Understanding the Mid-Atlantic Snowstorms During the Winter of 2009-2010

NOAA Attribution Team[#]

The United States Winter Season of 2009-2010

The 2009-2010 winter (December-February) was noteworthy for below-normal temperatures across much of the United States (excluding the Pacific Northwest, the Upper Great Lakes and New England), above-normal precipitation across the mid-Atlantic, southern U.S. and the Northern Plains, and an unusual frequency of major snowstorms across portions of the mid-Atlantic and the South.

Most remarkable was the all-time record seasonal snowfall impacting the mid-Atlantic. As of February 11, 2010, Reagan National Airport accumulated 55.9" for the season, eclipsing previous Washington D.C. record of 1898-99 (see snowfall time series, Fig. 1). Baltimore/Washington Thurgood Marshall Airport received 79.9", surpassing its highest total since record keeping began in 1893. And Philadelphia received 71.6", breaking a record set in 1995-96.In addition, monthly snowfall records were set in Flagstaff for January (54.2"), in Pittsburgh for February (40.0"), and New York Central Park for February (36.9"). For the winter-season as a whole (December-February), North American averaged snow cover was at or above the prior record value set in the winter of 1978-79 (based on snow extent data of the Rutgers University Global Snow Lab).

The severe 2009-2010 winter raises question about the causes for the mid-Atlantic snow storms, and how these extreme U.S. winter conditions are reconciled with global warming. To address these questions, the NOAA Attribution team, led by scientists at the Earth Systems Research Laboratory in partnership with Climate Prediction Center, National Climate Data Center and Geophysical Fluid Dynamics Laboratory, carried out an assessment of the 2009-2010 winter conditions. The assessment summarized in the present report is based on extensive analysis of historical observations and climate model simulations, and a review of key prior published literature.

[#] This expert assessment is a consolidated effort of the National Oceanic and Atmospheric Administration (NOAA). Lead author and contact is Martin Hoerling (martin.hoerling@noaa.gov).

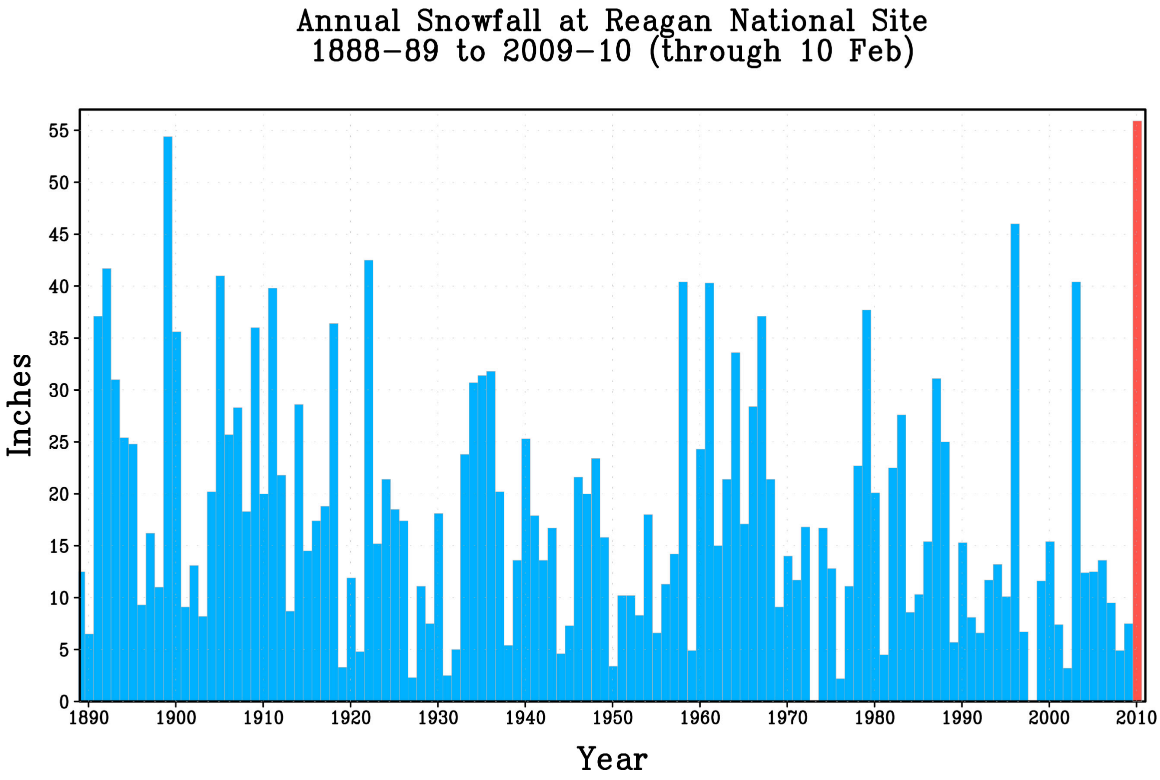

Figure 1. *Annual snowfall record at the Reagan National Site for 1888-89 thru 2009-2010. Red bar denotes the snowfall accumulated through 11 February 2010, whose 55.9" total breaks the 1898-99 record. Note that only 3 years in the last 20-yr period have experienced above-average seasonal snowfall (>15.2"). Data source: NOAA National Weather Service.*

Factors Responsible for Extreme Snow

Our analysis of observational records indicates that the principal factor responsible for the record snowfall along the metropolitan corridor of the mid-Atlantic was the comingled impact of the North Atlantic Oscillation (NAO) and El Niño, both features of natural climate variability. In our assessment, we address the individual role of both the NAO and El Niño and their combined impact.

Role of the NAO

The winter mean of a surface pressure-based NAO index for 2009-2010 was the lowest seasonal value on record, since at least 1950 (Figure 2). The North Atlantic Oscillation, a regional manifestation of the hemispheric-scale Arctic Oscillation (AO), is the dominant pattern of extratropical atmospheric circulation variability that drives climate variability from the eastern seaboard of the United States to Siberia, and from the Arctic to the subtropical Atlantic. The physics of the NAO dynamics[1], its climatic significance, and its environmental impacts have been studied extensively (*1*). The indices, or time series, of the NAO and AO are highly correlated. This assessment uses the NAO index because we focus on impacts that were local to the Atlantic sector, although the anomaly pattern of the winter circulation was highly annular and hemispheric in scale.

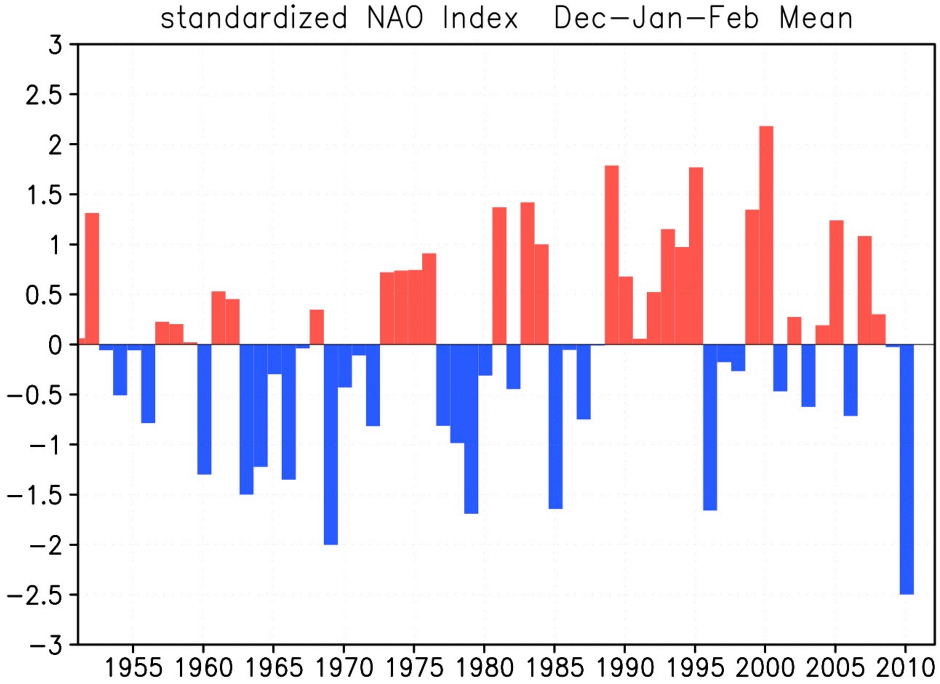

Figure 2. *Time series of the wintertime (DJF) North Atlantic Oscillation (NAO) Index from 1951 to 2010. The recent winter 2009-2010 witnessed one of the most extreme negative (blocked) NAO phases since at least 1950. Based on NCEP/NCAR reanalysis, the NAO index is determined as the difference of normalized surface pressure values between grid points closest to the stations Ponta Delgada (Azores) and Stykkisholmur/Reykjavik, Iceland. Units are of the standardized departures of the index.*

Key to the NAO's role in eastern U.S. snowfall is via its association with the region's surface temperature. Temperature is often the critical factor determining the chance for heavy snowfall (versus rainfall) events in the metropolitan east coast. Climatologically, the rain-snow line is located inland in the vicinity of the eastern

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[1] The NAO is primarily the result of dynamic feedbacks between mid-latitude weather systems, tropical convection, and the jet stream, producing extended periods where the North Atlantic jet stream is shifted north or south of normal (the jet stream was shifted southward in 2009-2010).

slopes of the Blue Ridge and Appalachian mountains in winter, whereas December-February average surface temperatures in the coastal zone, including Washington, D.C., remain above freezing. In the NAO's blocked (negative index) phase, that snow-rain line shifts eastward toward the coastal zone as a consequence of the southward displacement of the climatological North Atlantic storm track. The U.S. eastern seaboard becomes colder than normal and typically resides in the northern quadrant of storm systems resulting in snow rather than rain. Synoptic weather experience also indicates that blocked-NAO conditions sustain colder air throughout the lower troposphere needed for the precipitation to be snow rather than rain or freezing rain in the mid-Atlantic states. These climate and weather features associated with extreme phases of the NAO are shown schematically in Fig. 3.

Consistent with a negative NAO index, the spatial pattern of this winter's anomalous atmospheric circulation pattern at 500-mb (located near the jet stream level that steers storms) reveals the archetypical blocked NAO structure (Fig. 4). Its principal upper air features consist of high pressure over the far North Atlantic, and low pressure over the central North Atlantic. This pattern of climate variability contributed to a redirection of storms and cold air masses that were conducive for mid-Atlantic snow.

There is also an apparent connection of Atlantic conditions westward to include low pressure across the Gulf Coast to the North Pacific (Fig. 4). The Pacific conditions are likely linked to a different physical process of climate variability involving a strong tropical Pacific El Niño event. We discuss the role of El Niño in mid-Atlantic snowstorms later in this assessment.

Analysis of historical data indicates a strong NAO-eastern U.S. snow linkage. For example, 13 of the 15 heaviest snowstorms since 1891 in Baltimore and Washington occurred when the NAO index was negative, and case studies of heavy Northeast snowstorms also identify an NAO link (*2*). Published research of extreme snow event statistics reveal a threefold increase in the probability of heavy snow in Baltimore during the negative AO phase compared to the positive AO phase (*3*).

We found further evidence for a strong link between the NAO and Washington D.C. snowfall by analyzing historical records associated with the ten snowiest months in each of the three winter months December, January, and February since 1891. The resulting 30-month composite of 500-mb height and surface temperature departures (Fig. 5) reveals a characteristic blocked NAO pattern over the Atlantic Ocean, in remarkable agreement with recent conditions (compare Figs. 4 and 5). The association between the current snowfall and the NAO behavior is archetypical of historical relationships, further attesting to the natural (as opposed to anthropogenic) source of this winter's climate conditions.

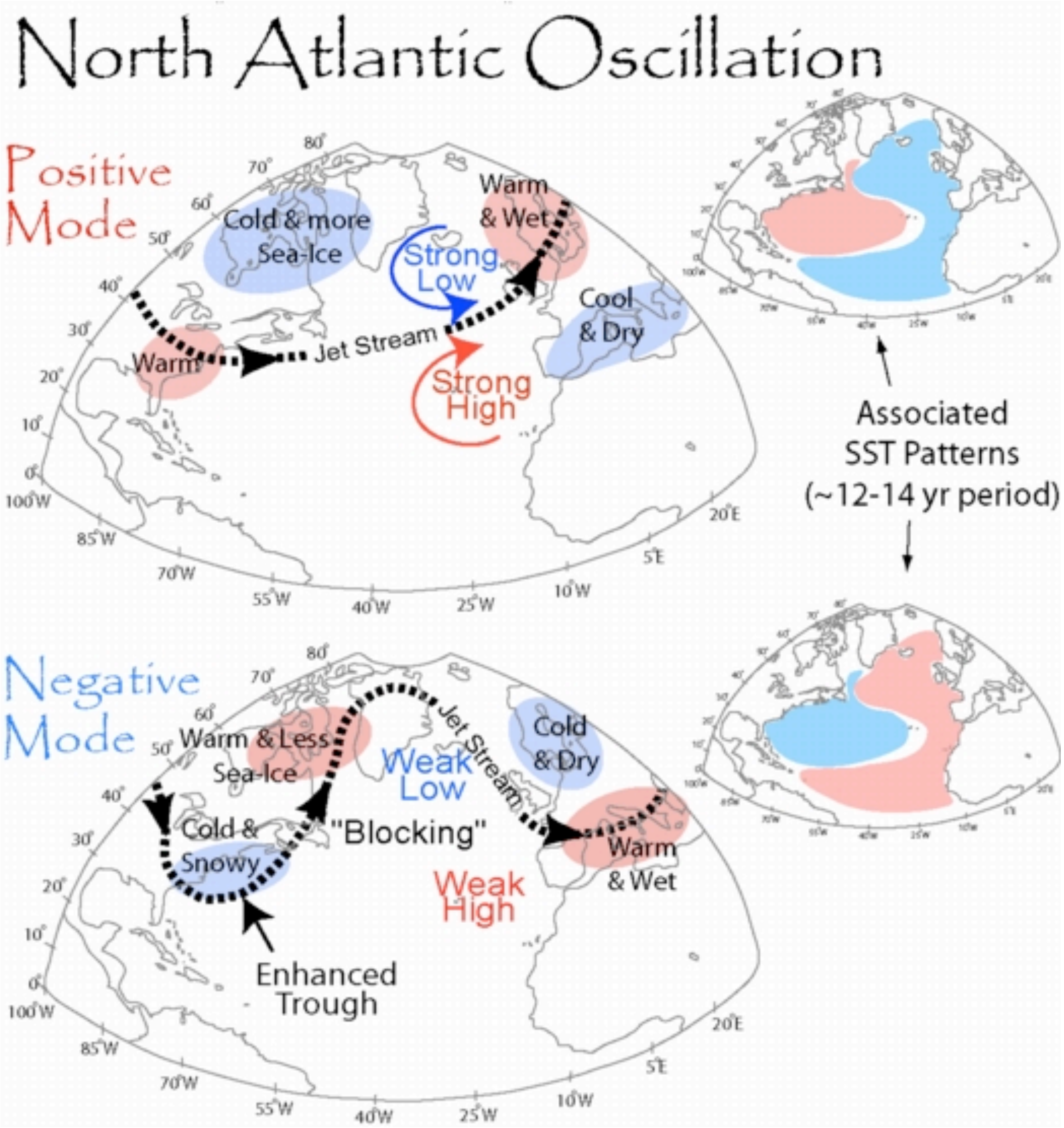

Figure 3. *Schematic of the climate condition (contours, showing jet stream) and weather events (color shading snowing surface temperature/precipitation) associated with the extreme phases of the North Atlantic Oscillation. Source: http://airmap.unh.edu/background/nao.html*

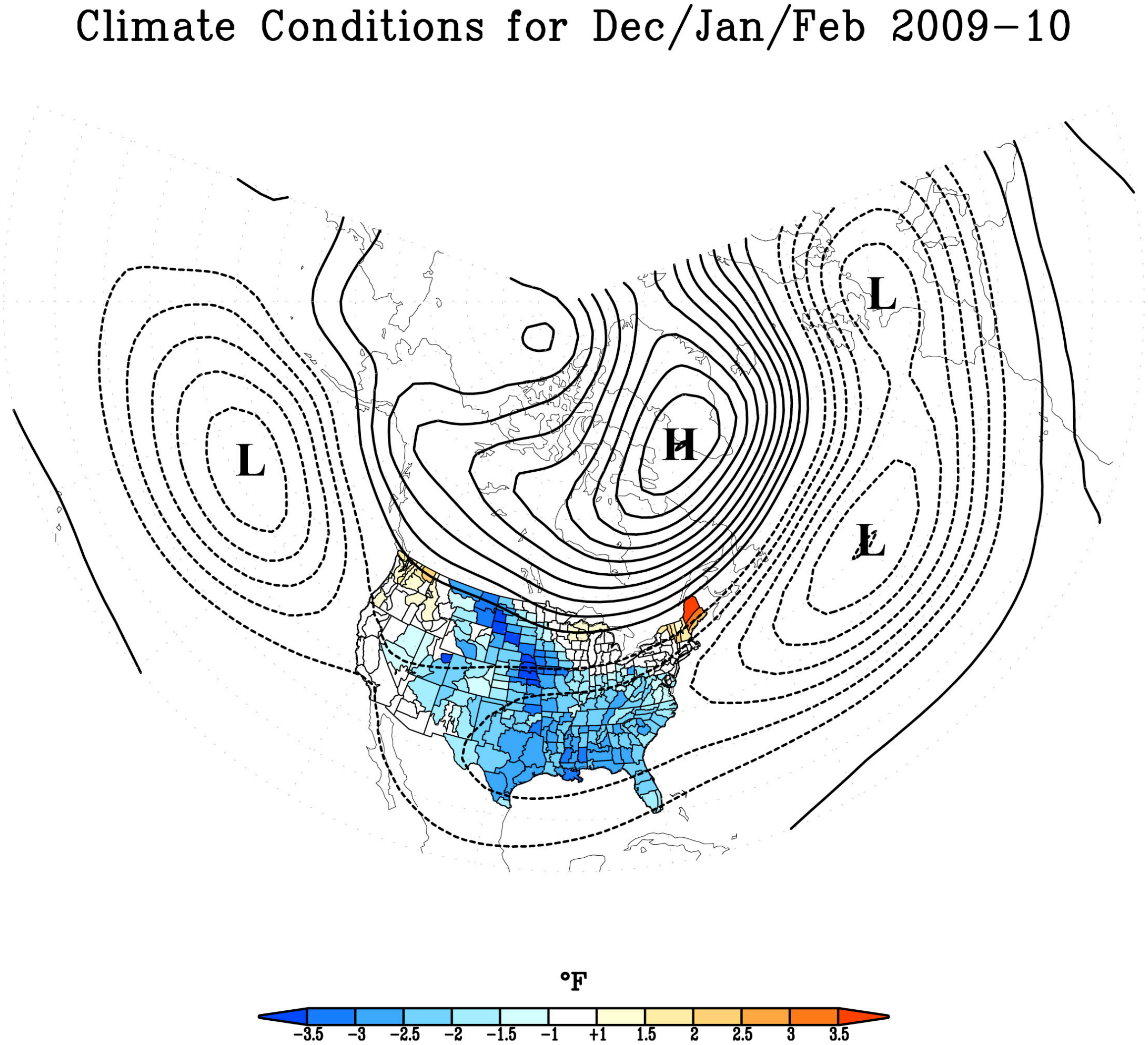

Figure 4. *The December-January-February 2010 anomalies in 500-mb height (contours) and U.S. surface temperature. Anomalies are determined relative to the period 1971-2000. The Atlantic circulation is symptomatic of the blocked phase of the North Atlantic Oscillation, with anomalous upper-air high pressure over Greenland and low pressure over the middle North Atlantic. Contour interval is 20m. Surface data is the NOAA Climate Divisions, and upper-air data derived from the NOAA/NCAR Climate Data System Analysis (CDAS).*

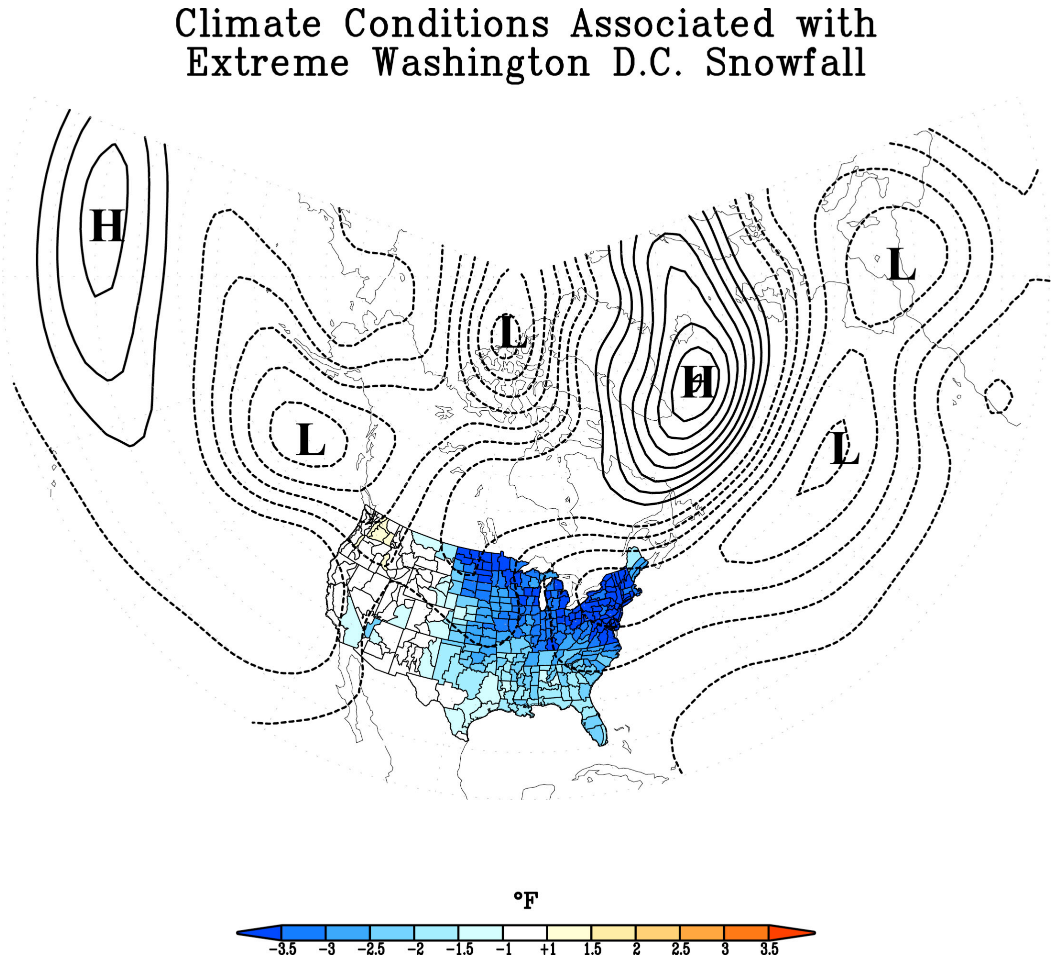

***Figure 5**. The composite anomalies of 500-mb heights and U.S. surface temperature associated with the 30 snowiest winter months recorded at the Reagan National cite during 1895-2008. Reference is 1971-2000 climatology. Contour interval is 5m. Surface data is the NOAA Climate Divisions, and upper-air data derived from the NOAA 20th Century Historical Reanalysis.*

Role of the El Niño

NOAA's TAO/TRITON tropical Pacific Ocean monitoring network indicated that a moderate El Niño had developed by early Fall 2009, which subsequently became a marginally strong event by winter.

Analysis of historical data also reveals a link between El Niño and heavy mid-Atlantic snow. Published results indicate a roughly 30% increase in winter season (December-February) snowfall during El Niño events of 1950-1994 (*4*), on average.

Likewise, a ranking of the top ten largest snowstorms at major cities in the mid-Atlantic during the past century indicates a statistical relationship with El Niño. Philadelphia experienced a remarkable three of its top ten historical snowstorms during this past El Niño winter alone, and six of that city's ten largest snowstorms have coincided with El Niño events (Table 1). Likewise, Baltimore and Washington, D.C., data reveal that six and five of the ten largest snowstorms have coincided with El Niño in each city, respectively (Tables 2 and 3)[2]. It should be noted in Tables 1-3 that many of the El Niño-related snowstorms were also accompanied by a blocked phase of the NAO, making unique attribution to a single factor difficult. Also, not all El Niños (nor all blocked-NAO winters) have yielded heavy mid-Atlantic snowstorms--notably, the statistical El Niño relation did not deliver increased snowfall during 1997-98 (one of the region's least snowiest winters, see Fig. 1) when one of the strongest El Niños of the century occurred. As such, the existence of El Niño alone does not discriminate with certainty between a snowy winter or a "snow drought."

North Pacific pressure, both at the surface and in the upper troposphere was abnormally low during this winter (see Fig. 4), consistent with the teleconnection patterns associated with historical El Niño events (*5*). El Niño's downstream influence on North American climate conditions is principally rendered via changes in the tracks of wintertime storms, which take a more southerly track delivering heavy precipitation from southern California, Texas, and across the southeast U.S.

Tables 1-3. *Top 10 heaviest snowstorms for three mid-Atlantic cities. "E" denotes an El Niño year, based approximately on a 25 percentile of warmest wintertime tropical east Pacific SST. "B" denotes blocked-NAO based on approximately the lowest 25 percentile of the monthly index values of the NAO. Note that both El Niño and blocked-NAO conditions have occurred simultaneously during the majority of historical record snowstorms, making sole attribution to one or the other factor difficult. Snow data source, Weather Underground (Jeff Masters), El Niño source, ESRL/PSD (Klaus Wolter).*

Table 1. ***Philadelphia, PA: Top 10 Snowstorms on Record***
(as of 11 February 2010)

30.7"	*Jan 7-8,*	*1996*	*B*
28.5"	*Feb 5-6,*	*2010*	*B, E*
23.2"	*Dec 19-20,*	*2009*	*B, E*
21.3"	*Feb 11-12,*	*1983*	*B, E*
21.0"	*Dec 25-26,*	*1909*	
19.4"	*Apr 3-4,*	*1915*	*E*
18.9"	*Feb 12-14,*	*1899*	
16.7"	*Jan 22-24,*	*1935*	*B*
15.8"	*Feb 10-11,*	*2010*	*B, E*
15.1"	*Feb28-Mar1*	*1941*	*B, E*

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[2] *The sampling expectation for an El Niño-snowstorm relation due to chance alone is roughly 2-3 out of the top 10. Thus, the observed count of 5 to 7 at the 3 cities is indicative of a doubling in the frequency relative to chance.*

Table 2. ***Baltimore, MD: Top 10 Snowstorms on Record***
(as of 11 February 2010)

28.2"	*Feb 15-18, 2003*	*E*
26.5"	*Jan 27-29, 1922*	
24.8"	*Feb 5-6, 2010*	*B, E*
22.8"	*Feb 11-12, 1983*	*B, E*
22.5"	*Jan 7-8, 1996*	*B*
22.0"	*Mar 29-30, 1942*	*E*
21.4"	*Feb 11-14, 1899*	
21.0"	*Dec 19-20, 2009*	*B, E*
20.0"	*Feb 18-19, 1979*	*B*
19.5"	*Feb 10-11 2010*	*B, E*

Table 3. ***Washington D.C: Top 10 Snowstorms on Record***
(as of 11 February 2010)

28.0"	*Jan 27-28, 1922*	
20.5"	*Feb 11-13, 1899*	
18.7"	*Feb 18-19, 1979*	*B*
17.8"	*Feb 5-6, 2010*	*B, E*
17.1"	*Jan 6-8, 1996*	*B*
16.7"	*Feb 15-18, 2003*	*E*
16.6"	*Feb 11-12, 1983*	*B, E*
16.4"	*Dec 19-20, 2009*	*B, E*
14.4"	*Feb 15-16, 1958*	*E*
14.4"	*Feb 7, 1936*	*B*

El Niño also renders a cooling effect on the eastern seaboard (though this effect is weaker than that rendered by a blocked NAO pattern). This is related to the increased storminess in the south, and the absence of northward tracking storms up the Ohio and St. Lawrence Valleys. A typical St. Lawrence Valley wintertime storm track would promote warm rainstorm events along the mid-Atlantic, but their frequency was reduced this year owing partly to El Niño.

The NOAA official seasonal forecast indicated an increased probability for colder-than-average winter conditions throughout the South and mid-Atlantic, consistent with the scientific studies and the historical impact of past El Niños (see NOAA's seasonal temperature outlook issued mid-October, Fig. 6). Currently, NOAA's official seasonal forecast does not include expectations for snow conditions.

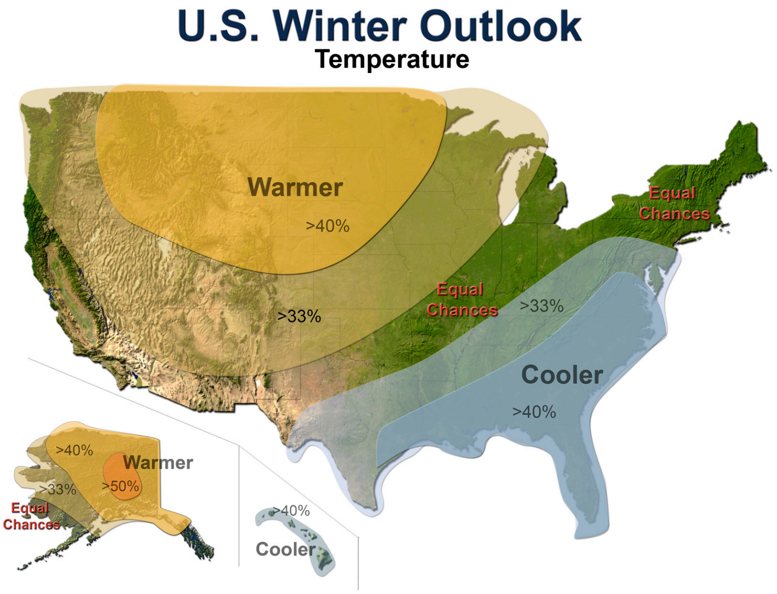

Figure 6. *NOAA's December-February 2010 seasonal climate outlook for temperature. Issued mid-October 2009 by NOAA's Climate Prediction Center.*

The Comingled Role of El Niño and Blocked-NAO in 2009-2010

The above discussion, based on analysis of historical data and review of key prior published papers, leads to the following assessment: Both blocked-NAO atmospheric circulation and El Niño tropical sea surface temperatures yielded climate conditions conducive for cold winter temperatures, above-average seasonal snowfall, and an enhanced risk of heavy snowstorms along the mid-Atlantic corridor (in addition to other regions from the southern central U.S. through the Southeast).

> ***Both blocked-NAO atmospheric circulation and El Niño tropical sea surface temperatures yielded climate conditions conducive for cold winter temperatures, above-average seasonal snowfall, and an enhanced risk of heavy snowstorms along the mid-Atlantic corridor. The NAO and El Niño are both features of natural climate variability.***

To illustrate the relative contribution of these two modes of natural variability during 2009-2010, we diagnose how each factor, and their linear combination, affected December-February surface temperatures over the entire North Hemisphere. Shown in the lower panels of Figure 7 are the contributions of El Niño (left) and the NAO (right) to the DJF seasonal temperature departures. While the characteristic pattern of the El Niño impact is discernable over the U.S., and is consistent with the official NOAA seasonal outlook for the 2009-2010 winter, it fails to explain much of the spatial pattern and intensity of the hemisphere-wide conditions that were observed (top left panel). In contrast, the NAO condition is found to explain much of the amplitude and pattern of winter conditions, including the severity and large scale of U.S. coolness, and the extreme winter conditions over the Eurasian land mass. The linear combination of the El Niño and NAO impact on surface temperature, shown in the upper right panel of Fig. 7, is in excellent agreement with observations. We should point out that, at present, there is no scientific basis for predicting the phase of the NAO on seasonal time-scales, and therefore NOAA's official seasonal forecasts (Fig. 6) do not account for NAO variability.

While NAO dynamics were principally responsible for the temperature conditions this past winter, it is unlikely that the remarkable occurrence of numerous record-setting snowstorms in the mid-Atlantic can be reconciled with a sole or even dominant NAO effect alone. A quantified evaluation of the impact of each mode of climate variability on the snowstorm occurrences, and the reasons for the strong annularity of hemisphere-wide anomalies as indicated by the AO index, is not possible without the use of climate simulations.

The anomalous air mass sources associated with *both* Pacific and Atlantic storm track displacements were likely important for the mid-Atlantic snows. Figure 8 (color shades) illustrates the storm tracks during this past winter, and the comparison with their climatological tracks reveals several key shifts. First, the Pacific sector experienced a slight southward and eastward displacement, consistent with the known effect of El Niño on storms. Second, the typical storm track that emerges from the lee of the Rockies was virtually absent. And third, the Atlantic storm track was shifted considerably south of its normal position.

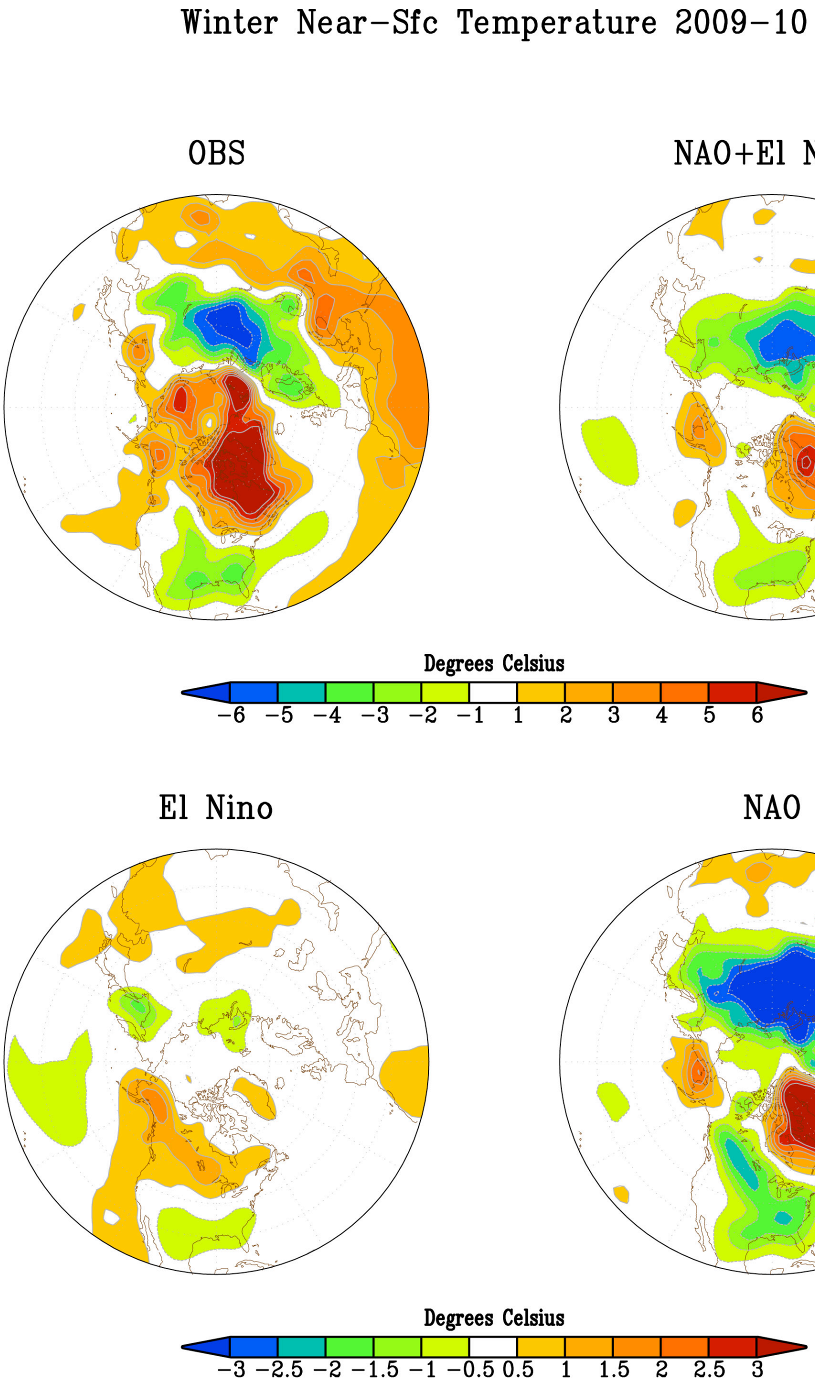

Figure 7. *December-February 2010 observed near-surface temperatures anomalies (top left), and the components linearly related to the El Niño conditions (bottom left), the NAO condition (bottom right), and the linear combination of El Niño and NAO. Data is based on the monthly NCEP/NCAR Reanalysis 1000mb temperature. Contour interval in the lower panels is ½ that in the upper panels. The El Niño impact is calculated by regressing the index of Niño3.4 SSTs on wintertime 1000mb temperatures during 1951-2010, and then scaling by the observed Niño 3.4 seasonal index value of +1.69 for 2009-2010 (Data source: CPC ERSST.V3B SST Niño 3.4 index). The NAO impact is calculated by regressing the NAO index in Fig. 2 on the wintertime 1000mb temperatures during 1951-2010, and then scaling by the observed NAO seasonal index value of -2.49 for 2009-2010.*

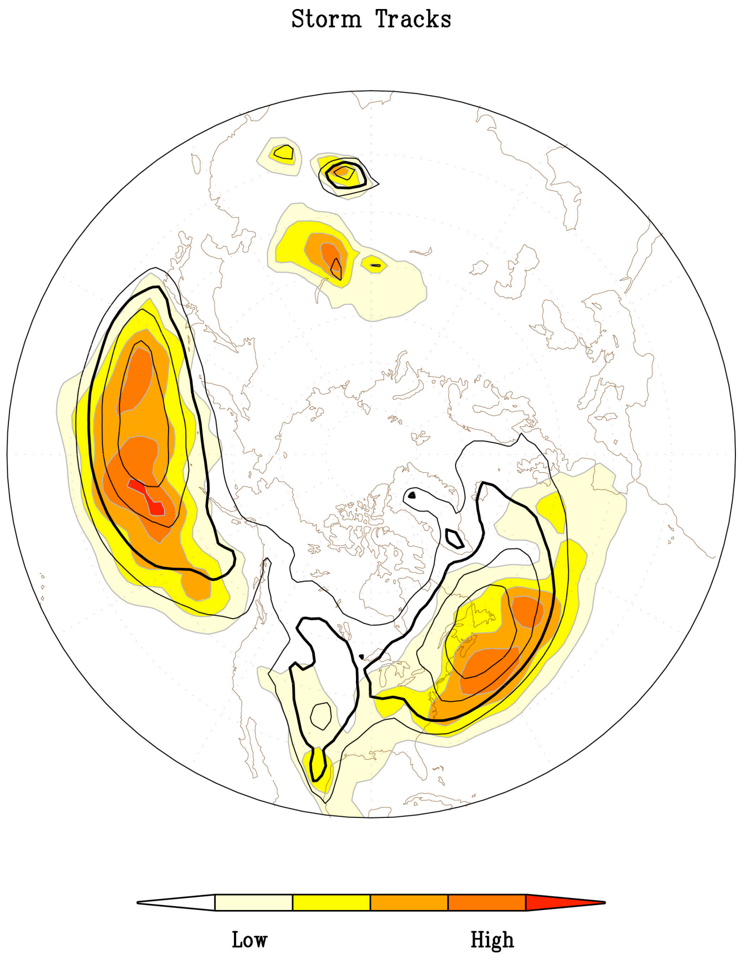

Figure 8. *Storm tracks during December-February 2010 (shading) compared to the climatological storm tracks during 1971-2000. The analysis is based on the variance of daily surface pressure tendency from 1 December thru 28 February. The pressure tendency is normalized by the Coriolis parameter. The regions of high variance are indicative of the dominant trajectory of synoptic weather systems, in particular cycles. The bold solid contour of daily surface pressure tendency variance from the climatological analysis corresponds to the same amplitude during 2009-2010, enclosed by yellow shading.*

Is the Record Mid-Atlantic Snow Symptomatic of Climate Change?

Historical analysis of U.S. snowfall indicates that there has been no detectable increase in heavy snowstorms in the mid-Atlantic region (*6*). The results from Changnon, *et al.,* in fact suggest that the period 1901-50 experienced a greater frequency of heavy snowstorms as the period 1951-2000 (Fig. 9).

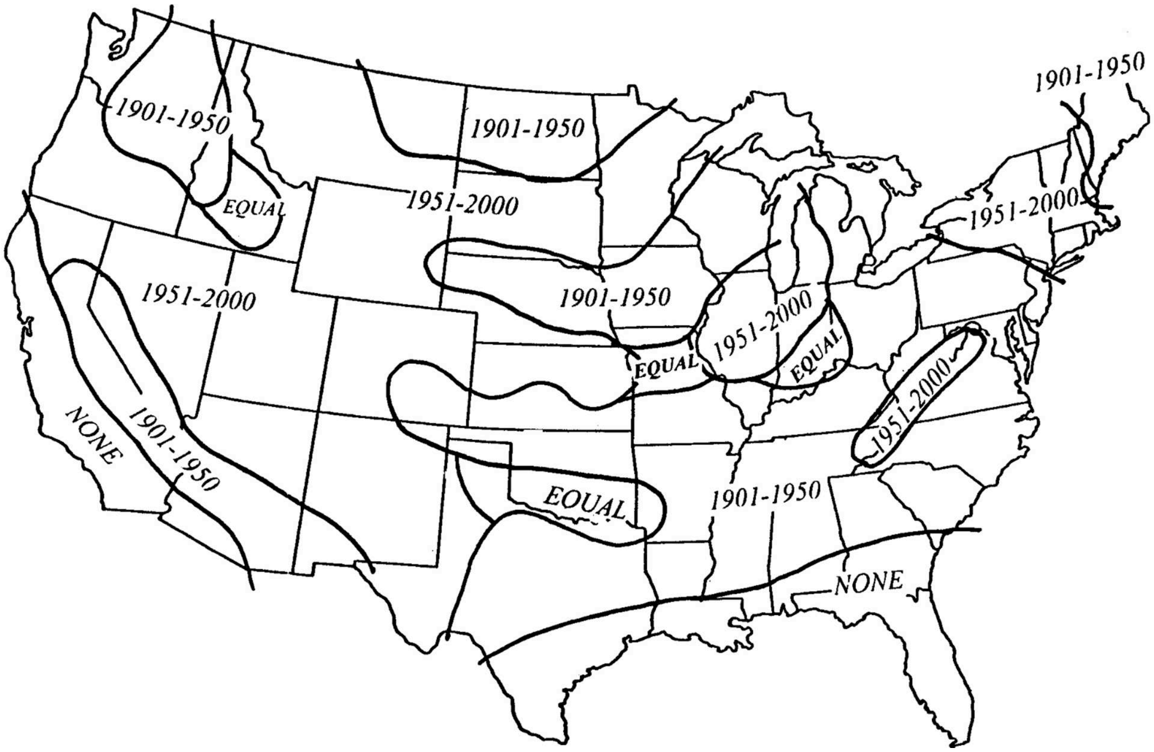

Figure 9. The areas illustrating differences between the 1901–50 and 1951–2000 snowstorm frequencies (from Changnon et al. 2006). Shown is the 50-year period of the 20th century that has the greater frequency of heavy snowstorms (<6”) based on analysis of first-order weather service stations. Areas where the two periods had similar values are also denoted.

Climate model projections of the future change in storm behavior due to increased greenhouse gases indicate a greater percentage of a region’s precipitation falling in fewer, more intense events (6). However, the heavy snowfall in 2009-2010 is not part of a trend toward heavier winter precipitation (Fig. 10). We note also in Fig. 1 that 17 of the past 20 years experienced below-normal seasonal snowfall in the Washington, D.C., region. Thus, historical records of U.S. snowfall and climate projections indicate that the record snowfall is not indicative of a trend toward greater seasonal snowfall. Also, there has not been an upward trend in winter season precipitation over the Washington, D.C., region during winter.

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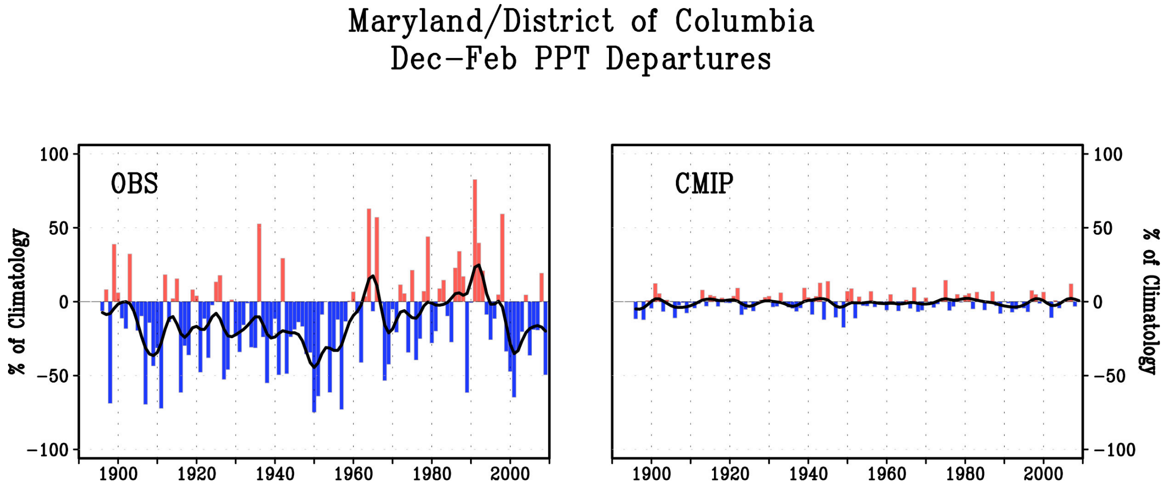

Figure 10. *The 1895-2009 time series of observed (left) and simulated (right) winter season Washington D.C. area precipitation. Simulations are the 22 models of the IPCC Fourth Assessment (CMIP) forced by greenhouse gas, aerosol, solar, and volcanic forcing (so-called All Forcing and Anthropogenic Forcing runs). Observations are the NOAA U.S. Climate Divisions for the Washington D.C. region defined as eastern Maryland and northern Virginia. Model simulated temperatures were interpolated to the Climate Divisions.*

According to the IPCC Fourth Assessment Report (6), the future changes in the extratropical circulation are likely to be characterized by increases in the positive phases of the AO (referred to as the Northern Annular Mode (NAM) in the report) over the 21st century as the climate warms. The AO is closely related to the NAO in the Atlantic sector, so we infer that a positive trend in the NAO index would also occur. Therefore, we conclude that the 2009-2010 blocked, negative phase NAO is an extreme event that is not consistent with the overall upward trend in the NAO index since 1950, and is opposite to the current understanding of projected future change in the NAO.

It is believed that the stratosphere may play an important role in how climate responds to greenhouse gas forcing. The diagnosis of sensitivity in new climate models having a more highly resolved stratosphere than those available to the Fourth Assessment may clarify the AO's sensitivity to climate change.

The 2009-2010 blocked, negative phase NAO is an extreme event that is not consistent with the overall upward trend in the NAO index since 1950, and is opposite to the current understanding of projected future change in the NAO.

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