P5.19 TOWARD GREATER UNDERSTANDING OF INTER-SEASONAL AND MULTI-DECADAL VARIABILITY AND EXTREMES OF EXTRATROPICAL STORMINESS IN FLORIDA

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## 1. INTRODUCTION

In their continuing investigation into the prediction of Florida Dry Season (DS) storminess (1 November - 30 April) from the ENSO signal Hagemeyer and Almeida (2004) found that other teleconnections, particularly the North Atlantic Oscillation (**NAO**) and Pacific/North America (**PNA**) patterns can play an important role in interseasonal and intraseasonal variability. The authors updated the DS storminess climatology for the Florida grid (Fig. 1) using the latest version of NCEP re-analysis data and extended the period of record back to 1948 (see Hagemeyer and Almeida (H&A) 2002 and 2003 for storminess calculation methodology). A plot of the number of Florida DS storms from the 1948-49 through 2002-03 dry seasons compared to normal storminess (6 storms) is shown on Figure 2.

Previously the authors had found a very strong relationship between the phase of ENSO and Florida DS storminess ( H&A 2002, 2003, 2004) for the1960 through 2000 seasons. New multiple linear regression (MLR) analyses for the 53 seasons from 1950 through 2002 were completed and again confirmed the strong relationship between Florida DS storminess and sea surface temperature (SST) in the central and eastern Pacific, especially the Nino 3.0 (**$R^2$** = 0.57) and Nino 1+2 (**$R^2$** = 0.55) regions (Fig. 3). As before, correlations were weaker for the Nino 3.4 (**$R^2$** = 0.47) and Nino 4.0 regions (**$R^2$** = 0.27).

Hagemeyer and Almeida (2004) noted that experimental forecasts of Florida DS storminess in moderate to strong La Nina or El Nino conditions since the 1997 season have been successful and useful for decision makers. However, ENSO neutral seasons such as 2001-02 remain problematic. Indeed, in a review of all seasonal hindcasts using the new Nino 1+2 and Nino 3.0 regression equations the authors noted that the two greatest seasonal storminess outliers were the 1983-84 and 2001-02 dry seasons. Both were ENSO neutral seasons, but the 2001-02 season produced only one storm (5 below normal) and was comparable to the greatest La Nina (1988-89) while the 1983-84 season produced 13 storms (7 above normal) and was comparable to a major El Nino in impact.

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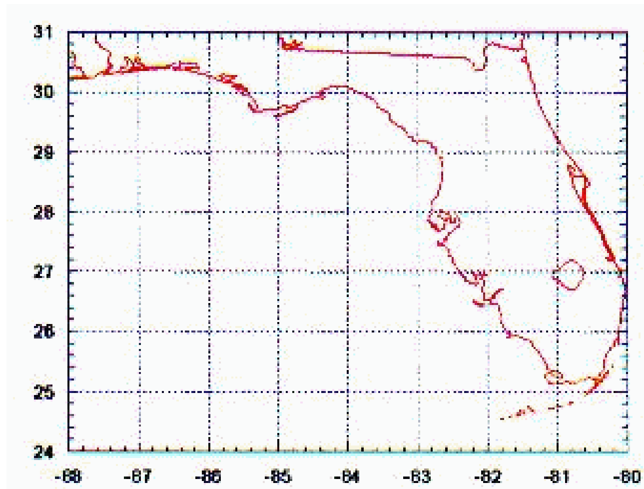


**Figure 1.** Grid used for computation of Florida storminess.

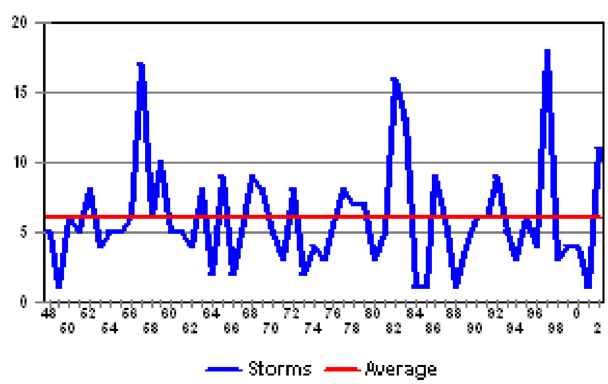


**Figure 2.** Florida dry season storms from 1948-2002 compared to normal (6).

The authors had always expected that during neutral years when the ENSO signal is not a factor other teleconnections might play dominant roles in influencing Florida storminess. The most likely predictor candidates for seasonal storminess forecasting were the NAO and PNA with the negative/positive phases of NAO increasing/decreasing the chances of Florida storms and the negative/positive phases of the PNA decreasing/increasing the chances of Florida storms.

The phasing of the two teleconnection patterns in the absence of ENSO was expected to have the most significant impact on seasonal storminess with positive PNA and negative NAO combining to enhance storminess and negative PNA and positive NAO combining to reduce storminess.

Anecdotal evidence was intriguing as the ENSO neutral 2001-02 dry season with only one storm was the season with the greatest difference between a seasonal average negative PNA and a seasonal average positive NAO of all 53 seasons. The lack of storminess in 2001-02 rivaled the great La Nina of 1988-89. The ENSO neutral 1983-84 dry season with 13 storms had the fourth highest average PNA since 1950, exceeded only by the great El Ninos of 82-83 and 97-98, and the 1976-77 season. The average PNA was positive for every month of the dry season from November 1983 through April 1984. Storminess during the 1983-84 DS was remarkable, and only exceeded by the strong El Ninos of 1997-98, 1982-1983, and 1957-58.

The two outlier seasons of 1983-84 and 2001-02 with the poorest storminess hindcast based purely on ENSO were two ENSO neutral years characterized by PNA and NAO outliers. Removing these two years from the database and re-computing the regression equations increased $\mathbf{R^2}$ from 0.57 for 53 seasons to 0.65 for 51 seasons, a clear indication that accounting for the PNA and NAO in ENSO-based seasonal forecasts might result in improved results.

Discussions of La Nina and El Nino have become commonplace in the Media and among users of seasonal forecasts. Most customers have a basic understanding of how ENSO works. As users become more educated on the limitations of seasonal forecasts based on ENSO the focus will shift to other teleconnections like NAO and PNA, especially in neutral or weak ENSO seasons.

The authors' goals in this latest study are threefold: 1) investigate in more detail the PNA and NAO indices and their relationship to Florida storminess and develop conceptual models of their influence for educational aides to help decision-makers better understand the role of the PNA and NAO within the context of ENSO, 2) improve the seasonal prediction of Florida dry season storminess, especially during ENSO neutral seasons by incorporating a seasonal indicator of the NAO and PNA phase into the ENSO-based forecast scheme, and 3) explore long-term trends in Florida storminess.

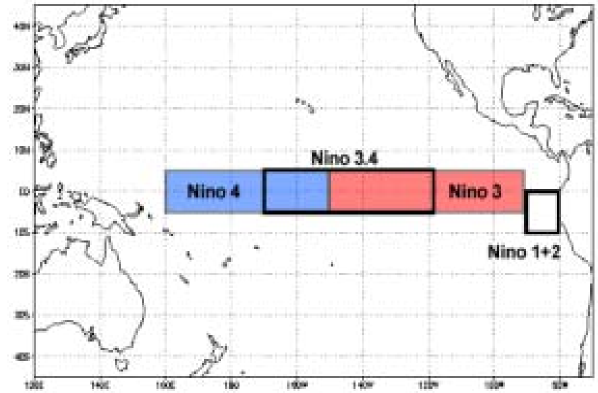


**Figure 3.** SST areas used as predictors in MLR.

## 2. THE PNA NAO AND FLORIDA DRY SEASON WEATHER

Archives of daily and monthly (3-month running means centered on a given month) PNA and NAO indices from the Climate Prediction Center (CPC) since 1950 and maps of mean sea level pressure (MSLP), 250 mb U and 500 mb height from NCEP re-analysis data were used for this investigation.

From the CPC website: *The PNA pattern reflects a quadripole pattern of height anomalies, with anomalies of similar sign located south of the Aleutian Islands and over the southeastern United States. Anomalies with sign opposite to the Aleutian center are located in the vicinity of Hawaii, and over the interrmountain region of North America (central Canada) during the Winter and Fall (Spring).* Experience in Florida is that the positive phase of the PNA is generally characterized by the potential for enhanced storminess and the negative phase by the potential for reduced storminess.

From the CPC website: *The NAO exhibits little variation in its climatological mean structure from month-to-month, and consists of a north-south dipole of anomalies, with one center located near Greenland and the other center of opposite sign spanning the central latitudes of the North Atlantic between 35 N and 40 N. The positive phase of the NAO reflects below-normal height and pressure across the high latitudes of the North Atlantic and above normal heights and pressure over the central North Atlantic, the eastern United States and western Europe. The negative phase reflects an opposite pattern of height and pressure anomalies over these regions.* Experience in Florida is that the positive phase of the NAO is generally characterized by reduced storminess and the negative phase by increased storminess potential.

The authors' working theory was that negative NAO and Positive PNA were more conducive to Florida dry season storminess, attendant flooding and severe weather, while positive NAO and negative PNA were more detrimental to Florida storminess or conducive to drought and wildfire. A calculation of the months with the greatest differences between the PNA and NAO indices [PNA-NAO] assuming that positive PNA and negative NAO were conducive to storms (highest positive number) and negative PNA and positive NAO were detrimental to storms (lowest negative number) was completed. The month representing the greatest difference between a positive PNA and a negative NAO was January 1977 (weak El Nino) - a stormy and cold month and the only month it has ever snowed in south Florida. The month with the greatest difference between a negative PNA and a positive NAO was April 2002 (neutral ENSO) - the driest and least stormy month (zero storms) within the season that tied the record for fewest storms.

To gain further insight into the physical relationships between the ENSO, NAO, and PNA teleconnections and Florida weather the authors considered the 27 possible combinations of ENSO, PNA and NAO phases. The authors considered neutral and extreme monthly values of the PNA, NAO, and ENSO indices to identify archetypical examples for each possible combination. The top and bottom 10 cases of monthly PNA and NAO values during the dry seasons from November 1950 through April 2003 and a second population of neutral ( . 0) monthly PNA and NAO values occurring during strong EL Ninos, strong La Ninas and ENSO neutral conditions were selected as potential case candidates.

The case selection was conditional in that the focus was to be first on identifying extremes (+/-) of the PNA and NAO indices and then to look at their distributions for neutral and extremes (+/-) of ENSO phases. This course was chosen because the impacts of strong La Nina's and El Nino's on Florida's dry season weather are already well known. The goal here was to try and diagnose the role or contribution of the PNA and NAO in all phases of ENSO to improve understanding of these teleconnections and seasonal forecasting. Monthly mean maps of MSLP, 500 mb height, and 250 mb U, and daily maps of each variable within each month were reviewed for each potential case to develop conceptual synoptic models to provide a physical framework for statistical forecasting, forecaster training, and educational material for customers of the seasonal forecast.

The authors' realize that there is acontinuum of possible teleconnection interactions, however, we believe that first looking at extremes of teleconnection combinations was the best method for developing conceptual models. The results of the case reviews are shown on Table 1 where months most illustrative of the various teleconnection combinations are entered in the appropriate place.

The dominance of strong El Ninos and Strong La Ninas is immediately evident on Table 1. Strongly negative PNA and positive NAO patterns do not coexist on the scale of months with strong El Ninos and that is not a problem because we already know what impacts extremes of El Nino are likely to produce. PNA positive and neutral and NAO negative and neutral patterns occur in strong El Nino's and would theoretically be neutral or cumulative to El Ninos impact. It also appears that strongly positive PNA and neutral NAO patterns are less likely during strong La Ninas. Interestingly, most of the real-life combinations of strong NAO and PNA patterns during strong La Ninas are theoretically cumulative to La Nina's impact. In contrast to strong EL Nino and La Nina conditions, all possible combinations of extreme PNA and NAO patterns readily exist during ENSO neutral conditions.

These basic results appear to confirm the authors' beliefs that the major forecast advances for the Florida dry season are to be made in ENSO neutral seasons and that a greater understanding of the role the PNA and NAO play in dry season weather is needed. Conceptual synoptic models of the combinations of teleconnections shown on Table 1 will be presented at the poster session. In general, the teleconnections acted to influence the latitude, strength and longitudinal extent of the jet stream and thus storm track. The authors next conducted multiple linear regression of SSTs, PNA, and NAO on dry season storminess to see if improvements could be made in seasonal forecasts, especially in ENSO neutral years.

**3. MULTIPLE LINEAR REGRESSION OF SST, NAO, AND PNA ON STORMINESS**

The first challenge was to develop seasonal measures of NAO and PNA to combine with SST variables. The most obvious method was to simply average the monthly values of NAO and PNA for each dry season (November - April) provided by the CPC and to do test correlations among all the variables. Seasonal averages of NAO and PNA from the 1950 through 2002 dry seasons were calculated and average values of Nino 1+2, 3.0, 3.4 and 4.0, including 6 months lead time, were calculated using the methods in H&A (2002, 2003, and 2004). These variables were regressed on dry season storms from 1950 through 2002 and on each other.

The results of the regressions are shown on Table 2. As before, Nino 3.0 and 1+2 had the greatest correlation with storms, followed by Nino 3.4 and 4.0. However, PNA alone ($R^2$ = .33) outperformed Nino 4.0 ($R^2$ = .27). The PNA is significantly correlated with all the Nino indices, especially 1+2 and 3.0 which indicate that ENSO likely plays a significant role in the PNA pattern itself. In contrast, the NAO showed no correlation with any of the Nino SST indices, and although its correlation with storms was relatively low ($R^2$ = 0.10), it was still significant at the 95% level.

| | ENSO, PNA and NAO Scenarios | | | |
|---|---|---|---|---|
| | PNA (-) | PNA (0) | PNA (+) | |
| El Nino | | March 1958 | Feb 98/Feb 83 | NAO (-) |
| El Nino | | Nov/Jan 1973 | March 1983 | NAO (0) |
| El Nino | | | | NAO (+) |
| Neutral | Mar 1965 | March 1962 | Feb 1978 | NAO (-) |
| Neutral | Mar 2002/Jan 1952 | Feb 1961/Feb 1972 | Mar/Apr 1984 | NAO (0) |
| Neutral | April 2002 | Nov 1978 | March 1986 | NAO (+) |
| La Nina | Nov 1973 | | Feb 1968 | NAO (-) |
| La Nina | | Feb 1974/Dec-Jan 1976 | | NAO (0) |
| La Nina | Feb 1989 | Feb 2000 | | NAO (+) |
| | PNA (-) | PNA (0) | PNA (+) | |

**Table 1.** Matrix of 27 possible combinations of PNA, NAO, and ENSO phase. Months illustrative of extreme and neutral cases are given for each combination observed in the historical record. Combinations with no strong cases on the scale of months are shaded and left empty.

| $R^2$ | PNA | 1+2 | 3.0 | 3.4 | 4.0 | Storms |
|---|---|---|---|---|---|---|
| NAO | 0 | 0 | 0 | 0 | 0 | .10 |
| PNA | | .34 | .33 | .26 | .17 | .33 |
| 1+2 | | | .82 | .60 | .34 | .55 |
| 3.0 | | | | .92 | .66 | .57 |
| 3.4 | | | | | .85 | .47 |
| 4.0 | | | | | | .27 |

**Table 2.** Correlation coefficients ($R^2$) of regressions between predictor variables and of predictor variables on Florida dry season storms.

| Indices | $R^2$ |
|---|---|
| PNA + NAO | 0.42 |
| 3.0 + NAO | 0.64 |
| 3.0 + PNA | 0.60 |
| 3.0 + PNA + NAO | 0.67 |

**Table 3.** Correlation coefficients ($R^2$) from MLR of selected predictor variables on Florida dry season storms.

These initial results were encouraging, and for simplicity's sake, further multiple linear regression analyses focused on just the Nino 3.0 index and PNA/NAO combinations with dry season storms. The results, all significant at the 99% level, are shown on Table 3. The PNA and NAO together perform reasonably well ($R^2 = 0.42$), but one must remember that the PNA contains a significant component of ENSO in it. Nino 3.0 and NAO ($R^2 = 0.64$) outperform 3.0 and PNA ($R^2 = 0.60$) as the NAO is totally additive to Nino 3.0 versus the PNA which is duplicative of Nino 3.0 to a degree. All three indices combined together produce a very respectable $R^2 = 0.67$ over the 53-season period of record.

Hindcasts for the past 53 seasons resulted in mean absolute errors of 1.95 for Nino 3.0 alone, 1.82 for Nino 3.0 and NAO, and 1.68 for Nino 3.0, NAO, and PNA. This indicates there is significant value in adding NAO and PNA to the ENSO-based seasonal forecast. The resulting experimental MLR seasonal storminess forecast is shown as Equation (1). The statistical results confirm the authors' thesis that negative NAO and positive PNA act to increase the potential for storminess while negative PNA and positive NAO act to reduce storminess potential.

$$\textbf{Storminess}_{(NOV\text{-}APR)} = \mathbf{6.34 + 2.9(Nino3.0_{MAY\text{-}APR}) + 1.6(PNA_{NOV\text{-}APR}) - 2.1\,(NAO_{NOV\text{-}APR})} \quad \mathbf{(1)}$$

Comparisons of forecast storminess using Equation (1) and actual storminess are shown on Figure 4. The forecast for the outlier season of 1983-84 improved from 6 using the previous ENSO-based forecast to 8 versus 13 actual storms, and although still low, would have at least indicated above normal storminess. The forecast for the outlier season of 2001-02 improved from 6 storms to 3 storms versus 1 actual storm and would have clearly signaled below normal storminess.

To gauge the reality of the statistical storminess forecasts, all possible combinations of conditions were simulated using the historical extreme seasonal values of Nino 3.0, NAO and PNA. The results are shown in red numbers on Table 4 compared to the actual seasonal cases (blue numbers) that met the criteria. Interestingly, **Eq. 1** predicts a theoretical range of storminess from zero (strong La Nina, +NAO, and -PNA) to 17 (strong El Nino, -NAO, and +PNA) which compares to the observed range from one to 18 storms. Perhaps most important, however, was the variability accounted for by Eq. 1 during ENSO neutral conditions which were the primary focus of this investigation. Previously, ENSO-based forecasts would always forecast a normal six storms in ENSO neutral conditions, making the ENSO neutral forecast obviously problematic. With the new forecast equation including NAO and PNA the range of storm values under ENSO neutral conditions now is from two to 10 compared to an observed range in neutral conditions of from 1 to 13. The new forecast scheme is a significant improvement over the previous ENSO-only method, assuming some measure of seasonal NAO and PNA is predictable.

The authors also investigated using other measures of seasonal NAO and PNA, such as averaging all 181 daily NAO and PNA values in a season and counting the number of days during a season that the NAO and PNA were above or below thresholds of +/- 1 and +/- 2. However, these methods gave significantly poorer results than the simple seasonal average from the three-month running means centered on the current month used by CPC. The poorer results for predicting seasonal storminess were perhaps not surprising because daily computations of predictors resulted in noisy, high-frequency signals and every swing to maxima or minima isn't always associated with an individual storm. Just as in the case with ENSO, when the PNA or NAO patterns persist in a manner favorable/unfavorable for storms affecting Florida (altering jet stream - storm tracks) they alter the odds of storm occurrence.

## 4. MULTI-DECADAL TRENDS IN FLORIDA STORMINESS

One of the interesting by-products of the authors' research and interactions with users of seasonal forecasts over the years is the impression through anecdotal evidence that Florida has experienced more storminess and extreme weather since the 1980's. The great El Ninos of 1982-83 1997-98 are, of course, most noteworthy and memorable, and El Ninos in 1986-87 and 2002-03 brought above normal storminess in recent decades, but El Nino's in 1957-58, 1965-66 and 1972-73 also brought above normal storminess in the past. Indeed, the trend in the number of storms has not increasied in recent decades because just as many minima as maxima in storminess have occurred since 1980 as there have been 4 years (3 strong La Ninas) with just one storm. It is not the trend of storminess that has been increasing, but the "trends" of greater extremes of inter-seasonal variability and storm intensity since 1980 are inescapable.

Plots of the minimum and maximum daily MSLP for each dry season from 1948 to 2001 are shown on Figs. 5a-b respectively. Noteworthy is that 7 of the 10 most intense storms as measured by MSLP have occurred in the 20 seasons since 1982, while the other 3 most intense storms occurred within the 33-year period prior to 1982. Likewise, 7 of the 10 highest MSLP values have occurred since 1980. Clearly, the period since 1980 has been marked by extremes of storminess and drought.

To try to determine if these trends are related to trends in the predictor teleconnections PNA, NAO, and Nino 3.0, trend analyses and MLR were conducted. Figures 6a-b show the results of the simple linear trend analyses. Overall, minimum MSLP has been trending downward, indicative of more intense storms, while the

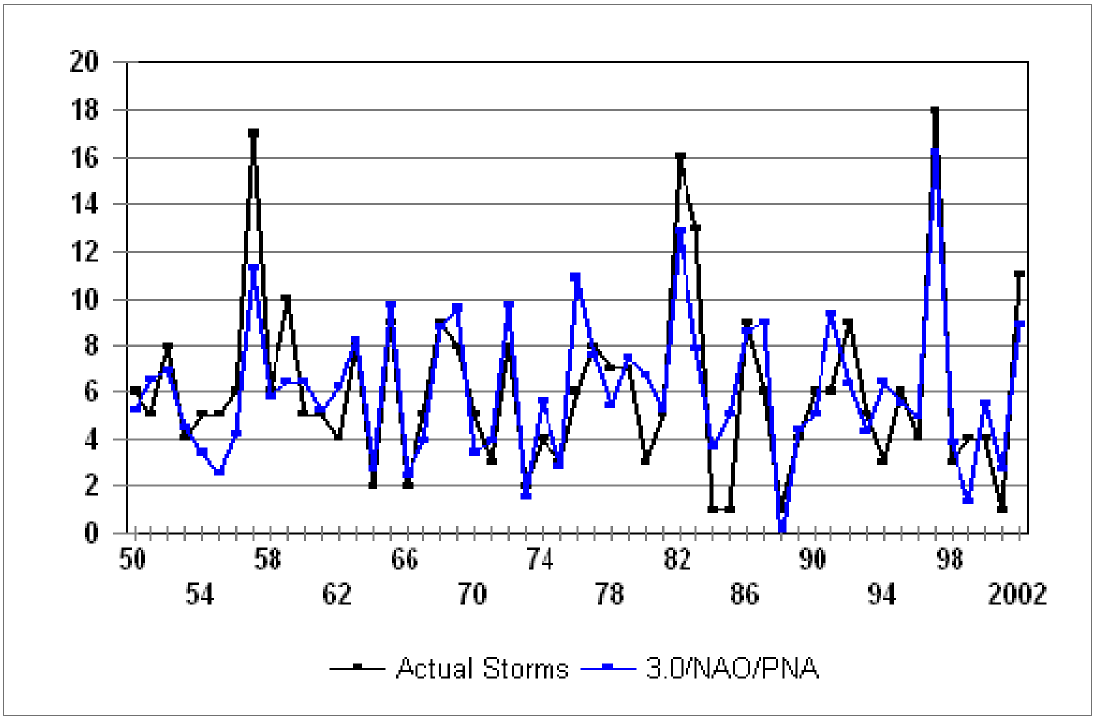


**Figure 4.** Number of Florida dry season storms from 1950 - 2002 seasons (black line) compared to dry season storms predicted by Equation 1 (blue line).

| | Theoretical Maxima/Actual Cases | | | | | | |
|---|---|---|---|---|---|---|---|
| | PNA (-) | | PNA (0) | | PNA (+) | | |
| El Nino | 14 | 9 | 16 | 17 | 17 | 18 | NAO (-) |
| | 12 | | 14 | 6 | 16 | 16 | NAO (0) |
| | 10 | | 12 | 8 | 13 | 6 | NAO (+) |
| Neutral | 6 | 7 | 8 | 9 | 10 | 8 | NAO (-) |
| | 5 | 5 | 6 | 4 | 8 | 13 | NAO (0) |
| | 2 | 1 | 4 | 5 | 6 | 9 | NAO (+) |
| La Nina | 2 | 5 | 4 | 6 | 5 | | NAO (-) |
| | 0 | | 2 | 3 | 4 | | NAO (0) |
| | 0 | 1 | 0 | 4 | 1 | | NAO (+) |
| | PNA (-) | | PNA (0) | | PNA (+) | | |

**Table 4.** Comparison of forecasts of dry season storminess using Equation 1 for extreme combinations of seasonal ENSO, PNA, and NAO from the historical record (red numbers) versus actual observed scenarios (blue numbers).

NAO, PNA, and Nino 3.0 have been trending upward (Fig. 6a). Increasing PNA and Nino 3.0 would tend to be favorable more intense storms and one might conclude increasing NAO would tend to favor higher pressures. MLR of NAO, PNA and Nino 3.0 on minimum seasonal MSLP revealed a relatively strong relationship with PNA and Nino 3.0, significant at the 95% level, while no relationship at all was found with NAO ($R^2 = 0$). The trend is maximum seasonal MSLP (i.e. strongest high pressure system) is positive (Fig. 6b) and NAO has the highest correlation, although not significant at the 95% level. PNA and Nino 3.0 had nearly zero correlation with maximum seasonal MSLP.

The authors have just begun to examine this issue. However, what is clear is that Florida's geography makes it very sensitive to changes from the climatological mean locations of the subtropical jet stream and Atlantic ridge axis which are controlled to a large extent by ENSO, the PNA and NAO. As Florida's population and sensitivity to weather extremes continue to increase every year, greater awareness and understanding of factors influencing storm potential are vital.

## 5. CONCLUDING REMARKS

Clearly, considering seasonal indicators of the PNA and NAO, in addition to Nino 3.0 results in improvements in forecasting Florida DS storminess. Strong El Ninos and La Ninas are still the dominant signal, but the improvement is most significant in ENSO neutral seasons which have been problematic. These results, of course, further complicate the interpretation and use of the seasonal forecast by decision makers and speak to the need for the development of educational material. The authors' development of simple conceptual models is a first step in the process for Florida. The results presented here also beg the question: how reliably can seasonal measures of the PNA and NAO be forecast? Since the PNA is somewhat implicit in the ENSO forecast in non-neutral years, the greatest challenge is likely predicting the higher frequency NAO signal. Progress is being made by others in the long-range prediction of the NAO and PNA. Given the significance of the results shown here, until reliable forecasts of NAO and PNA are available, any reasonable indication that the PNA or NAO will favor one phase or the other can be used to subjectively adjust the ENSO-based forecast and increase awareness and understanding of potential forecast outcomes.

## 6. REFERENCES

Please see: http://www.srh.noaa.gov/mlb/research.html for a complete list of references.

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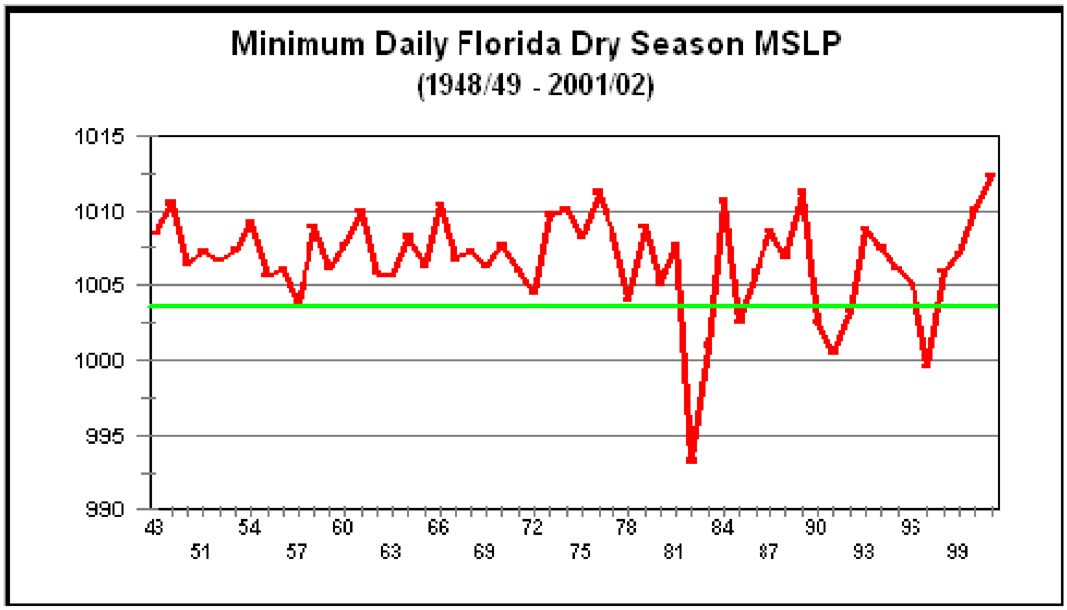


**Figure 5a.**

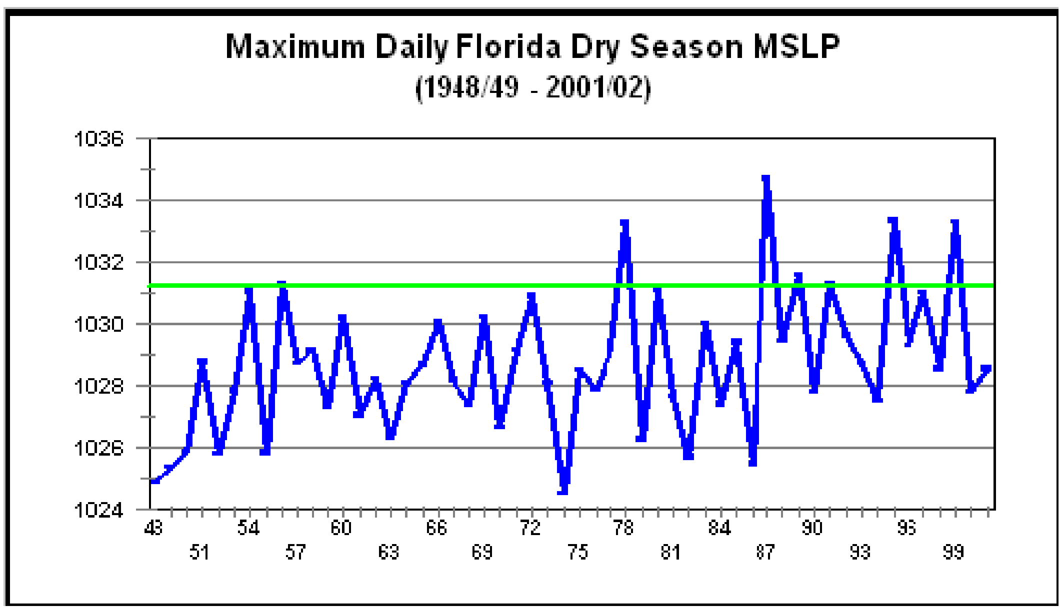


**Figure 5b.**

**Figures 5a-b. Plot of lowest MSLP for each season (5a) and highest MSLP for each season (5b) from 1948 - 2001.**

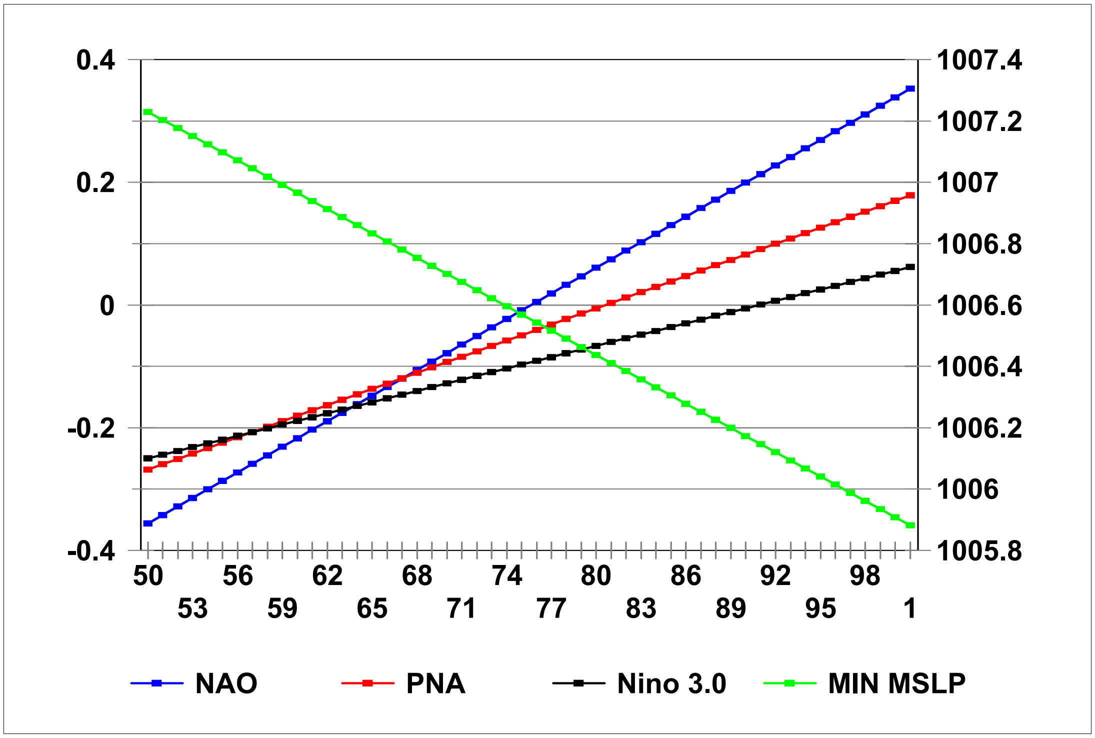


**Figure 6a.**

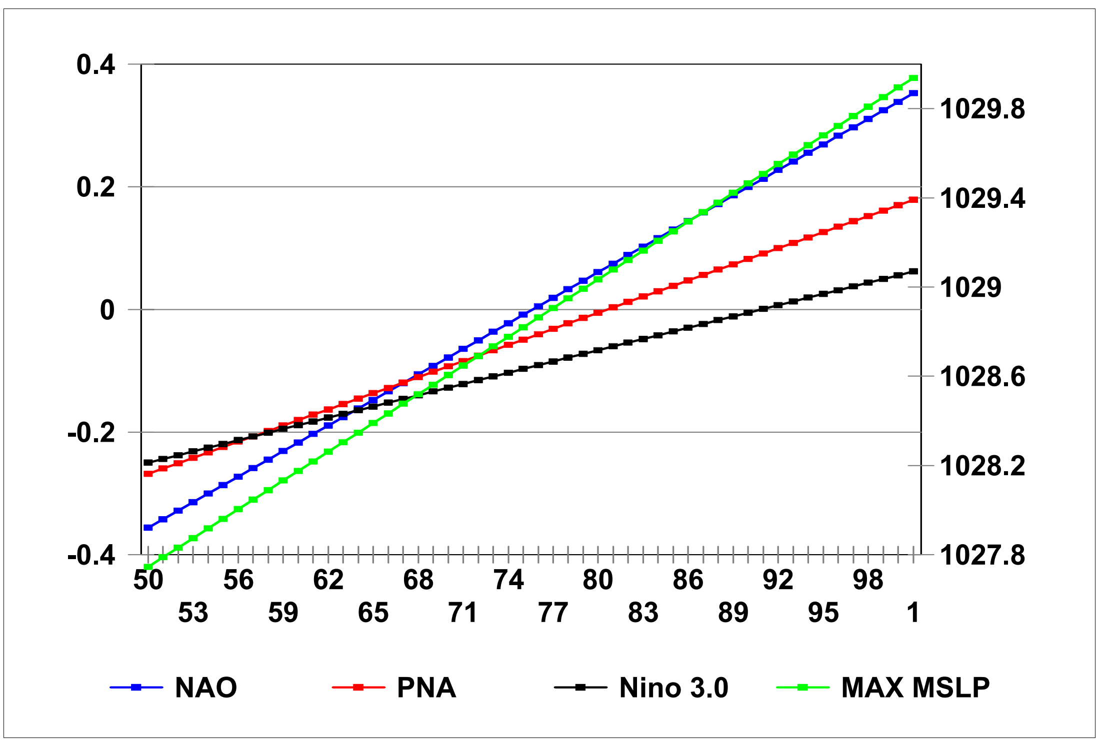


**Figure 6b.**

**Figures 6a-b.** Linear trend analysis of seasonal NAO, PNA, Nino 3.0, and season minimum MSLP (6a) and seasonal NAO, PNA, Nino 3.0, and seasonal maximum MSLP (6b) from 1950 - 2002.