Polar Water Column Stability

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ABSTRACT

An expression is derived for the surface salt input needed to induce complete convective overturning of a polar water column consisting of 1) a layer of sea ice, 2) a freezing temperature mixed layer, 3) a pycnocline with linearly varying temperature and salinity, and 4) deep water with fixed temperature and salinity. This quantity has been termed the *bulk stability* by Martinson. The bulk stability is found to consist of three components. The first two make up Martinson's *salt deficit* and are the salt input needed to increase the density of the mixed layer and the pycnocline layer to that of the deep water (the *mixed layer stability* and *pycnocline layer stability*, respectively). The third component is Martinson's *thermal barrier*: the potential for pycnocline heat to melt ice, reducing the surface salinity. It is found that when the pycnocline density gradient due to temperature offsets more than one half of that due to salinity, the pycnocline layer stability is negative. Consequently, it is possible for a stably stratified water column to have zero or negative bulk stability.

1. Introduction

Polar sea ice plays a number of important roles in climate: it insulates the atmosphere from the ocean; it increases the surface albedo; and, when it moves, it transports heat and freshwater. The heat content of the deep ocean below the sea ice is nearly always sufficient to melt it completely. The static stability afforded by a near-surface halocline protects the sea ice from this heat. When the halocline breaks down, the sea ice can be melted and a large quantity of heat can be vented from the deep ocean to the atmosphere. The Weddell polynya of the mid-1970s was apparently such an occurrence (Gordon 1982). Winter cruises to the region of the polynya have shown that the halocline there is quite weak (Gordon and Huber 1990). Martinson (1990) reconciled this observation with the infrequent occurrence of ocean-heat-driven (sensible heat) polynyas. He showed that the heat content of the halocline represents a barrier to halocline breakdown (in addition to the static stability) because it can melt ice at the surface, thereby strengthening the halocline. Martinson and Iannuzzi (1998) calculate this *thermal barrier* along with the total or *bulk stability* numerically from vertical profiles taken in the Weddell Sea. Their results show that the thermal barrier frequently represents 80% of the bulk stability.

The purpose of this note is to augment Martinson's heuristic diagrams of the bulk stability components and Martinson and Iannuzzi's numerical calculations of the bulk stability from observed profiles with an analytical expression for the bulk stability having a simple but exact diagramatic representation. In the next section, an expression is derived for the bulk stability of the same idealized polar water column studied by Martinson (1990). This analysis shows that the bulk stability minus the thermal barrier (Martinson's *salt deficit*) can be thought of as consisting of two components: 1) the *mixed layer stability* and 2) the *pycnocline layer stability*. These are the salt inputs needed to increase the density of the mixed layer and the pycnocline layer (respectively) to that of the deep water assuming freezing temperature. The pycnocline layer stability can be negative, so, in section 3, we determine the circumstances under which the bulk stability can be brought to zero in a stably stratified water column. Section 4 summarizes the conclusions.

2. The bulk stability

The bulk stability is defined as the surface salt input required to break down the stratification and induce convective mixing between the surface and deep ocean. Martinson and Iannuzzi calculate this quantity for observed temperature–salinity profiles placed on high-resolution grids by adding salt to the surface mixed layer until it becomes neutrally stable with respect to the grid point just below. The properties of this cell are then homogenized with the mixed layer. The temperature of the new mixed layer is reset to freezing, with heat extracted being converted to ice melt, which is then ap-

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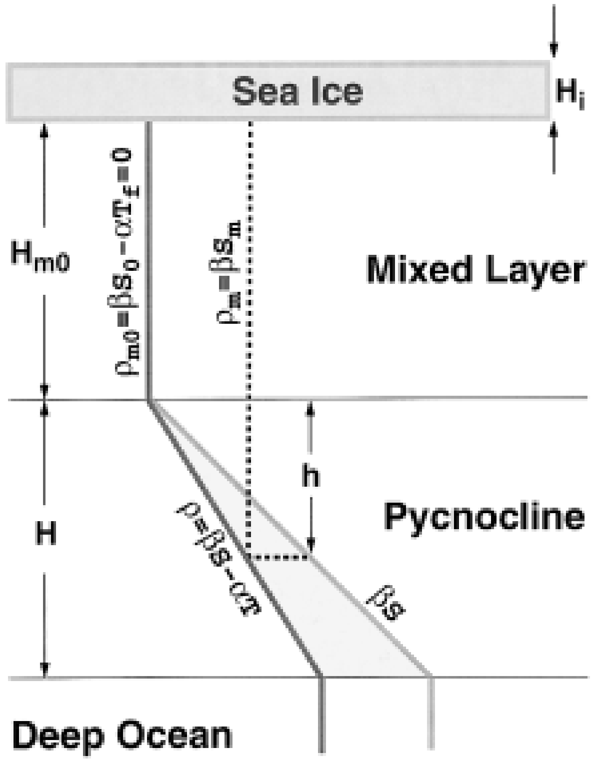

FIG. 1. Initial profiles of mixed layer, pycnocline, and deep ocean densities. The salinity contribution to density is also plotted (light line). The integrated surface salt flux needed to eliminate the stratification (i.e., to increase the mixed layer depth from H_{m0} to $H_{m0} + H$) is the bulk stability.

plied as a mixed layer salinity reduction. This process is repeated until convective deepening can occur by cooling alone. The total salt added to this point is the bulk stability (D. Martinson 1998, personal communication).

Here, the bulk stability B will be determined analytically for the water column depicted in Fig. 1 by integrating an equation for mixed layer salt conservation between $h = 0$ and $h = H$, where h is the distance below the base of the initial mixed layer and H is the initial pycnocline thickness. Conservation of mixed layer salt is written

$$\int d[S_m(h + H_{m0})] = \int S(h)\, dh - \int E\frac{c_w\rho_w\sigma}{L_i\rho_i}(T(h) - T_f)\, dh + B, \tag{1}$$

where ρ_w and ρ_i are the densities of water and ice (respectively), c_w is the heat capacity of water, L_i is the latent heat of freezing, and σ is the salinity difference between sea water and sea ice; E is a melting efficiency (between 0 and 1), which might depend upon the ice coverage, for example. The left side of (1) represents the change in mixed layer salt content. The first term on the right is the entrainment salt flux, and the second term is the salt flux due to ice melted by the entrained heat.

To determine S_m, S, and T in (1) we assume the following:

1) The equation of state is linear
$$\rho = \beta S - \alpha T. \tag{2}$$
2) The temperature and salinity scales are shifted (for notational convenience) so that
$$T_f = S_{m0} = 0, \tag{3}$$
where S_{m0} is the initial mixed layer salinity.
3) The profiles of temperature and salinity in the pycnocline below the mixed layer are linear (i.e., ∇T and ∇S are constant) so that the pycnocline temperature, salinity, and density are
$$S(h) = h\nabla S \tag{4}$$
$$T(h) = h\nabla T \tag{5}$$
$$\rho(h) = h(\beta\nabla S - \alpha\nabla T) = h\beta\nabla S(1 - R), \tag{6}$$
where
$$R = \frac{\alpha\nabla T}{\beta\nabla S}. \tag{7}$$

From (2) and (3) the mixed layer density can be written

$$\rho_m = \beta S_m. \tag{8}$$

As we add salt to the mixed layer, it deepens until it is neutrally stable with respect to the top of the pycnocline. So we have the condition $\rho_m = \rho(h)$ implying that

$$S_m = (1 - R)\nabla S h. \tag{9}$$

Substituting (3), (4), (5), and (9) into (1), we obtain

$$\int d[(h + H_{m0})(1 - R)\nabla S h] = \int \nabla S h\, dh - \int EMR\nabla S h\, dh + B, \tag{10}$$

where

$$M = \frac{c_w\rho_w\sigma\beta}{L_i\rho_i\alpha} \tag{11}$$

in which M is the ratio of the buoyancy change obtained from a given heating by warming a parcel of seawater to that obtained by melting ice into it.

Finally, performing the integration of (10) from $h = 0$ to $h = H$ gives the bulk stability,

$$B = B_{\mathrm{ML}} + B_{\mathrm{PL}} + B_{\mathrm{TB}}, \tag{12}$$

where

$$B_{\mathrm{ML}} = \nabla S(1 - R)HH_{m0} \tag{13}$$

$$B_{\mathrm{PL}} = \nabla S[(1 - R)H]^2/2 - \nabla S[RH]^2/2 \tag{14}$$

$$B_{\mathrm{TB}} = \nabla SEMRH^2/2. \tag{15}$$

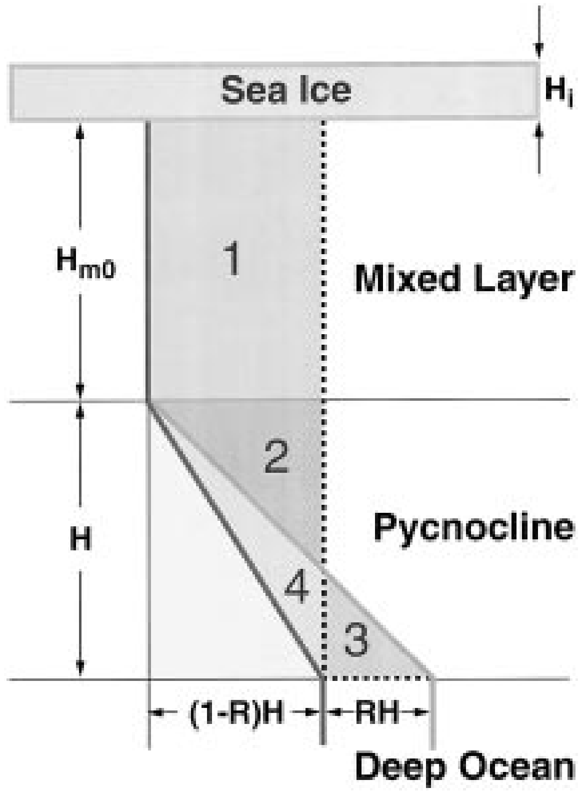

FIG. 2. Graphical representation of the bulk stability [see Eq. (16)]. The horizontal axis is density normalized by $\beta\nabla S$. The bulk stability is the sum of three components: 1) the mixed layer stability, which is equal to the area of region 1; 2) the pycnocline layer stability, which is equal to the area of region 2 minus that of region 3; and 3) the thermal barrier, which is equal to *EM* times the sum of areas 3 and 4.

Here B_{ML}, B_{PL}, and B_{TB} are the portions of the stability that are attributable to the initial mixed layer, pycnocline layer, and sea ice layer, respectively. The first two make up Martinson's salt deficit and the last is his thermal barrier term.

The components of the bulk stability are proportional to areas on the density/salinity-density plot (Fig. 1). Figure 2 is a reproduction of Fig. 1 where the horizontal (density) axis is density normalized by $\beta\boldsymbol{\nabla}S$. In Fig. 2, B_{ML} is equal to the area of region 1; B_{PL} is equal to the area of region 2 minus that of region 3; and B_{TB} is equal to *EM* times the sum of areas 3 and 4. Hence the bulk stability can be written

$$B = A_1 + A_2 - A_3 + EM(A_3 + A_4), \qquad (16)$$

where A_n refers to the area of region n in Fig. 2.

3. Conditions for neutral stability

From (14) and Fig. 2, it is evident that the pycnocline layer stability, unlike the other two components of the bulk stability, can be negative. This will occur when $R > ½$. Since the pycnocline is stably stratified for $R > 0$, the the bulk stability can be zero or negative in a stably stratified water column. In this section we explore this possiblity. Since M is large in cold water, the bulk stability depends critically upon the melting efficiency E.

We consider two simplified cases. In the first case, the sea ice layer is so thick that it cannot be completely melted by the pycnocline heat content and all of the entrained heat goes into melting sea ice. For this case $E = 1$, so

$$B = \frac{\boldsymbol{\nabla}SH^2}{2}[2(1 - R)H_{m0}/H + (1 - 2R + M)]. \qquad (17)$$

Since $0 \leq R < 1$, from this expression and from the corresponding graphical representation [Eq. (16)], it is evident that if $M > 1$ the bulk stability will be positive. Here M is most strongly dependent upon temperature through the thermal expansion coefficient, and M ranges from about 6 at 3°C to 12 at the seawater freezing temperature. Hence, the bulk stability will be positive as long as entrained heat goes into melting sea ice.

For the second case, the pycnocline heat content is greater than needed to melt the sea ice layer. For this case $E = 1$ until the sea ice is completely melted and $E = 0$ thereafter, so the thermal barrier is capped by the salt deficit of the sea ice layer

$$B_{TB} = \sigma H_i. \qquad (18)$$

The bulk stability then becomes

$$B = \sigma H_i + \boldsymbol{\nabla}S(1 - R)HH_{m0} + \boldsymbol{\nabla}S(1 - 2R)H^2/2. \qquad (19)$$

In this case there is the possibility that the bulk stability of the water column is zero even though the static stability is positive ($R < 1$ and $B = 0$). From (17) this will be true when $R < R_c$, where

$$R_c = \frac{1/2 + H_{m0}/H + \sigma H_i/(\boldsymbol{\nabla}SH^2)}{1 + H_{m0}/H}. \qquad (20)$$

As we increase the temperature gradient from zero, we will encounter zero bulk stability ($B = 0$) prior to encountering static instability ($R = 1$) when $R_c < 1$ or

$$H_i < \frac{\boldsymbol{\nabla}SH^2}{2\sigma}, \qquad (21)$$

that is, when the salt content of the pycnocline exceeds the salt deficit represented by the sea ice layer. Using some values characteristic of the Southern Ocean, that is, $H_i = 0.5$ m, $\boldsymbol{\nabla}SH = 0.5$ per mil, and $\sigma = 30$ per mil, we find a pycnocline thickness of only 60 m is needed for bulk instability to occur prior to gravitational instability.

Physically, the reason that the pycnocline layer stability (and hence the bulk stability) can be negative is the difference in boundary conditions that operate upon entrained heat and salt. While salt, which makes the mixed layer denser, is conserved in the mixed layer, we have assumed that heat entrainment is counteracted by the surface boundary condition. Therefore the bulk instability described in this note is a kind of mixed-boundary-condition convective instability.

An important assumption underlying the bulk stability concept is that sea ice melting and air–sea heat exchange are capable of pinning the mixed layer temperature at freezing. Since melting makes seawater lighter ($M > 1$) to the extent that melting is less than perfectly efficient, the bulk stability will underestimate the true stability. The opposite is true for air–sea heat exchange. Since the heat capacity of the air column is far less than that of the water column, substantial cold air advection will be necessary to maintain an ice-free mixed layer at freezing temperature as it entrains warm water at its base. In this case, the bulk stability expression derived in this note will be most accurate at small scales near sources of cold dry air—in leads near the Antarctic coast, for example.

4. Conclusions

The main conclusion of this note is contained in Fig. 2 and Eq. (16). These equivalently show that the bulk stability of an idealized polar water column contains three components: 1) a mixed layer stability, 2) a pycnocline stability, and 3) a thermal barrier. The bulk stability of profiles having various shapes as well as the relative importance of the three components can readily be visualized from diagrams like Fig. 2. The bulk stability is sometimes a more useful measure of the susceptibility of a water column to vertical mixing than the static stability because it (partially) accounts for the interaction of vertical mixing with surface boundary conditions.

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