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AUTUMN PRECIPITATION TRENDS IN THE NORTHEAST UNITED STATES

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ABSTRACT: *The northeastern United States experienced significant increases in precipitation from 1900-1999. Precipitation changes have been most prominent in the autumn. In western New York and Pennsylvania, and in coastal New England, seasonal precipitation totals have risen 25-45% over the 100-year period. Concurrent decreases in temperature indicate that early season precipitation increases may be associated with earlier upper-level troughing, while large-scale November changes may be linked to an enhanced subtropical high pressure system. Autumn precipitation steadily increased over the century and has impacted regional hydrology. At least three major rivers have shown increased autumn flow. This impact is potentially important given that autumn is usually a time of rising river levels before high winter and spring runoff periods.*

INTRODUCTION

Recent research on global climate change has highlighted precipitation trends as a leading signal in change detection. In North America precipitation has increased significantly in many regions over the past century. Groisman and Easterling (1994) found that total precipitation rose about 4% over the continental United States and close to 13% in southern Canada over a one hundred year period. Using slightly different techniques, Karl and Knight (1998) estimated that precipitation has increased by 10% over the contiguous United States. Since 1970 precipitation in the United States has remained about 5% above long-term normals (Karl et al., 1996). At the regional scale, areas such as the south-central and mid-western United States have experienced large increases in the last 50 years. But since 1900 the largest precipitation change has been found in eastern Canada and the adjacent northeastern United States (Groisman and Easterling, 1994). Polsky et al. (2000) found that annual precipitation has risen 10% over the last 100 years in the Mid-Atlantic Region. Much of the increase in precipitation, both at the national and regional level, can be attributed to changes during the autumn season (Karl et al.; 1996, Karl and Knight, 1998).

Precipitation changes have been associated with an increase in large precipitation events (Karl et al., 1996). Karl and Knight (1998) suggest that over half of the measured precipitation increase across the country has been caused by increases in the largest 10% of storms. While precipitation events of all levels have become more frequent, only the intensities of the largest events have increased (Karl and Knight, 1998). Kunkel et al. (1999) also found significant increases in extreme precipitation events over many portions of the United States. The largest increases in extreme rainfall events have occurred in the northern Great Plains for seven-day events (Kunkel et al., 1999) and the northeastern United States for one-day events (Karl and Knight, 1998). Regardless of whether these changes are a result of anthropogenic climate changes or natural fluctuations, a significant trend has been identified with potentially serious hydrologic impacts. It is important that the patterns, causes, and consequences of these trends are examined in more detail to highlight regional impacts.

PRECIPITATION DATA

This paper examines patterns of autumn (September through November) precipitation change at the regional scale in the Northeast United States. Precipitation data come from two sources. Primarily the study utilizes United States Divisional Data available from the National Climate Data Center (NCDC). In this data set climate observations from many individual stations are averaged over larger regional divisions. Monthly divisional data were obtained for 48 climate divisions over 11 states in the Northeast United States for the years 1900-1999. The advantage of this data set is that it is less influenced by data quality problems at any one station, and it provides complete regional coverage. However, more systematic data quality problems may affect long-term temporal patterns.

In order to verify the temporal trends of the divisional data, a second data set was also obtained for validation purposes. The United States Historical Climate Network (HCN), also available from NCDC, consists of long-term station data that have passed through rigorous analysis checks for data inhomogeneities and represent the best station data available for long-term climate trend studies. Monthly HCN data from 160 stations were used here to confirm the patterns of change identified in the divisional data, and also to provide more description of local-scale patterns. All 160 stations had data covering the 1932-1998 period, with 80% extending all the way back to 1900. In general, HCN stations provide adequate spatial coverage, though notable gaps exist in places such as western Pennsylvania, Connecticut, New Hampshire and Maine.

PRECIPITATION TRENDS

Precipitation in the Northeast United States is distributed evenly throughout the year. Climate divisions within the region receive eight to twelve

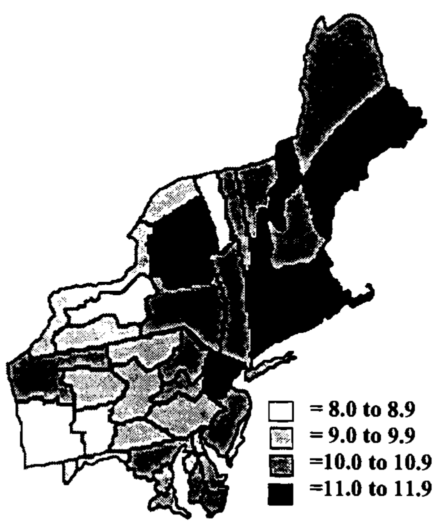

Figure 1: Average autumn precipitation in inches.

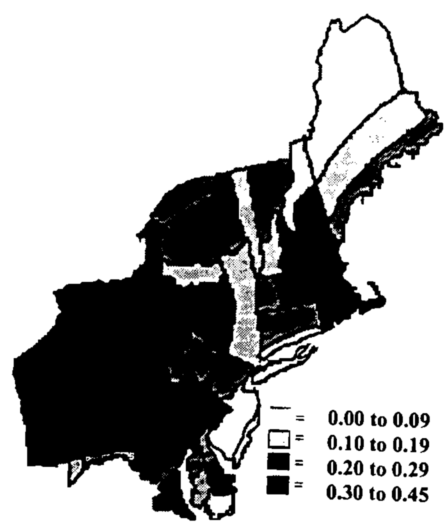

Figure 2: Correlation coefficients between autumn precipitation and year. Values above 0.20 are significant at the 0.95 level.

inches of precipitation in the autumn season (Figure 1). Higher totals are found in coastal New England and in the Adirondack Mountains of northern New York. Totals closer to eight inches appear in western New York, Pennsylvania, and Maryland. These totals account for slightly less than one quarter of each region's respective annual precipitation totals, with fractions just above 25% in the north.

Trends in Total Precipitation

In order to investigate whether these seasonal precipitation totals have been increasing over the last 100 years, simple correlations were calculated between autumn precipitation and year, and a linear regression line was fit to the annual data. Correlation results show that autumn precipitation increased during the 1900-1999 period in virtually every climate division (Figure 2). Highly significant positive correlations can be found in Pennsylvania and western New York in the western portion of the study area, and eastern New England along the Atlantic Coast. These two areas are separated by a region where results are not statistically significant at the 0.95 level. Lower correlations exist along a corridor running from the Hudson River basin through to New Jersey, Delaware, and eastern Maryland. It would appear that while the northeastern United States as a whole has experienced an increase in autumn precipitation, this increase can really be separated into two distinct zones.

These results can be confirmed by looking at similar patterns in correlations calculated for the HCN data (Figure 3). Though a larger degree of spatial complexity exists in these results, stations with statistically significant increasing precipitation trends are clustered in those areas where the divisional data showed the strongest results. A number of individual stations with significantly increasing trends are spread across Pennsylvania and western New York, as well as in eastern Massachusetts, Rhode Island, southern New Hampshire, and coastal Maine. Conspicuous clusters

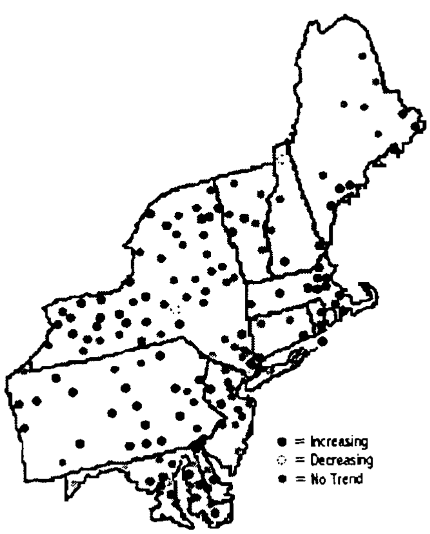

Figure 3: Significant (0.95 level) autumn precipitation trends at HCN stations.

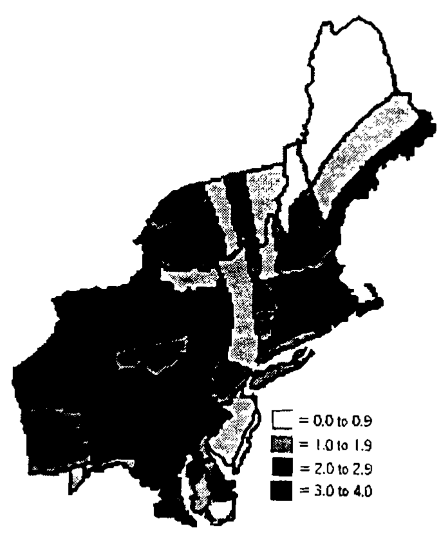

Figure 4: Linear precipitation trend (in inches) over 100 years.

of stations with insignificant trends can be seen in eastern New York and New Jersey. Because the long-term data quality of the HCN data sets is trusted more than the divisional data, it is interesting to note that the overall pattern of precipitation change is virtually identical in the two data sets. The spatial patterns of the divisional results are unlikely to be a consequence of data quality problems.

Results of the linear regression analysis show that the increases experienced over the last 100 years represent a major increase in total precipitation. The slope of the regression lines indicate that autumn precipitation trends of three to four inches over the 100 year period have been recorded in both the Pennsylvania/western New York region and in coastal New England (Figure 4). In the latter region this represents an overall increase of 25-35% over the long-term mean. In Pennsylvania and western New York, where total autumn precipitation is lower, the increase represents a change of 30-45%. Much smaller increases are evident in the northern and central portions of the study region. The smallest trends are found in northern New Hampshire and Maine, where insignificant slopes of less than one inch per 100 years were calculated.

Trends in Variability

In addition to changes in total precipitation, any simultaneous changes in precipitation variability would also produce potentially important climate impacts. To test whether precipitation variability has also increased in the northeastern United States, interannual precipitation differences were calculated. The absolute difference in autumn precipitation totals from one year to the next was used as a measure of interannual variations. Interannual differences average two to three inches over much of the region, with slightly smaller differences in the west and north and larger differences along the Atlantic Coast. Correlations between the interannual differences and year indicate that much of the study region has experienced small, insignificant increases. In northern New England correlation coefficients are negative, suggesting a slight decrease in variability. However, the only areas where results proved to be statistically significant at the 0.95 level were in western New York, and extreme eastern Massachusetts, both areas that have experienced large increases in total precipitation. Therefore it may be concluded that autumn precipitation has increased significantly in both the western and eastern portions of the study region, and that this increase has been accompanied by only a small increase in interannual variations.

Temporal Patterns of Trends

Figure 5 shows the temporal patterns of precipitation change for four representative climate divisions. In eastern Massachusetts and Rhode Island, autumn precipitation totals have risen at a relatively steady rate over the 100-year period. Though the time series displays a great deal of interannual variability, the underlying trend has continued to be upward. Autumn precipitation time series for western New York and northwestern Pennsylvania also display long-term upward trends, but much of the increase appears to be a function of a step change in the late 1960s. Though the two regions both contain significant increases, the temporal patterns of change are somewhat different, and therefore the causes of the changes may be different.

The two major regions of precipitation change also differ when the seasonal trends are broken down monthly. In September only easternmost Massachusetts shows a statistically significant precipitation change in the east. The remaining climate divisions with significant trends are all found in western New York and Pennsylvania. Very few climate divisions show any significant trends in October. The most dramatic pattern of precipitation trends occurs in November, when virtually the entire study region, with the exception of northern New England and southern Delaware, displays significant trends. For the region as a whole, climate changes in November are most important in explaining autumn precipitation trends. For the western portion of the study region, however, it is also necessary to consider early season changes in September as well.

POSSIBLE CAUSES OF PRECIPITATION TRENDS

Autumn is a transitional season for the climate system over the northeastern United States. As the season progresses, the upper-level atmospheric circulation patterns begin to shift southward. By November a large upper-level trough becomes established over the eastern United States (Harman, 1991). This deepening trough allows the jet stream to penetrate into the region more frequently, and upper-air divergence promotes the formation of midlatitude cyclones along the accompanying polar front. At the surface, a strong high pressure zone is maintained along the southeastern coast of the United States and in the subtropical Atlantic (Davis et al., 1997). Clockwise circulation around this surface anticyclone advects warm, humid air into the Northeast where it can feed into the passing cyclones and provide moisture for autumn precipitation. Changes in precipitation are no doubt linked to changes in either upper-level circulation patterns, surface advection, or both.

Because little atmospheric circulation data are available as far back as 1900, especially for the upper-air, circulation changes over the 100-year period can only be estimated using other proxy data. The causes of century-scale precipitation changes can only be speculated upon. One good indicator of upper-level troughing, and consequently frontal position, is surface temperature. Encroaching polar air masses from Canada often accompany enhanced upper-level troughing, and surface temperatures can be linked closely to continental-scale flow patterns in the Northeast (Leathers et al., 1991). Divisional temperature data for the period 1900-1999 were tested for trends in the same 48-division region. In September, a number of climate divisions in the north and west display significantly negative trends. This result shows that cold air is entering the Northeast earlier in the season, perhaps indicative of earlier upper-air troughing. Fronts entering the region earlier in September may explain the increases in precipitation noted in the western portion of the region. October temperature changes also show a few divisions with decreasing trends, but by November the vast majority of the divisions show increasing temperature trends. In November the

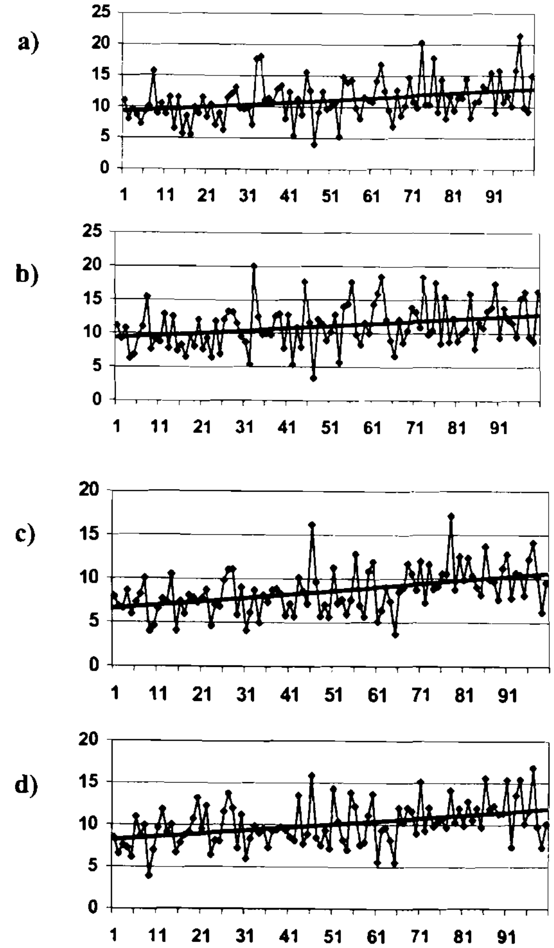

Figure 5: Precipitation (inches) time series from 1900-1999 for a) eastern Massachusetts, b) Rhode Island, c) western New York, and d) northwestern Pennsylvania.

earlier progression of cold air southward has been stalled. This may indicate that the approaching polar front and its accompanying storm tracks arrive in the region earlier in September in the west, pass through the region in October, but are then stalled over the area in November rather than moving farther south and east. This position may then steer cyclones through the Northeast more often and bring higher the region in October, but are then stalled over the area in November rather than moving farther south and east. This position may then steer cyclones through the Northeast more often and bring higher rainfall totals throughout the area. Polsky et al. (2000) suggest that Mid-Atlantic precipitation has been influenced by a deepening upper-level trough through the 1960's, which shifted westward after the 1970's and has brought storm tracks over the region more frequently since then.

Circulation data are more readily available after 1950. A common method of describing circulation patterns is to use teleconnection indices to measure variability. Teleconnection data for 14 major northern hemisphere patterns are available from the Climate Prediction Center (CPC). Monthly data for each teleconnection index were tested for trends since 1950 and also correlated with divisional precipitation data in the Northeast. Only one teleconnection pattern has shown a significant trend in autumn. The East Atlantic pattern describes circulation over the Atlantic basin. The pattern has two major centers of action in autumn, one over the northern Atlantic, and the other over a broad subtropical region in the vicinity of the semi-permanent anticyclone (Barnston and Livezey, 1987). Significantly increasing trends of the East Atlantic index in autumn, especially in November, indicate that this subtropical anticyclone has become stronger over the past 50 years. A stronger subtropical high would both inhibit the southward expansion of cold air, as seen above, and enhance the advection of moisture into passing storms. Significant correlations between the East Atlantic pattern and precipitation in western New York and Pennsylvania indicate that this change has played a role in the major precipitation changes that have taken place across the Northeast in November.

IMPACTS OF PRECIPITATION TRENDS

Increases in autumn precipitation have likely had a number of impacts. Most directly, precipitation changes may be reflected in regional river levels. To test this hypothesis, river flow data for seven rivers in the Northeast were obtained from the United States Geological Survey (USGS). Long-term data were available for the Allegheny, Susquehanna, Schuylkill, and Delaware rivers in Pennsylvania, the Genesee in New York, and the Connecticut and Merrimack in New England. Unfortunately, a station with long term data was not available along the Hudson River. River flow data extend back to at least 1938 for all seven rivers and as far back as 1911 for the Delaware River.

In the annual cycle of stream flow, autumn represents a season of recovery. In all seven river basins, average minimum flow values were recorded in August. As temperatures begin to fall and soil moisture deficits decline in September, more surface runoff begins to reach the rivers. Average flows slowly begin to rise early in the autumn, and by late October and early November are more than double their August levels. High runoff totals persist through the winter months, with all seven rivers recording their highest flows in March or April. Autumn therefore is a critical time for river flow. An unusually dry autumn will extend low-flow periods from the summer and may drop stream flows below critical values for water supply or water quality. A wet autumn will quickly replenish stream flows and may establish a higher base level for high-flow periods later in the winter and spring. Anecdotal evidence suggests that autumn precipitation may even have a large impact on stream flow the following summer. Along the Schuylkill River, a major supplier of drinking water for the Philadelphia area, river flow in summer is only 82% of its average when it follows a year with autumn precipitation deficits of greater than one standard deviation. Conversely, summer flow averages 133% of normal when it follows an autumn that had precipitation surpluses of greater than one standard deviation. Seven of the ten lowest summer river flow values followed autumns of less than normal precipitation, while eight of the ten highest summer flows followed an autumn with above normal precipitation. There are certainly more immediate causes of high and low river flow in spring and summer, yet the evidence suggests that important flow regimes may become established during the autumn period.

Daily stream flow values along all seven rivers were summed for the autumn season and tested for trends. Positive correlations between autumn river flow and year were found for all seven rivers. However, these trends were only statistically increased by 88%, while smaller increases of 38% and 34% were recorded on the Connecticut and Merrimack, respectively. These three rivers lie in the portions of the study region where significant increases in precipitation have also occurred. Increases along the Genesee River, in western New York, were significant at the 0.90 level. Flow data for the Allegheny, and to a lesser extent for the Genesee, also exhibit an abrupt step change in the late 1960s. The concurrence of this step change with that of precipitation in western Pennsylvania and New York (Figure 5) suggests that this increase was real and not a result of instrumental changes in rainfall measurements. The three rivers in the central portion of the study region, where precipitation changes were less pronounced, do not display significant trends. These changes suggest that in the areas of largest precipitation increases, hydrologic impacts have occurred. Any influence of autumn precipitation changes on later season river levels is not evident. Summer flows on the Allegheny, Connecticut, and Merrimack have increased, but these trends are not statistically significant.

CONCLUSIONS

The northeastern United States experienced a significant increase in autumn precipitation between 1900 and 1999. Thirty-four of the 48 climate divisions in the region displayed statistically significant trends over the century. The largest increases were found in western New York and Pennsylvania, where changes in September and November have produced a 30-45% increase in autumn precipitation totals, especially since 1970. In coastal New England changes in November have increased overall precipitation by 25-35%. These increases in autumn precipitation totals have been accompanied by small increases in interannual variability. Precipitation has not changed significantly in northern New England, and along a north-south transect from eastern New York, through New Jersey, to Delaware.

Early season precipitation increases in the western portion of the study region have occurred simultaneously with decreases in temperature in the latter portion of the time period, indicating that enhanced upper-level troughing and earlier appearances of the polar front may be linked to precipitation changes in this area. In November widespread precipitation increases have been accompanied by temperature increases. This may indicate that the polar front has not passed through the region by this month and may continue to encourage storm tracks to pass through. Additionally, an increasing trend in the strength of the East Atlantic teleconnection pattern since 1950 indicates that the subtropical high has increased in strength during the latter half of the century. This may retard the movement of the polar front southeastward, and would also encourage enhanced advection of moisture into the Northeast. While not conclusive, these results should be followed up in the future to more definitively explain the rainfall changes.

Precipitation increases in the Northeast have had an impact on local river basins. Rivers in western Pennsylvania and New England have experienced significant increases in autumn flow levels. These increases occur at a time in the seasonal cycle when rivers are recovering from low summer flows. Increasing autumn flows then carry over into the winter, spring, and even the following summer to influence hydrologic impacts. Climate change over the last 100 years, whether naturally-induced or anthropogenic, have brought a wetter regime to the northeast United States in autumn. These increases in precipitation have raised river flows and reduced the risk of extending summer dry periods later into the year. Conversely, higher base flow may set the stage for later problems in the winter and spring when runoff increases. Whether this has led to an increase of flooding potential will, of course, depend upon the types of climate changes that have occurred in those seasons.

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