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Relationships Between Synoptic Weather Type Frequencies and Snowfall Trends in the Lee of Lakes Erie and Ontario

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ABSTRACT

The relationship between synoptic weather type frequencies and snowfall trends in the lee of lakes Erie and Ontario is investigated. Large positive trends in monthly snowfall values are documented for the traditional snowbelt regions for the period 1931 through 1990 for the month of January. The Temporal Synoptic Index (TSI) is used to identify synoptic patterns that are common to the eastern Great Lakes region during the snowfall season (November through March). The association between an individual synoptic pattern and snowfall is evaluated by consideration of basic meteorological principals. Results indicate that the positive snowfall trends in this region during the month of January are coincident with increasing frequencies of synoptic patterns found to be associated with lake-induced snowfall. Thus, secular variations of the large-scale atmospheric circulation are likely to be an important contributor to the observed positive trend in January snowfall in the snowbelt region of the eastern Great Lakes. No relationship between variations in lake surface conditions and the snowfall trends are apparent.

INTRODUCTION

The influence of the Great Lakes on surrounding local and regional climate has been well documented by a number of authors (i.e. Eichenlaub 1970; 1979; Changnon and Jones 1972). During the winter months, vertical fluxes of sensible heat and moisture, from the lake surface to the atmosphere, cause a destablization of the lower atmospheric layers, resulting in increased cloudiness and precipitation on the lee side of the lakes (Eichenlaub 1970; Holroyd 1971; Jiusto and Kaplan 1972). If the passage of a cold air mass over the warmer waters results in the establishment of a superadiabatic lapse rate somewhere in the surface to 850 mb layer, lake effect precipitation is likely to occur (Holroyd 1971). As the convective clouds produced by this situation move inland, interactions with the large-scale synoptic situation and the local topography may further enhance the precipitation (Dewey 1979). Snowfall produced from such a situation can be extremely intense, with tens of centimeters falling in a 24-hour period. Eichenlaub (1970) estimates that at least 30% of the seasonal snowfall in the lee of Lake Michigan is the result of lake-atmosphere interactions, while other authors have suggested snowfall increases of 40% to as high as 300% at upwind locations with optimum slope and aspect characteristics (Dewey 1970; Strommen 1974; Gatz and Changnon 1976; Braham and Dungey 1984).

Previous work indicates that large increases in seasonal snowfall in the areas to the lee of the Great Lakes have taken place during this century (i.e. Namias 1960; Eichenlaub 1970; Braham and Dungey 1984; Leathers et al. 1993). Although the interannual variation in snowfall in these areas is great, a general monotonic increase is evidenced at many stations. For example, Figure 1 shows seasonal (November through March) snowfall values for Fredonia, New York for the period 1931 through 1990. Over this 60-year period a linear trend of 2.16 cm/year is indicated, giving a total increase of 126 cm over the period of record. Such large increases in snowfall are of potentially great societal importance affecting among other segments of society transportation, recreational activities, educational institutions and agricultural concerns. The mechanisms responsible for the large snowfall increases are not well known. Some mechanisms that have been suggested as possible causes of the snowfall increase include more frequent outbreaks of arctic air over the region (Namias 1960; Eichenlaub 1970; Wagner 1979; Braham and Dungey 1984), fluctuations in lake surface conditions (temperature and ice cover) and

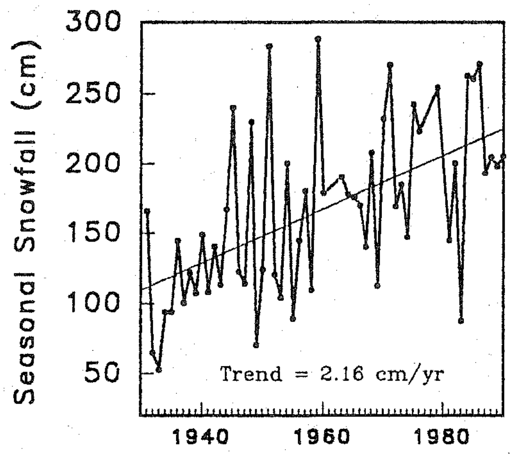

Figure 1. Seasonal (November - March) snowfall values for Fredonia, New York 1931 - 1990.

human induced snowfall enhancement through pollution increases (Changnon 1968; Schaefer 1969). This paper presents a detailed analysis of the mechanisms responsible for increases in January lake-induced snowfall in the lee of lakes Erie and Ontario during the period 1950 through 1982, through the use of a synoptic climatological approach.

DATA AND METHODOLOGY

The snowfall data used in this research is extracted from the NCDC Summary of Day data archive. This data set includes daily snowfall amounts for both first order and cooperative weather stations covering the states of Pennsylvania and New York. Daily data is collected at 160 stations for the 5-month period November through March for the years 1950 through 1982 (Figure 2). Daily 1200 UTC surface pressure and 850 mb temperature data are taken as a subset of the National Meteorological Center octagonal grids (Jenne 1975). Thus, the atmospheric data represent synoptic conditions during the morning hours. The surface pressure data is collected for the entire period of record while 850 mb temperatures are available beginning in 1962.

An automated Temporal Synoptic Index (TSI; Kalkstein and Corrigan 1986; Kalkstein et al. 1987) is constructed for Syracuse, New York. The TSI uses principal components analysis and a clustering procedure to assign each of the 4840 days included in the study period (November 1 through March 31 for the period 1950 through 1982) to a particular synoptic category, based on that day's surface meteorological conditions at

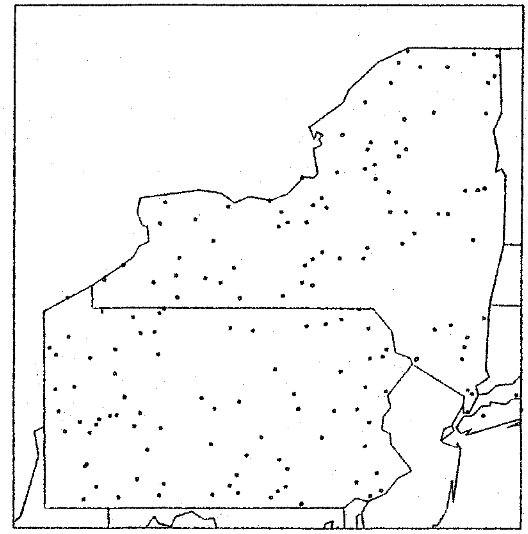

Figure 2. Distribution of stations with daily snowfall observations.

Syracuse. To accomplish the classification, each day of the period is defined by 24 meteorological variables that are available from the TD-1440 hourly data archive (Kalkstein et al. 1990). The variables included in the analysis are air temperature, dewpoint temperature, cloud cover, sea level pressure, wind speed and wind direction, all of which are collected at six hour intervals each day. Twenty synoptic types are identified for Syracuse for the snowfall season. However, 12 of the 20 categories account for over 94% of the days contained within the period. During January, six synoptic categories are associated with snowfall. These six categories account for 80% of the total days. Subsequent to the identification, the surface pressure and 850 mb temperature fields representing each synoptic type are produced through standard compositing techniques using the days contained within a particular synoptic category. These fields represent the general character of the atmosphere on days of a given synoptic type. Syracuse was chosen as the key station for the TSI because of its central location in the Lake Ontario/Erie snowbelt region. We hypothesize that a synoptic-scale event affecting Syracuse will be representative of the synoptic situation over the entire region.

All subsequent contour maps are produced in two steps. First, the irregularly spaced data points are interpolated to a regularly spaced grid using an inverse distance squared, nearest neighbor technique. The regularly spaced grid is subsequently contoured using an automated computer routine.

RESULTS

The linear trend in January snowfall across Pennsylvania and New York is shown in Figure 3 for the snowfall seasons 1950-51 through 1981-82. It is clear from inspection of this figure that the areas to the lee of Lake Erie and especially Lake Ontario have experienced very large snowfall increases over the 32-season period.

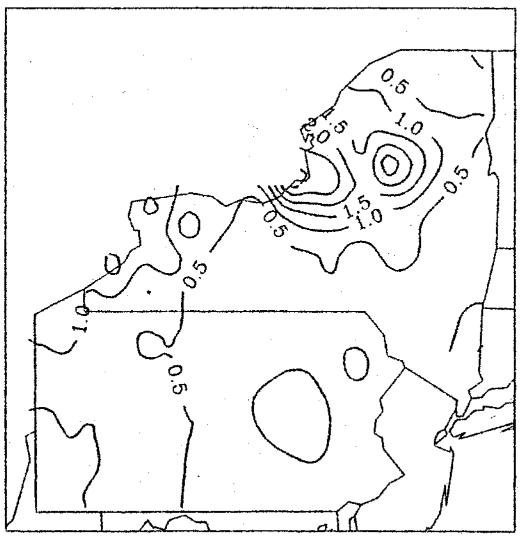

Figure 3. Linear trend of January snowfall 1950-51 through 1981-82 (cm/year).

Areas located a greater distance from the lake influence have experienced smaller increases over the same time. Six synoptic patterns are identified as snowfall producers for the region during January. Of these, four are identified as "lake snow" synoptic situations and two as being associated with cyclones (designated as "cyclone snow" patterns). These identifications were made by inspection of the surface pressure and 850 mb composites that correspond to each synoptic type. In addition, for a synoptic pattern to be designated a "lake snow" pattern the temperature difference between the 850 mb level and the Lake Ontario surface temperatures must be greater than 13° C with a prevailing westerly wind component at the surface (Holroyd 1971).

An example of a "lake snow" pattern is shown in Figure 4. The surface pressure associated with this synoptic type is characterized by a strong area of high pressure located in the mid-Mississippi valley and relatively low pressures northeast of New England (Fig 4a). Between the two, a strong pressure gradient is evident across the eastern Great Lakes with surface flow crossing the lakes from a WNW direction. At 850 mb, composite temperatures over the Lakes are very low, as low as -24° C over Lake Ontario (fig 4b).

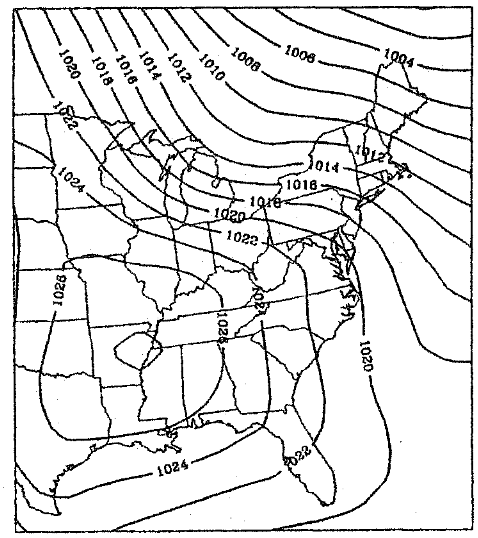

Figure 4a. Surface pressure (mb) associated with "lake snow" synoptic type 4.

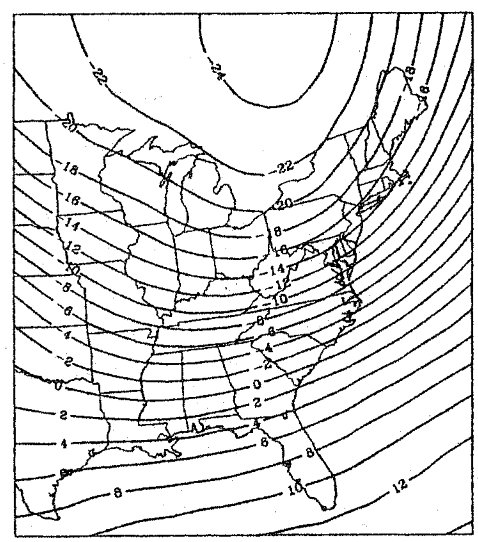

Figure 4b. 850 mb temperature (C) associated with "lake snow" synoptic type 4.

This low 850 mb temperature combined with an average lake temperature of approximately 2° C for Lake Ontario and 1° C for Lake Erie (Environment Canada 1992) gives a surface to 850 mb temperature gradient of 26° C and 25° C respectively. This temperature difference is twice the gradient commonly considered sufficient for the initiation of lake-induced precipitation (Holroyd 1971). The percentage of days on which snow occurs under this synoptic situation is shown in Figure 4c. In the general area to the lee of the lakes, snowfall is recorded on greater than 80% of the days on which this synoptic type occurs. This percentage drops rapidly away from the lake areas. Figure 4d shows the average daily snowfall that occurs on days of this synoptic type. These values are calculated by dividing the total snowfall that occurs at each station on days of this synoptic type by the number of days that the type occurred over the 32-season period.

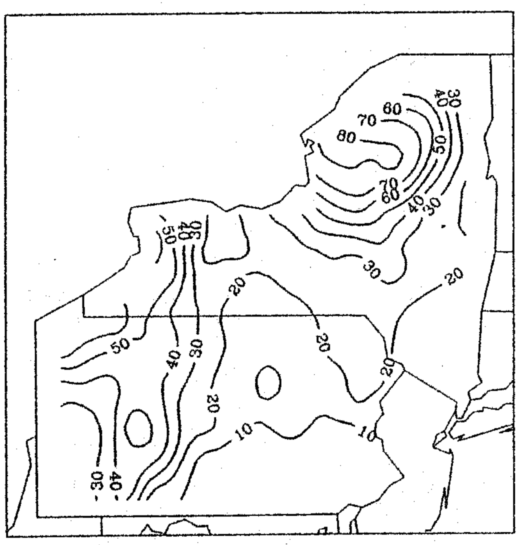

Figure 4c. The percentage of days on which snow occurs on days of "lake snow" synoptic type 4.

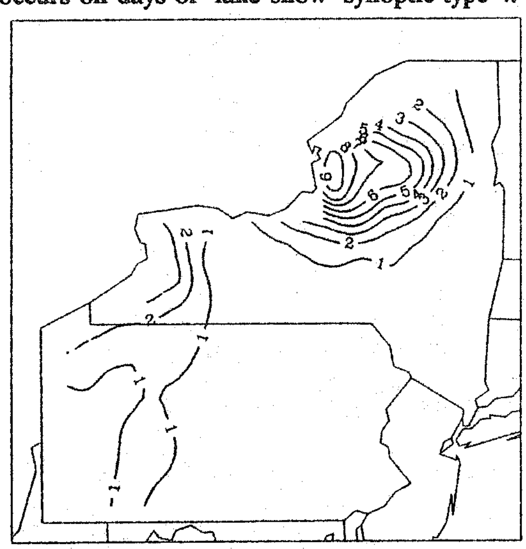

Figure 4d. Average daily snowfall on days of "lake snow" synoptic type 4.

It is clear that areas to the west of Lake Ontario are most greatly affected by this pattern. Up to 10 cm of snowfall per day falls from this synoptic type over the Tug Hill plateau region of New York. Given the very unstable nature of the over-lake atmosphere and the general flow direction, this snowfall distribution is very realistic.

A time series showing the number of January "lake snow" days (the sum of all synoptic types classified as "lake snow") is shown in Figure 5. A modest increase in the number of "lake snow" days occurs over the period, with a linear trend of 0.10 days/yr or an increase of 3.2 days over the period of record.

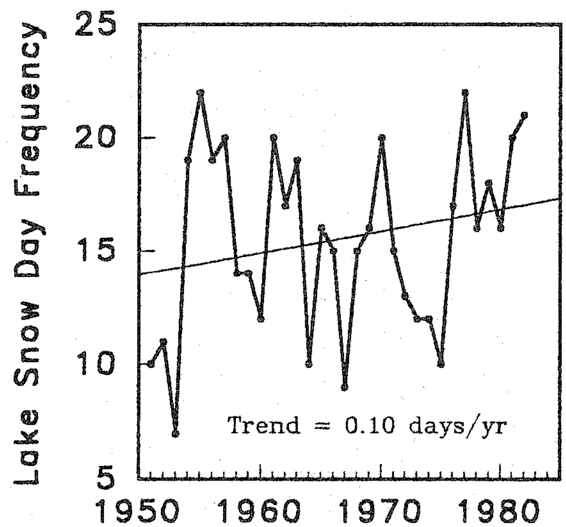

Figure 5. Time series of the number of January "lake snow" days 1950-51 through 1981-82.

Figure 6 gives the predicted snowfall trend associated with the increase in "lake snow" days for the month of January. This predicted trend is calculated by multiplying the trend in a "lake snow" synoptic types by the average snowfall that occurs at each station on days of that synoptic type. Clearly, the area to the east of Lake Ontario would experience the greatest effect of the increase in "lake snow" days with predicted linear trends of greater than 1.0 cm/year. To the lee of Lake Erie predicted snowfall trends are less. This is likely associated with extensive ice coverage on shallow Lake Erie during this month (Environment Canada 1992). A comparison of Figures 3 and 6 show that a large percentage of the snowfall increase in the lake effect area is associated with an increase in the frequency of "lake snow" days. The correspondence of the

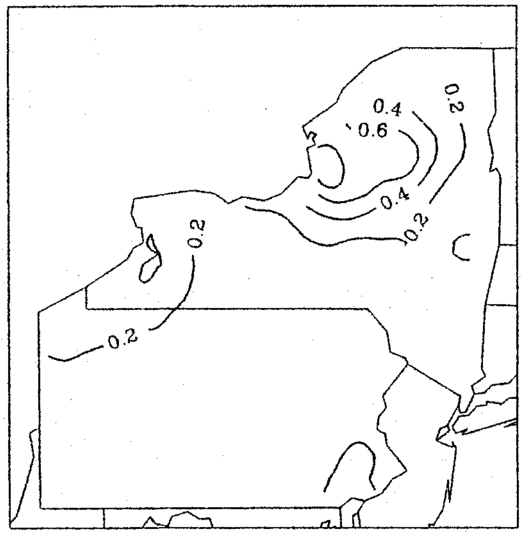

Figure 6. Predicted January snowfall trend associated with all "lake snow" synoptic types (cm/year).

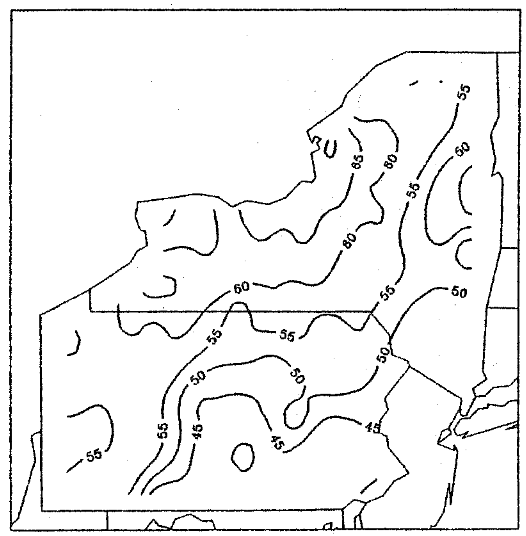

Figure 7. The percentage of total January snowfall attributed to the four "lake snow" synoptic types.

spatial patterns between the predicted and observed trends is very good.
However, the magnitude of the predicted snowfall trend is smaller than the observed. Two likely explanations can be advanced for this discrepancy in the magnitudes. First, the magnitude of the observed trends is affected by the Januaries of 1977 and 1978 when extreme snowfall amounts were common across the region. With these years removed from the analysis, the magnitude of the observed trends in the lee of Lake Ontario decrease by approximately 33%. Therefore, the magnitude of the observed and predicted snowfall trends matches more closely if these extreme values are removed. Second, additional results have shown a tendency for an increase in snowfall amount on "lake snow" days. Thus, an increase in the amount of snow that falls on "lake snow" days may be responsible for the larger observed trends.

Finally, Figure 7 shows the percentage of total January snowfall that is attributed to the four "lake snow" day synoptic patterns. In the lee of the lakes, at least 60% of the snow that falls during January is associated with lake-induced precipitation.

DISCUSSION

The analysis presented above indicates that an increase in the frequency of synoptic types that are associated with lake-induced snowfall accounts for much of the observed trend in snowfall in the lee of Lakes Erie and Ontario. Analyses for the other winter months (December and February) suggest a similar relationship. The influence of changing lake surface temperatures and/or ice cover was also evaluated in this study. No lake surface changes were identified that are likely to be statistically or physically related to the observed snowfall trends in the snowbelt region. Future work will focus on hemispheric and planetary-scale changes that are associated with the increase in "lake snow" synoptic patterns during the winter months and in the potential mechanisms associated with the within-synoptic type snowfall increases. Knowledge of the components of the climate system responsible for the regional-scale changes in snowfall in the eastern Great Lakes may lead to a better understanding of potential cyrospheric variations associated with global environmental change.

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