WIREs CLIMATE CHANGE

**Article type:** **Opinion**

# Article title: The impact of Arctic warming on the midlatitude jetstream: Can it? Has it? Will it?

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## Abstract

The Arctic lower atmosphere has warmed more rapidly than that of the globe as a whole, and this has been accompanied by unprecedented sea ice melt. Such large environmental changes are already having profound impacts on the flora, fauna and inhabitants of the Arctic region. An open question, however, is whether these Arctic changes have an effect on the jetstream and thereby influence weather patterns farther south. This broad question has recently received a lot of scientific and media attention, but conclusions appear contradictory rather than consensual. We argue that one point of confusion has arisen due to ambiguities in the exact question being posed. Here we frame our inquiries around three distinct questions: *Can Arctic warming influence the midlatitude jetstream? Has Arctic warming significantly influenced the midlatitude jetstream? Will Arctic warming significantly influence the midlatitude jetstream?* We argue that framing the discussion around the three questions: *Can it?, Has it?, Will it?* provides insight into the common themes emerging in the literature as well as highlights the challenges ahead.

# Introduction

The possibility that recent Arctic sea ice loss and surface warming could be impacting the Northern Hemisphere jetstream and, thereby, extreme weather in the Northern Hemisphere midlatitudes, has recently has received a lot of scientific and media attention. The devastation wrought by the landfall of Superstorm Sandy in 2012[1], the frigid temperatures over North America in the winter of 2013/2014[2], the cold and snowy winters of 2009/2010 and 2010/2011 over Europe and North America[3,4] and bouts of extreme summer weather[5-7] have all been linked to Arctic sea ice loss over the past decade, in both the scientific literature and the media. Furthermore, there are suggestions that as the Arctic continues to see unprecedented sea ice decline and warmer near-surface temperatures in the coming decades, extreme weather in midlatitudes may become more commonplace[7,8]. This hypothesis has been well publicized, to the extent that many non-scientists believe that future Arctic warming will have major effects on weather where they live[9]. These views, however, are not shared by the climate science community as a whole, with some scientists suggesting that there is in fact no robust evidence for such a link between Arctic warming and midlatitude weather[10] and that, for example, the chances of cold weather extremes in the coming decades may actually decrease because of Arctic warming[2,11-13].

The Northern Hemisphere jetstream encapsulates the large-scale, atmospheric circulation in the mid-latitudes and is the "river" on which synoptic storms grow and propagate. Given that the jetstream is strongly coupled to the storm tracks and related surface weather in this way, we limit our discussion here to whether Arctic amplification is a major driver of midlatitude jetstream variability and change. We suggest that confusion has arisen, at least in part, due to ambiguities in the exact question being posed and the evidence used to answer it. Specifically, that evidence showing that the Arctic *can* influence the midlatitude jetstream has perhaps been wrongly interpreted as evidence that the Arctic *has* had a significant influence or that it *will* have a significant influence in the future. Thus, we choose to frame our discussion using three related, but distinct, questions:

(1) **Can** Arctic warming influence the midlatitude jetstream?

(2) **Has** Arctic warming significantly influenced the midlatitude jetstream?

(3) **Will** Arctic warming significantly influence the midlatitude jetstream?

In what follows, we briefly discuss the state of the science for each of these three questions, and articulate some of the challenges with answering each.

A likely key to the scientific discussion, we note, is the definition of the phrase "significantly influence". Does this phrase mean "significantly influence" in a statistical sense, where the impacts are compared to some null hypothesis? Or does it mean, perhaps, that the impacts are noticed by the average person? Or does it mean that a particular socioeconomic risk threshold is reached? There is certainly no single answer that applies in all cases, and a thorough discussion of this topic is far beyond the scope of this Opinion article. However, we wish to state explicitly that in the context of our framing questions above, we define "significantly influence" to mean that the effects can be distinguished from the background internal variability of the midlatitude circulation. This is not to say other definitions are less valid; we just will not explore them here.

## Can it?

Whether Arctic warming *can* influence the midlatitude jetstream requires isolating the effects of Arctic warming from other aspects of climate variability and change, and thus, one typically cannot use observations alone to determine a causal link. Instead, the '*Can it?*' is best explored with well-designed model simulations and supporting theoretical arguments.

### Modeling efforts

Atmospheric General Circulation Model (AGCM) experiments with imposed sea ice loss or Arctic warming have been used extensively to explore whether the Arctic can impact the midlatitude atmospheric circulation. Nearly all of these experiments demonstrate a clear causal influence of Arctic warming on the midlatitude circulation[14-17]. In many of these studies, the wintertime Northern Hemisphere circulation is found to exhibit a weaker and more equatorward jetstream (often interpreted as a negative Arctic Oscillation/North Atlantic Oscillation) in response to a warmer and less sea-ice-covered Arctic[18-20]. This large-scale response is associated with colder and drier winters in northern Europe and eastern North America. In fact, this weakening and equatorward shift of the jetstream in response to polar warming can also be simulated in very simple models, such as in a dry dynamical core with imposed surface heating[21] (Figure 1). Thus, model simulations clearly demonstrate that Arctic warming *can* impact the jet (and therefore, surface weather) in midlatitude regions. However, we note that in most of these simulations the responses are small compared to the internal variability, and this will be discussed in more detail in the next section.

Even such carefully designed modeling studies do not always agree on the atmospheric response to the same Arctic change. Recent work showed that two state-of-the-art AGCMs forced with identical sea ice loss produce significantly different circulation responses[22]: one model produced *no* significant Arctic Oscillation response, while the other produced a *positive* Arctic Oscillation response. Therefore, not only did the models disagree with respect to the circulation changes, but neither model exhibited the *negative* Arctic Oscillation response that has been identified in other model experiments. Other studies have documented that the same model can produce very different responses to Arctic surface changes, depending on the precise details of the sea ice and sea surface temperature anomalies imposed[23]. Thus, while model experiments consistently show a response of the midlatitude jetstream to surface changes in the Arctic, the nature of the response is far from robust and may be highly non-linear.

A different modeling approach is to consider the improvement, or not, of hindcasts (retrospective forecasts) when Arctic conditions are known. Whereas a forecast makes a prediction based only on known starting conditions, a hindcast can selectively incorporate some of aspects of the observed evolution of weather (i.e., what actually happened) to see if knowledge of these aspects improves the hindcast in other ways. Studies have shown a more realistic depiction of midlatitude winter weather (e.g, surface temperature, mid-tropospheric circulation) in hindcasts that incorporate the known evolution of Arctic conditions[24,25]. Such improvement in simulating the midlatitude circulation appears to be a result of imposing a more realistic Arctic state and therefore constitutes another strand of evidence of an Arctic influence in midlatitudes.

### Synthesis

Model evidence strongly suggests that near-surface Arctic warming and sea ice loss can modify the midlatitude jetstream. Complications arise, however, when we ask *how* does circulation respond to this Arctic warming? Exactly how this influence propagates from high to low latitudes and how it is manifest in midlatitudes is far from understood. Many mechanisms and plausible pathways have been explored (see Sidebar 1), however, no single dominant pathway has emerged, owing in part to model disagreement on the response itself. Finally, the fact that Arctic warming *can* influence the midlatitude jetstream does not imply it *has* had a significant impact, nor does it imply it *will* have a significant impact in the future. We address these additional two questions in the following sections.

## Has it?

Arctic sea ice has exhibited an unprecedented decline over the past three decades. At the same time, near-surface Arctic air temperatures have warmed substantially more than the global average. The question many people ask is: "Have the rapid changes in the Arctic significantly influenced the weather where I live?" Causality is difficult, if not impossible, to determine unambiguously from observations alone. Furthermore, no consensus currently exists among scientists in the field on whether significant changes in the midlatitude jetstream have even been detected, let alone whether Arctic warming is to blame.

### Observational evidence

Multiple studies over the past few years have reported observational evidence that near surface Arctic warming has modified the jetstream in the midlatitudes. One study in particular by Francis and Vavrus[8] (refer to Box 1) has garnered a lot of attention and suggests that Arctic warming has caused slower-moving circulation patterns and larger north-south deviations in the jetstream in all seasons but spring. However, this work has received significant criticism from the atmospheric science community[15-17]. Specifically, that the observations do not support this hypothesized mechanism[26-28], and that the conclusions are highly sensitive to the choice of methodology[26,27].

Other studies have attempted to address "*Has it?*" by searching for correlations between the atmospheric circulation and Arctic conditions (both sea ice and temperature) over the historical period[4,6,29-31]. This approach has significant drawbacks however, given that causality is very difficult to demonstrate using observations alone and nearly impossible to pin down without a hypothesis based solidly in atmospheric dynamics. Below we list three of the major obstacles that confront these types of observational studies.

*Decoupling from internal atmospheric variability*

One of the major issues with using observations alone is that the internal variability of the midlatitude circulation is substantial. For example, the jetstream position can vary by up to 10 degrees latitude from year to year (Figure 2). Even on decadal timescales, the jet and the associated storm track exhibits enhanced fluctuations in both strength and position[32] (Figure 2). Thus, with only 30 years or so of reliable satellite-era atmospheric (and sea ice) data, it would be nearly impossible to distinguish a forced signal from the background variability[17]. To further support the dominance of internal variability, Screen and coauthors[22] analyzed the midlatitude circulation in an ensemble of model simulations where sea ice concentrations were reduced at the observed rate, and they concluded that if only Arctic sea ice were changing, it would take 50 years or more for the forced signal in the large-scale winds to be distinguishable from internal variability.

*Which way does the arrow point?*

The issue of correlation versus causation plagues all sciences, and the topic of Arctic linkages with midlatitude weather is no exception. For example, while it is not yet clear how important the Arctic state is in driving midlatitude jetstream variability (the topic of this article), it is well accepted by the scientific community that the midlatitude circulation is an important driver of Arctic climate[33-35]. In such a strongly coupled system, diagnosing cause and effect is a nearly intractable problem with observations alone. For this reason, recent work has turned to a "modeling attribution" approach and multiple studies have implicated fluctuating sea surface temperatures outside the Arctic as an important driver of Arctic warming over the past two decades[10,34,36,37]. Thus, if recent Arctic warming is partly driven by processes outside of the polar cap[34,35] (Figure 3), any significant correlations between the high-latitude warming and the lower-latitude circulation patterns could reflect the role of midlatitudes forcing the Arctic, rather than the other way around.

*Incomplete mechanistic understanding*

Studies on this topic have argued for links between Arctic warming and wave amplitudes[8], blocking anticyclones[8,38], heat waves[6,7], cold snaps[3,4,39,40], hurricanes[1] and extreme precipitation events[41], just to name a few. In arguably all cases, the precise mechanisms remain uncertain and thus, the proposed linkages should be viewed with extreme caution. Without concerted efforts to better understand the mechanisms underpinning these proposed linkages, the community will likely continue to search and identify correlations between the Arctic and a slew of atmospheric phenomena, confronted at every step with this issue of correlation versus causation.

### Synthesis

Whether recent Arctic surface warming and sea ice loss has significantly impacted the midlatitude jetstream is still a topic of much debate. The weight of evidence suggests that if there has been Arctic influence on the midlatitude circulation to date, it has probably been small compared to internal atmospheric variability. It is our opinion that that no study (or set of studies) has sufficiently demonstrated a significant Arctic influence on the jetstream, and that many alternative hypotheses exist that can account for the observed variability that are well-supported by fundamental atmospheric dynamics theory and model experiments. Furthermore, the simplest explanation still cannot be ruled out – namely, that the jetstream behavior we have observed over the past few decades is no more than internal midlatitude variability.

## Will it?

While there is strong modeling evidence that lower-tropospheric Arctic warming *can* cause significant changes in the midlatitude jetstream (see previous discussion), this does not imply that Arctic warming *will* have a tangible effect on future jet behavior. While the "*Can it?"* captures the relevant processes when all other factors are held fixed, e.g., only considering the influence of Arctic warming, the "W*ill it?*" captures our best guess of the most likely path our climate system will take in the coming years. Thus, one must consider the effects of increasing greenhouse gas concentrations at all latitudes, altitudes and scales and assess whether these responses will interact constructively or destructively over the next century. To do this, we look to the fifth Coupled Model Intercomparison Project (CMIP5) experiments, which offer state-of-the-art projections as to how all of the different pieces in the climate system may interact. Although these models exhibit well-known biases in relevant aspects of the large-scale circulation (e.g. jetstream position[42]), they are the best tools we have for predicting the feedbacks and interactions of the climate system over the next century.

## Tug-of-war: Tropics versus Poles

As an example, although every CMIP5 model projects that the Arctic will warm substantially over the 21st Century, these models tend to exhibit a robust *poleward* shift of the Northern Hemisphere jetstreams in all seasons but winter[42] (Figure 5a; in winter, model spread is too large to discern any robust response). Recall that models with imposed near-surface Arctic warming or sea ice loss tend to depict an *equatorward* shift of the jet[18-21]. A more poleward jet is associated with less frequent blocking episodes, which is opposite to the changes some have proposed due to Arctic sea ice loss[3,8].

This apparent discrepancy is likely due to the many competing effects of climate change on the midlatitude jetstream response. Referring back to our example above, while the Arctic lower-troposphere is projected to warm more than the tropics by 2100, the opposite is true in the upper-troposphere, where tropical warming is projected to dominate (Figure 4). Thus, the north-south temperature gradient is projected to decrease near the surface, but increase at upper-levels. An increased upper-level temperature gradient has been shown to shift the jetstream poleward and increase storm track activity, while a decreased lower-level temperature gradient may shift the jetstream equatorward and decrease storm track activity[43]. A handful of studies have assessed the relative importance of polar versus tropical warming in models of varying complexity[21,44-47], and although all of these studies agree that both the Arctic and tropical warming responses are relevant to the circulation response, it is still uncertain which effect will ultimately win the tug-of-war on the jetstream.

## A modulating influence

The tug-of-war on the jetstream due to the differing effects of tropical warming and Arctic warming suggests that Arctic warming has the potential to *modulate* the response of the midlatitude circulation to future climate change. Analyzing the CMIP5 models, Barnes and Polvani[47] showed that while the models do not agree on the whether the North America/North Atlantic jetstream will speed up or slow down by 2100 (Figure 5b), the model spread of the response is highly correlated with the degree of Arctic warming in spring and summer (Figure 5d). In addition, the jet latitude response is negatively correlated with the degree of Arctic warming in winter (Figure 5c), suggesting that wintertime Arctic amplification may reduce the magnitude of the poleward shift driven by the tropical warming (Figure 5a).

Other studies have also concluded that the projected changes in the mid-tropospheric winds and storm tracks are correlated with the magnitude of Arctic warming[45-47]. While we stress that causality cannot be explicitly determined from correlation analysis, these results suggest that future Arctic warming may modulate the circulation response to increasing greenhouse gas emissions.

Nonetheless, the net response of the circulation — that is, our best estimate of what ultimately *will* occur — may not be what is expected from Arctic warming alone.

### Synthesis

The response of the midlatitude jetstream over the 21st Century will ultimately be determined by the nonlinear interaction of many factors, only one of which is Arctic surface warming. While the latest climate models suggest a possible role for Arctic warming in modulating this response, all of these competing influences must be considered if one is interested in the ultimate fate of midlatitude weather.

## Conclusions

Does rapid Arctic warming have tangible implications for weather in lower latitudes? The jury is still out. While there is a growing consensus in the model-based literature that that Arctic warming *can,* in isolation, significantly influence the midlatitude circulation, this neither implies that it *has* in the past*,* nor that it *will* in the future. This is because internal atmospheric variability may obscure the influence of Arctic warming and/or the Arctic influence may be small compared to other factors that control midlatitude weather. We suggest that it useful to frame inquiries using the “*Can it?*”, “*Has it?*” and “*Will it*?” approach. The “*Can it*?” and “*Will it*?” questions are potentially tractable as we continue to improve our mechanistic understanding of the high-to-mid- latitude connections, and as our models improve in their ability to simulate the related dynamics. However, the “*Has it?*” is likely to continue to be more challenging to answer given the short observational record and large internal variability of the midlatitude atmosphere.

The last two questions (*“Has it?” “Will it?”*) are likely still a long way from being fully answered. However, to more fully understand the influence of rapid Arctic change on weather in lower latitudes, we must make appreciable progress towards addressing both of these questions separately. And even if our efforts ultimately lead us to the conclusion that the answers are “no”, there’s still a good chance we’ll have learned a lot about our climate system along the way.

## Sidebar 1: Possible pathways for Arctic warming to influence midlatitude weather

### *Reduced meridional temperature gradient*

If the Arctic surface warms faster than that at lower-latitudes, the lower-tropospheric temperature difference between the tropics and the pole will decrease. This reduced gradient implies reduced baroclinicity, which would lead to reduced storm activity. Furthermore, a reduction in the meridional temperature gradient would be expected to lead to smaller temperature variations across the midlatitudes, and thus, fewer temperature extremes than one might expect due solely to the climate shifting toward warmer temperatures[11-12].

### *A more sinuous jetstream*

One widely debated mechanism by which Arctic warming could influence midlatitude weather extremes is through changes in the undulations of the jetstream. If the meridional temperature gradient decreases (see above), and one assumes that the midlatitude surface winds and storm tracks remain unchanged, the jet stream may be expected to slow down due to the relationship between temperature and wind known as thermal wind balance (which states that a reduced meridional temperature gradient is dynamically linked to a reduced vertical gradient in wind). Francis and Vavrus[8] hypothesized that the slower jetstream may cause more amplified Rossby waves, increasing the frequency of atmospheric blocking and thus, persistent and extreme weather in midlatitudes. However, this hypothesis has been questioned in the recent literature[26-28,42,48], and we note, leads to more extreme temperature variations, while the pathway described in the section above would lead to fewer.

### *Trapped atmospheric waves*

Coumou and coauthors[7] proposed a similar, but distinct, mechanism whereby a weaker meridional temperature gradient favors the occurrence of splits in the jetstream. Double jet configurations occur when the jet stream splits into two distinct filaments, one usually following a more northerly route and the other a more southerly route, with this jet pattern more common in summer than in winter. These double jets act as barriers trapping the lower level atmospheric flow in the mid-latitudes. In such circumstances, known as “quasi-resonance”[5,7], circulation patterns tend to stagnate, leading to bouts of persistent and extreme summer weather.

### *Modified storm tracks*

At more regional scales, changes in sea ice can alter local temperature gradients because the newly open ocean is warmer than the surrounding sea-ice surface. This leads to local warming of the atmosphere overlying the newly open water, which can trigger anomalous planetary wave activity with downstream effects[30,39-41]. The large temperature gradients at the ice-ocean boundary act as a hot spot for the growth of mesoscale storm systems. As the average sea ice edge migrates in a warming climate so do the regions of cyclogenesis, which can affect the larger-scale circulation by modifying the storm tracks[38,49].

### *Weakened stratospheric polar vortex*

Another possible pathway involves the two-way interaction between the troposphere and the stratosphere above it. Planetary-scale Rossby waves transfer energy from the troposphere to the stratosphere. When these waves reach the stratosphere they “break” (analogous to an ocean wave at the beach) and this stratospheric wave breaking impacts the strength of the polar vortex. Increased vertical wave propagation tends to weaken and warm the polar vortex in early winter. Anomalies in the stratosphere in early winter descend back down into the troposphere by mid-to-late winter. Specifically, a weakened stratospheric polar vortex often precedes the negative phase of the Arctic Oscillation or North Atlantic Oscillation, which tends to be associated with cold midlatitude winters at the Earth’s surface. Decreased autumn sea ice, especially in the Barents and Kara seas, has been proposed to trigger anomalous vertical wave propagation into the stratosphere. This process weakens the polar vortex, which shifts the Arctic Oscillation towards its negative phase, and ultimately, favours cold winter conditions over North America and Eurasia[15,50].

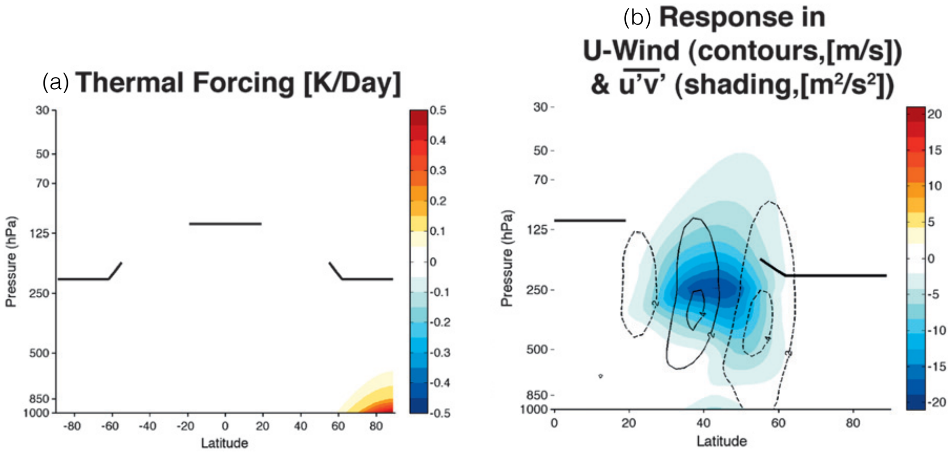
## References

1. Greene, C.H., J.A. Francis and B.C. Monger. Superstorm Sandy: A series of unfortunate events? *Oceanography* **26**, 8-9 (2013)
2. Wallace, J.M., I.M. Held, D.W.J. Thompson, K.E. Trenberth and J.E. Walsh. Global warming and winter weather. *Science* **343**, 729-730 (2014)
3. Liu, J., J.A. Curry, H. Wang, M. Song and R.M. Horton. Impact of declining Arctic sea ice on winter snowfall. *Proc. Natl. Acad. Sci. USA* **109**, 6781-6783 (2012)
4. Tang, Q., X. Zhang, X. Yang and J.A. Francis. Cold winter extremes in northern continents linked to Arctic sea ice loss. *Environ. Res. Lett.* **8**, 014036 (2013)
5. Petoukhov, V., S. Rahmstorf, S. Petri and H.J. Schellnhuber. Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes. *Proc. Natl. Acad. Sci. USA* **110**, 5336-5341 (2013)
6. Tang, Q., X. Zhang and J.A. Francis. Extreme summer weather in northern mid-latitudes linked to a vanishing cryosphere. *Nature Clim. Change* **4**, 45-50 (2014)
7. Coumou, D., V. Petoukhov, S. Rahmstorf, S. Petri and H.J. Schellnhuber. Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer. *Proc. Natl. Acad. Sci. USA* **111**, 12331-12336 (2014)
8. Francis, J. A. and S.J. Vavrus. Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett.* **39**, L06801 (2012)
9. Hamilton, L.C. and M. Lemcke-Stampone. Arctic warming and your weather: public belief in the connection. *Int. J. Climatol.* **34**, 1723-1728 (2014)
10. Trenberth, K.E., J.T. Fasullo, G. Branstator and A.S. Phillips. Seasonal aspects of the recent pause in surface warming. *Nature Clim. Change* **4**, 911-916 (2014)
11. Schneider, T., T. Bischoff and H. Plotka. Physics of changes in synoptic midlatitude temperature variability. *J. Clim.* in review (2014)
12. Screen, J.A. Arctic amplification decreases temperature variance in northern mid- to high-latitudes. *Nature Clim. Change* **4**, 577-582 (2014)
13. Screen, J.A., C. Deser and L. Sun. Reduced risk of North American cold extremes due to continued Arctic sea ice loss. *Bull. Amer. Meteorol. Soc.* in review (2014)
14. Bader, J. et al. A review on Northern Hemisphere sea-ice, storminess and the North Atlantic Oscillation: observations and projected changes. *Atmos. Res.* **101**, 809-834 (2011)
15. Cohen, J. et al. Recent Arctic amplification and extreme mid-latitude weather. *Nature Geosci.* **7**, 627-637 (2014)
16. Vihma, T. Effects of Arctic sea ice decline on weather and climate: A review. *Surv. Geophys.* **35**, 1175-1214 (2014)
17. Walsh, J.E. Intensified warming of the Arctic: Causes and impacts on middle latitudes. *Global and Planetary Change* **117**, 52-63 (2014)
18. Deser, C., R. Tomas, M. Alexander and D. Lawrence. The seasonal atmospheric response to projected Arctic sea ice loss in the late 21st century. *J. Clim.* **23**, 333-351 (2010)
19. Screen, J.A., I. Simmonds, C. Deser and R. Tomas. The atmospheric response to three decades of observed Arctic sea ice loss. *J. Clim.* **26**, 1230-1248 (2013)
20. Peings, Y. and G. Magnusdottir. Response of the wintertime Northern Hemisphere atmospheric circulation to Arctic sea ice decline: A numerical study with CAM5. *J. Climate* **27**, 244-264 (2014)

21. Butler, A.H., D.W.J. Thompson and R. Heikes. The steady-state atmospheric circulation response to climate change-like thermal forcings in a simple general circulation model. *J. Climate* **23**, 3474 (2010)
22. Screen, J.A., C. Deser, I. Simmonds and R. Tomas. Atmospheric impacts of Arctic sea ice loss, 1979-2009: Separating forced change from atmospheric internal variability. *Clim. Dyn.* **43**, 333-344.
23. Balmaseda, M.A., L. Ferranti, F. Molteni and T.N. Palmer, Impact of 2007 and 2008 Arctic ice anomalies on the atmospheric circulation: Implications for long-range predictions. *Q. J. R. Meteorol. Soc.* **136**, 1655-1664 (2010)
24. Jung, T., M.A. Kasper, T. Semmler and S. Serrar. Arctic influence on subseasonal midlatitude prediction. *Geophys. Res. Lett.* **41**, 3676-3680 (2014)
25. Lim, Y.-K., Y.-G. Ham, J.-H. Jeong and J.-S. Kug. Improvement in simulations of Eurasian winter climate variability with a realistic Arctic sea ice condition in an atmospheric GCM. *Environ. Res. Lett.* **7**, 044041 (2012)
26. Barnes, E.A. Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes. *Geophys. Res. Lett.* **40**, 4728-4733 (2013)
27. Screen, J.A. and I. Simmonds. Exploring links between Arctic amplification and mid-latitude weather. *Geophys. Res. Lett.* **40**, 959-964 (2013)
28. Barnes, E.A., E. Dunn-Sigouin, E. Masato and T. Woolings. Exploring recent trends in Northern Hemisphere blocking. *Geophys. Res. Lett.* **41**, 638-644 (2014)
29. Overland, J.E. and M. Wang. Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. *Tellus A* **62**, 1-9 (2010)
30. Jaiser, R., K. Dethloff, D. Handorf, A. Rinke and J. Cohen. Impact of sea ice cover changes on the Northern Hemisphere atmospheric winter circulation. *Tellus A* **64**, 11595 (2012)
31. Hopsch, S., J. Cohen and K. Dethloff. Analysis of a link between fall Arctic sea ice concentration and atmospheric patterns in the following winter. *Tellus A* **64**, 18624 (2012)
32. Woolings, T., C. Czuchnicki and C. Franzke. Twentieth Century North Atlantic jet variability. *Q. J. R. Meteorol. Soc.* **140**, 783-791 (2014)
33. Graversen, R.G. Do changes in the midlatitude circulation have any impact on the Arctic surface air temperature trend? *J. Clim.* **19**, 5422-5438 (2006)
34. Perlwitz, J., M. Hoerling and R. Dole. Why has the Arctic warmed? *J. Clim.* in revision (2014)
35. Screen, J.A., C. Deser and I. Simmonds. Local and remote controls on observed Arctic warming. *Geophys. Res. Lett.* **39**, L10709 (2012)
36. Ding, Q. et al. Tropical forcing of the recent rapid Arctic warming in northeastern Canada and Greenland. *Nature* **509,** 209–12 (2014)
37. Palmer, T. Record-breaking winters and global climate change. *Science* **23**, 803-804 (2014)
38. Zhang, X., C. Lu and Z. Guan. Weakened cyclones, intensified anticyclones and recent extreme cold winter weather events in Eurasia. *Environ. Res. Lett.* **7**, 044044 (2012)
39. Petoukhov, V and V. Semenov. A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents. *J. Geophys. Res.* **115**, D21111 (2010)
40. Honda, M., J. Inoue and S. Yamane. Influence of low Arctic sea-ice minima on anomalously cold Eurasian winters. *Geophys. Res. Lett.* **36**, L08707 (2009)
41. Screen, J.A. Influence of Arctic sea ice on European summer precipitation. *Environ. Res. Lett.* **8**, 044015 (2013)

42. Barnes, E.A. and L.M. Polvani. Response of the midlatitude jets, and of their variability, to increased greenhouse gases in the CMIP5 models. *J. Clim.* **26**, 7177-7135 (2013)
43. Held, I. Large scale dynamics and global warming. *Bull. Amer. Meteorol. Soc.* **74**, 228-241 (1993)
44. Deser, C., R.A. Tomas and L. Sun. The role of ocean-atmosphere coupling in the zonal-mean atmospheric response to Arctic sea ice loss. *J. Climate,* in press.
45. Haarsma, R.J., F. Selten and G.J. van Oldenborgh. Anthropogenic changes of the thermal and zonal flow structure over Western Europe and Eastern North Atlantic in CMIP3 and CMIP5 models. *Clim. Dyn.* **41**, 2257-2588 (2013)
46. Harvey, B.J., L.C. Shaffrey and T.J. Woolings. Equator-to-pole temperature differences and the extra-tropical storm track responses of the CMIP5 climate models. *Clim. Dyn.* **43**, 1171-1182 (2014)
47. Barnes, E.A. and L.M. Polvani. CMIP5 projections of Arctic amplification, of the North American/North Atlantic circulation, and of their relationship. *J. Clim.* in review.
48. Hassanzadeh, P., Z. Kuang and B.F. Farrell. Responses of midlatitude blocks and wave amplitude to changes in the meridional temperature gradient of an idealized dry GCM. *Geophys. Res. Lett.* **41**, 5223-5232 (2014)
49. Inuoe, J., M.E. Hori and K. Takaya. The role of Barents Sea ice in the wintertime cyclone track and emergence of a Warm-Arctic Cold-Siberia anomaly. *J. Clim.* **25**, 2561-2568 (2012)
50. Kim, B.-M. et al. Weakening of the stratospheric polar vortex by Arctic sea-ice loss. *Nature Communications* **5**, 4646 (2014)

## Figures


(a) Thermal Forcing [K/Day]

(b) Response in U-Wind (contours,[m/s]) & $\overline{u'v'}$ (shading,[$m^2/s^2$])

**Figure 1: Circulation response to polar surface heating in a simplified GCM. (a)** The applied thermal forcing (K/day) in the GFDL dry dynamical core. **(b)** The total eddy momentum flux response (shading) ($m^2/s^2$) and the zonal-mean zonal wind response (contours) (m/s). Bold black lines denote the control run tropopause. The model simulation was run under perpetual equinoctial conditions. *[Adapted from Butler et al 2010[21]].*

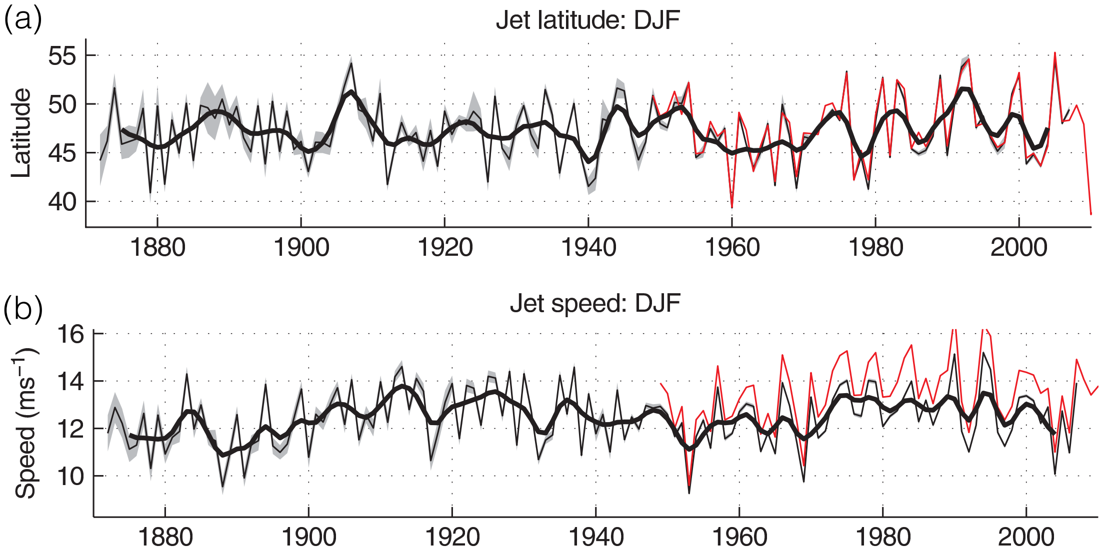


**Figure 2: Internal variability of the jetstream.** Time series of winter (December-January-February) mean jet latitude (**a**) and jet speed (**b**) from the 20th Century Reanalysis (black), with the ±2 standard deviation range across the ensemble (shaded). The thick lines show versions that have been smoothed with a 7-point binomial filter, which strongly damps time scales shorter than 5 years. Red lines indicate indices derived from the NCEP–NCAR reanalysis in recent decades. *[Adapted from Woollings et al 2014*[32]*]*

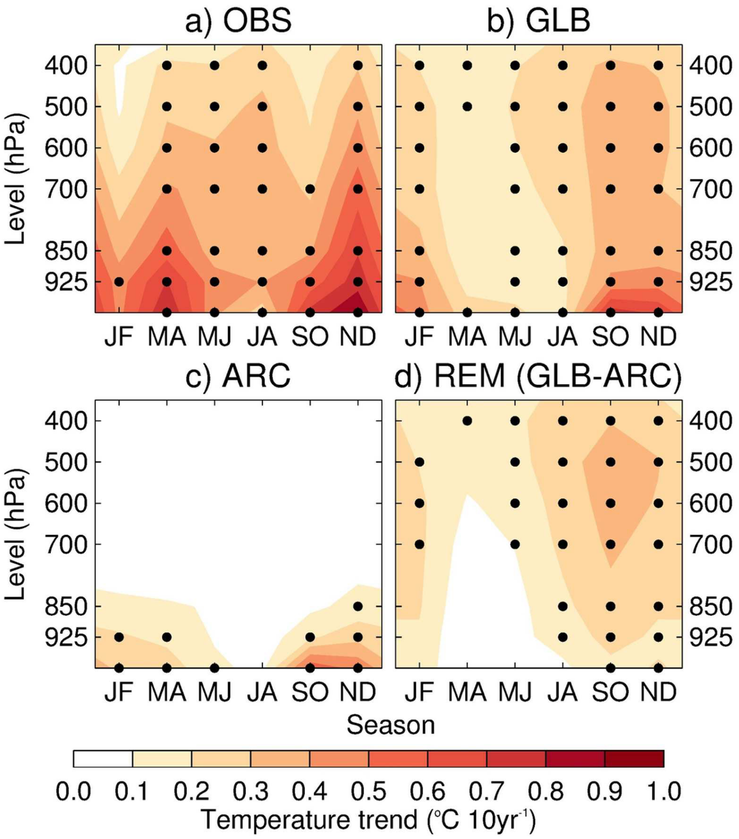


**Figure 3: Local versus remote causes of Arctic warming.** Vertical and seasonal structure of Arctic-mean temperature trends (1979-2008) in observations (**a**), in model ensembles forced by global sea ice and sea surface temperature changes (**b**) and forced by only Arctic sea ice and sea surface temperature changes (**c**) and their difference (**d**). Panels c and d provide estimates of the local and remote influences on Arctic warming, respectively. Black dots show trends that are statistically significant at the 95 percent level [*From Screen et al 2012*[35]].

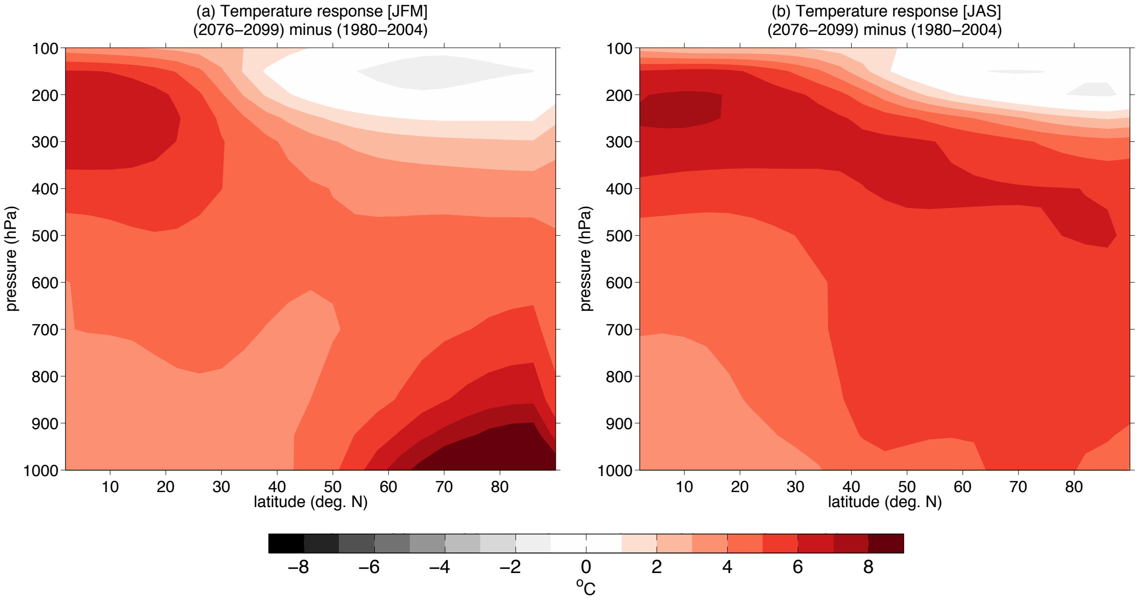


**Figure 4: The horizontal and vertical pattern of projected warming.** Zonal-mean, multi-model mean air temperature response (shading) between 2099-2076 and 1980- 2004 under RCP8.5 for 21 CMIP5 models for winter (**a**; January-February-March) and summer (**b**; July-August-September). *[Adapted from Barnes and Polvani 2014*[47]*]*

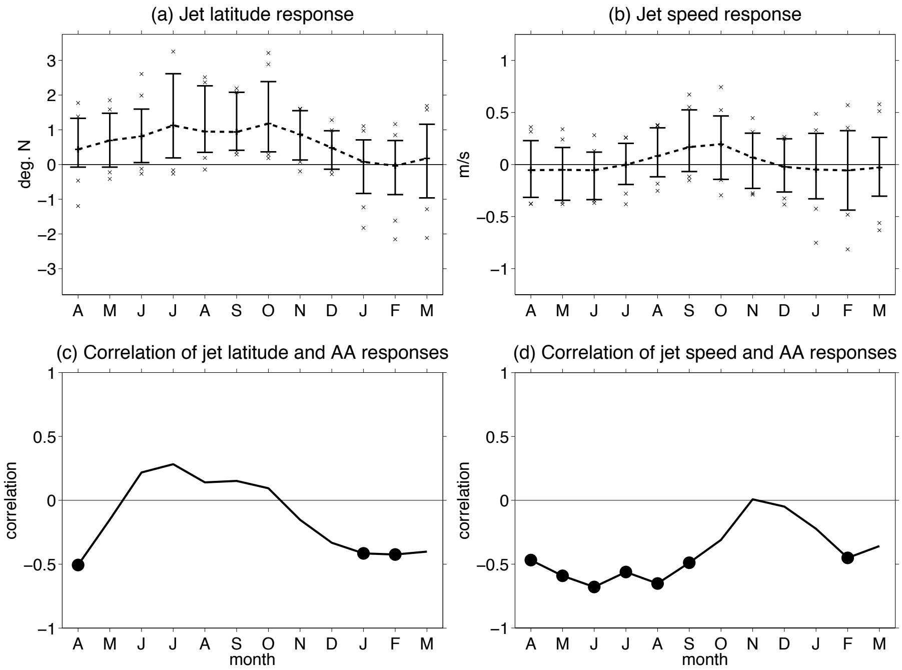


**Figure 5: Relationships between projected future Arctic Amplification and the jetstream.** North Atlantic jet latitude (**a**) and jet speed (**b**) responses as a function of month between 2099-2076 and 1980- 2004 under RCP8.5 for 21 CMIP5 models. Bars signify the 10th-90th percentile range and crosses denote model responses outside of this range. **(c-d)** Correlation across the CMIP5 models of the North Atlantic jet latitude **(c)** or jet speed **(d)** and Arctic amplification responses as a function of month. Solid circles denote correlations significant at the 95% confidence level. *[Adapted from Barnes and Polvani 2014*[47]*]*

## Further Reading/Resources

1. US National Academy of Sciences report *Linkages between Arctic warming and midlatitude weather patterns*: http://www.nap.edu/openbook.php?record_id=18727
2. Annual reports (since 2011) explaining the extreme weather events in the past year from a climate perspective: http://www.ncdc.noaa.gov/bams-state-of-the-climate/extreme-events/

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