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Florida wildfire activity and atmospheric teleconnections

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Abstract. Since 1991, the Florida Division of Forestry has been making seasonal fire severity forecasts based on a relationship between area burned in Florida and El Niño–Southern Oscillation (ENSO). The present study extends the original analysis on which these forecasts are based and attempts to augment it with the addition of other patterns of climate variability. Two atmospheric teleconnection patterns, the North Atlantic Oscillation and Pacific–North American pattern, are examined as potential indicators of seasonal and monthly area burned in Florida. Although ENSO was the only climate index to show a significant correlation to area burned in Florida, the Pacific–North American pattern (PNA) is shown to be a factor influencing fire season severity although the relationship is not monotonic and therefore not revealed by correlation analysis.

Introduction

Each of the past 3 years, a group of climatologists, meteorologists and fire managers has been meeting to produce an assessment of the severity of the upcoming fire season in the south-eastern United States. This effort has been part of a larger national effort headed by the National Predictive Services Group (NSPG), the Climate Assessment for the South-west (CLIMAS), and the Program for Climate, Ecosystem and Fire Applications (CEFA). The goal of these regional assessments is to provide land managers and key governmental officials with a look at expected fire conditions over the next 6 months.

In developing these assessments, a wide variety of tools are used to link expected climate conditions with different levels of fire activity. A key tool is the many scientific studies that link climate features such as El Niño–Southern Oscillation (ENSO) to precipitation and in some cases fire activity. Brenner (1991) presented a strong case for a significant linkage between sea surface temperatures in the equatorial Pacific Ocean and wildfire activity in Florida. ENSO has a strong influence on storm tracks across the United States. During the warm phase, two storm tracks cross the country, one along the northern border and another across the southern portion of the country, which brings above-normal rainfall to the south-eastern United States during winter. During the cold phase, a single storm track is the dominant pattern, which steers most storms away from Florida and results in below-normal rainfall for Florida. Brenner found that the cold ENSO phase correlated with above-normal area burned in Florida. This study relied on simple linear regression to develop its relationship between January–May mean sea surface temperature (SST) anomalies and annual area burned in Florida for the period of 1950 to 1989. The results of Brenner's study have been the cornerstone for the State of Florida's seasonal wildfire activity forecasts since 1991.

In 1998, Florida experienced one of its worst fire seasons on record, as over 2200 wildfires scorched nearly a half million acres and 126 homes were lost (Wade *et al*. 1998). According to the methodology of Brenner (1991), 1998 should not have been a severe fire season as the warm ENSO phase dominated the first 4 months of the year before switching to the cold phase beginning in May. Although the overall January–May mean SST anomaly was positive in 1998, ENSO was in its cold phase during the time period when severe fire conditions occurred (May through July), revealing the potential for a more concurrent connection between Florida wildfires and ENSO.

Although ENSO has been shown to be a dominant climate oscillation, there are several other modes of climate variability that can significantly influence regional climate. Teleconnection patterns are modes of atmospheric variability often revealed through empirical orthogonal function (EOF) analysis of geopotential heights. The relative importance of each teleconnection pattern typically varies with season, as some are dominant in the winter whereas others may dominate during the summer. The influences of several teleconnection patterns manifest themselves by either enhancing or mitigating the impact of ENSO.

Heilman (1995) employed EOF analysis of the observed geopotential height of the 50-kPa (500-mb) pressure level to determine atmospheric circulation patterns that were prevalent at the onset of severe wildfires in six different regions of the United States. Three distinct circulation patterns emerged as significant for wildfires in the south-central and south-eastern United States. The first two of these patterns represented the positive and negative phases of the Pacific–North American teleconnection pattern (PNA). The PNA oscillation is related to variability in mid-tropospheric flow over North America and the North Pacific. Positive PNA is defined when the 700-hPa heights indicate a ridge over Alberta, Canada, and troughs over the south-east USA and the Aleutian Islands, whereas negative PNA indicates a generally zonal flow across the United States (Wallace and Gutzler 1981). Correlations between the PNA and

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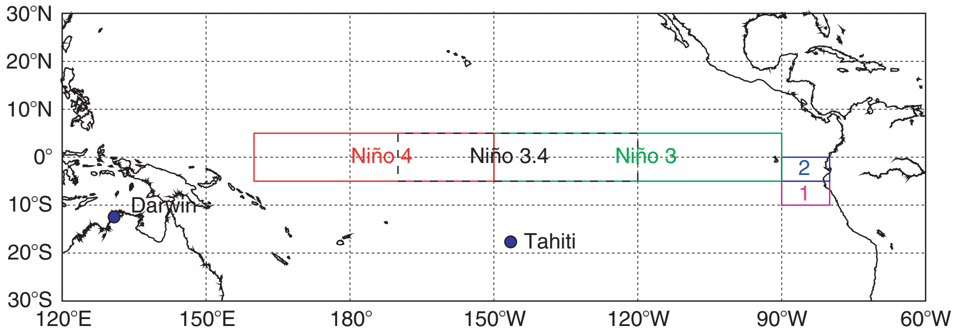

Fig. 1. Regions used for monitoring El Niño–Southern Oscillation (ENSO) conditions.

precipitation show a strong negative relationship over the Ohio River Valley of the eastern United States in January that weakens and shifts northward by the spring, being replaced by a weak positive relationship in the south-eastern coastal plain (Leathers *et al*. 1991). The PNA shows substantial interseasonal, interannual, and interdecadal variability. The period 1976–88 was dominated by a positive PNA pattern whereas 1989–90 was primarily negative and PNA returned to positive values during the fall of 1991 and remained positive through the spring of 1993.

Another prominent northern hemisphere teleconnection pattern consists of a north–south dipole of anomalies, with one center located over Greenland and the other center of opposite sign spanning the central latitudes of the North Atlantic between 35°N and 40°N, and is known as the North Atlantic Oscillation, or NAO (Barnston and Livezey 1987). Various changes in temperature and precipitation patterns across eastern North America and western and central Europe can be associated with the NAO (Walker and Bliss 1932; van Loon and Rogers 1978; Rogers and van Loon 1979) as the pressure dipole forces basin-wide variations in the strength and location of the North Atlantic jetstream and storm track (Hurrell 1995). The positive phase of the NAO implies warmer and wetter than normal conditions over the South-eastern United States whereas the negative NAO phase indicates the opposite. As with the PNA, the NAO exhibits considerable interseasonal and interannual variability. The wintertime NAO has also been noted to exhibit multidecadal variability (Hurrell 1995; Chelliah and Bell 2004).

The present paper is not intended to be an exhaustive examination of possible teleconnection links to Florida's wildfire activity. The PNA and NAO were selected for the current analysis as they are known to influence weather patterns in the south-eastern United States and the frequency of their oscillations is a good match to the length of the available fire activity time series. Lower frequency modes of variability such as the Atlantic Multidecadal Oscillation have also been shown to influence precipitation patterns in the United States (Mestas-Nuñez and Enfield 1999; Enfield *et al*. 2001), but the fire activity time series is currently too short for rigorous analysis.

The present paper has three primary objectives. The first is to reexamine the work of Brenner (1991) relating ENSO to total area burned during the fire season (January–May) in Florida by extending the datasets to the present. Second, it evaluates the impact of how the fire season is defined on the results of Brenner (1991) by examining an alternative fire season definition (January–June) as well as the relationship on a monthly time scale rather than just the seasonal averaging. The third objective is to integrate the PNA and NAO into the analysis and determine whether these teleconnection patterns are associated with area burned by Florida wildfires.

Methods

Fire data

At the time of Brenner's original work, the state of Florida only had digital monthly wildfire activity information for the period of 1981–89, hardly optimal for any type of climate study. Brenner's dataset was augmented by collecting and digitizing paper records that extended the time series back to 1950. In a report commissioned by the Florida Division of Forestry to further investigate the relationship between ENSO and area burned in Florida, Barnett (1991) discovered some slight discrepancies in the early fire activity data used by Brenner due to changes in area protected by the state that led to the fire activity distribution being non-stationary and decidedly non-Gaussian. Jones *et al*. (1999) limited the fire history data in their study of ENSO, rainfall and fires in Florida to only the period of 1981–89. The present study will focus on the period covered by digital data (1981–2003) rather than the longer time series originally used by Brenner to avoid the previously noted inconsistencies in the pre-1981 data.

ENSO data

Many indices are available for assessing the current state of ENSO such as the Southern Oscillation Index (SOI), which is calculated from the monthly or seasonal fluctuations in the air pressure difference between the island of Tahiti (French Polynesia) and Darwin, Australia. An alternative measure is examining SST anomalies in the equatorial Pacific Ocean. Sea surface temperature anomalies are typically monitored in five regions across the equatorial Pacific: Niño 1, Niño 2, Niño 3, Niño 3.4 and Niño 4 (Fig. 1). As both Brenner (1991) and Barnett (1991) achieved their best correlations using SST anomalies from the central part of the Pacific, the present study makes use of SST anomalies measured in the regions denoted as Niño 3, which extends from 5°N to 5°S and 90°W to 150°W, and Niño 3.4, which extends from 5°N to 5°S and 120°W to 170°W. Although the original study focused on the Niño 3 region, some recent studies have found the Niño 3.4 region to be a more discerning index for examining ENSO impacts (Hanley *et al*. 2003; Larkin and Harrison 2005).

Teleconnection data

Monthly indices for the PNA and NAO were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/tele_index.nh, accessed 15 December 2007). These indices are based on the Rotated Principal Component Analysis (RPCA) used by Barnston and Livezey (1987). The RPCA technique is applied to monthly mean standardized 50-kPa (500-mb) height anomalies over the region 20–90°N.

Statistics

In Brenner (1991), a Pearson product–moment correlation was the statistic of choice. Although Brenner did achieve good correlation ($r = -0.71$), later work by Barnett (1991) raised some concerns about the area burned data (lack of stationarity and non-Gaussian distribution) that raise some concern over Brenner's methodology. Barnett circumvented these obstacles by neglecting some early data and performing a log-transform of the area burned data. In the present study, our statistical measure of choice is the Spearman rank correlation, in which values in each time series are ranked and a correlation coefficient is calculated based on these ranks rather than the raw data. For a time series x with N values, the smallest value in x is assigned a rank of 1 while the largest receives a rank of N. Ties are resolved by splitting the rank among the identical values.

The Spearman rank correlation coefficient provides a robust and resistant alternative to the Pearson product–moment correlation coefficient (Wilks 1995). The Spearman rank correlation coefficient is robust in that it is not sensitive to departures from linearity as it reflects the strength of monotonic relationships rather than strictly linear relationships. The very nature of replacing data values with their rank within the set makes the Spearman rank correlation coefficient resistant to outliers within the data. These characteristics make the Spearman rank correlation coefficient appropriate for use with small datasets (O'Brien and Griffiths 1965). Examination of the combined influence of ENSO and the PNA and NAO will utilize partial correlations of the ranked data.

Results and discussion

Relationships averaged over the fire seasons

The use of the shorter 1981–present fire dataset over the longer 1950–present dataset originally used by Brenner can be justified by applying Brenner's methodology and comparing correlations for the truncated and complete time series. In Brenner (1991), the best correlation obtained between Niño 3 SST anomalies averaged over the fire season (January–May) and total area burned for the corresponding period was −0.71. Following the methodology of Brenner but using only the data for 1981–90, a Pearson correlation coefficient of −0.65 is obtained, which is a significant correlation at the 0.05 confidence level. Use of a rank correlation improves the r value to −0.78. Extending the dataset forward in time beyond 1990 results in some minor changes in correlation (Fig. 2), but the results remain significant at the 0.05 level. The rank correlation for the entire period of analysis (1981–2003) is −0.64.

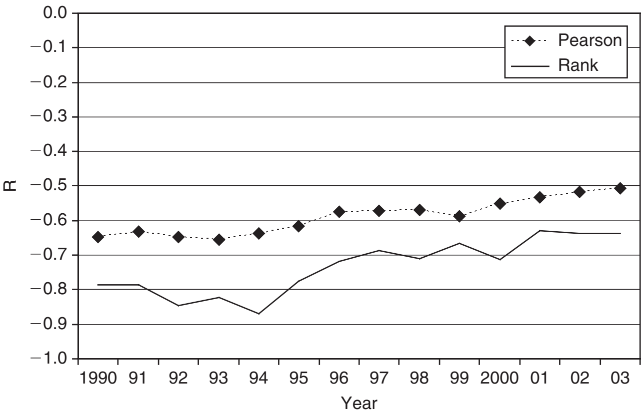

Fig. 2. Comparison of correlation coefficients calculated using Pearson and Rank methods for total area burned each fire season in Florida starting in 1981 to fire-season averaged Niño 3 sea surface temperature anomalies.

Table 1. Rank correlation of fire season (January–May) average sea surface temperature and teleconnection indices to total area burned over the same period for 1981–2003

Abbreviations are: PNA, Pacific-North American pattern; NAO, North Atlantic Oscillation

Parameter	r correlation	r^2 variance explained
Niño 3	−0.64	41%
Niño 3.4	−0.63	40%
PNA	−0.21	4%
NAO	+0.11	1%

SST anomalies and teleconnection indices averaged over the fire season were correlated against total area burned for each fire season. Rank correlations were calculated for each climate parameter (Table 1). The best correlations were found between the SST anomalies and area burned ($r = -0.64$) for the Niño 3 region, with a slightly weaker correlation for Niño 3.4. The resulting relationships are weaker than those of Brenner, but are in general agreement and still significant at the 0.05 confidence level. Although not significant, the PNA exhibits a weak negative relationship, indicating that its negative phase might have a weak relationship to above-average area burned in Florida. The NAO explained only 1% of the variance in area burned.

Examination of a scatter plot of Niño 3 and PNA against area burned further illustrates the monotonic relationship between the indices and area burned (Fig. 3). Of note is the group of four apparent PNA outliers, two in the lower left and two in the upper right corner of Fig. 3, representing the years 1982 and 2002 in the lower left corner, and 1992 and 1993 in the upper right. Removal of these 4 years from the analysis elevates the strength of the relationship between area burned and PNA slightly to −0.27. All four of these cases represent years where the PNA and Niño 3 values are out of phase. Renwick and Wallace (1996) found that during periods of cold ENSO

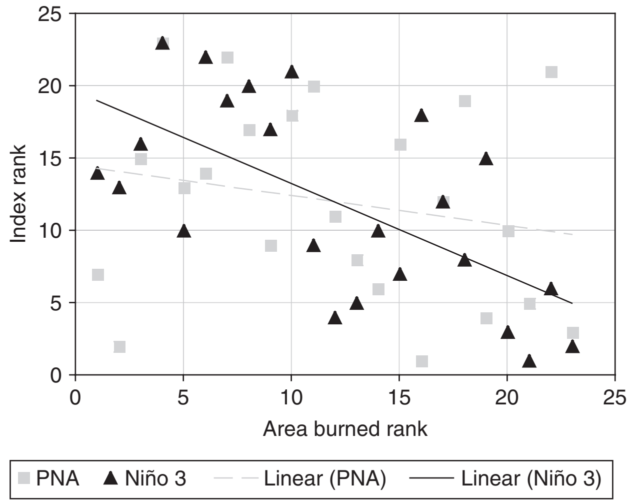

Fig. 3. Scatter plot of Niño 3 and Pacific–North American pattern (PNA) ranks *v.* area burned rank for January–May 1981–2003. Both climate indices indicate a negative relationship with area burned.

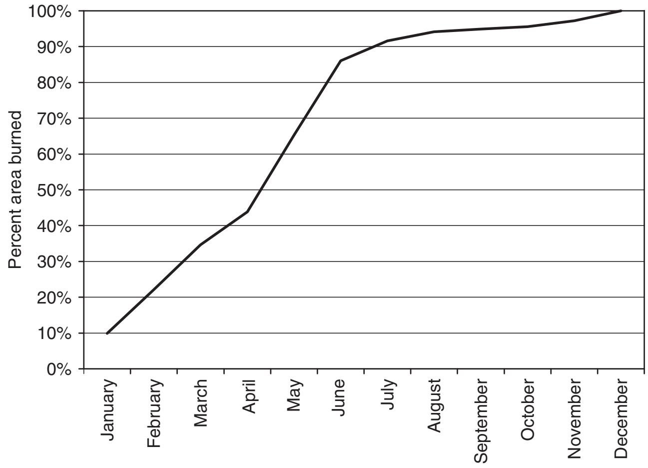

Fig. 4. Cumulative percentage of area burned by month for wildfires in Florida during 1981–2003. Defining a fire season as January–June captures 86% of the total area burned.

phase, the negative phase of the PNA typically dominates (the warm ENSO phase conversely favors the positive PNA phase), suggesting a potential correlation between ENSO and PNA. The negative relationship between PNA and area burned is somewhat contrary to the findings of Heilman (1995), in which both phases of the PNA were associated with major wildfire episodes; however, Heilman was specifically examining circulation patterns that preceded significant fire events rather than seasonal averages.

Extended fire season definition

In 1998, the January–May area burned in Florida ranked as the sixth lowest for the period dating back to 1981. During this year, most of the acres burned occurred in June and extended into early July, outside the fire season definition used in previous studies. This raises a question as to the suitability of the definition of a fire season as being January through May. Summing the area burned by month and plotting the cumulative percentage of the area burned reveals that the fire season would more accurately be defined as January through June (Fig. 4). Ending the fire season in May captures only 65% of the total area burned; the addition of June brings the total to 86%.

Rank correlation coefficients were recalculated using the revised fire season definition for the averaging period (Table 2). Extension of the fire season by 1 month dramatically reduces the strength of the correlations between SST anomalies and area burned, more so for Niño 3 than for Niño 3.4. However, the PNA correlation is largely unchanged. The reduction in correlation for the SST indices is largely attributable to 1998 as SST anomalies were strongly positive until late May when conditions reversed. June of 1998 accounted for 83% of the total area burned that year and during this month, the SST anomalies were negative after having been strongly positive for 13 of the preceding 14 months. Exclusion of the June 1998 data from the analysis raises the Niño 3 and Niño 3.4 correlations back up to −0.57 and −0.61 respectively. The area burned during June 1998 was sufficient to change that year's rank from sixth lowest to third highest; the rank of the Niño 3 anomaly remained unchanged (second warmest during the period). Although the magnitude of the change in Niño 3 *r* values is attributable to small sample size, a perfectly correlated time series of 100 values would still show a marked reduction in *r* if the third highest and lowest values were interchanged (the rank correlation would drop from 1.0 to 0.89). The Niño 3.4 correlation showed less of an impact as the June SST anomaly in this region was cooler, resulting in a lower ranking compared with Niño 3. For the purposes of the present study, the Niño 3.4 SST anomalies appear to be a more robust indicator of area burned than the Niño 3 values, which is consistent with the findings of Hanley *et al.* (2003) as the westward shift of the Niño 3.4 region relative to that of Niño 3 incorporates an area of the Pacific Ocean that is more sensitive to the cold phase of ENSO.

Table 2. Rank correlation of fire season (January–June) average sea surface temperature and teleconnection indices to total area burned over the same period for 1981–2003

Abbreviations are: PNA, Pacific-North American pattern; NAO, North Atlantic Oscillation

Parameter	*r* correlation	r^2 variance explained
Niño 3	−0.42	18%
Niño 3.4	−0.49	24%
PNA	−0.18	3%
NAO	−0.01	<1%

Monthly relationship to area burned

As the addition of June to the fire season had such a dramatic effect on the relationship between area burned and SST anomalies, a monthly time series covering the months of January–June for each year between 1981 and 2003 was examined. Table 3 reveals a dramatic drop (−0.18 to −0.07) in correlation for the PNA while the SST anomalies are weakened only slightly. For

Table 3. Rank correlation of area burned to sea surface temperature and teleconnection indices for using individual monthly values (January–June 1981–2003)

Abbreviations are: PNA, Pacific-North American pattern; NAO, North Atlantic Oscillation

Parameter	*r* correlation	r^2 variance explained
Niño 3	−0.39	15%
Niño 3.4	−0.45	21%
PNA	−0.07	<1%
NAO	−0.04	<1%

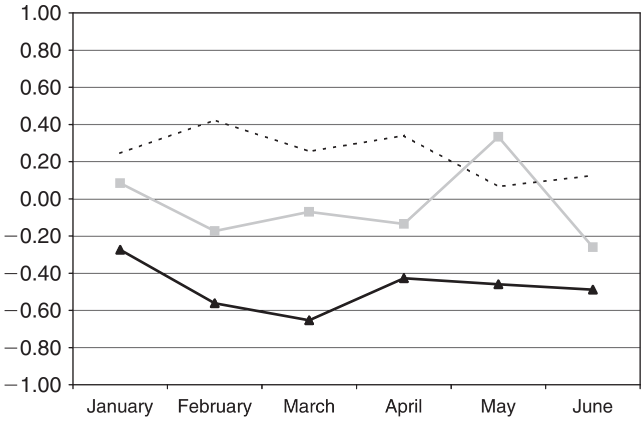

Fig. 5. Monthly rank correlation coefficients for Niño 3.4 (triangles) and Pacific–North American pattern (PNA) (squares). Dotted black line shows correlations between Niño 3.4 and PNA.

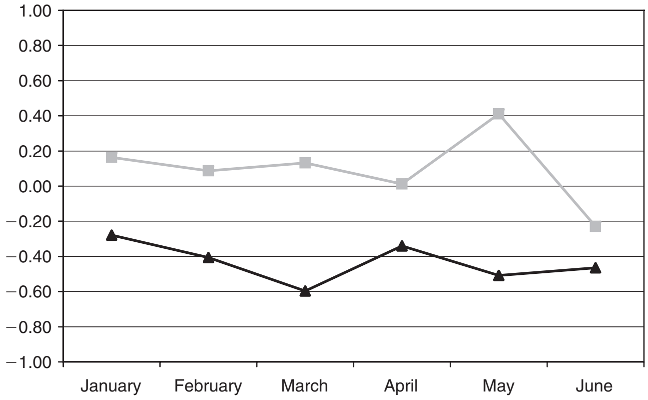

Fig. 6. Partial correlation between both Niño 3.4 (triangles) and Pacific–North American pattern (PNA) (squares) to area burned.

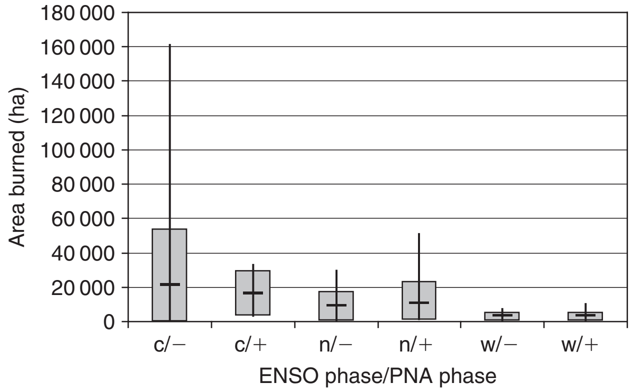

Fig. 7. Box and whisker plot of monthly area burned by El Niño–Southern Oscillation (ENSO) phase (c, negative; n, neutral; w, positive) and Pacific–North American pattern (PNA) phase (−, negative; +, positive). Box represents ±1 standard deviation and whiskers extend from minimum to maximum acres burned.

the PNA, this is likely a manifestation of the shorter time-scale variability of this pattern. As stated earlier, for cold ENSO phases the negative PNA phase tends to be preferred, which is likely to show up in the seasonal average but would not necessarily hold on the monthly time scale.

Correlations for each individual month were examined to see how the relationship between Niño 3.4 SST anomalies (and the PNA) to area burned changed by month (Fig. 5). The correlations for Niño 3.4 to area burned are strongest during winter months (January–March), peaking at $r = -0.65$ in March (r values in excess of ± 0.42 are significant at the 0.05 level). This is consistent with ENSO having its largest impacts during the winter months. The PNA correlations do not vary in a smooth manner as with the Niño 3.4 values. The PNA shows its best correlations to area burned during May ($r = 0.33$), followed by a second peak in June ($r = -0.26$), possibly reaffirming the dichotomy found by Heilman (1995). A possible confounding factor in the relationships is that we have not established that the Niño 3.4 SST anomalies and the PNA index are independent; in fact, the contrary is indicated as the cold ENSO phase tends to favor the negative PNA phase. Correlation between the indices for each month (dotted black line, Fig. 5) reveals a modest positive correlation for January–April with no relationship indicated for the other months.

Partial correlations were calculated to try and isolate the influence of each index on area burned by accounting for their interrelationship (Fig. 6). With the influence of ENSO held constant, the PNA displays a weak positive correlation to area burned that peaks in May before transitioning to a modest negative relationship in June. This timing corresponds with the breakdown of the pressure dipole that characterizes the PNA during the winter months. For positive PNA phase, this would imply the building of the subtropical ridge across the region to fill in the trough of the dipole pattern. The partial correlation weakens the relationship between Niño 3.4 and area burned for February–April, reducing the maximum variance in area burned explained by Niño 3.4 SST anomalies in any month from 43% down to 36%. This drop in variance explained when the influence of the PNA is held constant suggests the possibility that the preference for the negative PNA phase during times of cold ENSO phase is part of the mechanism through which tropical Pacific SSTs are linked to weather conditions over Florida during their fire season.

Examination of the distribution of monthly area burned by both Niño 3.4 phase (cold, neutral and warm) and PNA phase (±) reveals that the warm ENSO phase represents the absolute lowest levels of fire activity regardless of the PNA phase (Fig. 7). For the neutral ENSO phase, defined as Niño 3.4 SST anomalies

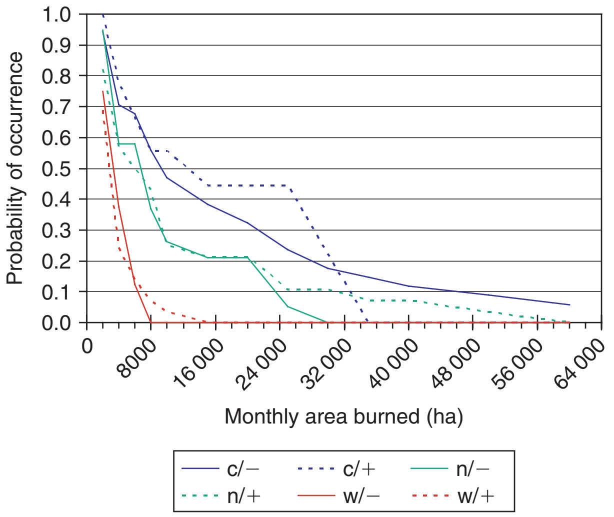

Fig. 8. Probability of burning *n* acres in a given month during the fire season (January–June) by El Niño–Southern Oscillation (ENSO) (cold/neutral/warm) and Pacific–North American pattern (PNA) (±) phase.

±0.5°C, mean area burned increases by a factor of ∼3 over that of the warm ENSO phase, and the positive PNA phase increases the standard deviation in area burned relative to the negative phase by almost 50%, with the maximum area burned during the positive phase showing a similar increase. The majority of the area burned during the January–June period (56%) occurs during the cold ENSO phase, particularly in conjunction with negative PNA values (34% of the total area burned during the fire season). However, when the PNA switches to positive, the distribution of area burned is much more similar to the neutral ENSO distributions.

Although examining the distributions of monthly area burned as a function of ENSO and PNA is informative, it does not provide much in the way of useful guidance for decision support. Decision support is better served by information regarding the probability of fires consuming a certain area based on ENSO and PNA values (Fig. 8). Each month of the fire season (January–June) for the years 1981–2003 was classified based on the state of ENSO (cold, neutral or warm) and the PNA phase (positive or negative), and for each of these six sets, the probability of area burned exceeding a given acreage threshold was determined. This graph clearly shows the dominant role of ENSO in determining the severity of Florida fire seasons; however, the PNA provides a subtle variation for the rare events. During the warm and neutral ENSO phases, positive PNA values increase the probability of extreme events (those occurring less than 10% of the time) being more severe, whereas for the cold ENSO phase, negative PNA values represent the most severe events. This dichotomy in the PNA's influence on area burned adds further support to the findings of Heilman (1995) that both phases of the PNA relate to large fires in the southern United States.

Summary

The present paper revisited the work of Brenner (1991) relating area burned in Florida to ENSO, and extends this original work by updating the datasets, reassessing the definition of Florida's fire season and incorporating the potential influences of additional climate patterns, the PNA and NAO. Despite using a shorter time series than in the original work, similar correlations were achieved and eventually improved by switching to rank correlations that helped account for the non-Gaussian distribution of area burned. Using a fire season defined to extend from January to May, the correlation between ENSO (as indicated by either the Niño 3 or Niño 3.4 SST anomalies) was −0.64, a slight drop from Brenner's −0.71; however, the January–May definition of a fire season only accounted for 65% of the area burned. Extending the fire season through June accounted for nearly 86% of the area burned. This adjusted averaging period dramatically reduced the strength of the correlation ($r = -0.49$ for Niño 3.4); however, significance at the 0.05 confidence level was maintained.

At the seasonal time scale, the addition of the PNA and NAO teleconnection patterns initially yielded little insight into Florida's fire season severity. Neither the NAO nor the PNA yielded significant correlations at the seasonal time scale; and switching to a monthly time scale only further weakened the correlations. However, partitioning the area burned in Florida by ENSO phase and PNA phase revealed a distinct relationship between the combination of ENSO and PNA to area burned that was not captured by the correlation test, likely a result of the relationship not being monotonic. For January through June, 56% of the area burned in Florida coincides with the cold phase of ENSO whereas 34 and 10% coincide with the neutral and warm phases of ENSO respectively. Using PNA phase to further break down the area burned reveals that 34% of the total area burned coincided with the cold ENSO and negative PNA phases whereas 22% occurred with the cold and positive combination. During neutral ENSO phases, there was little difference in the mean area burned for the different PNA phases, but the positive phase of the PNA exhibited increased variability and maximum area burned exceeding that of the cold ENSO and negative PNA combination. This dichotomy in the PNA's influence on area burned supports the findings of Heilman (1995) that both phases of the PNA relate to large fires in the southern United States. Accounting for the correlation between the Niño 3.4 SST anomalies and the PNA values substantially weakened the relationship between area burned and ENSO, indicating that the preference for negative PNA values during cold ENSO events is an important mechanism for ENSO's relationship to Florida's area burned.

The present study represents only a glimpse of the many linkages between wildfire activity and teleconnection patterns. As the time series of fire activity lengthens, one will be able to examine a broader spectrum of climate oscillations, such as the Atlantic Multidecadal Oscillation. Just as examining the interrelationship of ENSO and the PNA expanded our understanding of the seasonal variability of Florida's wildfire activity, an understanding of linkages to low frequency oscillations would provide another piece to the puzzle of predicting wildfire season severity.

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