P 1.7   USING THE MONTHLY CLASSIFICATION OF GLOBAL SSTs AND 500 hPa HEIGHT.

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1.   INTRODUCTION

Recent studies have attempted to link variations in global circulation (e.g., Wallace and Gutzler, 1981; Gershanov and Barnett, 1998; Wiedenmann et al. 2002), or local (and regional) climate variations (e.g., Kung and Chern, 1995 [*hereafter KC95*]; Kunkel and Angel, 1999; Lupo et al., 2007) with interannual and interdecadal variations in sea surface temperatures (SSTs) and pressures in the Pacific Ocean basin and/or the changes in the character of the atmospheric and oceanic circulations in the Atlantic Ocean Basin (e.g., Hu et al., 1998). The interactions between the atmosphere and oceans are important processes to consider when attempting to either understand the relevant physics of the earth's climate system or to make long-range forecasts (e.g, Anderson et al., 1999; Barnston et al., 2005).

The dominant interannual variations in global and regional climate characteristics are largely influenced by El Niño and Southern Oscillation (ENSO) modes (e.g., Mokhov et al., 2000, 2004). It is known that tropical SST distributions and "anomalous" SST distributions have a large impact on the weather and climate by changing heat and mass distributions of the troposphere. Through this influence, SSTs can ultimately alter the prevailing wind patterns over a large portion of the globe (e.g., Namias 1982, 1983; Enfield and Mestas-Nuñez, 1999; Mestas-Nuñez and Enfield, 1999, 2001; Wiedenmann et al., 2002). This in turn can impact the frequency, occurrence, and intensity of such phenomena as mid-latitude cyclones (e.g., Key and Chan, 1999), tropical cyclones (e.g., Gray, 1984) and blocking anticyclones (e.g., Wiedenmann et al., 2002). However, there are studies (e.g, Enfield and Mestas-Nuñez, 1999; Mestas-Nuñez and Enfield, 1999, 2001; Kushnir et al., 2002) that point out that mid-latitude SSTs may not be very influential on mid-latitude circulations. Nonetheless, the influence of tropical SSTs on the mid-Missouri area regional climate have been demonstrated, albeit indirectly, via the impacts on snowfall regimes (e.g., Lupo et al., 2005), tornado occurrences (Akyuz et al., 2004), and temperature and precipitation regimes (e.g., Hu et al., 1998; Lupo et al., 2007).

KC95 used principal component analysis to extract the

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large-scale modes of monthly mean global SST anomalies and the Northern Hemisphere tropospheric circulation anomalies during the period 1955 – 1993. The KC95 study provided an archive which can be used as guidance for long-range forecasting applications (e.g., forecasting by the use of analogs and/or contingency tables). This analysis was then extended to 2005 by Lupo et al. (2007). A by-product of these analyses demonstrate that global SST anomalies could be classified into one of seven distinct pattern types (A – G). Each of these was correlated with corresponding Northern Hemisphere tropospheric mass distributions or flow anomalies, and in subsequent work, correlated with surface climatic characteristics in mid-Missouri (Lee and Kung, 2000). KC95 and Lupo et al. (2007) also noted that anomaly types (clusters) A, B, E, and G (C, D, and F) are representative of La Niña or neutral (El Niño) type SST distributions within the Pacific Ocean basin. They also demonstrated that clusters A-D dominated the negative phase of the Pacific Decadal Oscillation (PDO) (1955 – 1977, and 1999-present), while E and F type clusters dominated the middle portion (1977-1998).

Thus, this work has two primary objectives. First, the work of Lupo et al. (2007) will be discussed (section 2 and 3) and this includes an analysis of SST anomaly types and their correlation to monthly temperatures and precipitation in the mid-Mississippi valley region as represented by a time series from the Columbia regional Airport. Their work is then extended here (section 4) to discuss the synoptic-scale flow regimes associated with prolonged SST anomaly distributions of each of the seven types discussed above. This work then examines the usefulness of these results in making long range forecasts made by the long range prediction group at the University of Missouri – Columbia, and the verification of these forecasts (section 5). This includes a discussion of summer season blocking in the East Pacific and the relationship to temperatures and precipitation in our study region. We will demonstrate that these forecasts are better than a commonly used baseline forecast (climatology).

2.   METHODS AND ANALYSES

2.1. Analyses and ENSO

The analyses used in this study were the global monthly mean and reconstructed SSTs and SST anomalies compiled

by the National Centers for Environmental Prediction (NCEP) and available through the National Oceanic and Atmospheric Administration (NOAA) online archive[1]. Monthly SSTs and anomalies are available and these can also be found in the monthly Climate Diagnostics Bulletin[2]. The mean SST anomalies in the ENSO region are available from 1864 to the present through the Center for Ocean and Atmospheric Prediction Studies (COAPS – www.coaps.fsu.edu), and the phase of the ENSO (Table 1), which can also be found at the COAPS site.

Table 1. A list of years examined in this study separated by ENSO phase (ENSO definition found at http://www.coaps.fsu.edu/climate_center/). The El Niño year (for example 1969) is defined as starting in October (1969) and ending in September (1970).

La Niña (LN)	Neutral (NEU)	El Niño (EN)
1949	1945-1948	1951
1954-1956	1950	1957
1964	1952-1953	1963
1967	1958-1962	1965
1970-1971	1966	1969
1973-1975	1968	1972
1988	1977-1981	1976
1998-1999	1983-1985	1982
2007	1989-1990	1986-1987
	1992-1996	1991
	2000-2001	1997
	2003-2005	2002
		2006

The ENSO definition is used in many studies (e.g., Lupo et al. 2005; 2007 *and references therein*). In summary, the index classifies years as EL Niño, La Niña, and neutral based on 6-month running-mean Pacific Ocean Basin sea surface temperatures (SST) anomaly thresholds bounded by the region 5° N, 5° S, 150° W, and 90° W. The defined region encompasses both the Nino 3 and 3.4 regions in the tropical Pacific. The anomaly thresholds used to define EN (LN) years are those greater than $+0.5^o$ C (less than -0.5^o C), and NEU otherwise. The El Nino year is defined as beginning on 1 October for the year appearing in Table 2 and ending in September the next year.

The 500 hPa heights and height anomalies from the NCEP re-analyses (Kalnay et al., 1996) were also examined and are available via the many of the same sources referenced above. Finally, the mean monthly temperature and precipitation records for the Columbia Regional Airport (1955

– 2008) were provided through the Missouri Climate Center and the Midwestern Regional Climate Center.

[1] wesley.wwb.noaa.gov/ncep_data/index_sgi62_png.html
[2] www.cpc.ncep.noaa.gov

2.2. Methods

For each month, visual inspection of the monthly SST and 500 hPa height charts was shown to be a reliable method by KC95 and Lupo et al. (2007, 2008) for classifying the SST anomaly distributions into one of seven different synoptic categories (A – G) over the entire map area (see their Fig. 1 and Table 2). Manual inspection was also used by KC95 after they used the clustering method of Fukunaga (1972) to derive seven distinct anomaly types.

Briefly, SST clusters B and G are representative of La Niña type clusters in the Pacific Ocean basin. These clusters have the opposite signal of each other in the Atlantic Ocean Basin, where one is positive the other is negative in general. Clusters A and E are characteristic of weak La Niña to ENSO Neutral type conditions, including a fairly weak signal in the tropics and a stronger mid-latitude signal. These SST anomaly distributions are similar in each major ocean basin, with the exception that E-type anomalies are associated with a more widespread coverage of warm anomalies in general. The remaining clusters are C, D, and F type anomalies, which are representative of El Niño SST distributions in the Pacific Ocean basin. The D-type cluster represents weak ENSO conditions, with the strong SST anomaly located closer to the east-central Tropical Pacific. The C and F type anomalies represent stronger El Niño conditions, with the warm SST anomalies located in the far eastern Tropical Pacific Ocean.

Table 2 was reproduced from Lupo et al. (2008). These results show that following 1994, there was an extended period of E-type anomalies (34 months), which correspond to the extended period of ENSO neutral conditions during the mid-1990's (Table 1). This compares to the extended period (40 months) of B-type anomalies which were characterized by La Niña and ENSO neutral conditions during the mid-1970s. This period of B-type anomalies was book-ended by mostly C-type anomalies representing the 1972 and 1976 El Niños.

The strong El Niño of 1997 was characterized by the presence of F-type anomalies, and this El Niño was similar in character to the strong El Niño events of 1982 and 1986 - 1987. These El Niño events were also predominated by F-type SST anomalies, although a few C-type anomalies were associated with the 1982 El Niño. Thus, all the El Niño events that occurred during the period 1977–1998 were characterized by the presence of primarily F-type anomalies. This contrasts with the earlier (1955-1976) and later (1999-2007) periods when El Niño events were dominated by C and D-type anomalies (Tables 1, 2). Additionally, the beginning and end of each El Niño (Table 2) described here was matched to the beginning and end of the event as defined using the definition of COAP based on the Japanese Meteorological Agency (JMA) definition. Each ended within one month of the end of ENSO as identified by this ENSO criterion and each began within 2-4 months of the identified beginning of event as well.

Then, during the latter part of 1998 through early 2008, the occurrence of G-type anomalies was prominent, but these were interspersed with the occasional periods of A, B, or D-

type anomalies. The occurrence of G-type anomalies accompanied the La Niña years of 1998 and 1999 and these became A and B-type anomalies thereafter. Until the recent re-emergence of these G-type anomalies, this SST type was not observed to occur often in the KC95 analysis. In their analysis, these G-type anomalies were associated with La Niña years.

Lupo et al. (2007, 2008) suggested that the re-emergence of the G-type anomalies was associated with a change in the phase of the PDO (Table 3). Just as the occurrence of the predominant SST anomalies changed from E and F type to G, A, and B-type during 1998 and 1999, there was the earlier change noted by KC95 and Mestas-Nuñez and Enfield (1999) around 1977, which are now widely accepted as changeover period in the PDO (Table 3). Thus, this archive may capture the change in phase of the PDO. It is noted here that the positive phase of the PDO is characterized by an anomalously deep Aleutian Low. Cold western and central north Pacific waters, warm eastern Pacific coastal waters, and warm tropical Pacific waters also characterize this phase of the PDO, which we refer to as PDO1. The reverse conditions characterize the low phase of PDO and we refer to these conditions as PDO2. This conclusion is further bolstered by the onset of D-type anomalies beginning in June 2002 and 2004, which corresponded to the weak El Niño[3] of 2002-2003 and 2004-2005 (Note: the JMA archive at COAPS does not classify 2004-2005 as an El Niño year, see Tables 1 and 2). Additionally, many studies have shown that significant interdecadal variability in the ENSO pattern can be identified in the Pacific Region SSTs (e.g., Gu and Philander, 1995; Mokhov et al., 2004). While this study has identified changes in phase of ENSO and the PDO using SST clusters and associated certain clusters with the phases of each oscillation, there is no speculation here as to the driving mechanism(s) as this subject is beyond the scope of this work at present.

3. VARIABLE TRENDS AND ANALYSIS

Park and Kung (1988) and Lee and Kung (2000) demonstrate that tropical Pacific SSTs have a significant influence on seasonal temperatures and precipitation variations and anomalies in the middle Mississippi region, and this information can then be used to make seasonal forecasts. They also demonstrate there is approximately a 3-6 month lag between the tropical Pacific region SSTs and the seasonal climate of the middle Mississippi Valley region. These findings support the results of other studies which examined the impact of tropical SSTs on North American seasonal climates (e.g., Enfield and Mestas-Nuñez, 1999; Mestas-Nuñez and Enfield, 1999, 2001; Lupo et al., 2005). We note here, however, that there is considerable disagreement among these and other studies about the degree of the impact of mid-latitude SSTs on mid-latitude weather and climate, and correlations between tropical SSTs and climate do not describe a dynamic link between the two. Additionally, Hu et al. (1998), Ratley et al. (2002), and Palecki and Leathers (2000), who used principal component analysis, suggested the interannual variability in this region may behave similarly for most stations within this geographic region.

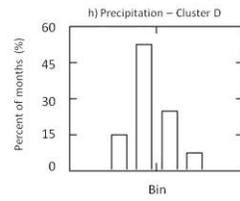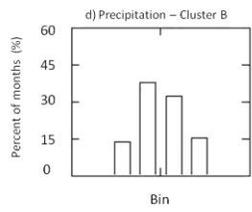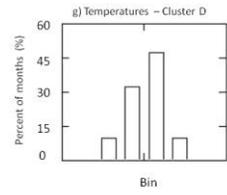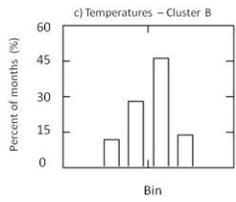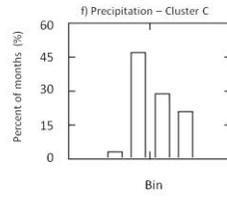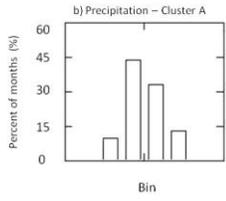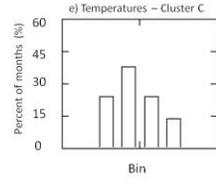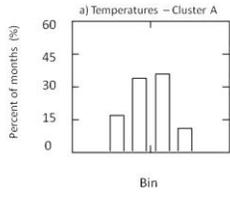Lupo et al. (2007, 2008) found some statistical relationships between prolonged periods of certain SST regimes and mid-Missouri monthly mean temperature and precipitation records. These will be summarized here. The results of their analysis are shown in Fig. 1 and Tables 4-5. In Fig. 1, the probability distributions are displayed using a bar-graph. None of temperature and precipitation regimes for each SST type could be classified as a normal distribution at standard levels of confidence (90% or more), when tested using a simple chi-square goodness of fit test and assuming the null-hypothesis or that there is no *a priori* relationship between SST type and temperature regime.

3.1 PDO2 SST clusters

During PDO2 years the predominant SST types were A – D, and G. For the A-type regime, the distribution monthly mean temperature regime was skewed toward cooler temperatures, but these departures did not rise to the level of statistical significance (Fig. 1a). The precipitation regime was skewed toward drier months being associated with A SST types, and this distribution was different from a normal distribution at the 90% confidence level (Fig. 1b). The analysis of prolonged B-type anomalies showed no tendencies that rose to the level of statistical significance (Figs. 1c,d). While the monthly mean temperatures were skewed toward warmer months during B regimes, these months were evenly split between warm and wet, and warm and dry regimes. A simple test for the statistical independence of bivariate multinomial populations (here monthly mean temperatures and precipitation) demonstrated that for A- and B-type regimes, these variables are independent of each other. Also, the A- and B-type anomalies do display a very strong tropical signal, but they do have stronger extratropical anomalies which have been shown to be not as influential on extratropical weather as natural synoptic variability (Kushnir et al., 2002). Thus, this may explain the weak correspondence between A and B patterns and the climate of the mid-Mississippi Valley region.

An analysis of prolonged D-type regimes demonstrates the monthly mean temperatures are skewed toward cooler months (Fig. 1g), and the distribution is different from the normal distribution at the 95% confidence interval indicating a strong relationship. Prolonged D-type regimes are heavily skewed toward the drier months (70% of these months were drier than normal) (Fig. 1h), and this distribution was different from normal at the 99% confidence level. However, about 45% of all D-type months (18) were warm and dry. This is particularly true of D-type months in the warm season (warm and dry), and this result was significant at the 95% confidence level. The D-type months tended to lead to cooler than normal conditions for the region during the cold season (not shown here). Nonetheless, examining the distribution of monthly mean temperatures and precipitation anomalies separately and forming conclusions based on these (e.g., for D-type SST anomalies cool - dry months probably prevail in the mid-Mississippi region) may lead to an erroneous forecast. Recently, two prolonged periods of D-type anomalies in 2002-2003 (2004-2005) (Table 2), in which four of six (all seven) months were cooler (warmer) than normal. In both cases, however, the period was drier than normal (10 of 13 months).

The analysis for G-type anomalies revealed both the monthly mean temperature and precipitation anomaly distributions (Figs. 1m,n) were different from normal at the

a) Temperatures – Cluster A

e) Temperatures – Cluster C

b) Precipitation – Cluster A

f) Precipitation – Cluster C

c) Temperatures – Cluster B

g) Temperatures – Cluster D

d) Precipitation – Cluster B

h) Precipitation – Cluster D

i) Temperatures – Cluster E

m) Temperatures – Cluster G

j) Precipitation – Cluster E

n) Precipitation – Cluster G

k) Temperatures – Cluster F
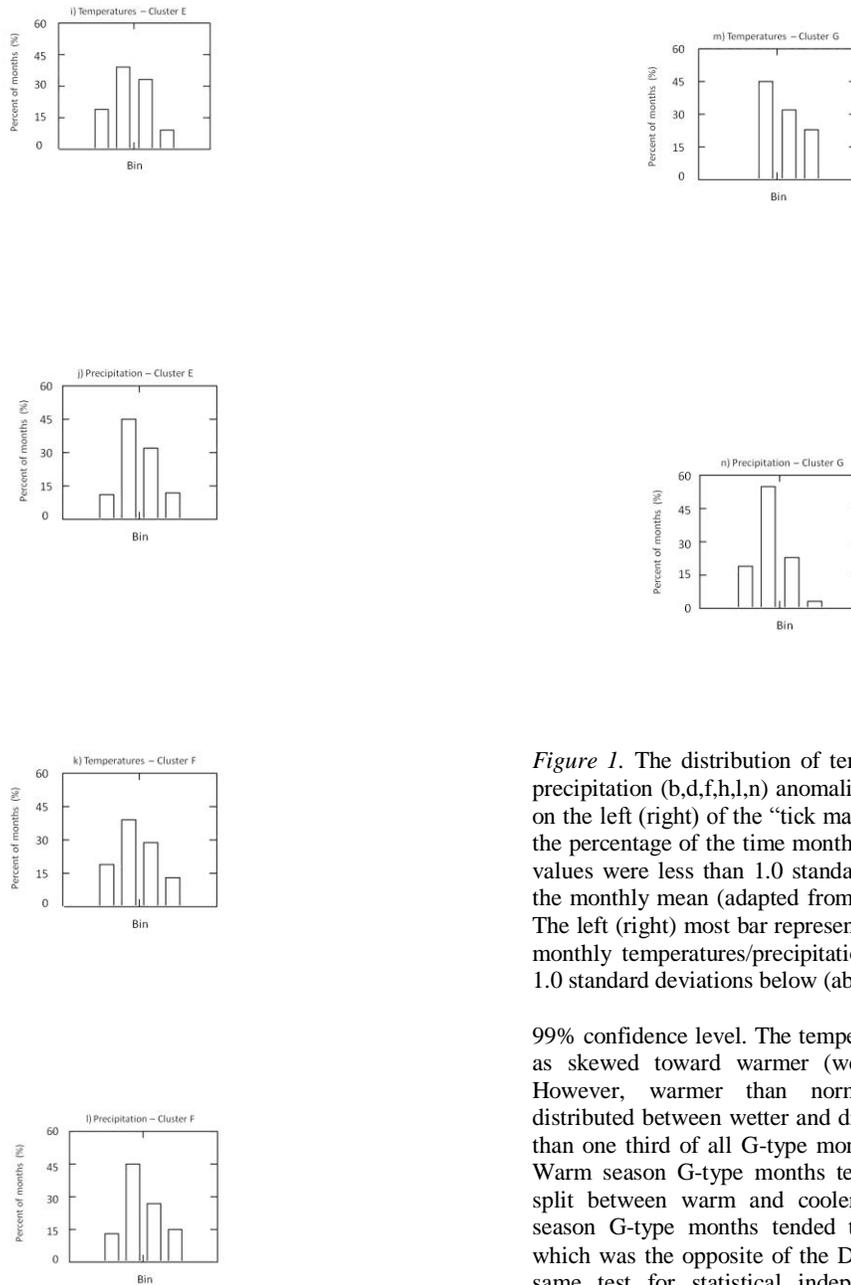

l) Precipitation – Cluster F

Figure 1. The distribution of temperature (a,c,e,g,i,k,m) and precipitation (b,d,f,h,l,n) anomalies by SST category. The bar on the left (right) of the "tick mark" on the abcissa represents the percentage of the time monthly temperatures/precipitation values were less than 1.0 standard deviations below (above) the monthly mean (adapted from Lupo et al., 2008 – Fig. 3). The left (right) most bar represents the percentage of the time monthly temperatures/precipitation values were greater than 1.0 standard deviations below (above) the monthly mean.

99% confidence level. The temperature (precipitation) regime as skewed toward warmer (wetter) than normal months. However, warmer than normal months were evenly distributed between wetter and drier than normal, while more than one third of all G-type months (13) were cool and dry. Warm season G-type months tended to be dry (but evenly split between warm and cooler than normal), while cool season G-type months tended to be warmer than normal, which was the opposite of the D-regime. When applying the same test for statistical independence of monthly mean temperature and precipitation in the D- and G-type regimes, these variables were found to be dependent variables at the 95% confidence level. That these variables demonstrate a high degree of statistical dependence in the D-and G-type regimes when there is no reason to believe they should be dependent *a priori*, suggests there may be a synoptic explanation for this dependence and this issue will be explored below. This also suggests operational value for these results found here, since D and G anomalies had a strong tropical signal, and had a profound impact on mid-Mississippi valley climate.

Table 2. The monthly classification of global SSTs from 1955 – 2008. The classifications from 1955 – 1993 are adapted from Kung and Chern (1995).

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1955	A	A	A	A	A	A	A	A	A	G	G	G
1956	A	A	A	A	A	A	A	A	A	G	G	G
1957	G	A	A	A	A	F	F	F	F	F	F	D
1958	D	D	D	D	D	D	F	F	F	D	D	D
1959	D	D	D	D	D	D	A	A	A	A	A	A
1960	A	A	A	A	A	A	D	A	A	A	G	A
1961	A	A	A	A	A	A	A	A	A	A	G	G
1962	G	G	G	G	G	G	G	D	G	G	G	G
1963	A	A	D	D	D	D	D	D	D	D	D	D
1964	D	D	A	D	A	A	A	G	G	G	A	A
1965	A	A	A	A	A	A	A	F	F	F	F	F
1966	D	D	D	D	D	A	A	A	A	D	D	D
1967	A	A	A	A	A	A	A	A	A	A	A	A
1968	A	A	A	A	A	A	A	F	F	F	D	D
1969	D	D	D	D	D	F	D	E	E	E	D	D
1970	C	C	C	C	C	C	C	B	B	B	B	B
1971	B	B	B	C	B	B	B	B	B	B	B	B
1972	B	B	B	C	C	C	C	F	C	C	C	C
1973	C	C	C	B	B	B	B	B	B	B	B	B
1974	B	B	B	B	B	B	B	B	B	B	B	B
1975	B	B	B	B	B	B	B	B	B	B	B	B
1976	B	B	B	B	B	B	B	C	C	C	F	F
1977	C	C	C	B	B	E	E	E	E	E	C	F
1978	F	F	F	E	E	B	C	E	E	C	F	F
1979	C	C	C	C	C	C	F	F	F	F	F	F
1980	F	F	F	F	F	E	E	E	E	E	E	E
1981	F	F	F	C	C	E	E	E	E	E	E	E
1982	E	E	E	E	C	F	F	C	C	C	C	F
1983	C	F	F	F	F	F	F	E	E	C	E	E
1984	E	E	F	B	E	B	E	E	E	E	B	B
1985	B	B	B	B	B	E	E	E	E	E	E	E
1986	E	E	F	E	E	F	F	F	F	F	F	F
1987	F	F	E	E	F	C	F	E	F	E	F	F
1988	E	E	E	E	E	E	E	E	E	A	A	G
1989	G	G	G	G	F	F	E	E	E	E	F	F
1990	A	E	E	F	F	F	F	F	D	D	D	D
1991	D	F	F	C	C	E	E	E	E	F	F	F
1992	F	F	F	F	F	F	F	F	F	F	F	F
1993	F	F	F	F	F	F	F	F	D	F	F	F
1994	D	D	F	E	F	F	D	E	D	D	D	D
1995	E	E	E	E	E	E	E	E	E	E	E	E
1996	E	E	E	E	E	E	E	E	E	E	E	E
1997	E	E	E	E	E	E	E	E	E	E	F	F
1998	F	F	F	F	F	F	F	G	G	G	G	G
1999	G	G	G	G	G	G	G	G	G	G	G	G
2000	G	G	B	B	B	G	G	A	A	A	A	G
2001	G	B	B	B	G	G	G	G	G	A	A	A
2002	B	A	A	A	A	D	D	D	D	D	D	D
2003	D	D	D	B	B	A	A	A	E	E	A	A
2004	A	A	A	B	B	D	D	D	D	D	D	D
2005	D	D	D	B	B	B	B	A	A	A	A	A
2006	A	B	B	B	B	B	B	D	D	D	D	D
2007	D	A	G	G	G	G	G	G	G	A	A	G
2008	G	G	G	G	G							

3.2 PDO1 SST clusters

The PDO1 years were dominated by the occurrence of more El Niño events and these El Niño events were stronger events (e.g., 1982-1983, and the 1997-1998 events). Prolonged periods of E- or F-type anomalies did not result in any statistically significant trends in the temperature or precipitation distributions (Figs. 1i-l) independent of seasons. When considering the combined E and F categories, cool dry months accounted for more than one-third of all months, while the rest of the sample months were distributed evenly among each category. Among F-type months only (strong El Niño type), however, these tended to be cooler than normal during the summer months and much warmer than normal during the winter months. It is well known that there is a strong correlation (e.g, use the statistical tool found at: http://www.cdc.noaa.gov/USclimate/Correlation) supporting the observation that El Niño winters were warmer than normal in the Midwest and upper Midwest during the 1977 – 1998 period (when F anomalies were a dominant El Niño type during these winters). For E-type months only there was no distinct tendencies for warm or cool season months and again the E-type SST pattern was representative of ENSO neutral or weak La Niña type conditions. The test for statistical independence of monthly mean temperatures and precipitation yielded similar results to the A- and B-type regimes, in that temperatures and precipitation were found to be independent variables in these regimes. Also, the explanation for the weak correspondence found for the E-category may also be similar to that for the A- and B-type anomalies.

Table 3. The phase of the Pacific Decadal Oscillation (PDO) (adapted from Gershunov and Barnett, 1998).

PDO Phase	Period of Record
Phase 1	1933 - 1946
Phase 2	1947-1976
Phase 1	1977 - 1998
Phase 2	1999 - present

3.3. C-type SST clusters

The sample size for prolonged C-type (ENSO type) clusters was small, but analyzing these is also more complex as it was the only SST type in which there were nearly equal occurrences of these in both PDO1 and PDO2 years. The overall behavior of these distributions (Fig. 1e,f) demonstrates that these distributions were different from normal at the 95% and 99% confidence level for monthly mean temperatures and precipitation, respectively. These C-type months were skewed toward cooler conditions and wetter conditions, but were fairly evenly distributed when considering these as a bivariate population.

3.4. an initial seasonal analysis

Table 5 displays the number of months in which the temperature and precipitation was above or below normal for the prolonged SST clusters analyzed above in order to determine if particular seasons showed any bias toward

Table 4. Number of months in each SST classification analyzed and the average magnitude of the positive and negative temperature and precipitation anomalies. Also given are the number of months when the anomaly is of the same sign (warm-wet/cool-dry).

Class	Months	Temperature °F		Precipitation (inches)		Months – Same Sign
		Positive	Negative	Positive	Negative	
A	63	2.9	-3.1	1.67	-1.30	36 (16/20)
B	58	2.2	-2.8	1.39	-1.53	25 (15/10)
C	29	2.7	-3.8	2.39	-0.89	19 (8/11)
D	45	2.8	-2.9	1.45	-1.20	17 (7/10)
E	61	1.9	-2.7	1.96	-1.46	29 (10/19)
F	62	3.2	-3.0	2.18	-1.23	35 (13/22)
G	35	3.4	-1.6	0.74	-1.46	22 (9/13)

particular conditions. No statistical analysis for significance was performed here for each season as the seasonal sample sizes are small. However, this information can provide supplementary guidance to the discussion above in order to determine whether SST clusters discussed above correlate uniformly across all the seasons, or whether the results discussed above were more prevalent in a particular season.

The warm bias noted above for the B-type clusters occurred primarily in the transition seasons, and these tended to be distributed such that the cold season as a whole was associated with warmer prolonged B-regimes. The dry bias found for the D-type clusters was nearly spread evenly throughout the year, except for the summer season. The cool bias found in association with E- and F-type anomalies was evenly distributed throughout the year, with the exception of winter season F-type anomalies. These months were associated with warmer than normal conditions and half of these warm anomalies were one to two standard deviations above the normal for the winter months. Remarkably, the summer and fall months were drier-than-normal for all 14 G-type anomalies during these seasons. Finally, the cool biases associated with the C – type clusters were especially strong during the June – February period, which resulted in cooler condition during the first part of the cool seasons.

4.   AN ANALYSIS OF HEIGHT ANOMALIES

An analysis of the monthly mean 500 hPa height anomalies yielded similar results to those of KC95 when these were categorized by type, and an example using individual monthly 500 hPa height anomalies for the Northern Hemisphere are shown in Fig. 2. Only the 500 hPa heights are examined here as many studies referenced above have shown

Table 5. Number of months in which a) temperature and b) precipitation in the study region for each SST classification were above or below (A/B) normal. These results are also stratified by season.

a. temperature

Class	Spring	Summer	Fall	Winter	Total
A	13 / 9	7 / 10	5 / 7	6 / 6	31 / 32
B	10 / 5	7 / 7	9 / 4	9 / 7	35 / 23
C	7 / 3	0 / 5	2 / 4	2 / 6	11 / 18
D	7 / 6	3 / 3	7 / 2	10 / 7	27 / 18
E	4 / 8	6 / 6	9 / 14	6 / 8	25 / 36
F	3 / 13	6 / 9	4 / 10	13 / 4	26 / 36
G	4 / 7	5 / 4	3 / 3	7 / 2	19 / 16

b. precipitation

Class	Spring	Summer	Fall	Winter	Total
A	11 / 11	9 / 8	4 / 8	5 / 7	29 / 34
B	8 / 7	4 / 10	6 / 7	10 / 6	28 / 30
C	8 / 1	1 / 4	3 / 3	3 / 5	15 / 14
D	3 / 10	4 / 2	3 / 6	5 / 12	15 / 30
E	6 / 6	5 / 7	9 / 14	7 / 7	27 / 34
F	6 / 10	8 / 7	6 / 8	7 / 10	27 / 35
G	6 / 5	0 / 9	0 / 6	5 / 4	11 / 24

monthly height anomalies tend to have a strongly equivalent barotropic structure (e.g. KC95). Over North America, the long-term mean 500 hPa height field shows ridging (troughing) over western (eastern) North America (e.g., Fig. 2h and see Bentley and Mote, 1998).

The A- and B-type anomalies (Fig. 2a,b) are suggestive of more zonal and meridional type flows over North America, respectively, however neither type could be statistically associated with anomalously warm or cool months over the region of study (Lupo et al., 2007, 2008 - although A months tended to be drier than normal), nor was there a qualitative trend for these type of months to appear in particular seasons. A- and B-type flows, which were associated with La Niña or neutral years, would suggest more blocking events over the eastern Pacific (e.g., KC95; Wiedenmann et al., 2002), however, the tendency for increased ridging over the eastern half of the US may account for the tendency toward warmer B-type months in the mid-Mississippi region. The E-type months seem to be similar to A-type months in that they would result in a more zonal type flow over North America, and these are also correlated to weaker positive and negative monthly temperature anomalies for the mid-Mississippi Region in Table 4. All three of these type of flow regimes demonstrate the difficulty in relating local or regional climates to global climates in that particular months may only be generally classified as one of these types, when reality may suggest mixed modes. Also, all of these SST – 500 hPa height anomaly clusters are La Niña or ENSO neutral, and a weak tropical signal.
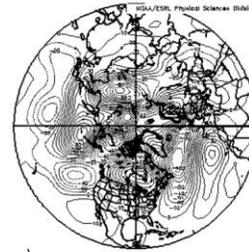
G-type 500 hPa anomalies (which were also associated with La Niña years) were dominated by drier than normal conditions in general. The G-type flow regimes (Fig. 2g) suggest more zonal conditions over North America. This is consistent with the observation that these months are warmer than normal in the cold season, and there were slightly more cooler-than-normal months in the warm season (which would be expected with air masses of Pacific origin) over the region of study. In fact, the strongest warm anomalies found in this study were associated with G-type flow regimes (Table 4), and these tended to be winter months. These warm winter months in La Niña years are associated with storm tracks that lay across the northern tier of the US during the cold season, which may also account for the tendency toward dry months in the mid-Mississippi river basin and mid-Missouri. However, the strong positive height anomaly in the Gulf of Alaska in G-type months also suggest more and/or stronger east Pacific blocking events and this is consistent with the observation of more and stronger blocking events in this region during La Niña years, especially in the cooler months (e.g., see Wiedenmann et al., 2002). The presence of blocking in the east Pacific can generally be associated with cooler conditions over the mid-continent and southeast US (e.g., Quiroz, 1984). Thus, there seem to be two distinct types of behavior for G-type winter months in the mid-Mississippi region, depending on the occurrence of east Pacific region blocking. Additionally, a seasonal analysis suggests that A-, E-, and G-type clusters are associated with dry summers in the region.

Examining the results found for the D anomalies (Fig. 2d) suggests anomalous troughing (ridging) over western (eastern) North America, while the F-type (and C-type as well) anomalies exhibited strong ridging over Canada. Anomalous ridging over much of North America (F-type) suggests weaker zonal winds over the US and split flow over the continent as a whole, as suggested here. Such flows tend to advect more Pacific region air masses over the continent. This observation would be consistent with warmer (cooler) conditions over the mid-Mississippi valley in the winter (summer) as was observed during ENSO episodes from 1977 – 1998, which were strongly associated with F-and C-type anomalies. The association of warmer winters over the study region and much of the northern US with ENSO conditions during the 1977 – 1998 period is fairly well documented (Section 3a) and websites can be used by the reader (e.g., http://www.cdc.noaa.gov/USclimate/Correlation) to create the 500 hPa height anomaly clusters (ENSO conditions) which were cool and dry.
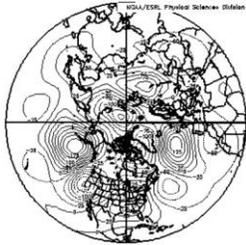
While this is a very small sample, the analysis of the individual SST cluster types may demonstrate part of the difficulties in using statistical studies to find strong statistical relationships between SST anomalies and local interannual and interdecadal climate variations. Local variations in climate are strongly suggested by Lupo et al. (2007), but these results also suggest that interannual temperature and precipitation variations due to ENSO-related SST variations may be modulated by interdecadal variations in the mid-Mississippi region (e.g., Gershanov and Barnett, 1998). Thus, when examining a long time series, i.e., the interannual variations in local climate, it is not enough to examine only the impact of ENSO. Rather, the interannual variability within
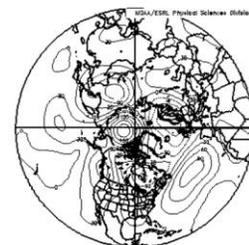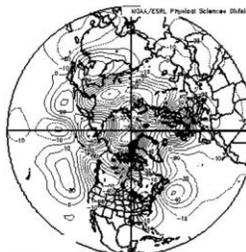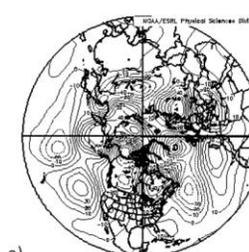
h) 1971 – 2000 annual means

c) October 1982

a) April 1987

d) January 1994

b) August 1975

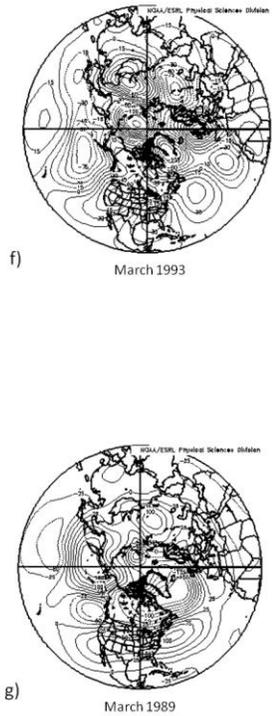e) October 1996

f)

March 1993

g)

March 1989

Figure 2. The 500 hPa monthly height anomalies for SST-type a-g) A – G, and including the h) 1971-2000 mean for reference. The contour intervals are a-g) 25 m, and h) 50 m.

"typical" temperature signatures of El Niño winters and correlate these to SSTs.

The D-type SST anomalies were associated with weaker ENSO events and the warm SST anomaly was located over the central Pacific, while C and F type ENSO events were associated with stronger events and the warm anomaly was located over the eastern tropical Pacific (e.g., Clarke and Li, 1995). This difference in the location (and even the shape and strength) of the warm SST anomalies may be responsible for the apparent "shift" in the phase downstream of the 500 hPa Pacific-North America (PNA) height pattern over North America (compare Fig. 2d and f). The location, shape and strength of the SST anomalies and the accompanying diabatic heating (latent and sensible) would all play a role in the mass field adjustment (height tendencies) as suggested in the model studies of Nakamura et al. (1997) or using simple diagnostic equations (e.g., see Lupo et al., 1992). The D-type height anomalies would suggest a weak trough over North America, but if the troughing is particularly strong, there would be cooler conditions over the United States in general. Within the study region, the winter season months of 1968-1969 and 2002-2003 were both associated with D-type SST and 500

an interdecadal time frame may be more reasonable as the response of local climatic parameters to ENSO may be different on an interdecadal timescale (Lupo et al., 2005). Additionally, as suggested by casual analysis of the F-type SST clusters, these studies may produce stronger results if the data were stratified by season, but as of yet, such a stratification provides samples too small to obtain any meaningful statistical analysis.

5. LONG RANGE FORECASTS

Using these results as one part of constructing long-range forecasts, seasonal forecasts were made and evaluated against climatology. The long range forecasts of temperature and precipitation were made for the winter (December – February) and summer seasons (June – August), which are the time periods of interest for the local and regional media and agricultural communities. The forecasts were made 4 – 5 months in advance of each season (see Lupo et al. 2008). The forecasts were made based on the prevalent SST patterns of the previous few months in Table 2, and a first guess as to how these may evolve over the next few months (using past history and/or forecast discussions/guidance of ENSO). The potential for atmospheric blocking and the evolution of large-scale flow regime (see below and section 4) will also be factors that contribute to the long-range forecast. Thus, the forecasters used the information in Tables 3 – 6 as well as previous or past experience to make the predictions.

Table 6. An assessment of blocking occurring over the East Pacific during the May – August period for the period 1970 – 2007.

Summers	Mean number of blocking events	Months primarily occurring	Mean number of blocking days	Intensity
10 warmest	2.9	July – August	24	2.13
10 coolest	3.4	May – June	28	2.16
10 wettest	3.3	May – June	25	2.26
10 driest	2.4	July – August	17	2.00

The forecasts were qualitative, and used the point-scoring scheme shown in Lupo et al. (2008). The scheme, which is modeled after Lupo and Market (2002), is based on defining normal as within +/- 0.5 standard deviations of the mean, and above and below normal as outside that range. Two points are awarded for a good forecast of seasonal temperature and precipitation (observed category matched the forecast category), while none are awarded for a poor forecast. For example, if a forecaster predicted the summer temperatures would be close to normal (-0.5 – 0.5 standard deviations from the seasonal mean) and the observed was within this range, this constitutes a good forecast. Using the example above, a poor forecast would constitute a situation where the observed seasonal temperatures were greater than

one standard deviation above normal. Also, since the understanding and influence of ENSO and the occurrence of blocking are both of crucial importance to long range forecasting, the seasonal potential for blocking was also considered here (see below). Additionally, Ratley et al. (2002) demonstrate there was a correlation between Pacific SST's and the warm season precipitation regimes in the forecast region (the Mid-Mississippi river valley and central Missouri) considered here.

The summer of 2004 in the central part of North America was unusually cool. During August, temperatures were $5^{o} - 7^{o}$ F cooler than normal across most of Missouri including the study region, and in Columbia this was the third coolest summer since 1889. The cool summer could be linked directly to unusually strong and persistent blocking in the East Pacific and Alaskan Sector (5 blocking events and 69 days). Conversely, blocking was also responsible for the devastating summer heat waves in Eurasia during the summers of 2002, and, especially, 2003 (e.g, Galarneau et al. 2005). In North America, historically (1970–2007) cooler and/or wetter summers can be linked to more and/or unusual summer blocking activity over the East Pacific region (Table 6). Thus, the role of blocking plays a significant role in influencing summer season temperature and precipitation regimes. Additionally, there is a strong tendency for cold conditions within the forecast region during individual winter season blocking events (e.g., Quiroz 1984), but also during La Nina years there are more blocking events in Pacific region (e.g., Wiedenmann et al., 2002) which are typically cooler than normal in our study area.

Table 7 shows the scoring results of ten long range forecasts over five years (five winter and five summer seasons). In examining the outcomes (not shown), one forecast by our group and climatology scored perfectly (winter 2003 – 2004), while one forecast was assessed as poor (winter 2004 - 2005). Additionally, two forecasts of the ten (summer 2003, winter 2006-2007) scored lower than climatology, and three scored higher. The winter forecast of 2006 – 2007 scored well, but climatology was perfect after the first part was unusually warm and the second part unusually cool. We also examined the skill scores (Table 7), and these were calculated using the formula from Lupo and Market (2002):

(our forecast – climatology) / (perfect forecast – climatology) * 100%   (1).

The long range forecasts issued by our group were better overall, but showed no improvement over climatology in the winter season. In Table 7 the numbers are large, since the number of forecasts issued (and therefore the sample size) is, as of yet, small. During the summer season, our forecasts were better than climatology by 38%, which compares to 0% during the winter season. When examining precipitation, our forecasts were significantly worse than climatology in the winter season (20%), but did not show any difference overall. None of the skill scores shown here are comparable to short range forecast improvement over persistence or climatology (Lupo and Market 2002), however, the overall scores for temperature reported here are good compared to the improvement of human forecasters over numerical models. This is especially true for the summer season Thus, the

information derived here has the potential for use as a tool or guidance for long range forecasts in our region (especially during the summer season), and this information could be constructed for other areas of the United States and applied to long range forecasts as well.

Table 7. Skill Scores for the long range forecast generated here versus climatology.

Forecast period	Skill Score (%)
Total (Temperature + Precipitation)	20%
Temperature	34%
Precipitation	0%
Total Summer Season	38%
Temperature	40%
Precipitation	33%
Total Winter Season	0%
Temperature	19%
Precipitation	-14%

6. SUMMARY AND CONCLUSIONS

Using monthly mean SST and 500 hPa height data routinely available via the internet or other regular monthly publications, as well as monthly mean temperature and precipitation time series from a long-record climate station that is representative of the mid-Mississippi valley, interannual and interdecadal variations in the climate of this region were examined and compared to synoptic flow regimes. In performing an analysis on the time series to identify the predominant SST clusters, the techniques of Lupo et al. (2007, 2008) (and references therein) were used. The SST anomaly classification archive initiated by KC95 and continued by Lupo et al . (2007, 2008) for the period 1955 – 2005 was used to define the SST regimes.

A further examination of the monthly mean temperature and precipitation record shows that the long-lived SST clusters were not associated with normally distributed monthly temperature and precipitation anomalies, which would be the case when all anomalies in the 52 year period were binned for the mid-Mississippi region (e.g., Lupo et al. 2003). However, most of the long-lived SST clusters were not associated with statistically significant deviations from normal. The long-lived B regimes tended to be warmer than normal (Table 5), while long lived C regimes produced cooler temperatures and greater than normal precipitation amounts. The long-lived D- (G-) type clusters were associated with distributions skewed toward cooler (warmer) and drier (wetter) conditions, and these were associated with El-Niño (La-Niña) years. However, during D- (G-) type months the statistical analysis of these two flow regimes was not straightforward, since during these months, the most common occurrence when treating the data as a bivariate population were warm and dry (cool and dry) months. A statistical test for independence demonstrated a statistical dependence between temperature and precipitation anomalies may be

explained by examining the 500 hPa height anomaly distributions.

This examination of the 500 hPa height anomalies reveals that G-type anomalies may be associated with either zonal flow over North America, resulting in warm (cool) conditions during the cold (warm) season for the mid-Mississippi region, or enhanced blocking over the eastern Pacific which would result in cooler conditions over the study region. D-type anomalies were associated with weak El-Niño events and cooler conditions over the study region during the cold season. Even SST clusters that did not result in strong statistical relationships overall revealed characteristics consistent with seasonal observations in this region (e.g., F-type clusters, associated with ENSO conditions in the 1977 – 1998 period were associated with very warm winters). However, a study of prolonged SST anomalies stratified by type may be the subject of future work when a greater volume of reliable data becomes available. Finally, it may not be enough to examine interannual variability over a consecutive 50, 70, or even 100 year period since the occurrence and amplitude of the ENSO phenomenon may change over an extended period (e.g., Gu and Philander, 1995, Mokhov et al., 2004), and thus result in a changed or modulated ENSO response in local climatic parameters on an interdecadal time-scale (e.g., Gershanov and Barnett, 1998; Lupo et al., 2005). Then, considering the interdecadal variability as superimposed on interannual variations should be considered as well.

Finally, the results of this study and previous studies by this group were used to generate long range forecasts for the summer and winter season temperatures and precipitation four to five months in advance. A forecast verification scheme based on Lupo and Market (2002) was designed and used to score the long range forecasts. The results show that our forecasts have been better than climatology, especially for summer season and temperature forecasts.

7.   REFERENCES

Akyuz, F.A., Chambers, M.D., and A.R. Lupo, 2004: The The short and long-term variability of F2 or stronger (significant) tornadoes in the central Plains. *Transactions of the Missouri Academy of Science, **38**,* 26 – 45.

Anderson, J., H. van den Dool, A. Barnston, W. Chen, W. Stern, and J. Ploshay, 1999: Present-day capabilities of numerical and statistical models for atmospheric extratropical seasonal simulation and prediction. *Bull. Amer. Meteor. Soc.*, **80**, 1349 - 1362.

Barnston, A.G., A. Kumar, L. goddard, and M.P. Hoerling, 2005: Improving seasonal prediction practices through attribution of climate variability. *Bull. Amer. Meteor. Soc.*, **86**, 59-72.

Bentley, M. L., and T. Mote, 1998: A climatology of derecho-producing mesoscale convective systems in the central and eastern United States, 1986-95. Part 1: Temporal and spatial distribution. *Bull. Amer. Meteor. Soc.*, **79**, 2527-2540.

Clarke, A.J., and B. Li, 1995: On the timing of warm and cold

El Niño – Southern Oscillation Events. *J. Climate*, **10**, 2571 – 2574.

Enfield, D.B., and A.M. Mestas-Nuñez, 1999: Multiscale variabilities in global sea surface temperatures and their relationships with tropospheric climate patterns. *J. Clim.*, **12,** 2719–2733.

Fukunaga, K., 1972: *Introduction to statistical pattern recognition.* Academic Press, 369 pp.

Galarneau, T.J, L.F. Bosart, and A.R. Aiyyer, 2005: A 54-year global closed anticyclone climatology (1950 – 2003). *AMS Meteorological Monograph, 94 pp..*

Gershunov, A., and T.P. Barnett, 1998: Interdecadal modulation of ENSO teleconnections. *Bull. Amer. Meteor. Soc.*, **79**, 2715 - 2725.

Gray, 1984: Atlantic season hurricane frequency. Part 1: El Niño and 30 mb Quasi Biennial Oscillation influences. *Mon. Wea. Rev.*, **112**, 1649 - 1668.

Gu, D., and S.G.H. Philander, 1995: Secular changes of annual and interannual variability in the Tropics during the past century. *J. Clim.,* **8,** 864 – 876.

Hu, Q., C.M. Woodruff, and S.E. Mudrick, 1998: Inter-decadal variations of annual precipitation in the central United States. *Bull. Amer. Met. Soc.*, **79**, 221 – 230.

Kalnay, E., and Co-authors, 1996. The NCEP/NCAR 40-year re-analysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437- 471.

Key, J.R., and A.C.K. Chan, 1999: Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies. *Geophys. Res. Lett.*, **26**, 2053-2056.

Kung, E.C., and J.-G. Chern, 1995: Prevailing anomaly patterns of the Global Sea Surface temperatures and tropospheric responses. *Atmosfera*, **8,** 99 – 114.

Kunkel, K.E., and J.R. Angel, 1999: Relationship of ENSO to snowfall and related cyclone activity in the contiguous United States. *J. Geophys. Res.*, **104,** 19425 – 19434.

Kushnir, Y., W.A. Robinson, I. Bladé, N. M. J. Hall, S Peng, and R. Sutton, 2002: Atmospheric GCM response to extratropical SST anomalies: Synthesis and evaluation**.** *J. Clim.,* **15,** 2233–2256.

Lee, J.-W., and E.C. Kung, 2000: Seasonal-range forecasting of the Ozark climate by a principal component regression scheme with antecedent seas surface temperatures and upper air conditions. *Atmosfera*, **13,** 223 – 244.

Lupo, A.R., E. P. Kelsey, D.K. Weitlich, N.A. Davis, and P.S. Market, 2008: Using the monthly classification of global SSTs and 500 hPa height anomalies to predict temperature and precipitation regimes one to two seasons in advance for the mid-Mississippi region. *Nat. Wea. Dig.,*

32, *in press.*

_____, A.R., Kelsey, E.P., D.K. Weitlich, I.I. Mokhov, F.A. Akyuz, Guinan, P.E., J.E. Woolard, 2007: Interannual and interdecadal variability in the predominant Pacific Region SST anomaly patterns and their impact on a local climate. *Atmosfera,* **20,** 147-170.

_____, D. Albert, R. Hearst, P.S. Market, F. Adnan Akyuz, and C.L. Allmeyer, 2005: Interannual variability of snowfall events and snowfall-to-liquid water equivalents in southwest Missouri. *Nat. Wea. Dig.,* **29,** 13 – 24.

_____, E.P. Kelsey, E.A. McCoy, C.E. Halcomb, E. Aldrich, S.N. Allen, A. Akyuz, Sara Skellenger, D.G. Bieger, E. Wise, D. Schmidt, and M. Edwards, 2003: The presentation of temperature information in television broadcasts: What is normal? *Nat. Wea. Dig.*, **27,** 53 -58.

_____, and P.S. Market, 2002: The verification of weather forecasts in central Missouri and seasonal variations in forecast accuracy. *Weather and Forecasting*, **17,** 891 – 897.

_____, P.J. Smith, and P. Zwack, 1992: A diagnosis of the explosive development of two extratropical cyclones. *Mon. Wea. Rev.*, **120,** 1490 - 1523.

Mestas-Nuñez, A.M., and D.B. Enfield, 2001. Eastern equatorial Pacific SST variability: ENSO and non-ENSO components and their climatic associations**.** *J. Clim.,* **14,** 391–402.
_____, and _____, 1999: Rotated global modes of non-ENSO sea surface temperature variability. *J. Clim.,* **12,** 2734–2746.

Mokhov, I.I., D.V. Khvorostyanov, and A.V. Eliseev, 2004: Decadal and longer-term changes in ENSO characteristics. *I. J. Climatol.,* **24,** 401 – 414.

_____, A.V. Eliseev, and D.V. Khvorostyanov, 2000: Evolution of characteristics of the climate variability related to the El Niño / La Niña phenomena. *Izvestiya, Atmos. Ocean. Phys.,* **36,** 741 – 751.
Nakamura, H., G. Lin, and T. Yamagata, 1997: Decadal climate variability in the Northern Pacific during recent decades. *Bull Amer. Met. Soc.*, **78,** 2215 – 2226.

Namias, J., 1983: Some causes of the United States drought. *J. Clim. and Appl. Met*., **22,** 30 – 39.

_____, 1982: Anatomy of great plains protracted heat waves (especially the 1980 U.S. summer drought). *Mon. Wea. Rev.***,** **110,** 824 - 838.

Palecki, M.A., and D.J. Leathers, 2000: Spatial modes of drought in the central United States. *Preprints of the 12th Conference on Applied Climatology*, 8 - 11 May, 2000, Asheville, NC.

Park, C.-K., and E.C. Kung, 1988: Principal components of the North American summer temperature field and the

antecedent oceanic and atmospheric condition. *J. Meteor. Soc. Japan,* **66,** 677 – 690.

Quiroz, R.S., 1984: The climate of the 1983 - 1984 winter - a season of strong blocking and severe cold over North America. *Mon. Wea. Rev.*, **112,** 1894 - 1912.

Ratley, C.W., A.R. Lupo, and M.A. Baxter, 2002: Determining the spring to summer transition in the Missouri Ozarks using synoptic-scale atmospheric data. *Transactions of the Missouri Academy of Science*, **36,** 69 – 77.

*Wallace, J.M., and D.S. Gutzler, 1981: Teleconnections in the geopotential height field during the northern hemisphere winter. *Mon. Wea. Rev.*, **109,** 784-812.

*Wiedenmann, J.M., A.R. Lupo, I.I. Mokhov, and E. A. Tikhonova, 2002: The Climatology of Blocking Anticyclones for the Northern and Southern Hemisphere: Block Intensity as a Diagnostic. *Journal of Climate,* **15,** 3459 – 3474.