GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L14703, doi:10.1029/2010GL043830, 2010

Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10

R. Seager,[1] Y. Kushnir,[1] J. Nakamura,[1] M. Ting,[1] and N. Naik[1]

Received 1 May 2010; revised 10 June 2010; accepted 22 June 2010; published 24 July 2010.

[1] Winter 2009/10 had anomalously large snowfall in the central parts of the United States and in northwestern Europe. Connections between seasonal snow anomalies and the large scale atmospheric circulation are explored. An El Niño state is associated with positive snowfall anomalies in the southern and central United States and along the eastern seaboard and negative anomalies to the north. A negative NAO causes positive snow anomalies across eastern North America and in northern Europe. It is argued that increased snowfall in the southern U.S. is contributed to by a southward displaced storm track but further north, in the eastern U.S. and northern Europe, positive snow anomalies arise from the cold temperature anomalies of a negative NAO. These relations are used with observed values of NINO3 and the NAO to conclude that the negative NAO and El Niño event were responsible for the northern hemisphere snow anomalies of winter 2009/10. **Citation:** Seager, R., Y. Kushnir, J. Nakamura, M. Ting, and N. Naik (2010), Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10, *Geophys. Res. Lett.*, *37*, L14703, doi:10.1029/2010GL043830.

1. Introduction

[2] The winter season of 2009–2010 had anomalously large snowfall in the mid-Atlantic states of the United States. December's snowcover in the contiguous U.S. was the greatest ever for that month while, for example, Dulles Airport, Washington DC (73.2"), Baltimore (80.4") and Philadelphia (78.7") had their snowiest winters ever. Much of northwestern Europe also had an anomalously cold and snowy winter (see http://www.ncdc,noaa.gov/special-reports/2009–2010-cold-season.html and http://www.knmi.nl/cms/content/79165/ for U.S. and European climate summaries). The wintry winter has encouraged deniers of global warming, and those opposed to restrictions on greenhouse gas emissions, to mock climate change science. While these attacks confuse climate and weather and take a very geographically limited view (for example much of the Pacific Northwest had below normal snowfall), it is worth examining the causes for the winter's snowfall anomalies. Such knowledge can be useful in climate prediction. In addition, explanations for climate and weather events that are in the news can help educate the public and diminish the effectiveness of efforts to exploit events to undermine the credibility of the science of climate change. In this paper we extend prior work by using data for both snow fall and snow water equivalent (SWE), taking a hemispheric perspective and relating snow anomalies to mean and transient circulation anomalies. We show that snow anomalies across the northern hemisphere this past winter are typical of winters with a negative North Atlantic Oscillation (NAO) and an El Niño and are related to mean temperature and storm track anomalies.

2. Data Sets Used

[3] We examine data sets of snowfall and SWE. Two ground station snow fall data sets were used: for the period 1950 to 1999 from the National Climatic Data Center (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.DAILY/.FSOD/.SNOW/.) and for the post 2003 period from the National Operational Hydrologic Remote Sensing Center (NOHRSC, http://www.nohrsc.noaa.gov) and both are for the U.S. only. The SWE data cover 1979 to 2007, are from microwave satellite readings and are global [*Armstrong et al.*, 2005]. (See http://nsidc.org/data/nsidc-0271.html for a discussion of limitations and errors of the SWE measurements associated with topography, land surface type etc.) The National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Reanalysis [*Kistler et al.*, 2001] is used to analyze temperature and storm track anomalies.

3. Relation Between Observed Snowfall, Snow Water Equivalent and ENSO and the NAO

[4] Our hypothesis is that snowy winters in the mid-Atlantic region, and, more broadly, the continental and hemispheric scale snow anomalies are, in part, caused by a combination of El Niño and a negative NAO. El Niño events are associated with a southward shifted storm track in both the Pacific and Atlantic sectors [e.g., *Seager et al.*, 2005, 2010] while a negative NAO causes cold in eastern North America and northern Europe [*Hurrell*, 1995]. Such a combination could cause increased snow as increased storminess impacts the central and southern latitudes of the U.S. while the NAO provides sufficient cold air for the precipitation to fall as snow. We therefore regress and correlate the snow data with the NINO3 sea surface temperature (SST) index (SST averaged $5°{-}5°N$, $150°W{-}90°W$), the NAO index provided by the Climate Prediction Center (CPC, the principal component of the Atlantic centered rotated EOF of 500mb height north of $20°N$). Since we expect seasons with both an El Niño and a negative NAO would favor positive snow anomalies in the mid-Atlantic U.S., we also use a third index, the normalized NINO3 index minus the normalized NAO index (NINO-NAO), that represents the combined effect.

[5] Figure 1 shows the correlation of snowfall with the NINO3 index and the NAO index times minus one and the regression and correlation with the NINO-NAO index for

[1]Lamont Doherty Earth Observatory, Earth Institute at Columbia University, Palisades, New York, USA.

0094-8276/10/2010GL043830

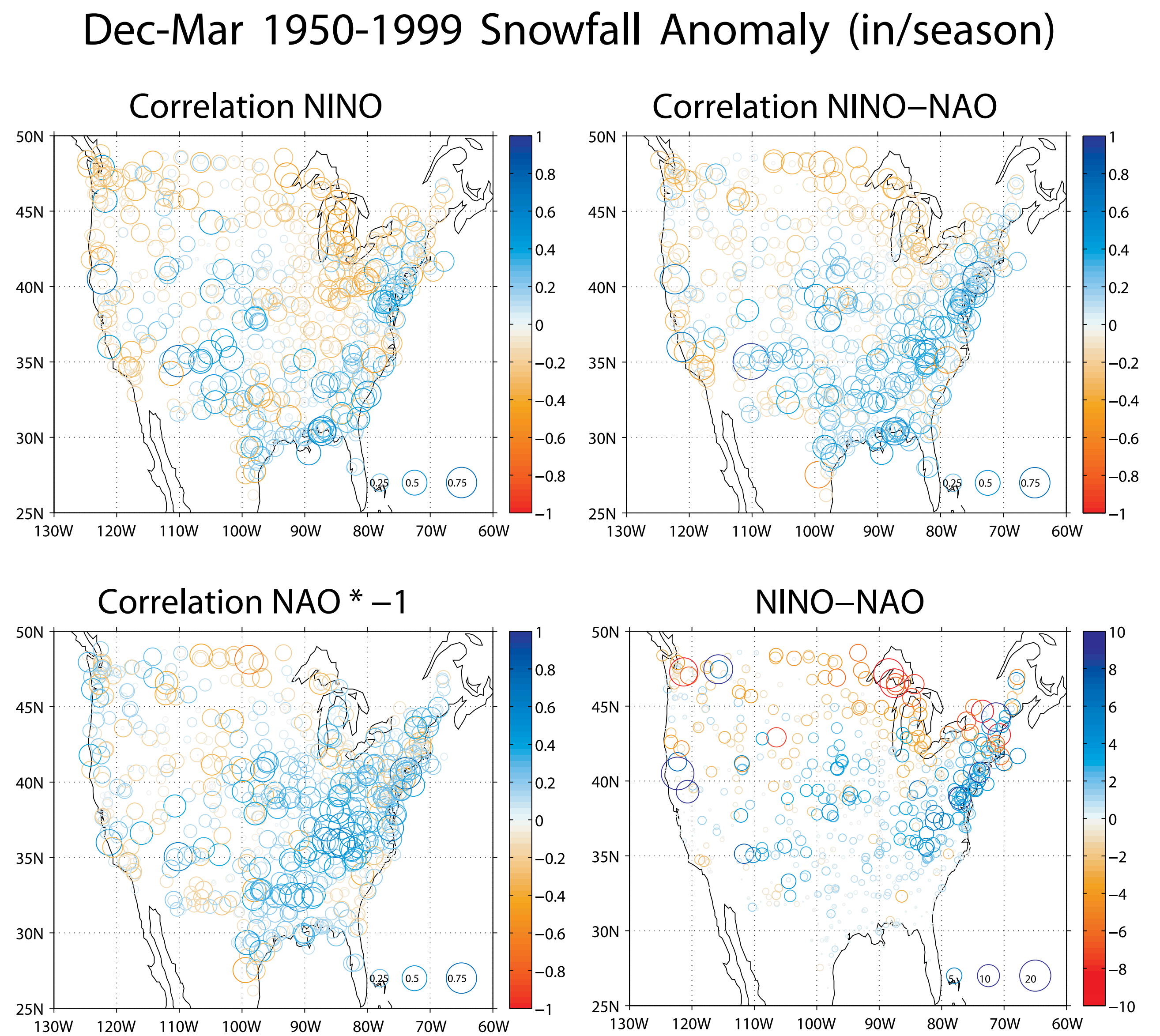

Figure 1. The correlation of snowfall with (top left) the NINO3 index, (bottom left) the NAO index and (top right) the standardized NINO3 minus standardized NAO (NINO-NAO) index and (bottom right) the regression of snowfall on the NINO-NAO index. All indices and the snowfall are for the winter (December to March) mean. Units for the regression are inches.

November through March seasons. The correlation with NINO3 shows generally positive associations in the southeast, along the east coast of North America and over the southern and central Rockies and negative correlations across North America north of these regions. In many of these regions the correlation coefficient exceeds the 1% significance level. The correlation of snowfall with the negative of the NAO index is stronger and more coherent with increased snowfall during negative NAO events in the mid-Atlantic states that are significant at the 1% level. The correlation with the combined index, NINO-NAO, reveals a north-south dipole with snowier conditions to the south and less snowy conditions to the north centered on the Great Lakes region.

[6] Figure 2 is as for Figure 1 but uses SWE for the entire hemisphere. For El Niño conditions SWE is increased in the U.S. Southwest, reduced in the center of the U.S. and Canada and the Pacific Northwest (consistent with the analysis of ground-based SWE measurements by *Jin et al.* [2006] and the snow depth analysis of *Ge and Gong* [2009]) and has a small area of increase on the U.S. Atlantic coast. A negative NAO is associated with increased SWE across most of the U.S. and reduced SWE in northeast Canada. The association with NINO-NAO shows increased SWE over the U.S and less in northeast Canada. Over Europe a negative NAO is quite strongly correlated with increased SWE over northern Europe (consistent with the snow cover analysis of *Clark et al.* [1999]) while the correlation to NINO3 is weaker. The correlation to NINO-NAO in Europe is dominated by the NAO pattern.

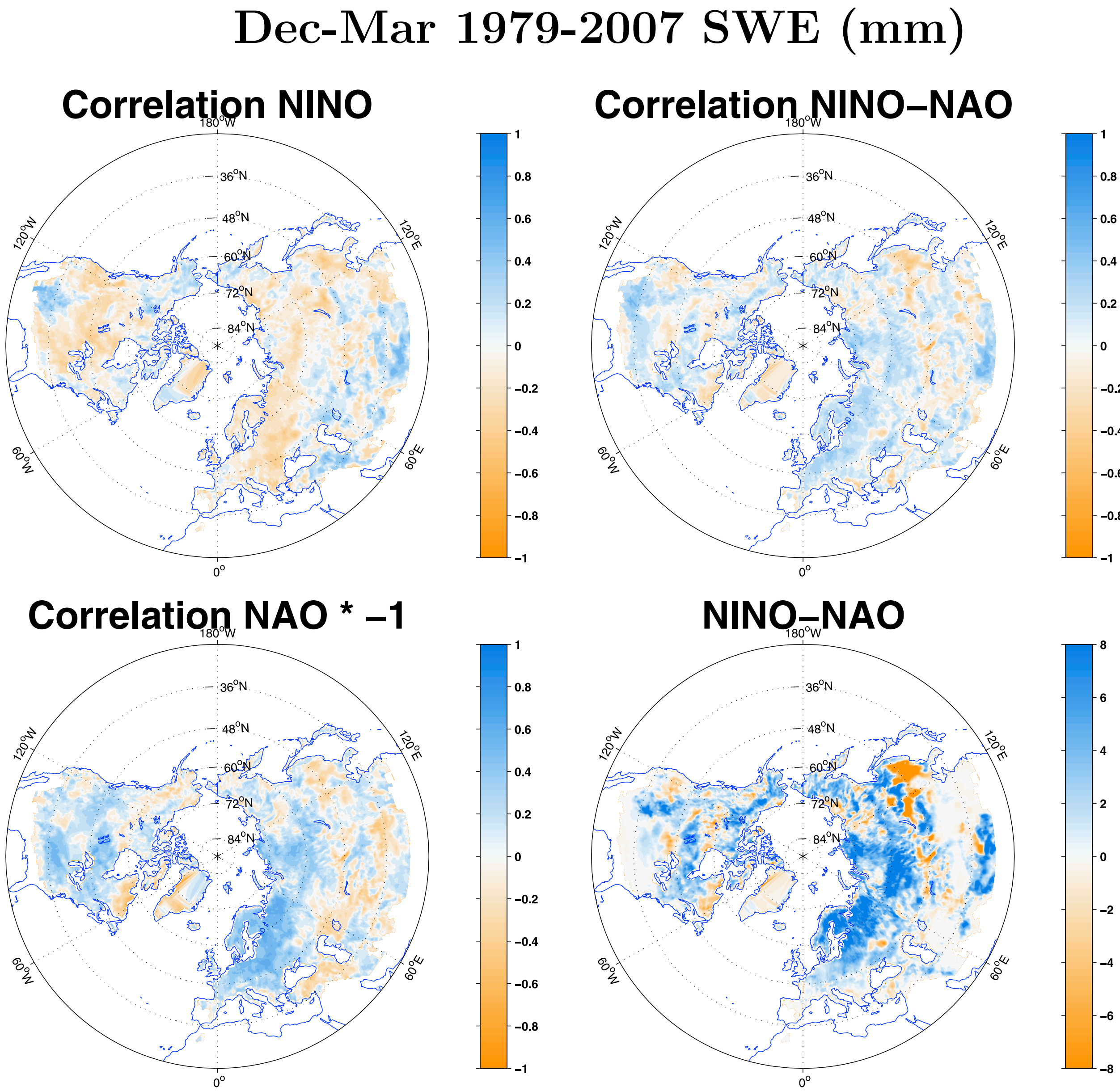

Figure 2. Same as Figure 1 but for snow water equivalent. Units for the regression are mm.

[7] The correlations between snowfall or SWE and ENSO and the NAO could arise from a change in total precipitation or from an increased proportion falling as snow. El Niño events tend to cause increased precipitation in southwest North America and the far southeastern U. S. and reduced precipitation in northwestern North America [e.g., *Ropelewski and Halpert*, 1986; *Dettinger et al.*, 1998; *Seager et al.*, 2005]. In contrast, the NAO has only weak correlations with precipitation amount over North America while a negative NAO causes wetter than normal conditions across southern Europe and drier than normal conditions in northwest Europe [*Hurrell*, 1995; *Hurrell et al.*, 2003]. Consequently, only in the mountain regions of western North America, where most winter precipitation falls as snow, are the snowfall and SWE anomalies corresponding to a positive NINO-NAO index likely to be caused by an increase in total precipitation [*Jin et al.*, 2006]. In the interior and east of North America, and in northern Europe, the increased snowfall and SWE associated with a positive NINO-NAO index must be associated with a higher proportion of the total falling as snow which would be expected if the temperature falls below freezing.

[8] Figure 3 shows the regression of 850mb temperature (from NCEP-NCAR Reanalysis data) on the NINO3, NAO and NINO-NAO indices along with the seasonal mean 850mb temperature. The El Niño related temperature anomaly is weak over Eurasia and has a strong dipole over North America with warm in the northern U.S. and Canada and cool in the southern U.S. and Mexico. The NAO times minus one regression has strong cooling across the eastern U.S. extending towards the northwest and across Eurasia with warming in the Arctic regions. The effects of both El Niño and a negative NAO show cool in the southern regions of North America and across northern Europe, consistent

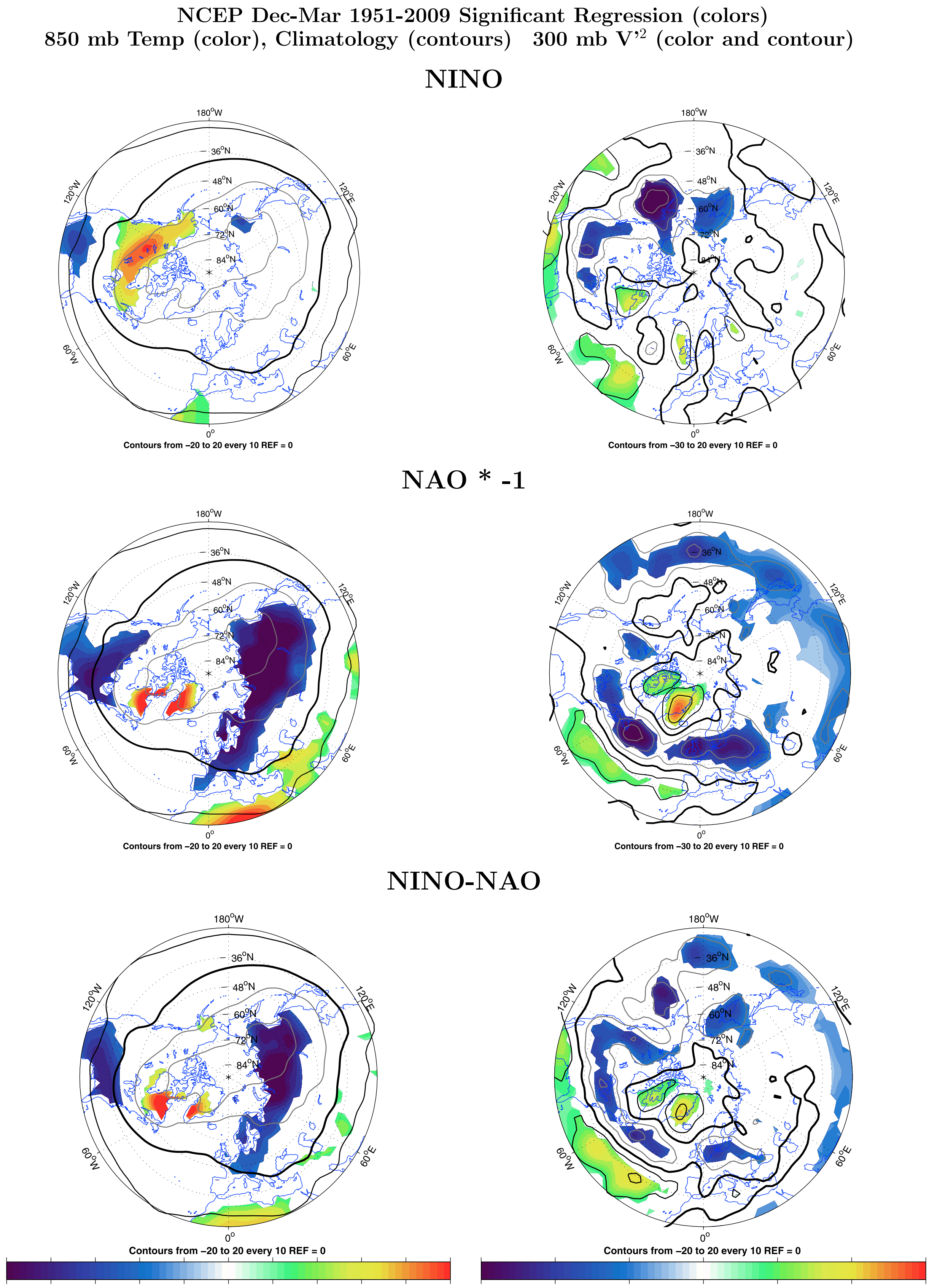

Figure 3. (left) The regression of the 850mb temperature on the NINO3, NAO and NINO-NAO indices (color) with the mean 850mb temperature contoured (0°C isotherm bold, negative contours dashed), and (right) the regression of 300mb submonthly transient eddy meridional velocity variance, $\overline{v'^2}$, all for the December through March seasonal mean. Patterns are plotted only where significant at the 5% level. Units are °C for temperature and m^2s^{-2} for velocity variance.

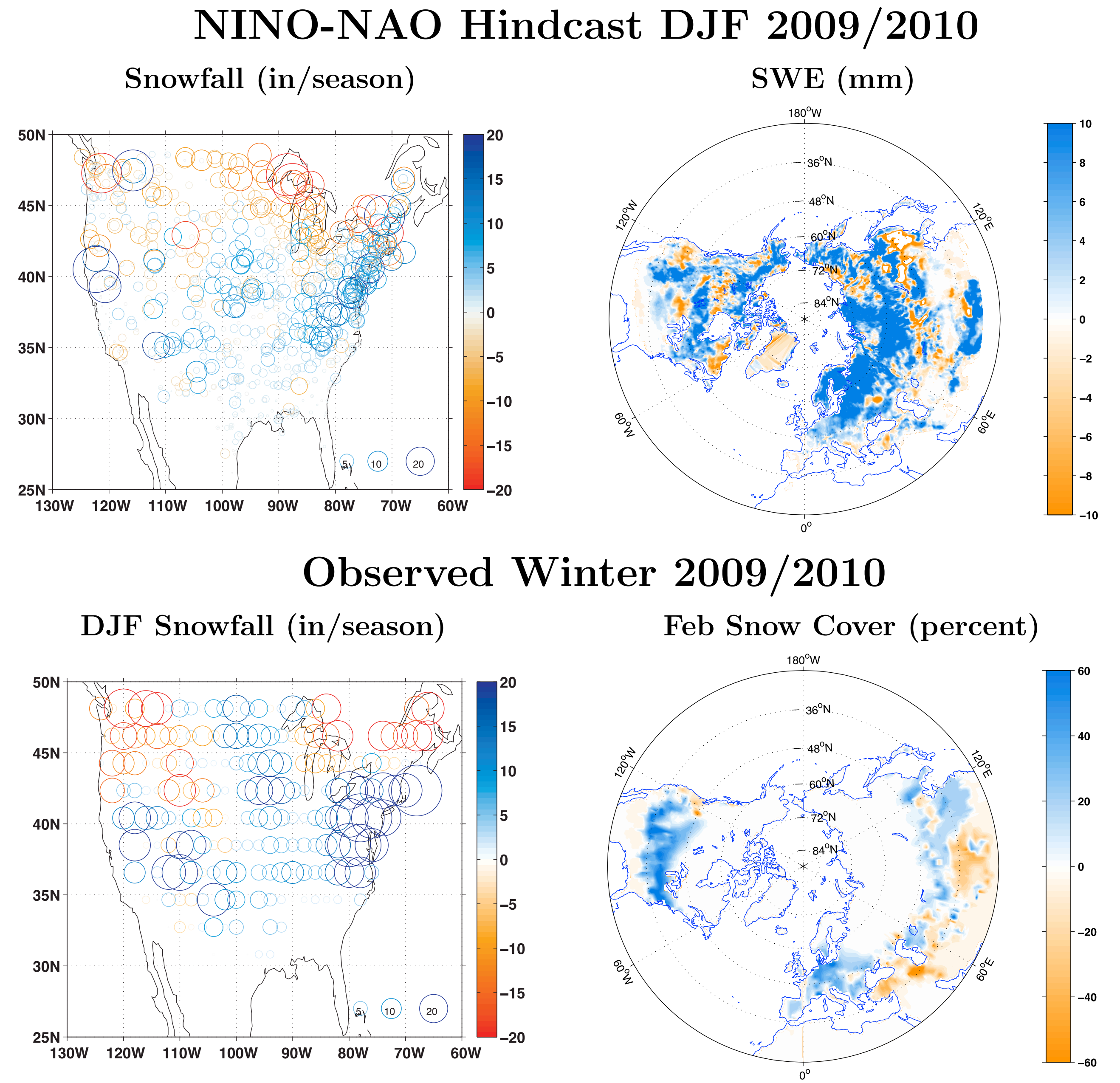

Figure 4. Attribution of (top left) snowfall (inches) and (top right) snow water equivalent (mm) for December 2009 through February 2010 based on the regression patterns shown in Figures 1 and 2 and the seasonal mean observed NINO-NAO index. (bottom left) Difference in observed station snowfall between the December 2009 to February 2010 season and the three previous December through February seasons (from NOHRSC data) and (bottom right) the observed, satellite-derived, snow cover anomaly in percent for February 2010. (Snow cover anomalies are zero in subpolar and polar regions that are always snow covered.)

with the snowfall anomalies (Figure 1). Where the anomalies tend to move the total temperature below freezing an increased proportion of precipitation will fall as snow, e.g., in the southeast U.S. and mid-Atlantic states [*Serreze et al.*, 1998] and northwestern Europe. In regions where the mean temperature is well below freezing (e.g., most of Canada) all precipitation typically falls as snow and a strong correlation between the snowfall and the climate indices is not expected.

[9] Figure 3 also shows the correlations of the three climate indices to the 300mb submonthly transient eddy meridional velocity variance, $\overline{v'^2}$, as calculated from the NCEP-NCAR Reanalysis daily data for 1950 to 2009, taken to be a measure of the mid-latitude storm tracks. El Niño is associated with a southward shifted storm track over the Pacific-North America sector. A negative NAO also causes increased storminess over the southeast U.S. and the subtropical Atlantic Ocean and reduced storminess over northern Europe. For the mid-Atlantic states and northeast U.S., El Niño and a negative NAO cause reduced storminess. Consequently, changes in storminess may help explain snow anomalies in western North America and the southeast

U.S. but in the mid-Atlantic and northeast U.S. and northern Europe the snow anomalies have to arise from the NINO-NAO associated temperature anomalies.

4. Attribution of the Snow Anomalies for Winter 2009–2010

[10] For December 2009 to February 2010 the NINO3 index, computed from the NCEP-NCAR Reanalysis, averaged 1°*C* or just over one standard deviation and the NAO index averaged −2.38 standard deviations according to values posted by CPC (http://www.cpc.noaa.gov/products/precip/CWlink/pna/nao.shtml), providing an observed value of the NINO-NAO index of −2.40. We calculate the expected snowfall and SWE anomalies for the last winter using the relations diagnosed here on prior data by multiplying the observed NINO-NAO index by the regression coefficients shown in Figures 1 and 2. Results are in Figure 4. Continuous snowfall and SWE data updated through the past winter are not available so, for verification, we show the difference in NOHRSC snowfall between the past winter and the average of the three previous winters and the satellite-derived anomalous global snow cover for February 2010 (Rutgers University Global Snow Lab, http://climate.rutgers.edu/snowcover/docs.php?target=cdr [*Frei and Robinson*, 1999]). Snow cover anomalies only appear in marginal areas for snow and not in the more poleward regions that are essentially always snow covered in winter (and where no verification is possible). The expected snowfall shows anomalous high values over the eastern U. S., negative values over the Great Lakes region and Pacific Northwest and positive values in the southwest U.S. The expected SWE also shows largely positive values across the U.S. with the exception of the Pacific Northwest and west of the Great Lakes, and positive values over northwest Europe and northern Siberia. In general, the expected patterns agree well with the observed snow cover anomalies over northwestern Europe and the U.S., but disagree west of the Great Lakes.

5. Conclusions

[11] In winters when an El Niño event and a negative NAO combine, analyses reveal that there are positive snow anomalies across the southern U.S. and northern Europe. In western North America and the southeast U.S. snow anomalies are associated with total precipitation anomalies and southward shifts in the storm track. In the eastern U.S., north of the Southeast, and in northwest Europe positive snow anomalies are associated with the cold temperature anomalies accompanying a negative NAO. The relations between large-scale climate indices and snow anomalies were used to attribute the snow anomalies for the 2009/10 winter with notable success in pattern and amplitude. We conclude that the anomalously high levels of snow in the mid-Atlantic states of the U.S. and in northwest Europe this past winter were forced primarily by the negative NAO and to a lesser extent by the El Niño. The El Niño was predicted but, in the absence of a reliable seasonal timescale prediction of the NAO, the seasonal snow anomalies were not predicted. Until the NAO can be predicted (which may not be possible [*Kushnir et al.*, 2006]), such snow anomalies as closed down Washington D.C. for a week will remain a seasonal surprise.

[12] **Acknowledgments.** This work was supported by NOAA grants NA030AR4320179 PO7 and NA08OAR432091 and NSF grants ATM-08-04107. LDEO contribution 7376.

References

Armstrong, R., M. Brodzik, K. Knowles, and M. Savoie (2005), Global monthly EASE-grid snow water equivalent climatology, digital media, Natl. Snow and Ice Data Cent., Boulder, Colo.
Clark, M., M. Serreze, and D. Robinson (1999), Atmospheric controls on Eurasian snow extent, *Int. J. Climatol.*, *19*, 27–40.
Dettinger, M., D. Cayan, H. Diaz, and D. Meko (1998), North-South precipitation patterns in western North America on interannual-to-decadal timescales, *J. Clim.*, *11*, 3095–3111.
Frei, A., and D. Robinson (1999), Northern Hemisphere snow extent: Regional variability 1972–1994, *Int. J. Climatol.*, *19*, 1535–1560.
Ge, Y., and G. Gong (2009), North American snow depth and climate teleconnection patterns, *J. Clim.*, *22*, 217–233.
Hurrell, J. (1995), Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679.
Hurrell, J., Y. Kushnir, M. Visbeck, and G. Ottersen (2003), An overview of the North Atlantic Oscillation, in *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, *Geophys. Monogr. Ser.*, vol. 134, edited by J. Hurrell et al., pp. 1–35, AGU, Washington, D. C.
Jin, J., N. Miller, S. Sorooshian, and X. Gao (2006), Relationship between atmospheric circulation and snowpack in the western USA, *Hydrol. Processes*, *20*, 753–767.
Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–268.
Kushnir, Y., W. Robinson, P. Chang, and A. Robertson (2006), The physical basis for predicting Atlantic sector seasonal-to-interannual climate variability, *J. Clim.*, *19*, 5949–5970.
Ropelewski, C., and M. Halpert (1986), Precipitation and temperature patterns associated with the El Niño-Southern Oscillation (ENSO), *Mon. Weather Rev.*, *114*, 2352–2363.
Seager, R., N. Harnik, Y. Kushnir, W. Robinson, and J. Miller (2005), Mechanisms of ENSO-forcing of hemispherically symmetric precipitation variability, *Q. J. R. Meteorol. Soc.*, *131*, 1501–1527.
Seager, R., N. Naik, M. Cane, N. Harnik, M. Ting, and Y. Kushnir (2010), Adjustment of the atmospheric circulation to tropical Pacific SST anomalies: Variability of transient eddy propagation in the Pacific-North America sector, *Q. J. R. Meteorol. Soc.*, *136*, 277–296.
Serreze, M., M. Clark, and D. McGinnis (1998), Characteristics of snowfall over the eastern half of the United States and relationships with principal modes of low-frequency atmospheric variability, *J. Clim.*, *11*, 234–250.

Y. Kushnir, N. Naik, J. Nakamura, R. Seager, and M. Ting, Lamont Doherty Earth Observatory, Earth Institute at Columbia University, 61 Rte. 9W, Palisades, NY 10964, USA. (seager@ldeo.columbia.edu)