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The thermodynamic predictability of sea ice*

ROBERT W. GRUMBINE
National Meteorological Center, Camp Springs, Maryland 20746, U.S.A.

ABSTRACT. Statistical analyses and model experiments suggest that the sea-ice cover is predictable weeks to months in advance. As such, it is one of the most highly predictable components of the climate system. The thermodynamic mechanisms by which this predictability can be realized are examined. It is found that the predictability is dependent on the differential growth/decay of sea ice as a function of thickness. In winter or year-round, for thin ice, the growth/decay rates are a strong function of thickness, which gives a relatively short period of predictability, though still long compared to the atmosphere. In summer, or year-round for thick ice, growth/decay rates are only weak functions of thickness and the period of predictability is comparatively long.

1. PHYSICAL PARAMETERS AND THEIR VALUES

f	$\mathrm{m\,s^{-1}}$	Ice growth/melt rate
g	$\mathrm{m^{-1}}$	Fraction of area centered at location x,y at time t which is covered by ice of thickness h to $h + dh$
ρ_a	$1.2\,\mathrm{kg\,m^{-3}}$	Air density
U_a	$5\,\mathrm{m\,s^{-1}}$	Air speed
C_h	1.75×10^{-3}	Sensible-heat transfer coefficient (Maykut, 1978)
C_p	$1004\,\mathrm{J\,kg^{-1}\,K^{-1}}$	Specific heat of air
T_s	K	Surface temperature of ice/snow
T_a		Air temperature
	243 K	Winter
	278 K	Summer
T_f	271.3 K	Freezing point of sea water
C_q	1.75×10^{-3}	Latent-heat transfer coefficient
L_v	$2.834 \times 10^6\,\mathrm{J\,kg^{-1}}$	Latent heat of vaporization of ice
k_s	$0.31\,\mathrm{W\,m^{-1}\,K^{-1}}$	Thermal conductivity of snow
k_i	$2.2\,\mathrm{W\,m^{-1}\,K^{-1}}$	Thermal conductivity of ice
H_s	m	Snow thickness
H_i	m	Ice thickness
C		Cloudiness
	0.5	Winter (Parkinson and Washington, 1979)
	0.75	Summer (Parkinson and Washington, 1979)
ϵ_i	0.97	Longwave emissivity of ice (Parkinson and Washington, 1979)
σ	$5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$	Stefan–Boltzmann constant
α		Albedo
	0.8	Winter
	0.5	Summer
LW	$\mathrm{W\,m^{-2}}$	Longwave radiation
$SW\downarrow$		Down-welling shortwave-radiation flux
	$0\,\mathrm{W\,m^{-2}}$	Winter
	$300\,\mathrm{W\,m^{-2}}$	Summer
I_0	0.34	Fraction of shortwave radiation which is not reflected that penetrates the ice surface (Maykut and Untersteiner, 1971)
τ_s	$15\,\mathrm{m^{-1}}$	Extinction coefficient for snow after Grenfell and Maykut (1977)
τ_i	$1.5\,\mathrm{m^{-1}}$	Extinction coefficient for ice after Grenfell and Maykut (1977)
ρ_i	$900\,\mathrm{kg\,m^{-3}}$	Density of ice
L_f	$3.34 \times 10^5\,\mathrm{J\,kg^{-1}}$	Latent heat of fusion of ice
F_w	$2\,\mathrm{W\,m^{-2}}$	Oceanic heat flux to ice (Maykut and Untersteiner, 1971)
q_a		Specific humidity
	1×10^{-3}	Winter
	3×10^{-3}	Summer

2. INTRODUCTION

Statistical analyses of sea-ice prediction (ice-edge location and area concentration) suggest that sea ice is predictable weeks and months in advance, given present anomaly fields (deviations from climatology) for one or more of the atmosphere, cryosphere and hydrosphere (Walsh and Johnson, 1979; Walsh, 1980; Chapman and Walsh, 1991; Marsden and others, 1991). Specific anomaly fields considered have included ice extent, surface salinity,

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50 m temperature, 400–600 m salinity (Marsden and others, 1991), ice area, sea-surface temperature, 700 mbar pressure field and surface-air temperature (Chapman and Walsh, 1991), surface temperature and sea-level pressure (Walsh, 1980), surface temperature, sea-level pressure, 700 mbar heights and temperatures (Walsh and Johnson, 1979). The apparent successes of the statistical analyses suggest that model-based ice forecasting might be successful on similar time-scales. Determining how far into the future such a forecast might be skillful (more accurate than climatology) is one purpose here.

An ice-model experiment (Hibler and Walsh, 1982) finds a significant correlation, 0.48, for a thermodynamics-only prediction of the Arctic ice-edge location. Adding dynamics increases the correlation to 0.58, which suggests that the dynamics are helpful but that much of the predictive skill lies with the thermodynamics.

An ice-thermodynamics model is taken to examine reasons for the predictability of sea ice. Specific features to be understood are: why is the present ice anomaly a better predictor (providing a more accurate forecast than climatology for a longer period, i.e. more skillful) than atmospheric anomalies (Walsh and Johnson, 1979; Walsh, 1980; Johnson and others, 1985); why is the time-scale of prediction weeks rather than days as it is for the atmosphere; and why is the time-scale of predictability longer in the spring and summer melt season than in the fall and winter freezing season. Since an incomplete physical model is taken here, rigorous answers to these questions are not possible. It is suggested, though, that if characteristics are found while examining the thermodynamic processes alone which are similar to the characteristics observed in Nature, then Nature is governed by thermodynamics in those situations.

3. ICE-THICKNESS DISTRIBUTION

An icepack is composed of many thicknesses of ice. We prefer to treat the icepack as a continuum, which means that we view the ice at a scale which is large compared to the size of individual floes. Consequently, each region of the continuum also contains floes of many different thicknesses. Certain thermodynamic processes, such as the conduction of heat through the ice, are sensitive to ice thickness. So, we need to track the fraction of the area of any region which is covered by ice of a given thickness. This gives rise to the notion of an ice-thickness distribution (Thorndike and others, 1975) $g(x, y, t; h)$. The fraction of area centered at location x, y at time t which is covered by ice between thickness h and $h + \mathrm{d}h$ is given by g. The ice-thickness distribution will change due to thermodynamic effects (freezing and melting) and dynamical effects (ridging, rafting and crushing). Only the thermodynamic part of the evolution equation for the ice-thickness distribution will be used as the basis for analysis in this study.

The thermodynamics-only ice-thickness distribution evolution is given by

$$\frac{\partial g}{\partial t} + \frac{\partial fg}{\partial h} = 0 \qquad (1)$$

after Thorndike and others (1975) but neglecting lateral ice freezing. f is the rate of freeze or melt, in m s^{-1}, of ice with thickness h.

Consider the meaning of climatology in this context. Climate refers to some typical annual cycles in both g and f, which will be denoted by $\overline{g}$ and $\overline{f}$. Also, the definition is required that:

$$\frac{\partial \overline{g}}{\partial t} + \frac{\partial \overline{f}\overline{g}}{\partial h} = 0 \qquad (2)$$

which includes the approximation that the mean of the products is equal to the product of the means.

Anomalies in ice extent or coverage will appear as anomalies in g. Thus, $g = \overline{g} + g'$, where g' are the anomalies. Atmospheric or oceanic anomalies, such as a warm summer or cold winter, will contribute to f'. Note that the anomalies from the atmosphere and ocean are only important to this model in so far as they affect the freezing or melting rate of the ice. The freezing rate and ice-thickness perturbations are not necessarily small. Near the ice edge, they are always large (the climatic term is near-zero). In order to examine the physical processes which are most important, Equation (1) will be linearized.

Here, $\overline{f}$ is considered known and is uncoupled from the ice-thickness distribution g. So we lack non-linear feed-back, the element which usually limits predictability. Consider instead the ice-thickness distribution perturbation, g'. If g' is smaller than our ability to distinguish it from zero, and hence our ability to distinguish g from $\overline{g}$, then predictability is lost. In this case, climatology is equally as good as the model at forecasting the distribution at this future time. Conversely, consider an initial state which contains an unmeasurably small error. If that perturbation grows large enough to be measurable, predictive skill is lost.

Now let us examine the perturbation equation derived by substituting $g = \overline{g} + g'$ and $f = \overline{f} + f'$ into Equation (1), suggestively rewritten, including both processes:

$$\frac{\partial g'}{\partial t} + \left[(\overline{f} + f')\frac{\partial g'}{\partial h} + f'\frac{\partial \overline{g}}{\partial h}\right] + \left[g'\frac{\partial(\overline{f} + f')}{\partial h} + \overline{g}\frac{\partial f'}{\partial h}\right] = 0 \qquad (3)$$

where the identity from Equation (2) has already been applied. The first bracketed term represents a one-dimensional wave equation for the thickness distribution propagating through time and thickness. The first half gives the propagation speed of thickness anomalies, while the second describes the perturbations due to a perturbed propagation rate of the climatological thickness distribution. The wave-like nature of this term was discussed by Coon and others (1974). The second bracketed term describes an anomaly dissipation or growth term. The first part amplifies (since $\partial f/\partial h$ is normally non-positive) the perturbation g'. The second part of the term contributes anomalies due to anomalous dispersion of the climatological thickness distribution.

The wave-like term suggests high predictability. Given f' and $\overline{f}$, g can be computed indefinitely into the future without g' decaying or growing. The purely propagating term has no means of amplifying or