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Report: Cryosphere and Climate

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This chapter will discuss two main issues related to the cryosphere and climate. One is the effect of sea ice and salinity gradients on ocean circulation, and in particular the possible role of sea ice transport on the ocean conveyer belt. The other is the effect of the cryosphere on climate, and in particular in high-latitude warming under increased CO_2.

In understanding the role of the cryosphere in both cases, it is useful to elucidate two types of toy sea ice models. Neither of these represents reality, but both are useful for illustrating the archetypal features of sea ice that control much of its large-scale behavior.

The first model is a simple slab thermodynamic sea ice model as presented by Thorndike (this volume). In this model there are no dynamical effects and the thickness of ice is determined by surface heat budget and oceanic heat flux considerations, with the thickness of the ice critically affecting the effective conductivity whereby heat is transferred from the bottom ice boundary to the upper ice boundary. In this model all of the sea ice characteristics are controlled by the vertical heat fluxes from the atmosphere and ocean into the ice. The thickness is controlled by the ice's becoming an effective insulator as it thickens, thus reducing conductive heat loss to the atmosphere.

A second model emphasizes the effects of dynamics (Hibler, this volume). It considers the ice pack to be a collection of floes moving in response to synoptic wind fields and ocean currents. These motions create semipermanent leads (open areas) over which ice can grow rapidly. Under the convergent phase the new ice is converted into sea ice pressure ridges. In this idealized model, growth over the ice floes is neglected, and all of the ice production occurs over leads. The mean ice thickness of this system is determined by a balance between the ice growth over the leads and the removal of ice from a region by ice transport. An important facet of this model is that we can view a region, such as the Arctic Basin, as being a source of a river of ice. This river of ice leaves salt behind in the Arctic Basin as it freezes at its source, and delivers fresh water at its terminus somewhere in the Greenland or Labrador seas where the ice melts. Similarly, in the Antarctic this river of ice can aid in the outward expansion of the ice edge by virtue of ice's being formed near the coast and being transported outward to where it melts (see, e.g., Hibler and Ackley, 1983).

Influence of the Arctic Ocean on the North Atlantic

A caricature of the Arctic Ocean (as opposed to a toy model) is that it is an estuary receiving fresh water in the form of runoff from the large basin draining into it and from net precipitation over the ocean itself. It receives warm, salty Atlantic water from the West Spitzbergen Current. Also, it exports Arctic water in the East Greenland Current. The fresh water mixes with the salty water to form a thermocline capped by low-salinity surface water. The surface of the ocean is frozen, as a consequence of the strong negative radiation balance in the winter. The annual cycle of freezing and melting maintains a buoyant mixed layer, which limits any exchange of heat or salt with the deeper ocean. In summer, the ice shields the ocean from sunlight.

Because the ice transport out of the Arctic Basin is a major source of fresh water to the Greenland Sea, it may play a role in shutting off or maintaining that thermohaline circulation conveyer belt mechanism. The basic mechanism here is that the outward motion of ice from the Arctic Basin into the Greenland Sea, where it melts, causes a stable stratification in the Greenland Sea and hence a sealing off of the ocean and possibly a diminution of the conveyer belt. Whether the conveyer belt runs steadily or whether it is intermittently controlled by more detailed processes (most notably the various salt sources) in the North Atlantic and Greenland Sea is still unclear. In the latter hypothesis, the polar and subpolar portions of the Atlantic are believed to exert a strong influence on the conveyer belt. To clarify this point, there is a need to take a closer look at precipitation, the salt budget, and the ocean circulation-stratification problem for the Arctic and sub-Arctic regions.

In the North Atlantic, the Arctic Ocean is then a source of cold, low-salinity surface water. The fact that some of this water is frozen may be of secondary importance. Having a large source of cold, buoyant water in a region where deep convection is supposed to occur is a potential embarrassment to theorists. Because of its low salinity and already low temperature, this water will not sink if it is cooled. It is the warm, salty Atlantic water that, after being cooled at the surface, may sink to the bottom. For deep convection to occur, the Arctic water must be shunted elsewhere. It is removed by forming the narrow East Greenland Current, which stays to the west of the regions of convection.

We can expect the Greenland Sea to be sensitive to climatic change. For one thing, it receives the ice exported from the Arctic Basin through the Fram Strait. The volume of this ice is determined by its thickness and motion, which in turn are determined by various energy fluxes and the winds and currents. All of these will change with a changing climate. About half of the ice in the Greenland Sea is formed locally in the winter and melts during the summer. As is the case with other regions of seasonal (not perennial) ice, the ice conditions are vulnerable to climate change.

The stability of the system that includes the East Greenland Current and the regions of deep convection in the Greenland, Iceland, and Norwegian seas is not known. Fluctuations that cause the buoyant Arctic water to spread out to the east might reduce or shut off the convection, with far-reaching implications for the thermohaline circulation of the world ocean.

An important issue is whether the conditions that regulate the deep convection are related to the limits of the ice extent. Thinking of the convection as part of the large-scale conveyor belt circulation, we may wonder whether the driving force is local or remote. If it is local, and related to sea ice extent in some way, the temperature of the sinking water may be fixed with respect to the freezing point, and therefore independent of global warming. In a changing climate, the location or the rate of the convection may change, but not the temperature of the downwelling water. This would be a powerful brake on global warming. On the other hand, if it is only a coincidence that the convection occurs in waters affected by the present ice edge, we should expect the deep ocean to be renewed with warmer water as the climate warms.

Another issue is the possibility of a hydrological-cycle oscillation. In this scenario, a reduction in ice extent causes greater precipitation, which in turn causes an increase in stratification, greater surface currents, and a gradual increase in ice export from the Arctic Basin, thus leading to greater ice extent. This in turn might decrease the precipitation.

The following work is needed:

- Improve our knowledge of the freshwater balance for the Arctic Ocean
- Monitor temperature, salinity, ice thickness, and ice velocity across the Fram Strait
- Model the upper Arctic Ocean, especially the role of sea ice processes in maintaining the ocean's vertical structure
- Model the Arctic Ocean circulation with the objective of learning the actual water, ice, and salt transports through Fram Strait.

Role of the Cryosphere in High-Latitude Warming under Increased CO_2

In this section, our focus is the role of sea ice (and, to a lesser extent, land snow) in the response of the high-latitude climate to atmospheric warming. The main mechanisms we will discuss are the feedback between ice extent and global albedo for both sea and land ice and increased sea-to-air heat transfer for a reduction of ice extent and thinning of ice that would occur under atmospheric warming.

Ice-Albedo Feedback and Climate

Most climate modelers include a positive ice-albedo feedback in their parameterizations. The reasoning hinges on the idea that increasing ice extent increases the global albedo. However, the extensive summer cloud cover at high latitudes means that the global albedo may not be sensitive to ice extent. That is, sunlight is now being reflected by clouds, so it cannot make much difference to the earth as a whole if sunlight is reflected by ice instead.

The relationship between sea ice extent and albedo is accessible to observations. The ice extent can be deduced from the 15-year satellite passive microwave record, because the microwave contrast between ice and water is much greater than the microwave contribution from clouds. The albedo can be determined from data collected by the Earth Radiation Budget Experiment (ERBE) satellite. A poor correlation between high albedo and ice extent would be interpreted to mean that the cloud cover remains more or less fixed despite variations in the underlying ice. On the other hand, a good correlation would mean either that the cloud cover is slaved to the ice extent or that the ice itself is contributing significantly to the albedo.

To understand the behavior of sea ice, we must know the albedo of the ice itself. Knowing the albedo at the top of the clouds is not enough. The ice albedo depends on the ice state, in particular, on the presence of snow or meltwater. The equilibrium thickness of the ice is sensitive to the albedo, because the albedo controls the surface melt during the summer. Because of the persistent summer cloudiness, the ice albedo cannot be measured from space. A sequence of aircraft albedo surveys would substantially improve our knowledge of this sensitive parameter.

The working group felt that there are two additional reasons why the surface ice albedo effect cannot be discounted in any consideration of future high-latitude atmospheric warming. First, observational evidence in both the Arctic and the Antarctic shows that any modification of the surface albedo has major consequences for the summer ablation. Thus, the amount of shortwave radiation penetrating to the surface is certainly significant. Second, clouds over the pack in summer tend to be very low and foglike so that they may well act as a diffuser rather than a carrier of radiation.

High-latitude clouds are also important because of their impact on the surface energy balance. During summer, they reduce the shortwave radiation reaching the ice or sea surface. Throughout the year, they increase the downward longwave radiation. In existing model treatments of sea ice, the radiation balance is prescribed. It may now be an appropriate time to explore coupling between the ice surface conditions, such as temperature, ice concentration, and albedo, and the atmospheric conditions that determine the incoming radiation. Such a treatment would need to account for clouds.

These issues highlight the current lack of a high-latitude cloud climatology. Work within the International Satellite Cloud Climatology Project may lead to some improvement, but the difficulty in distinguishing ice from cloud has ruled out interpreting the data using algorithms that work well at lower latitudes. Effective high-latitude algorithms are sorely needed. Some progress has been reported using texture in AVHRR data to discriminate ice from cloud.

Sea Ice in the Arctic and Antarctic

Although the sea ice physics may be the same for the Arctic and Antarctic, there are considerable differences in the physical mechanisms controlling the sea ice extent in the Northern and Southern Hemispheres. In particular, in the Northern Hemisphere the northward transport of heat in the ocean plays a key role in the location of the ice edge (Hibler and Bryan, 1987), and in fact recent interannual coupled ice-ocean simulations suggest that variations in the ice margin may be affected more by changes in icean circulation than by atmospheric cooling. Also, the relatively large land mass in the Northern Hemisphere (except in the Arctic Ocean) suggests that albedo feedback effects may not be as pronounced until significant variations of the ice occur north of 70° latitude. In the Antarctic, there is only weak vertical stratification, and hence convective overturning plays a greater role in the ice edge and thickness. However, it was also noted in this regard that although Antarctic sea ice simulations based on thermodynamics considerations alone need to invoke large amounts of heat flux to explain the summer ice decay, simulations including full ice dynamics can yield a realistic ice decay without large amounts of oceanic heat flux. This is mainly due to the creation of leads by ice dynamics, which increases radiation absorption and accelerates the ice decay in the spring, as well as to ice transport, which moves large amounts of ice into open water to be melted (see, e.g., Hibler and Ackley, 1983).

For the Antarctic, we would expect the ice-albedo feedback to operate effectively as normally perceived, i.e., an increased warming leads to less ice extent and hence more radiation absorption. In the Arctic, on the other hand, the ice-albedo feedback effect is significantly constrained by the land geography and the ocean circulation. Atmospheric circulation models with only a mixed-layer ocean probably have too much ice in the control case and hence may well overestimate the effects of albedo feedback on enhanced high-latitude warming in the Arctic.

With regard to the geographical constraints on Arctic sea ice, the land snow albedo feedback may compensate for the reduced ocean area (until the Arctic Basin is reached), although the seasonal cycle of amplified warming may be different than that obtained with sea ice due to the high heat capacity of the land.

Treatment of Sea Ice

In modeling both the Arctic and the Antarctic, the timing of the maximum warming is likely to be affected by the treatment of sea ice employed. In particular, the use of a thermodynamics-only sea ice model will lead to positive feedback effects whereby there will be greater sea-to-air heat fluxes under warming due to thinner ice. However, if we replace a thermodynamics-only model with a model where the growth is mainly over leads (continually created by dynamical effects), then we would have a negative feedback effect with less sea-to-air heat exchange under an atmospheric warming. All warming effects may be modified by the presence of water vapor in the air, which will increase the downward longwave radiation. For a smaller warming, ocean circulation effects may constrain many of the feedback effects in the Arctic ice margin.

Needed Observations

A variety of observations could be made over the next several decades to detect CO_2 warming or verify some of the above theories.

In the Arctic, because of the critical control of the ocean on the ice margin, it may not be possible to deduce much from ice edge variations. However, it may be possible to get some indication of atmospheric warming from monitoring the ice thickness in the Arctic Basin. In this regard one of the most promising measurements would be moored, upward-looking sonar buoys at several locations in the basin (and possibly in the Fram Strait) that would supply a long time series of measurements of the thickness distribution of the sea ice. Regular oceanic measurements of temperature and salinity in the Greenland and Norwegian seas as well as oceanic transport characteristics through the Fram Strait would be most valuable with regard to the salt budget in the ocean.

In the case of the Antarctic ice cover it may be that ice extent variations obtained from passive microwave satellite observations can give us some insight into long-term atmospheric warming or cooling in the Southern Hemisphere.

The following work is needed:

- Develop cloud climatologies for the Arctic and Antarctic
- Correlate ice extent and planetary albedo
- Develop a toy model linking ice surface and clouds
- Study high-latitude behavior in current GCMs
- Improve the observational base for surface radiation balance.

References

Hibler, W.D. , III, and S.F. Ackley. 1983. Numerical simulation of the Weddell Sea pack ice. *Journal of Geophysical Research 88*, 2873–2887.

Hibler, W.D., III, and K. Bryan. 1987. A diagnostic ice-ocean model. *Journal of Physical Oceanography 17*, 987–1015.