Implications of rapid Arctic change for weather patterns in northern mid-latitudes

Jennifer A. Francis[1] and James E. Overland[2]

[1]Rutgers University
[2]NOAA Pacific Marine Environmental Laboratory

A variety of positive feedbacks – processes that amplify an original change – cause the Arctic to be more sensitive to global temperature change than anywhere else on Earth. Consequently, the Arctic's lower tropospheric air temperature has continued to rise at three times the rate exhibited by Northern Hemisphere mid-latitudes during the recent slowdown in the global temperature increase (Figures 1 and 2), resulting in substantial losses of sea ice, land ice (glaciers and ice sheets), permafrost, and snow cover in spring (Jeffries et al. 2013). Recent studies suggest that the rapidly warming Arctic is associated with an increase in extreme weather events, such as cold spells (Tang et al. 2013a; Cohen et al. 2013) and heat waves (Tang et al. 2013b) in Northern Hemisphere continents, as well as wet summers in western Europe (Screen 2013). Identifying the mechanism(s) underlying the linkage is a focus of active research, including an assessment of the relative roles of forced versus random natural variation in these events. Evidence for complicating weather linkages includes observed asymmetrical surface temperature trends that vary by season. Winter continental regions, for example, have cooled during 1979-2011 (Cohen et al. 2012).

One hypothesis for a mechanism linking rapid Arctic warming with changing mid-latitude weather patterns is as follows. Arctic amplification (AA) – the heightened sensitivity of the Arctic to global temperature change – has reduced the Arctic/mid-latitude temperature contrast in recent decades, particularly during autumn in response to sea ice loss (Figure 1). Because this gradient is a fundamental driver of the jet stream's westerly wind speed, the weaker temperature contrast leads to weakened upper-level winds (Overland and Wang 2010; Francis and Vavrus 2012). A weaker jet stream tends to take a more meandering path as it encircles the Northern Hemisphere (Thompson and Wallace 2001; Palmén and Newton 1969). In highly meandering flows, the north-south waves in the jet stream tend to travel eastward more slowly, which increases the likelihood of persistent weather patterns that can cause a variety of extreme events (Screen and Simmonds 2014). This new manifestation of global warming is of great potential importance, as more frequent extreme weather events in mid-latitudes will affect billions of people directly through damage to property and infrastructure and indirectly through agriculture and water supplies. Moreover, even though they may not contribute to hemispheric temperature trends, the

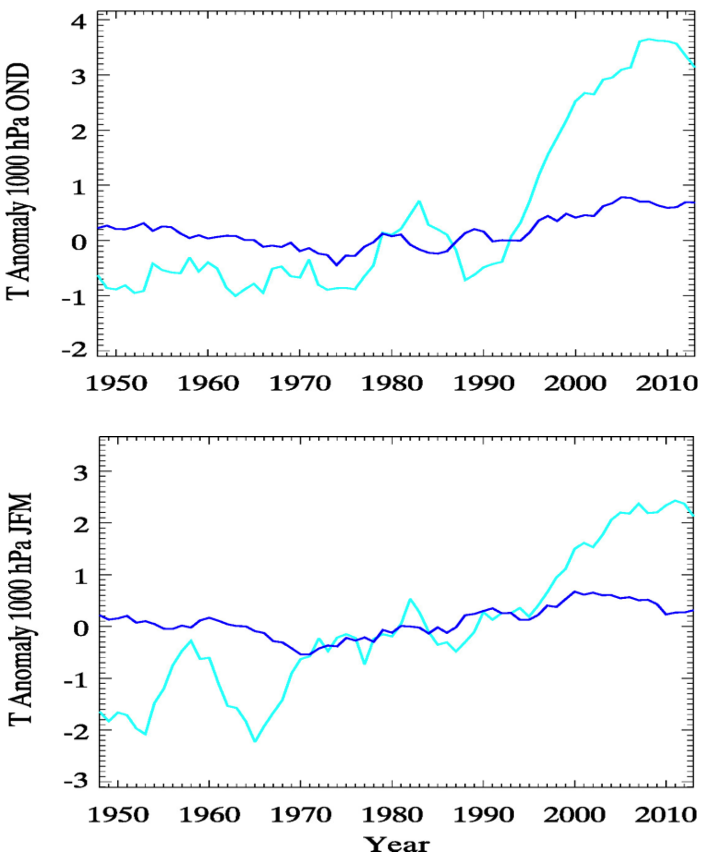

Figure 1. Five-year running means of near-surface air temperature anomalies (°C, relative to 1970-1999) during autumn (Oct.-Dec., top) and winter (Jan.-Mar., bottom) for the Arctic (70°N to 90°N, cyan) and for the Northern Hemisphere mid-latitudes (30°N to 60°N, blue). Data were obtained from the NOAA/ESRL Physical Sciences Division, Boulder CO, http://www.esrl.noaa.gov/psd/.

amplified patterns do exhibit regional preferences for anomalies in temperature and precipitation; thus it may be possible to predict which types of extreme events will be more likely to occur in certain areas, and in turn assist decision-makers in preparing for the future.

Because the atmosphere is inherently chaotic and the signal of AA has emerged so recently, it is a challenge to detect robust changes in the character of the jet stream (Barnes 2013; Screen and Simmonds 2013) and separate the various influences on its behavior. Here we briefly outline two new efforts to elucidate the issue.

The probability (P) of detecting a signal amid a noisy system can be estimated using Bayes Theorem (Silver 2012), which relates a known forcing (X) to the natural variability of the system:

$$P = \frac{XY}{XY + Z(1 - X)}$$

In this application, we assume the known forcing is the present (0.4) and future (0.9) estimates of open-water fraction in the Arctic Ocean at the time of minimum sea ice extent, as increased open water heats the atmosphere and is a primary driver of AA. The probability that a signal is detectable, if the hypothesized linkage is true, is represented by Y. For this value we use the fraction of variance in sea level pressure between 20°N and 90°N explained by the Arctic Oscillation (AO) index, as determined through an empirical orthogonal function (EOF) analysis (Overland et al 2008): Y = 0.23. Finally, the probability of detecting a signal if the hypothesized linkage is false is represented by Z, which we estimate to be of order 0.5, as the unexplained fraction of variability in sea level pressures, i.e., the chaotic noise.

The results of this Bayesian analysis suggest that under present conditions, the probability of detecting an atmospheric response (measured as a change in the AO index) to AA is approximately 0.21, meaning that natural variability (the noise) exceeds the signal. Although this is a simple calculation with approximate values, it is consistent with the current state of the science, i.e., that proposed linkages are provisional episodes and "unproven" in terms of statistical significance (e.g., Screen et al. 2013). In the future, as sea ice loss continues and the open water fraction approaches 0.90, the probability of signal detection increases to 0.78. With most sea ice researchers are expecting the Arctic Ocean to become nearly ice-free during summer within a few decades (Overland and Wang 2013), a robust change in the large-scale circulation should be evident in the future. However, other measures of inherent variability may produce different results, and certain regions may exhibit a detectable response sooner than others. New research suggests that the signal may already be emerging.

AA is largest in fall and winter, thus the atmospheric response should become evident first and be largest in cold seasons. In fall the signal is approximately concentric around the pole, but in other seasons the pattern is highly spatially variable (see Figure 2, Francis and Vavrus 2012). In all seasons, the northwest Atlantic appears to be a "hot spot" of AA, thus the circulation in this area should exhibit a more robust response than elsewhere. While previous studies investigated a change in amplitude of planetary waves, as hypothesized by Francis and Vavrus (2012), here we instead shift the focus to measure a changing frequency of highly amplified jet stream patterns. As in Francis and Vavrus (2012), our analysis is based on single height contours in the 500 hPa field such that the selected contours best represent the trajectory of the jet stream: 5600 m for cold months (October – April), and 5700 m for warm months (May – September). We use daily-mean data from 1979 to 2013 obtained from the NCEP/NCAR reanalysis (Kalnay et al. 1996).

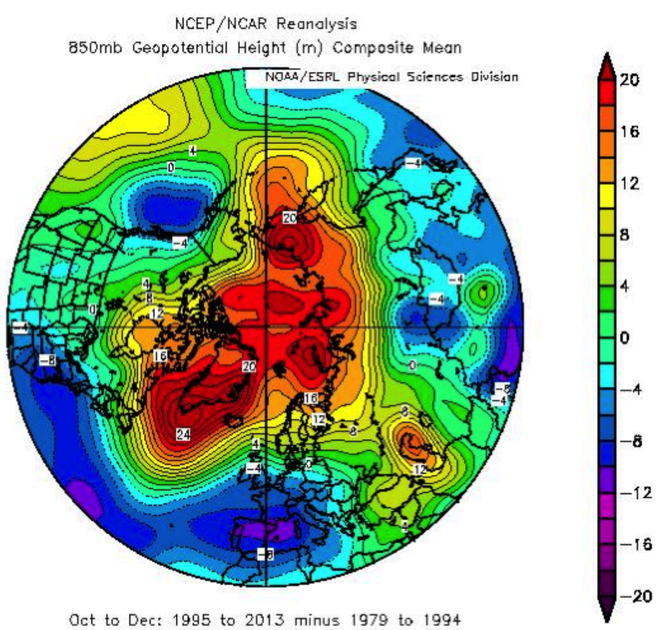

Figure 2. Difference in mean autumn (Oct.-Dec.) 850 hPa heights (m) between the period of recent Arctic amplification (after 1995) and earlier years (1979 to 1994). Data were obtained from the NOAA/ESRL Physical Sciences Division, Boulder CO, http://www.esrl.noaa.gov/psd/.

A highly amplified jet stream pattern is identified when the difference between the daily maximum and minimum latitudes of a single contour in a particular region exceeds 35°. This threshold is selected to obtain approximately 20 events per season, but the main conclusions are not sensitive to small variations in the threshold or to using other height contours within 100 m. In Table 1, we compare seasonal mean frequencies of high amplitude configurations during the period prior to the emergence of AA (1980-1994) to frequencies during recent years (1995-2013). Varying the division between these periods by five years earlier and later makes no appreciable difference to the results presented. Values and cell color indicate percentage differences in six regions and in each season.

Substantial increases in the occurrence of high amplitude jet stream patterns have occurred during autumn in all regions, with large increases evident over North America and the Atlantic during winter and summer. The results for fall and winter are consistent with the expected response to large AA in these seasons and support the hypothesis proposed by Francis and Vavrus (2012). We speculate that increased frequencies in summer may result in part from the rapid decline in late spring snow cover on high latitude land areas, which is collocated with the pattern of AA during summer (Francis and Vavrus 2012). Because highly amplified jet stream patterns have been linked with a variety of extreme weather types (Screen and Simmonds 2014), our findings suggest that the recent increase in extreme events throughout the Northern Hemisphere mid-latitudes (Coumou and Rahmstorf 2012) may be partly due to the rapid pace of Arctic warming.

Clearly much additional research is needed to understand better the mechanisms by which mid-latitude weather patterns will respond to the changing climate system, and particularly if and how they may be influenced by AA. There is also much to learn about the interplay among AA and modes of natural variability (such as the El Niño Southern Oscillation, the Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation). The recent flooding in the UK (winter 2014) and the North America "Snowmageddon" (February 2010), for example, were apparently caused by a combination of Arctic and tropical influences on the jet stream's configuration. Progress can be made by assessing the behavior and trends in weather patterns by region and season, as the globe – and particularly the Arctic – continue to warm in response to unabated emissions of greenhouse gases.

Region	JFM	AMJ	JAS	OND
Atlantic -75 – 0E	38	7	133	64
North America 220 – 290E	26	12	49	41
Europe -15 – 45E	1	-6	32	39
Asia 30 – 150E	2	-5	-21	113
Pacific 150 – 240E	-14	13	-5	43
Northern Hemisphere	3	1	-9	30

< -40%	-39 to 30%	-29 to 20%	-19 to 10%	-9 to 0%
0 to 9%	10 to 19%	20 to 29%	30 to 39%	> 40%

Table 1. Percentage change in seasonal frequency of extreme waves from the pre-AA period (1979-1994) to the AA-era (1995-2013). Extreme waves are identified when the difference between the maximum and minimum latitude of the 500 hPa height contour (selected to correspond with mean height of strongest westerly winds) within a specified region exceeds 35° latitude. Height data were obtained from the NCEP/NCAR reanalysis, NOAA/ESRL Physical Sciences Division, Boulder CO, http://www.esrl.noaa.gov/psd/.

References

Barnes, E. A., 2013: Revisiting the evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett.,* **40**, doi: 10.1002.grl.50880.

Cohen, J. L., J. C. Furtado, M. Barlow, V. A. Alexeev, and J. E. Cherry, 2012: Asymmetric seasonal temperature trends. *Geophys. Res. Lett.*, **39**, L04705, doi:10.1029/2011GL050582.

Cohen, J., J. Jones, J. C. Furtado, and E. Tziperman, 2013: Warm Arctic, cold continents: A common pattern related to Arctic sea ice melt, snow advance, and extreme winter weather. Oceanography, **26**, doi:10.5670/oceanog.2013.70.

Coumou, D. and S. Rahmstorf, 2012: A decade of weather extremes. Nat. Climate Change, **2**, 491-496, doi:10.1038/nclimate1452.

Francis, J. A. and S. J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett.,* **39**, L06801, doi:10.1029/2012GL051000.

Jeffries, M. O., J. A. Richter-Menge, and J. E. Overland, 2013: Arctic Report Card 2013, http://www.arctic.noaa.gov/reportcard.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, and R. Reynolds, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.,* **77,** 437-471, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Overland, J. E., and M. Wang, 2010: Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. *Tellus A,* **62,** 1-9, doi:10.1111/j.1600-0870.2009.00421.x.

Overland, J. E., and M. Wang, 2013: When will the summer Arctic be nearly sea ice free?, *Geophys. Res. Lett.,* **40**, 2097–2101, doi:10.1002/grl.50316.Overland, J. E., M. Wang, and S. Salo, 2008: The recent Arctic warm period. *Tellus A*, **60,** 589-597, doi: 10.1111/j.1600-0870.2008.00327.x.

Palmén, E., and C. W. Newton, 1969: *Atmospheric Circulation Systems: Their structure and physical interpretation*, Academic Press, 606pp.

Screen, J. A., 2013: Influence of Arctic sea ice on European summer precipitation. *Environ. Res. Lett.,* **8,** doi:10.1088/1748-9326/8/4/044015.

Screen, J. A., and I. Simmonds, 2013: Exploring links between Arctic amplification and midlatitude weather. *Geophys. Res. Lett.,* **40,** doi:10.1002/GRL.50174.

Screen, J. A., and I. Simmonds, 2014: Amplified mid-latitude planetary waves favour particular regional weather extremes. *Nat. Climate Change,* doi:10.1038/nclimate2271.

Screen, J. A., C. Deser, I. Simmonds, and R. Tomas, 2013: Atmospheric impacts of Arctic sea-ice loss, 1979-2009: Separating forced change from atmospheric internal variability. *Climate Dyn.*, 43, 333-344, doi:10.1007/s00382-013-1830-9.

Silver, N., 2012: *The Signal and the Noise*. Penguin Press, 533 pp.

Tang, Q., X. Zhang, X. Yang, and J. A. Francis, 2013a: Cold winter extremes in northern continents linked to Arctic sea ice loss. *Environ. Res. Lett.* **8,** 014036, doi:10.1088/1748-9326/8/1/014036.

Tang, Q., X. Zhang, and J. A. Francis, 2013b: Extreme summer weather in northern mid-latitudes linked to a vanishing cryosphere. *Nat. Climate Change,* **4,** doi:10.1038/nclimate2065.

Thompson, D. W.. and J. M. Wallace, 2001: Regional climate impacts of the Northern Hemisphere annular mode. *Science,* **293,** 85-89, doi:10.1126/science.1058958.

SAVE THE DATE

Ocean's Carbon and Heat Uptake: Uncertainties and Metrics
December 12 - 14 | San Francisco, CA

This workshop, organized jointly by the Ocean Carbon Uptake and Southern Ocean Working Groups of US CLIVAR and OCB, aims to catalyze progress toward understanding the ocean’s role in carbon and heat uptake by strengthening communication and collaboration across traditional disciplinary boundaries to facilitate the exchange of results from recent studies and discuss the most promising directions for future research.

More information