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# KEYNOTE ABSTRACT: Oceans, ice and atmosphere

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## Overview of Changes in the Arctic Sea Ice Cover

Arctic sea ice extent has declined over the past several decades, showing downward trends in all months, with the smallest trends in winter and the largest trends at the end of the melt season in September [*Serreze et al*., 2007]. However, the rate of decline is accelerating. In 2001, the linear trend in September monthly mean extent over the available satellite (1979 to present) record stood at -7.0% per decade. By 2006, it had increased to -8.9% per decade. Then, in September 2007, Arctic sea ice extent fell to the lowest value ever recorded, 23% below the previous record minimum set in 2005, boosting the downward trend further to -10.7% per decade [*Stroeve et al*., 2008]. Including September 2008, which ended up as second lowest in the satellite record, the trend stands at -11.8% per decade (Figure 1).

All coupled global climate models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) show declining September ice extent over the period of observations [*Stroeve et al*., 2007; *Zhang and Walsh*, 2006]. Although this is strong evidence for a role of greenhouse gas (GHG) forcing on the observed trend, the simulated trends, as a group, are smaller than observed. This finding has raised concern that ice-free summers might be realized as early as 2030 [*Stroeve et al*., 2007]. Some of the IPCC (Intergovernmental Panel on Climate Change) simulations also show that the September trend becomes steeper with time, but only later into the 21st century.

Why has the observed downward trend steepened? While natural variability in the coupled ice-ocean-atmosphere system has certainly been a player [see *Stroeve et al*., 2007 and papers cited therein], the rate of decline of sea ice extent in response to external GHG forcing is now being enhanced by three inter-connected processes. First, because of the extensive open water in recent Septembers, ice cover in the following spring is increasingly dominated by thin, first-year ice (ice formed during the previous autumn and winter) that is vulnerable to melting out in summer, especially under the influence of anomalous atmospheric circulation patterns that favor summer melt. Thus, back in the early 1980s when the Arctic Ocean in winter was dominated by old, thick ice, an unusually warm summer, such as what occurred in 2007, could promote a strong negative anomaly in summer ice volume, but only a modest negative anomaly in ice extent. However, at the same time that the overall spatial extent of sea ice has been declining, the winter ice pack has correspondingly become much younger and therefore much thinner [*Maslanik et al*., 2007], leaving little of the old, thick ice that can help stabilize the summer ice cover. Today a given summer decline in ice volume translates into even larger declines in ice extent simply because more of the icepack is so thin.

Second, the existence of more thin ice in spring allows open water areas to develop earlier in the melt season, leading to a stronger ice albedo feedback. Ice albedo feedback has always been part of the sea ice system - as the melt season commences, bare ice is exposed by melting snow, melt ponds form and areas of dark open water are exposed, which readily absorb solar radiation, fostering further melt. However, with the trend towards more thin ice in spring, open water areas form earlier and are present longer in the melt season so that the ice albedo feedback has grown in importance, accentuating summer ice melt and steepening the downward trend of September ice extent. It is this “boosting” of the ice-albedo feedback mechanism that has been implicated in rapid transitions towards a seasonally ice free Arctic in climate model simulations [*Holland et al*., 2006].

Third, the Arctic has warmed in all seasons, meaning that the likelihood of unusually cold conditions that could bring about temporary recovery through natural climate variability has declined. For example, Figure 2 shows 925 hPa temperature anomalies for an Arctic Ocean domain (the same as used in the Arctic energy budget analysis of *Serreze et al*. [2007]) from JRA-25 by year and month (top) and averaged for extended summer (MJJAS, middle) and extended winter (ONDJFMA, bottom) seasons. Anomalies are computed with respect to the period 1979-2007. In the earlier part of the record, it was common for an anomalously warm summer, contributing to a negative anomaly in September ice extent, to be followed by an anomalously cold winter or cold summer, helping to bring about recovery of the ice cover. Since about the year 2000, there has been warming in all months. Thus with rising air temperatures in all seasons, prospects for the ice to recover through a sequence of cold years have dimmed.

## Climatic Implications of Loss of Sea Ice

A seasonally ice free Arctic Ocean is expected to have widespread socio-economic, ecological and climatic impacts. One climatic impact already being observed is amplified warming during autumn. The concept of Arctic amplification is a near universal feature of climate model simulations [*Holland and Bitz*, 2003]. Arctic amplification refers to the idea that rises in surface air temperature (SAT) in response to increasing concentrations of atmospheric GHGs will be larger in the Arctic compared to the Northern Hemisphere as a whole. This is because as larger expanses of open water areas develop in summer, the oceans absorb the incoming solar radiation that would normally be reflected back out to space by the sea ice cover. The sensible heat content of the ocean increases, and ice formation in autumn and winter is delayed. However, before the ocean can once again refreeze in winter, it must first lose the heat it gained in summer. This promotes enhanced upward heat fluxes, seen as strong warming at the surface and in the lower troposphere. This vertical structure of temperature change is enhanced by strong low-level stability which inhibits vertical mixing. Arctic amplification is not prominent in summer itself, when energy is used to melt remaining sea ice and increase the sensible heat content of the upper ocean, limiting changes in surface and lower troposphere temperatures. Loss of snow cover contributes to an amplified temperature response over northern land areas, but this temperature change is not as pronounced as over the ocean.

Coinciding with the large ice losses observed since 2002, Arctic amplification has emerged in autumn [*Serreze et al*., 2009]. Evaluation of surface air temperatures from atmospheric reanalysis products show that Arctic Ocean SATs were 3 to 5$^{o}$C warmer in autumn (OND) for 2002 to 2007, compared to the long-term 1979-2007 mean (Figure 3b). The warming is centered directly over the areas of ice loss, but is also spread out over the adjacent land through atmospheric circulation. This warming associated with the loss of the summer Arctic sea ice cover may hasten permafrost degradation [e.g. *Lawrence et al*., 2008], leading to even more release of carbon to the atmosphere in the form of methane. With the expectation of continued summer ice loss, fostering more sensible heat gain in the upper ocean, autumn freeze-up will be further delayed, such that Arctic amplification should start to be seen in winter. Eventually, ice extent and thickness will be sufficiently reduced so that low-level warming will emerge in spring.

We also expect that warming associated with the loss of the summer ice cover will alter atmospheric circulation and precipitation patterns, not only in the Arctic, but also at lower latitudes. In a recent study by *Deser et al*. [submitted], climate model simulations were used to investigate the atmospheric response of a seasonally ice free Arctic Ocean. Results from the study reveal large impacts on atmospheric temperature, precipitation and snow cover in autumn and winter. Over Siberia and Canada, the largest temperature and precipitation responses are seen in November and December. Although the model experiments only addressed the direct impact of Arctic sea ice loss on atmospheric circulation and climate, the study serves as a guide. Oceanic feedbacks, in particular warming of the Arctic Ocean due to enhanced absorption of solar energy, may provide additional forcing to the atmosphere. In addition, warming of the high latitude Pacific and Atlantic Oceans may also alter the atmospheric circulation response through feedbacks with the midlatitude storm tracks [e.g. *Peng et al*., 1997].

Considering the potentially significant impacts that the continued reductions in Arctic sea ice will have on Northern Hemisphere climate during this century, scientific research needs to continue to focus on better understanding of the role of the Arctic in the global climate system.

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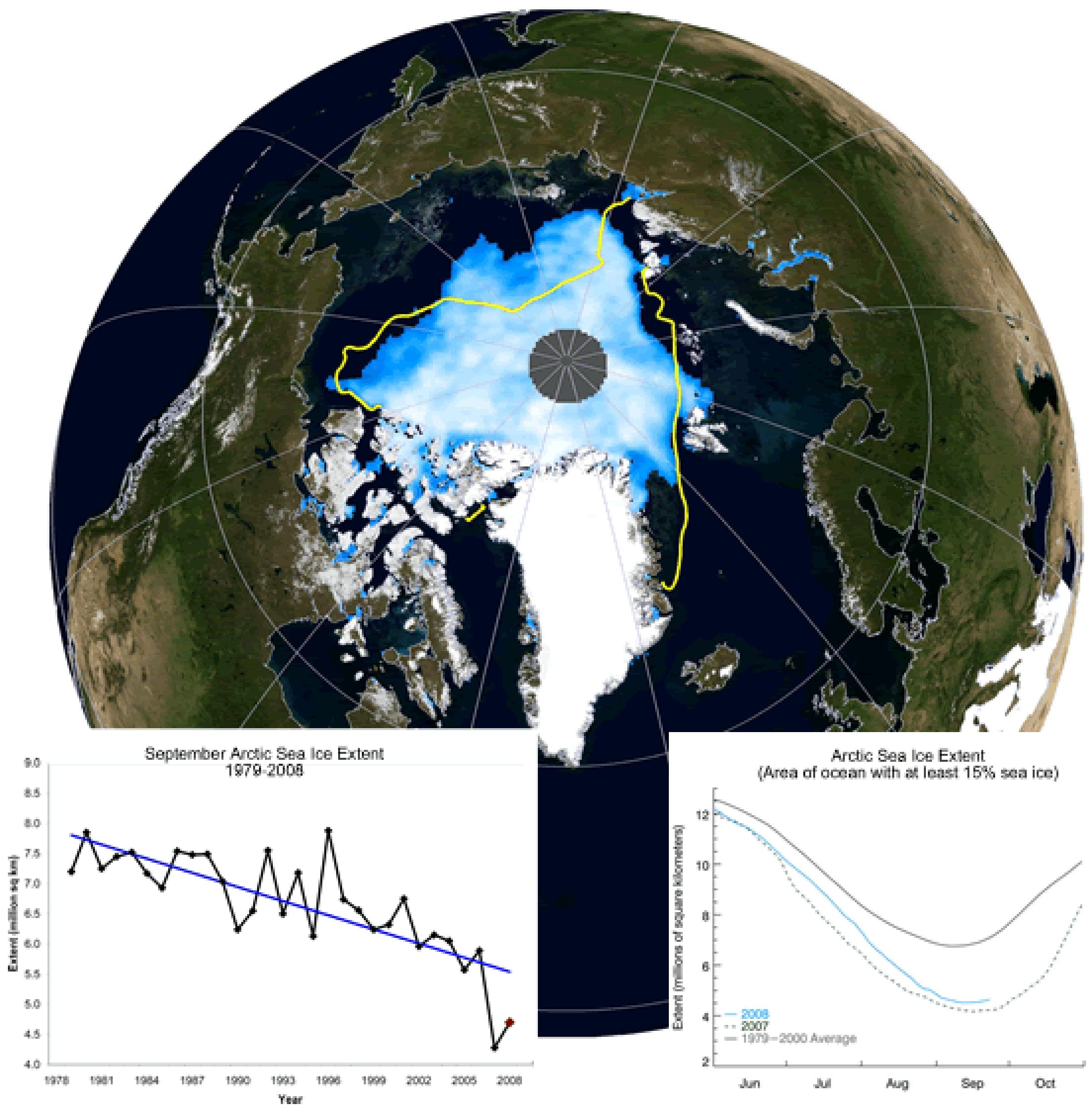

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Figure 1. Color map: Sea ice extent on 14 September 2008, the date of the minimum, when ice extent was 4.52 million km$^2$. The yellow line marks the extent for September 16, 2007.Right inset: Time-series of ice extent from June 1 through 24 September for 2008, and through end of October for 2007 and climatology (1979-2000). Left inset: Time-series of monthly averaged September sea ice extent.

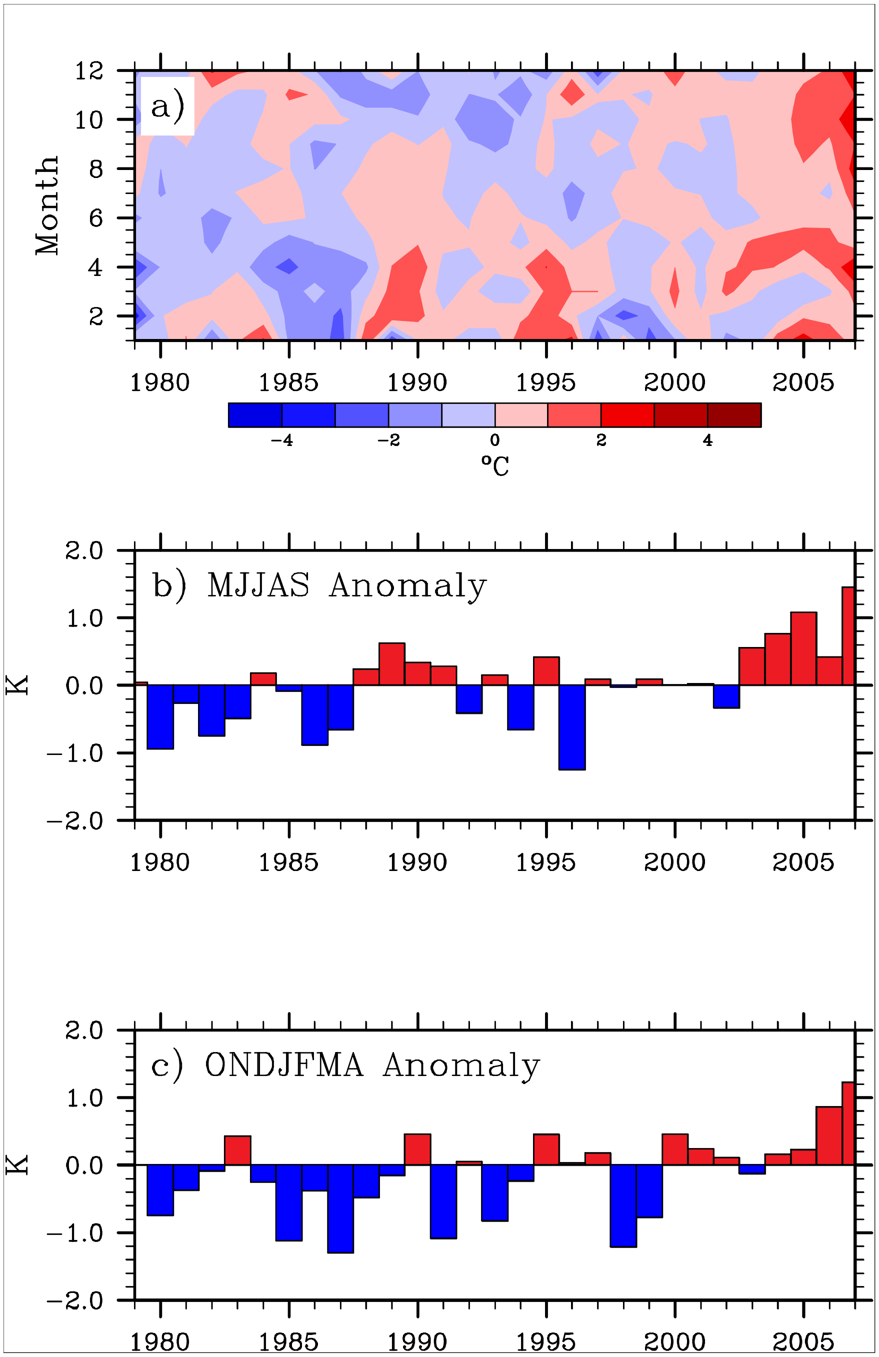
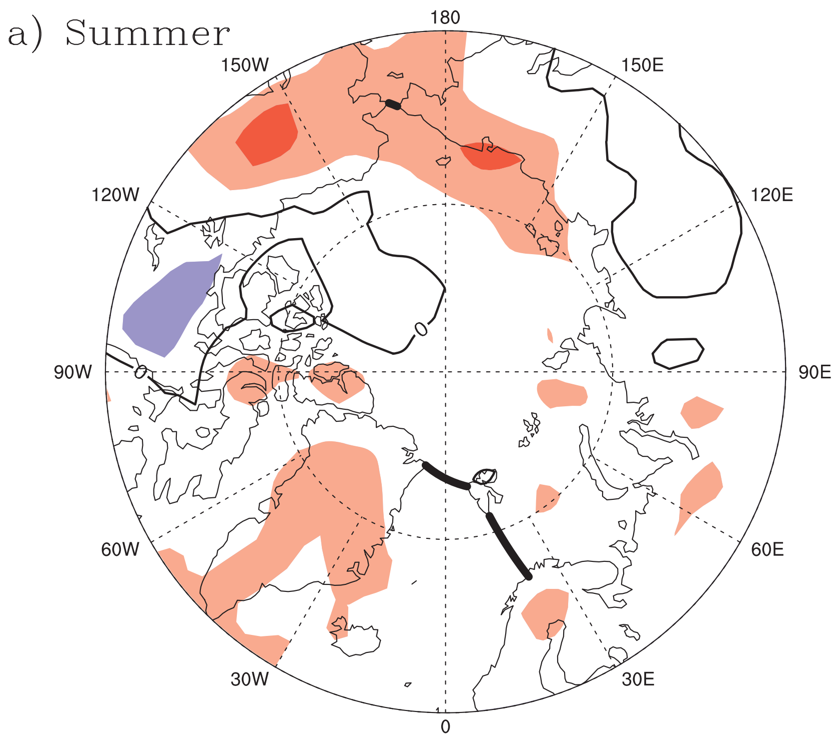


**Figure 2**. JRA-25 925 hPa temperature anomalies by year and month (top) and averaged for extended summer (MJJAS, middle) and extended winter (ONDJFMA, bottom) seasons. Results are for an Arctic Ocean domain. Anomalies are computed with respect to the period 1979-2007.


a) Summer

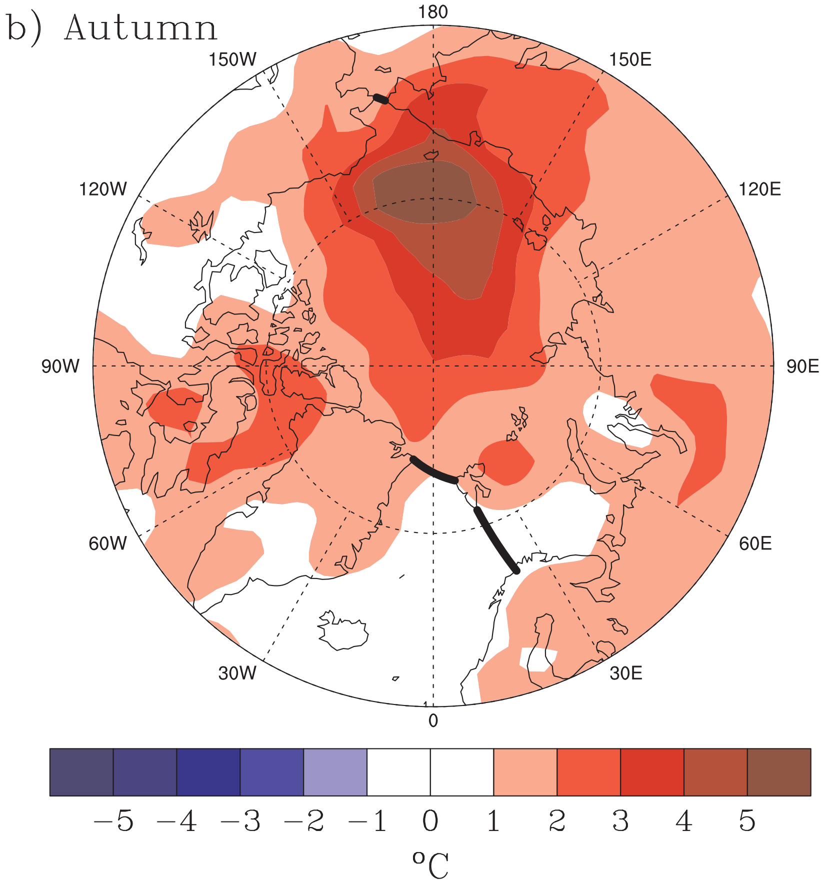

b) Autumn

**Figure 3.** Surface air temperature anomalies from NCEP/NCAR reanalysis from 2002 to 2007, relative to 1979-2007 for (a) summer and (b) autumn.