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What is the trajectory of Arctic sea ice?

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Significant changes in the Arctic sea ice, ocean, atmosphere, ice sheets, and freshwater cycle over the past few decades are well documented. Several recent articles refer to the trajectories of these components, in which the word "trajectory" is used in a figurative sense. In this work we give a precise meaning to the trajectory of Arctic sea ice, and then analyze that trajectory as determined by model output.

The sea ice thickness distribution g(h) over some region R gives the fractional area of R covered by ice of thickness h. It is the fundamental description of the Arctic sea ice cover. The processes controlling g(h) are ice growth, melt, ridging, and import/export (into or out of R). Models that simulate the evolution of g(h) use discrete bins of ice thickness. Let g_k represent the fractional area covered by ice with thickness in the range $h_k < h < h_{k+1}$, for k=1 to n, where n is the number of bins. The area with $h < h_1$ is considered open water. The sum of the fractional areas g_1 through g_n is the total ice concentration. Now consider $(g_1,\ldots,g_n)$ as a point in n-dimensional space. As time progresses, the point moves in the n-space, tracing out a trajectory. That is what we mean by the trajectory of Arctic sea ice. A point on the trajectory gives the ice thickness distribution at a particular time. Each component $g_k(t)$ is a time series of the fractional ice area in thickness bin k. The region R over which this description applies may be chosen to be as small as one model grid cell or as large as the entire Arctic Ocean.

We analyze the monthly output of an ice/ocean model covering the central Arctic Ocean for the period 1978-2005, with n=7 ice thickness bins. First we search for linear combinations of the bins $g_1 \ldots g_7$ that account for as much variance as possible, i.e. principal component analysis. It turns out that the first two principal components account for 98% of the variance – the trajectory of Arctic sea ice is essentially two-dimensional. However, the physical interpretation of the components is not straightforward. Instead, we group the ice thickness bins into thin ice ($h < 1.9$ m) and thick ice ($h > 1.9$ m). The annual trajectory in this two-dimensional phase space is roughly triangular: growth of thin ice in the fall, growth of thick ice in the winter (at the expense of thin ice), and loss of both thin ice and thick ice in the summer. The interannual variation on this cycle shows a gradual drift toward more thin ice and less thick ice. Several global coupled ocean/ice/atmosphere models predict a complete loss of summer Arctic sea ice before the end of the century. We construct a simple empirical model of the evolution of thin ice and thick ice, based on the output of the more complete models, and examine the transition from a perennial to a seasonal ice cover. The roles of external forcing and internal model dynamics are separated, and we show that multiple stable states of the ice cover are possible, raising the possibility that a “tipping point” could be crossed that would hasten the disappearance of the ice. While such a scenario does not imply that the ice is on an irreversible course, the current downward trend in Arctic sea ice is projected to continue.