Sea Ice in the Global Climate System

Kenneth M. Golden[1], Elizabeth Hunke[2], Cecilia Bitz[3], and Marika Holland[4]

[1]Department of Mathematics, University of Utah, [2]Los Alamos National Laboratory, [3]Department of Atmospheric Sciences, University of Washington, [4]National Center for Atmospheric Research

Figure 1. Pancake ice in the Southern Ocean off the coast of East Antarctica. (K. M. Golden)

Figure 2. The Antarctic sea ice pack with an open lead in the distance. (K. M. Golden)

Figure 3. Grease ice forming in front of grounded icebergs in Antarctica. (K. M. Golden)

Figure 4. Emperor penguins sliding across Antarctic sea ice. (A. Gully)

Will scientists who model the polar sea ice packs soon be out of a job? After stunning sea ice losses in the Arctic, one wonders! By the end of the 2007 summer melt season, the Arctic ice pack had shrunk by nearly 40 percent from its 1979-2000 average extent, and the fabled Northwest Passage was open to seafarers for the first time in human memory. The sharp decline of the summer Arctic sea ice pack is probably the most dramatic, large-scale transformation of the earth's surface which is apparently due to global warming. Sea ice returns during the dark, cold, winter months, but will it recede to more record lows in the coming years? There are too many competing factors to know for certain, but the likelihood of an ice-free Arctic summer is rising. We don't see such dramatic changes in the Antarctic sea ice pack yet, but will we? Modeling the complex interactions among the oceans, atmosphere, and cryosphere -- those portions of earth's surface where water is in solid form -- requires a lot of mathematics, computation, and many areas of science.

WHAT IS SEA ICE AND HOW DOES IT FORM?

Figure 5. Sub-millimeter scale brine inclusions in sea ice. (W. Weeks and A. Assur)

Sea ice is simply frozen ocean water, which freezes at a temperature of about -1.8 °C, or 28.8 °F. In turbulent conditions typical of the open ocean, small crystals called *frazil ice* form, which often aggregate near the sea surface into slick patches of *grease ice*. As freezing continues, the greasy surface congeals into larger, solid platelets called *pancake ice*. The pancakes eventually freeze together into small ice floes, which themselves aggregate into pack ice with floes up to many kilometers across. When sea ice forms in quiescent conditions, a thin skim of translucent ice called *nilas* is seen first, which can eventually thicken through freezing into large, undeformed floes. Under the influence of winds and currents, sea ice can also thicken through rafting, where ice floes ride up one on top of another, and ridging, where they crash into each other, breaking apart and forming small "mountain ranges." Sea ice that melts after one season is called *seasonal ice*, and sea ice that survives a summer season is called *multiyear ice*.

The continent of Antarctica sits atop the South Pole, and during the austral winter this land mass is ringed mostly by seasonal ice on the Southern Ocean, with maximal ice extent in September. The Arctic is almost the geographical opposite, with an ocean at the North Pole, surrounded by continents, and covered with both seasonal and multiyear sea ice, of maximal extent in March. Sea ice should be contrasted with icebergs, glaciers, ice sheets, and ice shelves, which all originate on land. The great ice sheets covering Antarctica and Greenland are up to two miles thick, and are composed of glacial ice formed from snow which has been compressed over thousands or millions of years into ice, somewhat similar in structure to the ice cubes in your freezer.

As a material, sea ice is quite different from the glacial ice in the world's great ice sheets. When salt water freezes, the result is a composite of pure ice with inclusions of liquid brine, air pockets, and solid salts. As the temperature of sea ice increases, the porosity or volume fraction of brine increases. The brine inclusions in sea ice host extensive algal and bacterial communities which are essential for supporting life like krill in the polar oceans, which supports fishes, penguins, seals, and Minke whales, and up the food chain to killer whales, leopard seals, and polar bears. The brine microstructure also facilitates the flow of salt water through sea ice, which mediates a broad range of processes, such as the growth and decay of seasonal ice, the evolution of ice pack reflectance, and biomass build-up.

WHY IS SEA ICE SO IMPORTANT IN EARTH'S CLIMATE SYSTEM

As the boundary between the ocean and atmosphere in the polar regions of earth, sea ice plays a critical role as both a leading indicator of climate change, and as a key player in the global climate system. Roughly speaking, most of the solar radiation which is incident on snow-covered sea ice is reflected, while most of the solar radiation which is incident on darker sea water is absorbed. The sea ice packs serve as part of earth's polar refrigerator, cooling it and protecting it from absorbing too much heat from sunlight. The ratio of reflected sunlight to incident sunlight is called *albedo*. While the albedo of snow-covered ice is close to 1 (larger than 0.8), the albedo of sea water is close to zero (less than 0.1). As more ice is melted, the albedo of the polar oceans decreases, leading to more solar aborption and warming, which in turn leads to more melting, in a positive feedback loop. It is believed that this so-called *ice-albedo feedback* has played an important role in the marked decrease in Arctic sea ice extent in summer.

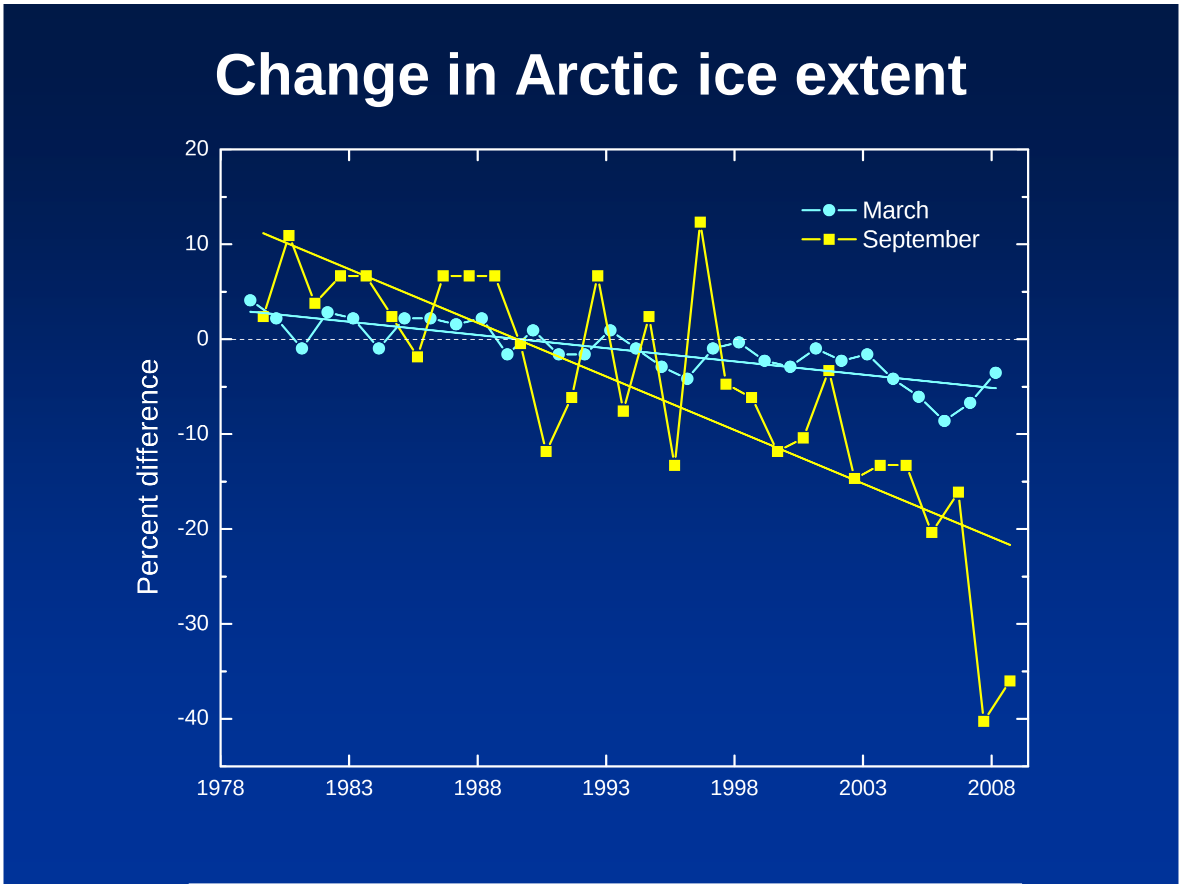

Figure 6. Decline of the Arctic sea ice pack over the past three decades, showing a dramatic fall-off of the summer ice extent (yellow) in 2007 and again in 2008, from its 1979-2000 average extent (courtesy of Don Perovich).

In considering the fate of earth's sea ice packs, ultimately, sunshine is king. It drives the climate system and melts the ice. Its disappearance at high latitudes in the winter allows the ice to grow back. But other factors are at work too, including the sea ice itself. Cold air from Siberia or the Antarctic continent cools the ocean's surface and new sea ice freezes. Winds blow it around, crashing it into the coast or icebergs or other sea ice, causing it to pile up into thick ridges of ice. Ocean currents bring warm waters beneath the ice, melting it from below. Sometimes winds and ocean currents together move the ice into warmer waters, where it melts.

In this tussle between atmosphere and ocean, sea ice is not a passive bystander. It has its own tactics for meeting the competition or, in some cases, becoming an accomplice to its own destruction. Sea ice is both ocean sunscreen and blanket, preventing solar rays from warming the waters beneath and thwarting ocean heat from escaping to warm the air above. But if gradually warming temperatures melt sea ice over time, as mentioned above, fewer bright surfaces are available to reflect sunlight, more heat escapes from the ocean to warm the atmosphere, and the ice melts further. Thus, even a small increase in temperature can lead to greater warming over time, making the polar regions the most sensitive areas to climate change on earth – global warming is *amplified* in the polar regions. But as sea ice melts, it leaves a layer of fresh water at the ocean's surface that can inhibit global ocean circulation, the "conveyor belt" that brings warm water toward the poles. Sea ice is both an obstacle and a catalyst for change, able to hasten the pace in either direction.

Figure 7. Melt ponds on Arctic sea ice in June 2007. (K. M. Golden)

What happens if there's no more Arctic ice in the summer? Polar bears lose their hunting platforms, for one thing. And they're at the top of the food chain! The web of life will be affected in ways we cannot yet imagine. However, sea ice in the Antarctic already retreats almost completely every summer, supporting a rich ecosystem based on algae and other microbes that thrive in the seasonal ice habitat. Will the Arctic become more like the Antarctic? Stay tuned -- some fear Arctic sea ice has already reached its tipping point. Predictions of global climate and the fate of earth's sea ice packs depend on careful modeling of the physical processes involved, as well as sophisticated mathematical and numerical techniques to solve these models on powerful computers.

HOW DO WE MODEL THE POLAR SEA ICE PACKS?

Modeling sea ice on a large scale to help predict global climate depends on understanding the physical properties of sea ice at the scale of individual floes and smaller. The sizes, geometries and volume fraction of the fluid inclusions of brine depend strongly on the temperature of the sea ice, and this feature of sea ice makes it not only a very interesting composite material, but also difficult to model. For larger scale models, relevant properties of sea ice include its thermal conductivity -- how easy it is for heat to flow though the ice, its fluid permeability -- how easy it is for fluid to flow though the porous sea ice, and its mechanical strength and fracture characteristics – determining how sea ice breaks up under stress from winds and currents, and from collisions with other ice floes.

Generally, these processes are modeled with differential equations, yet many mathematical and computational techniques are employed to estimate and analyze sea ice properties. For example, probability and statistics is used to characterize the brine microstructure, which exhibits an interesting critical phenomenon. For temperatures below about -5 °C, corresponding to a brine volume fraction of about 5% for a typical bulk sea ice salinity of 5 parts per thousand, the brine inclusions are mostly separated or disconnected, and the sea ice is effectively impermeable to fluid flow. However, for temperatures above -5 °C, the brine inclusions become connected over larger scales, and fluid can flow through the sea ice. Understanding this behavior, called the "rule of fives," is important for modeling nutrient replenishment for microbial communities, snow-ice formation where sea water percolates to the surface, floods the snow layer and then freezes, and the evolution of spring melt ponds -- important in determining the albedo or reflectance of the sea ice pack. Percolation theory, where one studies the connectivity of lattices whose bonds have been randomly removed, has been used to model this phenomenon. This mathematical theory has also been used to study flow in porous rocks, the electrical properties of semiconductors, and many other systems where the connectivity of one phase dominates the behavior.

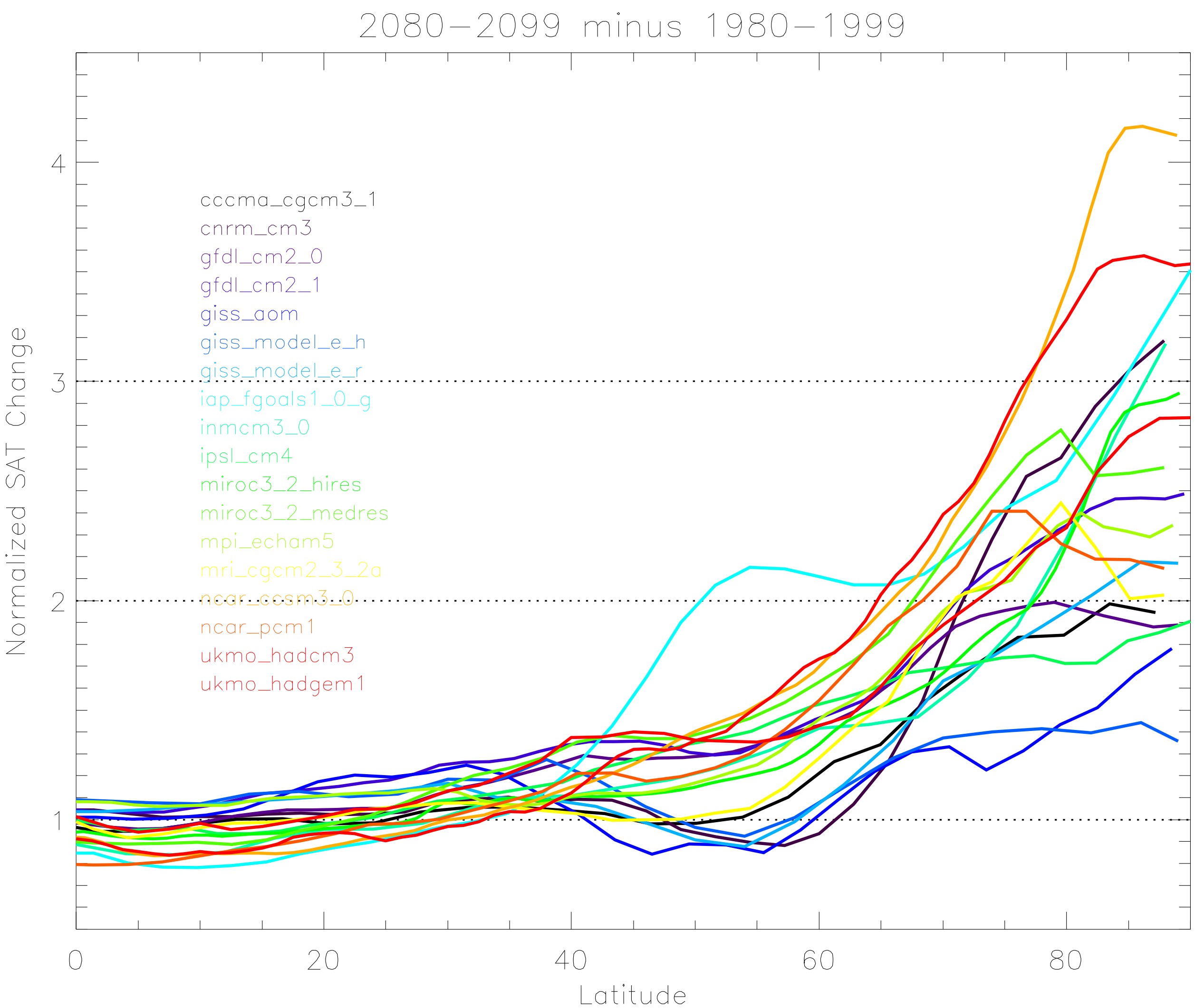

Figure 8. The zonally averaged change in surface air temperature (SAT) normalized by the global average surface air temperature change from a number of climate models for 2080-2099 minus 1980-1999. The normalized air temperature change provides a measure of *amplification*. For example, a value of 3 indicates 3 times the global average surface air temperature change at that latitude. Climate models consistently show amplified warming in the Arctic (high latitudes), although the magnitude varies considerably across different models.

Modeling these small scale processes in a climate model is a creative endeavor! Modelers must capture the chief characteristics of sea ice that control its own peculiarities and its behavior in a system strongly coupled to the atmosphere and ocean. Climate models exercise today's super computers to their fullest capacity, but even the largest computers still limit the horizontal resolution to 10's of kilometers and require clever approximations to model the basic physics.

The governing equations are conservation laws of mass, momentum, and energy, which take the form of differential equations. Although sea ice is an amalgamation of an often broken-up, jumble of pieces called floes, the pieces are generally small compared to the resolution of climate models. Therefore it is not yet possible to model individual floes per se. Rather, the momentum equation treats sea ice moving at typical speeds as a non-Newtonian fluid continuum, with material properties of a theoretical plastic at the breaking point. Sea ice rafting and ridging results from energy dissipation when there are gradients in the flow field. These gradients can also part sea ice floes, creating openings in the ice known as *leads*. The complexity of the sea ice geometry results in a large range of sea ice thicknesses within an area well below the horizontal grid size of climate models. This ice-thickness distribution is best treated in a statistical sense, so that the conservation equations for mass and energy involve probability density functions.

The important influence of variable brine volume fraction within the sea ice acts as thermal inertia in the sea ice – delaying the arrival of the summer melt season and fall freeze-up. The brine volume is modeled as internal melt that effectively increases the heat capacity of sea ice and reduces the amount of energy needed to melt the ice from the top or bottom surface. Modeling the reflection, absorption, and transmission of sunlight in sea ice is essential to capture the energy exchange with the atmosphere and ocean, as well as the proper light levels utilized by sea ice and ocean biota.

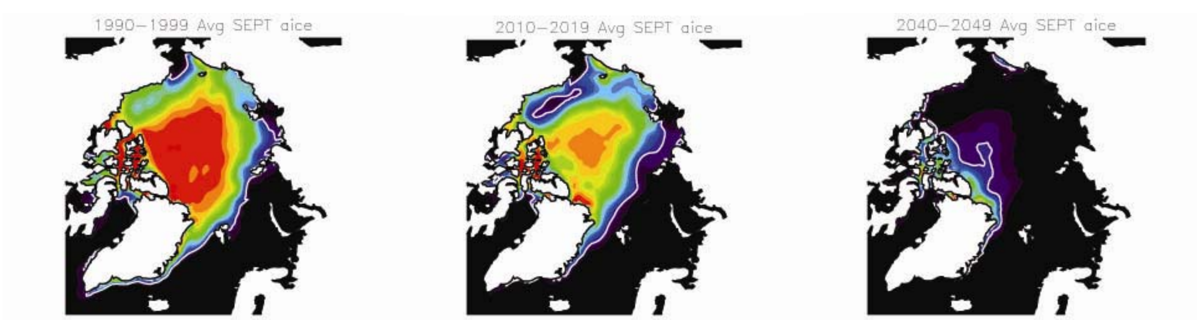

Figure 9. Coupled climate model simulations from the Community Climate System Model, version 3, showing September sea ice concentration averaged for three different time periods (left to right) 1990-1999, 2010-2019, and 2040-2049. The white line indicates the simulated ice extent, defined as the 15% ice concentration contour. This and other similar climate models suggest significant sea ice loss will occur over the next 50 years and near-ice free September conditions may be reached in the Arctic by the mid-21st century. Some scientists predict such a decline over an even shorter period of time.

HOW DO WE MONITOR THE HEALTH OF THE SEA ICE PACKS?

Monitoring the state of earth's sea ice packs is a key part of assessing the impact of global warming. Determining the extent of the sea ice pack is within the capability of current satellite systems and the mathematical algorithms used to interpret the huge volumes of data obtained. In addition to the tremendous amount of electrical engineering, mathematics and computation involved in the design of such systems, remote sensing scientists also must study the interaction of electromagnetic waves with sea ice. Such studies involve Maxwell's equations, the partial differential equations which describe the how light and other electromagnetic waves like microwaves and radar interact with materials. However, determining the health of the sea ice packs means obtaining the volume of sea ice, which requires knowing its thickness as well as its areal extent. Because the microwaves used by most satellites can only penetrate a few centimeters into a typical sea ice floe, other means are being developed. Bouncing laser beams from a satellite off the surface of the sea ice and comparing with the return from the sea surface in open leads is one method. In the Arctic, upward looking sonar measurements from submarines roaming under the sea ice pack have provided a wealth of thickness data. Also, in recent years, electromagnetic induction devices mounted on ships, helicopters and planes have been used to obtain thickness data. These instruments use low frequency waves which can penetrate all the way through sea ice floes. Interpreting the data requires an understanding of how the electrical properties of sea ice, such as its conductivity, depend on its composite structure, and how these properties vary throughout a floe, which requires differential equations, statistics, and computation. Ultimately, what is required for comparison with large scale sea ice models is statistical information about the distribution of floe sizes and thicknesses, and how they evolve with time.

Figure 10. An electromagnetic induction device for measuring sea ice thickness, called the “Worbot” after Australian sea ice scientist Tony Worby, mounted on the icebreaker *Aurora Australis*. (K. M. Golden)

FUTURE CHALLENGES FOR SEA ICE MODELERS

Numerous challenges remain in the modeling of sea ice for climate applications. A number of processes are only crudely represented, such as snow-ice formation, aspects of the snow pack overlying the ice cover, and the parameterization of ice strength and dynamic-driven ice ridging and rafting. Future research efforts are needed to improve the representation of these and other processes. For example, the large scale ramifications of recent progress on understanding the material properties of sea ice, such as fluid flow through the porous brine microstructure, need to be developed. Additionally, as fully coupled climate models move to increasingly higher (perhaps ocean eddy-resolving) resolutions, questions arise on the appropriateness of some approximations made in the current sea ice components. While a number of studies have examined this in ice-ocean coupled simulations, there has been very little research to date in a fully coupled context. In the ongoing transition from coupled climate system models to earth system models, sea ice components will need to fully interact in biogeochemical cycles requiring additional research and new model capabilities.

For more information:

http://www.ucar.edu/news/releases/2006/arctic.shtml

http://www.ucar.edu/communications/CCSM/index.html

www.math.utah.edu/~golden

See video from an Antarctic expedition at http://ucomm.utah.edu/current/antarctic.html

http://www.atmos.washington.edu/~bitz/

http://cafenm.org/2008/cafemar08.html

Global Climate Models and 20th and 21st Century Arctic Climate Change, Cecilia M. Bitz, Jeff K. Ridley, Marika Holland, Howard Cattle (http://www.atmos.washington.edu/~bitz/Bitz_etal2008.pdf)

Loss of Sea Ice in the Arctic, Donald K. Perovich and Jacqueline A. Richter-Menge, *Annual Review of Marine Science*, 2009. (link to follow)

Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007, Donald K. Perovich, Jacqueline A. Richter-Menge, Kathleen F. Jones, and Bonnie Light, *Geophysical Research Letters*, Vol. 35, L11501, doi:10.1029/2008GL034007, 2008.

http://www.arctic.noaa.gov/reportcard/
http://svs.gsfc.nasa.gov/vis/a000000/a003300/a003355/
http://www.nsidc.org/
http://arctic.atmos.uiuc.edu/cryosphere/

http://www.realclimate.org/
http://dotearth.blogs.nytimes.com/