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Ohio Winter Precipitation and Stream Flow Associations to Pacific Atmospheric and Oceanic Teleconnection Patterns[1]

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ABSTRACT. The relationship between the Pacific/North American (PNA) atmospheric circulation teleconnection, equatorial Pacific sea surface temperature anomalies (SSTAs), and Ohio winter (DJF) precipitation and stream flow is described using data for 84 statewide climate stations and 29 rivers. Maximum correlations between the PNA index (PNAI) and station precipitation reach r = -0.7 in southwestern Ohio (n = 53) and are as high as r = +0.6 (n = 104) using a proxy North Pacific index (NPI) comprised of sea level pressures. The Ohio winter precipitation and streamflow relationship with the PNAI and NPI is strongest in southern and southwestern Ohio, generally decreasing to non-significance over northern Ohio, and particularly the northeastern snow belt. In contrast, Niño 3.4 equatorial Pacific correlations reach r = 0.5 when SSTs precede winter by one month. Wettest (driest) Ohio winters occur during relatively zonal (meridional) flow, representing PNAI negative (positive) modes when north Pacific sea level pressure is anomalously high (low). Wet winters are characterized by a 500 hPa trough across the central US east of the Rockies, with surface cyclones and associated frontal activity traversing Ohio after originating in areas such as Colorado and the western Gulf of Mexico. When the meridional flow of the PNA positive mode occurs, Ohio winters are consistently drier than normal and stream flow is typically about 50% of the PNA wet winters. Much higher variability occurs during PNA negative mode winters; precipitation and stream flow are occasionally below normal, but more typically above normal with some extraordinarily wet winters.

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INTRODUCTION

It is widely recognized that winter weather systems most often approach Ohio from the west. However, specific mechanisms by which Ohio weather is affected over many years by events occurring in distant places, such as over the Pacific Ocean, are less well understood. Long-distance linkages in weather and climate, associated with highly significant correlations between atmospheric or oceanic conditions across widely separated points on the earth, are referred to by climatologists as atmospheric "teleconnections." This study shows the impact of Pacific atmospheric and oceanic teleconnections on Ohio winter (December–February; DJF) precipitation and stream flow. One feature in particular, the Pacific/North American teleconnection pattern (PNA), links atmospheric circulation anomalies over disparate regions such as the equatorial Pacific, the northern Pacific, northwestern Canada, and the southeastern United States (Wallace and Gutzler 1981). The PNA impact is such that atmospheric pressure over the Pacific is highly correlated to Ohio winter precipitation and stream flow. This relationship between the PNA and Ohio hydrology is quite strong and very statistically significant throughout the twentieth century, but it is little known until recently.

Variations in equatorial Pacific sea surface temperature anomalies (SSTAs) are known to induce winter atmospheric circulation anomalies such as the PNA across the northern mid-latitudes (Hoskins and Karoly 1981). Winters with unusually high equatorial Pacific SSTAs (El Niño winters) tend to be characterized by a highly amplified mid-tropospheric wave pattern exhibiting unusually low pressure over the northern Pacific and the southeastern United States (US) and an amplified ridge between these locales over northwestern North America. This is the PNA positive mode (Fig. 1b). Conversely, winters with low/negative SSTAs (La Niña winters) are characterized by a zonal wave flow pattern in which high pressure occurs over the northern Pacific and southeastern US while unusually low pressure occurs over central and western North America. This is the PNA negative mode (Fig. 1a). Although often treated as being synonymous with El Niño/La Niña, the PNA mode and amplitude is also affected by other mid-latitude processes associated with perturbations growing from longitudinal gradients in jet exit regions and momentum fluxes associated with high frequency transient storms (Trenberth and others 1998). As such, the PNA is not entirely produced or forced by anomalous equatorial Pacific heating.

Equatorial Pacific SSTAs also affect North American climate, particularly playing a role in regional US moisture budgets. Montroy (1997) links Niño 3.4 SSTAs, those occurring between 5° N and 5° S, 170° W to 120° W, to February and March precipitation variability around the Ohio River Valley. Montroy and others (1998) further suggest that the link is stronger in warm equatorial Pacific events than in cold events. Gershunov and Barnett (1998) find that Ohio River Valley extreme precipitation events have a lower (higher) frequency during warm (cold) equatorial Pacific SSTAs. Wang and Ting (2000) find that Ohio River Valley winter precipitation variations can be linked to SSTAs of both the equatorial Pacific and the mid-latitude Pacific. Enfield and others

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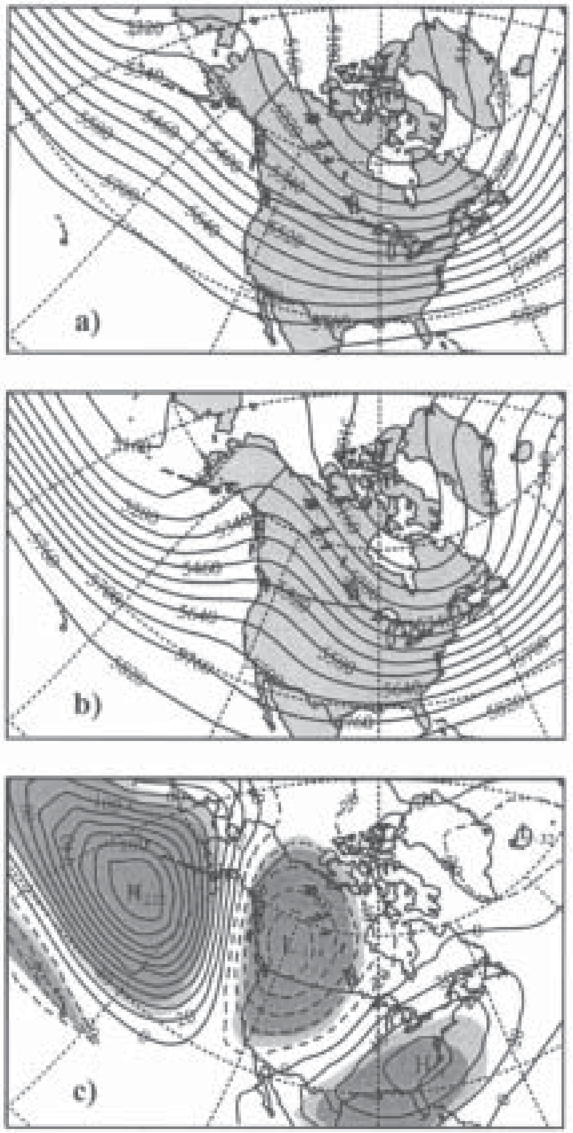

FIGURE 1. The mean 500 hPa height (c) differences (m) occurring between winters when the PNA index is (a) negative and (b) positive in Table 1. Areas are shaded where the differences are significant with 95% and 99% confidence, using a two-tailed *t*-test and dashed contours indicate negative differences.

(2001) show that a strong Niño 3.4 signal in Mississippi River Valley winter precipitation is modulated by the Atlantic multidecadal oscillation. The seasonality and spatial distribution of the US stream flow response to El Niño is described by Kahya and Dracup (1993).

Initially shown by Leathers and others (1991), the PNA influence on winter precipitation across the Ohio River Valley is more thoroughly described by Coleman and Rogers (2003). They show that the PNA/precipitation correlation is in excess of absolute r = 0.60 at many stations across the Midwest and Ohio River Valley, a relatively strong long-term relationship between the atmospheric circulation and climate. Their work also suggests that El Niño/Southern Oscillation signal is not as pronounced in midwestern winter precipitation as is the PNA. The purpose of this study is to increase the number of Ohio weather stations and incorporate a full set of Ohio stream flow records in expanding the analysis of Coleman and Rogers (2003). This study provides more detail of the impact of these Pacific teleconnections in Ohio's winter hydrology and climate, permitting more comparison between the PNA and equatorial SSTA influences. These links between the Pacific and Ohio winter precipitation have not been described in detail previously and are likely of interest to a wider audience beyond climatologists.

MATERIALS AND METHODS

Monthly precipitation data at 84 Ohio weather stations with varying periods of record over 1896-2002 were obtained from the National Climatic Data Center and Midwestern Climate Center. We used cooperative weather observer stations, National Weather Service offices, and airport data having the longest records and minimal missing data. Data accuracy and consistency has been evaluated using a variety of checks and procedures by the National Climatic Data Center. Long-term data sets were created at 14 stations by combining intermediate-length records at stations having the same city name and similar monthly precipitation totals and standard deviations over their periods of record. In these cases the precipitation data were transformed into departures from normal, separately for each, and combined to form one final station data record consisting only of the departures from normal. For the purpose of the correlation and compositing methods used in this study, departures from normal were just as useful as the raw data available for the other 70 stations.

Monthly mean stream flow records for 29 gauging stations were compiled from the US Geological Survey's Hydro-Climatic Data Network (HCDN) (Slack and Landwehr 1992). Stations were selected based on long record length (>50 years) and a paucity of missing data up to the HCDNs end of record in 1988. The HCDN rivers and creeks chosen by Slack and Landwehr had minimal impact from human activities in the form of water flow diversion or augmentation, large reservoirs or dams, and land use changes.

Three indices of the atmospheric and oceanic circulation teleconnection patterns were used. Equatorial Pacific SSTAs are available for the "Niño 3.4" area extending from 5° N to 5° S, 170° W to 120° W (Pielke and Landsea 1999). Niño 3.4 is often linked to US moisture variability (Montroy 1997; Montroy and others 1998; Enfield and others 2001; Schmidt and others 2001). The extreme warm (El Niño) and cold (La Niña) winters since 1920 are listed (Table 1) when SSTAs exceed absolute 0.75° C. The PNA index (PNAI) was calculated using 500 hPa geopotential heights at 4 key teleconnection centers (Wallace and Gutzler 1981). These centers are illustrated in Figure 1c, which shows the result obtained by subtracting the mean 500 hPa height fields of the negative (Fig. 1a) and positive (Fig. 1b) PNA modes. Upper air data for this index are only available since 1947, and the highest and lowest quintile PNAI winters are listed in Table 1. The winter mean PNAI/Niño 3.4 correlation (r = 0.43 from 1947-1999) has a coefficient of variation of only 19%, illustrating that a majority of the

TABLE 1

Winters used in the precipitation and stream flow composites created for negative and positive PNA and NPI modes and for warm and cold SST anomalies in the equatorial Pacific Niño 3.4 region. Winters are dated by the year in which January and February fall.

				Niño 3.4	
PNA-	PNA+	NPI+	NPI-	Cold	Warm
1947	1961	1903	1926	1925	1924
1949	1963	1904	1929	1934	1926
1950	1964	1907	1931	1939	1931
1951	1970	1910	1936	1943	1940
1952	1977	1911	1940	1950	1941
1956	1978	1916	1941	1956	1942
1957	1981	1922	1942	1965	1958
1965	1983	1932	1945	1971	1964
1969	1986	1937	1961	1974	1966
1971	1987	1943	1963	1976	1969
1972	1998	1948	1970	1985	1970
1979		1949	1977	1989	1973
1982		1950	1978	1999	1977
		1955	1981	2000	1978
		1956	1983		1983
		1957	1986		1987
		1969	1987		1988
		1971	1992		1992
		1972	1998		1995
		1989			1998

variance is unexplained and potentially originating from other mid-latitude phenomena. The North Pacific index (NPI) is the averaged mean sea level pressure over the Pacific Ocean between 30° N – 65° N, 160° E – 140° W (Trenberth and Hurrell 1994). This area generally corresponds to the large 500 hPa northern North Pacific center of the PNA (Fig. 1c). The PNAI/NPI correlation is r = -0.94 over 1947-1999 (see also Trenberth and Hurrell 1994). NPI data are available since 1899 and represent an excellent PNAI proxy prior to 1946. Positive (negative) NPI mode winters include those in which mean northern Pacific pressure is above 1011 hPa (below 1006 hPa) (Table 1). The Pacific SLP of the NPI is negatively correlated to the 500 hPa PNAI because the PNA phase is considered positive (Fig. 1b) when northern Pacific 500 hPa heights, and sea level pressures (NPI), are below normal. Conversely, high pressure (positive NPI) occurs across the northern Pacific in the negative phase of the PNA.

In addition to correlation analyses, composite mean winter precipitation and stream flow data were obtained for years with positive and negative extremes in the PNAI, NPI, and Niño 3.4. Mean differences were obtained between the positive and negative modes and are tested for statistical significance using a two-tailed t-test.

RESULTS

The Ohio mean winter station precipitation times series were correlated to the PNAI, NPI, and Niño 3.4 SSTA values. PNAI correlations, extending from 1947-1999 for stations with complete periods of precipitation record (n = 53), reached maxima exceeding of r = -0.65 at stations in southwestern Ohio (Fig. 2a), with four stations having coefficients of r = -0.70 (Table 2). A minimum of r = -0.35 occurred at Chardon in northeastern Ohio. Negative coefficients served to indicate that wet (dry) Ohio winters are linked to negative (positive) PNAI values, representing mean zonal (meridional) flow from the Pacific (Canadian Arctic). NPI precipitation correlations (Fig. 2b) peaked at r = +0.60 at Washington Courthouse (Table 2), and a low of r = +0.26 at Chardon. Although NPI correlations were slightly below those for the PNA, they were achieved generally with the additional index data (n = 104 maximum) extending over the period 1899-2002. Coefficients remained significant in the northern part of the state with values around r = 0.3. An analysis conducted using the nonparametric Spearman rank correlation coefficients, based on the ranks as opposed to actual values, confirmed the significance of the correlations shown in this study.

Niño 3.4 SSTAs are often statistically linked to US precipitation at time lags extending up to about four months in advance of winter (Enfield and others 2001). Two columns of Table 2 show examples of coefficients between concurrent (DJF), and preceding autumn (SON) Niño 3.4 SSTAs with DJF Ohio precipitation. In both cases correlation coefficients were lower than those for the PNA and NPI (Table 2). Coefficients were generally not statistically significant across northern Ohio, falling to values between r = -0.06 and r = -0.20. The highest Niño 3.4 correlations in these cases were at the Portsmouth Grant Bridge over the Ohio River (Table 2). In contrast however, winter (DJF) Niño 3.4 SSTAs were more highly correlated to Ohio mean precipitation during January through March (Fig. 2c, Table 2). Coefficients peaked at r = -0.51 at Portsmouth. The orientation of the correlation field (Fig. 2c) changes from the DJF and SON analyses (not shown) and from that of the PNA/NPI analyses (Figs. 2a,b). Highest coefficients now fall over the southeastern part of the state, decreasing to minima around r = -0.15 in the northwest.

Mean winter precipitation (Fig. 3a) obtained over the period of record at each station exceeded 20.0 cm across the southern third of the state, peaking at nearly 24.9 cm. along the Ohio River at Portsmouth. Precipitation reached minima under 16.0 cm in the northwest and 13.8 cm at Put-In-Bay, an island in Lake Erie. Precipitation in the northeastern snow belt region at Chardon (24.8 cm) rivals that occurring along the Ohio River. The standard deviation about the mean winter precipitation exceeded 8.0 cm in south-central and southwestern Ohio (Fig. 3b), but reached a relative minimum under 5.0 cm in east-central and northern Ohio. Of the

FIGURE 2. Isopleths of correlation coefficients obtained between Ohio winter station precipitation and the (a) PNAI, 1947-1999 and (b) the NPI, 1899-2002. (c) January through March precipitation correlations to the December through February Niño 3.4 Pacific SSTAs, 1920-2000. Contour intervals are 0.1. Large and medium sized dots indicate stations where statistically significant station coefficients occur at the 99% and 95% confidence levels, respectively, while open circles are stations with non-significant coefficients.

TABLE 2

Correlation coefficients between winter (DJF) Ohio station precipitation and atmospheric and oceanic teleconnection indices including the PNA, NPI, and three Niño 3.4 sea surface temperature anomaly (SSTA) relationships. The latter include (column 3) winter (DJF) SSTAs and Ohio DJF precipitation, (column 4) autumn SSTAs and Ohio winter precipitation, and (column 5) winter SSTAs with Ohio January-March precipitation. Coefficients in bold lettering are significantly different from a non-zero correlation with 99% confidence.

Weather Station	PNA	NPI	SSTA DJF	SSTA SON	SSTA JFM
Cincinnati Abbe	**-0.70**	**0.54**	-0.28	-0.28	-0.32
Dayton MCD	**-0.65**	**0.57**	-0.21	-0.21	**-0.31**
Lima WWTP	**-0.60**	**0.57**	-0.23	-0.22	-0.22
Miamisburg	**-0.70**	**0.54**	-0.17	-0.16	-0.29
Portsmouth Bridge	**-0.70**	**0.58**	**-0.44**	**-0.45**	**-0.51**
Washington C.H.	**-0.67**	**0.60**	-0.29	**-0.31**	**-0.42**
Wilmington	**-0.70**	**0.49**	-0.24	-0.29	**-0.33**

state's two high precipitation areas, the standard deviation about the winter mean is 8.1 cm at Portsmouth but only 5.5 cm at Chardon.

Mean winter precipitation differences were obtained between sets of years (Table 1) when extreme positive and negative modes of the PNAI and NPI, and warm and cold phases of Niño 3.4 occurred. Maximum mean precipitation differences (PNA negative mode minus positive) (Fig. 4a) generally decreased from southwest to northeast across the state. Near Lake Erie the mean precipitation differences decrease to less than 6 cm and are largely non-significant. Larger differences exceed 15 cm around Cincinnati and generally exceed 10 cm throughout the Great Miami and Scioto River Valleys. Precipitation differences were statistically significant with at least 95% confidence across the state except at the northernmost locales.

Differences exist in the relative magnitudes of winter precipitation standard deviations between the two PNA modes. In general, across the state, the standard deviation is substantially lower in the positive mode winters. The Wilmington station illustrates this statewide tendency. Wilmington has a mean seasonal precipitation that is 7.2 cm above normal in negative PNA extremes (n = 13) with a standard deviation of 9.9 cm. In positive mode (dry) winters (n = 11) the mean is 8.8 cm below normal with a standard deviation of only 4.5 cm. The low standard deviation for the positive mode is a product of consistently below normal precipitation occurring in all of the winters comprising this mode. The negative (wet) mode however, is typically characterized across the state by a small number of winters (three in the case of Wilmington) having below normal precipitation and some very wet winters with unusually high precipitation. The relatively low absolute value of the mean departure

FIGURE 3. (a) Mean Ohio winter precipitation (cm) and (b) the standard deviation (cm) about the mean, both at intervals of 2.0 cm.

FIGURE 4. Winter mean precipitation differences (cm) occurring between (a) negative and positive PNA modes, (b) positive and negative NPI modes, and (c) relatively low and high Niño 3.4 December–February SSTAs, all listed in Table 1. Significant positive differences occurring with 95% and 99% confidence are indicated by small and large filled circles, respectively, while open circles represent stations exhibiting non-significant differences.

in negative cases (7.2 cm versus 8.8 cm in positive) is a characteristic of PNA results around the state, but does not occur among longer-term NPI results.

Given the large differences in standard deviations between positive and negative modes, the data failed the statistical *F*-test at many Ohio stations. This suggests that the data samples of the two modes were not drawn from the same larger population, further suggesting that parametric statistical tests should not be employed in testing these data. Non-parametric tests such as the Pearson rank correlation were indeed applied but produced results similar to those of Figure 2 that remained statistically significant and suggestive of the same conclusion—that a close relation exists between the PNA and Ohio winter precipitation. It is only the one or two most extreme winters that are skewing the result, producing the disparate standard deviations between the positive and negative modes. If we drop the wettest winter (1950) on record and/or the second wettest (1949) from the PNA negative mode subset, its new standard deviation (and the mean) are substantially lower. Data subsequently pass the *F*-test and the magnitude of the *t*-value significance in analyses such as Fig. 4a maintain levels of statistical confidence nearly identical to those of the full set of 13 cases at most stations. We feel that the parametric *t*-test remains useful in evaluating the significance of subsequent figures, at least representing a relative indicator of the statistical interplay between the mode means, standard deviations, and degrees of freedom.

The mean NPI winter precipitation differences (Fig. 4b) since 1899 (Table 1) are below 12.0 cm in southwestern Ohio but exceed that amount near Portsmouth. The lowest mean differences are 2.7 cm at Chardon and 4.1 cm at Put-In-Bay. In Niño 3.4 extremes (Table 1), mean precipitation differences during DJF are high over southwestern Ohio near Cincinnati (Fig. 4c) but the largest values are near Portsmouth. Two lobes of relatively higher northward-extending differences, in western and southeastern Ohio, separate a relative minimum under 6.0 cm across much of central and northern Ohio. Precipitation differences during January-March (not shown), when Niño 3.4 precedes by one month (DJF), exhibit a similar spatial pattern of variation although exhibiting slightly larger and more significant differences in the western and eastern Ohio lobes. Differences between 6.0 cm and 13 cm occur across the southeast and eastern third of the state, while in western Ohio, north of Cincinnati differences range from 6-10 cm.

Using a representative example (Wilmington), regression analysis of the NPI with winter precipitation (Fig. 5a) yields a linear relationship Y = -1598.8 + 1.6 X, where X is the NPI value (ranging between 1002 and 1015 hPa) and Y is the mean winter precipitation (cm) departure from normal. In this relationship, Wilmington precipitation changes about 1.6 cm for every 1 hPa change in mean Pacific pressure (NPI index value). The diagram shows clearly, in its upper right corner, the occurrence of some of the extreme high precipitation winters. The four winters plotted in the extreme upper right corner represent the wet winters of 1924, 1937, 1949 and 1950, all of which but 1924 are associated with pressures (NPI) above 1011 hPa. The driest winter in the lower left corner is 1977.

Winter stream flow discharge differences between negative and positive PNA cases (Fig. 6a) are statistically significant across the southern half of Ohio and in parts of the northwestern and northeastern parts of the state. Statistical significance is consistently high in southern and southwestern Ohio across the Great Miami and Scioto River valleys. The stream discharge differences in the NPI (Fig. 6b) exhibit a somewhat greater level of statistical significance across the state, failing the significance test at only 5 rivers. The DJF Niño 3.4 river discharge differences for months January through March (Fig. 6c) have high statistical significance also but are distributed in a manner emphasizing central and east-central Ohio.

Mean composites of a small sample of the streams (Table 3) indicate that net discharge during wet winters (PNA negative, NPI positive, and La Niña) can exceed

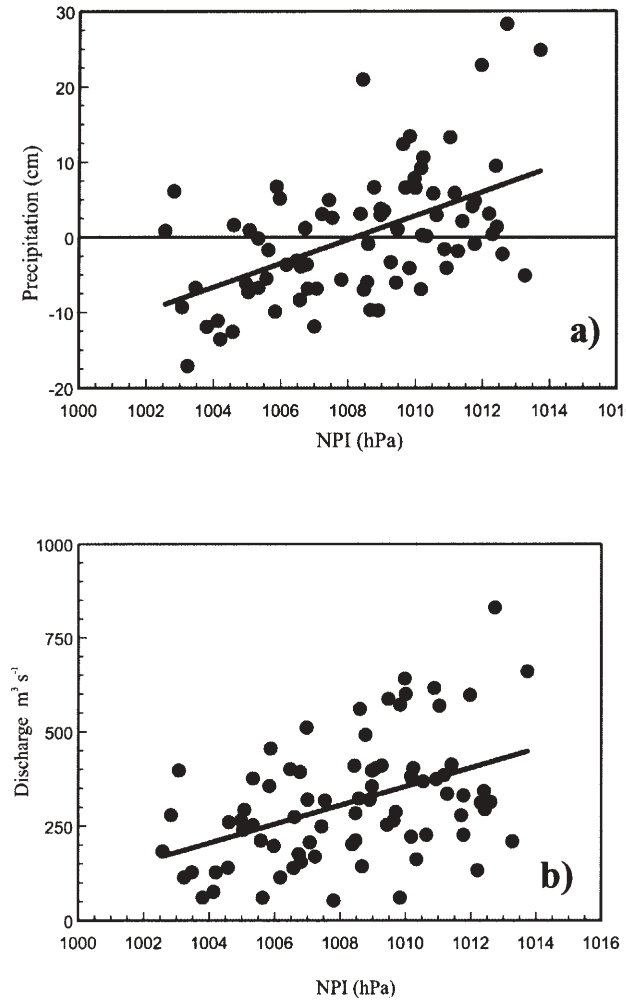

FIGURE 5. (a) Plot of Wilmington, OH, winter precipitation departure (in cm along the ordinate) from normal with the NPI (in hPa on the abscissa). The line represents the solution to a linear regression equation. (b) Plot and linear regression line relating stream discharge (m^3s^{-1}) for the Great Miami River at Dayton (ordinate) and the NPI (hPa).

their drier counterparts (PNA positive, NPI negative, El Niño) by over 100%. Although not included in Table 3, standard deviations of the mean discharge are lower in the dry winters than for wet winters, as was discussed for the precipitation data.

A relationship Y = -24811.9 + 24.9 X exists between Great Miami river discharge (Y, in m^3s^{-1}) and the NPI (X), wherein each hPa change in Pacific pressure is related to a 25 m^3s^{-1} change in winter mean river flow (Fig. 5b). During wet (dry) winters, the NPI averages about 1012 (1005) hPa. The net difference of 7 hPa corresponds to a mean discharge difference of approximately 175 m^3s^{-1}, which is close to the 170 m^3s^{-1} difference (331 vs 161) between NPI modes in Table 3 for the Great Miami at Dayton. A 7 hPa interannual variation in Pacific pressure can thusly lead to large swings in Ohio winter stream flows.

Historical synoptic weather charts were visually examined and storm track plots created during nine winter months (three each of December, January, and February) when the PNA was most negative, as well as during the extremely wet Ohio winters of 1949 and 1950, using

FIGURE 6. Statistically significant winter stream flow differences occurring between (a) negative and positive PNA modes, (b) positive and negative NPI modes, and (c) cold and warm Niño 3.4 December–February SSTAs (Table 1). The stream flow response in (c) is for January through March. Significant positive differences occurring with 95% and 99% confidence are indicated by small and large circles, respectively, while open circles represent stations exhibiting non-significant differences.

TABLE 3

Winter total mean stream discharge (m^3s^{-1}) for the PNA and NPI modes, and for warm and cold Niño 3.4 December–February winter with lagged January–March river flow.

River Gauging Station	PNA		NPI		Niño 3.4	
	-	+	+	-	Cold	Warm
Great Miami at Dayton	348	156	331	161	323	203
Big Darby at Darbyville	80	35	60	34	81	50
Auglaize at Defiance	284	121	249	114	337	192
Hocking at Athens	151	44	150	73	152	110
Scioto at Prospect	74	35	66	35	87	46

maps available from the National Climatic Data Center. Tracks of mid-latitude cyclones occurring during the heaviest rainy periods of the PNA negative winter months were plotted and simplified into the three main storm track patterns shown in Figure 7. PNA negative winter months were generally characterized by active frontal systems over the Ohio River Valley extending from cyclones lying as far west as Colorado and as far south as Texas, Louisiana, and Mississippi. The cyclones of these winters were not particularly intense, typically characterized by one or two closed isobars. Inverted troughs are common, extending northeastward across the Ohio River Valley from weak cyclones originating in the lower Mississippi River valley and Texas (Fig. 7). The idealized main precipitation-associated cyclone track traverses the Ohio River valley, generally staying just north of the Ohio River. Cyclones originate either in southeastern Colorado or appear in Texas after originating as troughs of low pressure in the western Gulf of Mexico. Precipitation is associated with warm frontal passage and subsequently by the low-level cyclone vorticity and the cold front. The second most common track extends northeastward from Texas and Louisiana, lying south of the Ohio River. It is associated with extensive overrunning from warm fronts and troughs protruding northeastward as the cyclones migrate northward from the Gulf. The least common track extends from Colorado through the upper midwest, well northwest of the Ohio River Valley. These systems are typically slow moving, having active and extensive warm, cold, and occluded fronts that sequentially pass over Ohio. The tendency observed here for storms to originate east of the Rockies is consistent with the existence of a subtle mean 500 hPa upper air trough over the central US illustrated for the PNA negative mode cases in Figure 1a.

DISCUSSION

A highly significant relationship exists between the PNA teleconnection pattern phase and Ohio winter precipitation, such that PNA negative (positive) mode winters, characterized primarily by zonal (meridional) flow, have above (below) normal precipitation. Some station correlations between precipitation and the PNAI

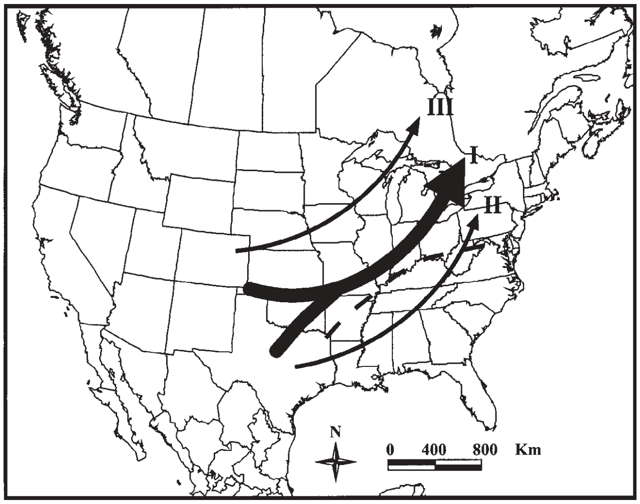

FIGURE 7. Three main paths of cyclones occurring during the three December, January, and February months (each) having the lowest PNA negative index values, as well as during the wettest days in the winters of 1948-1949 and 1949-1950. The dashed line indicates the typical orientation of inverted troughs extending northeastward from cyclones located to the south and west.

reached r = -0.70 since 1947 and coefficients as high as r = +0.60 occurred to the NPI Pacific sea level pressures since 1899. Overall, these long-distance atmospheric teleconnection correlations are among the highest known to exist between circulation and climate variables. In contrast, Niño 3.4 time series, both when Pacific SSTAs lead Ohio precipitation by a season and for concurrent (zero lag) relationships, have slightly lower correlations. Niño 3.4 DJF SSTAs are better correlated when linked to Ohio precipitation and stream flow during January through March. Relatively cold Niño 3.4 events (La Niña) typically occur in conjunction with PNA negative mode winters and are relatively wet. Overall, the correlation results confirm those of Leathers and others (1991), verifying that the longer-term circulation – climate relationship is fairly stable, given the relatively high NPI correlations extending to 1899.

Ohio winter precipitation variability is largest in the southern and southwestern portion of the state. This corresponds to the region where the PNA/NPI helps create relatively higher variances in statewide winter precipitation (Fig. 3b). The large differences in precipitation across the southern and southwestern portions of the state seem synonymous with the large differences in precipitation occurring between positive and negative PNA/NPI modes. Precipitation variability is smallest in the northeast, where the PNA/NPI has the lowest impact on winter precipitation variability. High northeastern Ohio precipitation totals are known to occur due to frequent lake effect snowfalls brought about by dry cold northwesterly flow off of Lake Erie into areas east of Cleveland. Over much of the state, the PNA positive mode variability is low indicating that most of these events, dominated by dry northerly flow, have below normal precipitation. In contrast, a PNA negative mode event does not guarantee a wetter than average winter, but sometimes the winter is extraordinarily wet. An aspect of this variability that has not been considered in this study is winter mean air temperature. PNA positive (negative) winters may likely be colder (warmer) than usual and Serreze and others (1998) indicate that much of the winter precipitation of the eastern US is rain rather than snow during the zonal flow dominating the negative PNA phase winters. It is possible that Ohio rain totals, drawing moisture northward in the negative mode, can vastly exceed the amount of snowfall (specifically its melted water equivalent) coming in the drier northwesterly flow precipitation events of the positive PNA phase.

The atmospheric circulation feature associated with wet winters is the 500 hPa trough lying over the central US, wedged between a ridge of high pressure over the northern Pacific and another over the southeastern US (Fig. 1a). Storms and fronts developing in the southern Plains or in the western Gulf of Mexico, moving northeastward (Fig. 7) with extensive frontal boundaries or inverted troughs, and large precipitation shields that track northeastward leading to the high precipitation of the negative PNA mode.

We show that the Ohio impact of El Niño and La Niña

1) is strongest from January–March in precipitation and stream flows based on the December through February Niño 3.4 index values,
2) and that the January–March response from the equatorial Pacific has a different spatial orientation in precipitation and stream flow from the December through February responses associated with the PNA/NPI, and
3) the magnitude of the PNA/NPI precipitation response exceeds that for the one-month lagged January – March Niño 3.4 signal (r_{max} . 0.7 versus r . 0.5).

Our results are in agreement with several studies recently suggesting that the El Niño/La Niña signal in midwestern precipitation is statistically quite strong. Ohio's precipitation and stream flow signal is consistently significant through the 20th century, occurring in an area least affected by changes in Atlantic oceanic phenomena (Enfield and others 2001). Finding 1) above is consistent with Montroy's (1997) discovery of a Niño 3.4 Ohio River Valley precipitation signal in February and March. Ohio's tendency for lower precipitation and stream flow variability in PNA positive (dry) winters is consistent with results pertaining to El Niño events by Montroy and others (1998) and with Gershunov and Barnett's (1998) finding of fewer (more) extreme winter precipitation events in warm (cold) Niño 3.4 events. Our results, however, suggest that while the PNA and Niño 3.4 responses in Ohio are similar, they are not identical, and that the PNA atmospheric circulation modes more consistently lead to distinctively dry or wet winters than one finds solely from Niño 3.4 statistical relationships. Niño 3.4 correlations to midwestern precipitation are at best statistical linkages, and the PNA circulation regimes represent the best possible manifestation occurring in the mid-latitude circulation that can physically link El Niño to the hydrology of the Midwest. Knowledge of the state of the equatorial Pacific is predictable several months prior to winter and provides the best possible predictor of Ohio River Valley winter precipitation at this time. The fact that PNA/NPI correlations are as high as they are to midwestern winter precipitation suggests that improved mechanisms for forecasting the upcoming winter's mode and magnitude of the PNA should also be pursued.

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