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Influences of the Bermuda High and atmospheric moistening on changes in summer rainfall in the Atlanta, Georgia region, USA

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ABSTRACT: This paper assesses the variability and trends in summer-season rainfall from 1948 to 2009 for the Atlanta, Georgia region. The rainfall variables are total rainfall, frequency of rainfall days, and frequency of heavy-rainfall days. The main methods involve classifying daily 500-hPa geopotential height fields into synoptic types, determining the rainfall characteristics of the synoptic types, testing for significant temporal trends in rainfall, middle-troposphere circulation, lower-troposphere circulation, and atmospheric humidity, and using multiple linear regression to determine the impact of circulation and humidity variables on inter-annual variations in the rainfall variables. There were a total of eight synoptic types: the wet types involved troughing across or to the immediate west of the Atlanta region, while the dry types involved either an anticyclone across or to the immediate west of the region. The rainfall variables and two lower-troposphere circulation indices, the Bermuda High Index (BHI) and the Western Bermuda High Index (WBHI), had significant positive trends in variance over time. Among the three rainfall variables, only the frequency of rainfall days had a significant trend: the periods 1976–2009 and 1977–2009 had significant positive trends in rainfall days. The BHI had a significant positive trend from the 1970s to 2009, and the western ridge of the Bermuda High moved significantly southeastward from approximately the mid-1970s to 2009. Atmospheric humidity (i.e. 850-hPa specific humidity, 500-hPa specific humidity, and precipitable water) over the region had significant positive trends during most periods, with all humidity variables having significant increases from the 1970s to 2009. Increased interannual variability in the WBHI appears to be the cause of the increased variance in rainfall variables. An increase in atmospheric humidity, which is actually a global phenomenon, appears to be the principal cause of the increase in rainfall days during the past three decades. Copyright © 2012 Royal Meteorological Society

KEY WORDS precipitation; rainfall; synoptic; southeastern United States; summer; circulation; Bermuda High; atmospheric moistening

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1. Introduction

Summer season rainfall in the southeastern United States is vitally important to the region. Nearly the entire region has a humid subtropical climate type, which is characterized by the usual absence of summer droughts (Trewartha and Horn, 1980). The presence of this climate type might lead one to believe that there is adequate water available during summer months; however, the interior portion of the southeast has a water deficit during July and August (e.g. Willmott *et al*., 1985). Water deficits in summer are intensified by municipal water use and agricultural consumption, and one of the impacts has been reduced fresh water quantity and quality for estuarine ecosystems (Feldman, 2008). Summer water deficits further heighten the water dispute between Georgia, Florida, and Alabama over the Apalachicola-Chattahoochee-Flint River (ACF) Basin: ACF water is needed for municipal use, mostly in Atlanta, hydropower generation downstream of Atlanta, agriculture, and to maintain a natural flow regime that is essential for the riverine and estuarine ecosystems (i.e. Apalachicola Bay) (Ruhle, 2005).

Dry and wet summers in the southeast are strongly linked to the synoptic-scale atmospheric circulation. Dry summers in the southeast have been associated with the following: (1) Decreased middle-troposphere troughing over the region (Diem, 2006), (2) A northward shift of the upper-level jet (Wang *et al*., 2010), (3) Weak westerly/northwesterly lower-troposphere flow over the region (Diem, 2006), (4) Negative values of the Bermuda High Index (BHI) (Henderson and Vega, 1996; Doublin and Grundstein, 2008), (5) Surface anticyclonic circulation over the region (Wang *et al*., 2010), and (6) A northward displacement of the western ridge of the North Atlantic Subtropical High (NASH) (i.e. Bermuda High) (Li *et al*., 2011). Wet summers in the southeast have been associated with the following: (1) Increased middle-troposphere troughing over the region (Diem, 2006), (2) Strong southerly/southwesterly flow in the lower troposphere flow over the region (Diem, 2006; Seager *et al*., 2009),

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(3) Positive values of the BHI (Henderson and Vega, 1996; Doublin and Grundstein, 2008); (4) Strengthened surface westerlies in the Western Hemisphere (Booth *et al*., 2006), and (5) A southward displacement of the western ridge of the NASH (i.e. Bermuda High) (Li *et al*., 2011). In addition, heavy-rainfall events during the warm season in the southeastern United States have been linked strongly to troughing events and associated surface fronts (Easterling, 1991; Keim, 1996; Gamble and Meentemeyer, 1997; Konrad, 1997; Diem, 2006).

The southeastern United States has much inter-annual variability in summer rainfall, and the inter-annual variability differed greatly between the middle and late 20th century. The largest variance in summer rainfall within the contiguous United States for the 1948–2007 period occurred in the southeastern and central United States; the variance and mean seasonal rainfall totals in the southeast were approximately 80 and 330 mm, respectively (given in Figure 1 in Wang *et al*., 2010). The inter-annual variability of summer precipitation in the southeastern United States was larger during 1978–2007 compared to 1948–1977, as reflected in the occurrence of more wet and dry summers during the latter period compared to the earlier period (Wang *et al*., 2010). Explanations for the increase in variability include higher Atlantic SST variability (Wang *et al*., 2010) and a westward movement of the western ridge of the Bermuda High coupled with increased latitudinal movement of the ridge (Li *et al*., 2011).

There exists little to no information on trends in summer rainfall in the southeastern United States over the past several decades. Precipitation information related most closely to actual trend values for summer rainfall in the southeast is presented in Diem and Mote (2005), where it is shown that stations in the interior portion of the southeast either had no change or were more likely to have a significant decrease in rainfall totals or number of heavy-rainfall days (i.e. days with $\geq$25.4 mm of precipitation) or both from 1953–1977 to 1978–2002. Groisman and Knight (2008) report a significant positive trend for multiple multi-decade periods, ranging from 27 to 43 years, ending in 2006 in the percentage of dry-day episodes for the eastern United States with one month or longer a duration during the warm season; there were no results specific to the southeast and the warm season encompassed the summer. It is worth noting that there were no significant decreases in the number of dry days (i.e. days when daily precipitation was below 1 mm) (Groisman and Knight, 2008).

The research presented in this paper is intended to improve the understanding of the causes of inter-annual variability in rainfall in the southeastern United States from 1948 to 2009, and to uncover trends in rainfall and provide explanations for significant trends. The major objectives of the research are as follows: (1) To determine the rainfall characteristics of circulation patterns, (2) To examine the multi-decadal variability of rainfall, circulation, and humidity variables, (3) To determine the circulation- and humidity-based causes of inter-annual variations in rainfall, and (4) To assess trends in rainfall, circulation, and humidity. This research focuses on the Atlanta, Georgia region. Data from the Atlanta region are optimal for an examination of summer rainfall in the southeast, especially the interior southeast, because Atlanta is near the geographical centre of the southeast, as defined by Wang *et al*. (2010) (Figure 1), and the southeast drought region identified in Ortegren *et al*. (2011).

2. Data and methods

2.1. Synoptic typing

A manual classification of 500-hPa circulation patterns was used to determine the synoptic types over the Atlanta metropolitan statistical area (MSA) during the summer

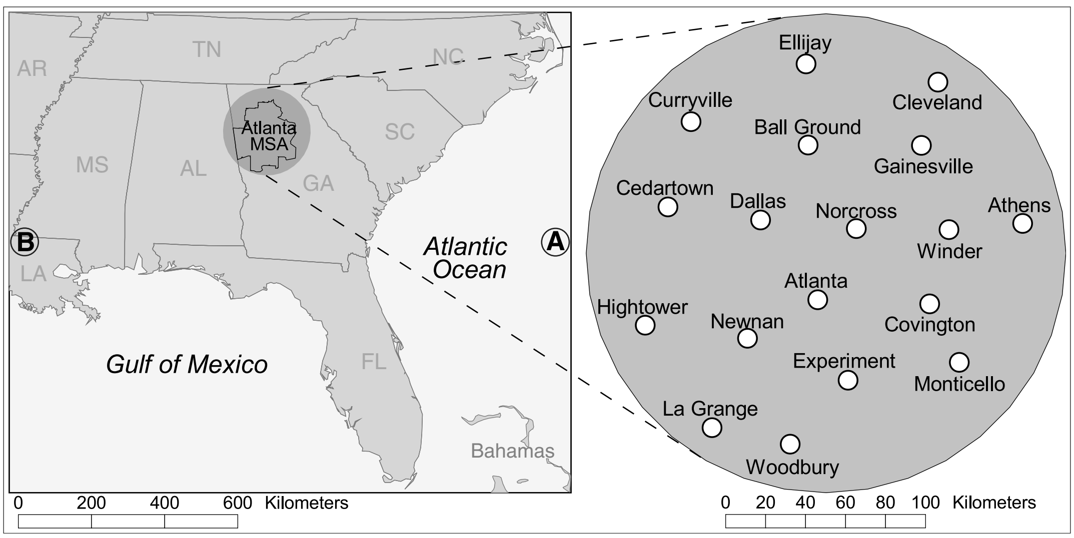

Figure 1. Location of the study region within the southeastern United States and locations of the 18 precipitation stations within the study region. Also shown are the two locations, A and B, where 850-hPa geopotential heights were obtained for the development of the Western Bermuda High Index. The land in the southeastern United States shown in this figure is the domain used by Wang *et al*. (2010).

season (i.e. June–August) from 1948 to 2009. The manual typing described in Diem *et al*. (2010) for the period 1978–2007 formed the basis of the typing used for this study. A manual, rather than an automated classification, was performed because it facilitates greater insight into climatic subtleties that might otherwise be missed using an automated procedure (Yarnal *et al*., 2001). The 500-hPa level was chosen over surface patterns for two reasons: (1) The 500-hPa patterns, as opposed to lower-troposphere patterns, are smoother and, thus, much easier to place confidently into the appropriate categories using a manual approach, and (2) 500-hPa patterns are linked to patterns in the lower troposphere and at the surface (Diem *et al*., 2010). Gridded 500-hPa geopotential-height data were extracted from the NCEP/NCAR Reanalysis dataset (Kalnay *et al*., 1996) of the Earth System Research Laboratory (ESRL) of the National Oceanic and Atmospheric Administration (NOAA). The globally gridded data had a spatial resolution of 2.5° and a temporal resolution of one day. The geographic scale for the typing, which initially was based on a cylindrical equidistant projection, ranged from 22.3 °N to 45.0 °N latitude, and from 70.8 °W to 98.1 °W longitude. The 500-hPa geopotential heights over the domain were contoured at 20-m intervals to produce daily circulation maps. The manual typing described in Diem *et al*. (2010) for the period 1978–2007 formed the basis of the typing used for this study.

The temporal sequencing of circulation patterns, which was used to assess the overall validity of the synoptic typing, was determined by analysing transitions in synoptic types. The probability of synoptic-type occurrence on the day following a given synoptic type was calculated for every combination of synoptic types. Since this procedure yielded within-type transition probabilities, it produced useful information for assessing the persistence of synoptic types.

2.2. Precipitation data

Precipitation data for the Atlanta region consisted of daily precipitation totals for summer (i.e. June–August) seasons from 1948 to 2009 for 18 National Weather Service cooperative stations within and proximate to the Atlanta MSA (Figure 1). The chosen network of stations was selected because it was relatively dense for a climatological study (i.e. it has a sampling interval of ∼50 km), and the employment of multiple stations minimizes the effects of inhomogeneities at one or more of the stations (Easterling and Peterson, 1995). Data were extracted from the TD3200 and TD3210 databases of the National Climatic Data Center (NCDC). The entire dataset was missing 4.2% of the daily precipitation totals (Table I). Although Experiment, La Grange, and Winder had relatively high percentages of days with missing values, the inclusion of these stations produced a dispersed network of stations with negligible spatial gaps in coverage. Using hour-of-observation data obtained from monthly climatological data publications provided by the NCDC for all applicable years, daily precipitation totals were associated with the day on which most of the precipitation most likely occurred. Missing values were replaced with precipitation estimates based on an inverse-distance weighting (IDW) scheme involving data from nearby stations. Xia *et al*. (1999) report IDW to be just as accurate as other missing-value-estimation-methods schemes. Automated Surface Observing Stations (ASOS) instrumentation, which includes tipping-bucket raingages, was implemented at Athens in 1994 and Atlanta in 1995; therefore, ASOS-measured precipitation values were multiplied by 1.12 to adjust for the reduced precipitation totals associated with the raingages (read Diem and Mote (2005) for an explanation).

Heavy-rainfall values were determined from the frequency distribution of rainfall totals on rainfall days (i.e. days with $\geq$0.254 mm of rainfall) over the 62-year period at the 18 stations. A log transformation was used to produce an approximately normal distribution. The heavy-rainfall threshold was the value at one standard deviation above the mean.

Several statistics were calculated to ensure that the study region was homogeneous and lacking strong spatial structure with respect to rainfall totals, frequencies of rainfall days, and frequencies of heavy-rainfall days. Coefficients of variation were calculated for the three rainfall variables; values less than 0.10 were desirable. A global Moran's I test (e.g. Rogerson, 2010) was used to test for significant ($\alpha = 0.01$) positive spatial autocorrelation for the three rainfall variables.

A separate database of precipitation associated with tropical systems was developed. Tropical-system days were identified by examining annual maps of tropical

Table I. The 18 precipitation stations used in the study along with the percentage of days with missing daily precipitation totals, the mean seasonal rainfall totals (in mm), the mean number of rainfall days (RD), and the mean number of heavy-rainfall days (HRD) for each station.

Station	%Missing	R	RD	HRD
Athens	0.1	325	29.8	4.6
Atlanta	0.0	326	31.1	4.8
Ball Ground	1.5	330	29.0	4.7
Cedartown	0.8	325	26.5	4.9
Cleveland	1.7	401	37.0	5.6
Covington	3.9	311	29.5	4.3
Curryville	1.5	300	26.3	4.4
Dallas	1.8	326	29.7	4.8
Ellijay	0.6	365	31.4	5.6
Experiment	9.9	344	34.7	4.6
Gainesville	0.2	326	29.4	4.6
Hightower	2.9	320	26.2	4.4
La Grange	11.9	333	30.1	4.9
Monticello	8.0	314	25.6	4.8
Newnan	3.9	319	30.6	4.6
Norcross	7.0	321	28.8	4.5
Winder	19.8	301	28.5	4.0
Woodbury	0.3	313	29.0	4.6

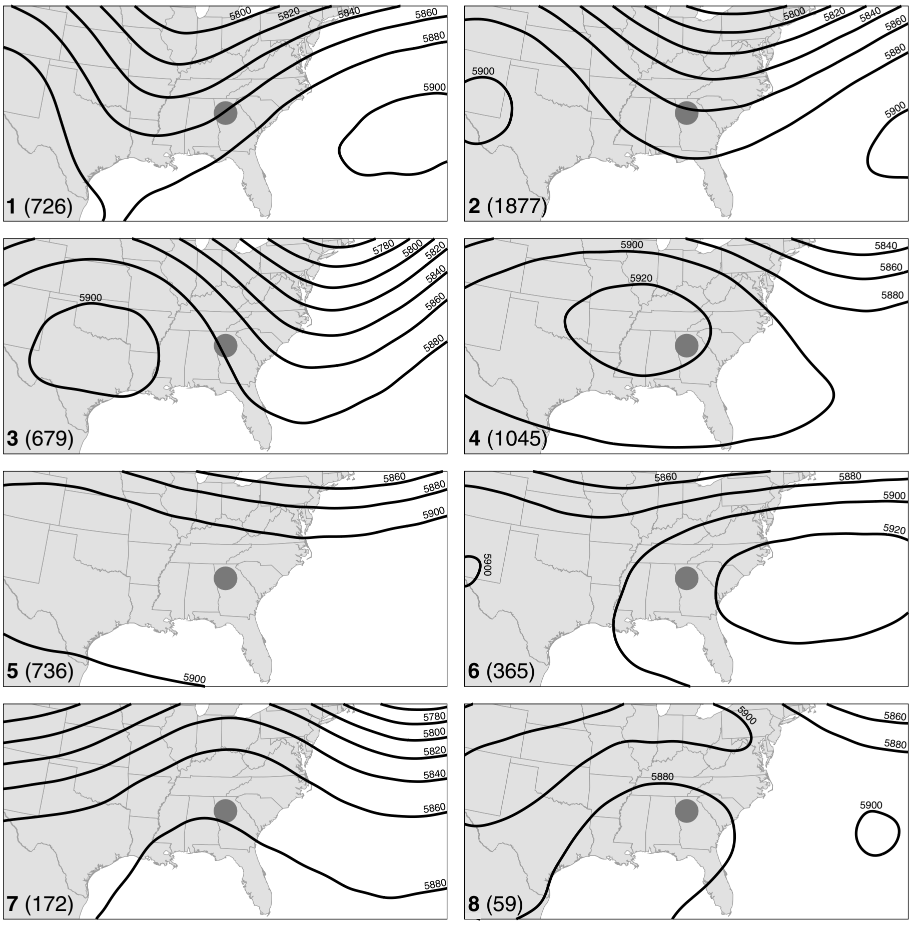

Figure 2. Mean 500-hPa geopotential heights during June–August of 1948–2009 for the eight synoptic types. The frequency of each type is shown in parentheses. The contour interval is 20 hPa. The shaded circle is the Atlanta region.

system tracks obtained from the National Weather Service's National Hurricane Center. All days with a tropical system within a 350-km-radius circle centred on Atlanta were classified as tropical system days. Tropical system swath size was based on methods and results in Rodgers *et al*. (2001).

Precipitation data for the entire southeastern United States also were used in this study. The precipitation data were normalized precipitation anomalies taken from Figure 2a in Wang *et al*. (2010). The original data were extracted from NOAA's Climate Prediction Center (CPC) US Unified Precipitation database for 1948–1998, and from the real-time US Daily Precipitation Analysis for 1999–2007; the data had a spatial resolution of 0.25° and covered 25°N to 36.5 °N and 76 °W to 91 °W (Wang *et al*., 2010). The domain is shown in Figure 1.

2.3. Rainfall characteristics of synoptic types

Multiple variables were used to assess rainfall differences among the synoptic types. The following values were calculated for each type: (1) Percentage of total seasonal rainfall, (2) Daily rainfall intensity, (3) Frequency of rainfall days, and (4) Frequency of heavy-rainfall days. Two-sample chi-square tests at the 0.01 significance level were conducted for the frequency variables.

2.4. Lower-troposphere circulation variables

Gridded sea-level pressure and 850-hPa geopotential-height data were extracted from the NCEP/NCAR Reanalysis dataset (Kalnay *et al*., 1996) of NOAA's ESRL to construct the following lower-troposphere circulation variables: (1) The BHI, (2) The western BHI (WBHI), (3) The longitude of the western ridge of the Bermuda High, and (4) The latitude of the western ridge of the Bermuda High. The BHI is an index of the difference between normalized sea-level pressure over Bermuda and New Orleans, Louisiana (Stahle and Cleveland, 1992); thus, monthly sea-level pressure values were acquired for grid cells corresponding to 32.5 °N and 64 °W and 30°N and 90 °W. The centre of the Bermuda High is typically located approximately 2500 km east of Bermuda during summer; therefore, the BHI shows the standardized pressure gradient across the western side of the Bermuda High. The WBHI is a newly developed index based on the BHI, with the major difference being that it uses 850-hPa heights and is centred over the southeastern United States. Monthly 850-hPa geopotential heights were acquired for grid cells corresponding to 30°N and 75°W and 30°N and 92 °W (Figure 1). Seasonal values of both the longitude and latitude of the western ridge of the Bermuda High were produced using 850-hPa geopotential-height fields; the location of the western ridge is the point where the 1560-hPa line intersects the ridge line of the Bermuda High (Li *et al*., 2011).

2.5. Atmospheric humidity variables

Atmospheric humidity has increased significantly over the past several decades at multiple geographic scales; thus, several atmospheric humidity variables were used in this study. Increases in specific humidity in the Northern Hemisphere from 1973 to 2002 have been the largest in summer (Willett *et al*., 2007). Atmospheric moistening has occurred over the Southeast; surface-500-hPa precipitable water increased significantly from 1973 to 1993 (Ross and Elliott, 1996) and surface specific humidity increased significantly from 1961 to 1995 (Gaffen and Ross, 1999) over the region. For this study, gridded 850-hPa and 500-hPa specific humidity data as well as surface-500-hPa precipitable water data were extracted from the NCEP/NCAR Reanalysis data set (Kalnay *et al*., 1996) of NOAA's ESRL. Seasonal values were obtained for the grid cell corresponding to the Atlanta region and for the 30 grid cells corresponding to the southeastern United States.

2.6. Temporal trend analyses

Spearman's ρ statistic, which is a rank-order correlation statistic, was used to test for significant temporal trends in seasonal values and inter-epochal variance for all Atlanta region variables. The chosen significance level was 0.01, and a one-tailed test was used. On the basis of the methodology presented in Groisman and Knight (2008), trends in seasonal values were assessed for all periods 30 years in length or longer, ending in 2009. Therefore, trends for 32 periods were examined. For the rainfall variables, correlation coefficients were calculated with and without tropical-system days included. Variance was calculated for overlapping 30-year periods for all variables; there were a total of 33 periods.

2.7. Correlations and linear regression

Temporal relationships between the 4 rainfall variables and the 15 circulation and humidity variables were determined. A Pearson product-moment correlation coefficient was calculated for the pairs of variables. The one-tailed significance level was 0.01.

Three linear-regression models were developed, with total rainfall, frequency of rainfall days, and frequency of heavy-rainfall days as the predictands. All 15 circulation/humidity variables were included initially in the models; thus, a backward-elimination stepwise procedure was used. Collinearity diagnostics were examined to ensure that a predictor variable in the final model was not a linear function of the other predictor variables. Spearman's ρ statistic was used to test for significantly ($\alpha = 0.01$) positive temporal trends in variance of the predicted values as well as significant trends in the residuals for the 32 periods noted in Section 2.6.

3. Results

3.1. Synoptic typing

The classification of 500-hPa circulation patterns produced 8 synoptic types (Figure 2). Less than 1% of the days were unclassifiable. Types 1, 2, and 3 were the troughing types; the three types had the Atlanta region under the eastern limb, axis, and western limb of a trough, respectively. Type 2 occurred on 33% of the days; thus, it was the most prevalent circulation pattern. The Atlanta region was under some portion of a trough on nearly 60% of the days. Types 4, 5, and 6 were the anticyclone types, with the types having the Atlanta region under a continental anticyclone, a continental/maritime anticyclone, and a maritime anticyclone, respectively. Type 4 was the most frequent of the anticyclone types. Types 7 and 8 were rare occurrences: these types occurred on only 3% and 1% of the days, respectively. Type 7 was ridging over the Atlanta region, while Type 8 was an inverse trough over the region.

The most likely synoptic type for a day was the type on the previous day; therefore, persistence of types was common (Figure 3). Nearly 60% of the days were followed by a day with the same circulation pattern. The troughing types (i.e. Types 1, 2, and 3) tended to occur together, with an exception being that Type 3 was more likely to transition into Type 4 rather than back to a troughing type. In addition, Type 1 transitioned into Type 2 much more frequently than it transitioned into other types. The anticyclone types (i.e. Types 4, 5, and 6) also tended to occur simultaneously.

3.2. Rainfall characteristics

There was little variation in rainfall totals throughout the Atlanta region (Table I). The mean rainfall total, frequency of rainfall days, and frequency of heavy-rainfall days, which was based on a 21-mm threshold value, for

From Type \ To Type	1	2	3	4	5	6	7	8
1	**0.54**	0.31	0.00	0.01	0.03	0.09	0.02	0.00
2	0.11	**0.64**	0.12	0.02	0.07	0.02	0.01	0.01
3	0.02	0.21	**0.50**	0.16	0.05	0.01	0.05	0.01
4	0.01	0.08	0.08	**0.67**	0.12	0.02	0.01	0.01
5	0.04	0.20	0.03	0.19	**0.45**	0.07	0.01	0.00
6	0.10	0.09	0.00	0.10	0.24	**0.44**	0.02	0.00
7	0.15	0.20	0.06	0.13	0.05	0.04	**0.37**	0.00
8	0.16	0.11	0.00	0.11	0.13	0.11	0.02	**0.38**

Figure 3. Probabilities of synoptic-type transitions during June–August of 1948–2009. A bold number is the largest probability for a type.

Table II. Rainfall characteristics of the eight synoptic types and the unclassified days. '% R' refers to percentage of total rainfall. 'RI' refers to rainfall intensity in mm day^{-1} for all days. For both 'RD' and 'HRD', which stand for rainfall days and heavy-rainfall days, respectively, a positive (negative) sign indicates a disproportionately large (small) number of days.

Type	% R	RI	RD	HRD
1	30	8.2	+	+
2	32	3.4	+	−
3	4	1.2	−	−
4	9	1.7	−	−
5	12	3.2		−
6	9	4.8	+	+
7	2	2.1	−	−
8	1	5.4	+	+
U	1	3.1		

the 92-day summer season were 328 mm, 29.6 days, and 4.7 days, respectively. Therefore, 32% of summer days had measureable rainfall. The spatial coefficients of variation for the three variables were 0.07, 0.09, and 0.08, respectively. In addition, there was no significant spatial autocorrelation among the rainfall totals. Finally, seasonal rainfall totals within the Atlanta region were typical of that for the southeastern United States as a whole.

Tropical systems contributed minimally to summer rainfall in the Atlanta region. A total of 171 days over the 62-year period (i.e. 3% of the days) had tropical systems that might have impacted the Atlanta region rainfall. Consequently, only 6.3%, 3.9%, and 6.7% of rainfall, rainfall days, and heavy-rainfall days, respectively, can be associated with tropical systems.

There was substantial variation among the synoptic types with respect to rainfall characteristics (Table II). Approximately 70% of the rainfall occurred when Types 1, 2, and 6 were over the region; those three types had a trough over or to the west of the region, and all three types were associated with a disproportionately large number of rainfall days. For example, rainfall occurred on approximately 60% of Type 1 days. Type 1, which occurred on much fewer days than did Type 2, differed from Type 2 in that it had much higher rainfall intensity and a disproportionately large number of heavy-rainfall days. Type 2 actually had a disproportionately smaller number of heavy-rainfall days. Types 6 and 8 were the other 'wet' types: both types had relatively high rainfall intensities and disproportionately large numbers of rainfall days and heavy-rainfall days. With low rainfall intensities and disproportionately smaller numbers of rainfall days and heavy-rainfall days, Types 3, 4, and 7 can be considered the 'dry' types. Rainfall occurred on fewer than 20% of those days with those circulation patterns.

3.3. Temporal trends and variability

Among the three rainfall variables, only the rainfall-days variable had significant trends (Figures 4 and 5). The periods 1976–2009 and 1977–2009 had significant positive trends in rainfall days. With the removal of rainfall days linked possibly to tropical systems, the only significant period was 1976–2009.

Types 1 and 5 were the only synoptic types with significant trends (Figures 4 and 6). Type 1 had significant negative trends beginning as early as the mid-1950s and as late as the early 1970s. Type 5 had significant positive trends during periods beginning in the 1960s.

Three of the four variables associated with lower-troposphere circulation had significant trends (Figures 4, 7, and 8). The BHI and the longitude of the western ridge of the Bermuda High had significant positive trends during the final ten periods (i.e. beginning as early as 1971) and six periods (i.e. beginning as early as 1975), respectively. The latitude of the western ridge of Bermuda High had significant negative trends during seven consecutive periods that began in the 1970s. Consequently, the western ridge of the Bermuda High moved significantly southeastward from approximately the mid-1970s to 2009.

All the atmospheric humidity variables had significant positive trends (Figures 4 and 9). Specific humidity at 850 hPa had significant trends during every period, while 500-hPa specific humidity had significant trends during 18 consecutive periods beginning as early as 1959 and as late as 1977. Precipitable water had significant trends for all but the first 4 and final 4 periods.

The three Atlanta region rainfall variables had considerable inter-annual variability, and 1979–2009 had more variability than did 1948–1978 (Figure 5). The temporal coefficients of variation for rainfall, rainfall days, and heavy-rainfall days were 0.27, 0.18, and 0.31, respectively. Therefore, the frequency of heavy-rainfall days had the most inter-annual variability. All coefficients of variation increased from 1948–1978 to 1979–2009.

The rainfall variables and the circulation indices had an increase in variance (Figures 10(a–d), while a majority of the synoptic types had a decrease in variance (Figure 10(c)). Among the rainfall variables, the frequency of heavy-rainfall days and the frequency of rainfall days had the largest and smallest increases in variance, respectively. Frequencies of Types 1, 2, 3, 4, and 6 had a decrease in variance. Finally, the WBHI had a larger positive trend than did the BHI.

3.4. Correlations and linear regression

Both the circulation and humidity variables were significantly correlated with the four rainfall variables (Table III). Among all variables, the WBHI had the highest correlations with all four rainfall variables; the coefficients ranged from 0.60 for heavy-rainfall days to 0.82 for the southeast precipitation anomaly. The other variables that were significantly correlated with all rainfall variables included Type 1, Type 2, Type 4, BHI, and latitude of the western ridge of the Bermuda High. Type 4 and latitude had negative correlations. Type 3 and 500-hPa specific humidity were significantly correlated with all rainfall variables except for heavy-rainfall days. Type 3 had a negative correlation.

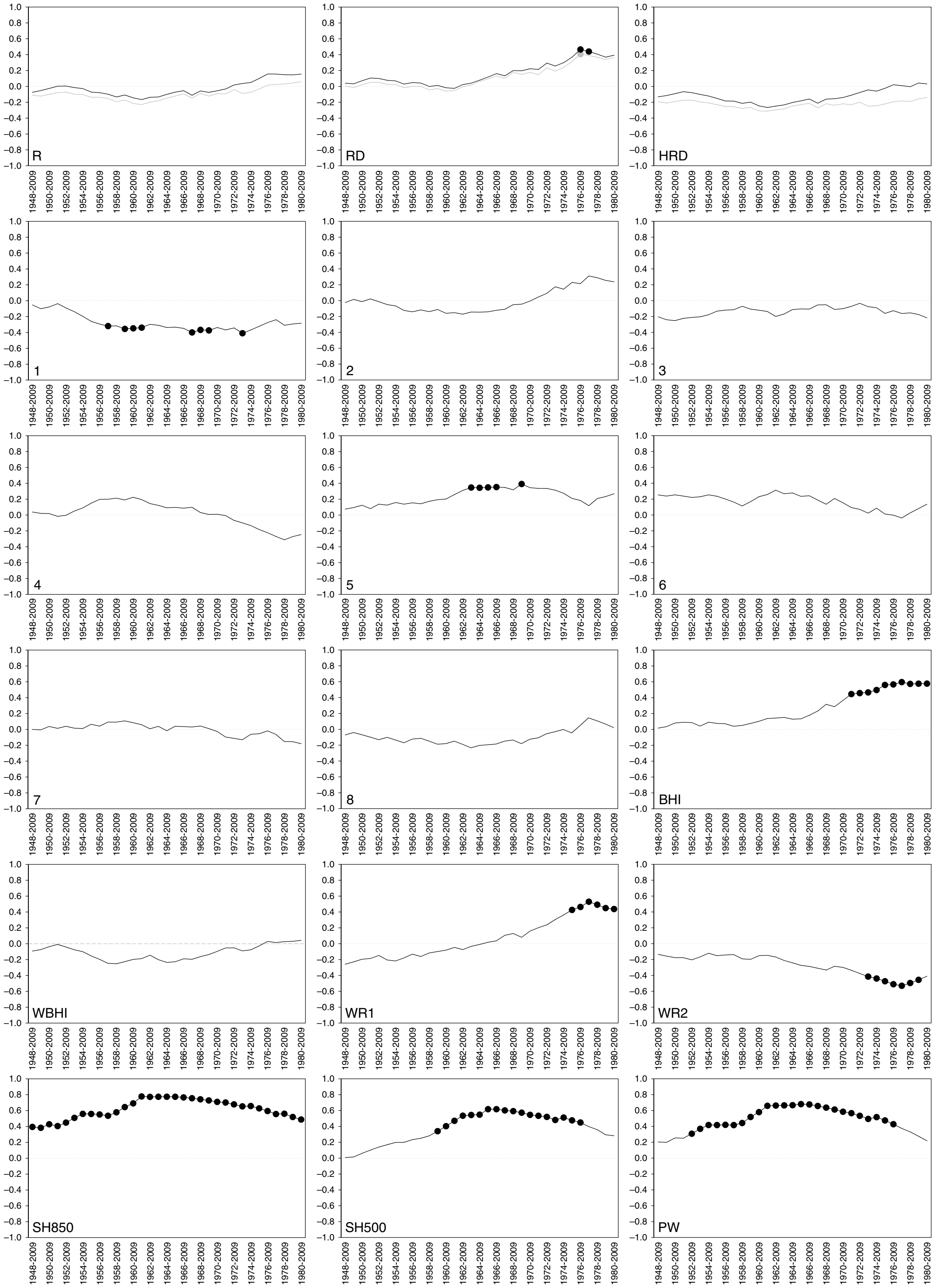

Figure 4. Trends in rainfall (R), rainfall days (RD), heavy-rainfall days (HRD), synoptic-type frequencies (1–8), Bermuda High Index (BHI), Western Bermuda High Index (WBHI), longitude (WR1) and latitude (WR2) of the western ridge of Bermuda High, and 850-hPa specific humidity (SH850), 500-hPa specific humidity (SH500), and precipitable water (PW) over periods ranging from 30 to 62 years. Values on the *Y*-axis are correlation coefficients. Circles denote trends significant at the 0.01 level. Results from the removal of tropical-system days from the rainfall values are shown as grey lines and circles in the top three panels.

The multiple linear regression models for the Atlanta region rainfall variables explained at least half the variance in the rainfall variables (Table IV). All three models had WBHI and Type 4 as predictors. On the basis of the standardized coefficients, either WBHI or Type 4 were the most important predictors in the models. Specific humidity at 500 hPa was an additional predictor variable in the rainfall days model, which had the highest

r^2 of the models, while Type 1 was an additional predictor variable in the heavy-rainfall days model. The presence of WBHI as a predictor in all three models caused the variances of the predicted values to have significant positive trends. Finally, there were no trends in the residuals during any of the 32 periods.

4. Discussion

The synoptic typing revealed the importance of middle-troposphere troughing with respect to rainfall in the southeast. The Atlanta region was under either the axis or the eastern limb of a trough on nearly half the summer days. Through either daily analyses or seasonal correlation analyses or both, the above troughing events were associated with increased rainfall over the Atlanta region and the entire southeastern United States. Conversely, an increase in days when the region was under the western limb of a trough or under a middle-troposphere anticyclone, with the exception of an anticyclone positioned over the western North Atlantic Ocean, was associated with decreased rainfall over both study regions. The same findings were found for the Atlanta region by Diem (2006) using a rainfall-to-circulation analysis: wet periods were generally associated with a middle-troposphere trough over the interior southeastern United States coincident with strong lower-troposphere flow into the southeast from the Gulf of Mexico, and dry periods were characterized by ridges or anticyclones over the midwestern and southeastern United States coupled with a weak lower-troposphere flow. The results also conform to the findings of Booth *et al.* (2006), where a significant positive correlation is observed between an Atlantic zonal index (i.e. strength of surface flow over the eastern United States and the Atlantic Ocean) and rainfall in the southeastern United States; there is increased precipitation in portions of the southeast during years with a high zonal index (i.e. increased frequencies of troughing days).

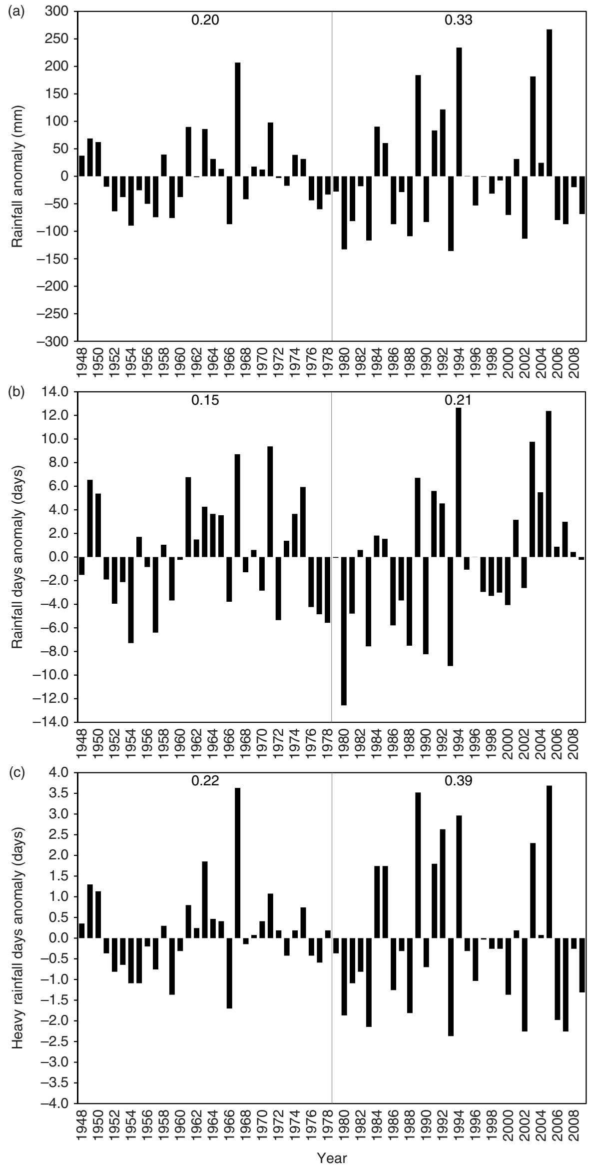

Figure 5. Inter-annual variations in anomalies of (a) total rainfall, (b) frequency of rainfall days, and (c) frequency of heavy-rainfall days. Anomalies were calculated using the 1948 to 2009 means. The vertical lines separate the 1948–1978 and 1979–2009 periods, and coefficients of variation are shown for each period.

The increased variance in rainfall in the interior portion of the southeastern United States corroborates the findings of Wang *et al.* (2010) for the entire southeast. The two domains differ dramatically in that Florida and other coastal areas receive much more rainfall during summer than do interior locales, such as the Atlanta region. Nevertheless, both datasets had the same mean rainfall total (~330 mm) and both showed increased variance in rainfall after the mid-1970s.

Increased interannual variability in the WBHI appears to be the cause of the increased variance in rainfall variables. The WBHI is positively correlated with rainfall in the southeast, and it an important predictor of rainfall, rainfall days, and heavy-rainfall days. The WBHI reflects both the movement of the western ridge of the Bermuda High over the southeast along with changes in meridional flow (Figure 11). Extreme negative values of the WBHI occur when the western ridge of the Bermuda High extends over much of the southeast, while extreme positive values of the WBHI occur when the western ridge extends over just the far eastern portion of the southeast. It also should be noted that the explanation put forth by Li *et al.* (2011) for the increased variability is incorrect. The western ridge of the Bermuda High has not moved westward over the past three decades; in fact; it has moved significantly eastward. In addition, there was no significant change in the latitudinal movement of the western ridge over time. Finally, increases in the variance of rainfall variables over time cannot be attributed to changes in the frequencies of middle-troposphere circulation patterns. None of the synoptic types had significant increases in variance of seasonal frequencies. In fact, five of the eight types had significant decreases in variance.

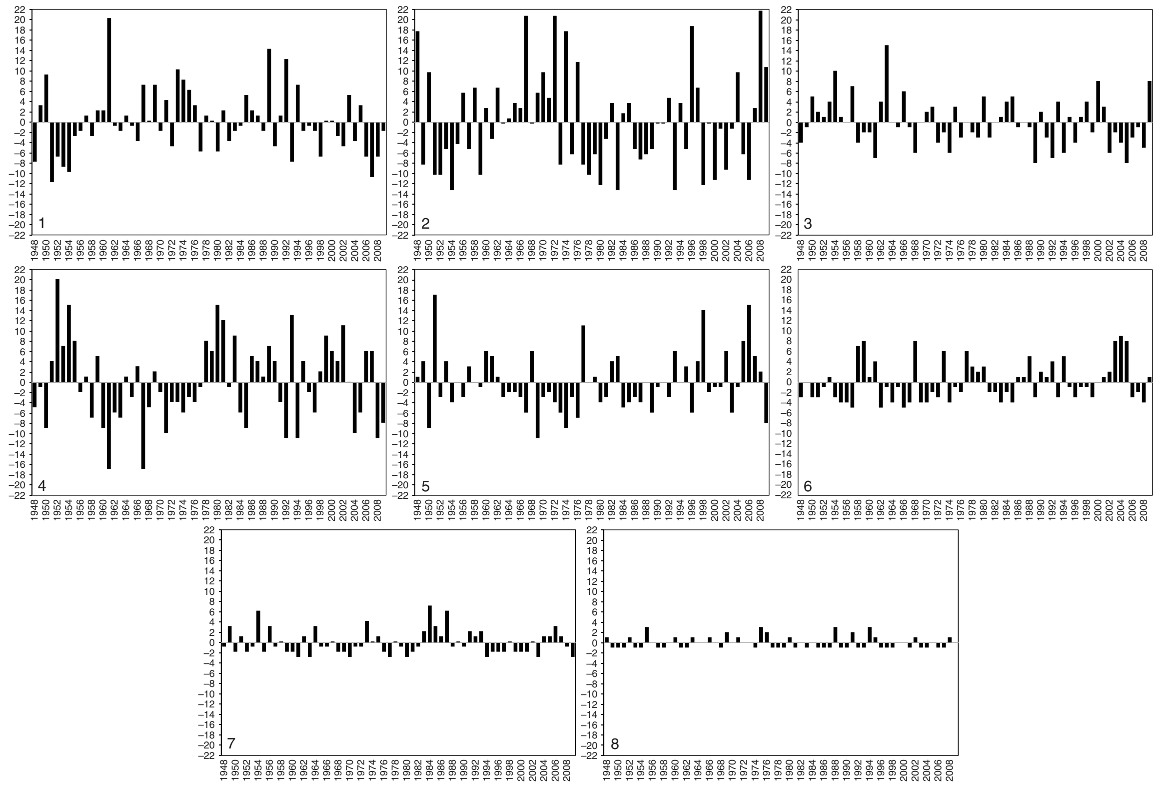

Figure 6. Inter-annual variations in anomalies of frequencies of the eight synoptic types.

The principal cause of the increase in rainfall days during the past three decades appears to be an increase in atmospheric humidity. Increased humidity is not specific to the southeast in summer, rather it is a global phenomenon at the annual scale (Willett *et al*., 2007). Another potential cause is specific to the southeast: the eastward movement of the western ridge of the Bermuda High and associated increase in the BHI. Decreased pressure over the southeastern United States, rather than increased pressure over Bermuda, has caused the BHI to increase (Figure 12).

Tropical systems definitely were neither the cause of the increased variability in the rainfall variables nor the cause of the increased frequency of rainfall days. The removal of days when Atlanta might have received tropical-system rainfall still yielded rainfall databases with the following characteristics: a significant positive trend in inter-epochal variance (Figure 10); and a significant positive trend in the frequency of rainfall days from 1976 to 2009 (Figure 4). Consequently, similar results were found with rainfall totals, rainfall days, and heavy-rainfall days with tropical-system days included in and excluded from the analyses.

While research suggests that global warming and the associated increase in atmospheric humidity since the 1970s should lead to an increase in heavy-rainfall days (IPCC, 2007), an increase in heavy-rainfall days was not found in this study. These results confirm the findings in Diem and Mote (2005). Other researchers (e.g. Groisman *et al*., 2004) have defined heavy rainfall as days above the 95th percentile, whereas heavy-rainfall days in this study were above the 85th percentile. If the 95th percentile had been used, then the heavy-rainfall threshold value would have been 39 mm, rather than 21 mm. Using the same

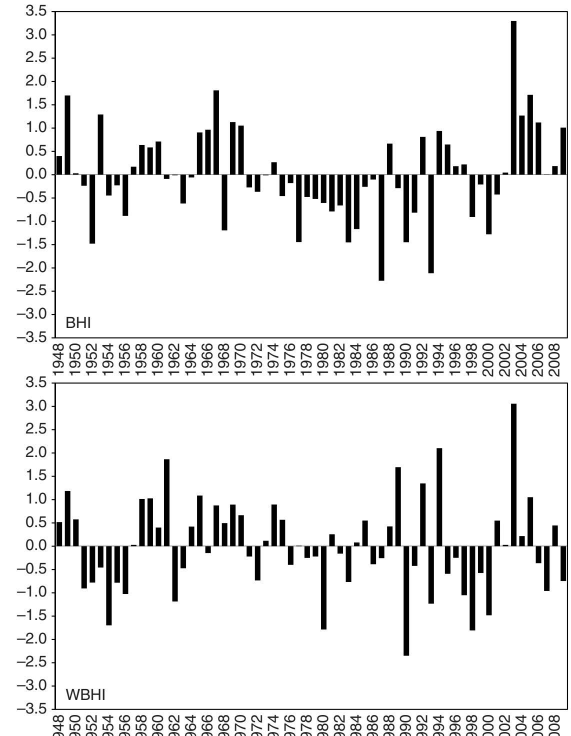

Figure 7. Inter-annual variations in values of the Bermuda High Index (BHI) and the Western Bermuda High Index (WBHI).

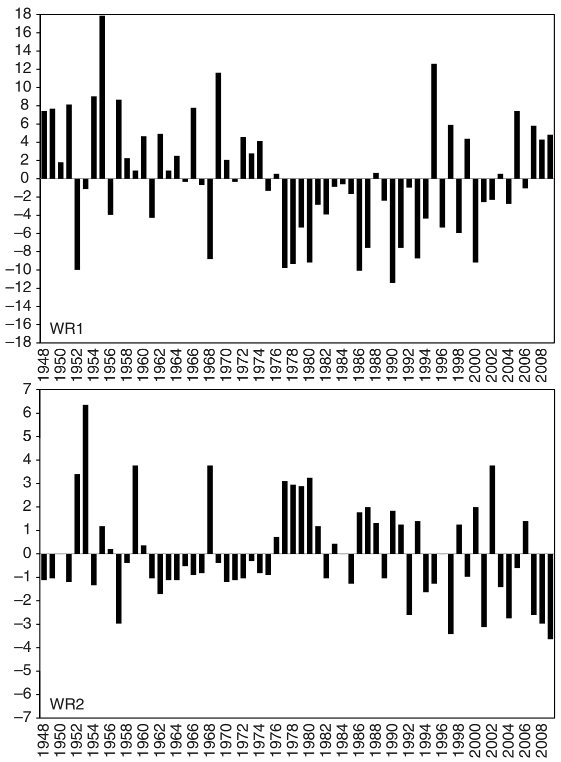

Figure 8. Inter-annual variations in the longitude (WR1) and latitude (WR2) of the western ridge of the Bermuda High. The unit is shown in degrees.

Table III. Correlations between the rainfall variables and the circulation and humidity variables. 'R', 'RD"', and 'HRD' are total rainfall, rainfall days, and heavy-rainfall days, respectively. 'PA' is the precipitation anomaly for the entire southeastern United States. 'BHI' and 'WBHI' are the Bermuda High Index and the Western Bermuda High Index, respectively. 'WR 1′' and 'WR 2′' are the longitude and latitude, respectively, of the western ridge of the Bermuda High. 'SH500', 'SH850', and 'PW' are 500-hPa specific humidity, 850-hPa specific humidity, and surface 500-hPa precipitable water, respectively. The correlations with 'R', 'RD', and 'HRD' involve 62 years (i.e. 1948–2009). The correlations with 'PA' involve 60 years (i.e. 1948–2007).

Variable	R	RD	HRD	PA
Type 1	+0.57[a]	+0.53[a]	+0.58[a]	+0.64[a]
Type 2	+0.32[a]	+0.31[a]	+0.31[a]	+0.33[a]
Type 3	−0.31[a]	−0.32[a]	−0.24	−0.45[a]
Type 4	−0.60[a]	−0.62[a]	−0.59[a]	−0.58[a]
Type 5	−0.19	−0.12	−0.24	−0.19
Type 6	+0.17	+0.16	+0.13	+0.23
Type 7	−0.01	+0.01	+0.04	−0.09
Type 8	+0.08	+0.12	+0.04	+0.03
BHI	+0.45[a]	+0.50[a]	+0.37[a]	+0.62[a]
WBHI	+0.66[a]	+0.66[a]	+0.60[a]	+0.82[a]
WR1	+0.15	+0.20	+0.06	+0.21
WR2	−0.40[a]	−0.43[a]	−0.34[a]	−0.44[a]
SH850	−0.06	−0.03	−0.12	−0.02
SH500	+0.32[a]	+0.44[a]	+0.22	+0.35[a]
PW	+0.13	+0.19	+0.06	+0.15

[a] significant at $\alpha = 0.01$.

trend-analysis approach adopted throughout this study, no significant trends in days with rainfall greater than or equal to 39 mm were found; the largest correlation coefficient was 0.136, and the time period corresponding to that coefficient was 1952–2009. One possible reason for the lack of an increase in heavy-rainfall days has been a significant long-term negative trend in the frequency of Type 1 days. Days with a Type 1 circulation, which involves the Atlanta region under the eastern limb of a trough, have an increased probability of heavy rainfall, and Type 1 frequency is an important predictor of the number of heavy-rainfall days.

5. Conclusions

Over the period 1948–2009, summer rainfall in the Atlanta region of the southeastern United States became much more variable beginning in the mid- to late-1970s. The rainfall variables specific to this study included seasonal rainfall totals, frequency of rainfall days, and frequency of heavy-rainfall days, which had the largest increase in variability. Rainfall was correlated significantly with the frequency of multiple middle-troposphere circulation patterns: an increase in troughing events was linked to increased rainfall, while an increase in anticyclone days was linked to decreased rainfall. Since none of the circulation patterns had an increase in variability over time, the patterns did not explain the increase in rainfall variability. A circulation-related cause of the increased variability in the three Atlanta region rainfall variables was increased variability of a circulation index known as the WBHI. This index reflects both the movement of the

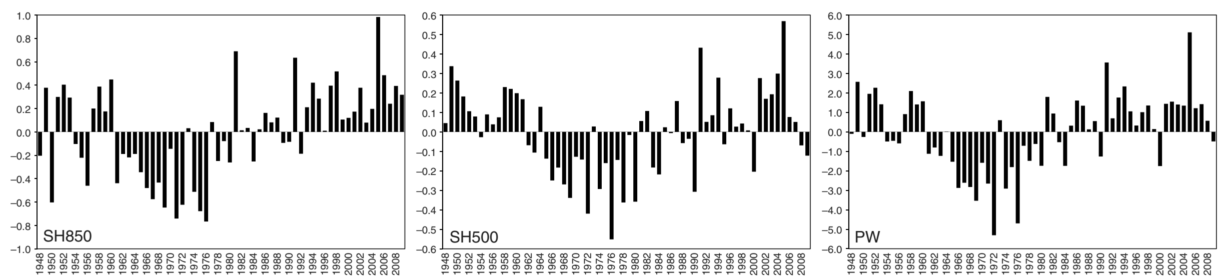

Figure 9. Inter-annual variations in 850-hPa specific humidity (SH850), 500-hPa specific humidity (SH500), and precipitable water (PW) over the Atlanta region. The unit for specific humidity is g kg^{-1}. The unit for precipitable water is kg m^{-2}.

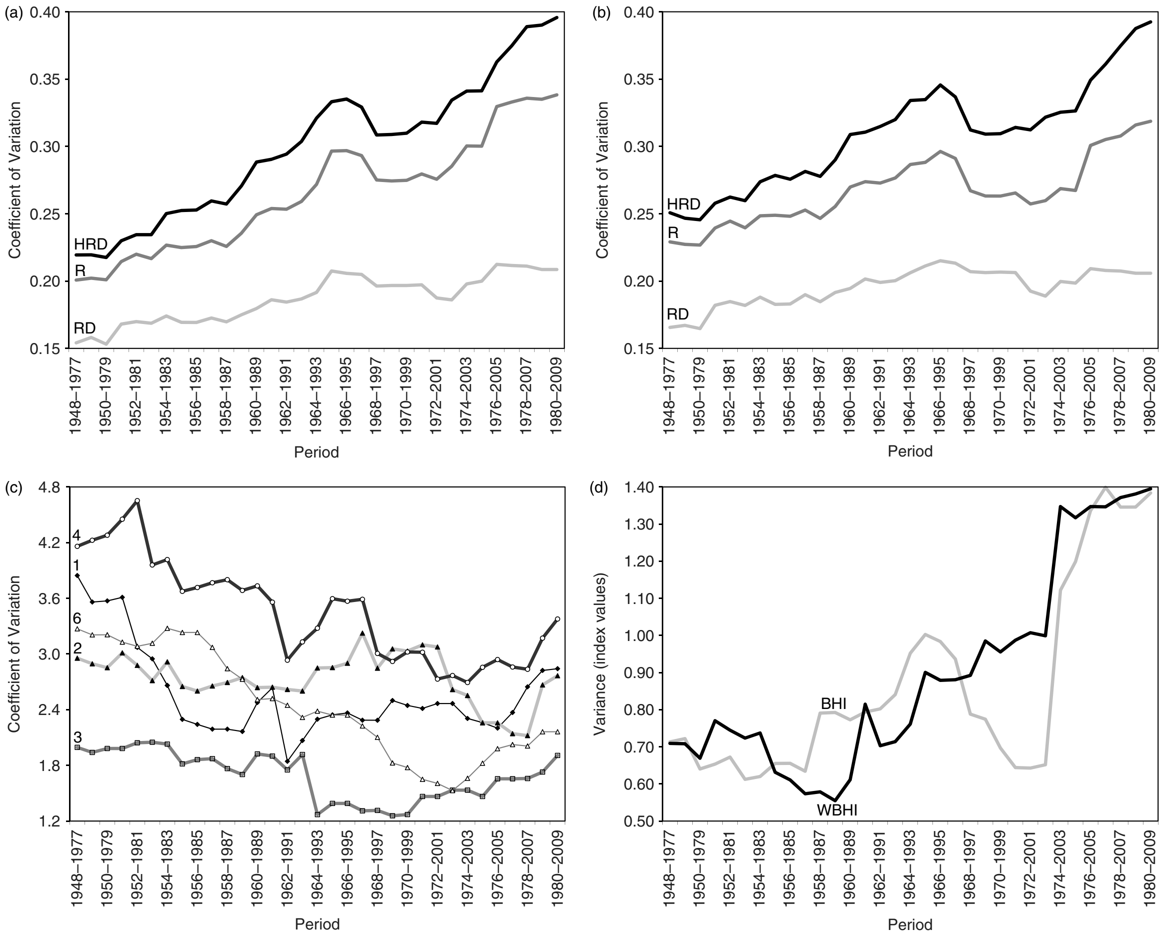

Figure 10. Inter-epochal variations in variance in (a) total rainfall (R), frequency of rainfall days (RD), frequency of heavy-rainfall days (HRD), (b) rainfall variables without tropical-system rainfall, (c) frequency of Types 1, 2, 3, 4, and 6, and (d) the Bermuda high Index (BHI) and the Western Bermuda High Index (WBHI).

Table IV. Characteristics of the multiple linear regression models for the Atlanta region rainfall variables. Standardized coefficients are shown in parentheses.

Predictand	r^2	Predictor$_1$	Predictior$_2$	Predictor$_3$
Rainfall	0.51	WBHI (+0.49)	Type 4 (−0.37)	N/A
Rainfall days	0.64	Type 4 (−0.42)	WBHI (+0.37)	SH_{500} (+0.29)
Heavy-rainfall days	0.55	Type 4 (−0.35)	WBHI (+0.29)	Type 1 (+0.23)

western ridge of the Bermuda High over the southeast along with changes in meridional flow. Regression models revealed the WBHI to be an important predictor of rainfall, rainfall days, and heavy-rainfall days.

There also was a positive trend in the number of rainfall days over the past three decades. Significant positive trends in rainfall days occurred during 1976–2009 and 1977–2009. The principal cause of the increase in rainfall days during the past three decades is hypothesized to be an increase in atmospheric humidity. Another possible cause was an increase in the BHI; this increase was caused by the eastward movement of the western ridge of the Bermuda High (i.e. a decrease in pressure over the southeast). The link between increased atmospheric humidity and an increased BHI was not investigated in this paper.

The increased variability and the increase in rainfall days were not caused by changes in tropical-system rainfall or changes in the frequencies of middle-troposphere circulation patterns. Even with the removal of all rainfall that could have been associated with tropical systems, there still was a significant increase in inter-epochal variance for the three rainfall variables as well as a significant positive trend in rainfall days for 1976–2009. The circulation patterns also were not responsible for the increased inter-epochal variance, since none of the patterns had significant increases in variance.

This study has uncovered an intriguing trend in rainfall days for the interior portion of the southeastern United States; therefore, future research should focus on determining if the trend is not exclusive to the interior southeast. The entire southeast, and possibly the entire eastern

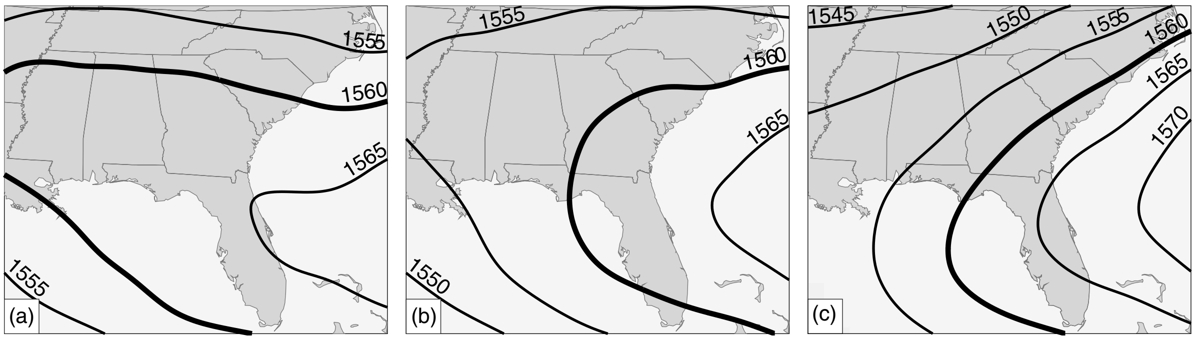

Figure 11. Mean 850-hPa geopotential heights for the (a) bottom six, (b) middle six, and (c) top six years with respect to values of the Western Bermuda High Index. The contour interval is 5 hPa. The 1560-m line is thicker than the other lines, because Li *et al*. (2011) used this line to represent the western boundary of the Bermuda High.

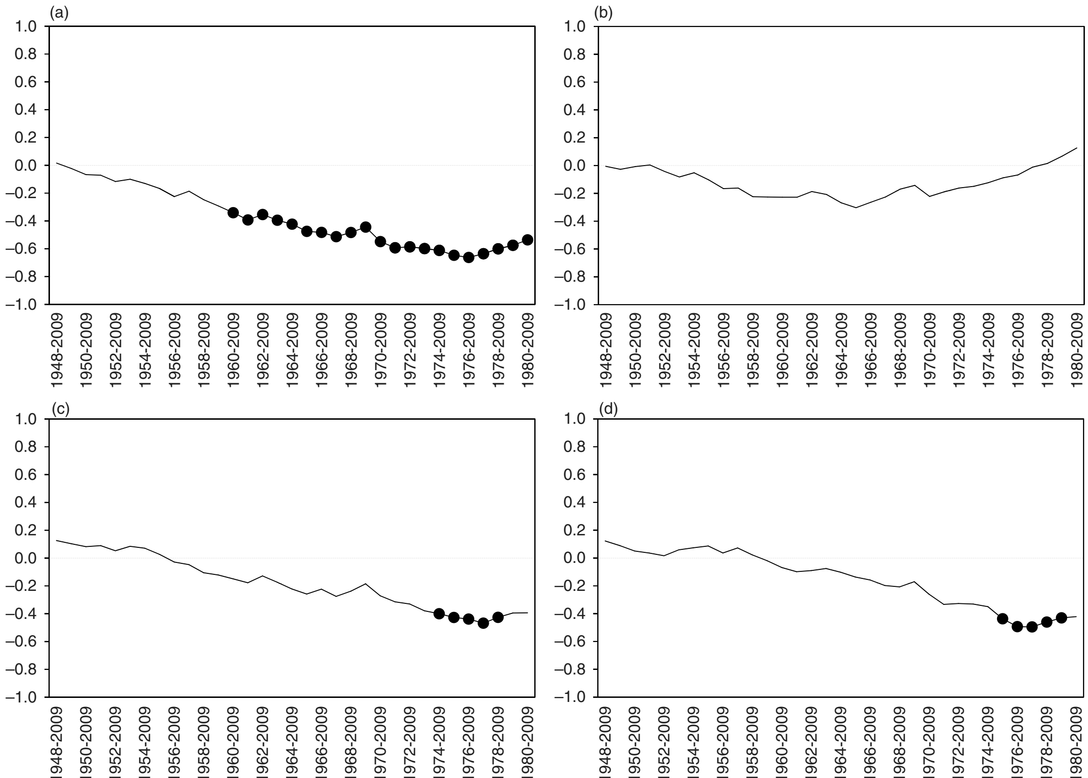

Figure 12. Trends in (a) New Orleans sea-level pressure, (b) Bermuda sea-level pressure, (c) 850-hPa geopotential heights at 30°N and 92 °W (i.e. point B in Figure 1), and (d) 850-hPa geopotential heights at 30°N and 75 °W (i.e. point A in Figure 1) over periods ranging from 30 to 62 years. Values on the Y-axis are correlation coefficients. Circles denote trends significant at the 0.01 level.

United States, should be examined at multiple spatial scales, and additional variables, such as dry-day episodes, also should be analysed.

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