magnitude of the westerly flow and the vertical motions in the forward trajectory varied significantly from case to case, with the air generally remaining in the tropical latitudes with the exception of the 2 February trajectory that originated in the Tropics, moved westward, and finally moved out of the Tropics into the relatively higher latitudes of the Southern Hemisphere. In some cases, the vertical displacement of the flow became quite large during the forward portion of the trajectory with upward motions associated with convection. The rapid development of deep convection following the arrival of dry air over equatorial regions is inconsistent with the results of past studies, which indicate that the dry air is associated with relative suppression of deep convection.

4. Synoptic analysis of the dry events

The analysis in the previous section indicates that the dry air events are relatively common with dry air over the IFA during approximately 9%–17% of the IOP. The trajectories showed some general consistencies from event to event, as the dry air rapidly advected in a time period of 4–8 days from edge of the midlatitude circulations to the deep Tropics. Due to the high-latitude origin of these events, we will examine midlatitude processes to determine if some common flow characteristics not readily evident in the Tropics can be distinguished in the midlatitudes. We will begin by discussing the general synoptic circulations, particularly the meridional winds associated with these events. As mentioned earlier, we employed the ECMWF analysis for this purpose.

a. Southern Hemisphere origin event

The 13 November case was the only event with Southern Hemisphere origin (Fig. 6). Daily horizontal cross sections of meridional winds at the 700-hPa level for the time period of 3–8 November are shown in Fig. 9. On 3 November (Fig. 9a), the meridional winds are generally located in midlatitudes in the latitude band between 30° and 60°S. On 4 November (Fig. 9b), the pattern becomes somewhat more regular, with a zonal wavelength of approximately 45°–50° longitude over the latitude of interest, characteristic of wavenumber 6 or 7. From the wavelength and general appearance of the flow, we conclude that the meridional circulations are midlatitude baroclinic waves (e.g., Simmons and Hoskins 1978). The meridional fluctuations associated with these baroclinic waves also extended further equatorward on this day. This equatorward expansion continues as on 5 November (Fig. 9c) there is a separate wave train with distinct maximum in meridional variations found between 20° and 40°S. These disturbances rapidly weaken over the next several days over the western Indian Ocean (Figs. 9d–f), while in the eastern portion of the analysis domain (in the vicinity of Australia) one of the troughs persists ahead of a strong midlatitude trough located near 120°E.

The extremely dry air in this event makes the location of this air mass very easy to distinguish in the horizontal cross sections of humidity in the GANAL and ECMWF analyses. Using these characteristics of the event, the locations of the center of the dry air mass in the ECMWF analyses are also shown in Fig. 9 for each day. Beginning on 3 November there is a good correspondence between the location of the dry air mass and southerly winds associated with this disturbance in the
meridional flow in the trough. If the sources and sinks of dry air and vertical advection are ignored, the centroids of the dry air mass can be used to produce a trajectory. This qualitative technique has the disadvantage that a parcel’s movement is not necessarily consistent with the wind field, but the technique also has the advantage that it is relatively free from the accumulation of analysis errors in the horizontal wind field or the computation of the vertical motions. Comparison of this trajectory with the previous GANAL trajectory for this event (Fig. 7) indicates excellent agreement between the two techniques and between the two different datasets.

In order to better clarify the subtropical and midlatitude wave patterns, we also show the wind vectors and contours of the zonal wind component at the 200-hPa level on 3 November at the start of this period (Fig. 10). At this time, there are two distinct jet streams over the region of interest, with a midlatitude jet maximum located between approximately 44° and 63°S, and a subtropical jet generally located poleward of 20°S. The behavior of the subtropical jet and its relationship to the circulation characteristics in the vicinity of Australia have been discussed by Hendon and Liebmann (1990). In general, the zonal magnitude of this jet increases across the Indian Ocean with the strongest winds located near eastern Australia. The general pattern of two jet streams persisted through this advection period. The occurrence of the wave pattern at the 700-hPa level (Fig. 9c) also roughly corresponds to the location of these two jets. At this level, the equatorward expansion of the midlatitude baroclinic waves seems to excite a distur-
bance in the vicinity of the subtropical jet. The amplification of the midlatitude baroclinic wave by the subtropical jets may have allowed the dry air in this one summer hemisphere event to reach tropical latitudes.

From these analyses we conclude that the initial advection of the dry air took place due to the equatorward flow in one of the waves of a series of subtropical disturbances near the subtropical jet. It appears that these subtropical waves had a connection to baroclinic waves, followed by the separation of amplifying waves into separate mid- and lower-latitude maxima resembles the well-known tendency of midlatitude baroclinic Rossby waves to become "fractured" as the more rapidly moving poleward portion of the wave separates from the slower moving equatorward portion (e.g., see Bluestein 1993, p. 119). At upper levels (i.e., 200-hPa level), however, there is the appearance of longer-lived disturbances along both jet axes (not shown), suggesting that there may also be a separate preexisting instability along the subtropical jet. Regardless of the details of these wave trains, we believe these results show the importance of waves outside of the Tropics in explaining this dry air event.

b. Northern Hemisphere origin events

The meridional wind patterns at 700 hPa for the late November event are shown in Fig. 11 at 2-day intervals beginning on 16 November. At this initial time (Fig. 11a), the meridional wind variations are generally restricted to higher latitudes in the Northern Hemisphere with maximum amplitudes located near 45°N. Two days later on 18 November (Fig. 11b), the pattern begins to change with strongest meridional winds located poleward of 45°–50°N and a weaker secondary maximum centered near 30°N. On 20 November (Fig. 11c), the pattern continues to evolve with increases in the amplitude of the disturbances, a shortening of the horizontal wavelength in the zonal direction, and a broadening of the latitudinal extent with the general appearance of amplifying midlatitude baroclinic waves. This amplification generally results in these midlatitude waves having significant amplitude at relatively lower latitudes compared to the pattern at earlier times. For example, 10 m s⁻¹ fluctuations extend nearly to 20°N on 20 November while on 16 November these changes were generally restricted to poleward of 35°–40°N. The strong amplitude pattern in the meridional winds continued on 22 November (Fig. 11d). On 24 November (Fig. 11e), the strong meridional winds in the midlatitudes and subtropics finally retreated poleward, although significant disturbances now seem to exist in the Tropics particularly west of the dateline.

Superimposing the locations of the dry air masses as defined in the horizontal projections of the trajectory for this event (Fig. 7) onto Figs. 11b–e allows us to relate the dry intrusion event to these synoptic events. From this superimposition, it is evident that the dry air mass is advected equatorward in the meridional winds associated with the secondary maximum centered on 30°N (Fig. 11b), is subsequently advected southward and eastward on the equatorward edge of the meridional wind pattern associated with the amplifying waves (Figs. 11c and 11d), and finally is advected toward the equatorial regions by the tropical disturbances that develop north of the IFA (Fig. 11e). [The reader is reminded that the height of the trajectory varies during
Fig. 11. Same as Fig. 9, but the two-day intervals beginning at 0000 UTC on 16 Nov 1992. The “X” in (b)–(e) indicates the dry air trajectory shown in Fig. 7.

At this time (Fig. 8) but examination of the meridional flow at different levels confirms this interpretation.

The wind vectors and contours of zonal winds at the 200-hPa level on 20 and 22 November are shown in Figs. 12a and 12b. Over much of the domain, zonal maximum can be observed with westerlies extending to nearly 20°N (Fig. 12a). During this period, the pattern across the Pacific at the 200-hPa level rapidly evolves from strong westerlies across the North Pacific on 20 November (Fig. 12a) to the development of intense easterly winds associated with the tilted trough near the date line (Fig. 12b).

The other two cases of the late December–early January and the late January–early February events show a number of similarities to the late November event. The 700-hPa level wind vectors and contours of meridional wind component are shown in Fig. 13a for 24 December and in Fig. 14a for 29 January, which correspond to the time when dry air was initially advected equatorward across the subtropics, respectively. In both cases, it is clearly evident that there is a latitudinal extent of northerly wind region associated with a midlatitude trough from the midlatitudes to the subtropics. Superimposing the horizontal projections from Fig. 7 for those events provides further evidence that the dry air is advected equatorward on the southern edge of the midlatitude baroclinic wave disturbances. In Fig. 14a, the trajectory of the 2 February event is also denoted. Although it shows that the dry air is advected from the far west region, it is suggestive because it is located south of the another midlatitude trough.

The 200-hPa level wind patterns for both events (Figs. 13b and 14b), on the other hand, show the strong westerly jet across the Pacific extending as far south as 20°N.
This jet is disturbed equatorward near the date line for Fig. 13b and east of the date line for Fig. 14b.

c. Discussion

From this analysis, we propose that midlatitude processes play an important role in advecting dry air into the midtroposphere in the subtropics. In each case we were able to correlate the advection of dry air into the Tropics with amplifying troughs that extended from higher latitudes into the subtropics. The westerly winds in these cases extended to a latitude of approximately 20° of the equator either in association with a subtropical jet or an equatorward displacement of a midlatitude feature.

Numaguti (1995) proposed that the intensification of a 200-hPa trough could bring high extratropical vorticity into low latitudes and that these events could generate intense counterclockwise vortices and perhaps excite an equatorial 15-day Rossby wave mode. Numaguti (1995) suggested that these processes were due to critical latitude absorption of extratropical Rossby waves, noting similarities to studies by Held and Phillips (1987) and Randel and Held (1991). Numaguti (1995) investigated Rossby wave breaking events in order to understand the forcing of tropical waves and the injection of midlatitude vorticity into the Tropics primarily at upper levels. There is a rich literature on Rossby wave breaking due to interest in how large-scale Rossby waves propagating along the edge of the polar vortex break and eject air into the midlatitudes (e.g., Polvani and Plumb 1992), with recent attention turned to the behavior of the subtropical and tropical flow to the south of the wave breaking region (Norton 1994; Polvani et al. 1995). The study of two idealized baroclinic wavenumber-6 disturbances by Thorncroft et al. (1993) is particularly relevant to the scale of the disturbances found in our study. Two different life cycles were isolated in idealized studies.
by Thorncroft et al. (1993) for these waves depending upon different initial mean flows first described in Simmons and Hoskins (1980) as “basic” and “anomalous” conditions. In the basic case with mean anticyclonic shear, conditions analogous to Rossby wave breaking occur with thin NE–SW-oriented troughs extending equatorward near the troposphere. These troughs can eventually also produce one or more cutoff cyclones at upper levels. In the lower troposphere, the flow during the wave breaking is dominated by anticyclones in the subtropics that eventually become elongated in the east–west direction.

Figure 15 shows the vorticity field for various dry intrusions including those discussed in terms of the trajectory analysis and other weaker events evident in Fig. 3b. The first five panels show Northern Hemisphere events for 3 and 24 November, 28 December, and 8 and 24 February. In nearly all these cases, there is a clear vorticity signal associated with a thin trough generally extending NE–SW into the lower latitudes. In these events, the troughs are clearly evident typically as far south as 10°–20°N. At lower levels, the subtropical flow is dominated by anticyclones whose behavior also has some similarity to the sequence of events described by Thorncroft et al. (1993). For example, the 850-hPa flow and geopotential field in the well-defined 21 November case shows strong anticyclonic flow near the time of the intrusion with low pressure centers primarily restricted to higher latitudes (Fig. 16a). Three days later these anticyclones become elongated and the flow becomes more zonal (Fig. 16b). While the Rossby wave breaking process is often studied in terms of polar–midlatitude interactions, these observations show that it is also quite relevant to study midlatitude–tropical interactions, es-
especially in cases where the westerlies are displaced equatorward.

The flow and advection patterns for these Northern Hemisphere events are consistent with the general schematic put forth by Thorncroft et al. (1993) (see their Fig. 1) and the Rossby wave behavior described in their study. We propose that our trajectory analysis of the Northern Hemisphere cases is also consistent with this mechanism in the following manner. First, dry air at the edge of the westerlies in the subtropics and lower mid-latitudes is incorporated into the amplifying troughs that are extending equatorward and elongating in a NE-SW direction. After entering the vicinity of the troughs, the dry air subsides as it moves equatorward within the trough with the largest subsidence taking place poleward of approximately 20°-22°N. From the pattern of westerlies the subsidence would tend to be greatest prior to the breaking of the waves. As the air moves equatorward and subsides, the flow becomes increasingly under the influence of the anticyclone in the lower and mid-troposphere. The flow generally remains on the eastern edge of the anticyclonic flow as evident by the continued general NE-SW flow. This general flow character is not unlike the general schematic of a baroclinic wave.

5. Conditions in the Tropics associated with the dry intrusions

The vorticity signal associated with the troughs typically extended to within 10°-15°N of the equator. Having established the mechanism for the advection of dry air into the Tropics, we now return to investigate the behavior of dry air events within the Tropics. Our motivation is partly driven by the impact of these troughs on the dynamics of the Tropics, as the sequence of events investigated for the 25 November case, there was evidence presented that tropical disturbances were amplified during these intrusion processes and that the
strong meridional circulations associated with these disturbances advect the dry air within the Tropics toward the equator (Fig. 11). Also, as mentioned earlier, Numaguti (1995) proposed that these thinning troughs may excite tropical wave disturbances. Our motivation is also partly driven by determining how the dry air moves from the edges of the Tropics to the equatorial areas.

a. Spectral analysis

We used spectral analysis to investigate the dynamics of the equatorial areas during TOGA COARE. This analysis is employed since it allows one to relate tropical circulations to periodic structures predicted from linear theory. Past studies revealed that there exist many kinds of periodic disturbances over the tropical western Pacific: 1.5–2.5-day inertio-gravity waves (Takayabu 1994b; Chen et al. 1996), 4–5-day mixed Rossby–gravity waves (Nitta 1970; Hendon and Liebmann 1991; Takayabu 1994a; Numaguti 1995; Pires et al. 1997), 8–20-day equatorially trapped $n = 1$ Rossby waves (Numaguti 1995; Kiladis and Wheeler 1995; Pires et al. 1997), and the 30–60-day intraseasonal oscillation (Madden and Julian 1971, 1972).
Due to our interest in the meridional transports of dry air, we begin by examining the sounding time series for periodic structures in the equivalent potential temperature (Fig. 17). Clear signals in the spectral analysis in the lower and midtroposphere are expected, since as was first noted by Parsons et al. (1994), these dry air events are associated with extreme reductions in the equivalent potential temperature as the reduced water vapor content dominates over the warming. In this spectral analysis (Fig. 17), significant variations in the equivalent potential temperature do occur between 9 and 14 days and at time periods greater than 25 days. The 9–14-day period corresponds to the vertical layers where the extreme dry advection occurs, while longer-period events extending to greater depths correspond to the general drying associated with the suppressed phases of the intraseasonal oscillation. The two different timescales and vertical levels of fluctuations are consistent with the earlier discussion of the plots of humidity deficits in Fig. 3, where a tendency for two different types of drying events was noted. The frequency of the midtropospheric events in Fig. 3 is generally consistent with the 9–14-day spectral peaks. The disturbances near the tropopause at these timescales might be consistent with the remnants of upper-level troughs associated with this advection mechanism, although we are somewhat skeptical of the results near the top of the domain as the sounding data, particularly for humidity, becomes unreliable.

We next examine the spectral densities of the meridional flow in the midlevels. Given the vertical extent of the trajectories, we will present data at the 700-hPa level. Figures 18a and 18b show the results of spectral analysis of the meridional wind component at 700 hPa along 154°E for November–December and for January–February, respectively. These two time periods were selected in part to compare to the work of Numaguti (1995) and to distinguish the different regimes described by Numaguti and Pires et al. (1997). For the November–December period (Fig. 18a), spectral peaks of 4–6 days can be found along the entire latitude range, 6–8 days between 3°S and 10°N, 10–20-day peaks to the south of 5°S and to the north of 10°N, and greater than 20-day peaks off the equator in both hemispheres. (Due to the short time record, the reader is urged to treat the results at longer time periods with some caution.) The 4–6-day period is consistent with the mixed Rossby–gravity waves, which Numaguti (1995) and Pires et al. (1997) found to be very active over the equatorial western Pacific during November, while the off-equator maximum between 15 and 20 days is likely to be related to the Rossby waves discussed by Numaguti (1995). In contrast, during January–February (Fig. 18b), the peaks are more localized in the shorter period range rather than extending over the entire latitude band, which is consistent with a general weakening of the mixed Rossby–gravity waves. In addition, during the latter two months there were 7–8-day spectral peaks in the Northern Hemisphere, a 10–15-day peak along nearly the entire latitude range, 16–24-day peaks between 5°N and 20°S, and over 30-day peaks off-equator in both hemispheres. The activity in the 7–10-day periods, with the tendency for meridional flow over the equator, is consistent with the work of Pires et al. (1997). One inference that does seem clear from this analysis is that at the 9–14-day period corresponding to the changes in the equivalent potential temperature the signals are concentrated at the poleward edges of the analysis domain, particularly in the Northern Hemisphere where the advection events typically occur. This behavior is consistent with our hypothesis that the advection events are forced by processes taking place at higher latitudes.

As mentioned earlier, the most noticeable difference between the two time periods is the clear 4–6-day signal spread across the entire range of latitude in November–December (Fig. 18a) that was clearly absent in January–February (Fig. 18b). This seasonal difference is to be expected, if the 4–6-day signal is due to mixed Rossby–gravity waves, as Hendon and Liebmann (1991) found 4–5-day mixed Rossby–gravity waves confined to the boreal fall and only within about ±30° longitude of the tropopause.
date line, because of a singularity in the sea surface temperature (SST) distribution. According to the SST analysis for the TOGA COARE IOP by Gutzler et al. (1994), the 3-month mean SST is greater than 29.5°C during the boreal fall and less than 29.5°C during the boreal winter north of the equator and near the date line, while south of the equator the SST is greater than 29.5°C during fall and winter (see their Fig. 2). Hence, this analysis indicates that a singularity of SST exists during this period, again suggesting that 4–6-day mixed Rossby–gravity waves are less likely during January and February.

Time–latitude sections of the mixing ratio and meridional wind component at 700 hPa along 154°E are shown in Figs. 19a and 19b. Figures 19c–e show the meridional wind after applying bandpass filters at 3–6, 6–16, and 24–60 days, respectively. As expected from the previous discussion regarding activity with 3–6-day periods, large-amplitude features with broad latitudinal extent with these short periods are only evident during November. The 3–6-day bandpass-filtered meridional wind components are in phase for both hemispheres and their phase speed is approximately 12 m s\(^{-1}\) (not shown here), again suggesting a mixed Rossby–gravity wave consistent with the findings of Numaguti (1995) and Pires et al. (1997).

The broad 6–16-day bandpass was selected to correspond to events that impact the equivalent potential temperature. This filtered wind field should contain several circulation features including the \(n = 1\) Rossby waves with periods of 15 days (Numaguti 1995) and a modified wave structures with periods between 7 and 10 days (Pires et al. 1997). From our study one would also expect to see the circulations associated with the penetration and breaking of Rossby wave at least near the poleward edges of our analysis domain. Some aspects of the 6–16-day filtered meridional winds (Fig. 19d) are consistent with the hypothesized presence of multiple disturbances as there are 1) time periods where near-equatorward maxima are found with periods of approximately 7–10 days, consistent with the waves discussed by Pires et al. (1997) typified by the period between days 22 and 50; 2) disturbances near the edge of the analysis domain that are consistent with either the breaking of midlatitude Rossby waves or the \(n = 1\) Rossby waves found by Numaguti (1995), such as evident during days 25–45 and days 50–81; and 3) disturbances with a broad latitudinal extent, which seem to correspond to some of the dry events intrusions, most notably the 12 November, the early January, and the late February events.

The final timescale shown is the 24–60-day analysis (Fig. 19e). This flow should include the timescales of the westerly wind bursts and the intraseasonal oscillation. This analysis shows a general pattern of confluence and diffluence of the meridional flow. The strongest confluence into the Tropics seems to correlate with the buildup of strong westerlies observed in early January and early February.

**b. Tropical circulations and advection**

The importance of tropical circulations in the advection process was noted by Numaguti et al. (1995), who...
showed that mixed Rossby–gravity waves played a role in arrival of dry air over the near equatorial region during the late November case. The relationship between the nature of circulations and the advection of dry air is also evident in the comparison of the bandpass winds in Fig. 19 with the timing of the intrusions in Fig. 3. In Fig. 19, the four well-defined dry events at Kapingamarangi are labeled as A, B, C, and D, respectively. The arrival of the dry air during mid-November (A) from the Southern Hemisphere and the advection of dry air from the north during the late November case (B) both suggest the possibility of mixed Rossby–gravity waves playing a role in advecting the dry air equatorward within the Tropics as the 3–6-day bandpass winds show significant meridional winds with the proper direction during these times (Fig. 19c). It is not possible, however, to link the other dry events to circulations with these 3–6-day periods as the filtered winds are far weaker. Hence, it is not likely that within the Tropics a single type of disturbance is responsible for the advection of dry air from the edges of the Tropics toward the equatorial regions.

Further evidence for this conclusion is our earlier discussion of the 6–16-day disturbances where it is mentioned that these filtered meridional winds correspond to advection of dry air for the 12 November (A), early January (C), and late February dry events. In addition, the multiple and long-lived dry advection during late December and early January corresponds to well-defined northerly winds in the total meridional wind field and strong northerly winds in the 24–60-day bandpass winds. These winds extend from the equator through the subtropics in the Northern Hemisphere in association with confluence into the Tropics and westerly wind bursts. The fluctuations in moisture during the prolonged late December–early January event can be viewed as smaller-scale transient features embedded in this generally favorable large-scale flow. Hartten (1996) found strong flow toward the Tropics in the synoptic setting of westerly wind bursts. While the existence of strong equatorward flow in the Tropics can account for the equatorward advection of dry air, tropical circulations opposing the advection process may account for those instances where tilted troughs extend into the Tropics, but no equatorial fluctuations in thermodynamics are readily observed, such as the Northern Hemisphere trough during mid-November (Fig. 15f), when dry air was instead being advected from the Southern Hemisphere. Thus, while a single mechanism (baroclinic waves) is responsible for advection of the dry air into the Tropics, once in the Tropics dry air is advected by different types of disturbances. The process is not simply one of passive advection, as we noted earlier that the troughs can excite wave disturbances in the Tropics and the dry air also impacts the thermodynamics of the tropical atmosphere and thus the cloud fields.

6. Conclusions

Analysis of the TOGA COARE dataset has revealed the frequent appearance of extremely dry air in the lower and midtroposphere over this equatorial region. Various aspects of these dry air events have been discussed in Parsons et al. (1994), Numaguti et al. (1995), Yoneyama and Fujitani (1995), Sheu and Liu (1995), Mapes and Zuidema (1996), and Johnson et al. (1996). These studies have shown that the dry air was advected into the TOGA COARE area from higher (subtropical) latitudes. Our study lends further support to these earlier findings, which show that the driest air in this equatorial region is often not simply subsiding tropical air in association with the suppressed phase of the intraseasonal oscillation, but is instead often gently subsiding air with origins outside the Tropics. Through extending the latitudinal range of the study of the origins of these dry air masses, we were able to link the advection events to processes in midlatitudes. Thus we can state that the suppression of deep convection in the Tropics during these dry air periods or tropical droughts (Brown and Zhang 1997) have midlatitude origins.

From our findings, we propose that the primary
framework for understanding these dry air events is favorable meridional circulations in the deep Tropics coupled with dry air from the higher-latitude westerlies being injected into the Tropics from breaking Rossby waves associated with the life cycle of baroclinic waves. From our results, we can suggest that one must treat the relationship between spectral analysis and linear tropical waves with some caution at timescales near those of
midlatitude waves as the troughs and accompanying vorticity fields clearly extend into the Tropics, producing a time series that may contain both tropical periodic disturbances and midlatitude effects. Although the superimposition of the subtropical and midlatitude circulations appears chaotic, the dry air events do have a characteristic timescale of between 8 and 15 days.

The general nature of exchanges of tropospheric air between the Tropics and midlatitudes is becoming well known (e.g., Newell et al. 1992; Pierrerehubert and Yang 1993; Yang and Pierrerehubert 1994; Tuck et al. 1997). Pierrerehubert (1995) showed the significance of this exchange for the climate of the Tropics, arguing that dry air exchanges can regulate the tropical climate to a larger degree than cloudiness. Our study shows that these exchanges can commonly produce extreme drying events in the Tropics, perhaps more efficiently than subsidence of tropical air. We believe that this finding underscores the potential importance of these exchanges.

This study raises a number of questions for future work, such as the seasonal dependence of these dry events and their spatial distribution on the global scale. Also since we have presented evidence that these events are poorly represented by global models, the implications, if any, of this analysis error on climate studies and weather prediction should be addressed. Problems in representing this dry advection in large-scale models is consistent with the work of Thornicroft et al. (1993), where the thinning troughs and the wave breaking process was only resolved at relatively high resolution. Finally, the impact of these systems on the tropical atmosphere–ocean system is also in need of further investigation. A companion paper by Parsons et al. (1997), manuscript submitted to Quart. J. Roy. Meteor. Soc.) addresses this interaction.

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