CONVECTIVE MIXING AND SEA ICE FORMATION IN THE WEDDELL-ENDERBY BASIN IN 1974 AND 1975

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Abstract: The formation of sea ice in the Weddell-Enderby Basin is examined using a one-dimensional convective mixing model. Oceanographic data obtained in late summer of 1974 and 1975 aboard the icebreaker FUJI are used as the initial conditions in the model. The results by the present model indicate that no sea ice forms in the Weddell Polynya region in 1974 and 1975. The major oceanographic criterion for sea ice formation in the winter is salinity of water in a mixed layer in the preceding summer; high salinity gives no sea-ice formation, which is due to an upward heat flux from deep water by deep convection.

1. Introduction

The Electrically Scanning Microwave Radiometer (ESMR) on board the Nimbus-5 satellite has been used to observe the sea-ice condition in the Southern Ocean since December 1972. From 1974 to 1976 a large open water or a polynya with an area of about $2\text{–}3 \times 10^5$ km^2 has persistently existed in the pack ice in the Weddell-Enderby Basin. This polynya is called the Weddell Polynya (ZWALLY and GLOERSEN, 1977; CARSEY, 1980).

The formation mechanism of the Weddell Polynya has been presented by several investigators. MARTINSON *et al.* (1981) suggest that the major oceanographic factors for forming the Weddell Polynya are the thinning of mixed layer with upwelling and the salt exclusion during the sea ice formation there; the salt exclusion causes deep convection and the upward transport of warm deep water results in the melting of the formed sea ice. According to PARKINSON (1983), a relatively small heat exchange due to the spatial heterogeneity of wind field forms the Weddell Polynya.

GORDON (1978) finds out the presence of a homogeneous, long water column in a deep layer in February 1977 in the Weddell Polynya region; the long water column is called "Weddell chimney". KILLWORTH (1979) suggests the formation of the Weddell chimney as the result of wintertime surface cooling. In February 1975 a similar water column occurred in the region where the Weddell Polynya had appeared in the winter of 1974 (ONO and MOTOI, 1983).

A comparison between the summer oceanographic data of 1973 (pre-Weddell Polynya year) and those of 1977 (post-Weddell Polynya year) in the Weddell-Enderby Basin shows that the cooling and freshening of deep water occur in the Weddell Polynya region (GORDON, 1982).

Japanese Antarctic Research Expeditions have carried out oceanographic observations aboard the icebreaker FUJI from late February to early March in 1974 and 1975. We will examine the response of the oceanic mixed layer to surface cooling and derive the criterion for sea-ice formation, introducing a one-dimensional Kraus-Turner type model (KRAUS and TURNER, 1967) and using the above-mentioned oceanographic data as initial conditions.

2. Model

A simplified Kraus-Turner model is used to examine the variations of mixed layer during the surface cooling. In the model the conservations of heat, salt and mechanical energy in the mixed layer are considered. The process of penetrative, convective mixing through an interface between the mixed layer and the underlying layer is taken into account in the model, but the mixing through stirring by the wind or the pack-ice drift, heating by penetrated solar radiation and horizontal advection of sea water is neglected.

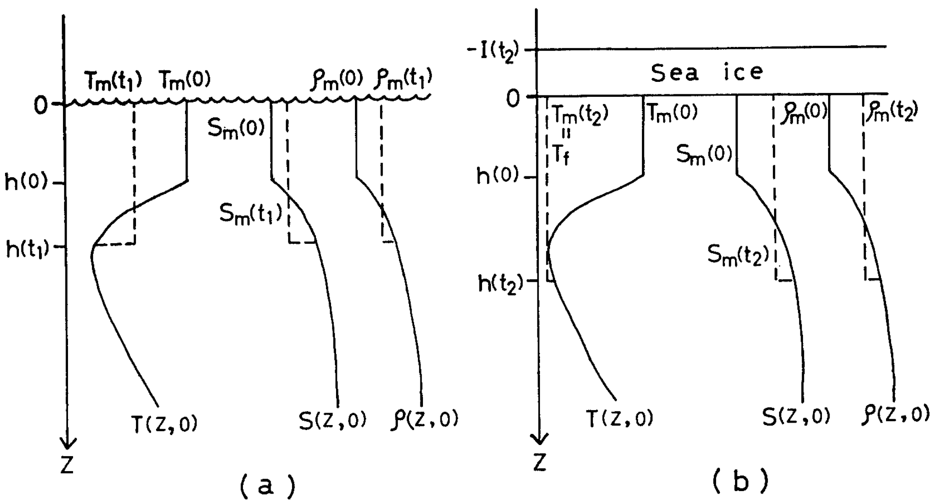

Fig. 1. Observed profiles (solid lines) of temperature $T(z,0)$, salinity $S(z,0)$ and density $\rho(z,0)$, which are used as the initial conditions in the present model. Vertical broken lines indicate the calculated profiles (a) before freezing and (b) after freezing.

Figure 1 shows the variations of the profiles of temperature $T(z,t)$, salinity $S(z,t)$ and density $\rho(z,t)$ due to surface cooling and sea ice formation. The density can be derived from a data set of temperature and salinity. The temperature $T_m(t)$ and salinity $S_m(t)$ of mixed layer with the thickness of $h(t)$ are vertically uniform. The initial values, $T_m(0)$, $S_m(0)$ and $h(0)$ are taken from observed profiles $T(z,0)$ and $S(z,0)$. Variations of mixed layer thickness $h(t)$, temperature $T_m(t)$ and salinity $S_m(t)$ due to surface cooling are calculated, but the temperature and salinity profiles under the mixed layer are kept as the same of initial profiles $T(z,0)$ and $S(z,0)$ during the calculation.

2.1. *Equations before freezing*

In the present model, the change of mixed layer temperature T_m is considered to be caused by heat fluxes through the surface cooling and entrainment. The conservation of heat in the mixed layer is expressed as

$$\rho_w c_w h(t)\frac{dT_m(t)}{dt}=F_h+\rho_w c_w\frac{dh(t)}{dt}(T_b-T_m(t))\,, \tag{1}$$

where ρ_w is the density of sea water (1.027 $g \cdot cm^{-3}$), c_w the specific heat of sea water (0.94 $cal \cdot g^{-1} deg^{-1}$) and F_h the upward heat flux from the ocean to the atmosphere due to surface cooling. F_h varies with time and space; according to GORDON's estimations (1981) for 60–70°S, F_h is $-39\ w \cdot m^{-2}$ in March, $-138\ w \cdot m^{-2}$ in April, $-148\ w \cdot m^{-2}$ in May, $-178\ w \cdot m^{-2}$ in June and $-206\ w \cdot m^{-2}$ in July. For simplification, we use a constant value of $-100\ w \cdot m^{-2}$ which may be regarded as an average value in the ocean of study during the surface cooling period.

Meanwhile, the second term in the right side of eq. (1) expresses the upward heat flux through the entrainment of water beneath the mixed layer. The temperature of the entrained water is T_b. In the present model the observed water temperatures at a depth of 1 m beneath the mixed layer are used as T_b.

Assuming that the salt fluxes by evaporation and precipitation are equal and opposite, the conservation of salt in the mixed layer is given by the equation

$$h(t)\frac{dS_m(t)}{dt}=\frac{dh(t)}{dt}(S_b-S_m(t))\,. \tag{2}$$

The right side of eq. (2) indicates the upward salt flux through the water entrainment. The water salinity S_b corresponds to T_b in depth. Equation (2) means that the change of $S_m(t)$ is driven from the salt flux through the entrainment.

The conservation of mechanical energy is expressed by

$$\frac{dh(t)}{dt}\{\alpha(T_b-T_m(t))+\beta(S_b-S_m(t))\}=\frac{\alpha F_h}{\rho_w c_w}\,, \tag{3}$$

where α and β are the expansion coefficients of sea water for temperature and salinity, respectively. Although they are functions of temperature and salinity, constant values ($\alpha=5\times10^{-5}\ deg^{-1}$ and $\beta=8\times10^{-4}$ ‰$^{-1}$) are taken for the sake of simplification. The right side of eq. (3) is the rate of potential energy gain due to surface cooling and the left side implies the work per unit time needed to entrain a dense water into the mixed layer and to mix it. Therefore, eq. (3) expresses that the potential energy gain due to surface cooling is used as the work for entraining the dense water beneath the mixed layer and for mixing the entrained water through the mixed layer.

The solutions of $h(t)$, $T_m(t)$ and $S_m(t)$ which satisfy the initial conditions and eqs. (1), (2) and (3) are derived numerically using the fourth-order Runge-Kutta method by 1-hour time step.

The freezing temperature T_f of mixed layer is calculated in each time step to judge whether the sea-ice forms or not. In general the freezing temperature of water is expressed as a function of its salinity. DOHERTY and KESTER (1974) give the formula of the freezing temperature,

$$T_f=-0.0137-0.05199\times S-7.225\times10^{-5}\times S^2\,. \tag{4}$$

Substituting $S_m(t)$ into S in eq. (4) in each time step, the freezing temperature T_f is calculated. If $T_m(t)$ is equal to or below T_f, the sea ice will form. The calculations in one-hour time step are continued until $T_m(t)$ reaches T_f.

2.2. Equations after freezing

When the temperature $T_m(t)$ of water in the mixed layer reaches the freezing temperature T_f, the sea ice will form. During the sea-ice formation, $T_m(t)$ is equal to T_f.

Ignoring the effect of snow cover and heat content of sea ice and taking the bottom of sea ice as the origin of the co-ordinate, the heat conservation gives

$$\rho_i L_i \frac{\mathrm{d}I(t)}{\mathrm{d}t} = -F_h + \frac{\mathrm{d}h(t)}{\mathrm{d}t}(T_f - T_b)\rho_w c_w , \tag{5}$$

where $I(t)$ is the thickness of sea ice, L_i the latent heat of sea ice (70 cal·g^{-1}) and ρ_i the density of sea ice (0.93 g·cm^{-3}). The left hand of the eq. (5) is the heat per unit time and per unit area needed to form the sea ice. The first term in the right hand of eq. (5) is the heat flux due to surface cooling and the second term is the heat flux through the entrainment.

During the sea-ice formation, a significant amount of salt is excluded from sea ice. Therefore, the salt exclusion indicates the appreciable change of salinity $S_m(t)$ in the mixed layer. The salt flux from growing sea ice depends upon both the growth rate and the thickness of sea ice (WAKATSUCHI and ONO, 1983). However, the effects of growth rate and thickening on the salt flux are not considered for the sake of simplification. The salt flux from growing sea ice is approximately estimated from a salinity difference between the original sea water and the formed sea ice.

The change of $S_m(t)$ is also induced by the salt flux through the entrainment. Therefore, the salt conservation is given by

$$h(t)\frac{\mathrm{d}S_m(t)}{\mathrm{d}t} = \left\{S_m(t) - S_i\left(\frac{\rho_i}{\rho_w}\right)\right\}\frac{\mathrm{d}I(t)}{\mathrm{d}t} + \frac{\mathrm{d}h(t)}{\mathrm{d}t}(S_b - S_m(t)) , \tag{6}$$

where S_i is the salinity of sea ice, taken as 5‰.

The conservation of mechanical energy is expressed as

$$\frac{\mathrm{d}h(t)}{\mathrm{d}t}\left\{\alpha(T_b - T_f) + \beta(S_b - S_m(t))\right\} = \beta\left\{S_m(t) - S_i\left(\frac{\rho_i}{\rho_w}\right)\right\}\frac{\mathrm{d}I(t)}{\mathrm{d}t} . \tag{7}$$

After freezing, the rate of potential energy gain is induced by the salt exclusion from growing sea ice, so that the right hand of eq. (3) is replaced by the rate of potential energy gain due to salt flux from growing sea ice.

The calculations of $h(t)$, $S_m(t)$ and $I(t)$ after freezing are also made, using the fourth-order Runge-Kutta method, by a 1-hour time step.

3. Calculated Results and Comparisons with Sea Ice Observations by Nimbus-5 Satellite

Figure 2 shows the locations of oceanographic stations occupied by the icebreaker

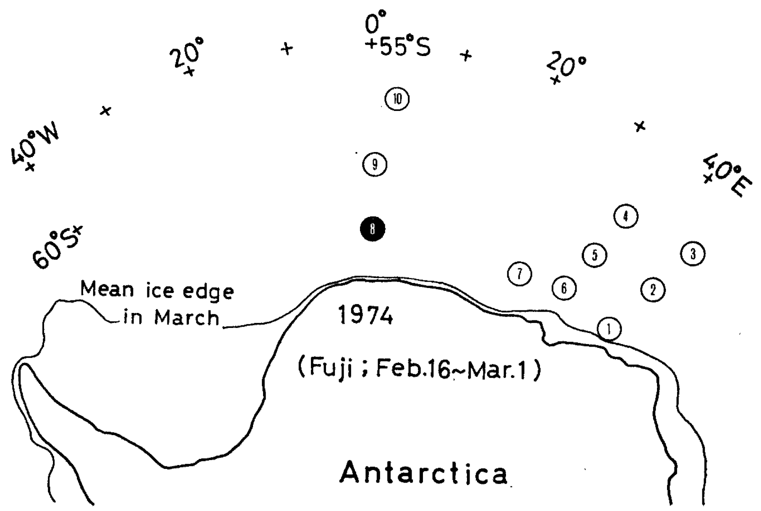

Fig. 2. Locations of oceanographic stations occupied by FUJI *in 1974. Oceanographic data obtained at the stations are used as the initial conditions in calculations.*

FUJI from 16 February to 1 March in 1974. The data obtained at these stations were used as the initial conditions in the calculations. The mean ice edge in March 1974 shown in Fig. 2 is taken from a chart given by ZWALLY *et al.* (1981).

The results of model calculations are shown in Fig. 3. At Stn. 8 the mixed layer temperature T_m initially decreases, in the same way as at other stations, and then it has a minimum temperature of about -1.4°C which is higher than the freezing temperature of about -1.9°C. Therefore, no sea ice forms at Stn. 8 whereas the sea ice forms at other stations. The mixed layer thickness h at Stn. 8 is thicker than those

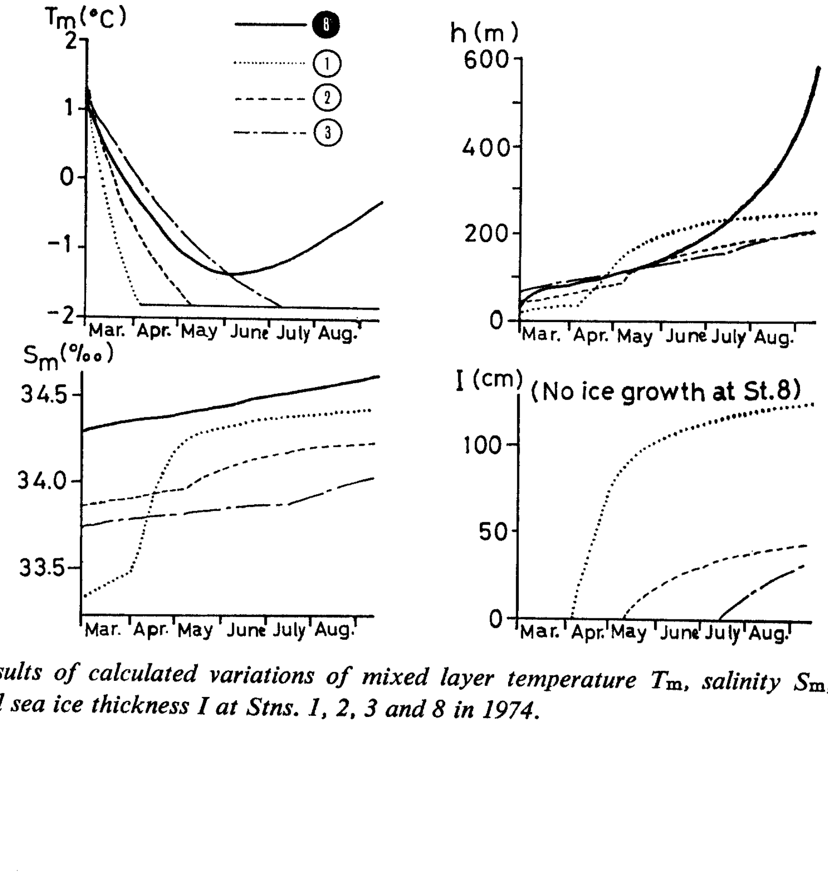

Fig. 3. Results of calculated variations of mixed layer temperature T_m, salinity S_m, thickness h and sea ice thickness I at Stns. 1, 2, 3 and 8 in 1974.

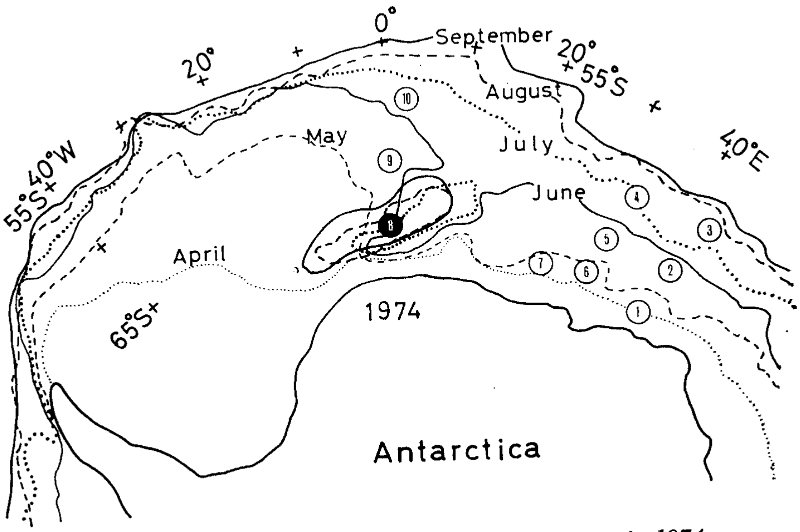

Fig. 4. Observed monthly mean sea-ice extent in 1974.

at other stations in August and exceeds 300 m, which indicates the occurrence of deep convection. The mixed layer salinity S_m at Stn. 8 is higher than those at other stations. The month of onset of sea-ice formation varies with stations as shown in Fig. 3.

Figure 4 shows the variations of monthly mean sea-ice extent from April to September in 1974 observed by the Nimbus-5 satellite (ZWALLY *et al.*, 1981). The Weddell Polynya in 1974 just occurred around Stn. 8 where no sea-ice formation is estimated by the present model calculation. The estimated month of onset of sea ice formation at other stations agrees with satellite observations.

Similar figures are also given for 1975: Figure 5 shows the locations of oceanographic stations occupied from 24 February to 1 March and the monthly mean sea-ice edge in March; Figure 6 shows the calculated results of T_m, S_m, h and I at the stations. At Stn. 13 the mixed layer temperature T_m has a minimum. The minimum

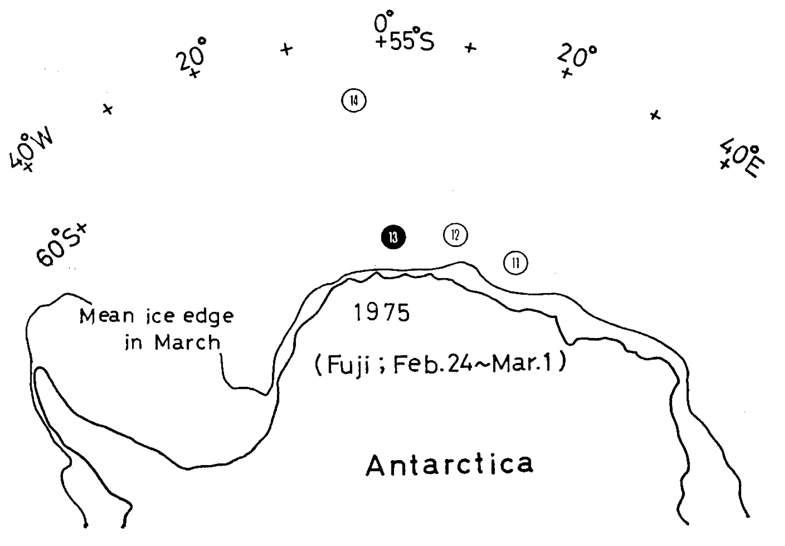

Fig. 5. Locations of oceanographic stations occupied by FUJI in 1975.

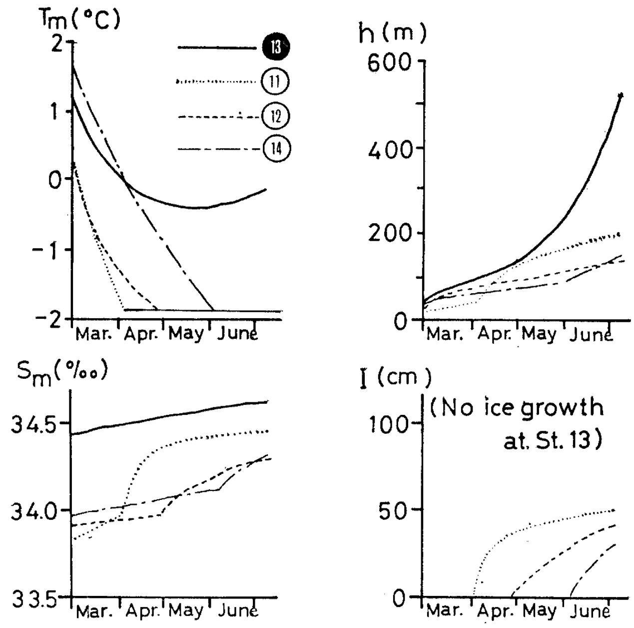

Fig. 6. Results of calculated variations of mixed layer temperature T_m, salinity S_m, thickness h and sea ice thickness I at Stns. 11, 12, 13 and 14 in 1975.

temperature is higher than the freezing temperature, so no sea ice forms at Stn. 13. At other stations, 11, 12 and 14, the sea ice forms. The mixed layer thickness h at Stn. 13 is thicker than those at other stations and exceeds 200 m. This result indicates that the deep convection occurs at Stn. 13. The mixed layer salinity S_m at Stn. 13 is higher than those at other stations.

Figure 7 shows the observed monthly mean sea-ice extent of April, May and September in 1975 (ZWALLY *et al.*, 1981), where observations are lacking for June, July and August. The estimated month of onset of sea ice formation at Stns. 11 and 12 agrees with the observation. The Weddell Polynya in 1975 occurred near Stn. 13 where no sea-ice formation is estimated by calculation.

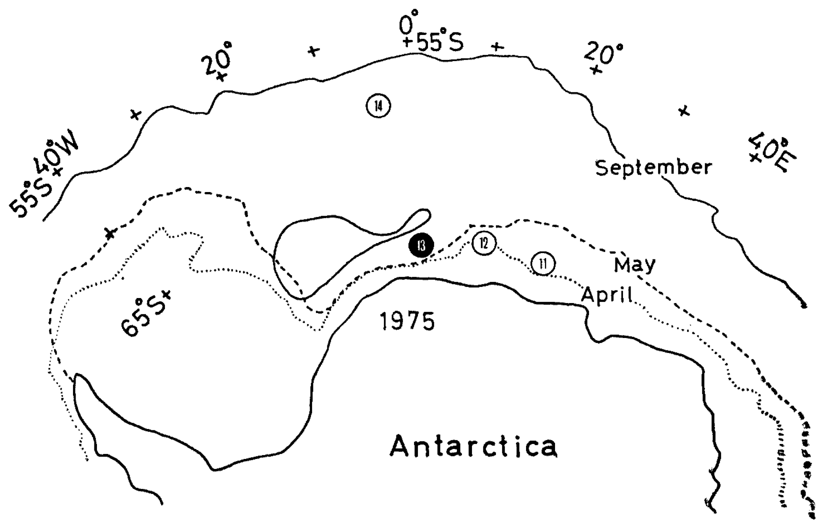

Fig. 7. Observed monthly mean sea-ice extent in 1975.

4. Modification of Deep Water

The results of model calculation show the occurrence of deep convection due to surface cooling only and no sea-ice formation at Stns. 8 and 13. The sea-ice observations by Nimbus-5 satellite indicate that the Weddell Polynya occurred just around Stn. 8 in 1974 and near Stn. 13 in 1975. The deep convection will cause the modification of deep water.

GORDON (1982) reports the modification of deep water in the Weddell Polynya region by comparison of the summer oceanographic data of 1977 (post-Weddell Polynya year) with those of 1973 (pre-Weddell Polynya year). In the present study the evidence of modification of deep water from 1974 to 1975, just during the Weddell Polynya years, is recognized by the comparison of data at two adjacent stations 8 and 13. Figure 8 shows the vertical profiles of temperature, salinity and oxygen at Stn. 8 on 27 February 1974 and Stn. 13 on 26 February 1975. The properties of water column between 200 and 2400 m varied remarkably from 1974 to 1975; the water column became cold, fresh and rich in oxygen.

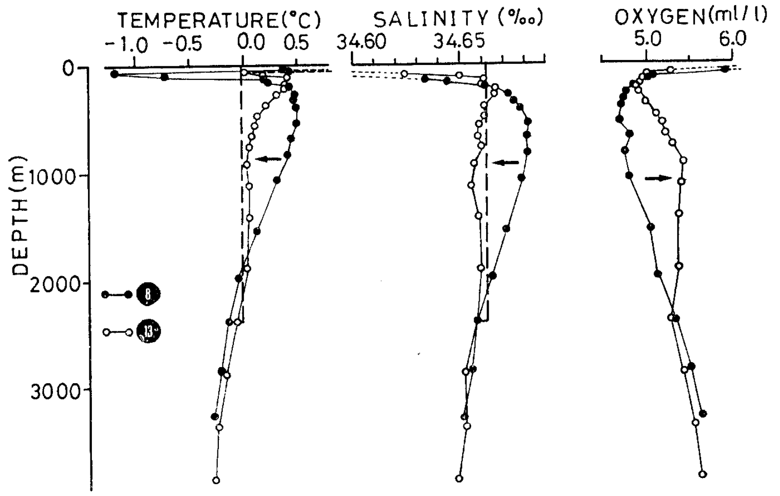

Fig. 8. Observed vertical profiles of temperature, salinity and oxygen at Stns. 8 and 13. Broken lines indicate the calculated temperature and salinity of the mixed layer with thickness 2400 m at Stn. 8.

Figure 9 shows the estimated variations of mixed layer thickness, temperature and salinity at Stn. 8 by means of the present model. No sea ice forms at this station as already mentioned and the mixed layer by deep convection extends to a depth more than 2000 m in October. Since the modification of deep water is recognized between 200 and 2400 m by observations, the calculated temperature and salinity of the mixed layer having the thickness 2400 m are compared with the observed ones at Fig. 8. The calculated temperature and salinity are -0.01°C and 34.662‰, respectively, for the mixed layer of 2400 m thick. The cooling and freshening of deep water are well derived by the model. The estimated quantities at St. 8 agree well with the observed data at Stn. 13 between 1000 and 2400 m. This agreement suggests that the modifica-

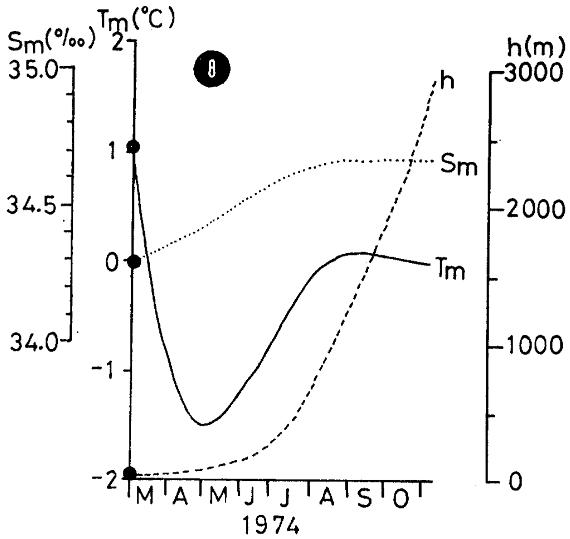

Fig. 9. Calculated variations of mixed layer temperature T_m, salinity S_m and thickness h at Stn. 8 in 1974.

tion of deep water is caused by the deep convective mixing. The profile of oxygen at Stn. 13 also suggests the occurrence of deep convective mixing since the oxygen at Stn. 13 between 1000 and 2400 m is higher than that at Stn. 8 and also uniform.

5. Concluding Remarks

The calculated results by the convective mixing model indicate that deep convection occurs by surface cooling only and no sea ice forms at Stns. 8 and 13 where the Weddell Polynya was observed by Nimbus-5 satellite, whereas sea ice forms at other stations.

In order to derive the criterion for sea-ice formation the dependence of sea-ice formation upon the observed initial thickness h, temperature T_m and salinity S_m of the mixed layer was examined. Figure 10 shows the results and indicates that sea-ice

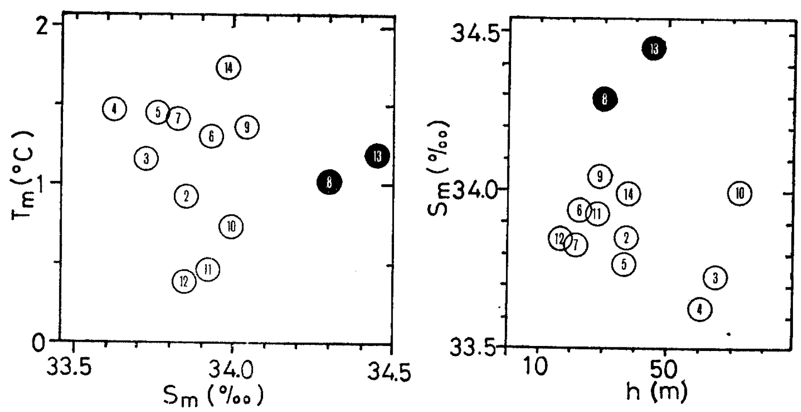

Fig. 10. Relations between T_m and S_m and between S_m and h. Symbols correspond to station symbols used in Figs. 4 and 7. No sea ice is estimated to form at Stns. 8 and 13. Sea ice is estimated to form at other stations.

formation in winter depends upon the summer mixed layer salinity; the oceanographic criterion for sea-ice formation in winter is the salinity of water in the mixed layer in the preceding summer. The high salinity of water in the summer mixed layer, for example 34.29‰ at Stn. 8 and 34.45‰ at Stn. 13, inhibits sea-ice formation in winter.

When the mixed layer salinity is high in the summer, the deep convection is caused only by winter surface cooling, as shown in Figs. 3 and 6. The deep convection modifies a deep water to be colder, fresher and richer in oxygen as shown in Fig. 8. In the process of modification, a significant amount of heat and salt is transferred upward from the deep water. The resultant warming of water in the surface layer obstructs the formation of sea ice even in the surface cooling period. The resultant gain of salt in the surface layer further accelerates deep convection.

MARTINSON *et al.* (1981) consider the formation mechanism of the Weddell Polynya as follows: The salt exclusion during the sea ice formation causes deep convection in the area with shallow pycnocline. The deep convection brings up enough heat from the deep water to melt the formed sea ice.

However, in the present study, it is concluded that the Weddell Polynya in 1974 and 1975 formed without sea-ice formation. Since the mixed layer salinity is high in the summer the deep convection is caused only by surface cooling. The deep convection modifies a deep water to be colder, fresher and richer in oxygen. In the process of modification, heat and salt are transferred toward sea surface. The heat obstructs sea-ice formation and the salt accelerates deep convection as far as the surface cooling continues.

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