13.9 DECREASING ARCTIC SEA ICE:
GREENHOUSE GASES VERSUS VARIABILITY AND NATURAL FORCING

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1. INTRODUCTION

The trend in decreasing Arctic ice extent evident from the satellite data since 1978, and the record minimum ice extent in 2002, are consistent with a warmer Arctic climate. Measurements of sea ice draft from submarine-based sonar have shown a reduction in sea ice thickness in the Arctic basin of 32% to 43% between the 1950's and the 1990's (Rothrock et al 1999). Surface air temperatures have shown regional warming trends since the 1950's that are greatest (warming) over Alaska and Siberia, and negative (cooling) over northeastern North America and Greenland (Chapman and Walsh 1993).

Is the Arctic sea ice disappearing because of increasing greenhouse gases? Alternatively, are these changes attributable to natural variability such as the Arctic Oscillation (AO) or to other natural forcing such as changing solar flux?

The AO signal in the sea level pressure was primarily positive from late 1987 through 2001. Lower sea level pressures in the Arctic basin have been associated with shifts in the ice drift patterns, higher temperatures over Alaska and Siberia, and reduced sea ice cover. Ice draft in the Beaufort Sea decreased rapidly by about 1.5 m between 1987 and 1991, along with the changing ice motion (Tucker et al. 2001). The timing of these changes suggests that they are caused in part by the AO and consistent with natural variability. However, this variability may also be superimposed on a long-timescale trend associated with both natural and anthropogenic climate forcing. An analysis by Vinnikov et al. (1999) of global climate model simulations with increasing greenhouse gases showed that the modeled ice cover was decreasing at a similar rate as the observed ice cover, but did not consider the range of natural variability in the ice cover.

Simulations with a coupled atmosphere-ocean-ice general circulation model (or global climate model or GCM) are used here to compare the effects of anthropogenic greenhouse gases, natural variability, and other natural forcing on the Arctic sea ice. The simulations span the period from the pre-industrial age (late 1800's) to the present (e.g. year 2000), and from the present through the next 100 years.

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2. MODEL DESCRIPTION

The global atmosphere-ocean-sea ice general circulation model used here is the Parallel Climate Model version 1 (PCM, see Washington et al. 2000). The PCM consists of the NCAR Community Climate Model version 3 (CCM3) atmospheric general circulation model at T42 resolution and 18 vertical levels the Parallel Ocean Program (POP) ocean model developed at Los Alamos National Laboratory, and a dynamic-thermodynamic sea ice model. The land surface processes model is also included as part of CCM3 in this configuration. The PCM has some similar components to the Climate System Model version 1 (Boville and Gent 1998); the CCM3 atmosphere and land models nearly the same (with the same resolutions), while the ocean and sea ice models are different.

The POP ocean grid is a curvilinear, orthogonal grid with the grid's north pole displaced to a position over Hudson Bay, and the south pole remaining at 90°S. It has a global- average resolution of about 0.6°, with 1° resolution at the equator, and about 0.25° in the Arctic Ocean. This allows the model to resolve the Bering Strait and some of the Canadian Archipelago, and is considered to be eddy-permitting at this resolution, but not explicitly eddy-resolving.

The sea ice model in the PCM is described fully in Weatherly and Zhang (2001). The ice thermodynamics are based on a two-layer version of the Semtner model, with one internal ice temperature and one snow layer temperature. The surface temperature is computed from the surface energy balance. There is a mean ice thickness and ice fraction for each grid cell, without an explicit multiple thickness distribution. The sea ice dynamics uses the elastic-viscous-plastic (EVP) ice rheology of the Hunke and Dukowicz (1997) model. The sea ice model is run on a Cartesian grid with uniform 0.25º by 0.25º (27 km by 27 km) spacing. There are separate grid domains for the Arctic and Antarctic. The sea ice variables (ice fraction, velocity, salinity flux) are interpolated from the sea ice grid to the ocean grid to couple these model components.

The PCM has been used for numerous studies of present and future climate change under a range of natural and anthropogenic forcings (see Meehl et al 2003). These studies show the simulations with transiently increasing CO_2 and other greenhouse gases from the pre-industrial period to the present, and from the present to the year 2100. In addition, Barnett et al. (2001) showed that trends in ocean heat content from PCM were similar to those in observational data from the 1950's to 1990's.

For other PCM-related papers, see: http://www.cgd.ucar.edu/pcm

3. MODEL EXPERIMENTS AND RESULTS

3.1 Model Experiments

Two sets of PCM simulations of the pre-industrial to present-day climate, called the Greenhouse and Natural Forcing simulations, are described here. The two simulations are initialized and integrated in the same manner, except the Greenhouse simulation includes the anthropogenic trend in greenhouse gases, and the Natural Forcing simulation does not. Both simulations begin at the year 1870, with atmospheric CO_2 concentrations set at 280 ppm, and other greenhouse gases appropriate for pre-industrial levels.

The Greenhouse simulation prescribes the CO_2 concentration increasing to 360 ppm in the year 2000, according to observations, along with increasing methane and other gases. There is also a prescribed increase in the direct radiative effect of sulfate aerosols that acts to cool the surface. These anthropogenic forcings in the Greenhouse simulation are prescribed in addition to two natural forcings.

The Natural Forcing simulation prescribes constant, pre-industrial levels for CO_2 and other greenhouse gases, and aerosol effects. It also includes a time-dependent value for the incoming solar flux, based on flux estimates from observations of solar brightness and sunspot numbers. The flux value varies around the average of 1370 W m^{-2}, with the an anomaly of –1 W m^{-2} around 1900, increasing to +2 W m^{-2} around 1950, drops to near zero around 1970, and returns close to +2 W m^{-2} in the 1990's. The other natural forcing included is a volcanic aerosol signal that prescribes a short-term, direct radiative cooling at the surface at the dates of observed volcanic eruptions.

Both the Greenhouse and Natural Forcing simulations were run in an ensemble of four independent simulations each. This allowed the natural, unforced variability of the climate system to be measured in comparison to the climate response to the prescribed forcings.

3.2 Past Climate Simulations 1900 - 2000

The global average surface anomaly for the ensemble-average of the Greenhouse simulations (red) is shown in Fig 1a, and the ensemble-average anomaly for the Natural Forcing simulations (blue) is shown in Fig 1b. Both are shown with the range of the temperature anomalies over the four runs for each case (gray bands). Also shown are the global average temperature anomalies from observed temperature data (black) cited by the Intergovernmental Panel on Climate Change (IPCC). The temperature anomalies in the Greenhouse simulation show better agreement with the observed data than the Natural Forcing simulation does.

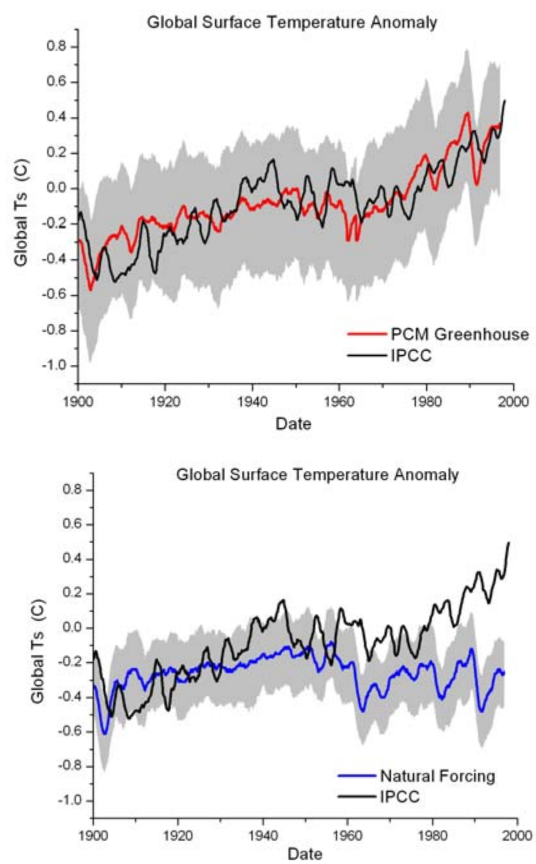

Fig 1. Global average temperature anomalies for the Greenhouse run (upper, red line) and Natural Forcing run (lower, blue line), along with the range of the ensemble for each run (gray band), and the global observed temperature anomalies from the IPCC (black).

Both simulations show an overall increasing temperature trend from 1900 to 1950 caused by the increase in solar flux, and a decreasing trend up to 1970 with the decreasing solar flux. From 1970 to 2000, the Greenhouse run and the observed data show increasing temperatures associated with the increasing greenhouse gases, not present in the Natural Forcing run.

The simulations also show that increasing greenhouse gases also affect the Arctic sea ice. In Fig. 2, the annual mean Arctic sea ice area in the ensemble of Greenhouse runs (red) is compared to the mean ice area in the Natural Forcing runs (blue), and the range of natural variability in those runs (gray).

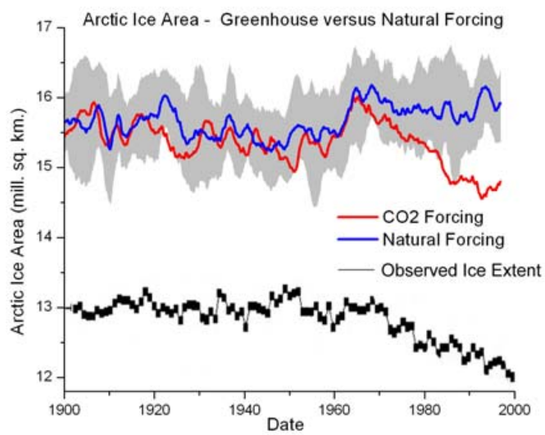

Fig. 2. Annual mean Arctic sea ice area in the ensemble-average of Greenhouse runs (red line) and the Natural Forcing runs (blue). The observed ice extent (black) is taken from W. Chapman and J. Walsh data at: http://faldo.atmos.uiuc.edu/CT/

While the ice area in the two ensemble simulations remains similar from 1900 to 1960 (and within the range of the natural variability of the ensemble), the ice area in the Greenhouse ensemble runs shows a decreasing trend beginning around 1960 that is not present in the Natural Forcing runs. The Greenhouse ice area decreases below the natural range of the Natural Forcing runs soon after 1980. By the year 2000, the Greenhouse ice area has decreased by about 1 x 10^6 km^2 below the mean value for 1900-1960. The observed data also show a decrease in ice extent of about 1 x 10^6 km^2 between 1960 and 2000.

While the modeled ice area and the observed ice extent values are not interchangeable, the Arctic area is often within 10% of the total extent, particularly for the annual mean values. The figures show that the PCM has a significant positive bias in the total ice area of approximately 3 x 10^6 km^2 or 25% of the observed area. Excessive sea ice covers portions of both the North Pacific and North Atlantic in the PCM, and this is discussed more fully in Weatherly and Zhang (2001).

The effect of the greenhouse gas forcing on the Arctic ice thickness is shown in Fig. 3. There is significant multi-year variability in the mean ice thickness (both in individual runs and the ensemble mean). The Greenhouse run ice thickness (red) remains close to the Natural Forcing (blue) ice thickness (and mostly within the ensemble range) from 1900 to 1970. From 1970 to 2000, the Greenhouse ice thickness decreases by approximately 5% of the mean. The Greenhouse thickness appears to decrease to just below the Natural Forcing range by the year 2000, since the natural variability of the thickness in the ensemble is almost 5% of the mean.

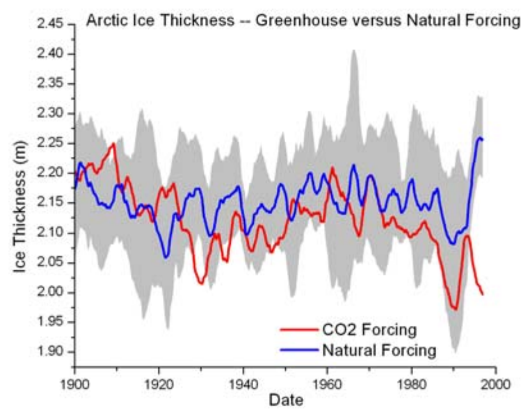

Fig. 3. Annual mean ice thickness averaged over the entire Northern Hemisphere for the Greenhouse case (red) and Natural Forcing case (blue).

To revisit the earlier question – Is the Arctic sea ice disappearing because of increasing greenhouse gases? Our ability to answer that may depend on what properties we can observe. According to these climate simulations, increasing greenhouse gases can cause the decrease in Arctic ice area beyond the range of natural variability. The observations of sea ice extent provided by satellite imagery shows a similarly decreasing ice cover.

The increasing greenhouse gases can also produce a thinning of the Arctic sea ice below that caused by the natural forcing included here, but only slightly what is beyond the natural range of variability in the latest years of the simulation. Several studies have reported on the thinning of the Arctic sea ice from a variety of locations spanning the last forty years. While the Arctic sea ice has thinned, our inability to measure ice thickness on a basin-wide scale makes it difficult to assess any large-scale trends with confidence.

The increasing solar flux has contributed to the global warming trend primarily from 1900 to 1950 but has not contributed more than that 1950 level. There is little trend in the modeled ice area or thickness over the years 1900 to 1950 in response to the solar flux trend.

3.3 Future Climate Simulations 2000 – 2100

The PCM has been used to simulate the effects of transiently increasing greenhouse gases beyond their present values through the next 100 years. These simulations begin with climate model state at the end of the Greenhouse runs for the year 2000. The CO_2 concentration is prescribed to increase at 1% per year, and other greenhouse gases also increase. This has been called the 'Business-As-Usual' (BAU) scenario, as it continues present trends in greenhouse gases without any stabilization before 2100. At 1% per year, the CO_2 concentrations double by the year 2070, and increase by a factor of 2.7 by 2100. There are some prescribed increases in the sulfate aerosol effects with are stabilized to a constant level during the next 100 years. There are no prescribed changes in the future solar flux or volcanic aerosols. An ensemble of four simulations is performed for this future climate scenario.

The global average temperature (not shown) increases steadily in these simulations, with an average warming of 1.8ºC by the year 2100 over the present-day temperatures. The largest regional temperature increase occurs in the Arctic, in the regions where the sea ice cover retreats. The annual temperature rise in the Arctic is 3.5ºC by 2100.

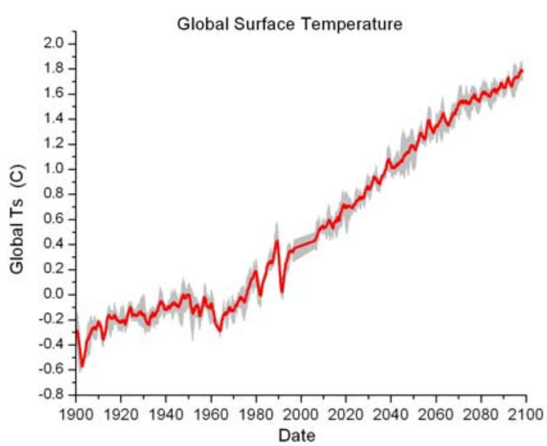

Fig. 4. Global average temperatures (ensemble and annual mean) for the entire simulation period 1900 to 2100 with increasing greenhouse gases (red). The gray band shows the ensemble maximum and minimum.

However, the warming is greatest in winter, over +10ºC greater over the ice-retreat regions, and least in summer when surface temperatures over ice remain near 0ºC. The warming over Arctic land areas is also +2 to +6ºC in winter by 2100.

The Arctic sea ice area (Fig. 5) decreases by about 25% by the year 2100 below average 20th century values with the increasing greenhouse gases. What does this mean for seasonal and regional ice cover changes? In assessing the most likely impacts of these changes, the biases in the excess ice cover in PCM should be considered, and the expected ice cover reduced accordingly. According to these simulations, the minimum sea ice cover in summer would not be completely ice-free by 2100, although both the extent of the ice pack and the thickness of that ice would be greatly reduced. The periods of seasonally open water surrounding the Arctic ice pack would also be longer.

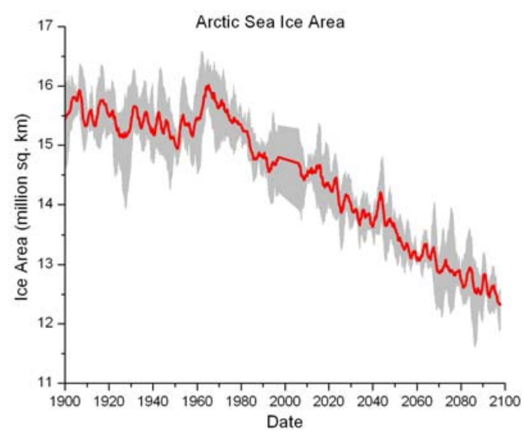

Fig. 5. Annual mean Arctic sea ice area over entire simulation period 1900 to 2100 with increasing greenhouse gases (Greenhouse and Business-As-Usual simulations).

The Arctic average ice thickness (Fig. 6) also shows an overall trend of decreasing thickness with the increasing greenhouse gases. However, there are also multiple multi-year periods in which the ensemble-mean thickness shows increasing ice thickness caused entirely by natural variability. This demonstrates the significant amount of variability in the Arctic ice thickness as it responds to changing dynamic and thermodynamic forcing over multi-year periods.

The average thickness is reduced by 25% below 20th Century values by the year 2100. Interestingly, a 25% reduction is less than the 37% reduction that has been estimated from submarine-based measurements at multiple locations between the 1950's and 1990's (Rothrock et al. 1999). These submarine-based differences over the 20- to 40-year timescales suggest they are a response to multidecadal forcing such as the anthropogenic climate change. However, the rapid reduction in ice thickness around 1988 appear to be a response to the shift in the Arctic Oscillation, winds and air temperatures.

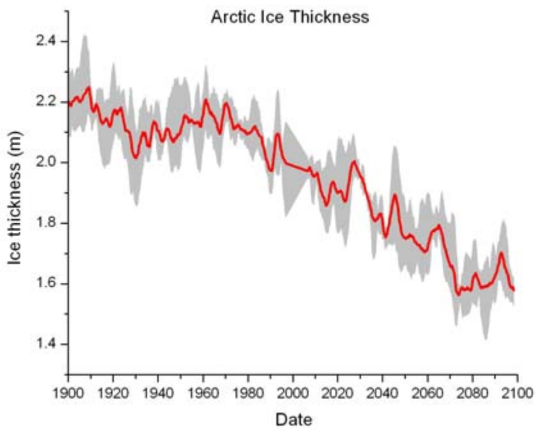

Fig. 6. Annual mean Arctic ice thickness over entire simulation period 1900 to 2100 with increasing greenhouse gases (Greenhouse and Business-As-Usual simulations).

4. SUMMARY

The simulations of pre-industrial to present-day climate with the PCM atmosphere-ocean-sea ice model show that:

- Increasing greenhouse gases have most likely caused the reduction in Arctic sea ice cover over the last 20 years (1980 to 2000). Increasing solar flux and natural variability have not likely caused this reduction.

- Greenhouse gases have most likely caused the global temperature rise over the last 20 years.

- Greenhouse gases have added some contribution to the observed thinning of Arctic sea ice. However, the observed thinning suggests that the recent phase of the Arctic Oscillation has also contributed to thinning ice.

- These effects of increasing greenhouse gases have exceeded those of natural forcing only recently.

- The ice cover is expected to continue shrinking and thinning as the anthropogenic greenhouse gases continue to accumulate.

5. ACKNOWLEDGEMENTS

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