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RELATIONSHIPS BETWEEN THE PACIFIC/NORTH AMERICAN TELECONNECTION PATTERNS AND PRECIPITATION EVENTS IN THE SOUTH-EASTERN USA

KEITH G. HENDERSON

Department of Geography and Anthropology, Louisiana State University, Baton Rouge, Louisiana, USA.

AND

PETER J. ROBINSON

Department of Geography, University of North Carolina, Chapel Hill, North Carolina, USA

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ABSTRACT

Precipitation event attributes, defined as the amount, duration, and frequency of individual rainstorms, vary considerably from place to place and season to season. Event variability is caused by a combination of large-scale and local climate processes. Correlations of seasonal time series show that the Pacific/North American (PNA) teleconnection pattern and local rainfall event attributes are significantly related in specific areas of the south-eastern USA in some seasons. Shifts in the zonal/meridional flow over North America affect both the number of events and the event size. The total number of events in some regions changes by as many as 10 to 12 events per season with shifts in continental-scale circulation. An analysis of attribute distributions shows that the percentage of total events falling into selected intensity categories may also change by as much as 10 per cent between flow regimes. Relationships have both temporal and spatial patterns. Shifts in continental-scale circulation affect event attributes most strongly in winter, with more events occurring in zonal years. Events with greater amounts and durations are found east of the Appalachians in meridional years and west of the mountains in zonal years.

KEY WORDS Precipitation events Rainfall variability Pacific/North America pattern South-eastern USA Teleconnections

INTRODUCTION

Precipitation event variability is caused by a combination of large-scale and local climate processes. The large-scale circulation regimes of the Rossby waves determine such factors as the location of baroclinic zones, the position of the jet stream and major storm tracks, and areas of upper level support for cyclogenesis (Henderson-Sellers and Robinson, 1986). Within this overlying climate structure local conditions dictate where individual events will form, what size the event will be, and how long the event will last. A feedback is established between the two scales of processes. Large-scale conditions provide the environment that enables and constrains local production of rainfall events. In turn, individual storms alter the characteristics of the mean atmospheric flow (Hoskins *et al*., 1983; Lau, 1988). Any variability or change in the climate structure at either scale can be expected to affect the spatial and temporal patterns of precipitation events.

Understanding the relationship between large-scale circulation and precipitation events is potentially important for two reasons. First, it contributes to the knowledge of climate variability and the predictability of local rainfall from larger scale climate parameters. This is especially relevant to climate impact studies that are concerned with the effects of local climate variability. Second, relating large-scale flow to rainfall events may constitute a method for linking historical data on precipitation event attributes to modelled circulation

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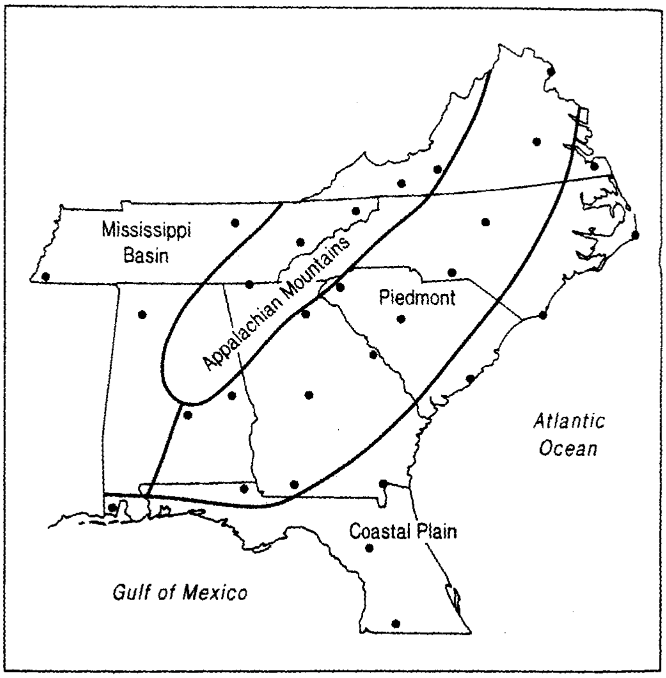


Figure 1. South-eastern USA study area and station locations

patterns for use in scenario production of future climate change, again with a focus on impact assessment (Robinson and Finkelstein, 1991).

Previous work attempting to link precipitation and circulation patterns has generally addressed the connection between rainfall totals for fixed time intervals, such as a month, over local areas and the features of overlying geopotential heights for long-range weather forecasts (e.g. Namias, 1978; Weare and Hoeschele, 1983; Cayan and Roads, 1984; Klein and Bloom, 1987). These studies have shown that 700 hPa heights directly overhead correlate well with monthly rainfall amount. Other research has examined the daily synoptic patterns associated with individual rainfall events, usually as case studies of extreme events (e.g. Winkler, 1988). Further, Hayden (1981) indicated that cyclonic frequency also can be related to shifts in the North American longwave pattern.

However, there has been relatively little research on the creation of a climatology that links individual event characteristics to quasi-stationary circulation features, such as continental-scale wave pattern structures, semi-permanent surface pressure cell locations, or orientation of the overlying flow. Leathers (1988) and Leathers *et al.*, (1991) have shown that monthly totals of rainfall have significant relationship with the Pacific/North America (PNA) pattern in some seasons, especially in the south-eastern USA. The goal of this paper is to use the PNA pattern as an example of large-scale flow in order to determine whether this relationship extends to individual events and to other characteristics of storms in south-eastern USA.

Here the south-eastern USA includes the states of Virginia, North Carolina, Tennessee, South Carolina, Georgia, Alabama, and northern Florida (Figure 1). Southern Florida has been omitted because it was determined that the climatological influences on that area differed considerably from the remainder of the study area (Robinson and Henderson, 1992).

DATA

A rainfall event has been defined as a continuous period of recorded rainfall at a station, separated from other periods by at least a 2-h dry interval (Robinson and Henderson, 1992). A 2-h interval was chosen in order to maximize separation of events and to allow for small breaks in a continuous event.

Precipitation event data for the years 1950–1986 were extracted from the hourly precipitation record obtained from the National Climate Data Center (Hatch, 1983). The use of hourly data allowed information to be obtained on individual events rather than on daily records of rain-days. Thirty stations across the south-eastern USA were chosen from the hourly recording locations for analysis (Figure 1). These particular stations were chosen so as to maximize the spatial coverage of the South-east region while at the same time maintaining a consistent record with little missing data. All months with no recorded precipitation were necessarily treated as missing because completely dry months could not be distinguished from months with periods of missing data in the original hourly record. Such cases were rare. However, the subsequent results may slightly overestimate the total number of events at some stations because months with no rainfall were eliminated. Three event attributes were recorded for every event during the 37 years: the amount of precipitation produced by the event in tenths of inches; the duration of the event in hours; and the length of the dry period that preceded the event in hours.

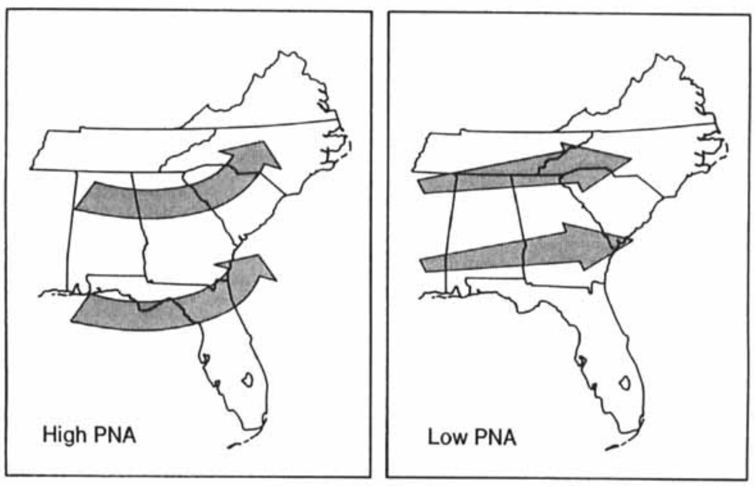
The Pacific/North America (PNA) teleconnection pattern has been used frequently to characterize circulation across the USA (e.g. Barnston and Livezey, 1987; Leathers *et al.*, 1991). This index is derived from the teleconnection patterns of Wallace and Gutzler (1981) and can be used to indicate the zonal or meridional characteristics of flow across the continent (Figure 2). The PNA index uses standardized monthly 700 hPa heights (z) at three points: the Gulf of Alaska (47·9°N, 170·0°W), western Canada (49·0°N, 111·0°W), and the south-eastern USA (29·7°N, 86·3° W) and combines the values using the formula:

$$\text{PNA index} = 1/3\ [-z(47{\cdot}9°\text{N}, 170{\cdot}0°\text{W}) + z(49{\cdot}0°\text{N}, 111{\cdot}0°\text{ W}) - z(29{\cdot}7°\text{N}, 86{\cdot}3°\text{W}).]$$

An index is produced in which large positive values indicate meridional flow (with a strong Aleutian Low, western USA ridge, and eastern USA trough), whereas large negative values are indicative of strong zonal flow (with a weak trough, ridge, trough) or even a ridge, trough, ridge during periods with extremely negative index values (Yarnal and Leathers, 1988).

In this paper the PNA pattern will be used as a convenient index to separate flow regimes across North America in order to test the relationship between large-scale flow and rainfall events. A number of similar teleconnection indices could also have been used to characterize large-scale flow over the continent. One, the North Atlantic Oscillation, was specifically tested but showed no significant relationship to rainfall events in the region (Henderson, 1991). Furthermore, the PNA index has been shown to be closely related to precipitation totals in the region and should be closely linked to rainfall events because one of its centers of action is located in the south-eastern USA (Leathers *et al.*, 1991).

The event and circulation data had to be combined at the same temporal scale. Although the PNA index can be constructed for any time-scale, monthly values are generally the most descriptive of atmospheric



Firure 2. Schematic of flow over the south-eastern USA during opposing phases of the PNA index

structure. However, while a monthly time series would maximize temporal resolution, individual months may not experience a large enough number of rainfall events to maintain statistical validity. Consequently, both sets of data were used at the seasonal level in order to provide enough events to allow statistical tests to be run. Standard 3-month seasons were used (e.g. winter included the months of December, January, and February). Seasonal values of the PNA circulation index were obtained by determining the unweighted average of the three months involved. The use of a seasonal PNA index introduces a potential problem with circulation variability. A season with a strong positive index may be composed only of 2 months of meridional flow and 1 month of strong zonal flow. Therefore, relationships between seasonal circulation and rainfall events are likely to be weaker than those found over monthly or weekly time intervals. Relationships that are significant at this temporal scale though represent the most robust connections between large-scale circulation and rainfall events.

Seasonal event attribute data were not normally distributed, preventing the use of the mean as a measure of the central tendency. Additionally, event data such as amounts and durations were heavily skewed toward the lower values so that the seasonal medians were often in the lowest categories and did not allow discrimination between seasons. Therefore, the third quartile of each event attribute was used to represent the events for each season. If one month within any season was missing in the original hourly precipitation record, that entire season was treated as missing in order to avoid possible skewing of the event distributions within those seasons.

METHODOLOGY

Two basic analysis techniques were used for determining the relationship between rainfall event attributes and the PNA index. First, time series correlations between event attributes and the PNA index were calculated at individual stations, and secondly, percentage differences between years of high and low PNA values were composited. Seasonal time series of the third quartile of event attributes were created for each station. These time series were then correlated with the time series of the PNA index. Since the data were not normally distributed, Spearman's rank order correlation was used. Correlations were calculated for each time series at individual stations. In order to produce spatial patterns, results were interpolated and mapped to show which regions were significantly related to circulation changes at the continental-scale. The patterns of correlations show the spatial nature of the relationship of circulation and events at this scale and suggest climatological reasons for the association.

The second approach was designed to discern what types of storms are most affected by changes in large-scale circulation. The 10 years with the most extreme positive values and the 10 years with the most extreme negative values of the PNA index were extracted from the record for each season (Table I). Ten years were chosen so as to provide a sufficiently large number of events within each composite, while at the same time

Table I. Years used to composite the 10 most zonal and meridional seasons

Winter		Spring		Summer		Autumn	
Zonal	Meridional	Zonal	Meridional	Zonal	Meridional	Zonal	Meridional
1950	1958	1953	1958	1950	1958	1951	1952
1952	1961	1954	1969	1951	1961	1955	1957
1956	1963	1955	1971	1952	1965	1958	1962
1957	1964	1962	1973	1953	1966	1961	1963
1965	1970	1963	1978	1954	1967	1970	1967
1969	1977	1964	1979	1955	1968	1973	1969
1971	1978	1967	1980	1959	1970	1978	1974
1972	1981	1975	1981	1962	1973	1984	1976
1979	1983	1977	1983	1979	1974	1985	1979
1982	1986	1982	1984	1980	1982	1986	1980

maintaining a significant difference in circulation between the two time periods. Years with index values between the two extremes were not examined. It was assumed that these years would show a combination of patterns found within both of the extreme composites. Seasonal averages of the PNA index were used rather than individual monthly values in order to maintain consistancy with the correlation results. Variability within each composite may result in individual years or months that differ considerably from the mean composite. Thus, it should be noted that the composite patterns represent only a sample of the total population of zonal or meridional years. Changes in the percentage of events falling into significant size categories between regimes of opposite index values were mapped. Differences were calculated by subtracting the percentage of events that fell in a category during meridional years from the percentage in zonal years. The spatial pattern of changes should validate the pattern of correlations found above and characterize the relationship between circulation and events by defining the sizes of storms that are most affected by shifts in flow patterns.

RESULTS

Correlations of the seasonal time series of the PNA index with the number of events varied between 0·59 and −0·61, with absolute values greater than 0·32 significant at the 0·05 level (Table II). Correlations were considerably higher than those for the other rainfall event characteristics, indicating that relationships between circulation and event frequency are likely to be stronger than relationships between circulation and event size. Correlations with event amounts varied between 0·52 and −0·51, and correlations with event duration ranged between 0·53 and −0·36. The relatively low values of the correlation coefficients were expected, because earlier studies of the relationship between PNA and total monthly rainfall explained, at best, only 0·60 of the variability in the south-eastern USA (Leathers *et al.*, 1991). Smaller correlations are expected between circulation patterns and individual events because a breakdown in the seasonal flow of only a few days in length can result in uncharacteristic events for that season. Nevertheless, in some areas and in some seasons significant, spatially coherent relationships do exist. Geographical patterns of these correlations are examined in more detail, by season, below.

Winter relationships

Throughout most of the South-east region, the number of rainfall events is strongly associated with the zonal/meridional characteristics of flow. In winter, stations in the majority of the region are negatively

Table II. Correlation results in precipitation event attributes and PNA index by season

Season	Attribute	Maximum r^2	Number of stations $>0{\cdot}32$[a]	Number of stations $<-0{\cdot}32$[a]	Minimum r^2
Winter	Number of Events	0·35	2	14	−0·61
	Event amount	0·40	5	2	−0·51
	Event duration	0·53	3	0	−0·29
Spring	Number of events	0·59	5	0	−0·08
	Event amount	0·44	4	0	−0·24
	Event duration	0·52	9	2	−0·36
Summer	Number of events	0·59	13	0	−0·09
	Event amount	0·39	2	0	−0·31
	Event duration	0·46	2	0	−0·23
Autumn	Number of events	0·43	2	1	−0·42
	Event amount	0·52	2	1	−0·35
	Event duration	0·48	7	0	−0·13

[a] Correlations $>0{\cdot}32$ and $<-0{\cdot}32$ are significant at the 0·05 level.

correlated, indicating that meridional years are associated with fewer events, and zonal winters with more frequent events (Figure 3(a)). Only in southern Georgia and Florida does the relationship reverse, indicating more frequent events in meridional winters. While these results are indicative of relationships across the South-east region they can be considered significant only at the stations used in the study. Testing the field significance of isolated, pseudo-random climate variables, such as precipitation events, deserves future study (Livezey and Chen, 1983).

Difference patterns of event frequency between flow regimes are similar to the correlation patterns. At certain stations, especially in the northern and western portions of the study area, as many as 10 more events occur in zonal winters than in meridional ones (Figure 3(b)). Considering that the total number of events in this area in winter is roughly 35 (Robinson and Henderson, 1992), this difference represents a change of 30–40 per cent in the total number of events. In Florida the opposite is true; meridional winters produce a larger number of events. Larger differences, exceeding six events per season, are noted in the southern portions of the part of the state studied here.

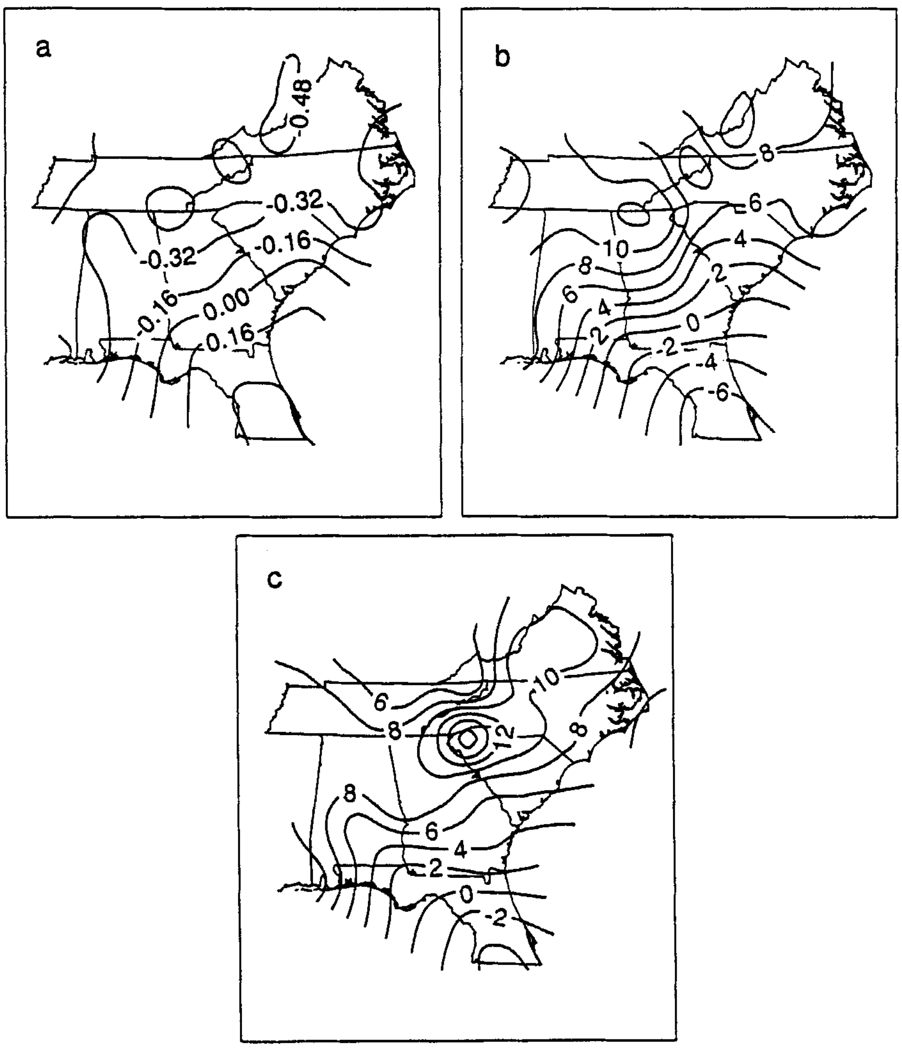


Figure 3. Winter relationships with the number of events. (a) Correlations with PNA. (b) Differences in number of events in zonal years minus meridional years. (c) Differences in percentage of events separated by less than 48 h

The majority of events (roughly 60 per cent) are separated by a dry period of less than 48 h, indicating that many events are associated with a single synoptic-scale system. However, this percentage of tightly clustered events changes considerably with shifts in the circulation regime. In zonal winters the same areas that experience a greater number of events also receive a higher proportion of clustered events, those separated by less than 48 h (Figure 3(c)). This similarity indicates that the increase in event frequency may not be a result of separate storm passages but instead, of larger storm system complexes that produce more than one event over the course of a day or two.

Relationships between the PNA index and event amounts and durations are not as strong. Few stations show correlations above the significance level. Nevertheless, the spatial distribution of correlations are interesting because they follow similar patterns. For both amounts and durations a dipolar pattern of correlations exists, with a zero line extending down the spine of the Appalachians and across northern Georgia and Alabama (Figures 4(a) and 5(a)). Larger storms accompany zonal flow to the north and west and meridional flow to the south and east. Though these correlation patterns are not statistically significant at most stations, the differences in the percentage of events that produce less than 0·5 in. of precipitation (roughly 78 per cent of the total number of events in winter) match the correlations almost perfectly, suggesting a link between circulation and event size in this season (Figure 4(b)). On the windward side of the Appalachian Mountains, events are smaller in meridional winters, with the percentage of events producing less than 0·5 in. increasing by as much as 8 per cent. Events lasting less than 3 h also increase as much as 10 per cent in meridional winters (Figure 5(b)).

Therefore, it may be concluded that during zonal circulation regimes a larger number of long storms (as many as 10), probably frontal in nature, are passing through the Mississippi and Ohio Valleys west of the Appalachians than during meridional time periods (Figure 6). This combination of larger, longer, and more frequent events accounts for the strong associations that Leathers *et al.* (1991) found for total precipitation in this area. In meridional years the strong trough of cold, dry air appears to discourage event formation in this region.

East of the Appalachians, in South Carolina, North Carolina, and Virginia, events are also more frequent in zonal winters. However, these events are smaller and somewhat shorter than storms in meridional years, especially in the coastal areas (Figure 6). Along the Coastal Plain of the Carolinas and on the Gulf Coast, a rise in the percentage of 0 to 0·5 in. events was noted during zonal winters (Figure 4(b)). As a result, no strong

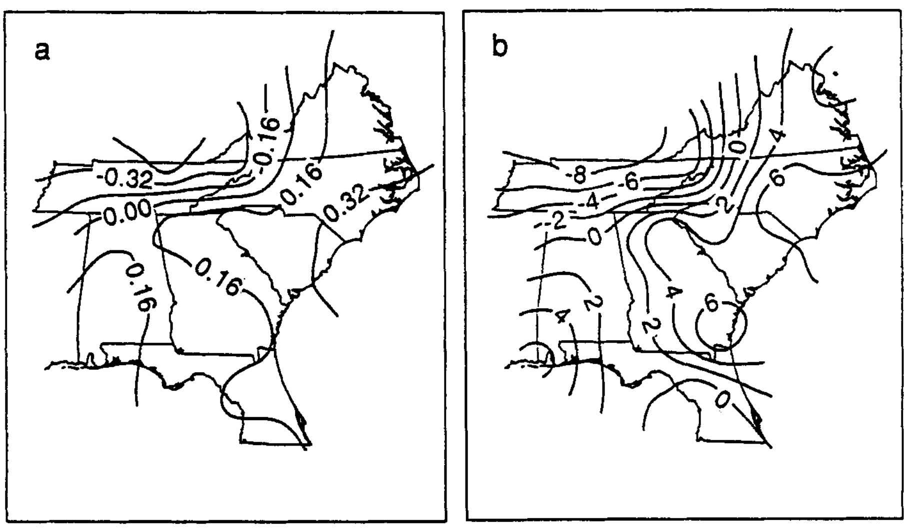


Figure 4. Winter relationships with event amounts. (a) Correlations with PNA. (b) Differences in percentage of events of less than 0·5 in. in zonal years minus meridional years

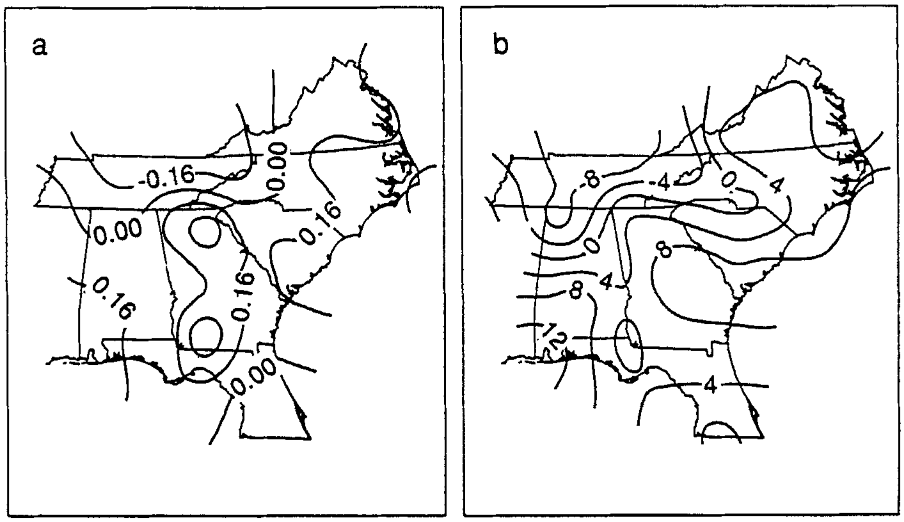


Figure 5. Winter relationships with event durations. (a) Correlations with PNA. (b) Differences in percentage of events of less than 3 h in zonal years minus meridional years

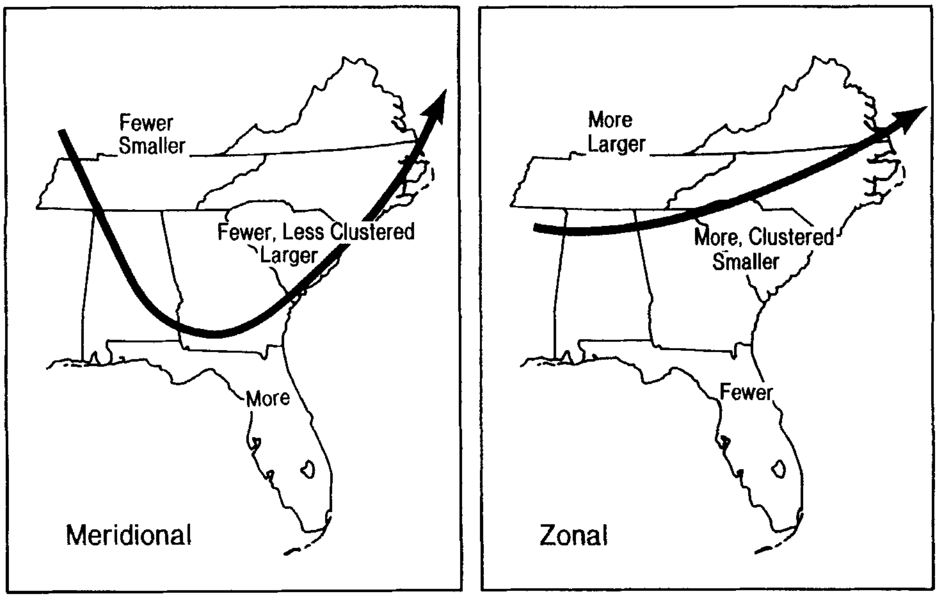


Figure 6. Summary of winter event changes associated with circulation changes. Arrows represent generalized continental flow

relationship is expected between circulation and total rainfall because an increase in the number of events in zonal years is offset by the smaller size of those storms. Nevertheless, important changes in rainfall event attributes do occur in these areas. With a shift toward meridional circulation, the alignment of the frontal storm track may move out into a more north-south oriented position over the Atlantic coast. In this position a 100 mile difference east or west can determine whether or not a station along the coast will receive rainfall as the storm travels past. This alignment of the storm track may explain the decrease in the number of events in the eastern areas in meridional winters. Those events that do occur, though, may typically be large, coastal storms forming in the baroclinic zone off the Outer Banks of North Carolina. These events would account for the high frequency of heavy rainfall events in the north-eastern portions of the study area.

In the extreme southern portions of the South-east, in Georgia and Florida, cyclone activity is at a minimum in the winter months. Only when outbreaks of cold air to the north push the frontal storm track far enough to the south could the number of events increase. This shift occurs more frequently in meridional winters (Lau, 1988). The present results show that events are more frequent in meridional years (Figure 6).

In general, the location of the cyclonic storm track appears to determine rainfall event attributes in the winter months. Judging from the results of this study, the position of the storm track appears, in turn, to be highly influenced by the strength and phase of the PNA pattern. As the circulation regime changes, the characteristics of rainfall events in the south-eastern USA vary significantly. Event amounts in meridional years increase south and east of the Appalachians and decrease in the west. This change in event size is superimposed on a substantial decrease in the number of events in meridional years everywhere except the extreme south. Both of these changes have significant effects on the variability of precipitation in the South-east and may be explained in future synoptic research through the connection between circulation and frontal storm track locations in the region in this season.

Spring relationships

In the remaining three seasons, generally weaker results were found (Table II). Spatial patterns may be dominated by results at individual stations, when large areas with low significance occur. While a detailed analysis has been performed on each season, only the strongest relationships are reported here.

As the polar vortex begins to shrink and the band of frontal storms moves northward in spring, the relationship between the PNA pattern and the number of events begins to reverse. Correlation patterns of circulation and the number of events display positive correlations across the region, indicative of greater event frequency in meridional years (Figure 7(a)). This relationship is particularly strong along the Gulf Coast of Florida and inland into south-eastern Alabama. In western Florida and in northern Tennessee the differences between zonal and meridional years range between six and ten storms, while throughout the rest of the region the differences are between two and four each spring (Figure 7(b)).

This result is climatologically plausible if one considers that within meridional seasons a large trough in the Rossby waves may maintain the frontal storm track southward in the region later in the spring. With cyclones

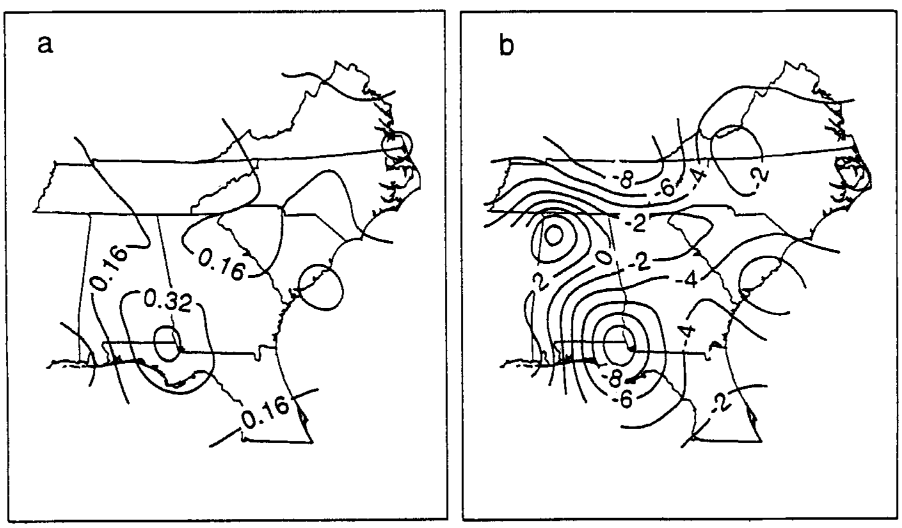


Figure 7. Spring relationships with the number of events. (a) Correlations with PNA. (b) Differences in number of events in zonal years minus meridional years

passing through the area later than is normally the case, an increase in the number of events would be expected.

Much smaller significant regions were found in the correlations with event amounts and durations, During meridional regimes events with longer durations are experienced along the coastal margins (Figure 8(a)). This result indicates that in these years more cyclones may pass over the entire South-east, but the dominant storm track tends to move out over the Coastal Plain of the Carolinas, maintaining its winter position and bringing longer and somewhat larger events to those regions. Zonal springs are associated with more frequent 1–3 h events along the Gulf Coast and in South Carolina, although the differences are smaller there, and these short storms are less frequent throughout Tennessee and northern Alabama (Figure 8(b)).

Overall, spring patterns are more complicated than winter patterns, as the climatology of the region shifts from one dominated by frontal cyclone passages to a convective regime. In zonal years events are less frequent but still bring longer storms to the north-west (Figure 9). With meridional flow the number of events increases across the South-east; the Coastal Plain and Gulf Coast experience slightly longer events because the circulation regime may allow the frontal storm track to influence the area longer.

Summer relationships

During the summer months the climatology of the south-eastern USA is dominated by the influence of the subtropical high-pressure region pumping warm, moist air into the entire region and suppressing activity through subsidence (Easterling, 1991). The frontal influence weakens considerably, resulting in summer precipitation generated almost exclusively from single-air-mass thunderstorms. The number of rainfall events experienced in the South-east during the summer is the largest of the year, but these events are, on average, much smaller in the amount of rainfall they produce and shorter in duration than storms in the other seasons (Robinson and Henderson, 1992). Summer events are influenced much more by small-scale flow patterns that are not resolved in the continental-scale analysis. This change in circulation is reflected by the fact that the PNA pattern is not a dominant mode of variability over the continent in summer (Barnston and Livezey, 1987). Nevertheless, there are some general relationships between the number of events and the PNA index that can still be identified. This connection is probably related to the fact that the index includes a centre of action in the South-east and may be influenced by the strength and/or position of the Subtropical High.

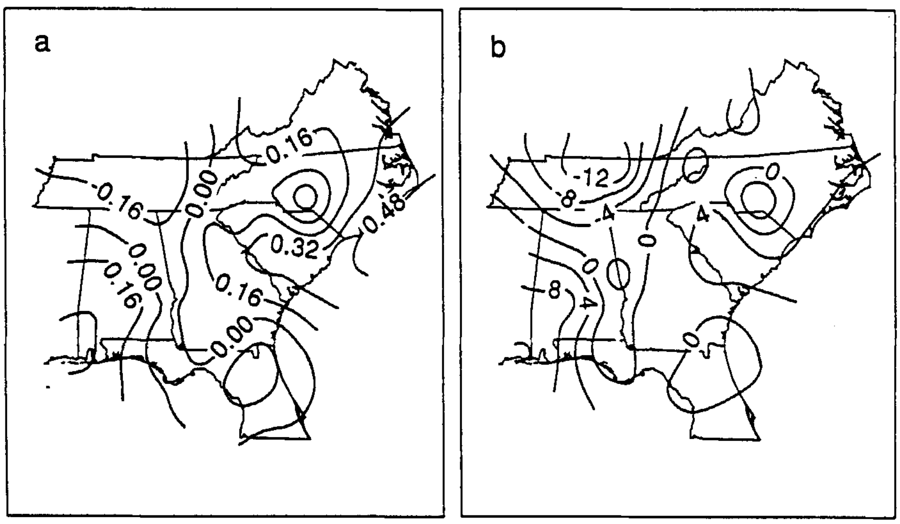


Figure 8. Spring relationships with event durations. (a) Correlations with PNA. (b) Differrences in percentage of events of less than 3 h in zonal years minus meridional years

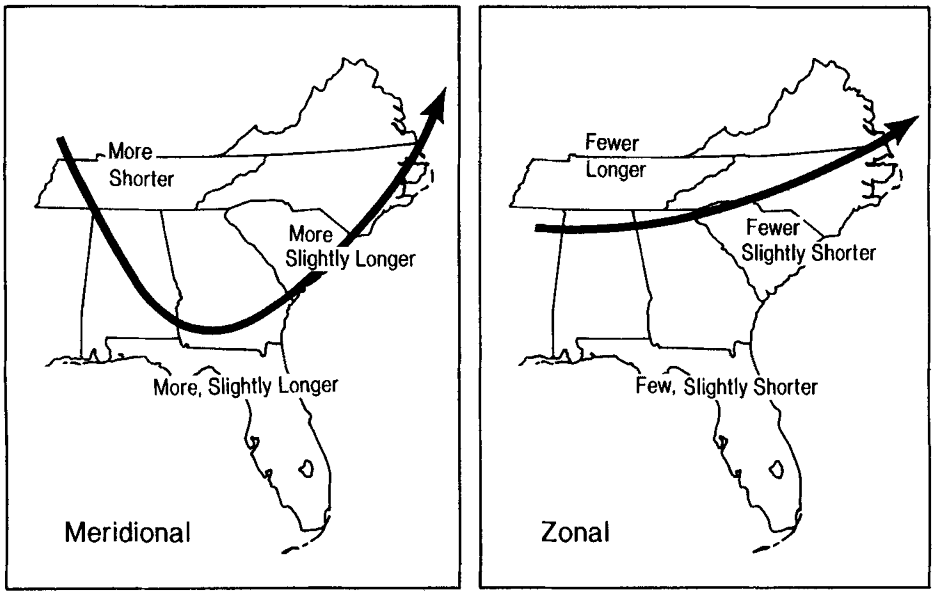


Figure 9. Summary of spring event changes associated with circulation changes. Arrows represent generalized continental flow

Therefore, the index may still be used as a convenient way of separating large-scale flow patterns, although it is no longer identifying coherent zonal and meridional flow across the continent.

A large area of strong positive correlations between the PNA and the number of events extends throughout the South-east (Figure 10(a)). Correlations are especially strong along the coasts and into South Carolina and Georgia. More frequent events accompany meridional years in the South-east in the summer (Figure 10(b)). Differences are large throughout the region, exceeding six events along the coast of North Carolina, most of South Carolina and Georgia, as well as southern Alabama.

In summer, meridional years are associated with a higher percentage of clustered events over most of the region south and east of the mountains (Figure 10(c)). Behind the Appalachians there is still a slight tendency for clustered events to occur in zonal summers. For most of the area though, especially along the southern Piedmont, percentages of clustered events increase by 4 to 6 per cent in meridional years as event frequency also increases.

These trends indicate that in the south and east, near the marine influence of the Atlantic Ocean and the Gulf of Mexico, thunderstorm complexes tend to form more frequently in meridional summers. This pattern may result from two processes. First, weak frontal boundaries passing across the continent may be pushed far enough south to provide the instability necessary to trigger convective activity. Second, the high value of PNA index is probably not indicative of cohesive meridional flow, but is instead influenced by a strong low pressure anomaly in the South-east. This anomaly weakens the subsidence of the Subtropical High, allowing for more thunderstorm production in the region (Easterling, 1991).

Although the change from zonal to meridional circulation affects the number of storms in the south and east, it appears to have very little influence on the size of those storms. No significant relationship exists with event amounts or durations. The resolution of the circulation analysis is too coarse to distinguish important shifts in flow patterns in the summer, when more localized factors are responsible for the amounts and durations of storms. Additionally, the average size precipitation events in the summer may be too small to be affected significantly by large changes in atmospheric flow.

In general, there is very little relationship between continental-scale circulation and rainfall event size in the summer. Events are influenced by circulation at a smaller scale. In the southern and eastern portions of the study area though, the number of events experienced can be related to large-scale circulation. Periods with a

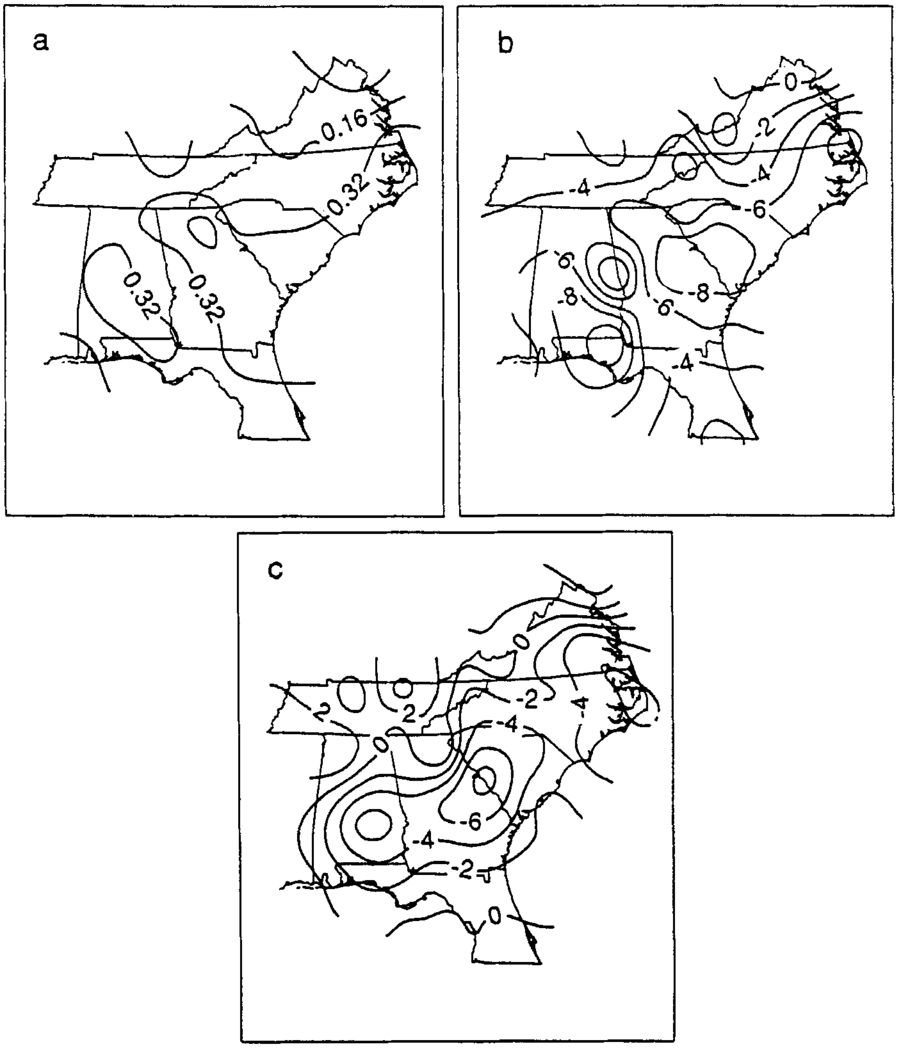


Figure 10. Summary relationships with the number of events. (a) Correlations with PNA. (b) Differences in number of events in zonal years minus meridional years. (c) Differences in percentage of events separated by less than 48 h

positive PNA index appear to signal a weakening of the influence of the Subtropical High, which may allow for more frequent convective activity (Figure 11). In the north and west there is no significant relationship between precipitation events and large-scale circulation.

Autumn relationships

The transitional autumn season marks a change in the climatology of the South-east from convective thunderstorms in September and October to frontal storms in October and November. Event activity in this season is at its lowest for the year. Few areas experience more than 30 events each autumn, and long dry periods dominate the region, especially in the central Piedmont (Robinson and Henderson, 1992). Because the autumn is the least active month, small changes in rainfall event attributes can result in significant differences between flow regimes.

In the south-eastern portions of the study region, event frequency follows the summer correlation pattern (Figure 12(a)). Dominant convective activity is enhanced, and earlier frontal passages may occur in

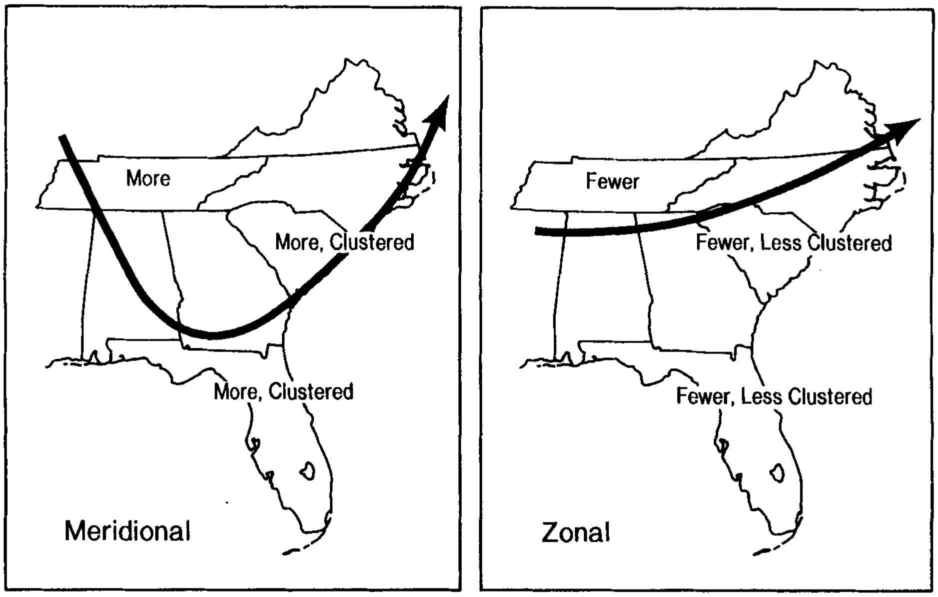


Figure 11. Summary of summer event changes associated with circulation changes. Arrows represent generalized continental flow, which is weak in the summer months

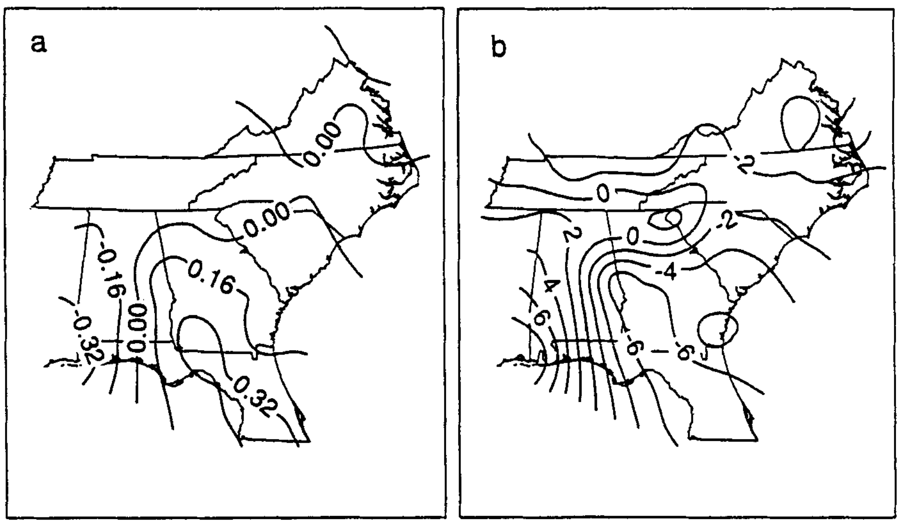


Figure 12. Autumn relationships with the number of events. (a) Correlations with PNA. (b) Differences in number of events in zonal years minus meridional years

meridional years, with four to six more events passing through southern Georgia and most of Florida in these seasons (Figure 12(b)). In this south-eastern portion of the region, the average number of autumn events is only 25, thus an increase of four to six events can represent a significant shift in the hydrological processes. The area of strong relationships, restricted to southern Georgia and Florida, is much smaller than it was during the summer. In the north and west the winter pattern begins to return as a few more events are experienced in zonal autumns in Alabama.

Very strong relationships exist between continental-scale circulation and event size in an area centred on the central Piedmont of South Carolina and Georgia. In this region events are larger and much longer in meridional autumns (Figures 13(a) and 14(a)). The percentage of events smaller than 0·5 in. decreases more than 5 per cent, and those lasting less than 3 h decrease more than 10 per cent in meridional years (Figures 13(b) and 14(b)). This demonstrates a significant shift in the characteristics of events in this region in autumn as circulation regimes change, and may indicate that in meridional years the number of larger frontal events may begin to enter the region south-east of the Appalachians earlier in the year.

As the climatological cycle returns from a convective to a frontal rainfall pattern in the South-east in autumn, the relationships between circulation and rainfall events shift from their summer patterns back

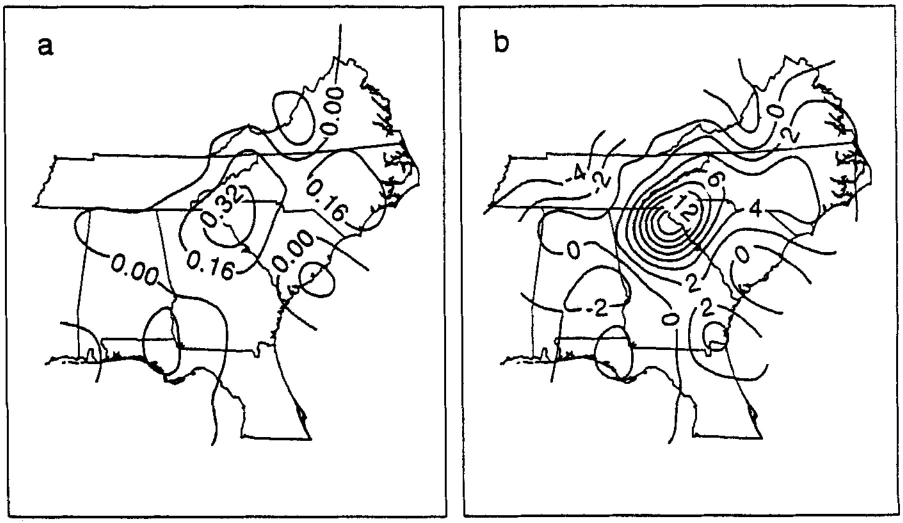


Figure 13. Autumn relationships with event amounts. (a) Correlations with PNA. (b) Differences in percentage of events of less than 0·5 in. in zonal years minus meridional years

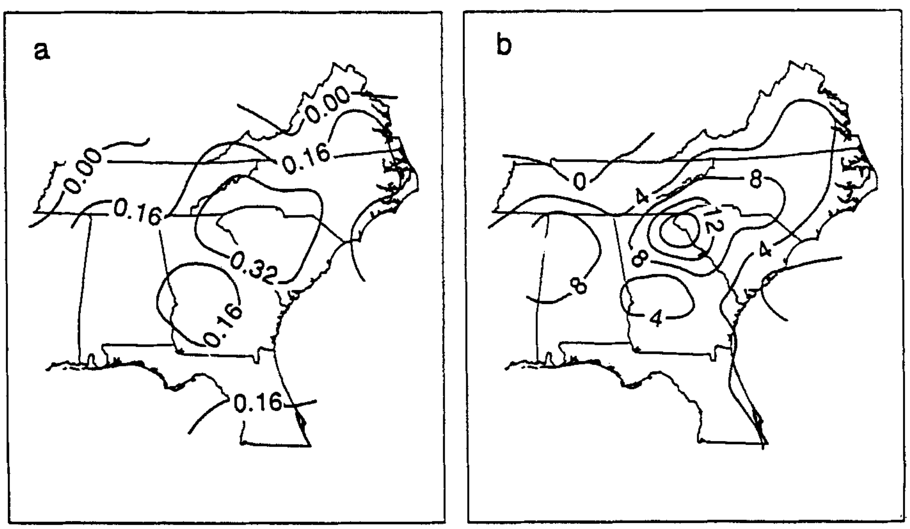


Figure 14. Autumn relationships with event durations. (a) Correlations with PNA. (b) Differences in percentage of events of less than 3 h in zonal years minus meridional years

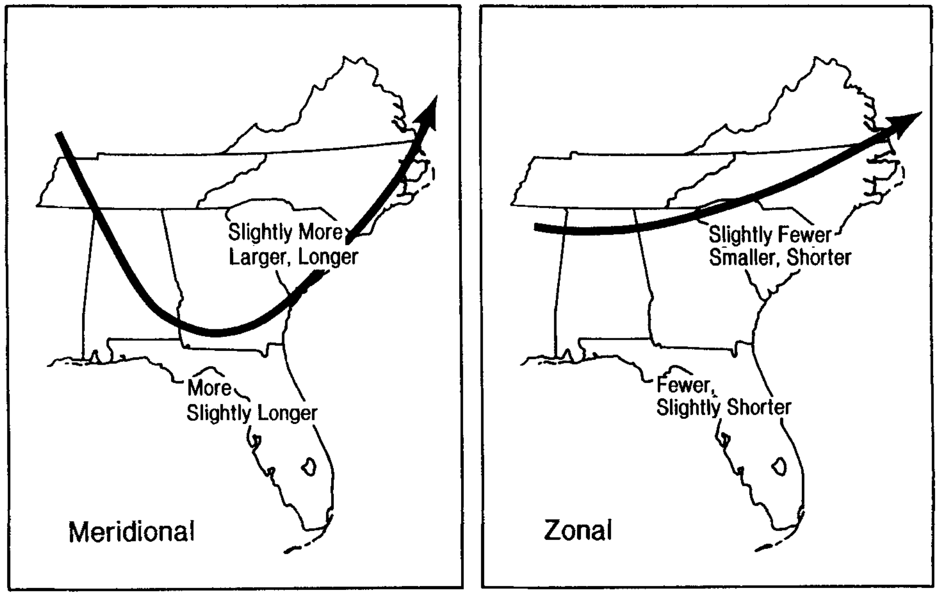


Figure 15. Summary of autumn event changes associated with circulation changes. Arrows represent generalized continental flow

toward the winter relationships. In the extreme south-east, where summer is still present, a greater number of events are produced by enhanced convective activity during meridional years (Figure 15). In the north-west this relationship ceases as the winter pattern of frontal storm tracks regains control. An important transitional zone becomes established between the two areas. In this region, event activity is at its lowest, and those few events that do occur vary considerably in size. The difference between zonal and meridional circulation has a large effect on the size of storms in this area by determining whether larger frontal events pass through during meridional circulation or whether small convective storms continue to provide most precipitation in zonal years. This large zone of strong relationships illustrates how important the relationship between continental-scale circulation and rainfall event attributes can be in certain locations at certain times of the year. Knowledge of the dominant circulation regime in a season can provide important information to water resource planners in the central Piedmont in autumn.

SUMMARY AND CONCLUSIONS

In certain areas of the south-eastern USA and in certain seasons, significant relationships exist between the zonal/meridional characteristics of atmospheric flow as represented by the PNA index and rainfall event attributes. The spatial patterns of these relationships can be attributed to the variability of the climate system, which alters storm tracks and moisture availability. Spatial and temporal patterns of the statistical relationships can be explained by the annual cycle of the climate system, indicating that there are underlying climatological reasons for the existence of these patterns.

Relationships in the South-east are strongest between circulation and the number of events, and are less strong with event amounts and durations. This relationship is probably caused by the ability of large-scale flow to steer frontal storms into an area, or to provide the conditions necessary for convective activity, whereas more localized conditions contribute more toward the amount of precipitation and the duration of a given event. In general, meridional flow is associated with:

(i) less frequent winter events;
(ii) more frequent summer events;

(iii) less temporally clustered events in winter and spring;
(iv) more temporally clustered events in summer and autumn;
(v) larger amounts, longer events east of the Appalachians;
(vi) smaller amounts, shorter events west of the Appalachians.

Results are opposite in seasons characterized by zonal flow regimes.

Relationships between circulation and event amounts and durations are opposite from one side of the Appalachians to the other. This pattern seems to be related to the position of the dominant frontal storm track, as it lies either across the Ohio Valley or along the coast of the Carolinas. In general, this situation creates a relationship between circulation and event attributes that is strongest in Tennessee, along the coasts of North Carolina and South Carolina, and on the Gulf Coast of Florida and Alabama.

Finally, the relationships between continental-scale circulation and rainfall attributes vary with season. Over the course of the seasonal cycle, the strength and nature of the relationships change. Relationships between the PNA index and the number of events are strongest in winter and summer, when either the frontal storm track is dominant in the north-western portions of the region or when convective activity provides virtually all the precipitation in parts of the south-eastern region. At these times the orientation of flow can influence the number of events by steering events through certain areas or by weakening the subsidence associated with the Subtropical High. In the other seasons, the transitional periods of spring and autumn, the number of events and continental-scale circulation are not related as simply.

Relationships with event size are strongest in the non-summer seasons, when a significant portion of the precipitation is produced by frontal storms. The presence or absence of these storms is determined by the orientation of the large-scale flow, which in turn influences the size of events experienced in many locations by determining whether these events pass directly overhead or just affect the periphery of the area. In the winter and spring the relationship is strongest in the north-west and south-east portions of the study area. In autumn, however, the area of strongest relationships shifts inland to a large region of the Piedmont centred on western South Carolina. In summer, when the majority of precipitation is produced by convective activity, no relationship exists. The sizes of events in this season are influenced by circulation patterns that are too small to be resolved in this analysis.

As an exploratory investigation into the spatial patterns of the relationship between continental-scale circulation and rainfall event attributes in the south-eastern USA, these conclusions provide a starting point for future work. Most importantly, more rigid testing must be applied to the explanations of the relationships. Detailed analyses of surface and upper level circulation patterns would provide the synoptic descriptions necessary to explain the temporal and spatial patterns of the significant relationships. This type of synoptic analysis could be used to explain the interesting effect the Appalachians seem to have on the relationship between circulation and rainfall events.

Future work also needs to address the question of circulation scales. Strong relationships with circulation at the continental-scale did not exist everywhere or at all times. Further analysis of circulation at other scales, especially at smaller, more regional levels, is important for understanding the relationships between the climate system and precipitation event characteristics.

This study has shown that significant relationships do exist between continental-scale circulation and rainfall events. It has also described their spatial and seasonal patterns, indicating possible climatological reasons underlying the relationships. In doing so it has provided a means for explaining patterns of rainfall event variability and represents one way of interpreting modelled circulation patterns of future climate impact scenarios.

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REFERENCES

Barnston, A. G. and Livezey, R. E. 1987. 'Classification, seasonality, and persistence of low-frequency atmospheric circulation patterns', *Mon. Wea. Rev.*, **115**, 1083–1126.

Cayan, R. R. and Roads, J. O. 1984. 'Local relationships between United States west coast precipitation and monthly mean circulation parameters', *Mon. Wea. Rev.*, **112**, 1276–1282.

Easterling, D. R. 1991. 'Climatological patterns of thunderstorm activity in south-eastern USA', *Int. J. Climatol.*, **11**, 213–221.

Hatch, W. L. 1983. *Selective Guide to Climatic Data Sources.* Key to meteorological records documentation 4.11, National Climatic Data Center, Asheville, NC.

Hayden, B. P. 1981. 'Secular variation in Atlantic coast extratropical cyclones', *Mon. Wea. Rev.*, **109**, 159–167.

Henderson, K. G. 1991. *Relationships between continental-scale circulation and rainfall event attributes in the Southeastern United States*, PhD dissertation, University of North Carolina.

Henderson-Sellers, A. and Robinson, P. J. 1986. *Contemporary Climatology*, Wiley, New York.

Hoskins, B. J., James, I. N. and White, G. H. 1983. 'The shape, propagation and mean-flow interaction of large-scale weather systems', *J. Atmos. Sci.*, **40**, 1595–1612.

Klein, W. H. and Bloom, H. J. 1987. 'Specification of monthly precipitation over the United States from the surrounding 700 mb height field', *Mon. Wea. Rev.*, **115**, 2118–2132.

Lau, N.-C. 1988. 'Variability of the observed midlatitude storm tracks in relation to low-frequency changes in the circulation pattern', *J. Atmos. Sci.*, **45**, 2718–2743.

Leathers, D. J. 1988. *The Pacific/North American teleconnection index and United States climate*, PhD dissertation, Pennsylvania State University.

Leathers, D. J., Yarnal, B. M. and Palecki, M. A. 1991. 'The Pacific/North American teleconnection pattern and United States climate. Part I: regional temperature and precipitation association', *J. Climate*, **4**, 517–528.

Livezey, R. E. and Chen, W. Y. 1983. 'Statistical field significance and its determination by Monte Carlo techniques', *Mon. Wea. Rev.*, **114**, 2488–2515.

Namias, J. 1978. 'Multiple causes of the North American abnormal winter 1976–77', *Mon. Wea. Rev.*, **106**, 279–295.

Robinson, P. J. and Finkelstein, P. L. 1991. 'The development of impact-oriented climate scenarios', *Bull. Am. Meteorol. Soc.*, **72**, 481–490.

Robinson, P. J. and Henderson, K. G. 1992. 'Precipitation events in the south-east USA', *Int. J. Climatol.*, **12**, 701–720.

Wallace, J. M. and Gutzler, D. S. 1981. 'Teleconnections in the 500 mb geopotential height field during the Northern Hemisphere winter', *Mon. Wea. Rev.*, **109**, 784–812.

Weare, B. C. and Hoeschele, M. A. 1983. 'Specifications of monthly precipitation in the western United States from monthly mean circulation', *J. Clim. Appl. Meteorol.*, **22**, 1000–1007.

Winkler, J. A. 1988. 'Climatological characteristics of summertime extreme rainstorms in Minnesota', *Ann. Assoc. Am. Geogr.*, **78**, 57–73.

Yarnal, B. and Leathers, D. J. 1988. 'Relationships between interdecadal and interannual climatic variations and their effect on Pennsylvania climate', *Ann. Assoc. Am. Geogr.*, **78**, 624–641.