

# Introducing sub-seasonal spatial and temporal resolution to winter climate prediction

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[1] The dominant Northern Hemisphere winter mode of variability is characterized by a same-signed sea level pressure anomaly at high latitudes with an opposite-signed anomaly stretching across mid-latitudes. The surface temperature pattern associated with this mode is a same-signed temperature anomaly across the major continents and an opposite-signed anomaly across the major oceans. We demonstrate that this temperature pattern is mostly an artifact of multi-year averaging, which results in the super positioning of two distinctive patterns. Separation of the two patterns allows for more accurate seasonal predictions and introduces a spatial and temporal resolution in forecasts previously not possible. **INDEX TERMS:** 3319 Meteorology and Atmospheric Dynamics: General circulation; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3364 Meteorology and Atmospheric Dynamics: Synoptic-scale meteorology. **Citation:** Cohen, J., Introducing sub-seasonal spatial and temporal resolution to winter climate prediction, *Geophys. Res. Lett.*, 29(0), XXXX, doi:10.1029/2002GL016066, 2002.

## 1. Introduction

[2] In the Northern Hemisphere (NH) the dominant mode of winter variability is referred to as the North Atlantic oscillation (NAO) or Arctic oscillation [AO; *Thompson and Wallace*, 1998]. Seasonal-interannual variability of the NAO/AO has been attributed to changes in eddy momentum fluxes, sea surface temperature variability, snow cover variability, sea ice variability, stratospheric forcing and aerosols [*Feldstein*, 2002; *Rodwell et al.*, 1999; *Cohen and Entekhabi*, 1999; *Mysak and Venegas*, 1998; *Baldwin and Dunkerton*, 1999; *Perlwitz and Graf*, 1995]. Forecasting the strength and phase of the NAO would potentially be one of the most important advancements for seasonal prediction, yet predictability has remained poor [*Hurrell et al.*, 2001]. And even if the phase of the NAO is correctly forecasted, it is not clear that such information would be of benefit, as illustrated by the two most recent Decembers, 2000 and 2001, both of which featured a strong negative phase of the NAO, yet opposite temperature anomalies were observed.

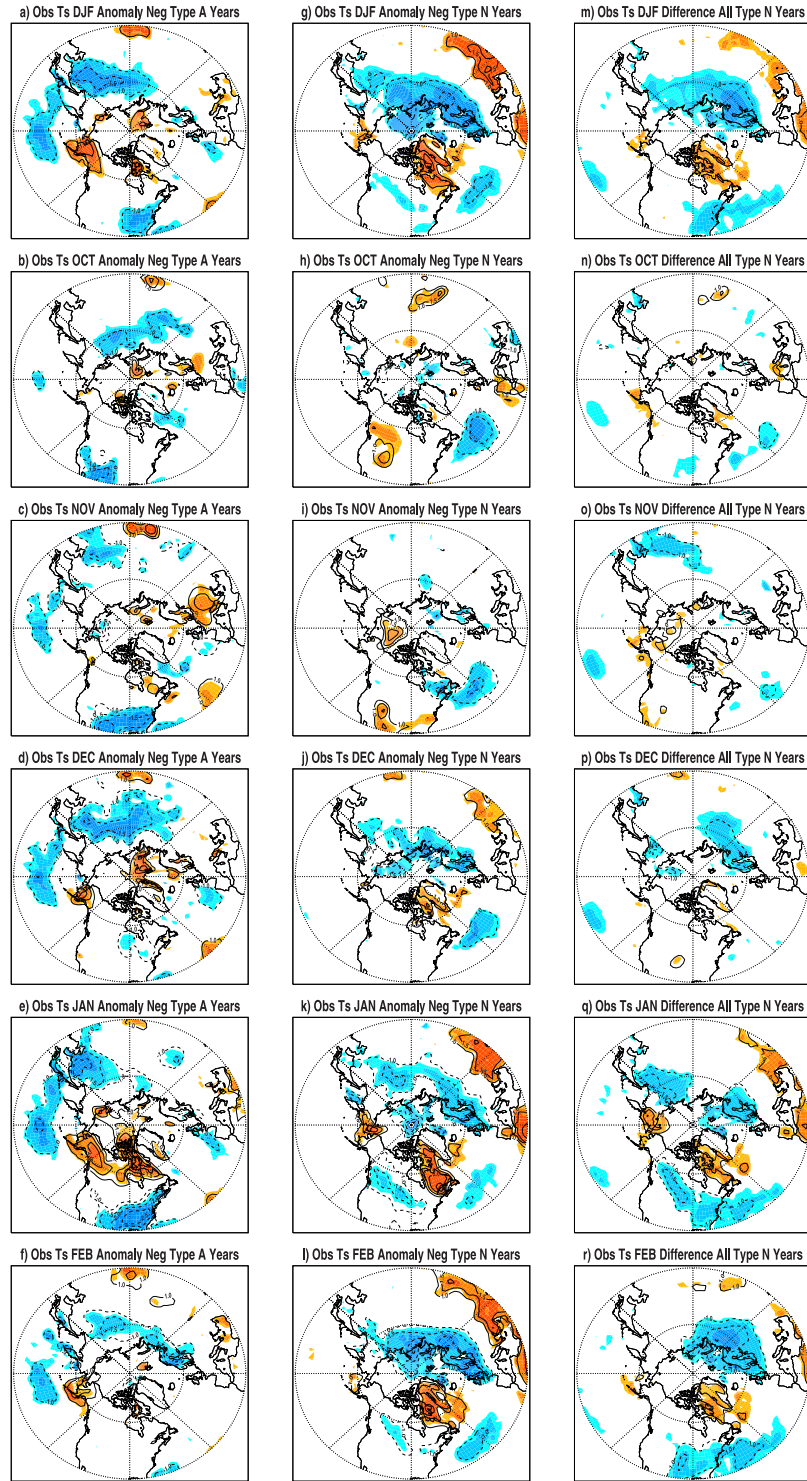
[3] December 2001 was one of the warmest Decembers ever recorded across the eastern United States. Meanwhile the warmth in the U.S. was not shared by Europe as many regions in central and eastern Europe suffered through the harshest winter weather in fifty years. This temperature pattern was the exact opposite of what had occurred in

December 2000, which was extremely cold in the U.S. (November and December 2000 were the coldest on record) while Europe basked in unseasonable warmth. All existing theories of the NAO are inadequate to explain the temperature flip-flop of the past two winters, regardless of the forcing mechanism. Furthermore, it has been suggested that the NAO is not strictly regional but part of a hemispheric-wide pattern or annular mode of variability [*Thompson and Wallace*, 1998, 2001]. Yet over the past two Decembers, despite sharing the same NAO phase, temperature anomalies of the opposite extreme have been observed in Europe and North America, in seeming contradiction to an annular structure. And even if the NAO is simply a more limited regional teleconnection [*Deser*, 2000; *Ambaum et al.*, 2001; *Cohen et al.*, 2001; *Cohen and Saito*, 2002], this paradigm cannot explain the opposite temperature extremes observed in the North Atlantic sector during the same phase of the NAO.

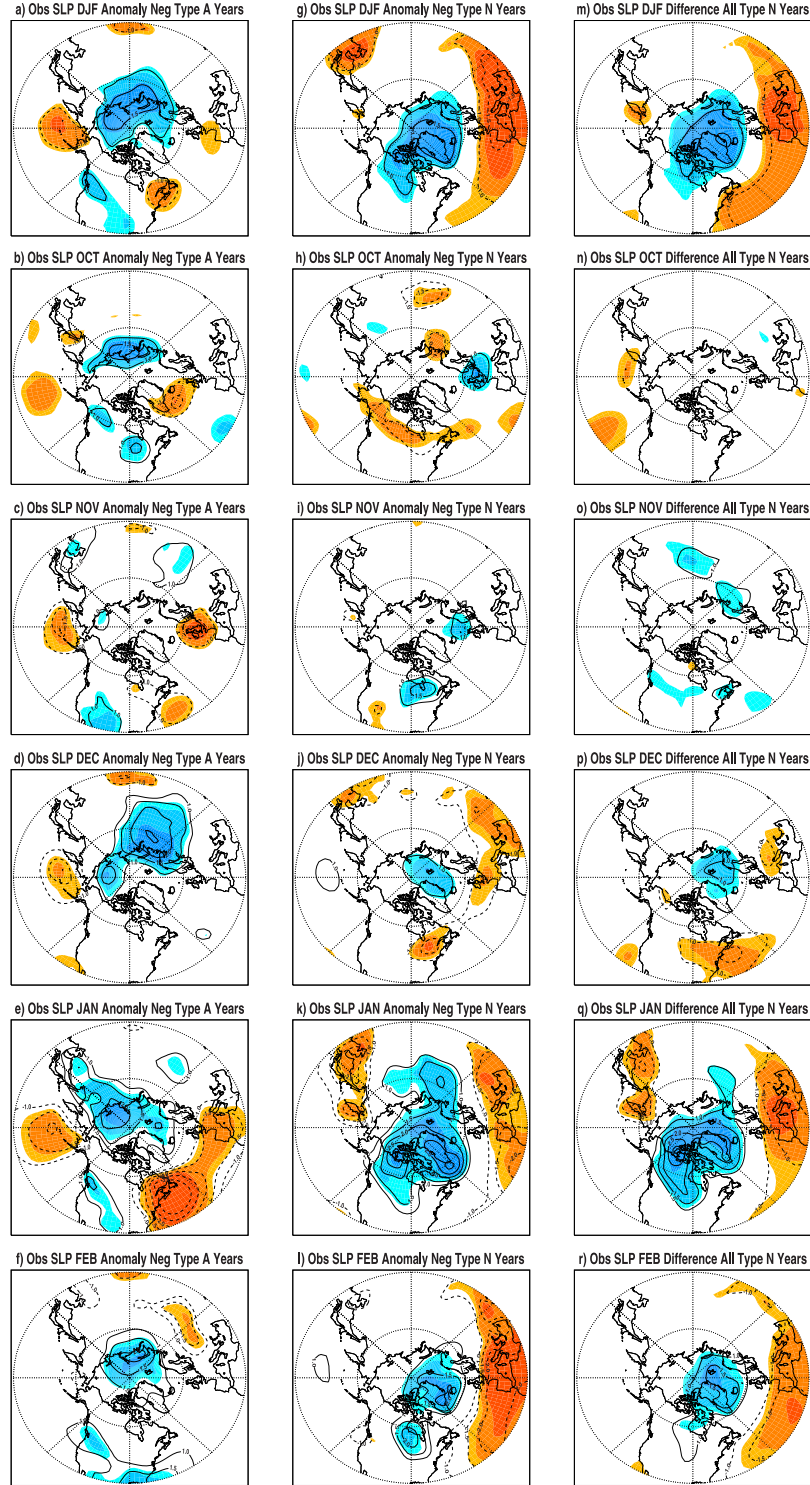
[4] We propose complementing the patterns of variability derived from the strictly statistical description of the NAO with those derived from dynamical arguments. *Cohen et al.* [2002] argued that the pattern of variability most closely associated with the NAO or the hemispheric-scale AO results from two distinctive dynamical evolutions during winter. One dynamical pathway starts with a lower tropospheric height anomaly in eastern Siberia in the fall, which propagates to the west and then rapidly spreads over the pole into North America and is referred to as Type A. Type A pattern of variability most closely resembles that associated with the AO or annular pattern of variability. The other dynamical pathway also begins as a lower tropospheric height anomaly in the fall, but originates in the North Atlantic sector and propagates eastward into Europe and western Asia and is referred to as Type N. Type N pattern of variability most closely resembles that associated with the NAO pattern of variability and the seasonal anomalies are mostly confined to the North Atlantic and adjacent land areas. All winters can be grouped into either Type A or Type N winters. We will demonstrate that compositing winters not only by phase of the NAO/AO but also by dynamic type, A or N, increases seasonal forecast skill and introduces spatial and temporal resolution previously not considered.

## 2. Results

[5] We commence our analysis by dividing the forty winters (1961–2000, with winter defined as DJF according to the calendar year of December) into Type A and Type N winters. Over the past forty winters, ten were classified as Type A (1966, 1969, 1975, 1976, 1979, 1984, 1988, 1991, 1992, 2000) and the remaining thirty, Type N. Type N



**Figure 1.** Maps of NH gridded mean Ts anomalies for 4 strongest negative Type A winters between 1961/1962-2000/01 for (a) DJF (b) October (c) November (d) December (e) January (f) February; for 4 strongest negative Type N winters for (g) DJF (h) October (i) November (j) December (k) January (l) February; and differences between 15 negative and 15 positive Type N winters for (m) DJF (n) October (o) November (p) December (q) January (r) February. All values are normalized by the standard deviation for DJF. Contour interval is  $\pm 1, 1.5, 2, 2.5, 3, 4, 5$ . Shading indicates 90% (light) 95% (dark) and 99% (darkest) confidence levels using the two-sided student's t-test.



**Figure 2.** Same as Figure 1 except for gridded sea level pressure.

winters are more frequent; yet Type A winters tend to produce stronger anomalies. We begin by displaying the DJF difference in surface temperature [Ts; Kalnay *et al.*, 1996]. In the remainder of the paper we discuss anomalies from the perspective of winters during which a negative phase of the AO was observed. In panel 1a we present the composited anomaly from the four strongest negative Type A winters; phase and strength for Type A and N winters are

determined by the AO time series. This figure closely resembles the canonical pattern of variability associated with the NAO/AO though the signal in Europe is smaller and weaker than typically shown. In fact, cold Ts anomalies in Eurasia are mostly east of 90°E.

[6] In panels 1b–f we present monthly Ts anomalies for the same four Type A winters for the individual months October–February. A strong regional cold anomaly is



observed in October in Siberia. The Eurasian cold anomaly persists throughout all five months. Further to the west, a warm anomaly is observed in Europe in November and somewhat less in December. During winter in the U.S., a cold Ts anomaly first observed in the Great Lakes region spreads south and east, peaking in January. In February, a temperature swing takes place as the cold anomaly in North America abates, and northern Europe experiences negative Ts anomalies.

[7] We repeat the analysis for Type N winters; the seasonal mean is shown in panel 1g. Also for comparison we present the difference for all negative minus positive Type N winters in panel 1m. In contrast to Type A winters, the largest Ts anomalies are observed in western Asia and Europe. Monthly anomalies for October–February (panels 1h–l, 1n–r) portray a very different evolution of Ts anomalies than observed for Type A winters. No significant anomalies are observed in October and November except for a cold anomaly in the North Atlantic. This is consistent with the idea that in Type N winters, the subsequent NAO winter pattern of variability is initiated upstream during the fall [Cohen *et al.*, 2002]. The first significant cold, continental anomalies appear in northern Europe and northwestern Asia in December. In the United States warm anomalies are observed in November and somewhat less in December. During January the cold anomalies in Europe and western Asia spread eastward and northward over the pole into Canada and the United States. In the United States cold anomalies are only observed in the latter half of winter, most notably in February.

[8] To better understand the dynamical forcing of the different temporal and spatial patterns between the two types, maps of sea level pressure (SLP) anomalies are presented in Figure 2, analyses of which are considered more accurate than Ts [Kalnay *et al.*, 1996]. The DJF mean of SLP anomalies for Type A winters (panel 2a) resembles the canonical pattern of variability associated with the AO with one signed anomaly over the Arctic and major continental land areas, and an opposite signed anomaly over the ocean basins. In October, a strong SLP anomaly is first observed in northern Siberia, which propagates westward and then across the pole into North America in December and January (panels 2b–e). The cold Ts anomalies observed in eastern Siberia and North America are associated with the cold high pressure and anomalous northward advection induced downstream, while upstream in Europe, anomalous southerly advection results in the observed warm Ts in November and December. In February (panel 2f), the anomalous northerly, cold advection abates, and temperatures begin to rebound. In Europe eastward penetration of low pressure into southern Europe now results in anomalous westward advection, and colder Ts are observed.

[9] Finally the DJF mean of SLP anomalies for Type N winters (panel 2g and 2m) resembles the canonical pattern of variability associated with the NAO with a dipole anomaly confined to the North Atlantic basin. A significant anomaly is not observed until December (panel 2j and 2p) with high pressure at high latitudes and low pressure at mid-latitudes. The cold Ts anomaly first observed in northern Europe in December is a product of the anomalous westerly flow between the anomalous high and low pressure. In January (panel 2k and 2q) the anomalous high pressure

**Table 1.** Example of Three-Month Forecast For Three Winter Months of December, January and February For Both the Eastern United States and Eastern Europe Based on Analysis Performed in Text

Dynamic Type	Region	December	January	February
All	eastern United States	Cold	Cold	Cold
All	eastern Europe	Cold	Cold	Cold
Type A	eastern United States	Cold	Cold	Normal
Type A	eastern Europe	Warm	Normal	Cold
Type N	eastern United States	Warm	Normal	Cold
Type N	eastern Europe	Cold	Cold	Cold

Examples are shown for “all” winters and for two dynamic types A and N for negative phase only. In general, with  $d$  departure from normal and  $\sigma$  standard deviation for DJF Ts, “cold”, “normal”, and “warm” represent  $d \leq -\sigma$ ,  $-\sigma < d < \sigma$ , and  $d \geq \sigma$  respectively.

propagates eastward, resulting in colder Ts downstream farther east. Eventually a portion propagates southward into North America, resulting in anomalous northerly advection and colder Ts first in Canada and eventually the United States (panel 2l and 2r). It is important to note that though advective processes on shorter time scales than a month may be important in the observed monthly temperature anomalies, consideration of sub-monthly variations is beyond the scope of this work.

### 3. Discussion and Conclusion

[10] It is widely accepted by scientists and forecasters that the negative (positive) phase of the NAO produces cold (warm) temperatures across the major land areas of the Northern Hemisphere (NH) at mid-high latitudes [Hurrell, 1995; Thompson and Wallace, 1998]. Our analysis shows this to be an oversimplification of what actually occurs.

[11] Currently, predictions of seasonal Ts anomalies associated with large-scale modes of variability are static in time and space due to a reliance on statistical averaging. So even if a correct forecast of the NAO/AO is made, the resultant Ts forecast does not allow the end user to anticipate sub-seasonal and regional variations, which, as demonstrated above, may be of opposite sign to the seasonal forecast. Currently a forecast based on the statistical averaging of the negative phase of the NAO would result in a simultaneous cold forecast across all of Europe and eastern North America; a forecast, which over the past two winters did not verify. Instead, we argue that the utility of forecasts of the phase and strength of the NAO would improve by incorporating a dynamic paradigm. In Table 1 we illustrate how the forecasts may vary, based on whether a negative Type A or Type N winter is forecasted (a brief discussion of when to forecast Type A or Type N, based on SLP, is given in Cohen *et al.* [2002]). For comparison we have also listed a forecast derived from a difference of all negative and positive NAO winters from the complete 40-year dataset; the forecast based on “all” winters exhibits no regional or temporal variation. But when winters are further subdivided based on dynamical evolution, not only does the predictive skill increase but the forecast varies regionally and month to month. As argued in the Introduction this is a step toward greater consistency of what is actually observed during same phases of the NAO. A negative NAO was observed in both December 2000 and December 2001, but during

2000 a Type A event was observed and during 2001 a Type N event was observed. Based on Table 1, for December 2000 the forecast is cold for the eastern United States but warm for eastern Europe and for December 2001 warm for the United States and cold for Europe, as observed both years. A dynamical rather than a statistical paradigm will both increase forecast skill on a seasonal time scale and potentially allow sub-seasonal resolution, which can be varied with time, similar to what is practiced for weather forecasting.

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