Influence of Cold Air Intrusions on the Wet Season Onset over Amazonia

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ABSTRACT

Using 15-yr data from the European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-15), the authors found that rapid southeastward expansion of the rainy area from the western Amazon to southeastern Brazil is a result of midlatitude cold air intrusions. During austral spring, as the large-scale thermodynamic structure over Amazonia becomes destabilized, the incursions of extratropical cold air can trigger intense rainfall along the leading edge of northwest–southeast-oriented cold fronts east of the Andes. As these fronts penetrate into Amazonia, the northerly or northwesterly wind transports warm, moist air from the western Amazon to southeast Brazil. Moisture convergence consequently intensifies, resulting in northwest–southeast-elongated rainy areas. The latter contribute to the observed rapid, southeastward expansion of rainy areas shown in rainfall climatology during austral spring.

The authors’ analysis suggests that cold air intrusions during austral spring collectively assist the transformation of large-scale thermodynamic and dynamic environments to those favorable for the wet season onsets. Each time the cold fronts pass by, they tend to increase the atmospheric humidity and the buoyancy of the lower troposphere, which destabilizes the atmosphere. In the upper troposphere, the cold air intrusions supply kinetic energy for the development of anticyclonic flow. Cold air intrusions in the transitional season are not different from those occurring immediately before the wet season onsets except that the latter occurs under a more humid and unstable atmospheric condition. Thus, cold air intrusions can trigger the wet season onsets only when atmospheric and land surface conditions are “ready” for the onset.

Comparisons among early, normal, and late onsets on an interannual scale further suggest that more frequent and stronger cold air intrusions trigger the early onsets of wet seasons given suitable large-scale thermodynamic conditions. Likewise, less frequent and weaker cold air intrusions could delay the wet season onset even though the large-scale thermodynamic conditions appear to be favorable. Occasionally, strong unstable atmospheric thermodynamic conditions and northerly reversal of cross-equatorial flow can lead to wet season onsets without cold air intrusions. In such cases, enhanced precipitation is centered over central and eastern Amazon, and rainfall increases more gradually compared to the onset with cold air intrusions.

1. Introduction

The spatial pattern and rapid pace of the wet season onset over South America have puzzled meteorologists for years, challenging their understanding of the processes that control the wet season onset. As documented by Kousky (1988), Horel et al. (1989), Marengo et al. (2001), and Gan et al. (2004), the wet season onset usually begins over the northwestern Amazon in austral spring and rapidly progresses southward and southeastward over the western Amazon and southeast Brazil across about 20°–25° latitudes within a few weeks (Horel et al. 1989). Such rapid southeast migration of the rainy area is unique to the South American summer monsoon system.

The onset dates of the rainy season over South America could vary up to three months on interannual scales (Marengo et al. 2001; Li and Fu 2004). Fu et al. (1999) have found that destabilization of the large-scale thermodynamic condition generally controls the seasonal change of rainfall. Li and Fu (2004) and Fu and Li (2004) further showed that the transition of the thermodynamic conditions from the dry to wet seasons is initiated by the increase of surface heat fluxes, then continuing with the increase of large-scale moisture transport resulting from the reversal of the cross-equatorial flow. The interannual variations of the large-
scale thermodynamic instability are largely determined by the variations of land surface fluxes during the dry and early transition seasons and the reversal of the cross-equatorial flow (Fu and Li 2004). While the general timing of the wet season onset appears to be mostly controlled by the transition of thermodynamic conditions, one cannot determine precise dates of sudden onset of the wet seasons nor fully explain their interannual changes of the onset. For example, in 1982 the land surface wetness and static instability in the lower troposphere appear to have provided a suitable thermodynamic environment for an early wet season onset, but the synoptic weather activities that penetrated into tropical South America were abnormally weak; the onset date is about 30 days later than that of the climatological onset.

Previous studies have shown that the onset of the Asian summer monsoon system can be triggered by a synoptic transient event such as a cold front or a disturbance such as those associated with the Madden–Julian oscillation (MJO: Madden and Julian 1994). The earliest onset of the Asian summer monsoon occurs in early to middle May over the South China Sea. Chang and Chen (1995) found that the equatorward intrusion of a midlatitude trough/front increased deep convection along a southwest edge of the cyclogenesis zone in the equatorial Indian Ocean, causing the summer monsoon onset over the South China Sea. In the western Pacific and Indian Oceans, the MJO has been suggested as a trigger for the onsets of the Indian (Webster 1987) and the Australian (Hendon and Liebmann 1990) summer monsoons, as well as a cause of the active-break cycles during the monsoon seasons (McBride et al. 1995).

The convective signal associated with the MJO is much weaker in austral spring in South America than it is in the Asian–Australian sector; therefore, it does not emerge as a prominent instigator of the onset mechanism (Liebmann et al. 2003), although it can modulate the South American low-level jet (LLJ) and the South Atlantic convergence zone (SACZ) during austral summer (e.g., Kousky and Kayano 1994; Kousky and Cavalcanti 1997; Nogués-Paegle and Mo 1997; Liebmann et al. 1998; Paegle et al. 2000). Midlatitude cold fronts, on the other hand, penetrate into subtropical and tropical South America along the east Andes all year-round (e.g., Oliveira and Nobre 1985; Garreaud 2000a; Siqueira and Machado 2004). Such surges dominate synoptic variations of atmospheric circulation and temperature over subtropical South America (Kousky and Cavalcanti 1997; Vera and Vigliarolo 2000). The structures of the cold frontal systems and their influences on precipitation during austral winter and summer have been documented extensively by previous studies (Kousky 1979; Kousky and Ferreira 1981; Marengo et al. 1997; Garreaud and Wallace 1998; Garreaud 1999, 2000a; Vera and Vigliarolo 2000; Vera et al. 2002). These strong cold fronts may account for about 50% of the total summertime precipitation south of 25°S, about 30% over the western Amazon basin, and 20% over the northeast coast of South America (Garreaud and Wallace 1998). The mean monthly distribution of the frequency of frontal passage between 5° and 20°S is the highest during the transition season (October–November: Oliveira 1986; Siqueira and Machado 2004; Machado et al. 2004). These cold fronts cause rainfall over an elongated area from the western Amazon to southeast Brazil similar to the typical geographic pattern of the rainy areas seen during the rapid onset of wet seasons. However, whether such midlatitude cold air intrusions indeed trigger the wet season onset and contribute to its interannual variations have not been previously investigated.

In this paper, we examine the cold air intrusions as a possible trigger of the wet season onset over the Amazon. This will not only help to determine the cause of rapid southeastward expansion of precipitation from the western Amazon to southeast Brazil, but also to further identify the cause of interannual variations for the wet season onsets. In section 2, data, methods, and definitions of cold air intrusions and the wet season onset are described. Section 3 gives the results. The discussion and conclusions are given in sections 4 and 5, respectively.

2. Data and methods

We use the European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA), rain gauge data (Liebmann and Marengo 2001; Marengo et al. 2001), and the Global Precipitation Climatology Project (GPCP) blended precipitation data in this study for the period from 1979 to 1993. The rain gauges are located within Brazil, and the rain gauge precipitation data were originally obtained from the National Water and Electric Energy Agency of Brazil (ANEEL). Over the Amazon basin, the gauge data were kindly provided by B. Liebmann. Six-hour instantaneous ERA data are on 2.5° latitude × 2.5° longitude resolution. ERA has been shown to better capture the seasonal cycle of the precipitation over tropical South America (Li and Fu 2004) than other reanalysis products. Similar to Li and Fu (2004), we focus on the domain, 5°–15°S, 45°–75°W, which will be referred to as the Southern Amazon region. The onset of the wet season over this region normally occurs in October or November (Marengo et al. 2001).
Since the wet season onset over Amazonia depends on the large-scale environment (e.g., Fu et al. 1999; Li and Fu 2004), we use surface sensible and latent heat fluxes, precipitation, temperature, humidity, and winds from ERA at 13 levels ranging from 1000 to 100 hPa to analyze land surface and atmospheric conditions. The kinetic conversion from divergent to rotational energy, which supports the upper-tropospheric anticyclonic circulation (Krishnamurti et al. 1998; Moscati and Rao 2001; Li and Fu 2004), is calculated as in Krishnamurti et al. (1998) and analyzed for the Southern Amazon region. Atmospheric thermodynamic fields related to the change of rainfall for the Southern Amazon region are represented by convective available potential energy (CAPE) and convective inhibition energy (CINE). CAPE and CINE are computed as in Williams and Renfro (1993) assuming convective air rising from 1000 hPa, and averaged over the Southern Amazon region. All variables associated with the land surface conditions and atmospheric thermodynamic background, especially those nonlinearly related to the input fields, are first computed from instantaneous values at 6-h intervals in the study. They are then averaged over a period of 5 days (a pentad). The pentad resolution has been shown to minimize daily variations and noise of the atmospheric background but is still fine enough to resolve the changes during the transition from the dry to wet seasons over Amazonia (e.g., Kousky 1988; Horel et al. 1989). Detailed evaluations of ERA precipitation and related atmospheric thermodynamic and dynamic fields by observations are given by Fu et al. (2001) and Li and Fu (2004).

The wet season onset is defined as the pentad before which rain rate is less than the climatological annual mean rain rate in the ERA (6.1 mm day$^{-1}$) during six out of eight preceding pentads and after which rain rate is greater than 6.1 mm day$^{-1}$ during six out of eight subsequent pentads. Detailed evaluation of this criterion for the wet season onset is described in Li and Fu (2004). Based on this definition, the onset dates are identified as shown in Table 1. The onset date of 1979 (pentad 49: 29 August–2 September) is more than one month earlier than that of the 15-yr average (pentad 62.5: 4 November). The onset dates for the 15 years occur in October or November, consistent with Marengo et al. (2001). Thus, we examine the climatological influences of cold air intrusions on wet season onsets for the period October–November for the 15 years. The corresponding fields influenced by the cold air intrusions are analyzed using daily resolution. A cold air intrusion is defined mostly according to Garreaud (2000a). The cold air index domain (referred to as the index area hereafter) is centered at 25°S, 60°W with a 5° latitude $\times$ 2.5° longitude grid. The index area is about 2.5° longitude narrower than it is in Garreaud (2000a) and seems to mostly capture the equatorward penetration of the cold fronts in austral spring based on the 15 years of ERA. As in Garreaud (2000a), we use the 24-h sea level pressure tendency (\delta SLP) as the key variable to identify the steep rise in sea level pressure (SLP) at the leading edge of cold air masses. The initial sets of cold air episodes are taken as the days when

<table>
<thead>
<tr>
<th>Year</th>
<th>Onset pentad</th>
<th>Onset calendar date</th>
<th>Dates of cold events appearing in Oct–Nov (with the wet season onset)</th>
<th>Annual mean rain rate (mm day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>49</td>
<td>29 Aug–2 Sep</td>
<td>13–17, 22–26 Nov (26–29 Aug)</td>
<td>8.2</td>
</tr>
<tr>
<td>1982</td>
<td>68</td>
<td>2–6 Dec</td>
<td>None (5–7 Dec)</td>
<td>6.0</td>
</tr>
<tr>
<td>1984</td>
<td>73</td>
<td>26–31 Dec</td>
<td>27 Sep–2 Oct (none)</td>
<td>4.9</td>
</tr>
<tr>
<td>1986</td>
<td>73</td>
<td>26–31 Dec</td>
<td>16–18 Oct, 9–12 Nov (none)</td>
<td>5.7</td>
</tr>
<tr>
<td>1987</td>
<td>64</td>
<td>12–16 Nov</td>
<td>30 Sep–3 Oct, 8–14 Nov (8–14 Nov)</td>
<td>5.4</td>
</tr>
<tr>
<td>1988</td>
<td>63</td>
<td>7–11 Nov</td>
<td>4–8, 26–28 Oct, 11–14 Nov (11–14 Nov)</td>
<td>5.6</td>
</tr>
<tr>
<td>1989</td>
<td>63</td>
<td>7–11 Nov</td>
<td>11–13, 25–30 Oct, 7–9 Nov (7–9 Nov)</td>
<td>6.4</td>
</tr>
<tr>
<td>1990</td>
<td>60</td>
<td>23–27 Oct</td>
<td>None (none)</td>
<td>5.9</td>
</tr>
<tr>
<td>1991</td>
<td>62</td>
<td>2–6 Nov</td>
<td>5–7 Oct (none)</td>
<td>6.0</td>
</tr>
</tbody>
</table>
δSLP is among the strongest 10% during the period October–November for the 15 years of our analysis. We only consider a cold air episode to be an independent event when it is separated from other similar events by at least five days, the same as in Garreaud (2000a). The criterion of SLP used by Garreaud (2000a) to identify cold air events in austral summer and winter is modified here for austral spring. Specifically, we retain those episodes in which SLP is higher than 1018 hPa based on its climatology during October and November. We also examine the evolutions of temperature at 925 hPa ($T_{925\,\text{hPa}}$) and 850-hPa geopotential height to verify the intrusion processes of the cold air events. The cold events that occurred in the period October–November and within the pentad in which the wet season onset are shown in Table 1. On average, two events could be seen in each transitional season. The most events happened in 1980; whereas in 1990 and 1982 there were no cold events in the austral spring.

We will first investigate the climatological influence of cold air penetrations on the wet season onset over Amazonia. Then we will compare the cold air influences on individual transitions of early and late onsets with those on the normal onset years (1990 and 1991) and the two very late onset years (1984 and 1986). We will discuss these special cases in section 3c.

To explore the connection between cold air intrusions and precipitation variations over South America during austral spring, Fig. 1a shows the linear regression coefficient of precipitation against SLP over the cold air index domain using ERA daily data in October and November for the 15 years. Shaded areas indicate the coefficient at the 95% significant level. Figure 1a shows that significant positive coefficients are found in the western Amazon and the SACZ, while significant negative coefficients are observed in the subtropics. This pattern is expected based on the typical location of cold fronts at the leading edge of the cold air mass. Since SLP increases and temperature decreases simultaneously during a cold air intrusion, negative correlations between the temperature and the precipitation fields in the western Amazon and the SACZ (Fig. 1b) are consistent with those shown in Fig. 1a. Figures 1a and 1b consistently suggest that precipitation increases over the western Amazon and decreases over most of the subtropics when a cold front approaches. The enhanced convection that precedes the cold fronts is consistent with the intense low-level wind convergence embedded in a conditionally unstable environment shown in Garreaud and Wallace (1998). The changes of SLP and temperature related to cold air surges during October and November also leave a clear imprint on convection over the SACZ as previously pointed out by Lenters and Cook (1999).

Figure 2 shows the composite sequence of 925-hPa geopotential height ($Z_{925\,\text{hPa}}$), equivalent potential temperature ($\theta_{e,\,925\,\text{hPa}}$), and low-level (1000–850 hPa) winds of the cold air events for the transition period. One day before the cold air approaches, a high pressure center is strengthened near the coast of Chile and a low pressure center can be observed on the east side of the Andes between 15° and 35°S (Fig. 2a). On day 0, the high pressure system becomes stronger and moves east-
ward, causing rapid increase of SLP and decrease of $T_{925 \ hPa}$ (Fig. 3) on the east side of the Andes. In the meantime, the lower pressure center moves northward so that it could tap the northerly warm and humid air from Amazonia, which leads to an increase of $\theta_{v,925 \ hPa}$ over the western Amazon north of 20°S (Fig. 2b). On day +1 and +2, a high pressure center develops to the east of the Andes (Figs. 2c and 2d). The low-level southerly winds also advance substantially farther north encompassing much of the western Amazon (Figs. 2c and 2d). Figure 3 shows the migration of the $T_{925 \ hPa}$ and precipitation during the cold air intrusion process. The 294-K isotherm appears to most closely follow the cold front; therefore, it is used here as an indicator of the leading edge of the cold air mass. Figures 3a and 3b show a warm and relatively lower rainfall over tropical South America before and when the cold air intrusions are first identified in the subtropics (day −1 and day 0). The heavy rainy area is mainly in the extratropics along the leading edge of the cold air mass (Fig. 3b). One day later (day +1, Fig. 3c), as indicated by the movement of the 294-K isotherm, the cold air mass moves northward into the tropical area and the cold front sharpens. Consequently, strong rainfall, which exceeds the 6.1 mm day$^{-1}$ criterion for the wet season onset, appears in a northwest-southeast area extending from the western Amazon, to southeast Brazil, and then to the southwestern Atlantic Ocean. On day +2 (Fig. 3d), as the cold air mass continues to move northward, so does the northwest–southeast elongated rainy area. Heavy rainfall is over the entire western and southern Amazon. The pattern of the rainy area shown in Figs. 3c and 3d closely resembles that typically associated with the wet season onset (e.g., Kousky 1988).

Wang and Fu (2002) and Li and Fu (2004) have suggested that the northerly reversal of the cross-equatorial flow, indicated by the averaged meridional wind at 925 hPa for the area of 5°N–5°S, 65°–75°W (referred to as the V index), is closely correlated with an increase of large-scale rainfall over Amazonia on an intraseasonal scale, including those that occurred during the wet season onset. When the V index is southerly, precipitation is mainly located to the north of the equator. When the V index is northerly, precipitation shifts toward the Amazon basin and subtropical South America (Wang and Fu 2002). Because the V index is often northerly during cold air intrusions in the seasonal transition, it raises a question as to whether the northerly cross-equatorial flow or cold air intrusions are mainly responsible for the rainfall increase as shown in Figs. 3c and 3d. In our attempt to separate the effects of these two processes on the rainfall, we exam-
ine the difference between the geographic patterns of rainfall associated with them during October and November. We compare the composite precipitation for all of the northerly V-index events to that of the northerly V index without cold air events for the 15 years. Assume that the latter only represents the effect of the northerly V index on rainfall and the former includes the influences of both cold air intrusions and the northerly V index. Subtracting the latter from the former allows us to isolate the influence of cold air intrusions by minimizing the rainfall increases associated with the V index (Fig. 4a). Only precipitation statistically significant at the 95% confidence levels is plotted here.

As illustrated in Fig. 4a, with the influence of the V index removed, precipitation caused by cold air intrusions increases along the western Amazon and southeast Brazil, with maxima around 5°–15°S, 75°–60°W and 10°–25°S, 50°–40°W. Figure 4b shows the precipitation pattern associated with the northerly V-index composite for all days with the northerly V index without cold front events. The maximum precipitation can be observed over the eastern Amazon around 5°–20°S, 55°–45°W, and over Paraguay and part of Argentina around 25°–35°S, 70°–60°W. Figures 4c, 4d, and 4e show the precipitation patterns at the wet season onset based on ERA, GPCP, and rain gauge data, respec-
tively. The composite method and definition of the wet season onset using GPCP and rain gauge data are the same as those of ERA but based on their own climatological annual rain rate for the 15 years. Notice that gauge data used in the study is only within Brazil and GPCP may be inaccurate in the subtropical South America due to using an infrared technique, which is more suitable for a deep convective system. Compared to GPCP and rain gauge data, the rain rate over the western Amazon in ERA (Fig. 4c) has similar magnitudes, but the maximum center is slightly more south than the centers of gauge and GPCP. Another maximum center of precipitation over the eastern Amazon shown in ERA is about 4 and 2 mm day\(^{-1}\) stronger, respectively, and about 5° north of the maximum centers shown in the composite results of GPCP and rain gauge data (Figs. 4d and 4e). The precipitation center near 30°S, 70°W seems to be a model bias. The bias will influence precipitation in subtropical South America along the east Andes, but will not influence the result over Amazonia. Comparisons between the precipitation pattern of Fig. 4a and those of the wet season onset (Figs. 4c, 4d, and 4e) suggest that the rainfall increase by cold air intrusions has made a substantial contribution to the rainfall pattern of wet season onsets, especially the rainfall increase extending from the western Amazon to southeast Brazil, whereas the northerly \(V\) index contributes to rainfall increase mostly over the central and eastern Amazon (Fig. 4b).

How cold air intrusions influence the atmospheric thermodynamic and dynamic structures and possibly contribute to the wet season onset is examined in Figs. 5 and 6. Figure 5 shows the evolutions of composite relative humidity (RH) and vertical velocity at 500 hPa from day \(-1\) to day \(+4\) during the cold air intrusion during the seasonal transition. On day \(-1\), strong vertical motion appears over central Argentina around 30°–35°S, 70°–60°W. High values of RH, such as RH > 60%, are mainly confined to the north of 10°S over Amazonia (Fig. 5a). On day 0 during the cold air intru-

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![Composite precipitation (shaded) and \(T_{925 \text{ hPa}}\) (contour with 2-K interval) on (a) day \(-1\), (b) day 0, (c) day \(+1\), and (d) day \(+2\) for the cold air intrusion during October–November. The 294-K isotherm is highlighted. Light and dark shaded areas represent precipitation greater than 6.1 and 10 mm day\(^{-1}\), respectively. Precipitation and \(T_{925 \text{ hPa}}\) locally significant at the 95% confidence levels are plotted.](image)
sion, RH increases about 10% in subtropical South America associated with the northward propagating strong upward motion (Fig. 5b). On day +1, the upward motion moves equatorward along the east Andes; at the same time, RH reaches 70% over some areas of the Amazon basin (Fig. 5c). On day +2, cold air moves into the northwest Amazon and RH increases to 70% over the western Amazon (Fig. 5d). The atmospheric moisture continues to increase mainly over the western tropical Amazon region on day +3 and +4 as seen for 70% RH. Such patterns of enhanced upward motion and therefore rainfall agree with those previously observed by Kousky (1979). Figures 5 and 3 suggest that cold air intrusions tend to moisten the troposphere and presumably the soil through increased RH and rainfall over the area from the western Amazon to southeast Brazil. Both can contribute to the destabilization of the atmosphere needed for the transition from the dry to wet seasons.

In Fig. 6 we examine how cold air intrusions may influence the transition of the upper-tropospheric circulation. Previous studies have used the conversion
function from divergent to rotational kinetic energy to diagnose the energy transformation needed for developing upper-tropospheric anticyclonic flow. The latter is a key feature of the wet season onset and summer monsoon circulation (Krishnamurti et al. 1998; Moscati and Rao 2001; Li and Fu 2004). In Fig. 6a the conversion function increases about 20% after the cold air passes the index area and reaches its peak value at day +3. The domain-averaged relative vorticity at 200 hPa first decreases when cold fronts penetrate, and then

\[ \Phi_{\text{day}+2} \]

\[ \Phi_{\text{day}+3} \]

\[ \Phi_{\text{day}+4} \]
increases (Fig. 6b). The increase of the 200-hPa vorticity reaches its maximum on day +4. These suggest that cold fronts act to accelerate the upper-troposphere anticyclonic flow as shown by more divergent kinetic energy converging into rotational kinetic energy and the vorticity increase when cold air passes. Figures 5 and 6 suggest that cold air intrusions not only increase tropospheric moisture and precipitation (Fig. 3), but also enhance the energy conversion from divergent to rotational kinetic energy and its vorticity in the upper troposphere. Collectively, these effects help to transform the circulation pattern from the dry to wet season configuration.

On average, several cold air intrusions occur during the transitional season, but only one event usually occurs concurrent with the wet season onset. What is special about this important event? Figure 7 examines the difference of the atmospheric fields between cold events that occurred during the transitional season (Figs. 7a and 7b) and those that occurred right before the wet season onset (Figs. 7c and 7d) along the southwest–northeast direction (25°S, 75°W to 0°, 25°W as shown by the bold line in Fig. 5a). During the transitional season, one day before the cold air intrusion, a high RH value, such as RH > 60%, can be seen in the whole area along the cross section, especially over 10°–15°S, 45°–55°W from 700 to 850 hPa (Fig. 7a). Wind converges along 50°W in the lower troposphere and 55°W in the middle troposphere; equivalent potential temperature at 850 hPa ($\theta_e$ at 850 hPa) reaches 342 K over tropical South America. One day after the cold air intrusion (Fig. 7b), RH increases to 75% over 57.5°–62.5°W, presumably due to the increase of moisture convergence and updraft along the leading edge of the cold air as wind converges about 2° latitude northward (Fig. 7b). For those cold events that appear right before the wet season onsets, on day −1 (Fig. 7c), the atmosphere is more humid than that of cold events as compared with Fig. 7a, although the wind convergence is stronger around 5°–10°S in Fig. 7a. For example, high RH values (RH > 60%) appear to be deeper throughout the atmosphere over 10°–15°S, 45°–55°W, and RH is greater than 75% in broader areas (Fig. 7c). On day +1 (Fig. 7d), $\theta_e$ at 850 hPa is about 3 K higher in the lower troposphere over the area 7.5°–12.5°S, 40°–50°W than it is in Fig. 7b. Deep convection dominates the entire cross-section area, as suggested by the RH value greater than 75% under 700 hPa (Fig. 7d). The upward velocity is higher over the area of 10°–15°S, about 5° latitude more northward compared to that in Fig. 7b. Figure 7 suggests that, right before the wet season onset, the atmosphere is more humid and unstable compared to that of previous cold air events during the transitional season. This allows the cold air intrusions to trigger rainfall strong enough to reach the onset criteria. For other earlier cold events, the atmospheric thermodynamic condition is not sufficiently unstable and humid to allow them to trigger deep convection and rainfall with the onset magnitudes.

b. Influence of the cold air intrusions on the early and late onsets

The notion that cold air intrusions trigger the wet season onset can be tested by examining their relationship on an interannual scale. To do so, we compare the frequencies and influences of cold air intrusions on the wet season onset among the following three years: the early onset year 1979 (onset at pentad 49: 29 August–2 September), a late onset year 1982 (onset at pentad 68: 2–6 December), and a normal onset year 1983 (onset at pentad 60: 23–27 October). Another late onset year, 1984, is also included but will be discussed in section 3c.

To better understand how and under what condition the cold air intrusions can trigger the wet season onset, land surface and atmospheric thermodynamic conditions are analyzed in Figs. 8 and 9 for their control on the seasonal changes of rainfall (Fu and Li 2004). Figure 8 shows the Bowen ratios and surface sensible and latent heat fluxes for 1979, 1982, 1983, and 1984 on
pentad resolutions. Considering the uncertainties of the ERA land surface fluxes, we can only qualitatively discuss their differences between normal, early, and late onsets. In a normal onset year, such as 1983, the Bowen ratio ranged between 0.5 and 0.7 during the dry season and decreased rapidly to 0.3 during the wet season onset. In this year, the sensible heat flux averaged over the southern Amazon domain gradually increased since January, more apparent from July to October, and surface latent heat flux in early August (pentad 43). Following the increase of the surface latent heat flux, CINE decreased rapidly starting from pentad 45 (Fig. 9a), and CAPE increased at the same time (Fig. 9b).

The influences of cold air intrusions during the transitional period in 1983 are studied in Fig. 10. Figure 10 shows the daily variations of SLP and $T_{925 \text{ hPa}}$ averaged since January, more apparent from July to October, and surface latent heat flux in early August (pentad 43). Following the increase of the surface latent heat flux, CINE decreased rapidly starting from pentad 45 (Fig. 9a), and CAPE increased at the same time (Fig. 9b).

The influences of cold air intrusions during the transitional period in 1983 are studied in Fig. 10. Figure 10 shows the daily variations of SLP and $T_{925 \text{ hPa}}$ averaged since January, more apparent from July to October, and surface latent heat flux in early August (pentad 43). Following the increase of the surface latent heat flux, CINE decreased rapidly starting from pentad 45 (Fig. 9a), and CAPE increased at the same time (Fig. 9b).
Fig. 8. Area-averaged (a) Bowen ratio, (b) sensible heat flux (W m\(^{-2}\)), and (c) latent heat flux (W m\(^{-2}\)) within 5°–15°S, 45°–75°W in 1983 (open circle), 1979 (closed circle), 1982 (solid line), and 1984 (dotted line), respectively.

Fig. 9. As in Fig. 8 but for (a) CINE (kJ kg\(^{-1}\)) and (b) CAPE (kJ kg\(^{-1}\)).
over the cold air index domain, 500-hPa RH, precipitation, and the kinetic energy conversion function averaged over the southern Amazon region in 1983, 1979, and 1982. In 1983, several episodes of cold air intrusions occurred during the transitional period as shown by the variations of SLP and $T_{925\text{ hPa}}$ (Fig. 10a). The earlier events that happened at Julian day 253, 265, and 271 (Fig. 10a) led to the increase of atmospheric humidity (Fig. 10b), moisture convergence (not shown) over the southern Amazon domain. Precipitation increased but did not reach the onset criterion (Fig. 10b). Right before the wet season onset in 1983, on day 295, cold air passed through the index area, lifting the moist air and leading to strong precipitation and wet season onset at pentad 60 (Julian day 296–300, Fig. 10b). The peaks of kinetic conversion function during this period (Fig. 10c) suggested that strong, deep convection was able to generate strong divergent flow and accelerate rotational flow in the upper troposphere. The increased frequency and strength of equatorward cold air intrusions along with normal thermodynamic instability led to a normal onset in 1983.

1) Early Onset

In 1979, the wet season began at pentad 49 (28 August–2 September, Table 1), about two months earlier than the climatological onset. Consistent with the required thermodynamic conditions for early onset, the Bowen ratio in 1979 was the lowest among the four transitions during August and September (Fig. 8a) as a result of both lower surface sensible heat flux and higher latent heat flux (Figs. 8b and 8c). Compared to the normal onset year 1983, CAPE was about 200% higher, and CINE was about 50% lower than those in 1983 as suggested in Fig. 9. Both the land surface and atmospheric instability conditions in early austral spring were ready for an early onset in 1979.

During this early austral spring (September), cold air

**Fig. 10.** Comparisons of (a), (d), (g) SLP (hPa, solid) and $T_{925\text{ hPa}}$ (°C, dotted) over the cold air index region; (b), (e), (h) rain rate (mm day$^{-1}$, bar) and moisture convergence (mm day$^{-1}$, solid) over the southern Amazon domain; and (c), (f), (i) kinetic energy conversion function ($10^{-6}$ m$^2$ s$^{-3}$) over the southern Amazon domain among (a)–(c) the normal onset year 1983, (d)–(f) the early onset year 1979, and (g)–(i) the late onset year 1982; thicker vertical lines represent the onset Julian day for the three years.
intrusions were strong (Oliveira 1986). As shown in Fig. 10d, right before the onset of the wet season at pentad 49 (Julian days 241–245) in 1979, a strong cold air event passed through the index area. It started at day 240 (28 August); subsequently SLP increased from 1004 to 1022 hPa and $T_{925}$ dropped about 10°C in 2 days (Fig. 10d), coincident with the wet season onset. Moisture convergence increased (not shown here), which led to RH increase, and precipitation increased to reach the onset criterion (Fig. 10e). The cold air appeared to trigger the onset presumably by releasing the potential energy of the atmosphere through enhanced moisture convergence along the cold front and therefore increasing precipitation. As expected, the wet season onset was apparently triggered by the cold air intrusion 2 months earlier than the climatological onset date.

2) LATE ONSET

In 1982, the sensible heat flux was about 40% lower and latent heat flux was about 25% higher than in 1983, a normal onset year (Fig. 8). Thus, the Bowen ratio of surface fluxes was actually lower than normal. The increase of CAPE began at a similar period (pentad 42) as it did in the “normal” 1983, but the magnitude was about 75% higher. CINE also started to decrease at a similar period (pentad 45) as that in 1983, and its value is about 30% lower than that in 1983 before the wet season onset (Fig. 9). Thus, the land surface and atmospheric thermodynamic conditions were more favorable for an early wet season onset in 1982 than in 1983. However, the actual onset was about 40 days later than in 1983. In this case, the land surface conditions and atmospheric static instability alone cannot explain the late wet season onset in 1982.

What could have caused the late onset in 1982? We compare the frequency of cold air intrusions and their influences on the wet season onset in 1982 to those in 1983, shown in Fig. 10. There was only one cold air surge in 1982 (Fig. 10g) from Julian day 247 to 249 (pentad 50), 88 days before the onset. Although this cold air intrusion increased atmospheric humidity, moisture convergence (not shown), and precipitation over the Southern Amazon region (Fig. 10h), the background atmosphere was too stable to support the wet season onset at such an early stage of the transition (Figs. 8 and 9). The kinetic conversion function was about 50% lower compared to that in 1983 (Fig. 10i). The other two weak cold air events occurred on Julian day 260 and 270 but did not reach the criteria of the cold front and failed to reach the central Amazon (Fig. 11). Figure 11 shows that infrequent and weaker cold air intrusions could not penetrate into tropical South America in 1982 compared to those in 1983. The lack of cold air penetration appears to inhibit the occurrence of large-scale convective rainfall, causing the delay of wet season onset in 1982. The infrequent and weak cold air
penetrations into tropical South America in 1982 coincide with the strong 1982–83 El Niño event. The 200-hPa circulation in 1982 (Fig. 12) showed that the subtropical jet stream was about 5 m s\(^{-1}\) (about 20%–30%) stronger than its climatological intensity during October and November. The abnormal strength of the subtropical jet stream in 1982 is unfavorable for the equatorward penetration of frontal systems and convective complexes that can normally reach central South America (Coelho and Ambrizzi 2000; Garreaud 2000b).

c. Wet season onsets without cold air intrusions

Under what conditions does wet season onset occur without cold air intrusions? For 1984 and 1986, both onsets happened at the end of the year. The late onsets appear to be caused by abnormally stable large-scale thermodynamic conditions until December (Fu and Li 2004) as shown in Figs. 8 and 9 for 1984. By then the cold air intrusions had become infrequent and too weak to penetrate into the region, which is typical for early austral summer (Oliveira 1986; Machado et al. 2004). The land surface fluxes gradually increased and the atmospheric conditions became more unstable as austral summer approached. The cross-equatorial flow changed to northerly and was persistent for about 3–4 days before the wet season onsets in these two years (not shown here). The transition of the land surface processes and large-scale thermodynamic conditions drove rainfall increase gradually, instead of suddenly, to reach the onset criteria.

In 1990 and 1991, there were no apparent cold air penetrations into tropical South America prior to the two normal onsets. The cross-equatorial flow had reversed to strong northerly (the V index \(< \sim 2 \text{ m s}^{-1}\)) since August 1990 and late September 1991 (Fig. 13a), about two months and a half month, respectively, earlier than its climatology (Wang and Fu 2002). This caused the atmosphere to be more unstable in 1990 with about 10% higher CAPE (not shown here) and 25% lower CINE compared to normal in 1983 (Fig. 13b). In 1991, an El Niño year, cold air intrusions were weak. However, the transition of large-scale thermodynamic conditions was faster, and the reversal of the V index was also earlier than the normal year of 1983 (Fig. 13). Specifically, CINE decreased faster from the beginning of October and was about 30% lower than that in the same period of 1983. The kinetic conversion function and divergent kinetic energy in 1991 were also much higher than in 1983 (not shown here). These help the large-scale circulation effectively transform into its wet season pattern even without strong cold air intrusions.

In short, strong unstable atmospheric thermodynamic conditions and the earlier northerly reversal of the V index lead to the wet season onsets without cold air intrusions. These onsets are usually associated with a more gradual increase of rainfall, whereas, in comparison, cold air intrusions tend to cause rapid onset with greater southeastward expansion of the rainy area.

4. Discussion

a. Different roles of the cold air intrusions in early and late onsets

Cold air intrusions play a different role in early and late onsets of the wet season over tropical South
America. When the atmosphere is too stable and the land surface is dry, cold air intrusions will cause strong variations in air temperature, wind, and SLP over tropical South America but with less increase of rainfall along the leading edge of cold fronts. However, when the background atmosphere in Amazonia is destabilized abnormally early, or on time, during the transition, cold air incursions appear to be more effective in triggering wet season onsets. For example, in 1979 cold air intrusions appeared to trigger the wet season onset in early September. The lack of cold air intrusions during 1982 could likewise delay the wet season onset by 40 days even though the large-scale thermal and dynamic conditions seem favorable for an early onset of the wet season. In 1990 and 1991, the atmosphere was abnormally unstable, episodes of the strong northerly V index could also lead to wet season onsets, usually for normal and late onsets. This can occur either due to an earlier and more robust transition (1990, 1991) or a delayed and weak transition (1984, 1986). In the latter, the atmospheric thermodynamic structure was not destabilized enough for the wet season onsets until the end of December when the cold air intrusions into the Amazon become substantially weaker and less frequent (Oliveira 1986; Machado et al. 2004). In fact, most onsets cannot meet the criteria for cold air intrusions as defined in section 2, as the Southern Hemisphere extratropical circulation shifts to its summer pattern. In both cases, the reversal of the cross-equatorial flow (the V index) appears to be more important.

In short, cold air intrusions appear to be a primary trigger of the wet season onsets during 11 out of the 15 years of our analysis. The exceptions are when 1) the destabilization of the large-scale atmosphere is too slow for it to be thermodynamically “ready” for the wet season onset during austral spring, thus missing the peak season of cold air intrusions into Amazonia, and 2) the northerly reversal of the V index occurs earlier and is strong. This could substantially increase rainfall in the eastern and central Amazon (Wang and Fu 2002) and thus lead to wet season onsets. However, the geo-

Fig. 13. Comparisons of (a) the V index (m s\(^{-1}\)) and (b) CINE (kJ kg\(^{-1}\)) among 1990 (dotted line), 1991 (solid line), and the “normal” onset year 1983 (bar).
graphic pattern of rainfall associated with this type of onset is different from that of a typical onset, and rainfall increase is more gradual.

b. Influences of El Niño events blocking cold air intrusions on the wet season onsets

Our results suggested that wet season onsets tend to be delayed during El Niño years. The influence of El Niño events on the precipitation variation in the western Amazon is probably not direct but through changing other factors such as the position and intensity of the subtropical jet stream. During El Niño years the subtropical jet stream is stronger than usual (e.g., Horel and Wallace 1981; Grimm et al. 2000; Nogués-Paegle et al. 2002). The abnormally strong subtropical jet stream is unfavorable for cold air intrusions into the Tropics and therefore leads to less (more) precipitation over the Amazon (subtropics of South America). This is consistent with the previously observed increased rainfall in southeastern Brazil during El Niño in austral spring (Grimm et al. 1998). Since the wet season onsets also rely on the land surface condition and atmospheric instability (e.g., Fu et al. 1999; Li and Fu 2004), the frequency and intensity changes of cold air penetration alone cannot explain all the changes of the wet season onset (e.g., the wet season onset of 1991). This is presumably responsible for the observed weak relationship between the precipitation over the western Amazon and ENSO warm events.

5. Conclusions

We have observed a close relationship between cold air intrusions and the wet season onset over Amazonia during 11 out of 15 years of our analysis. Our results suggest that during the transition period from the dry to wet season, usually in October and November, the enhanced precipitation due to cold air penetrations are found in the western Amazon to southeast Brazil. This spatial pattern of enhanced precipitation on a 5–12-day temporal scale resembles that of a latitudinally widespread rainy area rapidly developing from the western Amazon to southeast Brazil associated with the wet season onset.

When cold air penetrates from subtropical to tropical South America along the eastern Andes, the low-level meridional wind convergence ahead of the cold fronts becomes intense, and tropospheric moisture and rainfall increase through the increase of upward motion embedded in the unstable atmosphere for the development of moist convection during the transitional season. These processes not only cause synoptic episodes of rainfall over areas spanning from the western Amazon to southeast Brazil but also accumulatively increase atmospheric and presumably soil moisture. The rate of divergent kinetic energy conversion to rotational kinetic energy also increases due to the cold air intrusion. Thus, these episodes of cold air intrusions can effectively facilitate the transition of atmospheric thermodynamic structure and circulation and ultimately trigger the wet season onset. Compared to those cold air events during the transitional season, the cold air intrusions immediately preceding wet season onsets take place under more humid and unstable atmospheric conditions. Therefore, the state of readiness of the large-scale thermodynamic and circulation conditions, along with adequate strength of the cold front, mainly determines the cold event that triggers the wet season onset.

The cross-equatorial flow can contribute to a rainfall increase associated with the wet season onset, sometimes even triggering the onsets without cold air intrusions. The V index enhances precipitation mainly over the central and eastern Amazon, whereas cold air intrusions increase rainfall over the western Amazon. A cold air intrusion can be a trigger for the wet season onset only if the atmosphere is thermodynamically unstable. The northerly V index transports humid air from the Atlantic Ocean, which plays an important role in destabilizing the atmosphere; however, it is not a primary trigger for most of the wet season onsets.

Comparison among the early onset year 1979, the normal onset year 1983, and the relatively late onset year 1982 further suggest that cold air intrusions can be critical as a trigger in determining early and normal onsets. During the transitional period of the early onset in 1979, the atmosphere is destabilized for deep convection as early as August; the triggering mechanism appears to timely release potential energy, enhance moisture convergence and deep convection, and consequently lead to an early onset of the wet season. Without frequent and sufficiently strong cold fronts as in 1982, the wet season onset was about 30 days later than the climatological onset date even though the land surface and large-scale conditions were favorable for an early or normal onset. The cold air event immediately preceding the wet season onset in 1983 appeared to trigger a normal onset even though the land surface and atmospheric conditions were more stable than those in 1982.

Cold air penetrating into the Amazon usually becomes infrequent and weakens as austral summer approaches. And, thus, is not effective in triggering very late onsets such as occurred in late December in 1984 and 1986. Occasionally, normal wet season onsets could occur without cold air intrusions when the reversal of
northerly cross-equatorial flow is abnormally early and stronger, such as in 1990 and 1991.

El Niño years tend to exhibit a stronger subtropical jet stream over South America, which was also previously found by Lenters and Cook (1997), Coelho and Ambrizzi (2000), and Coelho et al. (2002). Such a condition tends to confine cold air to the subtropical region, thereby delaying the increase of precipitation during the transition from the dry to wet season over the Amazon basin.

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