A Diagnosis of the 1979–2005 Extreme Rainfall Events in the Southeastern United States with Isentropic Moisture Tracing

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ABSTRACT

A detailed analysis is performed to better understand the interannual and subseasonal variability of moisture sources of major recent dry (1980, 1990, and 2000) and wet (1994, 2003, and 2005) June–August (JJA) seasons in the southeastern United States. Wet (dry) JJAs show an increased (decreased) standard deviation of daily precipitation. Whereas most days during dry JJAs have little or no precipitation, wet JJAs contain more days with significant precipitation and a large increase of heavy (+10 mm) precipitation days. At least two tropical cyclone/depression landfalls occur in the southeastern United States during wet JJAs, whereas none occur during dry JJAs. The trajectory analysis suggests significant local recycling of moisture, implying that land surface feedback has the potential to enhance (suppress) precipitation anomalies during a wet (dry) JJA. Remote moisture sources during heavy precipitation events are very similar between wet and dry JJAs. The distinction between wet and dry JJAs lies in the frequency of heavy precipitation events. During the wet JJAs, heavy precipitation events contribute to more than half of the JJA precipitation total.

1. Introduction

Precipitation is one of the most important features in weather and climate variations. Over land, its seasonal prediction is not trivial because of the possibility of significant land surface feedback (Koster et al. 2000). Some of the most notable historical extreme floods and droughts in the United States have occurred in the Mississippi River basin and in the Great Plains, including the Great Mississippi Floods of 1927 (Barry 1997) and 1993 (Lott 1993), and the 1930s Great Plains Dust Bowl (Seager et al. 2008). Precipitation anomalies in the Mississippi basin and the Great Plains are mainly controlled by both atmospheric moisture transport and local evaporation (Trenberth and Guillemot 1996; Dirmeyer and Brubaker 1999; Brubaker et al. 2001; Ruiz-Barradas and Nigam 2005, 2006). Despite historical interests, the Mississippi River basin and the Great Plains are not the wettest regions of the United States during the boreal summer season. It is the Gulf Coast (overlapping with the lower reaches of the Mississippi River basin) and the southeastern United States that have the highest June–August (JJA) precipitation (Fig. 1a). The standard deviation of the JJA precipitation along the Gulf Coast and the Florida Peninsula is as large as the Mississippi River basin (Fig. 1b).

The Southeast climate area, as defined by the National Oceanic and Atmospheric Administration (NOAA), consists of Virginia, North and South Carolina, Georgia, Florida, Alabama, and Puerto Rico (NOAA/Applied Climate Information System 2009). Such definition is often of political and geographic convenience, and is not based on actual climate data. The Southeast (excluding Puerto Rico) boreal summer season (JJA) has many climatic differences from that of the Mississippi River basin (inland) and the Great Plains. The differences include proximity to a warm ocean (Gulf of Mexico), the lack of a dominant river system, and the lack of a dominant low-level jet (the Great Plains low-level jet).

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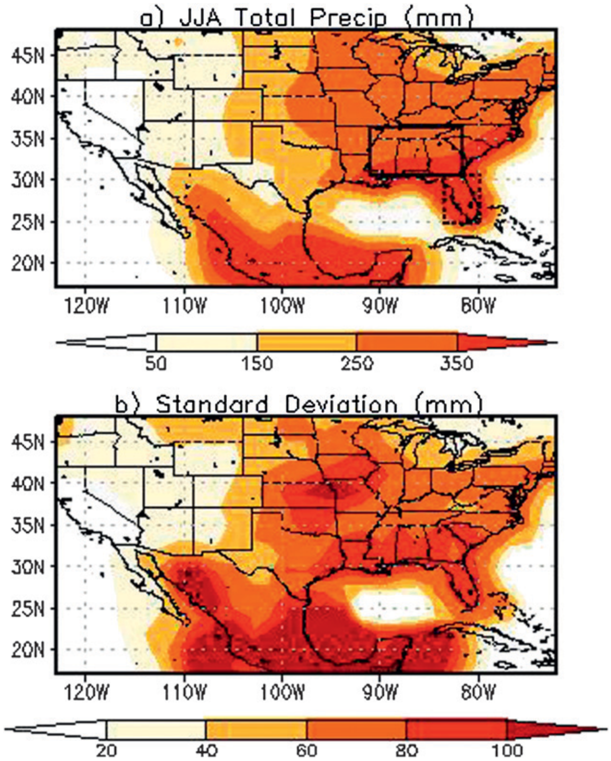

FIG. 1. (a) The 1950–2005 JJA total precipitation (mm) climatology from the Higgins et al. (2000) U.S.–Mexico precipitation dataset and (b) its standard deviation (mm). The two boxed areas (solid line box: Southeast, short dash box: Florida) in (a) are used for the box averages in Fig. 5.

In a recent study on the variability of the Southeast precipitation, Wang et al. (2010, hereinafter WFKL) indicate that there is an increased interannual variability of boreal summer precipitation over the Southeast in the last 30 years. They link this increased precipitation variability to increased Atlantic SST variations. This is in contrary to Seager et al. (2008), who argue that boreal summer Southeast precipitation variations are governed by internal atmospheric variability and climate model Southeast precipitation is insensitive to observed SST variations. The objective of this paper is, however, to diagnose the source of moisture in producing the seasonal extremes of wet and dry boreal summers over the Southeast. Furthermore, this study is also extended to understand the hydrology of the extreme weather events within these anomalous seasons.

2. Data

a. Precipitation

The NOAA Climate Prediction Center (CPC) daily 1° latitude × 1° longitude U.S.–Mexico merged precipitation station-based dataset is used (Higgins et al. 2000, 2004). This rain gauge based dataset spans from 1948 to 2005, and covers the entire continental United States and Mexico.

The precipitation data are interpolated to NCEP–Department of Energy (DOE) Reanalysis-II (Kanamitsu et al. 2002) grid for parcel trajectories (see below). For the sake of consistency, the precipitation is regridded to Reanalysis-II grid.

Our choice of dataset limits the ability to understand the multidecadal variability that WFKL argue is important. Analysis of the multidecadal variability (not shown) of the monthly Climatic Research Unit (CRU) TS2.0 precipitation dataset (Mitchell et al. 2004) shows 1979–2000 Southeast precipitation to be more variable than 1901–40 and even the epoch 1941–78 at the 10% significance level. The change in Southeast precipitation variability between epochs of 1901–40 and 1941–78 is not statistically significant at the 10% confidence level.[1]

b. Reanalysis (upper air and land surface)

The 6-hourly global 192 × 94 Gaussian Grid NCEP–DOE Reanalysis-II upper-air (in sigma-pressure coordinates) and surface data (Kanamitsu et al. 2002) are used to investigate Southeast precipitation moisture sources during dry and wet JJAs. The data are available from 1979 onward. Reanalysis-II improves upon various issues that exist in Reanalysis-I (Kalnay et al. 1996). Among the different improvements in Reanalysis-II is the use of observed pentad precipitation over land to address the land surface errors in Reanalysis-I.

Despite these improvements in the Reanalysis-II land surface data, (reanalysis) evaporation should be treated with caution, as it is still a model based estimate. For example, Nigam and Ruiz-Barradas (2006) argue that there are unacceptable moisture imbalances and excessive evaporation rates [versus offline (forced) land surface model estimates] in Reanalysis-I, the NCEP North American Regional Reanalysis (NARR; Mesinger et al. 2006), and the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005). Roads et al. (2002) show that the Reanalysis-II basic hydroclimate mechanisms are reasonable but are still in need of improvements. Shown in Fig. 2 are the 1979–98 JJA eastern U.S. and Gulf of Mexico climatological surface evaporation rates for Reanalysis-I/II, NARR, and ERA-40. Reanalysis-I has the largest

[1] The F test for the difference of standard deviation of JJA precipitation anomalies is performed for 1901–78, 1901–40, 1941–78, and 1979–2000.

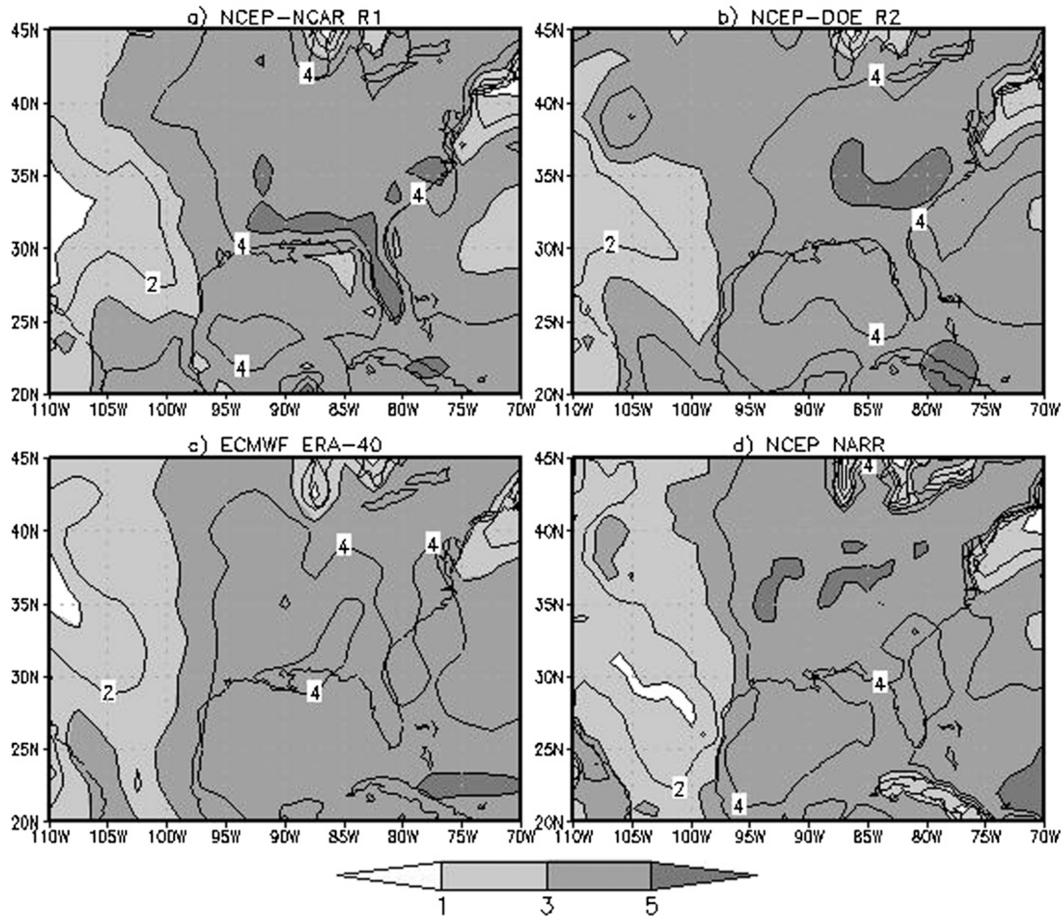

FIG. 2. The 1979–98 JJA mean surface evaporation rate (mm day^{-1}) for (a) NCEP Reanalysis-I, (b) NCEP Reanalysis-II, (c) ECMWF ERA-40, and (d) NCEP NARR.

evaporations rates in the Southeast, especially in the Gulf Coast and Florida. The differences between NARR and Reanalysis-II are smaller in the Southeast (both are ~4 mm day^{-1}, except in Florida, where NARR is relatively less evaporative). ERA-40 has the smallest evaporation rate (3–4 mm day^{-1}, approximately 10%–15% less than Reanalysis-II). ERA-40 evaporates more than the three other reanalyses in the Gulf of Mexico.

Had NARR been available over a much larger domain it would have likely been our choice for our analysis in this study. But because of its limited spatial extent, its scope for diagnosing nonlocal moisture sources is also limited. In this paper, we will use Reanalysis-II following Dirmeyer and Brubaker (2007).

c. Tropical cyclones

Tropical cyclone and depression (TC/TD) information is obtained from the online NOAA/National Hurricane Center archive (NOAA/National Hurricane Center 2009). The TC landfall dates are used to attribute subseasonal extreme precipitation events.

3. Methodology

a. Dirmeyer–Brubaker moisture parcel trajectories

An air parcel trajectory method (APT) is used to determine evaporative sources of Southeast precipitation events (Merrill et al. 1986; Dirmeyer and Brubaker 1999). The isentropic (potential temperature conserving) trajectory method traces air parcels backward in time with a scheme that uses surface evaporation as a moisture source to trace air parcels.

One hundred moisture saturated air parcels are launched from a grid box at a random humidity-weighted vertical level (favoring the lower troposphere where humidity is highest) whenever precipitation (grouped into pentads) has occurred. The total moisture of all launched air parcels is the same as the precipitation that has fallen in the grid box. The parcels are traced along isentropic surfaces backward in time using reanalysis winds. The parcel trajectory is the average of two trajectories:

1) The backward trajectory is calculated from the initial parcel location $\mathbf{X}_0 = \mathbf{X}(x_0, y_0, t_0)$ using the winds (vector $\mathbf{V}$) at that location $\mathbf{V}_0 = \mathbf{V}(\mathbf{X}_0, t_0)$.
2) From the end point of the backward trajectory $\mathbf{X}^* = \mathbf{X}_0 - \mathbf{V}_0\Delta t$ (after Δt), the forward trajectory is calculated: $\mathbf{V}^* = \mathbf{V}(\mathbf{X}^*, t_0 - \Delta t)$.

The new location of the parcel $\mathbf{X}_{-1}$ is then

$$\begin{aligned}\mathbf{X}_{-1} &= \mathbf{X}_0 - \frac{(\mathbf{V}_0 + \mathbf{V}^*)}{2}\Delta t \\ &= \mathbf{X}_0 - \frac{[\mathbf{V}(\mathbf{X}_0, t_0) + \mathbf{V}(\mathbf{X}_0 - \mathbf{V}_0\Delta t_0, t_0 - \Delta t)]}{2}\Delta t.\end{aligned} \quad (1)$$

If the parcel potential temperature is lower than the surface potential temperature, then the parcel potential temperature is set to the surface potential temperature. That is the same as the parcel following along the surface if the trajectory hits the ground.

We assume the surface evaporated moisture is well mixed in the troposphere. During the trajectory, surface evaporation ''removes'' parcel moisture at a fractional rate equal to the column precipitable water fractional gain attributable to surface evaporation [i.e., column precipitable water divided by surface evaporation amount $E(x, y, t)/\mathrm{PW}(x, y, t)$]. Following Dirmeyer and Brubaker (1999) and Brubaker et al. (2001), the tracing of the air parcel is stopped at 15 days after its release or when the parcel has ''lost'' 90% of the moisture content.

The evaporative source of the parcels are recorded every pentad (5-day mean). The NCEP–DOE Reanalysis-II evaporation rates are used here. No parcel moisture (precipitation) sinks are allowed during trajectory; such sinks would imply the existence of parcel diabatic heating (condensation), and parcel potential temperature would not be conserved. The no-sink assumption will however overextend the trajectories.

The Higgins et al. (2000) dataset is ''defined'' at coastal grid points, but that is because the dataset is spatially smoothed. No trajectories are performed with the over-water fictitious data. The diurnal cycle of the Reanalysis-II precipitation is used to interpolate the daily precipitation dataset into a 3-hourly dataset.

APT scheme assumes no atmospheric moisture storage, but Dominguez et al. (2006) have argued that it is important especially on daily time scales. In comparison to a recycling model that corrects to atmospheric moisture storage, Dominguez et al. (2006) have shown that APT scheme underestimates local recycling. The main objective here, however, is to examine interannual variability, so we argue that APT scheme is adequate.

b. Analyzing the moisture sources

We define the evaporation contribution from grid point (x, y) to precipitation at grid point (i, j) at time t as $S_{i,j,t}(x, y)$ (mm day^{-1}). Individual maps of S from point (i, j) are difficult to interpret, so $S_{i,j,t}(x, y)$ from different i and j (i.e., a box total over the Southeast) and over some span of time (i.e., pentads 31–49) can be totaled [TS(x, y)]:

$$\mathrm{TS}(x, y) = \sum_{i,j}\sum_{t} S_{i,j,t}(x, y). \quad (2)$$

The global spatial integral of TS is the precipitation (P) total inside the box:

$$\sum_{\mathrm{Global}} \mathrm{TS}(x, y) = \sum_{i,j}\sum_{t} P_{i,j,t}(x, y). \quad (3)$$

Pentads can be categorized (wet or normal, see section 4), and normalized by the number of days in that category [to give *daily averaged evaporative* (DES) source in terms of millimeters per day]:

$$\begin{aligned}\mathrm{DES}_{\mathrm{Wet/Norm}}(x,y) &= \frac{\displaystyle\sum_{i,j}\sum_{\mathrm{Wet/NormP}} S_{i,j,t}(x,y)}{(\text{No. of wet/norm pentads}) \times 5\dfrac{\text{day}}{\text{pentad}}} \\ &= \frac{\displaystyle\sum_{a} \mathrm{TS}_a(x,y)}{(\text{No. of wet/norm pentads}) \times 5\dfrac{\text{day}}{\text{pentad}}}.\end{aligned} \quad (4)$$

Index ''a'' represents different wet and normal events as defined by different pentads. The corollary to Eq. (3) for box precipitation during wet and normal pentads (PTot) is

$$\begin{aligned}\mathrm{PTot}_{\mathrm{Wet/Norm}} &= \sum_{\mathrm{Global}} \mathrm{DES}_{\mathrm{Wet/Norm}}(x, y) \\ &= \sum_{i,j}\left[\sum_{\mathrm{Wet/NormP}} P_{i,j,t}(x, y)\right].\end{aligned} \quad (5)$$

Equation (4) can be normalized the same way as in (4) to give the daily means (DMean):

$$\mathrm{DMean}_{\mathrm{Wet/Norm}} = \frac{\mathrm{PTot}_{\mathrm{Wet/Normal}}}{(\text{No. of wet/norm pentads}) \times 5\dfrac{\text{day}}{\text{pentad}}}. \quad (6)$$

The normalization to daily averages allows comparison between different categories that may have differences in sample sizes (i.e., different numbers of wet and normal pentads).

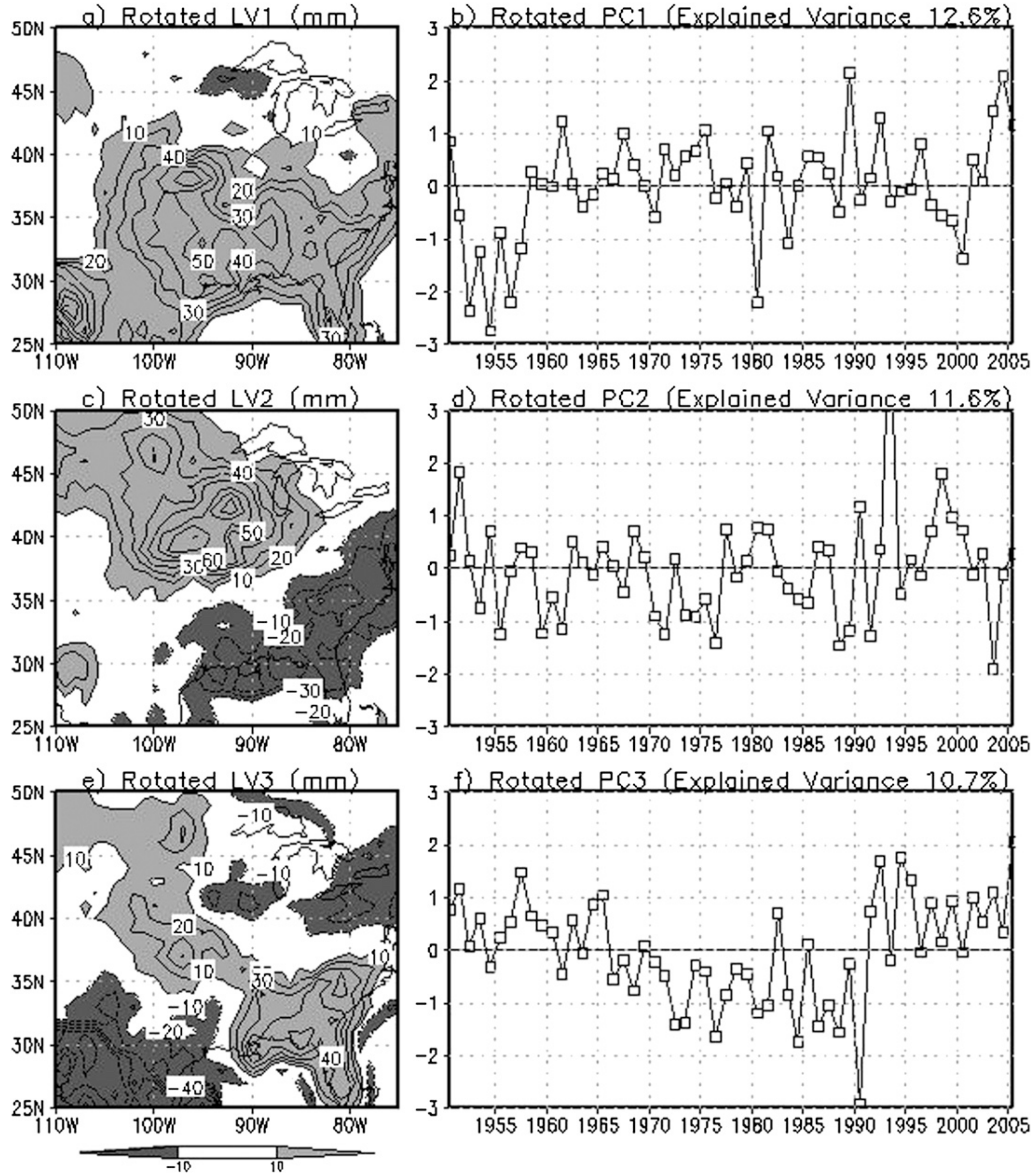

FIG. 3. (left) The three leading varimax-rotated LVs of 1950–2005 JJA precipitation (mm) and (right) its nondimensional PCs. All three LVs are comparable in explained variances (10.7%–12.6%), and explain up to ~1/3 of the total variance.

4. Results

a. Climatology and interannual variability

We focus our analysis over the solid line box outlined in Fig. 1a. South and Southeast precipitation is rather spatially homogeneous in both the seasonal cycle (exception Florida, seasonal cycle not shown) and in JJA standard deviation (Fig. 1b). The seasonal cycle in the Southeast excluding Florida is characterized by a lack of seasonal variability; in Florida, there is a clear maximum during the boreal (JJA) summer.

Since this study is comparing anomalous wet and dry JJAs, the JJA variability is more important than the seasonal cycle. Despite having a different seasonal variability over Florida, the interannual variability of Florida JJA precipitation is connected to the Southeast region as implied in Fig. 1b. The rotated loading vectors (LVs) and principle components (PCs) (Richman 1986) of the 1950–2005 JJA precipitation anomalies are shown in Fig. 3. The leading three LVs explain a total of about 35% of the variance. All three LVs overlap significantly in the Southeast including Florida. This supports our box as a

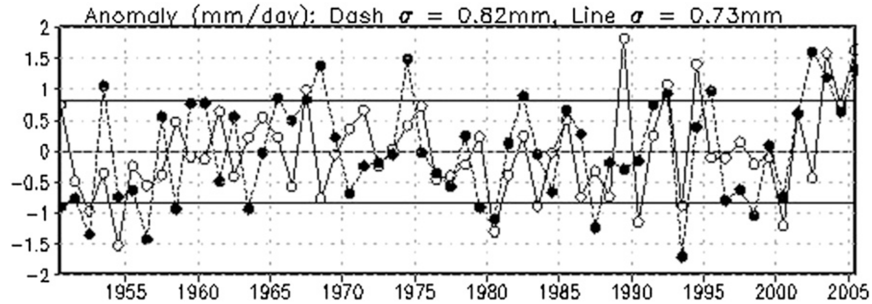

FIG. 4. The 1950–2005 boxes (see Fig. 1) averaged JJA precipitation anomaly (mm day^{-1}) with the line here corresponding to the box outline in Fig. 1 (solid line: Southeast, dash: Florida Peninsula). The 0 and ±1 standard deviation (for the Southeast box) lines are delineated.

reasonable choice for reflecting the precipitation variability of the broader Southeast region including Florida. The JJA-averaged precipitation anomalies for the Southeast and Florida boxes are shown in Fig. 4. The precipitation over Florida is correlated with the precipitation over the Southeast box at 0.34 between 1950 and 2005. But the correlation increases to 0.50 after 1979.[2] This gives further justification for our choice of time period and box.

Figure 4 also shows an increase in the Southeast precipitation variability after the 1980s as mentioned in WFKL. The notable anomalous (≥1 standard deviation) dry and wet JJAs are shown in Table 1. Out of the 16 anomalous dry/wet JJAs, 11 of them occurred in the last 30 yr. In total, 4 (5) out of the 5 driest (wettest) JJAs were from the last 30 yr.[3]

b. *Subseasonal variability of the driest and wettest JJAs*

Here we shall focus on the 3 driest (1980, 1990, and 2000) and wettest (1994, 2003, and 2005) Southeast JJAs from the past 30 yr. The time series of daily precipitation averaged over the Southeast box for the six anomalous JJA seasons are shown in Fig. 5. The standard deviation of the daily precipitation is comparable to the daily mean in all six anomalous years. The dry JJAs (top three panels) show a 50% reduction of the mean precipitation from the wet JJAs. The standard deviation for the dry JJAs is also about ½–⅓ of the wet JJAs.

The changes in Fig. 5 are associated with significant changes in the distribution of daily precipitation amounts. Shown in Fig. 6 are daily precipitation distributions for the dry JJAs, wet JJAs, and (normalized) climatology. The dry JJAs are dominated by weak–no precipitation days (<1 mm day^{-1}). The +10 mm day^{-1} precipitation events are rare with only a total of 6 counts in the 3 anomalous dry JJAs. The wet JJA distribution has the highest frequency of events occurring in the <1.0 mm day^{-1} (occurring at about one-third of the frequency of the dry JJAs) and the +10 mm day^{-1} bins. There are nearly 6 times more +10 mm day^{-1} in the wet JJAs relative to the dry JJAs. The 27-yr climatological frequencies of <1.0 and +10 mm day^{-1} are between the two extreme cases.

All three distributions in Fig. 6 are non-Gaussian. Precipitation persistence cannot be corrected easily. The daily precipitation autocorrelation can in principle be calculated (see Table 2), but the autocorrelation is tainted by the more common dry days. Nevertheless, a nonparametric Mann–Whitney U test shows that the differences between the wet and dry JJA daily precipitation distributions are significant at the 1% confidence

TABLE 1. The years with boxed average JJA (Higgins et al. 2000) precipitation anomalies that exceed one standard deviation between 1950 and 2005. The years in boldface type are for the last 30 yr (1979–2009). Four years have exceeded two standard deviations: 1955 (dry), 1989 (wet), 2003 (wet), and 2005 (wet). There are 6 events before 1980 (30 yr of data) vs 11 events from the next 30 yr (25 yr of data).

Event type	Dry/drought	Wet/flood
Yr	1952	1950
	1954	1967
	1968	**1989**
	1980	**1992**
	1983	**1994**
	1990	**2003**
	1993	**2004**
	2000	**2005**
No. of events	8	8
	(Pre-1980: 3)	(Pre-1979: 2)
	(Post-1980: 5)	(Post-1979: 6)

[2] The 1950–78 correlation ($r = 0.095$) is insignificant at the 10% level under a Student's t test. The 1950–2005 and 1979–2005 correlations of precipitation over Florida and rest of Southeast are significant at the 1% level.

[3] The driest JJAs were 1954, 1980, 1990, 1993, and 2000, and the wettest were 1989, 1992, 1994, 2003, and 2005.

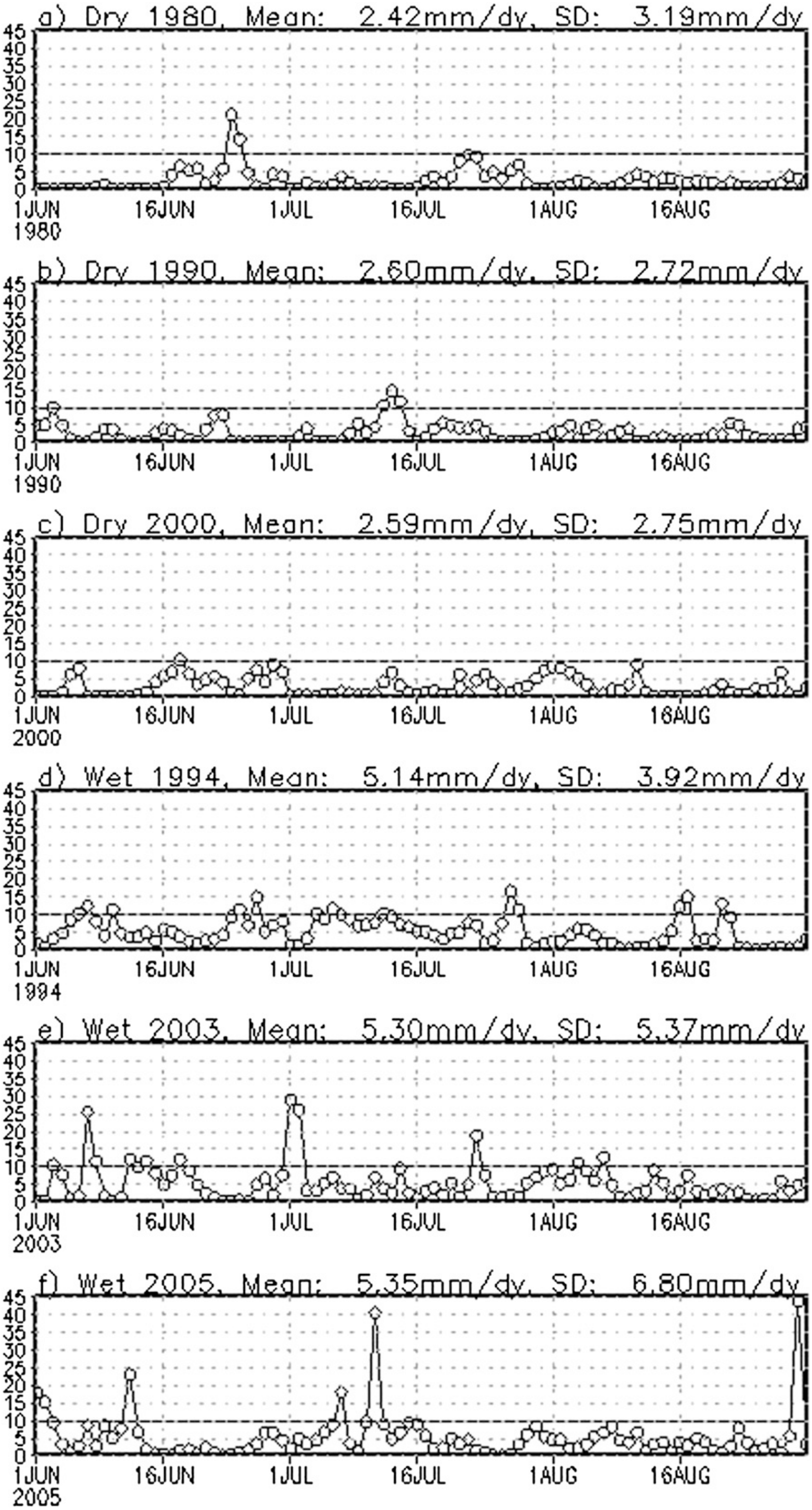

FIG. 5. The spatially averaged (using boxed area in Fig. 1) daily rainfall (mm) during JJA for the three recent (1980–2005) driest and wettest JJAs. The selected dry JJAs are (a) 1980, (b) 1990, and (c) 2000, and the selected wet JJAs are (d) 1994, (e) 2003, and (f) 2005. The time averages and standard deviations are shown at the top of (a)–(f).

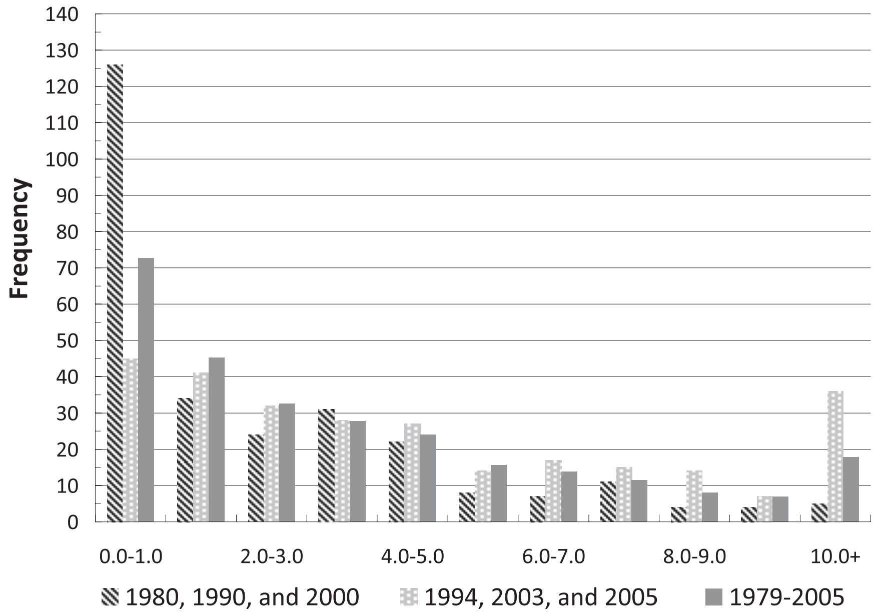

FIG. 6. The daily precipitation (mm) distributions divided into 11 bins for the dry JJAs (1980, 1990, and 2000, hatched), wet JJAs (1994, 2003, and 2005; light gray stippled), and climatological JJAs (1979–2005; solid gray). Climatology is normalized to appear have the same number of samples as the other two cases.

interval. With a large change in the numbers of +10 mm day^{-1} between wet and dry JJAs, we define a "wet pentad" as a pentad when the daily precipitation of a day within the pentad has exceeded 10 mm day^{-1}. There are a total of 19 pentads in JJA: P31 (31 May–4 June) to P49 (29 August–2 September). A synopsis of the wet pentads for the 6 selected JJAs is shown in Table 3. Pentads including TC/TD activity are as marked in the table.

The dry JJAs have far fewer wet pentads than the wet JJAs (4 versus 20), and only one independent +10-mm precipitation period for each dry JJA. Furthermore, the dry JJAs have no TC/TD landfalls in the vicinity of the Southeast. There is only one JJA TC/TD landfall elsewhere in North America for the three dry JJAs (1980 Hurricane Allen). The wet JJAs have at least two Southeast TC/TD events, and TD/TC activity accounts for about 8 out of 20 of the wet pentads. The 5 largest 1-day precipitation events (Fig. 5) are all in the wet JJAs. Of those five, the top three are associated with hurricanes (2003 Bill, 2005 Dennis, and 2005 Katrina). Discounting the TC/TD pentads, the wet JJAs still outnumber dry JJAs in wet pentads (12 to 4).

c. Moisture sources of dry and wet JJAs

Using the Fig. 1 Southeast solid line box, all the evaporative sources inside the box between pentads 31 and 49 (TS, total source) are totaled [Eq. (2)] and shown in Fig. 7. The largest evaporative sources for both the wet and dry JJAs are from local recycling. The maximum wet JJA local recycling source (130–150 mm) is approximately 2 times that of the dry JJA (~60–80 mm). This fractional difference is about the same as the fractional difference of the mean (Fig. 5).

The wet JJAs receive more moisture from the tropical ocean waters to the south: the Gulf of Mexico, Caribbean Sea, and tropical Atlantic—often collectively called the Atlantic warm pool (AWP; Wang and Enfield 2001). In the wet JJAs, the 10-mm contour extends as far as the Leeward Islands. In the dry JJAs, the tropical oceanic source is largely confined to the Gulf of Mexico. The 2000 JJA, however, shows some moisture source from the tropical Atlantic. The moisture sources for both wet and dry JJAs from the northwest subtropical Atlantic Ocean (the Gulf Stream) are relatively small.

d. Extreme events in the anomalous JJAs

The moisture sources from the wet (as defined for Table 3) and normal pentads (any nonwet pentads) for

TABLE 2. The day-1 autocorrelations of 31.4°–35.2°N, 90°–82.5°W box-averaged daily precipitation.

	Day-1 autocorrelation (ρ_1)
1979–2005	0.58
Top 3 dry JJAs (1980, 1990, 2000)	0.59
Top 3 wet JJAs (1994, 2003, 2005)	0.47

TABLE 3. An overview of the major precipitation events during the selected JJAs. A wet pentad is defined as a pentad with a boxed-averaged daily precipitation that has exceeded 10 mm. The overview below includes the number of wet pentads, number of wet pentads that can (cannot) be associated with TC/TD activity, the actual pentads that are defined as wet, and their dates. Wet pentads that are associated with TC/TD activities are boldface with the storm name given. The top five wettest pentads are shown in italics.

Year	1980	1990	2000	1994	2003	2005
Wet or dry?	Dry	Dry	Dry	Wet	Wet	Wet
No. of wet pentad	2	1	1	8	7	5
TC/TD	0	0	0	3	2	3
Non-TC/TD	2	1	1	5	5	2
Wet pentad	35, 36	39	34	32, 33, 36, **37**, **38 (Alberto)**, 42, **46 (Beryl)**, 47	31, *32*, 33, 34, ***37 (Bill)***, **41 (TD07)**, 44	31, *33*, **38 (Cindy)**, ***39 (Dennis)***, ***49 (Katrina)***
Dates	20–24 Jun, 25–29 Jun	10–14 Jul	15–19 Jun	5–9 Jun, 10–14 Jun, 25–29 Jun, **30 Jun–4 Jul**, **5–9 Jul**, 25–29 Jul, **14–18 Aug**, 19–23 Aug	31 May–4 Jun, *5–9 Jun*, 10–14 Jun, 15–19 Jun, ***30 Jun–4 Jul***, **20–24 Jul**, 4–8 Aug	31 May–4 Jun, *10–14 Jun*, **5–9 Jul**, ***10–14 Jul***, ***29 Aug–2 Sep***

the dry and wet JJAs are separated. Equation (4) is used to calculate wet and dry pentad DES, shown in Figs. 8 and 9.

The two wet pentads in the 1980 JJA are the same precipitation event, which lasted across two pentads (Fig. 5). Therefore, the evaporative source is from *one* wet event for each of the JJAs. The wet pentad moisture is drawn both locally and remotely from the AWP.

The local recycling source during wet pentads exceeds the local recycling source during normal pentads. For the dry JJAs, the local source is especially strong for 1980 and 1990. For 2000, the local source is much weaker, and the largest evaporative source is near the Strait of Florida. Probably not unexpectedly, the normal pentads draw much less moisture from the AWP. Figures 8a,c,e show different remote moisture sources. The wet event in 1980 JJA shows moisture being drawn along the extension between the Caribbean and the Great Plains low-level jets. The 1990 and 2000 wet events are more directly from the south.

Despite the increased number of wet *pentads* during the wet *JJAs* (Table 3), the evaporative source from wet pentads in the wet JJAs appears to be quite similar to the wet pentads in the dry JJAs—a combination of local recycling and AWP sources.

It is interesting to note that local recycling is a significant part of the wet pentads within both the dry and wet JJAs. They show a perceptible change in their contribution just as observed in the context of the anomalous seasonal means. This suggests that the land surface processes in the Southeast play a significant role in modulating the seasonal boreal summer climate anomalies and the weather extremes in the anomalous seasons.

The Southeast box totals of daily precipitation during the wet pentads in both the dry and the wet JJAs are comparable. However, the normal pentads in the wet JJAs are about 70% more wet than the normal pentads in the dry JJAs. The wet pentads are relatively more numerous during wet JJAs than in dry JJAs. The total precipitation from all wet pentads in the wet JJAs is about 6–8 times more than the wet pentads in dry JJAs. In other words, there are simply fewer major precipitation systems in dry JJAs relative to wet JJAs.

5. Discussion and conclusions

In this observational study, we find that there is a distinct change in the daily rainfall distribution between wet and dry boreal summers over the southeastern United States. In a wet JJA, there is a significant increase in rain events >10.0 mm day^{-1} and a decrease in light-to-no daily rainfall events. The dry JJAs are characterized by a higher frequency of light-to-no daily rainfall events.

The inventory of the moisture sources for the anomalous JJAs suggests that there is a significant increase in the oceanic moisture source in the wet boreal summer with a consequent increase in local recycling. This moisture supply seems to largely stem from the area of the AWP. The dry JJAs have a more limited moisture supply from the neighboring Gulf of Mexico. Recycling is only enhanced if soil moisture is enhanced; ultimately, increase of nonlocal source is the origin of the recycled precipitation.

To further illustrate the difference between wet and dry years, the JJA vertical integrated mass weighted

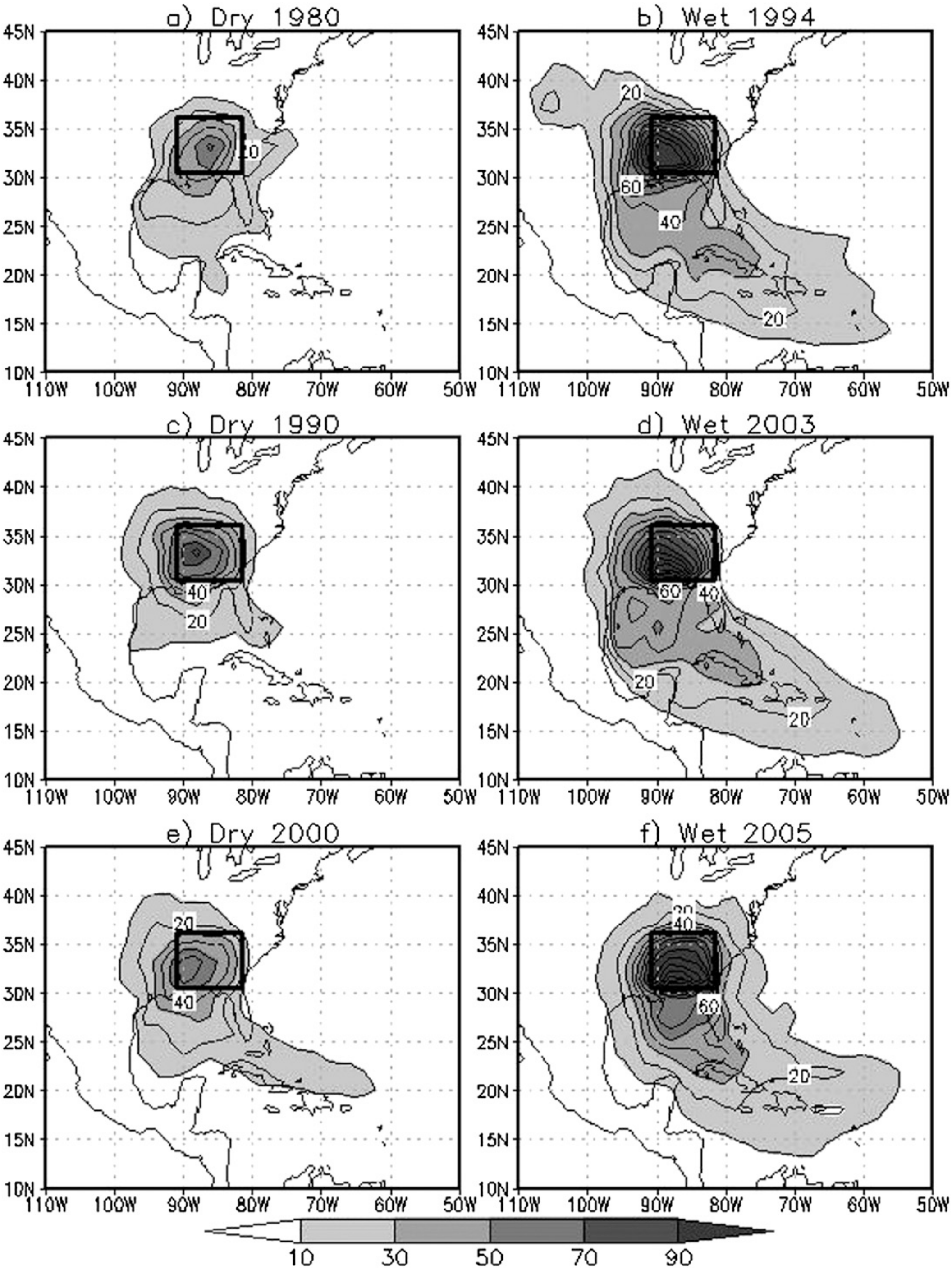

FIG. 7. The total evaporative sources (mm) between pentads 31–49 (31 May–2 September): (a) 1980, (b) 1994, (c) 1990, (d) 2003, (e) 2000, and (f) 2005.

moisture fluxes (MF) and its convergences (MFC) are calculated from 6-hourly data, and are shown in Fig. 10:

$$\mathbf{MF} = \int_{z_0}^{z_1} (q\rho\mathbf{V})\,dz = -\int_{\sigma_0}^{\sigma_1} \left(\frac{qP_{\mathrm{sfc}}}{g}\mathbf{V}\right) d\sigma, \qquad (7)$$

$$\mathrm{MFC} = -\nabla \cdot (\mathbf{MF}). \qquad (8)$$

The wet JJAs have an MFC that is 3 times that of the 6-yr mean. Wet JJA northward meridional moisture flux is also about 2–3 times stronger. The increased moisture

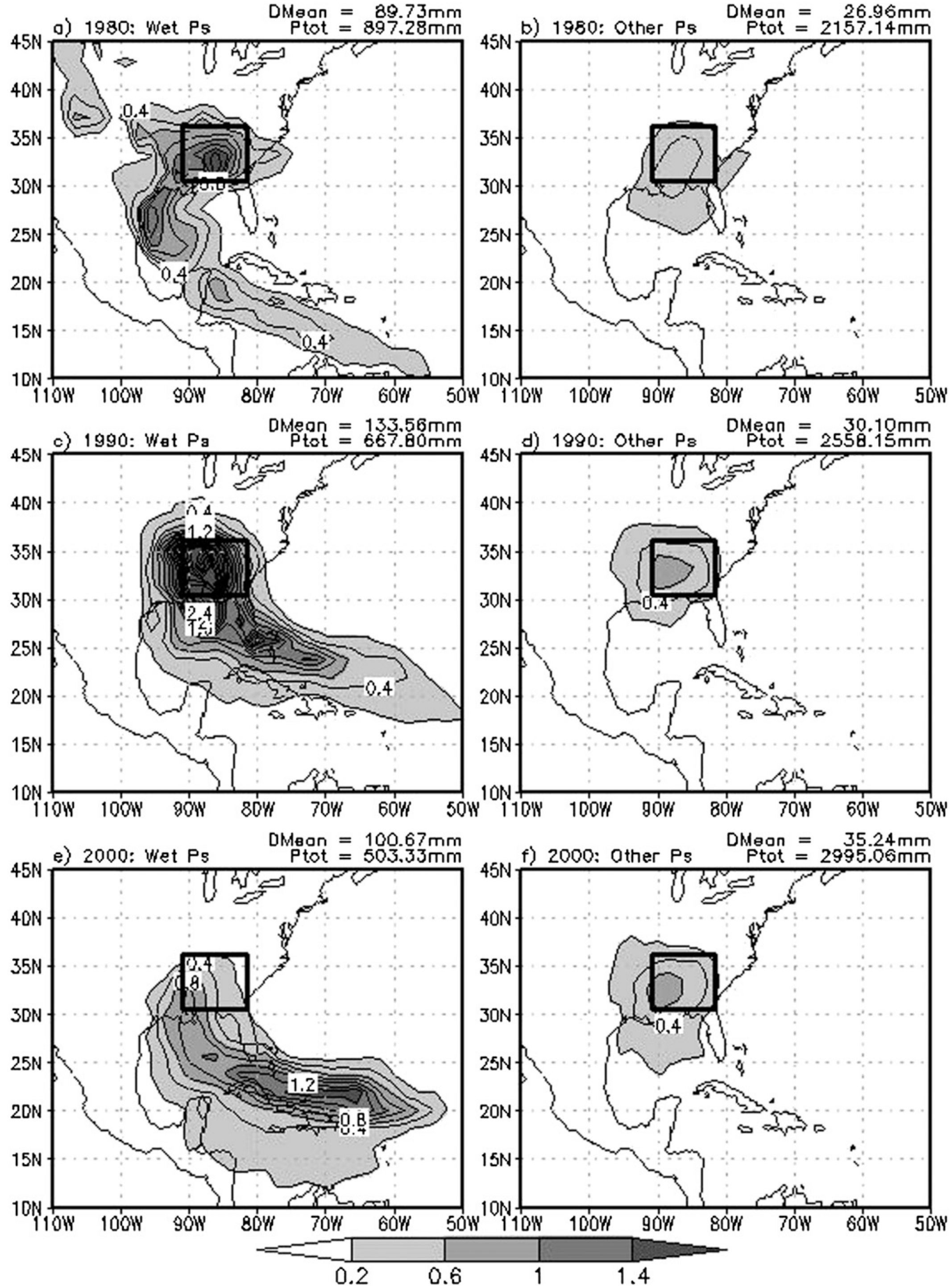

FIG. 8. As in Fig. 7, but only the pentads in the dry JJAs (1980, 1990, and 2000) that are (left) wet and (right) normal are used (see Table 2). Unlike Fig. 7, the evaporative source is daily averaged. The box total precipitation (Ptot) and daily means (DMean) for the wet and normal pentads are shown.

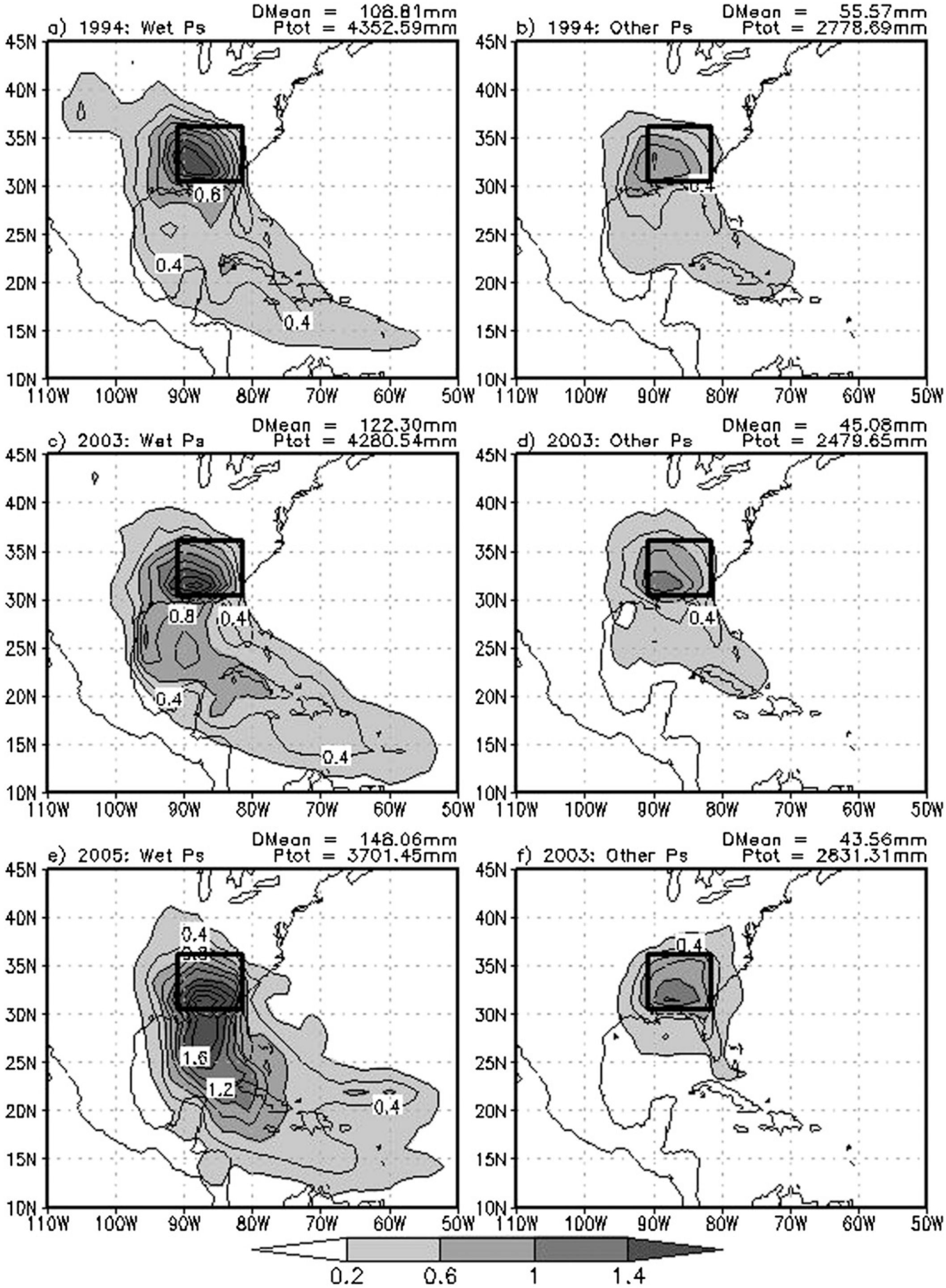

FIG. 9. As in Fig. 8, but for the wet JJAs (1994, 2003, and 2005).

flux itself is associated with the Bermuda high extending farther west and a weakening of the Great Plains low-level jet. The latter is strongly implied in Fig. 3 with a clear anticorrelation between the Great Plains/inland Mississippi basin and the Gulf Coast. Rodwell and Hoskins (2001) argue that the enhanced poleward flow in the boreal summer subtropics is related to large-scale ascent, which is favorable to positive precipitation anomalies. The wet (dry) JJAs are also associated with weaker tropical trade in both the Atlantic and Pacific, which is in

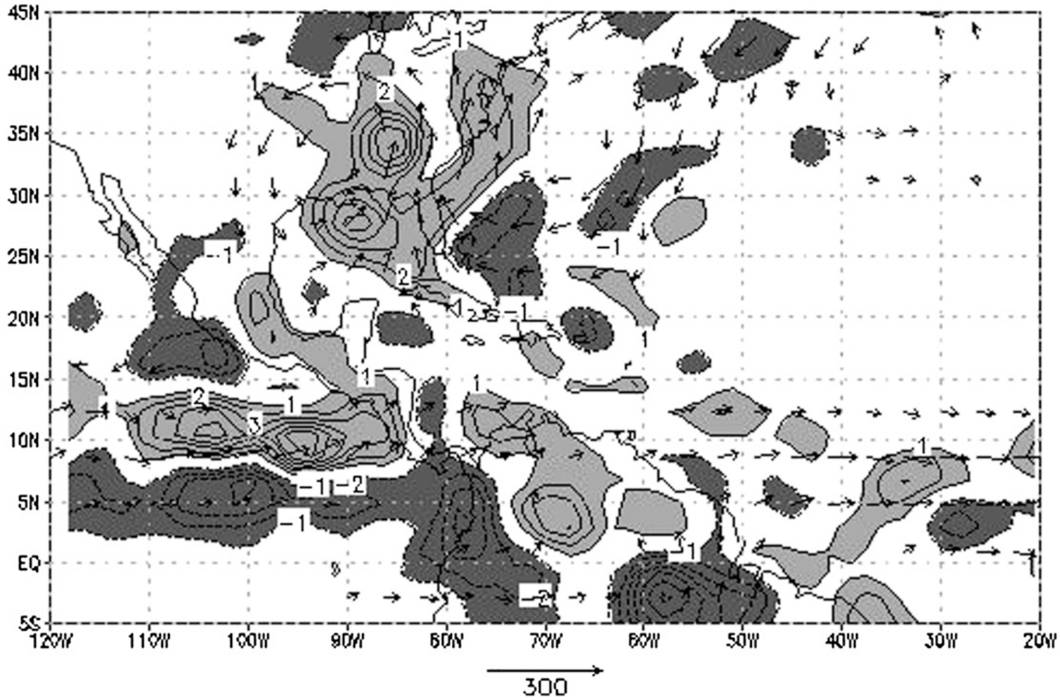

FIG. 10. The wet JJA differences with dry years for mean vertical integrated moisture fluxes (kg m^{-1} s^{-1}, vectors) from $\sigma = 0.995$ to 0.1682 and convergences (mm day^{-1} contours; light shading, positive values and dark shading, negative values).

agreement with WFKL's argument that Southeast precipitation is connected to Pacific and Atlantic variabilities. Weaker trades mean reduced vertical wind shear and an environment that is favorable to precipitation producing tropical cyclones (Gray 1968). As we show already, there is only one U.S. landfalling TC during the three dry JJAs.

In our analysis of the anomalous wet weather events, it appears that there are no significant differences in their moisture sources between anomalous wet and dry seasons. These wet events are characterized by significant oceanic transport of moisture and comparable recycling of precipitation. However, the wet weather events occur more often in the wet boreal summers relative to the dry boreal summers. This eventually causes the other pentads within the season to be wetter via local recycling. The increased frequency of wet events and local recycling both contribute to observed increase in precipitation during the wet JJAs.

We have not addressed the inherent differences between reanalyses. We have however drawn the attention of the readers to the fact that the evaporation estimates are disparate amongst the various reanalyses. This is a potential problem and we shall try to characterize this uncertainty in the future. It is not only evaporation and its recycling that can be quite different between reanalyses, but moisture fluxes can vary as well (Nigam and Ruiz-Barradas 2006).

The increase of precipitation correlation between the Florida Peninsula and the rest of the Southeast in recent decades is worth noting. From the perspective of this study, this increase further justifies the choice of our box (Fig. 1). But such variations of seasonal variability with time have important implications for data assimilation, regional predictability, and forecasting of the water cycle.

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