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RELATIONSHIPS BETWEEN GEOPOTENTIAL HEIGHTS AND TEMPERATURE IN THE SOUTH-EASTERN US DURING WINTERTIME WARMING AND COOLING PERIODS

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ABSTRACT

This paper discusses the relationship between geopotential heights and mean winter surface temperature and the characteristics of interannual variability in the south-eastern USA during cooling and warming periods from 1946 to 1992. Data from 83 Historical Climatology Network stations in 12 south-eastern states were examined. Factor analysis was used to separate the south-east into three climatic regions. These regions were then matched with both 500 hPa and 700 hPa pressure heights during two periods: the 1946–1976 cooling period and the 1976–1992 warming period. The degree of association between geopotential heights and surface temperature was greater during the cooling period than during the warming period. Possible influences may lie with differential temperature modification effects of the Gulf of Mexico and Atlantic Ocean, as well as soil moisture variability. The amount of geopotential height variability, as measured by standard deviations, was also compared between the cooling and warming periods, and was significantly greater during the cooling period. This explains a similar pattern in the surface temperature variability. A possible cause is the susceptibility of troughs to prolongation and amplification during cold winters. Both results suggest that not only is it difficult to determine the forcing mechanisms that cause short-term variability, but that the influence of the forcing mechanisms may not be consistent between cooling and warming periods as well.

KEY WORDS: south-eastern USA; winter temperature; temperature trends; geopotential heights; factor analysis; correlation; teleconnections

INTRODUCTION

Interannual and interdecadal temperature variability is a source of great interest to humankind because of the possible effects on human activities such as agriculture (Agee, 1980). Often, questions arise as to whether the recently observed variability is part of short- or long-term global or regional climate change, with its commensurate effects on biospheric and socio-economic systems (Karl and Quayle, 1988). Additionally, considerable discussion exists in understanding the physical mechanisms that cause the changes. Finally, differences in the degree of interannual variability during warming and cooling periods suggest that the effects of these mechanisms may not be consistent.

One of the most interesting features of interannual and interdecadal climatic variability is the frequent and regional nature of the changes (Trenberth, 1990). Climate variations often are associated with changes in general circulation patterns (van Loon and Williams, 1976), with accompanying changes of opposite magnitude occurring concurrently within the hemisphere (Stockton, 1990). During winter seasons in the eastern USA, for example, substantial cooling occurred between the early 1940s and 1980s (Agee, 1980), whereas winter temperature departures in the western USA were predominately above average (Dewey and Heim, 1993). In the last decade, eastern USA winters have been characterized by substantial warming (Dewey and Heim, 1993).

Cold and warm winters in regions of continental USA are often associated with anomalies of general circulation patterns (van Loon and Williams, 1976), particularly the Pacific–North American (PNA), North Atlantic

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Oscillation (NAO), and El Niño–Southern Oscillation (ENSO) teleconnections (Rogers, 1984; Yarnal and Leathers, 1988; Redmond and Koch, 1991). These teleconnections are the linkage between atmospheric conditions over long distances (≥ 2000 km), and the PNA teleconnection generally is viewed as the most important in influencing Northern Hemisphere winters on the North American continent (Wallace and Gutzler, 1981; Simmons *et al.*, 1983; Barnston and Livezey, 1987). The PNA teleconnection pattern is expressed as anomalies in either the 500 hPa or 700 hPa geopotential height field, and can be represented as an index (Horel and Wallace, 1981; Wallace and Gutzler, 1981; Yarnal and Diaz, 1986).

Variations in the PNA index represent periods of increased meridional or zonal flow, which in turn influence surface temperatures in various regions. The classic PNA pattern (phase) is characterized by enhanced upper-level troughing in the north-east Pacific, ridging centred over the western Canada Rocky Mountain Cordillera, and troughing over the eastern USA (Yarnal and Leathers, 1988). The opposite phase, the Reverse PNA (RPNA), is characterized by the lowered ridge and filled troughs at the above locations. In extreme cases, the placement of ridges and troughs is the opposite of the PNA phase (Yarnal and Leathers, 1988). The PNA index varies substantially during the course of the year. Amplification of the long waves in the mid-troposphere (i.e. positive PNA index values for increased meridionality) is associated with above-normal temperatures in areas located beneath the ridge (western USA) and below-normal temperatures in areas beneath the trough (eastern USA) (Leathers *et al.*, 1991). Flattening of the long waves (negative PNA index) increases zonal flow, which brings below-normal temperatures to the west and above-normal temperatures to the east. A PNA index value of zero indicates minimal deviations from mean temperature conditions.

Several studies have addressed specifically the relationship between upper-level circulation and winter temperatures in the USA. Erickson (1984) investigated the relationship between area-weighted surface temperature in the USA and zonally averaged 700 hPa height. During warm winters in the USA, the 700 hPa heights generally have positive anomalies over subtropical and mid-latitudes and negative anomalies over high latitudes. During cold winters in the USA, the opposite patterns were observed. Leathers *et al.* (1991) investigated the relationship between monthly temperature in the USA and upper-level flow patterns represented by a PNA index. They found that temperature is positively correlated with the PNA index in the eastern USA and is negatively correlated with the index in the west. Yarnal and Leathers (1988) examined interdecadal and interannual temperature variability in Pennsylvania between 1947 and 1982 and found that variations in PNA teleconnections explained 50 per cent of the wintertime variance. Klein and Kline (1984) examined correlations between concurrent winter mean monthly temperature anomalies at 109 stations and 700 hPa height anomalies in the USA between 1948 and 1981. They determined that surface temperature at a given station may correlate highly with pressure in two or more locations. The positive correlation centres tended to be located close to the reference station (< 1500 km), and the negative correlation centres were further away from the reference station. The highest positive correlations ($r > 0{\cdot}80$) were in the south-east. Skeeter (1990) calculated zonal and meridional flow gradients in the 500 hPa height field. He found that the surface temperature in the north-western and south-eastern USA were associated most strongly with upper-level flow conditions.

Complicating the relationship between upper-level atmospheric conditions and surface temperature, is the temporal and spatial inconsistency of interannual temperature variability during warm and cool periods. An often repeated axiom with little verification is that temperature variability increases during cool periods and decreases during warm periods (van Loon and Williams, 1978). Several studies (e.g. van Loon and Williams, 1978; Karl, 1988; Balling *et al.*, 1990), however, have shown that there may be no systematic association between seasonal mean temperature and associated standard deviations. Conversely, Diaz and Quayle (1980) did find that, at least for the winter mean temperature in the continental USA, cooler–more variable and warmer–less variable patterns existed.

The purpose of this paper is to address the relationship between interannual and interdecadal variability of geopotential heights and mean winter surface temperature in the south-eastern USA. In particular, we will examine two aspects of the relationship between geopotential heights and surface temperature that have been studied little. First, we will explore how the association between 500 hPa and 700 hPa heights and surface temperature varies between warming and cooling periods. Second, we will examine the degree of temporal variability of geopotential heights during warming and cooling periods.

Figure 1. Location of Historical Climatology Network station sites used in this study

STUDY AREA

The study area includes 12 States in the south-eastern USA: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia. The study area is located between 24°30′N to 40°36′N and 75°27′W to 94°37′W. The climate is characterized by hot, humid summers and mild winters (Trewartha and Horn, 1980). Mean January temperatures range from 0°C in the mountains of West Virginia to above 20°C in the Florida Keys.

DATA AND METHODS

Temperature data

Temperature data were acquired from the United States Historical Climatology Network (HCN) serial temperature data set (Karl *et al.*, 1990). These mean temperature data have been adjusted fully for urbanization effects, station moves, instrument changes, and time-of-observation biases. The original data set was pared from the 48 coterminous States to the 12 south-eastern States in the study area. The south-eastern data set included 276 stations, which was further reduced to 83 stations (Figure 1). We reduced the data set by including only stations with a HCN consistency ranking within the top 30 per cent of all stations. The ranking of a station is based on data for its 20 nearest neighbouring stations during the last 40 years (Karl *et al.*, 1990). The number of stations represented in each State ranged from three (Alabama) to 10 (Georgia and South Carolina).

The temperature data used were mean seasonal values beginning in 1946 and continuing through to 1992. Winter temperature data were represented by December (of the previous year), January, and February.

500 hPa and 700 hPa pressure height data

Both 500 hPa, beginning in 1946, and 700 hPa height data, beginning in 1947, were represented in seasonal format identical to temperature. The pressure data were provided by the National Center for Atmospheric Research from the National Meteorological Center data set (Jenne, 1975). The 700 hPa heights were observed twice a day (0000 and 1200 UTC). For each month, the 0000 and 1200 UTC monthly observations were averaged. The 500 hPa data were more complicated. During the period 1946 to March 1955, observations were taken only at 1200 UTC. During April 1955 to May 1957, observations were taken at 0300 and 1500 UTC. Afterward, observations were taken at 0000 and 1200 UTC, the same as the 700 hPa data. To avoid errors associated with changing observation times, we used only the observations at 1200 UTC from 1946 to March 1955 and from June 1957 through to 1992. From April 1955 to May 1957, we used the observations at 1500 UTC. Data for grid points, separated by 5° latitude and 5° longitude, ranged from 20°N to 60°N, and from 70°W to 125°W (Figure 2).

Sea-surface temperature data

Sea-surface temperature (SST) data were provided by Scripps Institution of Oceanography, and were a subset of the Comprehensive Ocean–Atmosphere Data Set (COADS). The data were presented as monthly means from ship observations based on 2° × 2° grid boxes. The length of record was from January 1946 to December 1992. We summarized the data seasonally, beginning in December 1946 (for winter 1947) through to 1992. We used SST data between 20°N to 40°W and 60°W to 96°W (Figure 3). We recognize that the reliability of SST is relatively low because the number of observations in each month was different, especially during the earlier years.

Regions

We defined our climatic regions by performing factor analysis on the 83 south-east HCN stations using mean annual temperature data. Annual temperature data were used because they give the best average approximation of the regional boundaries. Three factors were retained based on two criteria: cumulative eigenvalues exceeding 80 per cent of the total variance in the matrix (in this instance, the three factors represented 87·2 per cent) and identifying the point of inflection (break in slope) on the scree plot (Zar, 1984). The three factors were then orthogonally rotated using a VARIMAX rotation (SAS, 1988). The highest factor loading for each station was then used to place a station in a region (Figure 4). Region 1 represents 39 stations where the highest loading was on the first factor. Region 2 represents 27 stations with their highest loadings on the second factor, and region 3 marks 17 stations with their highest loadings on factor three. Regional temperatures were then calculated as the average for all stations within each region.

Methods

Pearson product-moment correlation analyses were performed for each region between winter temperature and both 500 hPa and 700 hPa pressure heights for each grid-point. Correlation coefficients were mapped using SURFER® to show spatial patterns of the correlation field. Similarly, Pearson product-moment correlation analyses were performed between winter surface temperature and winter SST. Likewise, correlation coefficients were mapped with SURFER®. For each region, we plotted temperature and pressure height of the grid-point with the highest correlation coefficient during the length of record. These plots allowed us to separate the temperature record into cooling and warming periods based on an inflection point. We selected five grid points (both 500 hPa and 700 hPa) that had the highest correlations between temperature and pressure heights for each region. The consistency of the relationship between temperature and pressure height was then examined using a matched-pairs Student's *t*-test on correlation coefficients during different periods. If the mean correlation coefficients for two periods (i.e. warming versus cooling) are statistically different, then the relationship between temperature and pressure heights is inconsistent between warming and cooling periods. Because the cooling period is almost twice the length of the warming period, potentially biasing the selection of grid-points, we also selected five grid-points (both 500 hPa and 700 hPa) that had the highest correlations between temperature and pressure heights for each

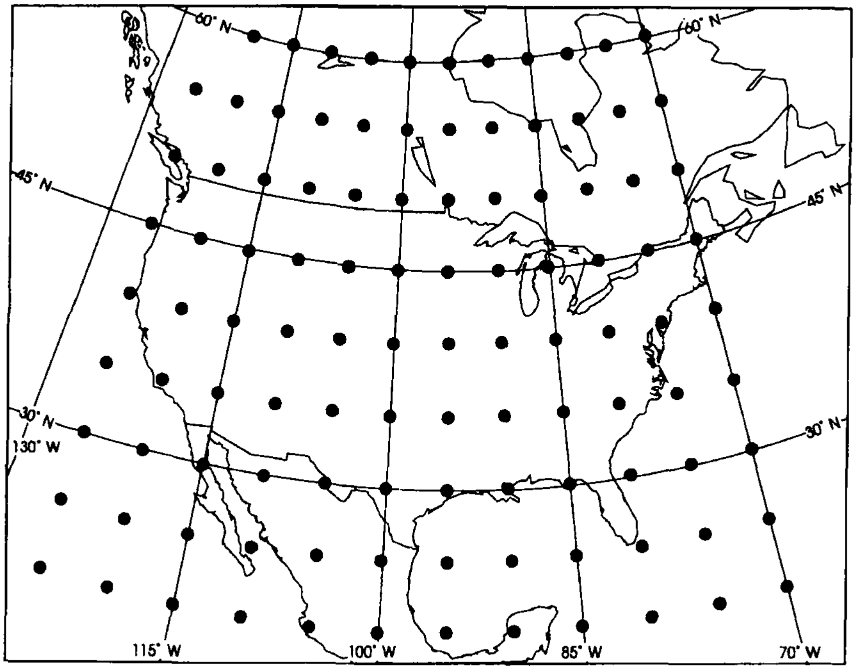

Figure 2. Locations of 5° latitude by 5° longitude intersections for 500 hPa and 700 hPa geopotential height data

region for both the cooling period and warming period. We then ran an independent Student's t test comparing correlation coefficients between time periods. Finally, we also performed similar analyses on the association between SST and surface temperature using the five grid-points with the highest correlations.

In comparing the interannual variability of pressure heights during warming and cooling periods, we determined the standard deviation of 500 hPa and 700 hPa height pressure at the same grid points as above (i.e. those with the five highest correlations) and again performed a matched-pairs Student's t test. Statistically different standard deviations of pressure heights between warming and cooling periods would suggest that the amount of interannual variability is also inconsistent.

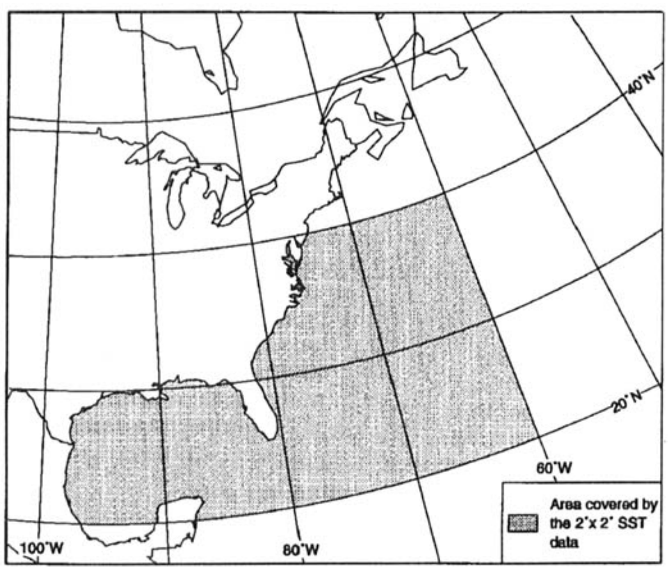

Figure 3. Shaded area represents region from where sea-surface temperature data were used in this study

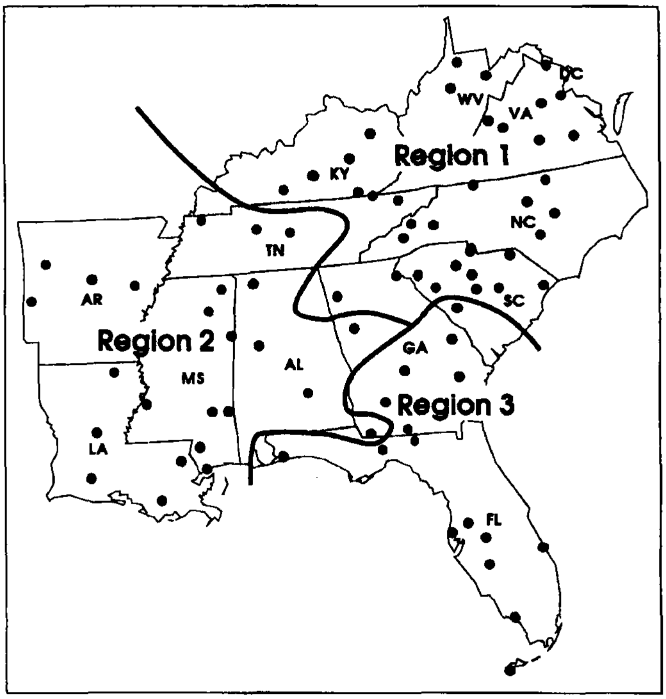

Figure 4. Boundaries of the three defined climatic study regions

RESULTS

Correlation coefficients between temperature and pressure for each region show distinct spatial patterns, and were consistent between 500 hPa and 700 hPa heights (Figures 5 and 6). The highest correlations for each region are centred on the southeast coast from the Florida Panhandle to Chesapeake Bay, as opposed to being centred directly over the specific regions. For region 1 and region 2, maximum correlation coefficients were below 0.90, whereas for region 3 maximum r values were greater than 0.90. Correlation coefficients decreased substantially west of 93°W to approximately 105°W. From the Rocky Mountains north-westward, correlation coefficients show an increasingly negative relationship, peaking between -0.50 and -0.60 in central Alberta.

The temperature record for all three regions show a distinct inflection point, from a cooling trend from 1946 through to 1975 to a warming trend from 1976 through to 1992 (Figure 7 and 8). Mean correlation coefficients between temperature and both 500 hPa and 700 hPa heights for selected grid points are statistically greater ($p < 0{\cdot}05$) during the cooling period than that during the warming period (Tables I and II). These correlation coefficients suggest that during periods of cooling, the linear relationship between temperature and pressure heights is stronger than during warming periods (Figures 7 and 8). Additionally, comparisons between Tables I and II show that the selection of grid-points in this study is not statistically biased by the differential length of warming and cooling periods. Although the pressure height grids with the high correlation coefficients shifted in the later warming period, this did not affect the results of the statistical test.

Standard deviations of both 500 hPa and 700 hPa pressure heights for selected grid points are significantly greater ($p < 0{\cdot}001$) during the 1947–1975 cooling period than during the 1976–1992 warming period (Tables III and IV). A similar decrease in standard deviation is also found for the surface temperature (Table V). Greater standard deviations suggest that during the cooling period, there is greater interannual variability in pressure heights and surface temperature. The initial sample size for pressure height standard deviation values was 30 (3 regions $\times$ 2 geopotential heights $\times$ 5 grid points per region), but was subsequently reduced to 17 because we did not double count 13 grid-point observations that were included in more than one region.

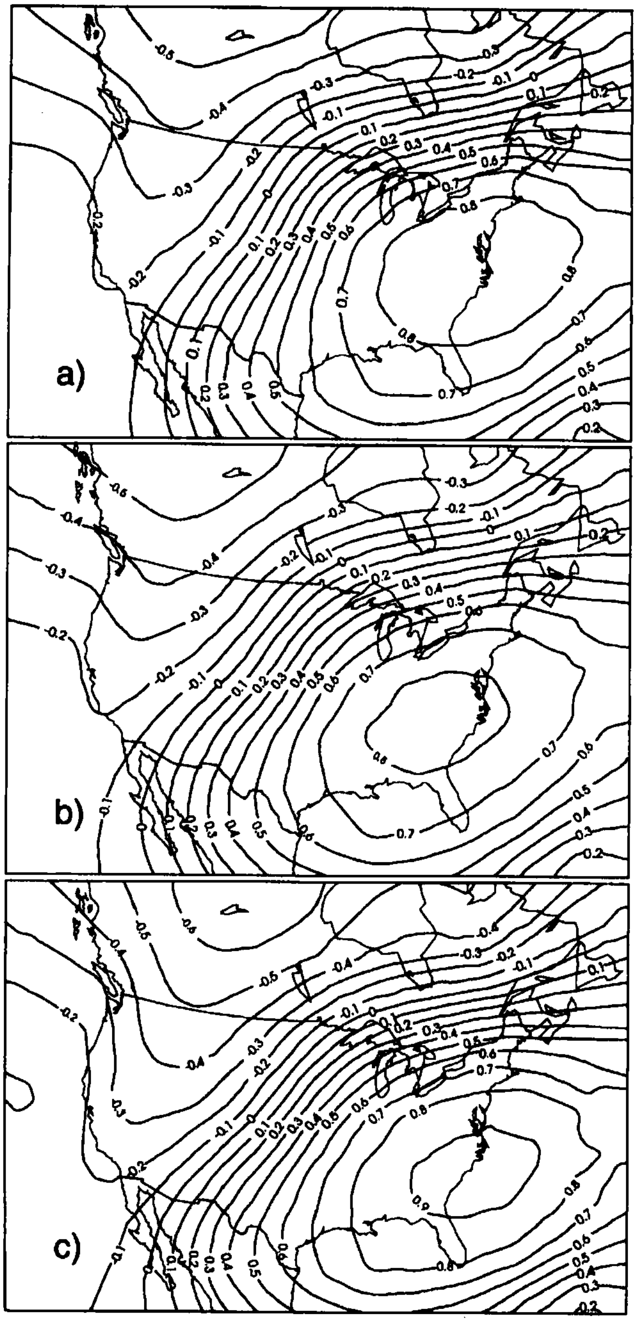

Figure 5. Correlation coefficients between mean winter temperature and 500 hPa pressure heights for (a) region 1, (b) region 2, and (c) region 3

Correlation coefficients between surface and sea-surface temperatures were typically highest (0·5–0·6) on the coastlines for both the Gulf of Mexico and Atlantic Ocean (Figure 9). Associations generally decreased south of the Gulf of Mexico and east of the Atlantic Ocean shorelines. Little spatial variation in correlation coefficients existed between the three regions. Correlations during the cooling period were again significantly greater ($p < 0{\cdot}0001$) than during the warming period (Table VI), suggesting that the influence of SSTs on surface temperatures is inconsistent.

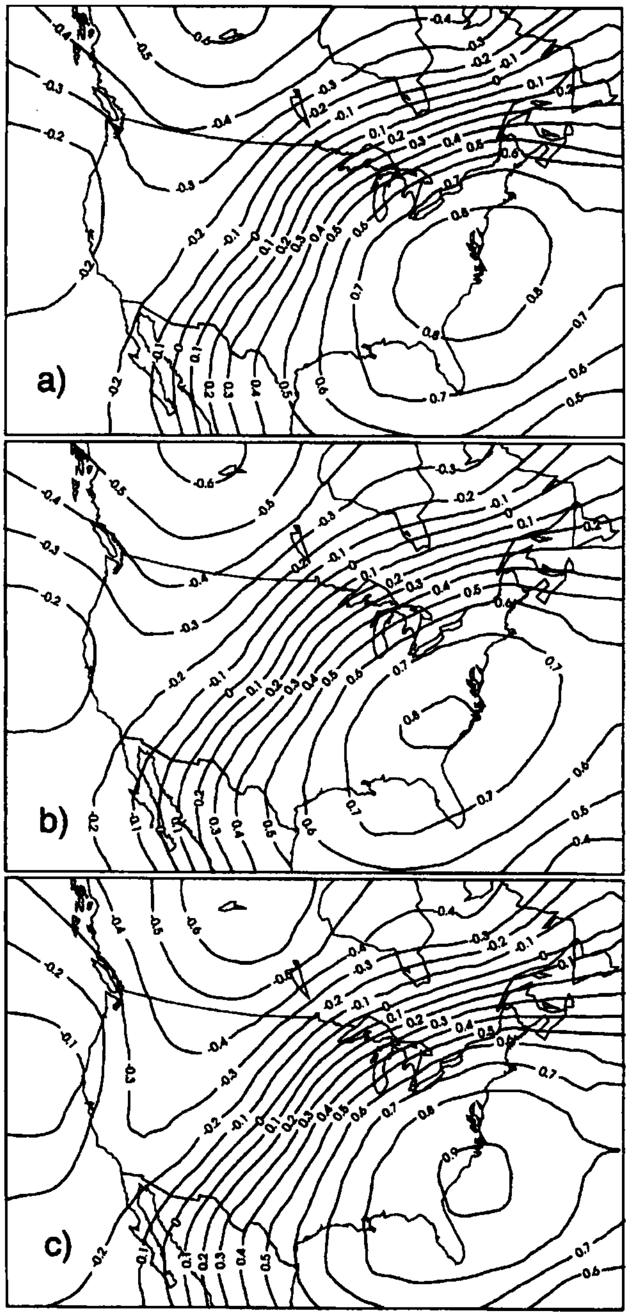

Figure 6. Correlation coefficients between mean winter temperature and 700 hPa pressure heights for (a) region 1, (b) region 2, and (c) region 3

DISCUSSION

Our results show a high degree of association between upper level pressure heights and surface temperature. These results are in close agreement to other similar studies (e.g. Klein and Kline, 1984), and further confirm that upper-level conditions have a strong influence on surface temperatures. What we found of great interest, however, was that this association was expressed stronger during the 1946–1975 cooling period than during the 1976–1992 warming period. Our interest in these transition periods as opposed to warm and cool periods was based on the

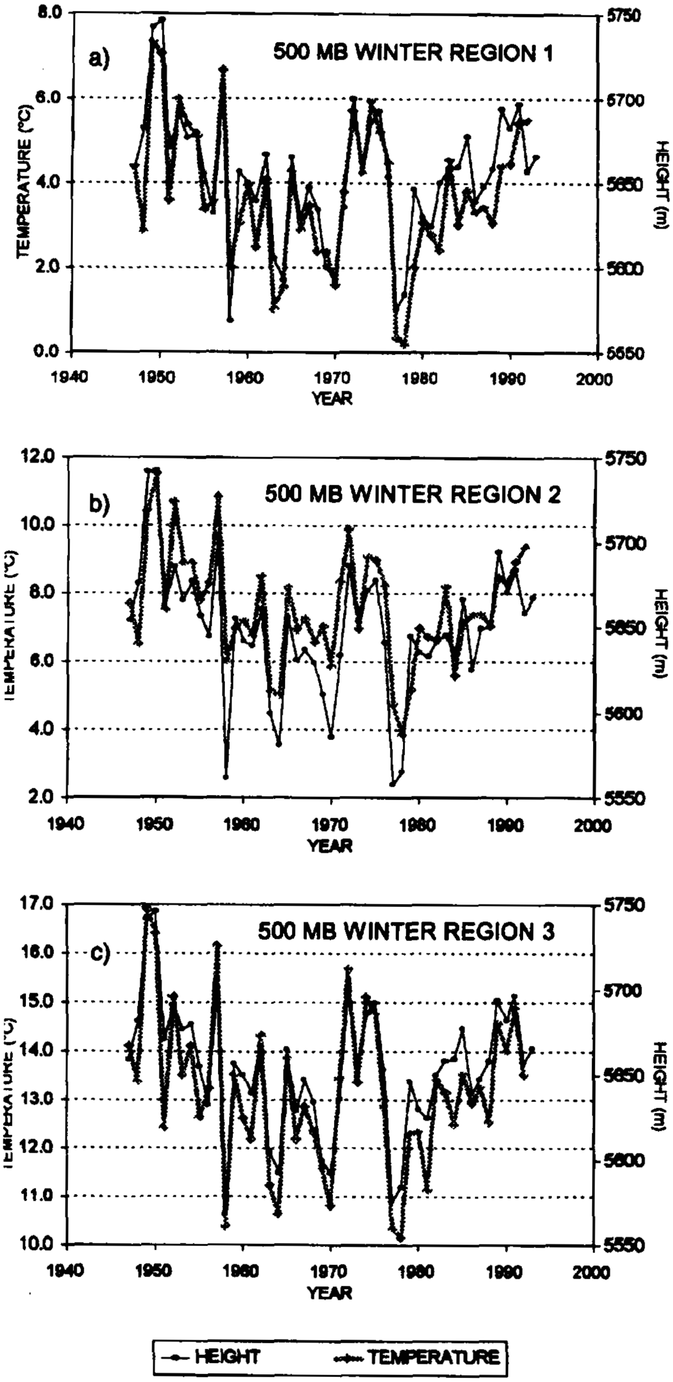

Figure 7. Time series of mean winter temperatures and 500 hPa pressure heights, 1946–1992

understanding that many positive feedback mechanisms occur during either warming or cooling periods, such as altered baroclinicity (Dickson and Namias, 1976), which enhances these trends. Further, as Stockton (1990) has argued, climatic variability on the order of 10 to 100 years is of greatest importance to human activities because the variability is typically regional in nature and affects all activities dependent upon temperature, including agriculture and municipal planning.

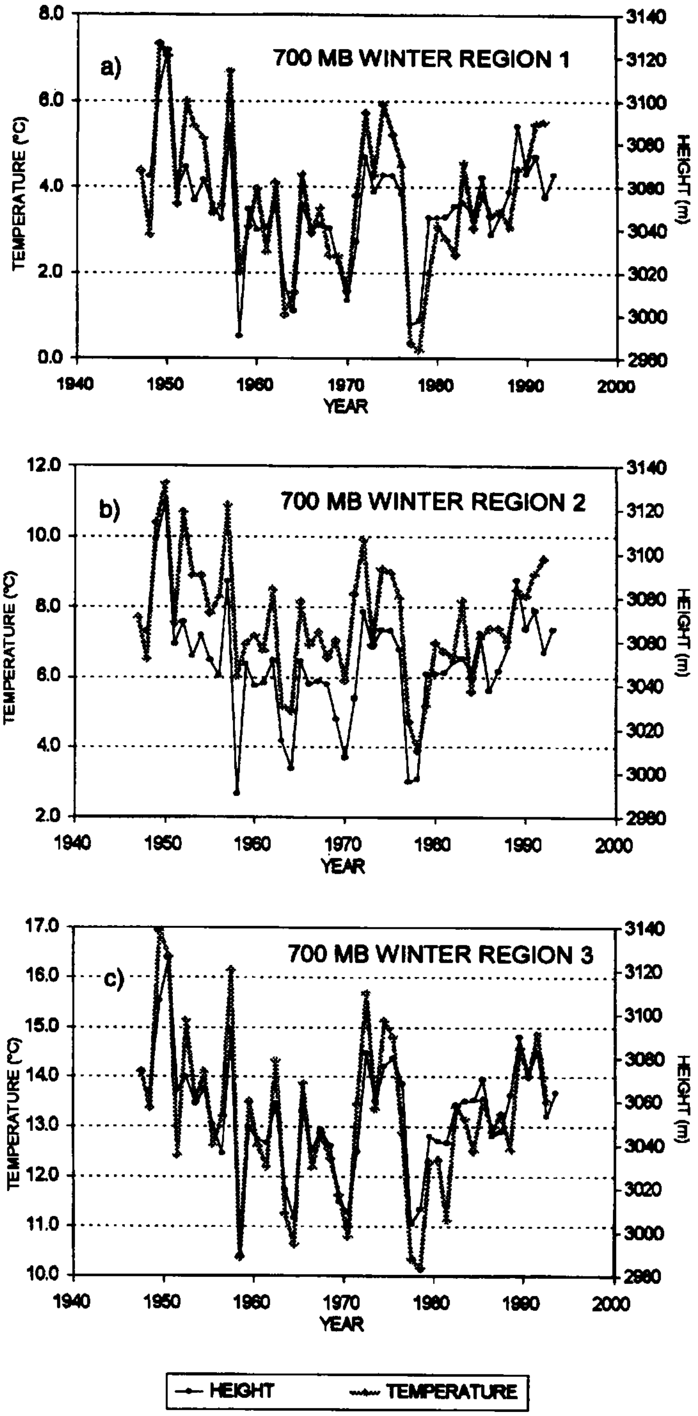

Figure 8. Time series of mean winter temperatures and 700 hPa pressure heights, 1947–1992

One explanation of stronger association during cooling periods may rest with the differential temperature modification effects of the Gulf of Mexico and the Atlantic Ocean. During periods of negative pressure height anomalies in the south-east (enhanced troughing that characterized the cooling period), the prevailing atmosphere dynamics involved the advection of cooler drier air from interior North America and a strong PNA teleconnection

Table I. Correlation between winter temperature and pressure heights of 500 hPa and 700 hPa levels for selected grid-points, and matched-pairs Student's t tests on correlation coefficients during 1946–1975 and 1976–1992

Geopotential height (hPa)	With temperature of	Grid-points	Years	
			1946–1975	1976–1992
500	Region 1	W70N35	0·89599	0·79914
		W75N35	0·90709	0·84618
		W75N40	0·88640	0·87480
		W80N35	0·89822	0·84930
		W80N40	0·87501	0·88660
	Region 2	W75N35	0·85703	0·75572
		W80N35	0·86840	0·79455
		W80N40	0·81330	0·80925
		W85N35	0·85891	0·81734
		W90N35	0·82153	0·81570
	Region 3	W70N35	0·92291	0·88857
		W75N30	0·91470	0·90324
		W75N35	0·94119	0·94366
		W80N30	0·91881	0·90303
		W80N35	0·93996	0·92071
700	Region 1	W70N40	0·85989	0·79255
		W75N35	0·90014	0·82846
		W80N35	0·88439	0·84573
		W80N40	0·84202	0·87154
		W85N35	0·83959	0·83187
	Region 2	W75N35	0·85499	0·75478
		W80N30	0·86239	0·63498
		W80N35	0·85679	0·79551
		W80N40	0·79441	0·80216
		W85N35	0·83693	0·81991
	Region 3	W75N30	0·94350	0·87790
		W75N35	0·93842	0·90627
		W80N30	0·93891	0·86844
		W80N35	0·92752	0·89913
		W85N30	0·91519	0·80874

	Matched-pairs Student's t test		
	500 and 700 hPa	500 hPa	700 hPa
N	30	15	15
Mean difference	0·0456	0·0341	0·0571
t	4·9763	3·7122	3·6515
α	0·0001	0·0023	0·0026

(Dickson and Namias, 1976; Klein and Kline, 1984). The north-westerly flow aloft tends to minimize the influence of moderating air flows, particularly the south-westerly flow from the Gulf of Mexico. The jet-stream trajectories shift southward and increase cyclonic activity in the south-east. During such times, strong cold waves may bring Arctic air to the Florida Peninsula, which has caused serious damage to the citrus trees (Rohli and Rogers, 1993). With the passage of each cold front, surface temperatures decrease rapidly because of the advection of cold air brought by the north-westerly flows as well as radiational cooling. The cold, dry weather behind the cold front reduces the frequency of events, such as persistent fog and low stratus clouds, that have been shown to lower correlations between surface temperature and geopotential heights (Klein and Kline, 1984).

Unlike the relatively dynamic forcing mechanisms dominant during the cooling period, surface temperatures in the south-east may be affected by several forcing mechanisms during the warming period. During periods of

Table II. Correlation between winter temperature and pressure heights of 500 hPa and 700 hPa levels for selected grid-points, and independent Student's *t* tests for correlation coefficients during 1946–1975 and 1976–1992

Geopotential height (hpa)	With temperature of:	Grid-points	Years 1946–1975	Grid-points	Years 1976–1992
500	Region 1	W7035	0·89599	W7535	0·84618
		W7040	0·87503	W7540	0·87480
		W7535	0·90709	W8035	0·84930
		W7540	0·88640	W8040	0·88660
		W8035	0·89822	W8540	0·86352
	Region 2	W7535	0·85703	W8040	0·80925
		W8030	0·84650	W8535	0·81734
		W8035	0·86840	W8540	0·81505
		W8530	0·85105	W9035	0·81570
		W8535	0·85891	W9040	0·81724
	Region 3	W7035	0·92291	W7035	0·88857
		W7535	0·94119	W7530	0·90324
		W8030	0·91881	W7535	0·94366
		W8035	0·93996	W8030	0·90303
		W8535	0·91545	W8035	0·92071
700	Region 1	W7035	0·88905	W7540	0·85076
		W7530	0·88247	W8035	0·84573
		W7535	0·90014	W8040	0·87154
		W8030	0·87995	W8535	0·83187
		W8035	0·88439	W8540	0·85628
	Region 2	W7535	0·85499	W8040	0·80216
		W8030	0·86239	W8535	0·81991
		W8035	0·85679	W8540	0·81257
		W8530	0·86326	W9035	0·79881
		W9030	0·85531	W9040	0·81736
	Region 3	W7035	0·92047	W7530	0·87790
		W7530	0·94350	W7535	0·90627
		W7535	0·93842	W8030	0·86844
		W8030	0·93891	W8035	0·89913
		W8035	0·92752	W8535	0·84593

	Independent Student's *t* test		
	500 and 700 hPa	500 hPa	700 hPa
N	30	15	15
Mean difference	0·0374	0·0286	0·0462
t	4·0671	2·0546	3·8145
α	0·0001	0·0494	0·0007

positive pressure height anomalies (decreased troughing that characterized the warming period) the polar front jet is displaced northward, and there is a substantially stronger south-westerly flow into the south-east. Consequently, there is an increase in the frequency of the warm, maritime air masses that originate in the Gulf of Mexico (Dickson and Namias, 1976; Leathers *et al.*, 1991). In this instance, warming temperatures in the south-east are not only influenced by south-westerly flow, but would be modified by SSTs that lag with upper level pressure heights. Lanzante (1984), for example, determined that 700 hPa heights significantly led Atlantic SSTs by one to two months from January to March.

Correlations between SSTs and surface temperatures during the cooling and warming periods support this notion of the complicating effects of the ocean. Similar to the relationship between surface temperatures and pressure heights, there is a weaker association between SSTs and surface temperature during the warming period than the

Table III. Means and standard deviations of 500 hPa and 700 hPa heights for selected grid-points during 1946–1975 and 1976–1992

Geopotential height (hPa)	Grid	1946–75		1976–92	
		Mean	SD	Mean	SD
500	W70N35	5664·40	40·523714	5661·98	30·87640
	W75N35	5657·44	42·012850	5650·31	32·10010
	W75N40	5511·87	42·100079	5505·79	37·48389
	W80N35	5652·46	41·276225	5642·52	34·61529
	W80N40	5509·47	40·078495	5503·64	39·13406
	W85N35	5646·00	39·206099	5638·49	34·92909
	W90N35	5641·75	34·359898	5638·91	31·89899
	W75N30	5771·39	32·271504	5766·98	23·71457
	W80N30	5764·75	33·617190	5759·57	25·70550
700	W70N40	2965·42	29·389631	2966·82	26·13959
	W75N35	3053·01	30·189971	3054·28	21·99158
	W80N35	3050·67	28·698330	3049·64	22·77114
	W80N40	2968·61	26·524244	2968·53	24·88834
	W85N35	3048·43	25·854473	3047·97	21·69543
	W80N30	3117·12	24·598164	3116·92	17·77444
	W75N30	3121·61	24·317037	3122·66	17·25569
	W85N30	3111·33	23·262143	3111·53	17·85444

Table IV. Matched-pairs Student's *t* test on standard deviations of pressure heights during 1946–1975 and 1976–1992 for selected grid-points

	500 and 700 hPa	500 hPa	700 hPa
N	17	9	8
Mean difference	5·7324	6·1098	5·3079
t	8·7039	5·7216	6·8979
α	0·0001	0·0004	0·0002

Table V. Means and standard deviations of surface temperature during 1946–1975 and 1976–1992

Location	1946–1975		1976–1992	
	Mean	SD	Mean	SD
Region 1	3·9927	1·6886	3·3207	1·5131
Region 2	7·9358	1·6727	7·0763	1·5185
Region 3	13·4205	1·7170	12·7896	1·3007

cooling period (Table VI). Apparently, strong dynamic forcing mechanisms also caused SSTs along the south-east coast to change, synchronized with the variations in the surface temperature during the cooling period. During the warming period, a plausible explanation may involve recent work that has refocused on the long-term memory of oceans to store heat and to modify the effect of surface heating (Watts and Morantine, 1991, 1993; Kellogg, 1993). These studies have suggested that oceanic circulation changes have the potential to redistribute sensible heat

Table VI· Correlation coefficients between surface temperature and sea-surface temperature for selected grid-points during 1946–1975 and 1976–1992

With T of:	Grids	1946–1975	1976–1992
Region 1	W78N34	0·70957	0·63123
	W96N28	0·70141	0·60115
	W82N30	0·76123	0·49066
	W66N36	0·60758	0·65235
	W94N22	0·78155	0·44509*
Region 2	W78N34	0·75370	0·57552
	W88N28	0·72031	0·57146
	W94N22	0·76661	0·53074
	W94N26	0·73530	0·23671*
	W96N28	0·78653	0·45697*
Region 3	W82N30	0·83716	0·62946
	W94N22	0·80714	0·66297
	W84N24	0·71552	0·72865
	W94N26	0·75194	0·51056
	W80N28	0·77013	0·53833

* Not significant at the 0·05 level.

energy and influence surface temperatures (Watts and Morantine, 1993). Hence, the reduced association between upper level pressure heights and surface temperatures during the 1976–1992 period may have been affected by the stored thermal energy coupled with the more northern position of the polar front jet.

Additional mechanisms may complicate the association between upper level pressure heights and surface temperature. Soil moisture variability has been shown to create surface temperature anomalies through modifications of the Bowen ratio (sensible/latent heating ratio) (Walsh *et al.*, 1985), although having little impact on the upper atmosphere (Yang *et al.*, 1994). Additionally, abnormally moist soil may be coupled with increased haziness, relative humidity, and cloudiness, which may further influence surface temperatures (Walsh *et al.*, 1985). Precipitation characteristics in the south-east tend to favour the modifying influences of increased soil moisture during the periods of enhanced zonal flow that occurred during the warming period. For example, Henderson and Robinson (1994) examined the relationship between the PNA teleconnection and precipitation events in the south-eastern USA. They determined that the frequency of wintertime precipitation events was substantially greater (30–40 per cent) and the duration shorter during winters characterized by predominantly zonal flow as opposed to winters characterized by meridional flow. These characteristics of rainfall events seem to indicate a convective nature.

We found greater interannual variability of upper level pressure heights during the cooling period as opposed to the warming period. Enhanced troughing that characterized the cooling period in the south-east may be subject to positive feedback mechanisms that amplify anomalous teleconnections. Dickson and Namias (1976) found winters of extreme cold over the south-eastern USA and an extensive change in the distribution of snowfall led to a southward shift in the coastal baroclinic zone that affected the principal zone of Atlantic cyclogenesis. This change in turn was linked with the anchoring and amplification of an anomalous teleconnection pattern with a deep trough in the (south)eastern USA and a large ridge over Greenland. Conversely, the authors found that during winters of extreme winter warmth in the south-east the zone of maximum storm activity was substantially further north than during cold winters, and that there was not the prolonging and amplifying effect to atmospheric circulation. Similarly, it is possible that during cooling periods, more troughs develop over the south-east, but the exact placement of the trough may vary substantially from year-to-year depending on the degree of prolongment and amplification. Therefore, at a given point over the south-east, a greater variability in pressure heights is experienced. During the warm periods, however, atmospheric conditions are not conducive for the amplification of the long wave. The filled trough over the south-east produces zonal flow. The overall reduction in amplitude of the

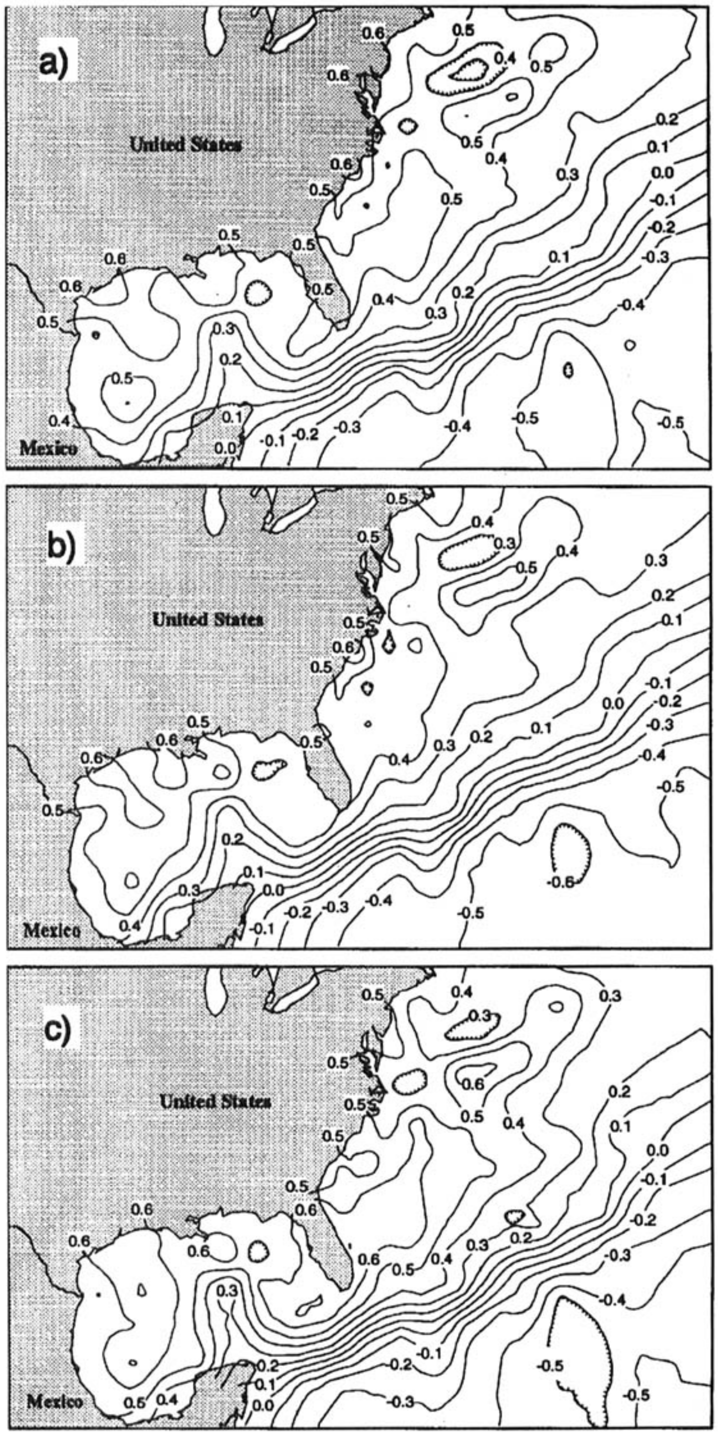

Figure 9. Correlation coefficients between mean winter surface temperature and sea-surface temperature for (a) region 1, (b) region 2, and (c) region 3

geopotential height field will result in low variability. As surface temperatures are so closely related to pressure heights, lower variability in pressure heights during the warming period corresponds well to the lower variability in surface temperature.

Although this pattern of cool periods (greater variability) and warm periods (less variability) has been shown to be spatially inconsistent (van Loon and Williams, 1978; Diaz and Quayle, 1980), our results for the south-east are in agreement with previous studies that also have examined the south-east. For example, results from van Loon and Williams (1978) show that six out of seven south-eastern stations had negative correlations between running 51-year standard deviations and mean winter temperature during 1876–1975 indicating cooler (more variable) and warmer (less variable) conditions. Similarly, Diaz and Quayle (1980) determined that winter seasonal temperature deviation in the south-east increased 15 per cent from the relatively warm 1921–1955 period to the relatively cool 1956–1978 period. If increased variability is related to amplification of the long waves, then the association between variability and temperature should be found only in locations where troughing and ridging are most intensive.

CONCLUSIONS

It has become increasingly apparent that interannual and interdecadal temperature variability is not uniform, but rather strongly regional in nature, and that temperature anomalies in one region are often matched by anomalies of opposite magnitude in other regions (Trenberth, 1990). Our results show additionally the importance of the mechanisms that cause these changes. Fluctuations in geopotential heights that in turn drive atmospheric circulation patterns, such as the PNA teleconnection, are not only regional, but behave differently during cooling and warming periods.

Most of the attention in recent years concerning short-term temperature variability has focused on three potential causes: external forcing mechanisms, including volumetric changes in atmospheric gases, dust, and volcanic ash (Thompson, 1989); internal forcing mechanisms, such as thermodynamic fluctuations within the oceans, which in turn alter atmospheric wind fields (Mitchell, 1976; Watts and Morantine, 1991; Stocker and Mysak, 1992); and a combination of the first two groups, involving a resonance between internal and external forcing mechanisms (Mitchell, 1976). Less emphasis has been placed on the effect of the forcing mechanisms on local climate and whether the relative importance of these mechanisms is consistent during warming and cooling periods.

During the warming period in the south-east between 1976–1992, our results suggest that the relative influence of upper atmospheric conditions are less important to surface temperature variation than are upper level conditions during the cooling period of 1946–1975. Additionally, the amount of temperature variability is greater during the cooling period than during the warming period. The significance of these results then is that not only is it difficult to attribute particular mechanisms to temperature variability, but that the influence of these mechanisms may not be consistent between warming and cooling periods. Certainly our results cannot be applied as axioms, but comparable examinations of other regions would help determine if similar conditions prevail, and would shed additional insight on the complicated subject of interannual and interdecadal variability.

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