1. ATMOSPHERIC CIRCULATION FEEDBACKS

Mark C. Serreze and Julienne Stroeve

Cooperative Institute for Research in Environmental Sciences,
University of Colorado, Boulder, Colorado, USA

ONE OF THE MOST DRAMATIC CHANGES to the globe in recent decades has been the rapid decline of arctic sea ice. The consequences of this sea ice retreat for the global climate system are becoming increasingly understood. The decline of sea ice is amplifying warming in the Arctic, which in turn has major implications for temperature patterns over adjacent, permafrost-dominated land areas and for weather patterns across the Northern Hemisphere. These changes in weather patterns can have widespread impacts, affecting resources relied upon by society.

Key Findings

- **Reduced sea ice amplifies warming.** Reduced sea ice cover is already amplifying warming in the Arctic earlier than projected. This amplification will become more pronounced as more ice cover is lost over the coming decades.

- **Amplified warming spreads over land.** Amplified atmospheric warming in the Arctic will likely spread over high-latitude land areas, hastening degradation of permafrost, leading to increased release of greenhouse gases presently locked in frozen soils, leading to further arctic and global warming.

- **Weather patterns are altered.** The additional warming in the Arctic will affect weather patterns by altering the temperature gradient in the atmosphere and atmospheric circulation patterns in the Arctic and beyond. It may also affect temperature and precipitation patterns in Europe and North America. These changes will affect agriculture, forestry and water supplies.

Arctic sea ice and atmospheric circulation

Because of the Earth's orientation relative to the sun, the sun's rays strike the Earth's surface more directly at the equator than at the poles. The inequality in the amount of solar radiation received gives rise to a gradient in atmospheric temperatures, driving circulation of air in the atmosphere that transports heat from regions of low-latitude warmth to the cooler poles, heat which is then radiated to space (**Figure 1**)[1]. Much of this atmospheric heat transport is accomplished by the traveling low and high pressure systems associated with day-to-day weather that affects commerce and other human activities. Arctic sea-ice cover modifies the basic temperature gradients from the equator to the poles and hence the manner in which the atmosphere transports heat. Sea ice influences temperature gradients because of its high reflectivity and its role as an insulating layer atop the Arctic Ocean.

Arctic sea ice is at it maximum seasonal extent in spring, when it covers an area roughly twice the size of the continental United States. At this time, the reflectivity (albedo) of the freshly snow covered ice surface may exceed 80 per cent, meaning that it reflects more than 80 per cent of the sun's energy back to space and absorbs less than 20 per cent. The ice cover shrinks to about half of its spring size by September, the end of the melt season. While summer melting causes the albedo of the ice pack to decrease to about 50 per cent through exposing the bare ice and the formation of melt ponds, this is still much higher than that of the ocean and land areas, which may have albedos of less than 10 per cent. Furthermore, of the roughly 50 per cent of solar energy that is absorbed by the ice cover in summer, most is used

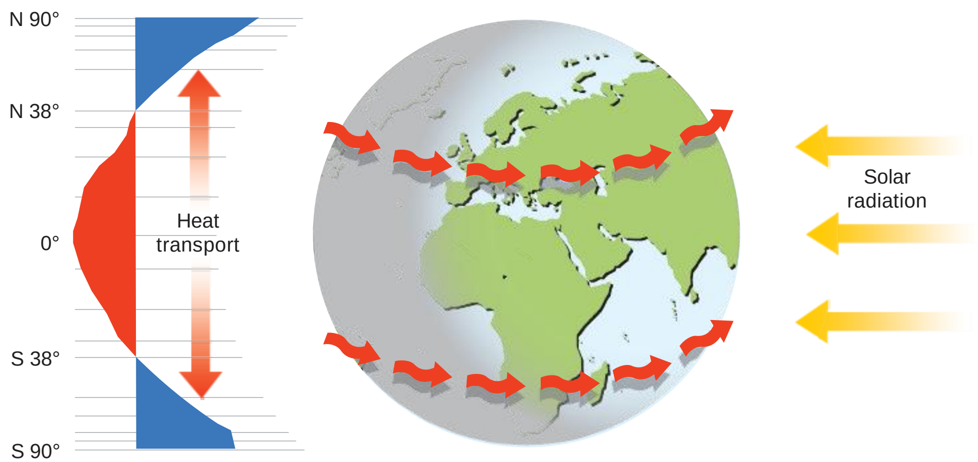
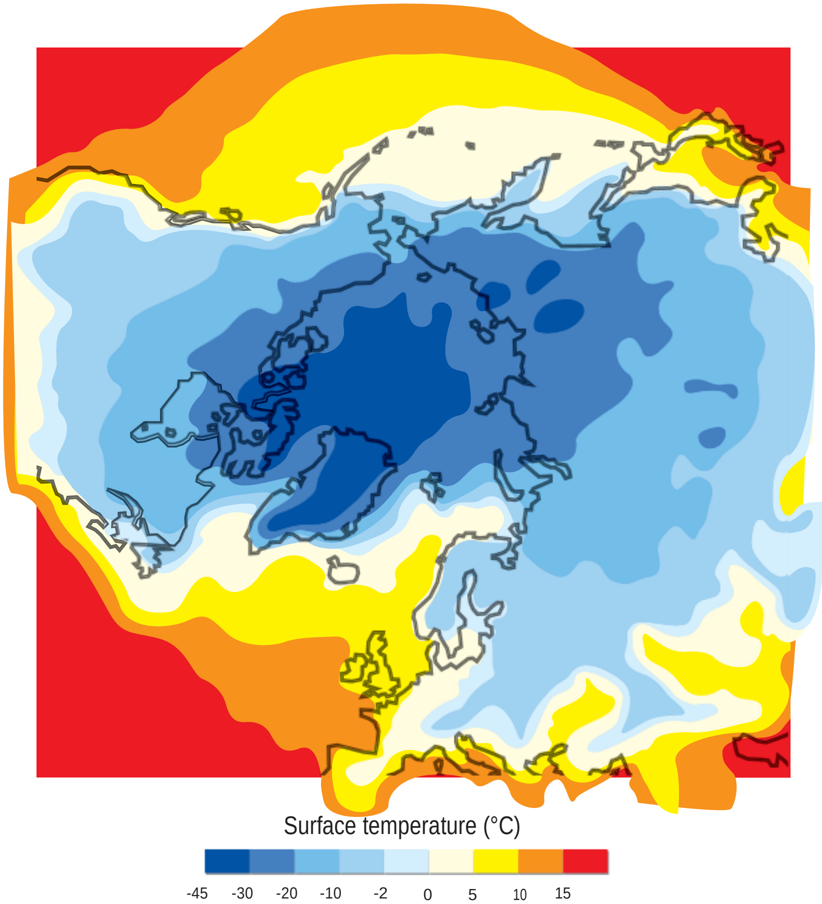


Figure 1. The sun's rays strike the surface more directly at low latitudes than at high latitudes, leading to an equator-to-pole gradient in the temperature of the atmosphere. This drives a circulation that transports heat toward the poles. Because of this transport, poleward of about 38° in each hemisphere, the Earth emits more radiation to space (as longwave, or heat radiation) than it receives from the sun as shortwave radiation. Much of the atmospheric heat transport is accomplished by weather systems travelling along the wavy jet streams of the middle and higher latitudes in each hemisphere (red arrows) [courtesy K.E. Trenberth, NCAR]



to melt ice, and the surface temperature of melting ice is fixed at the freezing point. From October through April, when there is little energy from the sun, sea ice acts as a very effective insulator, preventing heat in the Arctic Ocean from escaping upward and warming the lower atmosphere.

All of these properties of sea ice help to keep the Arctic's atmosphere cool. Without them, the atmospheric temperature gradient between the equator and the Arctic that drives weather systems would not be as strong as it is[2].

At the regional, ocean basin scale, the area between the insulating sea-ice cover and the open ocean (known as the ice margin) is characterized by particularly strong temperature gradients during winter (**Figure 2**), favoring the development of low pressure systems along the edge of the ice, as well as smaller, intense features known as polar lows that present hazards to shipping[3, 4, 5].

It follows that large changes in the distribution of arctic sea ice will affect patterns of atmospheric temperature and hence weather patterns. There is no question that ice cover is shrinking, and there is growing evidence that some of the anticipated impacts on the atmosphere have already emerged.

Figure 2. Surface temperatures averaged for November through March over the period 1979-1999. Strong horizontal temperature gradients in the extreme northern North Atlantic are linked to the location of the sea ice margin and cold Greenland Ice Sheet and affect the development of storms[5].

Observed sea ice trends

Sea-ice extent can be monitored year-round regardless of sunlight or cloud cover with satellite passive microwave sensors. Since the beginning of the modern satellite record in October 1978, the extent of arctic sea ice has declined in all months, with the strongest downward trend at the end of the melt season in September.

Since 2002, successive extreme minima in September ice extent have occurred, which have accelerated the rate of decline. Through 2001, the extent of September sea ice was decreasing at a rate of -7 per cent per decade. By 2006, the rate of decrease had risen to -8.9 per cent per decade. In September 2007, arctic sea ice extent fell to its lowest level recorded, 23 per cent below the previous record set in 2005, boosting the downward trend to -10.7 per cent per decade[6]. Ice extent in September 2008 was the second lowest in the satellite record. Including 2008, the trend in September sea ice extent stands at -11.8 per cent per decade[7] (**Figure 3**).

Compared to the 1970s, September ice extent has retreated by 40 per cent, an area roughly comparable to the size of the United States east of the Mississippi River.

The decreases in sea ice extent are best explained by a combination of natural variability (including changes in atmospheric and oceanic temperature and circulation) and rises in surface air temperatures linked to increasing concentrations of greenhouse gases in the atmosphere[8]. Climate models that incorporate the effects of greenhouse gas emissions from fossil fuel burning show declining September ice extent over the period of observations[7, 9, 10]. However, the model simulations mostly show smaller decreases in sea ice extent than has been observed. This argues that the models are too conservative and that ice-free summers might be realized as early as the 2030s[7, 11].

Reduced sea ice amplifies warming

Impacts of sea ice loss on atmospheric circulation can be linked to the anticipated stronger rise in arctic air temperatures compared to warming in middle latitudes, a process termed polar or arctic amplification[12, 13]. As atmospheric concentrations of greenhouse gases climb, the summer sea ice melt season will continue to lengthen and intensify, leading to less sea ice at the end of the summer. The retreat of the ice allows the dark, low-albedo ocean to readily absorb the sun's energy, increasing the summer heat content in the top 50 metres of the ocean (known as the mixed layer) (see *Ocean Circulation Feedbacks* chapter), which also further accelerates ice loss. Ice formation in autumn and winter, which is important for insulating the warm

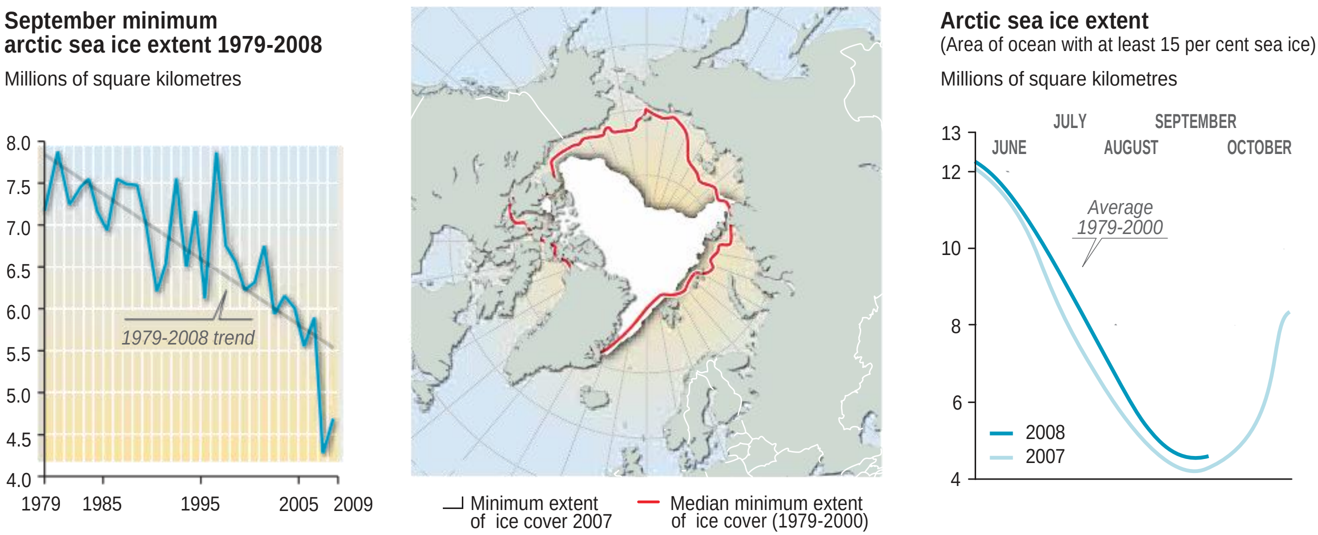


Figure 3. Map: Median sea ice extent (1979-2000) at the date of the seasonal minimum (red line) and on 16 September 2007 (white area) when ice extent was 4.13 million square kilometres. **Left graph:** Monthly averaged September sea ice extent from 1979 to 2008. **Right graph:** Time series of ice extent from 1 June to 24 September 2008 (dark blue line), and through end of October 2007 (light blue line), and average 1979-2000 (dotted line). Data from National Snow and Ice Data Center, USA.

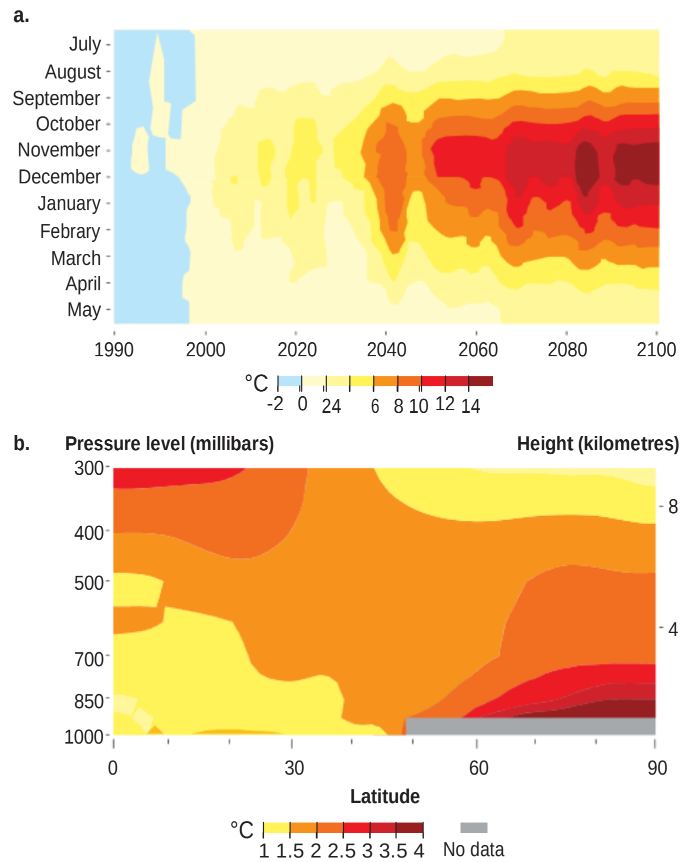


Figure 4. Depictions from the NCAR CCSM3 global climate model of: (a) near surface (2 metre) temperature deviations by month and year over the Arctic Ocean; (b) latitude by height plot of October-March temperature deviations for 2050-2059. Deviations are relative to 1979-2007 average. The simulation uses the IPCC A1B emissions scenario for this century and observed greenhouse gas concentrations for the 1990s[13].

ocean from the cooling atmosphere, is delayed. This allows for a large upward heat transfer from the ocean to the atmosphere. Simply phrased, the insulating effect of the ice that keeps the arctic atmosphere cool becomes less effective with time and the atmosphere warms significantly as a result.

Arctic amplification depicted from one of the climate models participating in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007) is summarized in **Figure 4**. The pattern of cold-season warming over the Arctic Ocean growing with time is obvious. The high-latitude warming becomes stronger from the lower troposphere (the lower part of the atmosphere) toward the surface, a pattern that in this model simulation emerges by the decade 2020-2029 and grows in prominence with time. An analysis of 16 different climate models participating in the IPCC 2007 reveals consistency in the basic seasonality and vertical structure of warming over this century, but with different timings, magnitudes and spatial patterns of change[14]. This, in part, reflects model-to-model scatter in rates and spatial patterns of ice loss through the end of this century[8, 9, 10]. Other contributing factors include differences in patterns of atmospheric heat transport, vertical mixing, and effects of clouds and water vapor. Through transport by atmospheric circulation, warming associated with the loss of the summer arctic sea ice is likely to spread over high-latitude land areas (**Figure 5**), hastening degradation of permafrost that is likely to lead to the release of carbon presently locked in frozen solids, and thus further global warming[15] (see *Land Carbon Cycle Feedbacks* chapter).

"Arctic amplification is already occuring. Autumn Arctic Ocean surface air temperatures have increased 3 to 5°C higher in recent years."

Heating the atmosphere over the Arctic Ocean through a considerable depth will alter both the change in temperature with elevation (the atmosphere's static stability) and the gradient of atmospheric thickness from the equator to the poles. Atmospheric thickness is the separation, in metres, between two adjacent pressure levels in the atmosphere, and it increases with increasing atmospheric temperature. The weaker the thickness gradient toward the poles, the weaker the vertical change in wind speed (known as wind shear). As the arctic atmosphere warms, the thickness gradient between the poles and the equator will decrease. Taken together, these changes will affect the development, tracks and strengths of weather systems, and the precipitation that they generate.

An analysis of atmospheric data sets[16, 17] reveals that anticipated arctic amplification is already occurring[14]. Consistent with recent extreme September sea ice minima, Arctic Ocean surface air temperatures are 3 to 5°C higher in autumn (October to December) for 2002 to 2007 compared to the 1979-2007 average. The warming extends through a considerable height of the atmosphere and, while centred over the areas of ice loss, also influences adjacent land and ocean areas.

Weather patterns are altered

The expected and observed decline of summer sea ice extent will affect heating in the lower atmosphere and, as a result, atmospheric circulation. These changes will influence temperature and precipitation patterns that affect transportation, agriculture, forestry and water supplies.

"The additional warming in the Arctic will alter atmospheric circulation and, through it, weather patterns, affecting transportation, agriculture, forestry, and water supplies."

Observational evidence for responses of atmospheric circulation to declining ice extent is just beginning to emerge. Varying summer ice conditions can be associated

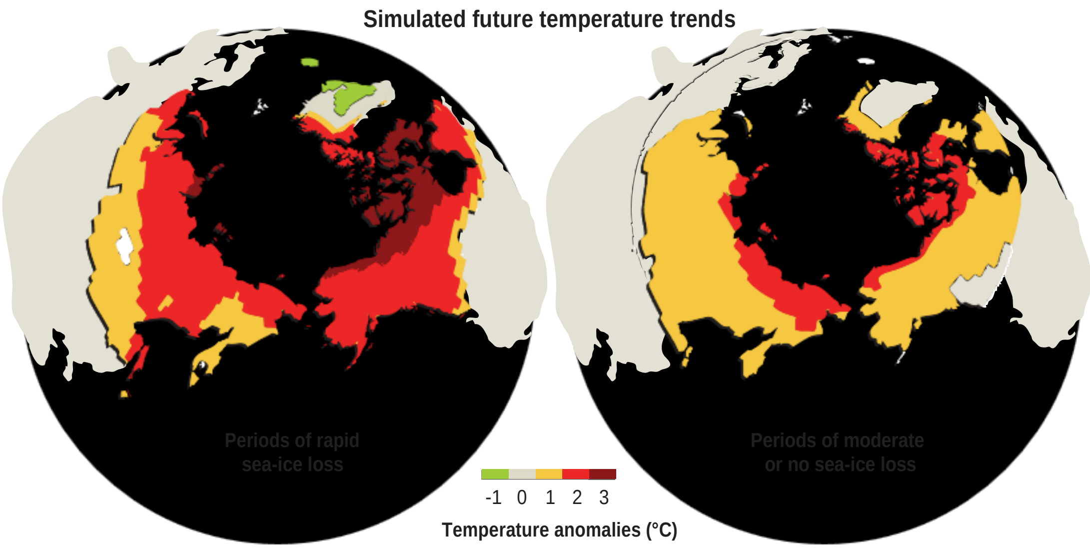


Figure 5. Expected surface air temperature trends associated with periods of rapid sea ice loss (left) and moderate or no ice loss (right) during this century. Rapid ice loss promotes strong warming over the Arctic Ocean, but atmospheric circulation spreads the heat out to influence land areas, potentially leading to thawing of permafrost and release of stored carbon to the atmosphere. Results are based on a simulation with the NCAR CCSM3 model[14].

North Atlantic Oscillation

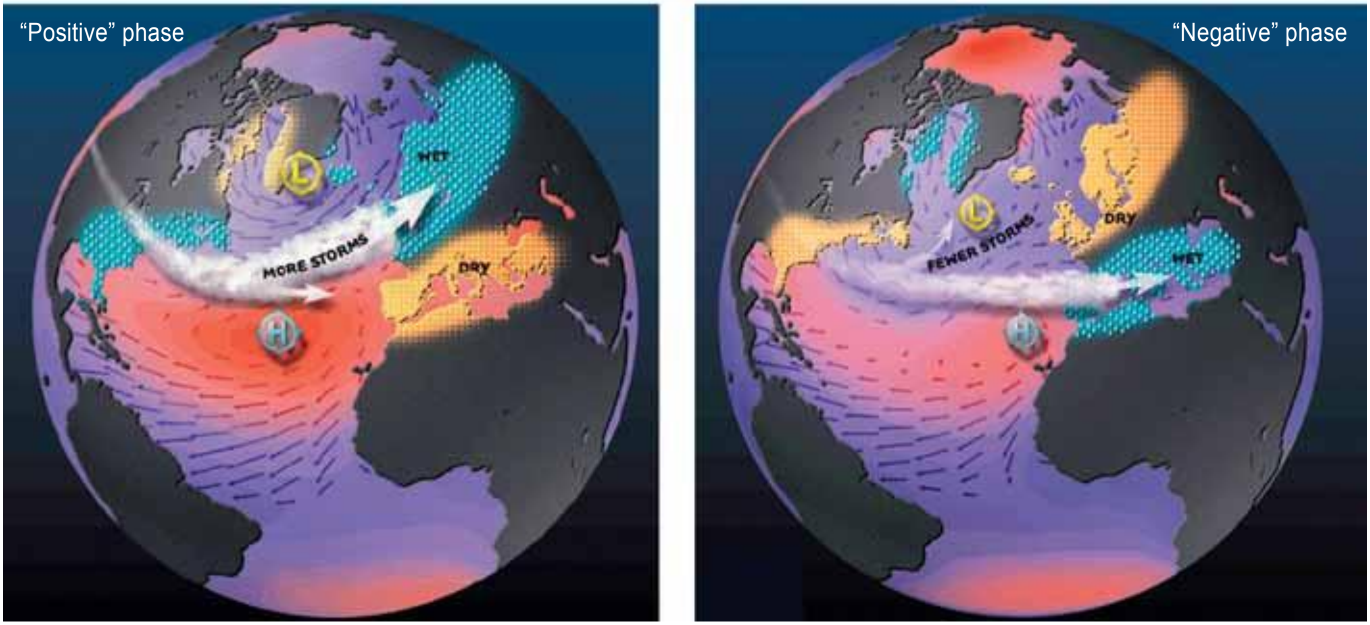


Figure 6. The "positive" (**left**) and "negative" (**right**) phases of the North Atlantic Oscillation (NAO) and anomalies in precipitation. In the positive NAO phase, the Icelandic Low (marked L) and Azores High (marked H) are both strong. Westerly winds between the two pressure centres are strong (winds indicated by arrows), bringing storms and wet conditions into northern Europe; southern Europe is drier than normal. In the negative phase of the NAO, both pressure centres are weaker, and the storm track is shifted south. Northern Europe is drier than normal, while southern Europe is wetter than normal [courtesy http://www.ldeo.columbia.edu/res/pi/NAO/].

with large-scale atmospheric anomalies (deviations from the average) during the following autumn and winter that extend beyond the boundaries of the Arctic[18]. The autumn sea level pressure fields following summers with less arctic sea ice extent exhibit higher pressures over much of the Arctic Ocean and North Atlantic, compensated by lower pressures in middle latitudes. The pattern in the North Atlantic is similar to what is known as the negative phase of the North Atlantic Oscillation (NAO).

The NAO describes a correlation in the strengths of the Icelandic Low (the semi-permanent low pressure cell centred near Iceland) and the Azores High (the semi-permanent high pressure cell centred near the Azores) — the major atmospheric "centres of action" in the North Atlantic. When both centres are strong (a deep low and a strong high), the NAO is in its positive phase. When both centres are weak (a shallow low and a weak high), the NAO is in its negative phase (**Figure 6**).

Changes in the NAO are tied to shifts in storm tracks and associated patterns of precipitation and temperature[19]. During the positive NAO phase (when both centres are strong), dry conditions typically occur over much of central and southern Europe and the Mediterranean, while stormier, wetter than normal weather conditions occur over Northern Europe. Temperatures in northern Eurasia tend to be above normal, and temperatures in northeastern North America tend to be below average. During negative NAO phases, the precipitation and temperature deviations are roughly reversed.

NAO phase	North Atlantic storm track	Northern Europe	Southern Europe	Canada	Northeastern North America
"Positive"	More northerly	Warmer and wetter than normal	Drier than normal	Cooler than normal	Cooler than normal
"Negative"	More southerly	Cooler and drier than normal	Wetter than normal	Warmer than normal	Warmer than normal

However, it is difficult from observations to unambiguously isolate circulation responses to declining ice extent from other factors. In recognition, the past decade has seen a growing number of studies addressing circulation responses to altered arctic sea conditions using climate models. The basic approach is to essentially tell the climate model what the sea ice conditions are (ice conditions are "prescribed") and then examine how the atmosphere responds to the prescribed conditions. Comparisons between simulations with one set of prescribed ice conditions (e.g., observed extent for the late 1900s) and another (e.g., expected ice extent by the end of this century), while keeping other factors, such as greenhouse gas concentrations, the same, isolates the effect of changing the ice[20].

While a more negative NAO phase with reduced winter ice extent finds support in a number of modeling experiments [21, 22, 23, 24], this is by no means a universal finding. One study finds that altered sea ice conditions in the Pacific sector (specifically in the Sea of Okhotsk) leads to a significant atmospheric response not only locally in the Sea of Okhotsk, but extending downstream over the Bering Sea, Alaska, and North America, with consequent changes in precipitation and temperature[25]. While another recent effort[26] concludes that parts of the Arctic and Europe may experience greater precipitation as the Arctic transitions toward a seasonally ice-free state; yet another emphasizes less rainfall in the American West[27]. A comprehensive study showed that although the loss of sea ice is greatest in autumn, winter is likely to see the strongest responses in temperature and precipitation. Snow depths may increase over Siberia and northern Canada because of increased precipitation[19]. Warming on land is mainly a result of warm air transport from the Arctic Ocean open-water areas.

"The transition to a seasonally ice-free Arctic may occur sooner than previously thought, affecting weather and precipitation patterns sooner than anticipated."

Summary

Arctic sea ice extent is declining in all months, with the strongest downward trend observed for the end of the melt season in September. Since the observed September trend exceeds that in simulations from most current global climate models, the transition to a seasonally ice-free Arctic may occur sooner than previously thought, affecting weather and precipitation patterns sooner than anticipated.

Today, amplified atmospheric warming in autumn over the Arctic Ocean is already evident, and this warming extends through a through a considerable depth of the atmosphere. Changes in the temperature structure of the arctic atmosphere are expected to become more pronounced in coming decades as the Arctic Ocean continues to lose its summer sea ice cover. These include alterations in static stability (the change in the atmosphere's temperature with height), the poleward gradient in atmospheric thickness and the vertical change in wind speed (wind shear). These changes will invoke responses in atmospheric circulation. While there is no universal consensus regarding the spatial patterns of change that will emerge, a common thread between different modeling studies is that changes may be significant and affect areas well beyond the boundaries of the Arctic.

References

1 Trenberth, K.E., J.T. Fasullo and J. Kiehl 2009. Earth's global energy budget. *Bull. Amer. Meteor. Soc*. 90: 311-323.

2 Serreze, M.C., A.P. Barrett, A.J. Slater, M. Steele, J. Zhang and K.E. Trenberth 2007. The large-scale energy budget of the Arctic. *J. Geophys. Res.* 112: D11122, doi:10.1029/2006JD008230.

3 Shapiro, M.A., L.S. Fedor, and T. Hempel 1987. Research aircraft measurements of a polar low over the Norwegian Sea, *Tellus*,*Ser. A,* 39: 272-306.

4 Deser, C., J.E. Walsh and M.S. Timlin 2000. Arctic sea ice variability in the context of atmospheric circulation trends. *J. Climate* 13: 617-633.

5 Tsukernik, M., D.N. Kindig and M.C. Serreze 2007. Characteristics of winter cyclone activity in the northern North Atlantic: Insights from observations and regional modeling, *J. Geophys. Res.* 112: D03101, doi:10.1029/2006JD007184.

6 Stroeve, J., M. Serreze, S. Drobot, S. Gearheard, M. Holland, J. Maslanik, W. Meier, and T. Scambos 2008. Arctic sea ice extent plummets in 2007. *EOS Trans. AGU* 89(2): 13-14.

7 National Snow and Ice Data Center. Arctic Sea Ice News & Analysis. http://nsidc.com/news/press/20081002_seaice_pressrelease.html

8 Stroeve, J., Holland, M.M., Meier, W., Scambos, T., and Serreze, M. 2007. Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.* 34: L09501, doi:10.1029/2007GL029703.

9 Zhang, X. and Walsh, J.E.: Toward a seasonally ice-covered Arctic Ocean 2006. Scenarios from the IPCC AR4 model simulations. *J. Climate* 19: 1730-1747.

10 Arzel, O., Fichefet T., and Goose, H 2006. Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs, *Ocean Modeling* 12: 201-415.

11 Wang M., and J.E. Overland 2009. A sea ice free summer Arctic within 30 years?, *Geophys. Res. Lett.* 36: L07502, doi:10.1029/2009GL037820.

12 Holland, M.M., and C.M. Bitz 2003. Polar amplification of climate change in coupled models. *Clim. Dynam.* 21: 221-232.

13 Serreze, M.C., and J. Francis 2006. The Arctic amplification debate. Climatic Change, doi:10.10007/s10584-005-9017.

14 Serreze, M.C., A.P. Barrett, J.C. Stroeve, D.N. Kindig and M.M. Holland 2009. The emergence of surface-based Arctic amplification, *The Cryosphere* 3: 11-19.