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Understanding the wet season variations over Florida

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Abstract The wet season of Florida is well defined and is invariably centered in the boreal summer season of June–July–August. In this observational study we objectively define the Length of the Wet Season (LOWS) for Florida and examine its variations with respect to El Niño and the Southern Oscillation (ENSO) and the Atlantic Warm Pool (AWP). Our study reveals that ENSO variability has a profound influence on the LOWS especially over south Florida and parts of panhandle Florida prior to 1976. In the post-1976 era the influence of ENSO has significantly diminished. Our results show that in this pre-1976 era, warm (cold) ENSO events in the boreal winter are followed by long (short) LOWS over the region. This variation is consistent with warm (cold) ENSO events influencing early (late) onset of the wet season in the region. There is significant relationship of the LOWS in south and northeast Florida with the variation of the AWP. Unlike the teleconnection with ENSO the relationship of the demise of the wet season with AWP is stronger in the post-1976 period compared to the pre-1976 period. Furthermore the variability of the LOWS has increased in the post-1976 period.

Keywords ENSO · Wet season · AMO · PDO · Climate change

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1 Introduction

There are only a minority of studies that have specifically examined the summer season variations over Florida (Misra et al. 2011; Chan and Misra 2010; Stefanova et al. 2011). This primarily stems from the observed lack of El Niño and the Southern Oscillation (ENSO) forced variations on the summer variability in the region (Laing et al. 2008). Kushnir et al. (2010) suggest that tropical north Atlantic SST anomalies have significant impacts on North American summer precipitation variability west of 90°W that are comparably much more than the ENSO influence. They suggest that the modulation of the North Atlantic Subtropical High (NASH) by the tropical north Atlantic Sea Surface Temperature (SST) is the mechanism by which this teleconnection is generated. Li et al. (2011) suggest that in the last 30 years the interannual variability of the summer precipitation in the southeast US has increased as a result of the enhanced meridional movement of the NASH. They attribute this feature of NASH to anthropogenic influence on the warming global climate. The region of the US Gulf coast and Florida is vulnerable to high impact weather and climate events like hurricanes, droughts, and wildfires. Therefore the quest to understand the low frequency variations of the summer climate in this region is extremely relevant.

ENSO is the strongest natural variability at interannual time scales and is well known for its remote teleconnection patterns (e.g., Philander 1990). Most notable is its influence on the North American winter climate with its high, low, high, and low pattern along the great circle in the mid-to-upper troposphere over the Northeast Pacific, Alaska, midwest US –Canadian prairies, and southeast US respectively (Wallace and Gutzler 1981). ENSO is also related to some of the summer phenomena like the frequency of the tropical cyclones over the Gulf of Mexico (Kunkel and Angel 1999), landfalling hurricanes (Bove et al. 1998) and to wildfire events in late spring and early summer over Florida (Harrison and Meindl 2001).

A number of studies have examined the variability of droughts in the region (e.g., Stahle and Cleaveland 1988; Seager et al. 2009; Ortegren et al. 2011). However, many of these studies relate the low frequency variations of these droughts to SST variations in the Atlantic on multi-decadal time scales. The warm season droughts of the region are not well understood (Seager et al. 2009; Ortegren et al. 2011). In their modeling study, Seager et al. (2009) conclude that the summer droughts are a result of the internal variations of the atmosphere, with no significant external forcing (like the ENSO anomalies). Ortegren et al. (2011) however claim that the low frequency variations of the summer drought in the southeastern Gulf region are closely associated with slowly varying North Atlantic SST variations and the position and strength of the Bermuda High. In a related study Misra et al. (2011) showed that the variations of the Bermuda high modulated the sea breeze variations of panhandle Florida that had an implication on the local seasonal precipitation anomaly.

A well known feature of Florida is its distinct seasonal cycle of rainfall (i.e., a well defined rainy season), that is typical of the monsoonal regions. The lack of global teleconnections with the summer season rainfall variations over Florida is one of the main factors for the poor predictability of climate models over this region (Stefanova et al. 2011). We therefore explore in this paper the variations of the Length of the Wet Season (LOWS) as a potential metric that can be related to global climate variations. The initial motivation for using LOWS is that we could probably leverage on the ENSO signal in the boreal spring months over the region and the variability of the Atlantic Warm Pool (AWP; Wang and Enfield 2001) for the demise of the season. In the following section we describe the datasets used and the methodology. The results are discussed in Sect. 3 followed by conclusions in Sect. 4.

2 Methods and data

The onset and demise of rainy seasons, which essentially define the end points of the season, have lots of practical significance, especially to plan cultivation of agricultural crops. In this paper we follow the objective method of defining the LOWS following Leibmann et al. (2007). They define cumulative anomalous rainfall accumulation (A') at every grid point of the dataset as:

$$A'_m(\text{day}) = \sum_{n=1}^{N\text{DAYS}} \{R_m(n) - \bar{R}_m\} \tag{1}$$

where, $R_m(n)$ is daily rainfall on day n and mth year, n is day number starting on day 1, which is January 1 and ending on day N, which is December 31, and $\bar{R}_m$ is annual average daily rainfall. The rainy season at any given point is defined as the period with the largest and the longest positive slope of the time series of A' from Eq. (1). This definition nominally at least for monsoonal regions as it was originally used for, reduces to the fact that the beginning of the rainy season corresponds to the period when the anomalous accumulation is above the annual mean and the demise corresponds to the time when the anomalous accumulation is maximum. However, unlike the Asian monsoon for example, A' along the US Gulf Coast and over Florida have substantial winter and spring season rainfall, which makes it essential to include in the definition that wet season is the period with the largest positive slope in the time series of A'. If S_m and E_m are the start and the end dates of the wet season for a given year m, then the LOWS for year m is defined as:

$$(\text{LOWS})_m = E_m - S_m \tag{2}$$

The anomalies of these quantities (S', E', and $(\text{LOWS})'$) are defined as

$$S' = S_m - \frac{1}{M}\sum_{m=1}^{M} S_m \tag{3}$$

$$E' = E_m - \frac{1}{M}\sum_{m=1}^{M} E_m \tag{4}$$

and

$$(\text{LOWS})' = (\text{LOWS})_m - \frac{1}{M}\sum_{m=1}^{M} (\text{LOWS})_m \tag{5}$$

where, M is total number of years. We have made extensive use of the unified daily US precipitation analysis of the Climate Prediction Center available at 0.25° resolution following Higgins et al. (2000) from 1948 onwards. It makes use of quality controlled rain gauge data from a variety of sources including the National Oceanic and Atmospheric Administration's (NOAA's) National Climate Data Center (NCDC), daily co-op stations, river forecast centers data, and NCDC's hourly precipitation database to generate this dataset. We also make use of the extended reconstructed SST version 2 (ERSSTv2) SSTs (Smith and Reynolds 2004). The significance of the correlations presented in the next section are computed based on the bootstrapping technique (McClave and Dietric II 1994; Efron and Tibshirani 1993). The pair of time series used in

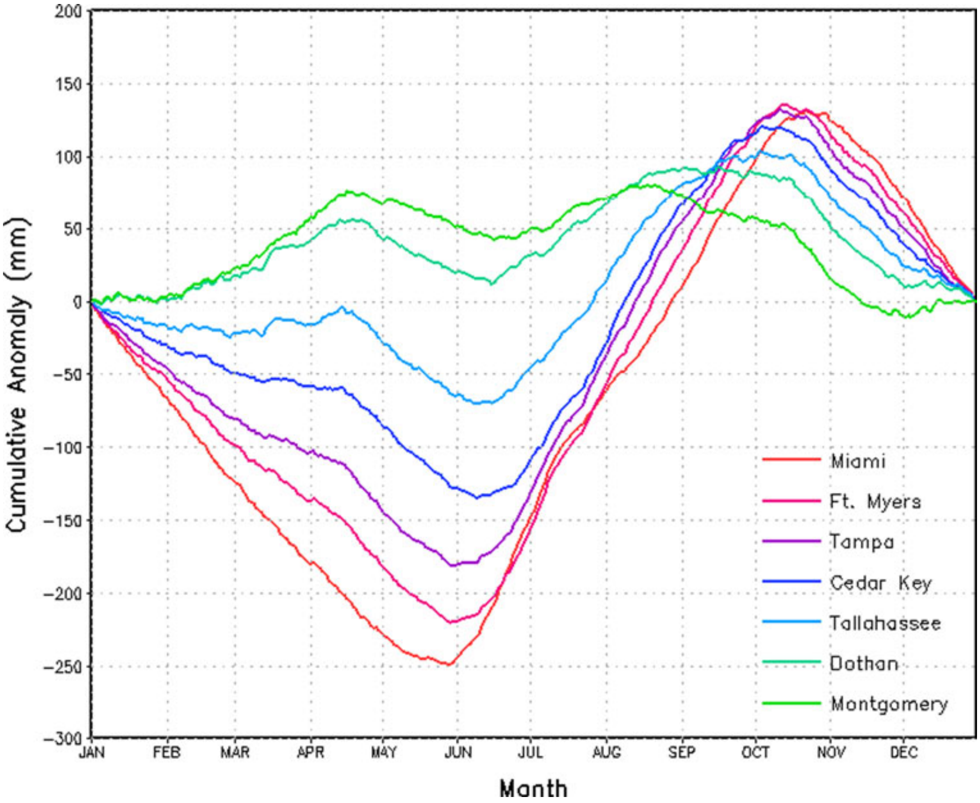

Fig. 1 The cumulative anomalies of daily rainfall (averaged over 58 years from 1948 to 2005) as defined in Eq. 1 in text for a number of stations along approximately a north–south transect from the tip of Florida (Miami) to 32°N latitude (Montgomery, Alabama)

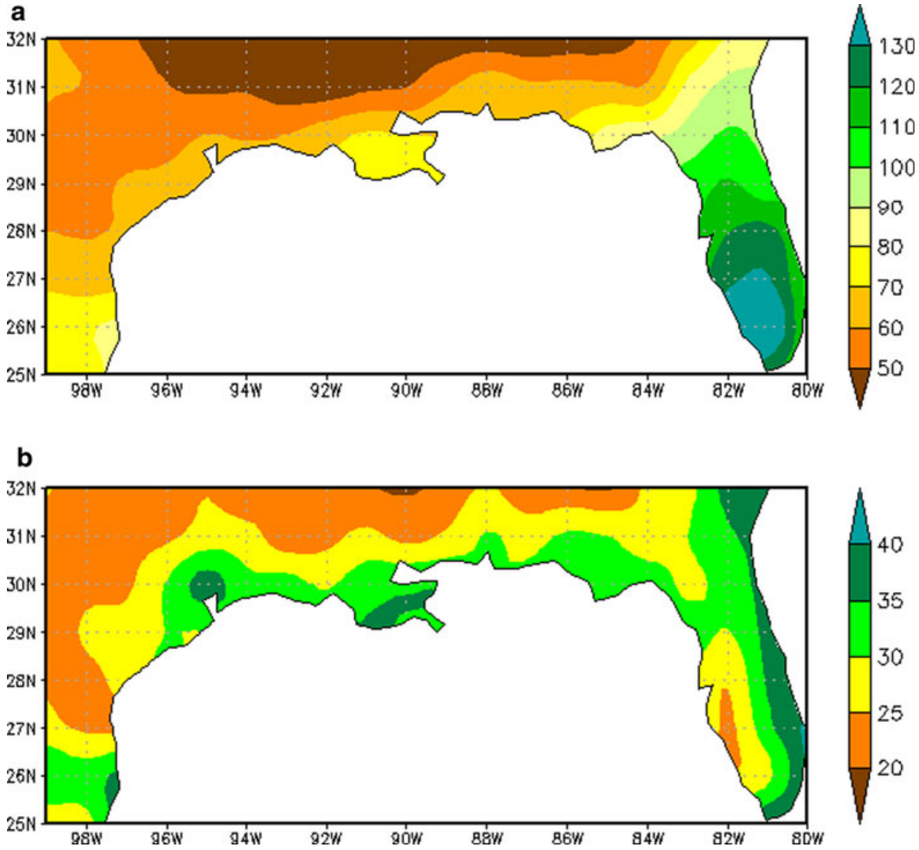

Fig. 2 **a** The observed climatological mean Length of the Wet Season (LOWS; in days) and **b** corresponding standard deviation (in days)

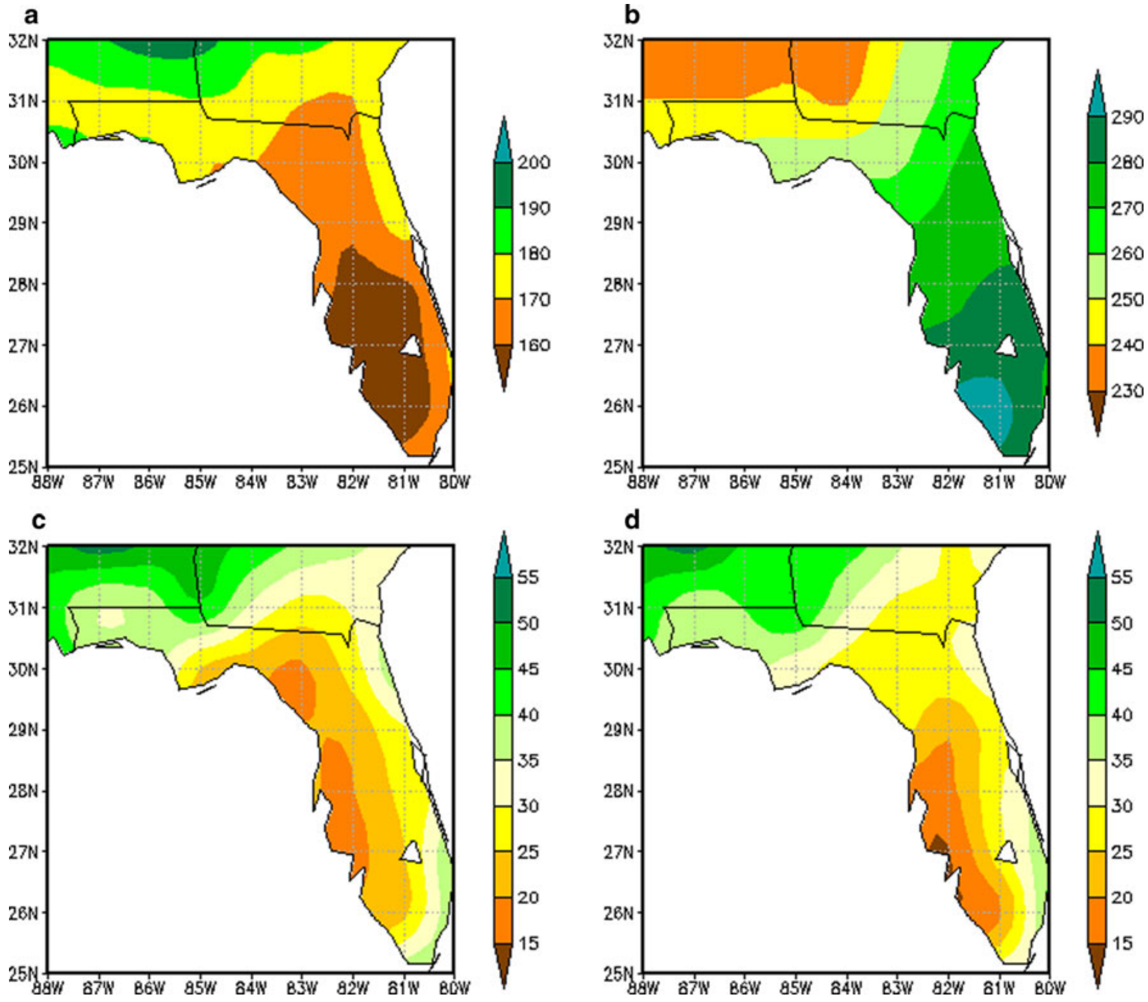

Fig. 3 The climatological mean **a** start and **b** end dates of the wet season in day number. The corresponding standard deviation of the **c** start and **d** end dates of the wet season in days

the temporal correlations is resampled 10,000 times randomly (with replacement). For the correlations to be significant at 90 % confidence interval it had to lie within the 10th percentile of the distribution of the correlations determined by the random shuffling of the time series.

3 Results

3.1 Climatology

In Fig. 1 we show cumulative anomalies of precipitation (A') for a northwest-southeast transect between Montgomery, Alabama to Miami, Florida. It is quite apparent from the figure that LOWS can be uniquely defined up to Tallahassee (30°N and 84°W). However as we move further north to Dothan, Alabama (31°N and 85°W) or Montgomery, Alabama (32°N and 86°W), the distinction of a unique wet season becomes more ambiguous with winter and summer season cumulative accumulation of precipitation anomalies being comparable. Therefore we restrict our analysis to around 31°N latitude that serves as the northern border of Florida.

The observed climatology of the LOWS and its associated standard deviation are plotted in Fig. 2a, b respectively. It may be noted from the figure that the longest wet season in the US Gulf is over the southwestern peninsular Florida, and progressively decreases as we move north and west along the US Gulf coast. In fact, west of Panama City, Florida, the climatological LOWS begins to drop rapidly below the usual 90 day seasonal length. This is again one of the reasons why we restrict the analysis in this paper to the wet season of Florida. The LOWS in southwestern peninsular Florida is climatologically over 4 months. This climatological LOWS begins to decline as we move north towards panhandle Florida and west from Jacksonville in northeast Florida towards Pensacola in northwest Florida. The standard deviation of LOWS is however smallest in

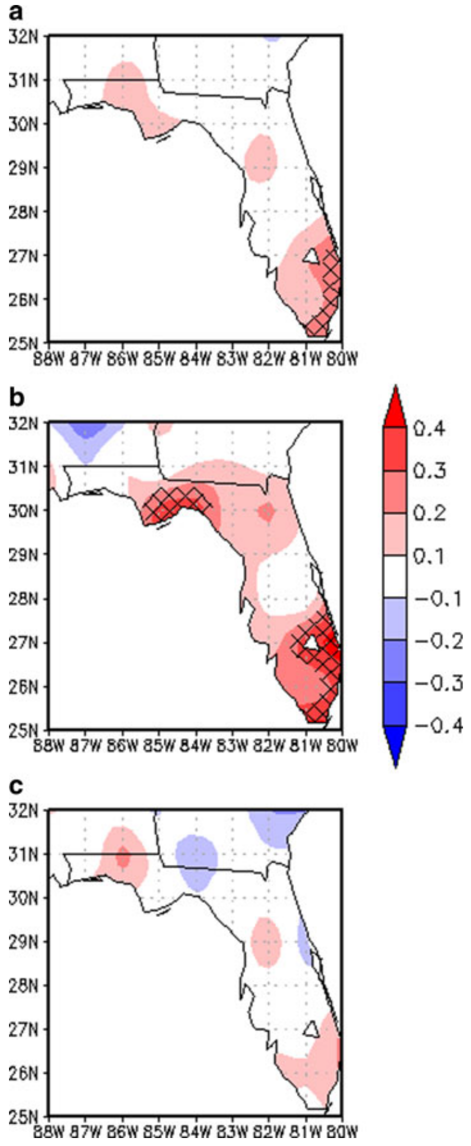

Fig. 4 The correlation of the LOWS with the preceding December–January–February averaged Niño3.4 SST anomalies for the period **a** 1948–2005, **b** 1948–1975 and **c** 1976–2005. Statistically significant correlation values at 90 % confidence interval are *hashed*

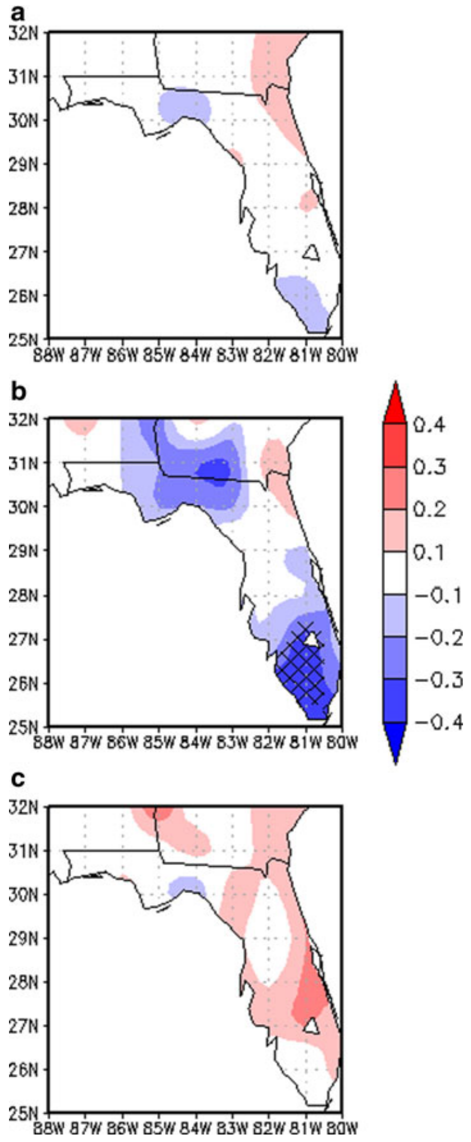

Fig. 5 The correlation of the start dates of the LOWS with the preceding December–January–February averaged Niño3.4 SST anomalies for **a** 1948–2005, **b** 1948–1975 and **c** 1976–2005. Statistically significant correlation values at 90 % confidence interval are *hashed*

southwestern peninsular Florida, progressively increasing to the east coast of south Florida as well as moving further north. The northern US Gulf coast exhibits moderately high standard deviation relative to southwest Florida with higher variability along coastal Louisiana and Texas. The variability reduces inland from the US Gulf coast with a steep gradient.

The wet season begins in late June or early July over the Florida panhandle. In south Florida, the rainy season is almost a month earlier in early June (Fig. 3a). Similarly, the demise is rather late in South Florida in October compared to northern Florida, which has the mean demise of the rainy season in September (Fig. 3b). The corresponding standard deviations (Fig. 3c, d) indicate that Panhandle Florida and south Florida have the highest variability with western peninsular Florida exhibiting the least variability both for the start and end dates of the wet season.

3.2 Interannual variability

One of the obvious relationships to interrogate is the relationship of LOWS with ENSO variability. This is because ENSO is one of the most well known and largest natural variability phenomena with robust teleconnections in the southeast US (Ropelewski and Halpert 1986; Barnston 1994; Higgins et al. 2000). The correlation of the preceding December–January–February (DJF) Niño3.4 index with the LOWS for the period of 1948–2005 (Fig. 4a) shows some significant relationship over peninsular south Florida. In other words, these positive correlations suggest that warm ENSO DJF is succeeded by longer wet seasons. However, if we were to split the period between pre-1976 and post-1976 periods, then these significant correlations seem to also appear in the big bend region of Florida in the pre-1976 period (Fig. 4b). However these correlations are rather diminished (and statistically insignificant) in the post-1976 (Fig. 4c) period.

The motivation to split the period to pre and post 1976 era stems from a growing realization that characteristics of ENSO changed in the late 1970's, concurrent with the Pacific-wide climate regime shift (Trenberth and Hurrell 1994; Wallace et al. 1998; An 2004). These studies observe that ENSO, after this rather dramatic regime shift in the Pacific in the mid-1970's, had higher amplitude, longer period, more eastward phase propagation and stronger El Niño and La Niña asymmetry.

More recently Mo (2010) examined the impact of interdecadal modulation of ENSO on winter precipitation and temperature variability over the continental US and found significant differences between the pre and post 1960 era. These are eras that differentiate between the more traditional eastern Pacific ENSO events in the pre-1960 period from the more central Pacific ENSO events (Ashok et al. 2007; Yu and Kao 2007) in the post-1960 period.

The Atlantic Multi-decadal Oscillation (AMO) with a period around 60 years (Schlesinger and Ramankutty 1994; Kerr 1997) also has an important bearing on the ENSO teleconnections of rainfall over the US (Enfield et al. 2001). In fact Enfield et al. (2001) show that in warm phases of the AMO, the ENSO teleconnection of boreal winter rainfall in the southeast US is confined to Florida. However in the cold phase of the AMO, the ENSO teleconnection of the boreal winter rainfall in the southeast US is further spread across the US Gulf coast up to Texas. The AMO changed its phase in the 1960's from a warm to a cold phase and then again flipped to a warm phase around the mid-1990's. Likewise the Pacific Decadal Oscillation (PDO), which has a shorter time scale than the AMO (Mantua et al. 1997), exhibits its influence on ENSO teleconnections with US boreal winter rainfall (Gershunov and Barnett 1998; McCabe and Dettinger 1999). In the warm phase of the PDO, Gershunov and Barnett (1998) found that El Niño winters were drier (wetter) in the northern (southern) tier of the US compared to the cold phase of the PDO. In the late 1970's PDO shifted from a cold phase to a warm phase. In this study we restrict our analysis to the influence of PDO. The time period of our observational datasets limits us from unambiguously examining the influence of AMO on the interannual variations of LOWS.

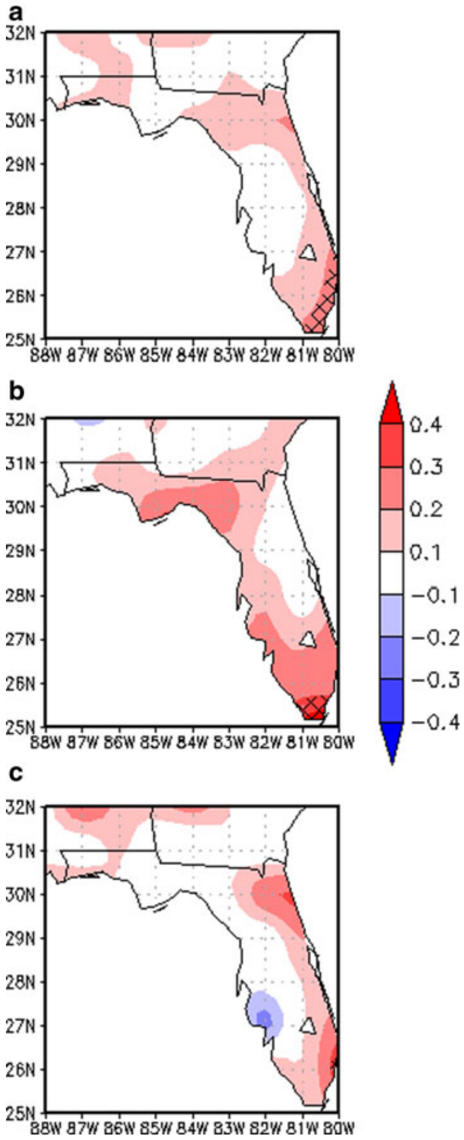

Fig. 6 The correlation of the LOWS with the mean June–July–August area of the Atlantic Warm Pool (AWP) anomalies for the period **a** 1948–2005, **b** 1948–1975 and **c** 1976–2005. Statistically significant correlation values at 90 % confidence interval are *hashed*

To further understand if the variability of the LOWS due to ENSO arises from the modulation of the start date of the wet season, Fig. 5 shows the correlation of the preceding mean DJF Niño3.4 index with the anomalous start of the wet season (S'). It is interesting to note that the correlations are weak when the whole period (1948–2005) is considered. However, in the pre-1976 period (Fig. 5b) the correlations are significantly negative over south Florida, suggesting that warm ENSO in DJF is succeeded by early onset of the wet season. There is similar appearance of negative correlation in the big bend region of Florida, which is however not statistically significant. In contrast these correlations are non-existent and appear diminished

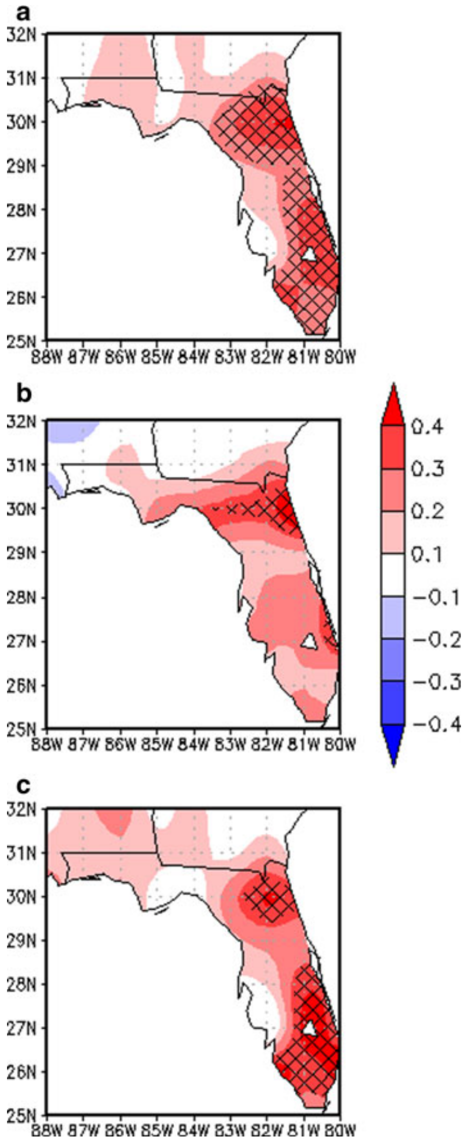

Fig. 7 The correlation of the end dates of LOWS for the period **a** 1948–2005, **b** 1948–1975, and **c** 1976–2005 with the preceding mean June–July–August area of AWP. Statistically significant correlation values at 90 % confidence interval are *hashed*

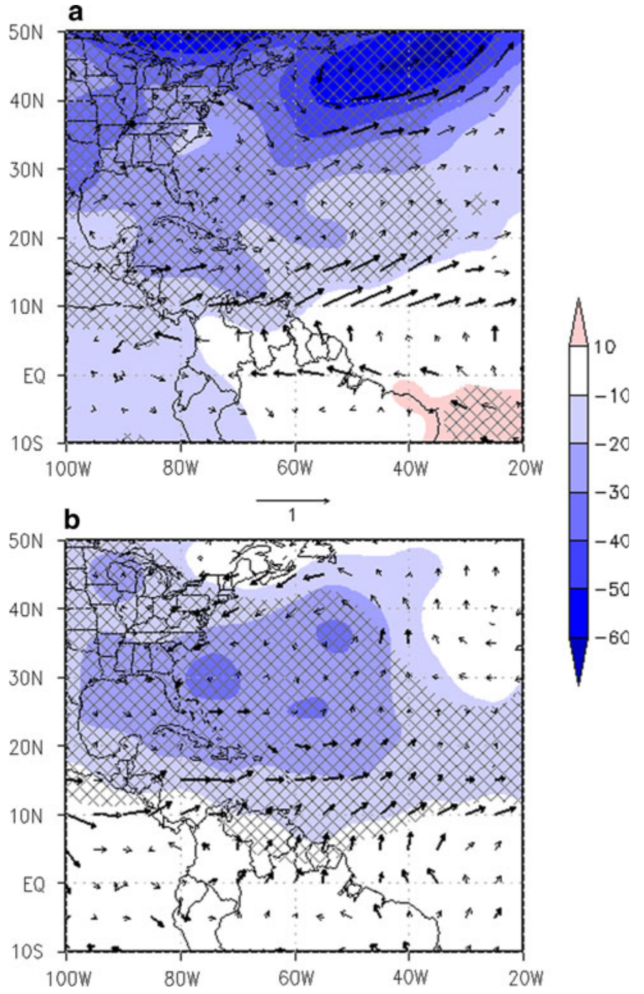

Fig. 8 The contemporaneous linear regression of the mean sea level pressure and 925 hPa winds on the JJA area of the AWP. The statistically significant regression coeffcients at 90 % confidence interval according to *t* test are *hashed* in case of MSLP and are in *bold* for the wind vectors

at other locations over Florida in the post-1976 period (Fig. 5c).

A comparison of Figs. 4, and 5 indicates that the lengthening of the wet season along the big bend region and southeastern peninsular Florida in pre-1976 period is primarily by the modulation of the start date of the wet season by ENSO. This is consistent with the well known fact of wetter Spring season in the southeast US during warm ENSO events (Ropelewski and Halpert 1986; Kiladis and Diaz 1989), which result in the transition from the Spring to Summer season to be far less discontinuous than in La Niña years.

Another important external forcing mechanism of the boreal summer rainfall variability over this region as mentioned in the introduction is the strength and position of the Bermuda high. However underlying this variation of the Bermuda high in the boreal summer season is also the variations of the AWP (Wang and Enfield 2003). The area enclosed by the 28.5°C isotherm in the western hemisphere defines the AWP. It has a distinct seasonal cycle and appears as most well defined in the boreal summer and fall seasons. There is growing observational evidence of the influence of the AWP variations on the warm season precipitation over the Caribbean, Mexico, Central America, southeast Pacific, northwest US and the Great Plains region (Wang et al. 2006). The variability of the AWP modulates the moisture transport into the continental regions of Mesoamerica and the Great Plains region of US through its influence on the low level jets (Wang et al. 2006; Wang and Lee 2007). In years of large AWP, Wang et al. (2008)

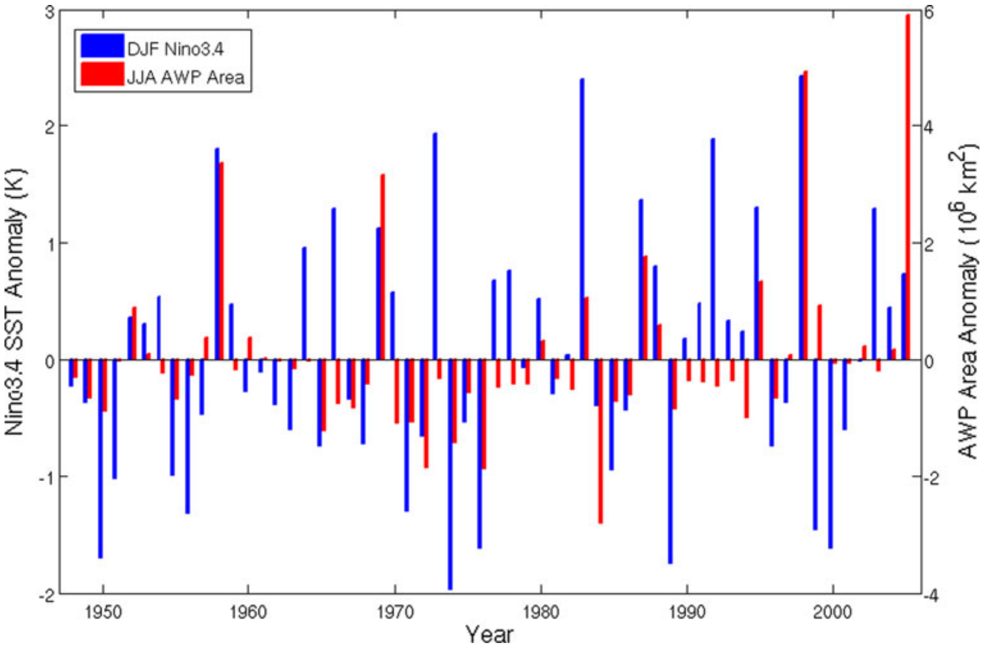

Fig. 9 The mean December–January–February (DJF) SST anomalies over the Niño3.4 region and the following mean June–July–August (JJA) anomalies of the area of the AWP

Table 1 Linear correlations of climate variability indices (ENSO: DJF Niño3 SST anomalies; MAM TNA: March–April–May Tropical North Atlantic SST anomalies; JJA TNA: June–July–August Tropical North Atlantic SST anomalies; AWP area: Atlantic warm pool area)

	1948–2005	1948–1975	1976–2005
ENSO-MAM TNA (1 season lag)	0.64	0.69	0.58
ENSO-JJA TNA (2 season lag)	0.51	0.63	0.39
ENSO-JJA AWP area (2 season lag)	0.52	0.55	0.49
MAM TNA- JJA AWP area (1 season lag)	0.70	0.72	0.71
JJA TNA-JJA AWP area (0 lag)	0.78	0.78	0.83
MAM TNA- JJA TNA (1 season lag)	0.81	0.86	0.78

All values shown are significant at 90 % confidence interval according to *t* test

observe that trade winds in the north Atlantic are relatively weak. Furthermore Misra et al. (2009) also note that evaporation from the western tropical Atlantic ocean surface is also weak in large AWP years. In addition, Wang and Enfield (2001) observe that there is an increased cloud radiative feedback leading to warmer temperatures of the ocean surface. Wang and Lee (2007) suggest that AWP acts as a conduit for the observed relationship of the Atlantic Multi-decadal oscillation and Atlantic tropical cyclone activity. The AWP induced atmospheric changes of vertical shear and convective instability are identified as the dynamical mechanisms by which they control the tropical cyclone activity in the region.

Figure 6 shows the correlation of the mean JJA AWP variations with the LOWS. The correlations are rather weak across all three periods of consideration (Fig. 6a–c). However, the positive correlations albeit statistically insignificant appear stronger and more widespread in the post-1976 era suggesting a possible lengthening of the wet season with larger AWP. Figure 7 shows similar correlations of the AWP variations but with the demise date of the wet season. Unlike the previous figure, the positive correlations with the demise date of the wet season become far more robust over peninsular Florida in the post-1976 era (Fig. 7c) compared to the pre-1976 era (Fig. 7b), which seems to be confined to northeast Florida. It may be noted that the variations of the area of AWP have a seasonal peak in the August–September–October (ASO) season. Furthermore the AWP variations in the ASO season are least related with ENSO variability. Therefore we repeated Figs. 6 and 7 with anomalies of the area of AWP in the ASO season (not shown), which showed nearly similar correlations as with the anomalies of the area of the AWP in the JJA season.

The changing relationship of the end date of the wet season with the AWP (Fig. 7) can be explained from the apparent shift in the linear relationship of the low level atmospheric circulations and the AWP variations (Fig. 8). In the pre-1976 era (Fig. 8a), the AWP variations in JJA are associated with sea level pressure changes and atmospheric circulation at 925 hPa associated with the Bermuda high further northeast of Bermuda (35°N and 65°W). In the post-1976 era (Fig. 8b) the AWP variations in JJA are associated with sea level pressure changes and 925 hPa

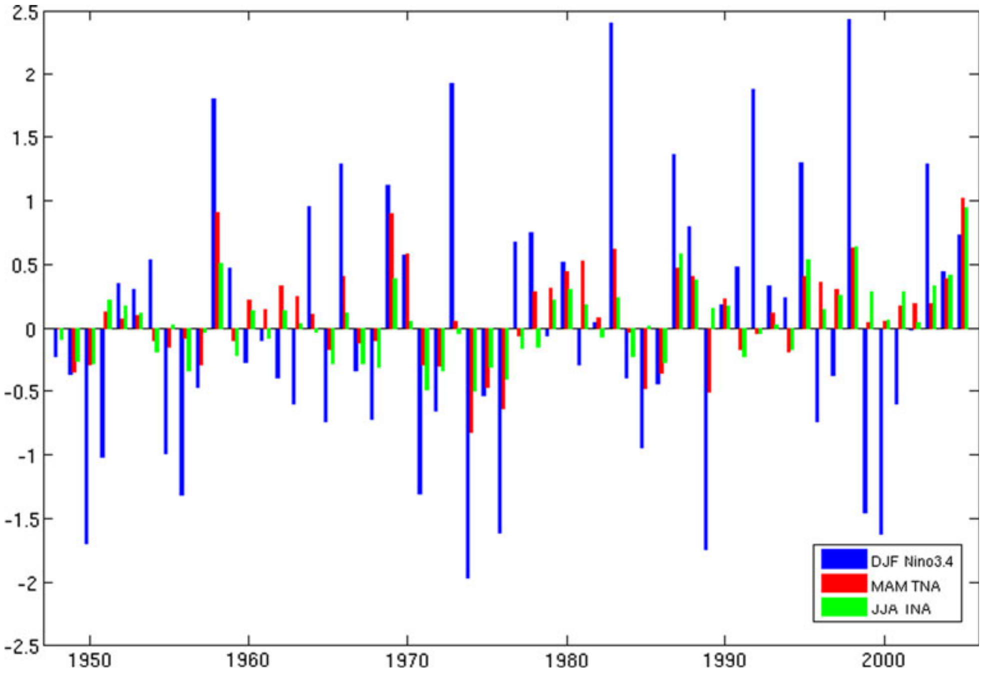

Fig. 10 The mean DJF SST anomalies over the Niño3.4 region and SST anomalies in the tropical north Atlantic (6°–22°N and 15°W–80°W) in the following March–April–May (MAM) and June–July–August (JJA) seasons

circulation further southeast of Bermuda that clearly has more of a bearing on the subsidence of the Bermuda high over Florida. Figure 8 clearly suggests that large AWP is associated with weakening of the Bermuda high, especially so with the weakening of its westward extent over Florida in the post-1976 era that explains the associated anomalous lengthening of the wet season with reduced large scale subsidence.

In the post-1976 era, the correlations of the JJA AWP area with the preceding DJF Niño3 SST index (Fig. 9, Table 1) drop compared to pre-1976 era. In fact, Wang et al. (2006) suggest that the AWP variations in the boreal summer and fall seasons are not intimately connected to the ENSO variations. We see here that this feature of independence of AWP with ENSO has a multi-decadal flavor, although the reduction in the correlation between the two periods is not appreciable. Further investigation of the anomalies over the Tropical North Atlantic Ocean (TNA; 6°–22°N and 15°W–80°W) in the boreal spring season, a region well known for its response to ENSO forcing (Nobre and Shukla 1996; Enfield and Mayer 1997) also shows appearance of more non-canonical SST anomalies in the post-1976 era (Fig. 10, Table 1) compared to the pre-1976 era. In the pre-1976 era, a majority of the years had similar sign of the SST anomalies in the TNA as the Niño3 index while in the post-1976 era several years had opposite signs of the SST anomalies in the two oceanic regions (Fig. 10) that led to a drop in the correlations between the ENSO index and the TNA SST anomalies (Table 1). This drop in correlation is most significant between the DJF Niño3 SST index and the JJA TNA SST anomalies between the two periods. In a related study, Lee et al. (2008) indicate the persistence of ENSO anomalies beyond February–March–April season is critical to sustain the teleconnection between ENSO and TNA SST anomalies. Furthermore, the persistence of the TNA SST anomaly from MAM to JJA (Fig. 10, Table 1) in both the pre-1976 period and the post 1976 era is consistently large and noteworthy. The persistence of these SST anomalies in the TNA from boreal spring to summer suggest the potential role of the conditioning of the lower atmospheric circulations by the underlying SST anomalies. The appearance of the SST anomalies over TNA contrary to the remote ENSO forcing are generated from the local coupled air-sea mode and are comparable to the remote ENSO forcing (Giannini et al. 2001; Chang et al. 2003; Huang et al. 2005). Kushnir et al. (2010) and Wang et al. (2006) suggest that the modulation of the spring season TNA SST anomalies affect the Bermuda high. In a more recent intercomparison study of three different ocean and atmosphere reanalyses, Stroman (2011) shows that the variations of the AWP in the boreal summer and fall seasons are intimately associated with SST anomalies in the preceding boreal spring season over the TNA, which is also corroborated in the correlations shown in Table 1. This is attributed to the conditioning of the Bermuda high and its associated low level circulation by the TNA SST anomalies that affect the wind induced surface evaporation and feedback to the underlying evolution of SST anomalies.

Finally, Li et al. (2011) showed that the variability of the Bermuda high has increased over the last three decades as a result of the anthropogenic influence of global climate from increasing greenhouse gases. The dominance of the non-

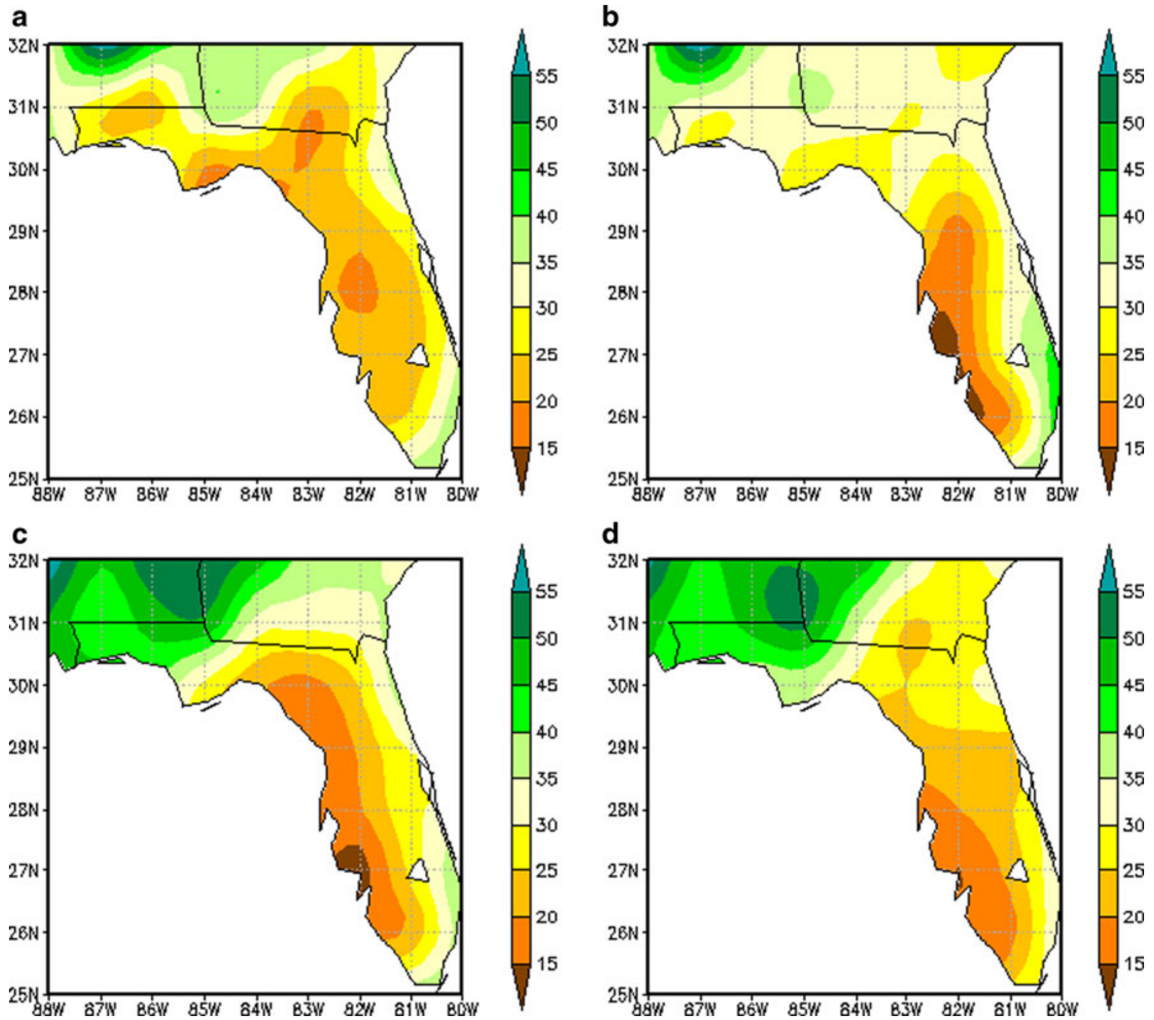

Fig. 11 Standard deviation in days of the **a** start date and **b** end date for the period 1948–1975. Similarly the standard deviation in days of the **c** start date and **d** end date for the period 1976–2005

canonical variations of TNA SST anomalies in the boreal spring season and AWP variations in the boreal summer season may also be related to the increased variability of the Bermuda high in the recent decades. Figure 11 shows that the variability of the start (end) date of the wet season has decreased (increased) in the post-1976 era compared to the pre-1976 period. This is consistent with our discussions thus far of the waning influence of ENSO on the start date and increasing influence of the AWP on the end date of the wet season in the recent decades.

4 Conclusions

The rainy season in the northern US Gulf coast and Florida is a robust feature with some semblance to the monsoonal type of seasonal transitions. It may be noted that the wet season (climatologically $\geq$90 days) is very narrowly located along the Florida Gulf coast and south of 32°N and spread over peninsular Florida. Interestingly, interannual variations of the Length of the Wet Season (LOWS) are small where the season is climatologically long in south Florida and large where the season is climatologically short along the northern Florida Gulf coast.

The ENSO forcing on this feature is sporadic spatially and exhibits a decadal variation, with stronger influence on the start date of the LOWS, especially over south Florida in the pre-1976 era compared to the post-1976 era. The two eras are demarcated by the Pacific wide regime shift somewhere in the mid-1970's. This relationship of ENSO with LOWS at onset is intuitive as the influence is in the late spring months, when the influence of ENSO on the southeast US although diminishing continues from the so called Pacific-North American pattern (Wallace and Gutzler 1981).

The influence of the Atlantic Ocean on the LOWS is also significant. In fact it is far more significant spatially and temporally than the ENSO forcing, especially on the end date of the wet season. Our results indicate that the weakening (strengthening) of the Bermuda high associated with large (small) AWP leads to lengthening (shortening) of the end date of wet season over Florida. There are however some important variations between the pre-1976 and post-1976 era of the relationship between LOWS and AWP. In the pre-1976 era, the AWP is associated with variations of the Bermuda high northeast of Bermuda. In the post-1976 era, the AWP variations are associated with variations of the Bermuda high southwest of Bermuda that has a direct bearing on the associated large-scale subsidence over Florida. This change in influence of AWP with the Bermuda high is also observed with the variability of SST anomalies over north tropical Atlantic (6°–22°N and 15°W–80°W) in the boreal spring season and AWP variations in the boreal summer season develop more often non-canonically to ENSO forcing in the post-1976 era compared to the pre-1976 era.

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