NOTES AND CORRESPONDENCE

Great Lakes Winter-Weather 700-hPa PNA Teleconnections*

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ABSTRACT

A positive 700-hPa Pacific–North America (PNA) circulation index in December 1989 was replaced by a negative PNA index in January and February 1990. This circulation pattern reversal was associated with an anomaly reversal in air temperatures over the eastern half of the United States and anomaly reversals in the air temperature, snowfall, and ice cover of the Great Lakes. Evidence of PNA teleconnections with these Great Lakes climatic variables for a 20-winter base period is presented through correlations of anomalies in the monthly 700-hPa PNA index and PNA coordinates with anomalies in Great Lakes average monthly air temperature, snowfall, and ice cover.

1. Introduction

Winter 1990 was unusual because of large anomaly reversals in monthly temperature, lake-effect snowfall, and ice cover (Assel and Norton 1990) and a large December 1989–January 1990 anomaly reversal in monthly 700-hPa geopotential heights (Janowiak 1990). December 1989 had the lowest December temperature, and January 1990 had the third-highest January temperature of the past 93 years in the Great Lakes region. During December 700-hPa height anomalies were negative over the North Pacific, southeastern United States, and North Atlantic Ocean, and positive over western Canada. During January 1990 these 700-hPa anomaly patterns reversed. Lake-effect snowfall along the lee shores of the Great Lakes (portions of the southern and eastern shores) was above average in December 1989 and below average in January 1990 relative to a 20-winter average (1960–79). The mild January temperature continued into February, bringing an unusual midwinter decline in ice cover on Lakes Erie, Michigan, and Ontario.

In this paper, winter anomalies in average monthly Northern Hemisphere 700-hPa heights for the Pacific–North America (PNA) index and PNA coordinates (Wallace and Gutzler 1981) are correlated with coincident regional Great Lakes anomalies in monthly air temperature, snowfall, and ice cover for the 20-winter period of 1960–79. Ancillary correlations are also made between monthly values of snowfall and regional air temperature and between monthly ice cover and regional air temperature. The correlation coefficients and the significance probability of the correlations under the null hypothesis that the statistic is zero are calculated using a computer algorithm called CORR (SAS 1990, 209–235). The discussion of possible teleconnections is arbitrarily limited to those correlation coefficients that were significant at the 10% level or lower, although all correlation coefficients calculated for this study and their significance level are presented for the convenience of the reader.

2. The PNA pattern, winter 1990, and possible Great Lakes teleconnections

Average monthly 700-hPa heights for the 20-winter base period were calculated using twice-daily 700-hPa heights from the National Meteorological Center's (NMC) Northern Hemispheric diamond grid 700-hPa dataset. December 1989–February 1990 monthly 700-hPa heights and the difference between winter 1990 and the average in the base-period 700-hPa heights (Fig. 1) portray the hemispheric patterns of upper-air circulation and anomalies for winter 1990.

The circulation of December 1989 resembles the PNA upper-air circulation pattern described by Wallace and Gutzler (1981). Their PNA index, given in the following, is a measure of 700-hPa anomalies at four locations: central and north Pacific ($Z1$ and $Z2$), western Canada ($Z3$), and southeastern United States ($Z4$). Thus,

$$\mathrm{PNA} = \tfrac{1}{4}[Z1^*\,(20°\mathrm{N}, 160°\mathrm{W}) - Z2^*\,(45°\mathrm{N}, 165°\mathrm{W}) + Z3^*\,(55°\mathrm{N}, 115°\mathrm{W}) - Z4^*\,(30°\mathrm{N}, 85°\mathrm{W})],$$

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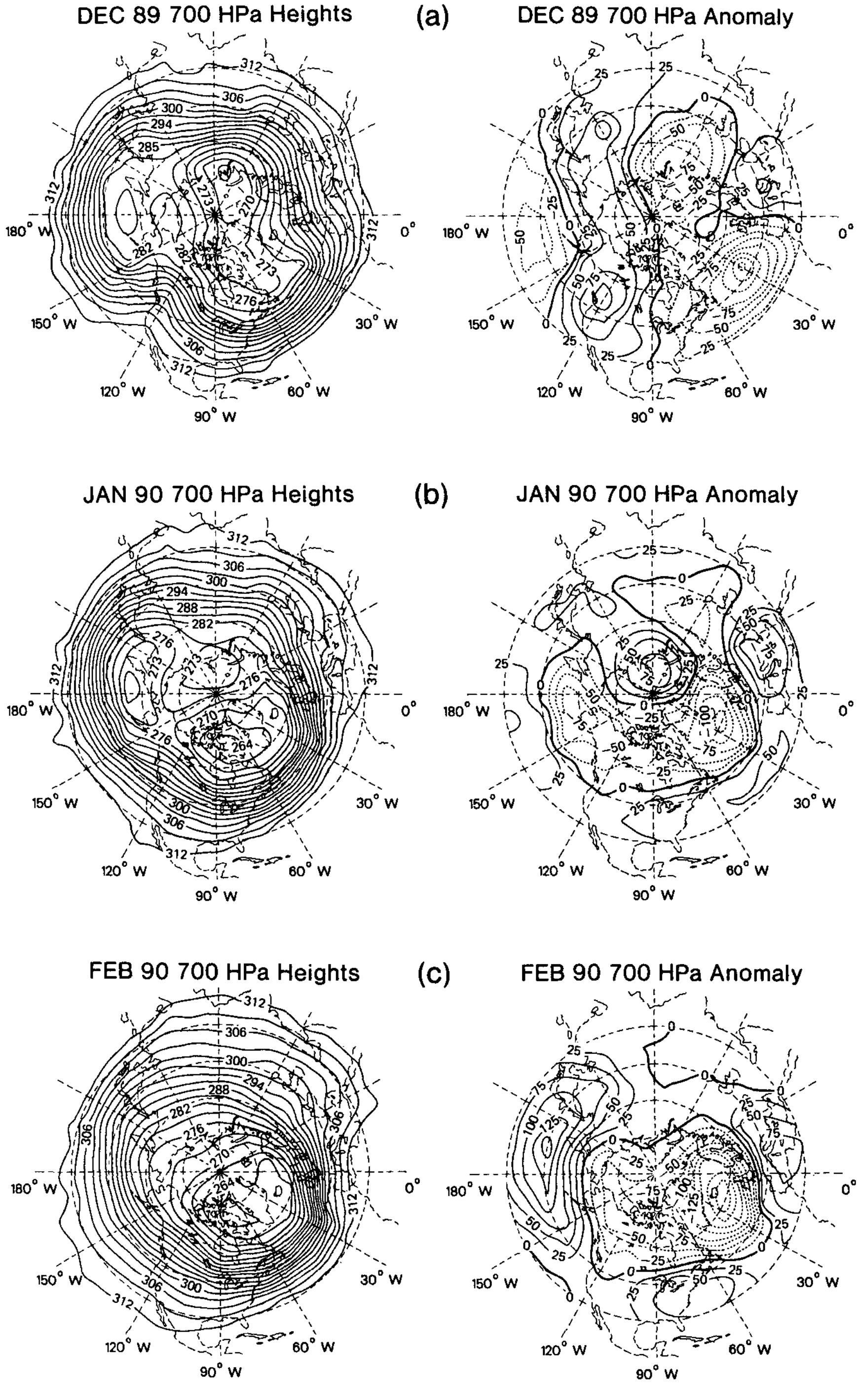

FIG. 1. Monthly 700-hPa height (dam) and 700-hPa height deviations from a 20-yr (1960–79) average (m) for (a) December 1989, (b) January 1990, and (c) February 1990. Dashed lines are for negative deviations from the 20-yr average.

where Z^* is the normalized 700-hPa height anomaly (that is, the difference of the monthly 700-hPa height for given month and the long-term mean monthly 700-hPa height for that month divided by the standard deviation of the long-term mean).

A positive PNA index occurs when a strong trough forms south of the Aleutian Islands in the North Pacific, a strong ridge forms along the western Canadian coast, and a strong trough forms over the eastern United States and adjacent Atlantic Ocean during the winter months, as occurred in December 1989 (Fig. 1a). This circulation pattern results in the advection of polar and arctic air into the midsection of the continent and is associated with above-normal snowfall over the eastern United States (Namias 1960; Wagner 1979). The strong west coast ridge is also associated with above-normal Great Lakes ice cover (Quinn et al. 1978; De Witt et al. 1980; Assel et al. 1979).

A negative PNA index occurs when the Pacific trough and west Canadian coast ridge weaken, allowing zonal flow from the central Pacific to continue across the continent, as occurred in January and February 1990 (Figs. 1b and 1c). With a strong negative PNA index, anomalies in the 700-hPa height field are positive over the central Pacific Ocean, in the eastern United States, and adjacent Atlantic Ocean, and negative over the west coast of Canada. This circulation pattern permits mild maritime air to move into the midsection of the continent producing above-normal temperatures. If temperatures are sufficiently high, negative anomalies occur in Great Lakes ice formation (Assel et al. 1985) and in snowfall in the eastern United States (Namias 1960; Wagner 1979).

3. Great Lakes regional air-temperature and snowfall anomalies

Regional monthly averages were calculated for lake-effect snowfall (nine stations), for non–lake-effect snowfall (ten stations), and for air temperature (all stations) in Fig. 2 for the 20-winter base period and for winter 1990. Normalized values of these climatic variables were calculated by subtracting the 20-winter monthly mean for a given month and then dividing by the standard deviation for that month. Lake-effect snowfall occurs when a cold air mass becomes enriched with moisture as it moves over the relatively warmer lake waters in late autumn and in winter (Hill 1971; McVehil and Peace 1965). In general, any station in the proximity of the Great Lakes can receive lake-effect snowfall, but for the purposes of this study lake-effect stations are defined as those stations along the southeastern shores of Lakes Superior, Erie, and Ontario and the eastern shores of Lakes Michigan and Huron. These stations are more likely to receive lake-effect snowfall than stations located along western and northern shores of the Great Lakes because of the prevailing westerly winds and the southerly movement of cold air masses during winter. Sault Ste. Marie on Lake Superior (Fig. 2) is not included as a lake-effect station because its prevailing winds are out of the east in December and January. The lake-effect stations also receive snowfall due to cyclonic storms, so their monthly snowfall is usually greater than snowfall for windward shore stations whose monthly snowfall reflects primarily mesoscale cyclonic wave activity (Fig. 3).

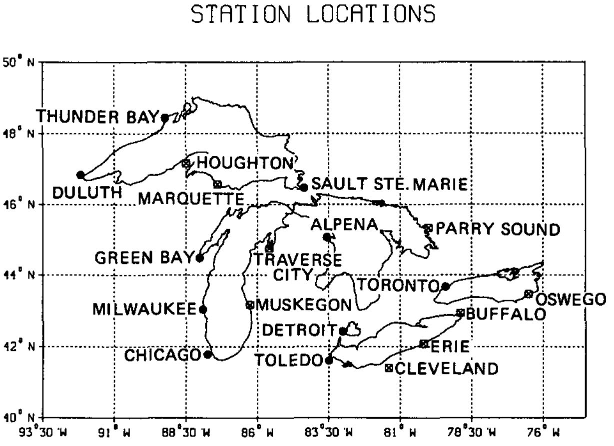

FIG. 2. Air temperature and snowfall stations used to calculate the regional average monthly air temperature (all stations), lake-effect snowfall (open square with cross), and non–lake-effect snowfall (filled circle).

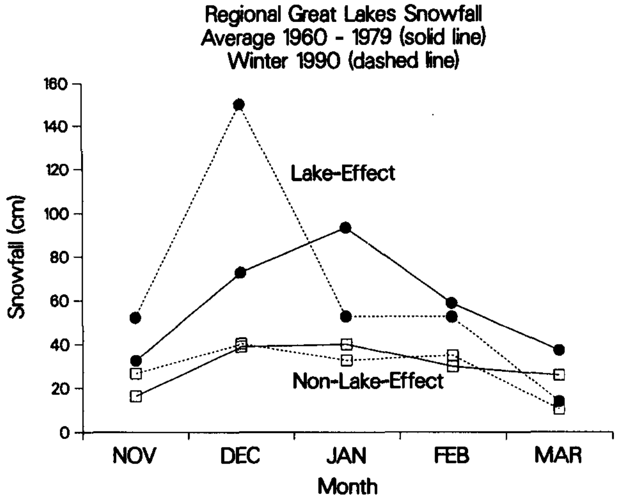

FIG. 3. Regional monthly Great Lakes snowfall: 1960–79 winter average (solid line) and winter 1990 (dashed line).

Large differences between regional snowfall at lake-effect and non–lake-effect stations occurred in December 1989 due to the severity of the cold-air advection into the Great Lakes and the location of the upper-air trough over the eastern United States eastward of its normal position. This eastward shift in the upper-air trough deprived migrating cyclones of moisture from the Gulf of Mexico as they passed by the Great Lakes. By comparison, in December 1977 (and January 1978), a well-developed trough over (and only slightly east of) the Great Lakes extended southward, providing infusion of moist Gulf of Mexico air aloft for cyclonic storms moving eastward (or northward up the east coast of the United States), bringing both above-normal lake-effect (via northwest wraparound cyclonic flow over the Great Lakes during and after storm passage) and non–lake-effect storm-passage snowfall to the Great Lakes.

In January 1990, the ridge over western Canada weakened, resulting in above-freezing average monthly temperatures over southern portions of Lakes Michigan, Erie, and Ontario. These conditions produced a dramatic anomaly reversal in lake-effect snowfall from the previous month (Fig. 3). This anomaly reversal is coincident with an anomaly reversal in the December 1989–January 1990 PNA index and PNA coordinates.

a. Air-temperature teleconnections

Correlation coefficients (Table 1) provide evidence of teleconnections between the PNA index and the *Z2*, *Z3*, and *Z4* PNA coordinates with Great Lakes regional monthly air temperatures for December and January but not for February. The observed positive correlation between winter-season 700-hPa height anomalies in the southeastern United States (*Z4*) with anomalies in monthly regional winter air temperatures in the Great Lakes is in good agreement with previous studies (Dickson and Namias 1976; Wagner 1979). The fact that the lower February correlations of the PNA index and PNA coordinates with air temperature and greater-probability February coefficients are not significantly different from zero may reflect the increasing influence of local factors on the regional air-temperature regime by midwinter (such as increasing regional snow cover and Great Lakes ice-cover extent).

b. Snowfall teleconnections

There does not appear to be a teleconnection between lake-effect snowfall and the PNA index (Table 1) although possible lake-effect snowfall teleconnections were found for December and January snowfall with the 700-hPa anomaly over the southeastern United States (*Z4*). Similarly, correlations between the PNA index and non–lake-effect snowfall provide little evidence of a teleconnection but a teleconnection may exist between non–lake-effect snowfall for February with the 700-hPa anomaly over western Canada (*Z3*).

The negative correlation of 700-hPa anomalies over the southeastern United States with lake-effect snowfall is in general agreement with Wagner (1979), who, for the years from 1947 to 1978, compared the 11 months with the most snow to the 9 months with the least snow for averaged monthly snowfall over 28 stations in the eastern United States with 700-hPa anomalies. However, the negative correlation between snowfall at non–lake-effect stations with 700-hPa height over western Canada is not in agreement with Wagner's (1979) study. The cause for this difference is due to the fact that the non–lake-effect stations in this study average farther north than the lake-effect stations and much farther north than stations Wagner used in his study (Wagner 1991, personal communication). Temperatures are well below freezing in midwinter at most non–lake-effect stations in this study, and Great Lakes ice extent is approaching its seasonal maximal coverage so moisture availability and not temperature is the principal limiting factor for snow at these locations. Negative 700-hPa anomalies over western Canada are associated with more zonal flow, possibly with a southerly component, and air with greater moisture content. A secondary effect of a circulation pattern with a southerly component is that a weak lake effect may operate for stations in the northern portion of the Great Lake (Wagner 1991, personal communication).

c. Air-temperature–snowfall correlations

Climatologically speaking, a greater percentage of December snowfall at lake-effect locations is likely to

TABLE 1. Correlation coefficients (×100)/significance levels (×100). Significance levels are the attained significance levels under the null hypothesis of zero correlation, for example, the December entry for "index" under "air-temperature correlations" (*−45/4*) indicates the correlation coefficient is −.45 and the probability that the sample correlation is from a population with correlation zero is 4%. Coefficients with significance levels under 10% are italicized. It should be cautioned that the significance levels given may not be independent.

Air-temperature correlations with PNA index, PNA coordinates, and snowfall

	Index	*Z1*	*Z2*	*Z3*	*Z4*	Lake effect	Non–lake effect
December	*−45/4*	−26/26	*51/2*	*−38/9*	*39/8*	*−78/<1*	−26/25
January	*−40/7*	30/19	*43/5*	*−45/4*	*60/<1*	*−67/<1*	*−40/7*
February	−13/58	16/48	18/42	−16/48	22/34	−19/40	−29/20

Snowfall correlations with PNA index and PNA coordinates

	Lake-effect snowfall					Non–lake-effect snowfall				
	Index	*Z1*	*Z2*	*Z3*	*Z4*	Index	*Z1*	*Z2*	*Z3*	*Z4*
December	28/23	12/60	−29/20	15/52	*−38/9*	42/85	19/41	<1/97	−27/24	−23/32
January	25/27	−16/48	−26/26	20/38	*−49/2*	−33/88	−23/31	11/63	−3/89	−27/23
February	−19/42	−24/29	6/79	−25/28	5/82	−36/11	−14/55	26/25	*−45/4*	31/17

be due to the lake effect that month compared to later in the winter because of the less extensive December ice cover and the greater air–water temperature gradients possible in December. Therefore, it is not too surprising to find a negative correlation (Table 1) between December lake-effect snowfall and air temperature. Similar correlations are found for both lake-effect and non–lake-effect snowfall in January. The January non–lake-effect snowfall correlation with lower air temperature may reflect increased or more intense cyclonic activity associated with the southward movement of cold polar air masses over the still relatively warm waters of the Great Lakes.

4. Great Lakes ice-cover anomalies

Great Lakes monthly ice cover for December through April was calculated for winter 1990 and for the 20-winter base period. Winter 1990 lake-averaged monthly ice cover was estimated from data given in Assel and Norton (1990) for each Great Lake. The lake-averaged monthly ice covers were summed to produce a monthly value of total ice-covered area for the Great Lakes. The 20-winter average monthly ice cover for the Great Lakes was calculated in a similar manner from data given in Assel et al. (1983). The 20-winter average ice cover, winter 1990 ice cover, and the differences between 1990 and the 20-winter average Great Lakes ice cover, which defines the 1990 anomaly, are given in Table 2 along with cumulative monthly PNA indices.

The 1990 monthly ice cover was above normal in December 1989 and January 1990 and below normal the rest of the winter (Table 2). The above-normal January ice cover occurred despite mild air temperatures because of the carry-over effect of the large positive December 1989 ice-cover anomaly. Above-freezing air temperatures along the southern margin of the Great Lakes in January and February resulted in an anomalous midwinter decrease in February ice cover on portions of Lakes Erie, Ontario, and Michigan (Assel and Norton 1990) and, as a result, below-average February monthly ice cover (Table 2). An increase in ice extent occurred from February to March because of a cold spell starting near the end of February and ending the first week of March. However, above-normal temperatures the second week of March brought a virtual end to any significant new ice formation, and March and April ice covers were below the 20-winter average.

a. Air-temperature–ice-cover correlations

Correlations between air temperature and ice cover have been known for quite some time. Richards (1963) and Rogers (1976) have shown that ice extent is correlated with cumulative freezing degree-days over a winter season. Later, Assel et al. (1985) demonstrated that Great Lakes seasonal maximal ice cover is also correlated with regional monthly winter air temperature. These findings are verified in a climatic sense in this study using the cumulative value of the 20-winter regional average monthly air temperature (Table 2) and the 20-winter average monthly ice cover (Fig. 4).

b. Ice-cover teleconnections

A linear trend was found between the average 20-winter cumulative monthly PNA index and the average monthly ice cover of that 20-winter period (Fig. 5). Thus, there appears to be a teleconnection *in a climatic sense* between the 700-hPa index and Great Lakes monthly ice cover. This climatic teleconnection may be useful in studies of climate change, such as the recently completed study by Smith and Tirpak (1989), as a proxy of multiyear *time-averaged monthly ice cover.*

The linear trend between the 1990 cumulative value of the monthly PNA index departure from its 20-winter average and monthly ice-cover departure from its 20-winter base period (Fig. 6) provided the incentive to examine potential teleconnections between the PNA index and individual coordinates of the PNA index with monthly ice cover.

It was not feasible to make calculations of average monthly ice cover for the total surface area of the Great

TABLE 2. Total Great Lakes ice cover and cumulative* values of PNA index and 20-winter regional-average monthly air temperature.

	Great Lakes ice cover					Cumulative		
	Average		Winter 1990		(1990 − average) (km^2)	PNA index		Air-temperature average (°C)
	(km^2)	(%)**	(km^2)	(%)		Average (m)	(1990 − average) (m)	
December	4 752	1.9	28 928	11.9	24 176	4.9	161.1	−4.3
January	48 983	20.1	62 115	25.4	13 132	15.6	71.3	−12.1
February	125 638	51.5	66 197	27.1	−59 441	39.4	−131.5	−18.9
March	99 956	41.0	82 977	34.0	−16 979	42.0	−84.9	−20.0
April	24 537	10.1	10 008	4.1	−14 528	19.7	4.8	−11.0

* Accumulations start in December

** The percent of total surface area covered with ice

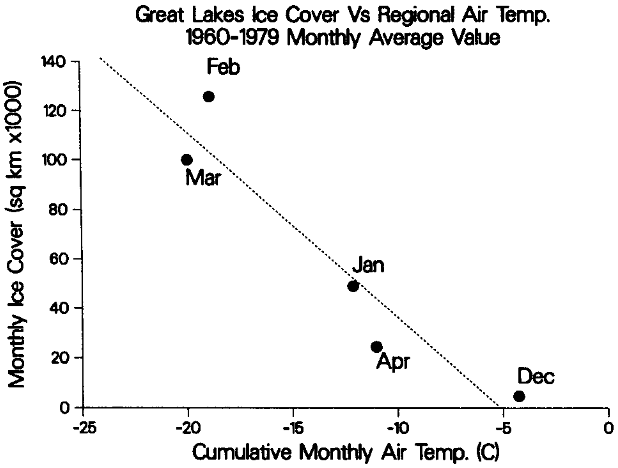

FIG. 4. 20-winter average of monthly Great Lakes ice cover ($\times 1000$ km^2) and cumulative monthly regional air temperature (°C). The dashed line is the linear regression for these data. The correlation coefficient is $-.94$.

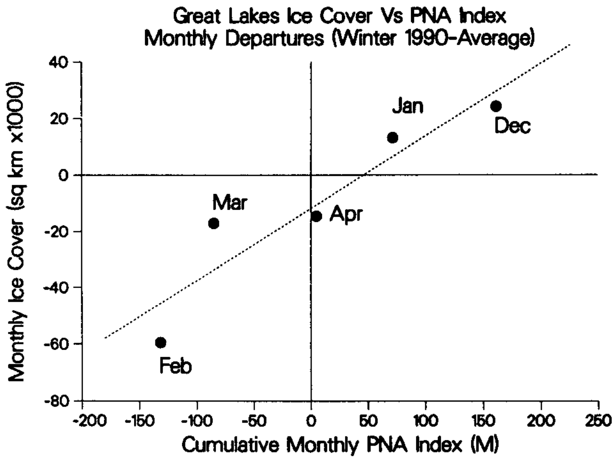

FIG. 6. Monthly departures (winter 1990 − 1960–79 winter average) of Great Lakes ice cover and cumulative monthly PNA index (m). The dashed line is the linear regression for these data. The correlation coefficient is .93.

Lakes for each of the 20 winters because of a lack of observations. However, using freezing degree-day ice-cover models for Lakes Erie and Superior (Assel 1990), monthly ice cover (for December, January, February, March, and April) was calculated for the combined areas of Lakes Erie and Superior for the 20-winter base period. The monthly ice cover was normalized by subtracting out the 20-winter monthly average and dividing that difference by the 20-winter monthly standard deviation. The normalized monthly ice cover of the combined area of Lakes Erie and Superior was correlated with the normalized cumulative monthly PNA coordinates and with the normalized cumulative PNA index for monthly ice covers of December to January, December to February, December to March, and December to April. Results (Table 3) indicate possible teleconnections for the cumulative PNA index through February, for the cumulative values of the $Z2$ and $Z3$ coordinates through March, and for the cumulative value of the $Z4$ coordinate through April. However, coefficients decreased in magnitude and significance in February, March, and April, casting doubt on possible teleconnections past January.

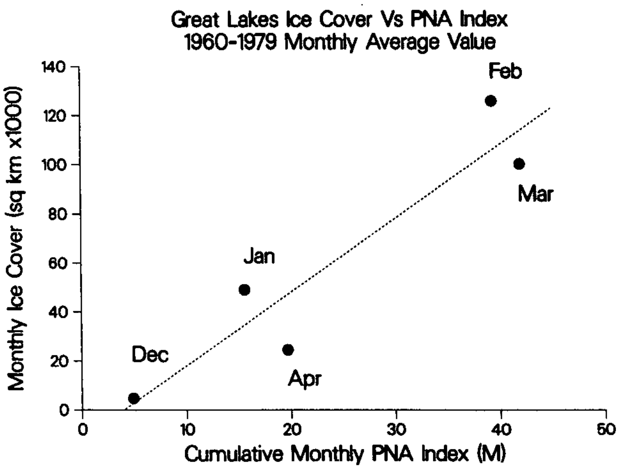

FIG. 5. 20-winter average of monthly Great Lakes ice cover ($\times 1000$ km^2) and cumulative monthly PNA index (m). The dashed line is a linear regression for these data. The correlation coefficient is .93.

A second analysis was suggested by the fact that air temperature appears to be teleconnected with *individual monthly values* of the PNA index and at PNA coordinates $Z2$, $Z3$, and $Z4$ (Table 1) and because ice cover is known to be correlated with air temperature. Therefore, a correlation was made between the ice cover for a given month over the 20-winter base period with the PNA index and with individual PNA coordinates. This was done for each month (Table 3) and the results also indicate that it is plausible that December and January ice-cover anomalies are teleconnected with the PNA index and with 700-hPa anomalies over the North Pacific Ocean ($Z2$), over western Canada ($Z3$), and over the eastern United States ($Z4$), as was the case with the monthly regional air temperature.

5. Summary and conclusions

The results presented here are preliminary in nature. Additional analysis is needed to further investigate the possible teleconnections between 700-hPa heights and climate variables for individual stations, individual Great Lakes, for the decade of the 1980s, and for other 700-hPa NMC grid coordinates.

During December 1989, a strong upper-air ridge along the west coast of Canada and a concurrent strong trough over the southeast United States were associated with record low temperatures over the Great Lakes.

TABLE 3. Correlation coefficients (×100)/significance levels (×100) for PNA index and PNA coordinates with monthly average ice cover for the combined area of Lakes Erie and Superior. Significance levels are explained in Table 1. Coefficients with significance levels under 10% are italicized in this table. Parameter *N* is the number of observations; Index is the PNA index; *Z*1, *Z*2, *Z*3, *Z*4 are the PNA coordinates.

Monthly average ice-cover correlations with cumulative value of monthly PNA index and cumulative value of monthly PNA coordinates

	Index	*Z*1	*Z*2	*Z*3	*Z*4	*N*
December–January	*48/<1*	16/30	*−47/<1*	*47/<1*	*−54/<1*	40 (20 winters × 2 months)
December–February	*29/2*	<1/99	*−32/1*	*30/1*	*−39/<1*	60 (20 winters × 3 months)
December–March	16/14	−13/22	*−19/8*	*22/4*	*−29/<1*	80 (20 winters × 4 months)
December–April	6/54	−15/12	−10/29	8/41	*−21/3*	100 (20 winters × 5 months)

Monthly average ice-cover correlations with monthly PNA index and coordinates

	Index	*Z*1	*Z*2	*Z*3	*Z*4	*N*
December	*55/1*	−26/26	*−57/<1*	*59/<1*	*−46/3*	20
January	*52/1*	−5/81	*−51/2*	*49/2*	*−70/<1*	20
February	8/71	−8/71	−25/26	14/53	4/85	20
March	−3/87	−31/17	13/58	32/16	2/92	20
April	−29/20	−10/66	25/26	−29/21	22/33	20

The negative air-temperature anomaly affected the ice cover and snowfall over the Great Lakes; lake-effect snowfall along lee shores and ice-cover formation was above normal. A change in the upper-air circulation to a zonal flow pattern occurred in January 1990. This new flow regime was associated with above-normal temperatures and below-normal snowfall. Average January temperature was above freezing on southern Lake Michigan (at Chicago, Illinois, and Muskegon, Michigan), on Lake Erie, and over southern Lake Ontario (at Rochester, New York). However, the average January ice cover remained above normal because air temperatures remained below freezing over the northern portion of the Great Lakes and because of the carry-over effect of the large positive December ice-cover anomaly.

Evidence of teleconnections between regional Great Lakes snowfall and regional temperature with 700-hPa heights (at PNA coordinates) is weak, as indicated by the relatively low value of correlation coefficients for these monthly regionally averaged climatic parameters with PNA coordinates.

The PNA teleconnection between Great Lakes ice cover and 700-hPa circulation is more complex than for snowfall or air temperature because of the continuity in ice cover from one month to the next, and because the ice cover is affected by episodic events such as storms (Rondy 1976) and cold-front passage. There appears to be a climatic teleconnection between the 20-winter average PNA index and 20-winter average monthly ice cover that may be useful in the analysis of the impact of climatic change on ice-cover climatology (multiyear-averaged ice cover) in the Great Lakes. There is also possibly a teleconnection between December and January ice cover and the 700-hPa index and 700-hPa coordinates over the North Pacific Ocean, over western Canada, and over the southeast United States. Similar teleconnections were found for regional average monthly air temperatures. The ice-cover teleconnection is more tentative, however, because the ice cover used in this study was based on a freezing degree-day ice-cover model and not actual ice-cover observations.

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