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Potential Arctic Change Through Climate Amplification Processes

BY JAMES E. OVERLAND

Credit: NASA (see http://www.nasa.gov/mission_pages/arctas/arctasimg_20080707c.html)

ABSTRACT. Could a gradual warming trend, combined with a large atmospheric or oceanic event, and mediated by Arctic-specific feedbacks, lead to persistent changes in Arctic climate? Several recent observed shifts follow this pattern: they are large, they occur across the Earth system, they are happening decades earlier than suggested by climate models, and while they may or may not be irreversible, they at least carry multiple-year memory (i.e., they are longer than the extreme event that was their proximate cause). When the 2007 summer sea ice minimum occurred, Arctic temperatures had been rising and sea ice had been decreasing over the previous two decades. Nevertheless, it took an unusually persistent southerly wind pattern over the summer months, and perhaps ocean transport and other factors, to initiate the loss event. The abrupt warming and associated record ice loss in West Greenland in 2010 also fit this hypothesis, initiated by southerly winds associated with an unusual manifestation of a natural climate pattern, the North Atlantic Oscillation. Extensive forest fires are causing deep burning of the soil layer, changing the carbon response of Arctic landmasses with lasting effects. Anomalous atmospheric circulation patterns in winter 2009–2010 and December 2010 linked cold-air outbreaks from the Arctic with mid-latitudes. While continued anthropogenic forcing predicts continued temperature increases and sea ice loss, these larger variations or "surprises" introduce uncertainties in the timing and magnitude of future Arctic shifts, the degree to which they are reversible or not, and how they will influence future local and global climate. Climate models, while imperfect, can be run multiple times, in series that are called "ensemble members," to capture a range of potential responses to randomly occurring extreme events combined with continuing anthropogenic warming trends.

INTRODUCTION

The Arctic is changing. In September 2007, the minimum Arctic sea ice extent was 37% below climatology (long-term average climate). Sea ice minimums in all years since 2007 are in excess of two standard deviations below the 1979–2000 average, minimum extents after 2007 are below all values prior to 2007, and sea ice has remained at record low levels during the October freeze-up season. In addition to summer changes, January 2011 had the lowest sea ice extent in the satellite record for that month. Hudson Bay did not completely freeze up until mid-January, about a month later than normal, and the Labrador Sea region was still largely ice-free (http://nsidc.org/arcticseaicenews). September minimums in recent years are associated with minimums occurring at the beginning of summer. Sea ice thickness and the amount of multiyear sea ice in the Arctic basin have continued downward trends (Kwok et al., 2009). Record-setting high air temperatures, ice loss by melting, and marine-terminating glacier area loss marked the West Greenland climate in 2010 (http://www.arctic.noaa.gov/reportcard/greenland.html). In Nuuk (64.2°N along Greenland's west coast), temperatures in summer, spring, and winter were the warmest since record keeping began in 1873. A combination of a 2009–2010 warm and dry winter and the very warm summer resulted in the highest melt rate since at least 1958 and an area and duration of ice sheet melting that was above any previous year on record since at least 1978 (Fettweis et al., 2010). The largest recorded glacier area loss observed in Greenland occurred at Petermann Glacier. The annual rate of area loss in marine-terminating glaciers was 3.4 times that of the previous eight years when regular observations are available. Wildfires throughout the northern Arctic rim countries have increased over the last decade. Deep burning of the soil layer has occurred with extensive fires. Fire-regime changes over the past decade may have caused Alaskan boreal ecosystems to switch from a long-term net soil (carbon) sink toward a (carbon) source, with recent soil (carbon) losses exceeding decadal uptake owing to an increase in late-season burning (Turetsky et al., 2011).

The common feature of sea ice loss, Greenland changes, and extensive Arctic forest fires is that they are all occurring now. The Stroeve et al. (2007) graph showing future model projections for Arctic sea ice cover suggests the observed rate of summer sea ice loss is faster than the set of projections from climate models available from the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4; IPCC, 2007; Figure 1). Rather than considering future Arctic change as simply a steady rise in temperature of

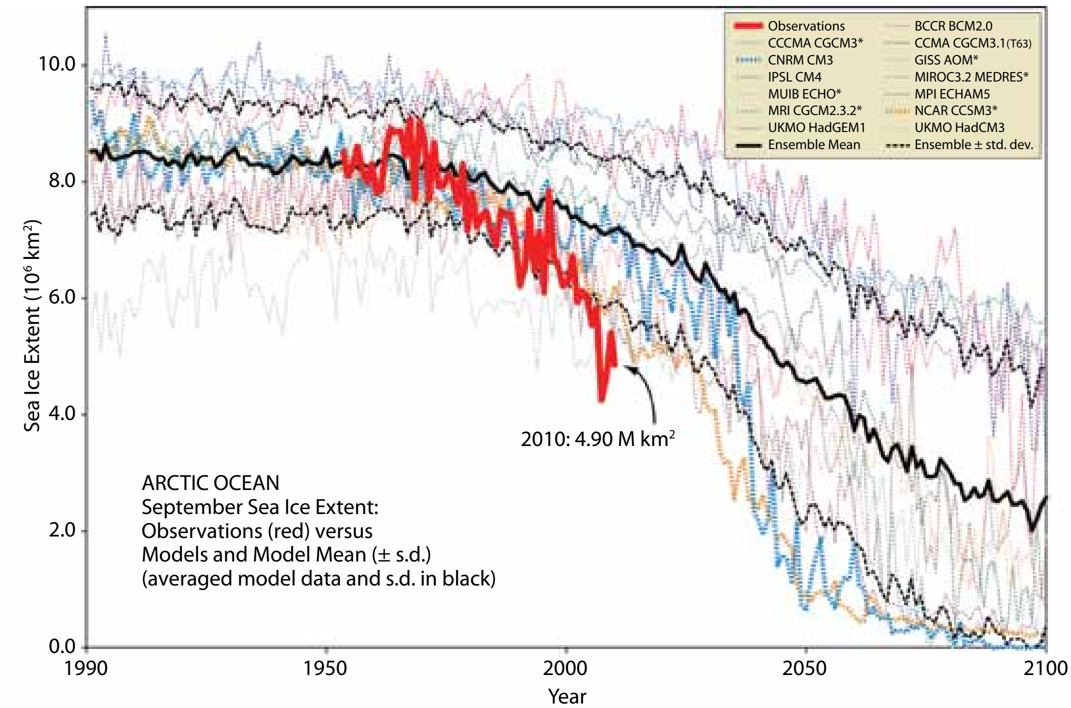

Figure 1. Arctic September sea ice extent ($\times 10^6$ km^2) from observations (thick red line) and Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007) climate models together with the multimodel ensemble mean (solid black line) and standard deviation (dotted black line). Models with more than one ensemble member are indicated with an asterisk. *Updated from Stroeve et al. (2007)*

3–6°C over the remaining twenty-first century (Chapman and Walsh, 2007), Arctic change can be viewed as a result of coupled air-ice-land-ocean feedbacks. Extreme conditions can be created by a combination of gradual warming or loss of sea ice and an extreme event, for example, fortuitous natural variability in atmospheric or oceanic general circulation. In this sense, we will call these changes *surprises* in that they are large, they are occurring across the Earth system, and they are happening decades earlier than suggested by the Arctic Climate Impact Assessment (ACIA, 2005) or the AR4. And, while these shifts may or may not be completely irreversible, they at least carry multiple-year memory (i.e., they are longer than the extreme event), for example, changing soil and permafrost conditions or loss of old, thick sea ice or glacial mass. Are the changes we are currently seeing in the Arctic beyond the range of statistical distributions based on historical understanding of Arctic variability, or are they occurring more frequently than expected based on previous data or model results?

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ARCTIC WARMING

Attributing increases in greenhouse gases as the primary cause for Arctic changes is difficult to assess because of the large range of natural variability over the Arctic area. Such variability is often observed at decadal time scales as changes in wind patterns (Maslanik et al., 2008). Because of the difficulty in separating human-induced global warming from natural variability (e.g., Serreze et al., 2010), it is particularly important to assess global warming impacts in the Arctic through application of known scientific methodologies. One can assess the present status of Arctic change based on four main approaches or standards of the scientific method (Overland, 2009):

- Methodological standards: induction, deduction, and falsification (be disprovable)
- Evidence standards: reliability (replication, independent corroboration, and peer review), consistency of multiple lines of evidence
- Performance standards: predictive, consistent over time, useful
- Community standards: best explanation among competing hypotheses, rejection of speculative hypotheses

At the global scale, the case for anthropogenic warming is laid out in the AR4: "The warming of the climate system is unequivocal," and "most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." Development of this case in the IPCC report proceeds in three steps: change is occurring, these changes are then related to the most plausible causes, and projections are made. There is a deductive relation between the quantitative increases in CO_2 and increases in temperature. That the rise in CO_2 is coincident with increases in fossil fuel burning since the Industrial Revolution is the best explanation among competing hypotheses (and is an application of the community standard).

The case for recent changes in the Arctic can be assessed through application of the four standards listed above. First, there is a consistency of multiple lines of evidence (evidence standard) that indicate climate change in the Arctic, including increased temperatures, diminished sea ice, degraded permafrost, enlarged melt area on Greenland, increased water vapor, decreased snow extent, increasing number of forest fires, increased river discharge, and resulting ecosystem impacts (see Vörösmarty et al. [2008], Callaghan et al. [2010], and http://www.arctic.noaa.gov/reportcard for discussion).

With regard to performance and community standards, climate models predicted "Arctic amplification"—that the Arctic will warm faster than more southerly latitudes (Manabe and Stouffer, 1980) and that temperature increases will be Arctic-wide in contrast to more regional warming patterns associated with climate variability such as the Arctic Oscillation (AO) or the Pacific North American Pattern (PNA) (Quadrelli and Wallace, 2004; Chapman and Walsh, 2007). Figure 2a shows the annual near-surface air temperature anomalies in 2020–2029 from AR4 for a middle range of anthropogenic forcing. For comparison, Figure 2b shows the annual near-surface air temperature anomalies in 2001–2010 for the high-latitude Northern Hemisphere. There is a uniform pattern of increased temperatures in the Arctic in both model projections and data. If the observed temperature change is broken down regionally and seasonally, there is an increase of +1°C relative to climatology throughout the Arctic, with hot spots that vary in location and timing (Overland, 2009). Autumn temperature anomalies increased the most over much of the Arctic; this increase is also a prediction of anthropogenic forcing in climate models (performance standard). In contrast, during the Arctic warm period of the 1930s, the positive temperature anomalies were only on the Atlantic side of the Arctic (Wood and Overland, 2010). In the early 1990s, there were strong regional positive temperature anomalies over Eurasia consistent with the AO temperature footprint (Quadrelli and Wallace, 2004). The hypothesis that recent Arctic changes can be explained solely by variability of natural dynamic climate patterns can be rejected (community standard) (Przybylak, 2002). A global warming influence on Arctic change can be accepted based on multiple standards for the application of the scientific method.

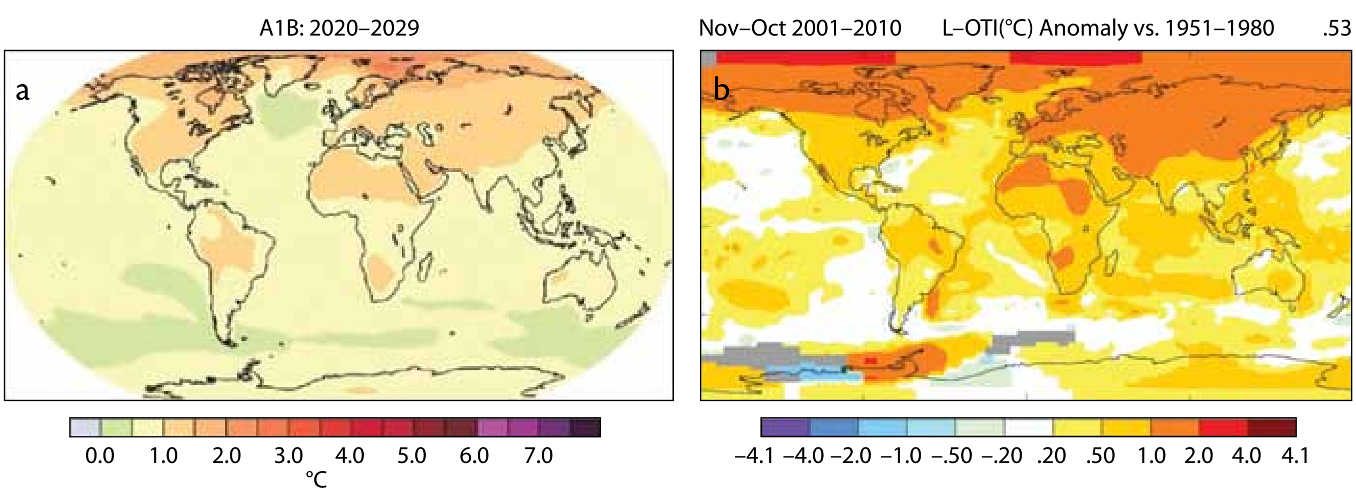

Figure 2 (a) IPCC model projected change in air temperatures for 2020–2029 using a mid-range carbon emission scenario (A1B). *From IPCC (2007)* (b) Near-surface air temperature anomaly multiyear composites (°C) for 2001–2010. Anomalies are relative to the 1951–1980 mean and show a strong Arctic amplification of recent temperature trends. Note the slightly different map projection and temperature scale from (a). *Data are from Hansen et al. (2010) as plotted through http://data.giss.nasa.gov/gistemp/maps*

ARCTIC AMPLIFICATION AND FEEDBACKS

The term "Arctic amplification" refers to the phenomenon of faster warming toward the northern pole than at lower latitudes. Arctic amplification has been observed in recent years (Serreze and Barry, 2011), and it has also been identified in paleoclimate data (Axford et al., 2009; Fitzpatrick et al., 2010; Miller et al., 2010). Arctic amplification can have multiple causes (Miller et al., 2010; Serreze and Barry, 2011). Historically, sea ice formed rapidly during autumn in open ocean areas, a strong negative radiative feedback that overwhelmed other Arctic processes. But recently, increased sea ice mobility and loss of multiyear sea ice, combined with enhanced heat storage in newly sea ice-free ocean areas (that, in turn, returns this heat to the atmosphere in the following autumn), form connected positive feedback processes that increase Arctic temperatures and sea ice loss (Gascard et al., 2008). While amplification of Arctic temperature is most traditionally associated with local loss of sea ice and an ice-albedo feedback, polar amplification also results from the process of poleward heat and moisture transport (Döscher et al., 2010). Research suggests that amplification would occur even on a planet that had no land or sea ice (Langen and Alexeev, 2007; Graversen and Wang, 2009). However, a main mechanism of recent Arctic amplification is loss of summer sea ice and related increases in autumn temperatures (Screen and Simmonds, 2010). Rather than just an *ice albedo* feedback that would be most active in summer in response to *insolation*, recent years show evidence of a late summer/early autumn positive *ice insulation* feedback due to additional ocean heat storage in newly sea ice-free areas (Serreze et al., 2008). Sea ice insulation refers to isolating the relatively warm Arctic Ocean from the colder atmosphere as autumn and winter approach.

Figure 3 summarizes hypothesized recent Arctic amplification feedback systems, as discussed in Overland et al. (in press) and Stroeve et al. (2011). Increases in Arctic atmospheric temperatures in all seasons and increased advection of heat and moisture further into the central Arctic are associated with increased sea ice-free Arctic Ocean areas, especially in the Chukchi Sea, Siberian coastal waters, and the northeastern Barents Sea (Comiso et al., 2006;

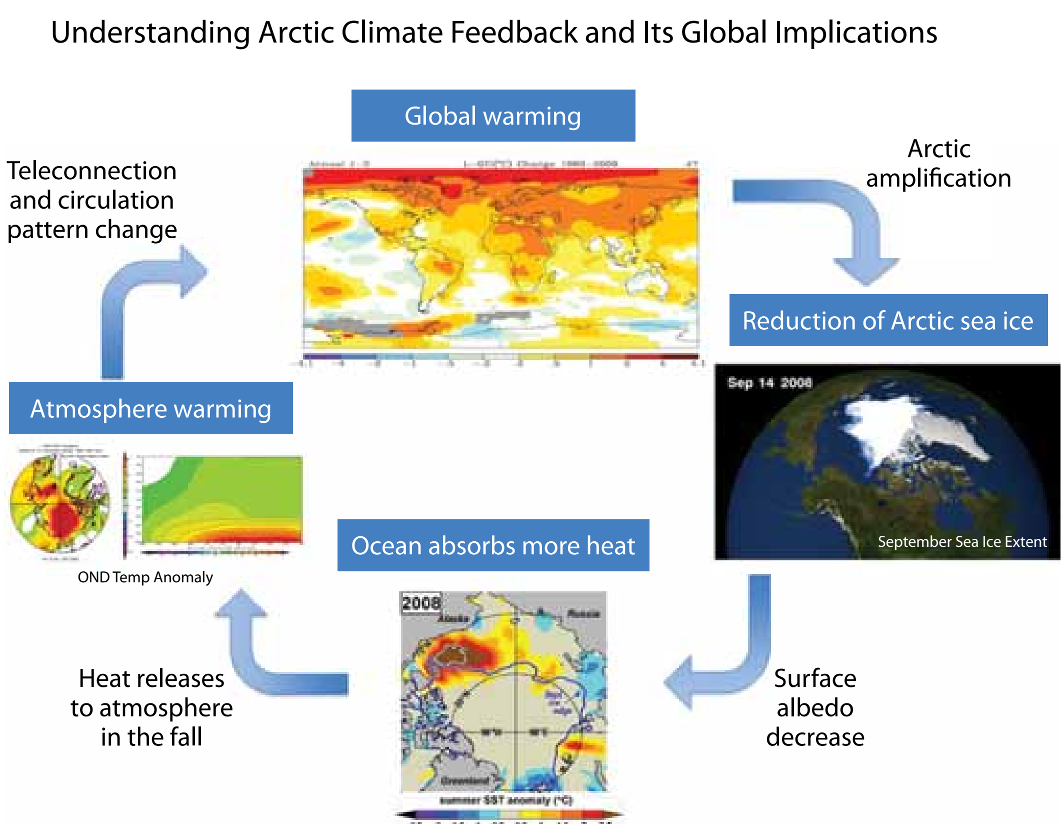

Figure 3. A representation of current and future Arctic climate feedbacks. Starting at the top, warming and changes in atmospheric circulation lead to loss of summer sea ice and increased storage of heat in newly sea ice-free ocean areas. This ocean heat is returned to the lower troposphere the following autumn, increasing the height of geopotential height fields and impacting local and far field winds through teleconnections. *From Overland et al. (in press)*

Giles et al., 2008; Zhang et al., 2008; Wang et al., 2009; Inoue and Hori, 2011). An increase in sea ice-free area allows an increase in absorbed heat in the upper 20 m of the ocean, creating a new near-surface temperature maximum (Jackson et al., 2010; Steele et al., 2010). Ocean transport processes are also important in maintaining Arctic Ocean heat anomalies (Sumata and Shimada, 2007; Woodgate et al., 2010). Return of locally stored ocean heat to the atmosphere occurs the following autumn (Deser et al., 2010; Screen and Simmonds, 2010; Kumar et al., 2010). This additional heat from the ocean does not remain at the surface but penetrates into the Arctic troposphere (Schweiger et al., 2008; Serreze et al., 2008). Warmer air is less dense, which in turn influences Arctic wind fields. The loss of sea ice influences wind direction, opposing the usual westerlies of the polar vortex and favoring more meridional (north-south) flow (i.e., weak or negative Arctic Oscillation fields; Overland and Wang, 2010).

A main hypothesis of this article is that Arctic *surprises* are a result of gradual processes, such as weak global increases in temperature combined with an atmospheric or oceanic event mediated by the particular climate processes associated with the Arctic. For example, when the 2007 sea ice minimum occurred, Arctic temperatures had been rising and sea ice thickness had been decreasing over the previous two decades (Stroeve et al., 2008; Screen and Simmonds, 2010). Nevertheless, it took an unusually persistent southerly wind pattern over the summer months (and possibly ocean transport and other factors) to initiate the loss event (Sumata and Shimada, 2007; Zhang et al., 2008; Wang et al., 2009; Woodgate et al., 2010). Similar wind patterns in previous years did not initiate major reductions in sea ice extent because the sea ice was too thick to respond (Overland et al., 2008). In a further example, ocean-sea ice-atmospheric processes from the first decades of the twentieth century increased oceanic heat transport into the Barents Sea and may have contributed to increased temperatures and reductions in sea ice in the Atlantic Arctic in the 1920s and 1930s (Dickson et al., 2002; Semenov, 2008).

Changes in West Greenland in 2010 also fit this hypothesis. There had been modest changes in temperatures and glacial ice conditions over the last decade, but the changes in 2010 were due to a combination of this trend plus a highly unusual negative North Atlantic Oscillation (NAO)/AO pattern throughout winter 2010. Negative NAO favors warm air advection into the region. Observed temperatures were 3.8°C to 8.8°C above the 1971–2000 baseline. Winter warming is relevant to increased summer melt because warmed snow or ice volumes require less heat to be brought to the melting point (http://www.arctic.noaa.gov/reportcard/greenland.html). Under these conditions, melt onset occurs earlier than normal, and the snow cover duration is shorter. These conditions lead to a lower average albedo earlier in the summer, allowing for a greater absorption of solar energy, more melting, and higher temperatures, especially on land once snow cover is completely melted and exposes bare land.

Understanding Arctic change is still an issue for debate that is confounded by the problem of interpreting the appearance of a single or a few extreme events. Is the event within the range of normal distribution of variability or a true outlier? Some climate models hypothesize a linearity and reversibility of simulated Arctic change (Tietsche et al., 2011). Further, increased variability in summer sea ice is expected as sea ice extent decreases (Goosse et al., 2009). Climate models can be helpful as they include many Arctic feedback processes and combine natural variability with anthropogenic forcing. By such methodologies, climate models can be run many times to create ensemble members that map out the possible distribution of interacting random and directly forced (anthropogenic) processes. While some model simulations demonstrate abrupt sea ice retreat, it remains to be studied how well the range of current models compares with observations (Eisenman et al., 2008).

ANOTHER SURPRISE: ARCTIC-SUBARCTIC LINKS DURING WINTER 2009–2010 AND DECEMBER 2010

China, the eastern United States, and Europe experienced unusually cold and snowy conditions during winter 2009-2010, especially in December and February (Seager et al., 2010). Washington, DC, set a record for winter snow accumulation. Record low temperatures and major economic disruptions were observed throughout northern Europe. A similar pattern of extreme weather returned in the following December and early January 2011. A Warm Arctic-Cold Continent pattern of air temperatures represents a paradox of recent global warming: there is not a uniform pattern of temperature increases (L'Heureux et al., 2010;

Cattiaux et al., 2010).

Cold air is normally partly confined in the Arctic in winter by strong polar vortex winds that circle the Arctic, consistent with low heights of constant pressure surfaces (geopotential height field) over the central Arctic (see Figure 4a, where purple colors indicate low climatological values of the geopotential height [in dynamic meters] of the 850 mb constant pressure surface). This pattern broke down in December 2009 (Figure 4b; Overland et al., in press); the polar vortex winds, normally blowing from west to east parallel to the geopotential height contours, weakened as shown by the increased heights of the 850 mb constant pressure surface (blues and greens) over the central Arctic. As air trajectories tend to follow lines of constant geopotential height, a potential origin for the cold air in the eastern United States was the Beaufort Sea. This situation created the so-called Warm Arctic-Cold Continent Pattern shown in Figure 5 for December 2009. December 2010 had a similar pattern. Warmer than normal Arctic temperatures (red) were seen, especially in regions that were sea ice-free in the previous summer: north of Alaska and in the Barents Sea. The cold continents (purple) are seen where Arctic air penetrated southward, an Arctic climate-subarctic weather linkage. One indicator of a weak polar vortex was the NAO index. The historical record

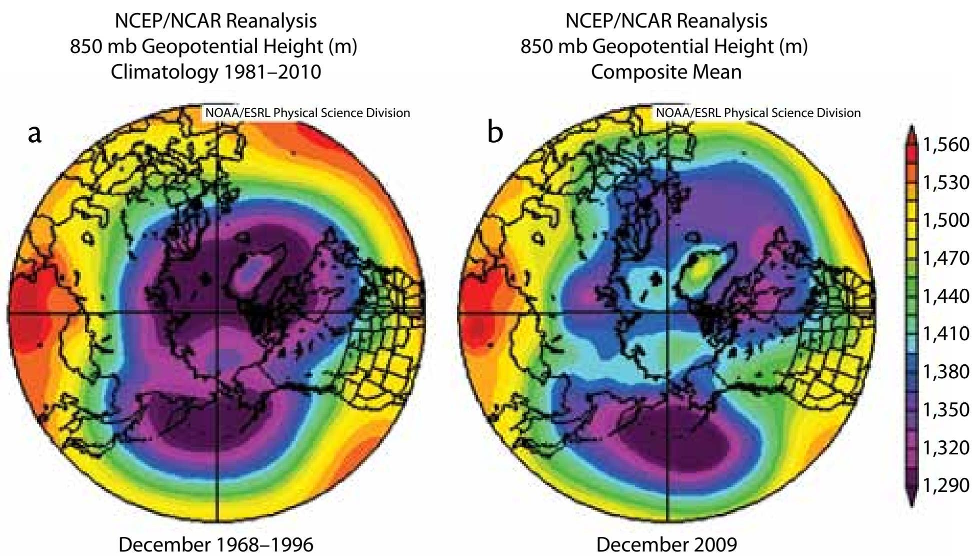

Figure 4. (a) Climatological geopotential height values for the 850 mb constant pressure surface observed for December from 1968–1996, and (b) unusual 850 geopotential height maximums over the Arctic observed for December 2009. *Figure from Overland et al. (in press). Data are from the NCEP-NCAR Reanalysis through the NOAA/ESRL Physical Sciences Division*

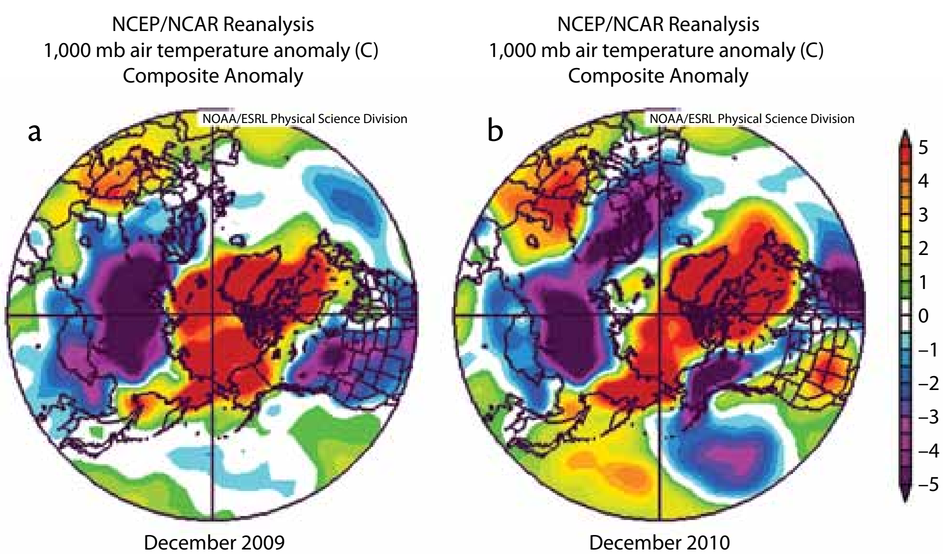

Figure 5. Warm Arctic-Cold Continents Climate Pattern for (a) December 2009, and (b) December 2010. The figure shows anomalies from the normal 1,000 mb air temperature values observed from 1968–1996. *Figure from Overland et al. (in press). Data are from the NCEP-NCAR Reanalysis through the NOAA/ESRL Physical Sciences Division*

shows that the winter of 2009–2010 had the lowest NAO value in 145 years (http://www.cgd.ucar.edu/cas/jhurrell/indices.html).

Attribution for these cold mid-latitude winters is nearly impossible, given the random nature of atmospheric circulation. However, recent changes in the Arctic might have made a contribution to the unusual wind pattern. Warmer Arctic air in autumn is less dense and increases the geopotential thickness between constant pressure surfaces, thus working against the stability of the polar vortex (Schweiger et al., 2008; Serreze et al., 2008; Overland and Wang, 2010). There are also suggested Arctic-subarctic teleconnections from model results (Singarayer et al., 2006; Sokolova et al., 2007; Seierstad and Bader, 2008; Budikova, 2009; Deser et al., 2010; Kumar et al., 2010; Petoukhov and Semenov, 2010).

The intensity of a link between cold Arctic air and the subarctic regions through increased meridional flow in the last two winters was clearly an Arctic *surprise*. Yet, it is uncertain whether the observed severe mid-latitude weather in 2009 and 2010 was simply due to an extreme in random processes alone, or could include a small but important Arctic forcing connection due to recently changing conditions. Further research is needed on the interactions of changes in Arctic climate with variability of natural climate patterns such as NAO and Pacific Decadal Oscillation.

DISCUSSION AND CONCLUSIONS

How to interpret *surprises* is an important philosophical, scientific, and societal question. What does a new extreme value mean? Is it an extreme value in an existing distribution of processes based on historical data mostly near the center of the distribution? Does it imply that a new external forcing is present or an additional process is involved because a new threshold of change has been reached and the climate system has moved to a new climate state? Climate models can help, but a major question arises regarding the AR4 set of model projections: while some conclusions such as the signs of air temperature changes and sea ice loss are consistent between models, why are the ranges of magnitude of regional changes in model projections often different when they are nominally trying to address the same problem (Overland et al., 2011)? It is important to interpret models carefully, noting their strengths and weaknesses.

The extreme negative NAO in winter 2009–2010 and December 2010 provides an example of an Arctic event. Severe winter weather contributed to a number of deaths, widespread transportation disruptions, power failures, and loss of work productivity in many regions of the Northern Hemisphere. These conditions were atypical in recent experience and represented roughly a one-in-100-year event followed by a one-in-50-year event. But two years of data certainly cannot be interpreted as a trend. One shies away from attribution of the causes of the event even if some Arctic-subarctic teleconnections are present in some diagnostic models.

Change is occurring in the Arctic. Four approaches or standards of the scientific method document that anthropogenic forcing is modifying the Arctic system. At present, there are multiple lines of observational evidence of Arctic change (Vörösmarty et al., 2008; Callaghan et al., 2010). Models successfully predict observed change, at least qualitatively on the large scale, and attribute Arctic changes to human causes. Recent shifts have the appearance of surprises, where gradual anthropogenic forcing, combined with a large atmospheric or oceanic event and mediated by Arctic-specific insolation and insulation feedbacks, leads to persistent changes in Arctic climate. These large variations introduce uncertainties in the timing and magnitude of future Arctic shifts, the degree to which they are reversible or not, and how they will influence future local and global climate. With a range of projections from climate models and the potential for surprises, it is challenging to plan mitigation and adaptation strategies for a no-regrets future while minimizing short-term costs.

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