This figure indicates that, in accordance with earlier estimates, the ocean area of the southern hemisphere affected by ice cover (15–100-percent concentration) decreases to a minimum of about 4 million square kilometers in February and increases to a maximum of about 20 million square kilometers in September. Well over half the reduction of ice extent occurs within the 2-month period from mid-November to mid-January, and in general this ice decay proceeds more rapidly than the ice growth from February to September.

The data show a mild trend between 1973 and 1975 toward a smaller extent of sea ice, particularly during the growth season. However, no similar trend appears for the area of waters with highly concentrated ice. A major polynya in the Weddell Sea in 1974, 1975, and 1976 accounts for much of the interannual difference in total ice extent. It is interesting to note that Kukla (1978) found a general decrease in arctic ice from 1973 to 1975, following an increase from 1967 to 1973.

In 1973, the maximum antarctic ice extent occurred in late September or early October, but it was 2 to 4 weeks earlier in 1974 and 1975. The largest decrease in the area of highly concentrated ice occurred with a dramatic 1-month decrease of 6 million square kilometers from October to November of 1973 and with a slower 2-month decrease of slightly less total magnitude in October–December of 1974 and September–November of 1975. The largest decrease in the area of highly concentrated ice precedes by about a month the largest decrease in total ice area noted above. This reduction of highly concentrated ice could be attributable to an increase in ice divergence or more likely to a decrease in new ice production in newly formed leads.

With data assembled for only a 3-year time period, it is not possible to draw firm conclusions on the nature of interannual variability of antarctic ice. There is some interannual variation in the phase and amplitude of maxima and minima in the curves and also a slight trend toward reduced total ice extent from 1973 to 1975.

The southern ocean has been divided into five sectors—the Weddell Sea, Indian Ocean, Pacific Ocean, Ross Sea, and Bellingshausen-Amundsen Sea sectors—and similar analysis has been performed on each of these (Zwally et al., 1979). The individual sectors show much more variability than the sum. The tendency for an increase of ice in one sector to compensate for a decrease in another suggests a large-scale interaction among the sectors requiring further investigation. The different sectors show varying proportions of highly concentrated ice, indicating regionally different meteorological and oceanographic processes.

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A simple parameterization for salt flux to upper ocean owing to freezing and melting at the surface

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As ocean water freezes to ice, its salt content partly settles to the water underneath and partly becomes entrapped in pockets of brine within the ice. The amount of salt settling to the water below depends on the rate of freezing, the temperature, and the initial salinity of the upper ocean. Because the salt collected in brine pockets slowly diffuses downward as the ice ages, the salinity of an individual ice floe typically decreases with time, eventually exhibiting a gradient from very low salinity at the top of the floe to somewhat higher salinity at the bottom. This yields a salinity structure of sea ice that is both complicated and variable, as is evident from actual salinity profiles.

Current limitations in computer time and core space realistically prevent insertion of elaborate salinity profiles into large-scale numerical models. However, the importance to the ocean of the salt fluxes resulting from the formation and melting of sea ice suggests that an attempt should be made to parameterize these fluxes, even if the detailed salt structure of the ice cannot be included.

To simplify the complicated salinity distribution in sea ice consistent with the degree of simplification common in large-scale sea ice and ocean models, a uniform ice salinity S_I can be assumed. A reasonable value for S_I would be four parts per thousand, a number suggested by Weber (1977) as one appropriate for the bulk of sea ice. The assumption of constant S_I allows immediate calculation of the average salinity change in the upper layer of the ocean attributable exclusively to ice ablation and accretion. The accompanying figure presents the relevant variables,

where Δz = depth of ocean's upper mixed layer,
S_t = salinity of mixed layer at timestep t,
h_t = ice thickness at timestep t,
ρ_I = density of sea ice,
ρ_w = density of sea water, and
C_t = fractional ice coverage at timestep t.

Conservation of salt from one timestep to the next timestep requires:

$$S_t\Delta z(1-C_t) + S_t\left(\Delta z - \frac{\rho_I}{\rho_w}h_t\right)C_t + S_I\frac{\rho_I}{\rho_w}h_tC_t$$
$$= S_{t+1}\Delta z(1-C_{t+1}) + S_{t+1}\left(\Delta z - \frac{\rho_I}{\rho_w}h_{t+1}\right)C_{t+1}$$
$$+ S_I\frac{\rho_I}{\rho_w}h_{t+1}C_{t+1} \quad (1)$$

Equation (1) is readily solved for S_{t+1} as follows:

$$S_{t+1} = \frac{S_t\Delta z - S_t\frac{\rho_I}{\rho_w}h_tC_t + S_I\frac{\rho_I}{\rho_w}h_tC_t - S_I\frac{\rho_I}{\rho_w}h_{t+1}C_{t+1}}{\Delta z - \frac{\rho_I}{\rho_w}h_{t+1}C_{t+1}}$$
$$= S_t + \frac{(S_t - S_I)\left(\frac{\rho_I}{\rho_w}\right)(h_{t+1}C_{t+1} - h_tC_t)}{\Delta z - \frac{\rho_I}{\rho_w}h_{t+1}C_{t+1}} \quad (2)$$

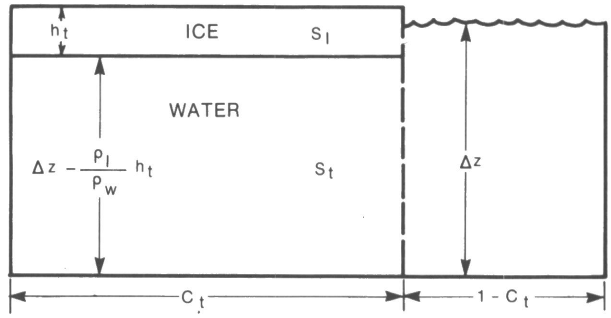
The resulting formulation—equation (2)—for S_{t+1} is easily inserted into the computer code for any large-scale model including both ice and water.

When such a model does not allow for leads within the ice pack, the ice concentration in any ice-covered grid square is 100 percent. Accordingly, equation (2) reduces to:

$$S_{t+1} = S_t + \frac{(S_t - S_I)\left(\frac{\rho_I}{\rho_w}\right)(h_{t+1} - h_t)}{\Delta z - \frac{\rho_I}{\rho_w}h_{t+1}} \quad (3)$$

Equivalently, this can be written in differential notation as:

$$\Delta S = \frac{(S - S_I)\left(\frac{\rho_I}{\rho_w}\right)(\Delta h)}{\Delta z - \frac{\rho_I}{\rho_w}(h + \Delta h)} \quad (4)$$



Schematic of variables involved in calculating salinity change in upper ocean owing to sea ice formation and melt (variables identified in accompanying text).

where it is understood that S and h in the right-hand expression denote the respective quantities at the start of the timestep. Typically, the ratio ρ_I/ρ_w is approximately 0.88.

Plans are under way to include this salt flux formulation, equation (2), upon coupling a large-scale sea ice model of Parkinson and Washington (1979) with an ocean model of Schopf (1977). This coupling is scheduled for 1980.

Including a calculation for the ice-to-water salt flux will provide an opportunity to examine numerically the importance of this flux to such processes as the formation of antarctic bottom water. As is well known, the salt influx to the upper ocean during ice formation increases the density of this upper water, thereby encouraging convection. As ice melts, the upper ocean receives an influx of cold, low-salinity melt water; upon diffusing into the ocean mixed layer, this melt water tends to reduce the average salinity of the layer. Although the assumption of uniform ice salinity is a severe constraint, it will nevertheless allow modeling, in an approximate fashion, of these important consequences of ice formation and melt.

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