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An investigation of the link between lead-induced thermohaline convection and arctic eddies

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Abstract.
A recent laboratory study indicates that a turbulent buoyant line plume discharging into a rotating stratified fluid provides a natural mechanism for generating a series of anticyclonic geostrophic vortices [*Bush and Woods* 1999]. Here we examine the implications of these experimental results in the context of the thermohaline convection which develops when saline water is released as leads freeze over in the polar oceans. Using the experimental results in conjunction with a simple numerical model of plume dynamics in a non-uniformly stratified environment, we develop a model which characterizes the geometry of the eddies which would develop owing to lead-induced convection. The model predicts that, in the absence of strong currents, lead-induced thermohaline convection may generate anticyclonic geostrophic vortices of characteristic radius 2-10 km at the base of the mixed layer; however, this mechanism cannot account for the arctic eddies observed at substantial depths beneath the mixed layer, cyclonic, or strongly ageostrophic eddies.

Introduction

The production of polar ice from seawater leads to the rejection of relatively saline water and so to thermohaline convection in the polar seas. The majority of such freezing events occurs along 'leads', linear fractures in the ice cover typically 10-100 km long [*Morison et al.* 1992]. There have been several recent field studies of lead-induced thermohaline convection [*The Leadex Group* 1993; *Morison and McPhee* 1997], and these have motivated the development of a number of numerical [*Smith and Morison* 1993; *Kantha* 1995; *Lavelle and Smith* 1996] and experimental [*Fernando and Ching* 1993; *Ching et al.* 1993] models of lead-induced thermohaline convection. Field studies of polar oceans have identified the prevalence of lenticular eddies with characteristic radii of ten kilometres between the mixed layer and 200 m depth [*Hunkins* 1974; *Manley and Hunkins* 1985]. In the Beaufort Sea, such eddies account for nearly 30% of the kinetic energy in the uppermost 200 m, and cover approximately 25% of the sea surface [*Hunkins* 1974]. While lead-induced convection has been tentatively proposed as a possible source of arctic eddies [*Manley and Hunkins* 1985], there has yet to be a model capable of predicting the size and depth of the eddies which would result from lead-induced convection. Here we develop such a model and so investigate the plausibility of lead-induced convection as a source of the observed arctic eddies.

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Model of vortex generation

A series of laboratory experiments examining the motion of turbulent line plumes in a stratified rotating environment have recently been reported by the authors [*Bush and Woods* 1999]. Buoyant dyed water was fed for a finite time t_s through a 40 cm long line source into a rotating stratified saltwater solution, and rose in the form of a turbulent buoyant line plume. As the plume rises and entrains ambient fluid, its buoyancy decreases until it reaches the neutral buoyancy height Z_n. The plume fluid then spreads out laterally in the form of a neutral cloud, across which a strong along-source shear develops as a result of the influence of the Coriolis force. After several rotation periods, the neutral cloud breaks into a chain of lenticular anticyclonic vortices (Figure 1). The ratio of the half-height, h, to radius, R, of the resulting individual vortices was found to be

$$\frac{h}{R} = (0.47 \pm 0.12)\frac{f}{N} \quad , \tag{1}$$

where f is twice the rotation rate and N is the Brunt-Vaisala frequency associated with the ambient stratification. Relation (1) indicates that the dynamics of the individual vortices is governed by a geostrophic balance between the radial pressure force and the Coriolis force associated with the anticyclonic swirling motion within the vortex. The size of the vortices may be derived from conservation of mass. The total volume per unit length supplied to the neutral cloud is given by

$$Rh \sim Q(Z_n)t_s \tag{2}$$

where t_s is the source discharge time, and the depen-

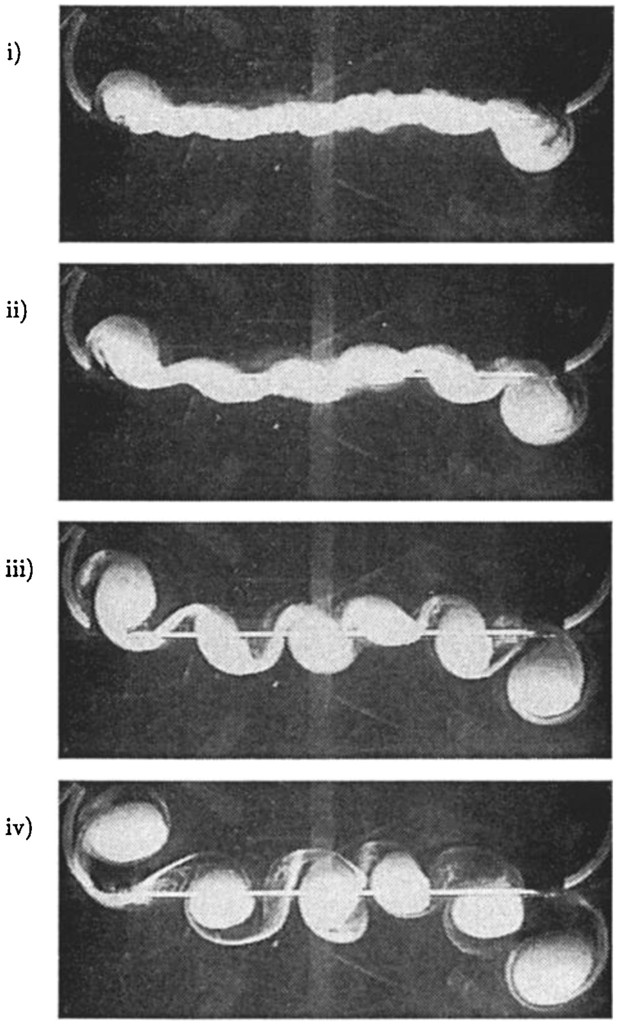

Figure 1. The development of coherent vortices from the discharge of a 44cm long line plume in a rotating stratified fluid as viewed from above. Here $N = 0.82$ s^{-1}, $B_0 = 3.1$ cm^3/s^3, $f = 1.5s^{-1}$ and $t_s = 15/f$. (i) $t = 11/f$: the plume fluid spreads at its level of neutral buoyancy. The Coriolis force generates a strong shear across the neutral cloud. (ii) $t = 17/f$: the neutral cloud develops an instability. (iii) $t = 23/f$: the neutral cloud breaks into six distinct anticyclonic vortices. (iv) $t = 37/f$: the persistence of six lenticular vortices of comparable size.

dence of the volume flux per unit length supplied to the neutral cloud on the source buoyancy flux per unit length B_0 is known from dimensional considerations to be $Q(Z_n) \sim B_0^{2/3}/N$. Substituting $Q(Z_n)$ and (1) into (2), we predict the eddy radius to be

$$R = \lambda B_0^{1/3} t_s^{1/2} / f^{1/2} \tag{3}$$

where λ is a dimensionless constant. Figure 2 shows the excellent agreement between the measured eddy radii and the scaling (3), and indicates that $\lambda = 0.77 \pm 0.15$.

Application to lead-induced convection

The instability of the neutral cloud generated by a buoyant line plume in a stratified ambient provides a natural mechanism for generating a series of anticyclonic lenticular vortices. We proceed by examining the dimensions and depth of the eddies which would be produced by lead-induced convection in the polar seas (Figure 3). As a first simplified model, we could examine the penetration of the line plume across the density interface between two uniform layers of fluid corresponding to that above and below the pycnocline (e.g. [*Ching et al.* 1993]). However, in the present work, we also account for the stratification of the water above and below the pycnocline which has an important role in arresting the plume. Specifically, we develop a model of a turbulent line plume descending through a non-uniformly stratified environment ([*Morton et al.* 1956], [*Caulfield and Woods* 1998]). When the lead is sufficiently narrow to be treated as a line plume, the cross-plume averaged mass flux $Q = \int_{-\infty}^{\infty} u dx$, momentum flux $M = \int_{-\infty}^{\infty} u^2 dx$ and buoyancy flux $B = \int_{-\infty}^{\infty} u g' dx$ per unit length along the lead vary with distance z below the source according to

$$\frac{dQ}{dz} = \epsilon \frac{M}{Q} \quad , \quad \frac{dM}{dz} = \frac{BQ}{M} \quad , \quad \frac{dB}{dz} = -N^2(z) Q \quad , \tag{4}$$

where the entrainment coefficient for a line plume is taken to be $\epsilon \sim 0.1$ [*List* 1979]. We adopt a simple model of the ambient stratification $N(z)$ in a polar ocean, based on winter measurements taken during the LeadEx expedition.[1] The profile in Figure 4a reveals a very strong density gradient at the pycnocline, 40-45m below the surface at the base of the well-mixed upper layer. Numerical solutions of equation (4) relate the properties of the plume at the neutral buoyancy height, Z_n, to the buoyancy flux, B_0, released by freezing at

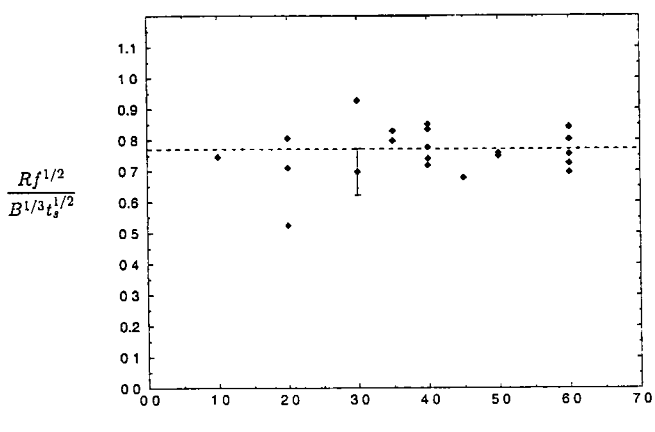

Figure 2. The average size of the emerging eddies. The data were gathered from a series of experiments in which 1 to 6 eddies were produced through varying the source strength, rotation rate and stratification of the ambient fluid. The dashed line represents $R = 0.77 B^{1/3} t_s^{1/2} / f^{1/2}$.

[1] Morrison, J.H., private communication via J.S. Wettlaufer, data collected at BASE302 during LeadEx expedition.

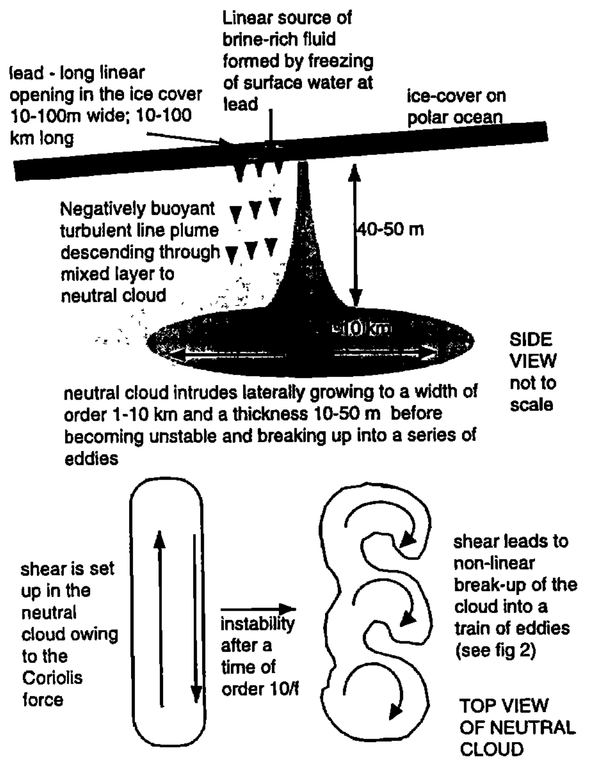

Figure 3. Schematic of lead-induced eddy formation beneath the ice cover.

the lead. In turn, the lead buoyancy flux, B_0, is related to the freezing rate, $\dot{z}$, of the surface ice according to

$$B_0 \;=\; g\beta\,(\,S_w - S_i\,)\,W\,\dot{z} \quad , \qquad (5)$$

where g is the gravitational acceleration, W is the lead width, β is the solutal expansion coefficient for seawater, and S_w and S_i represent the salinity of the ambient seawater and the ice, respectively [*Wettlaufer et al.* 1997].

Using (1), (2) and (5) together with the numerical solution of (4) to determine $Q(Z_n)$, we can estimate the radius and depth of the resulting vortices as a function of the rate of freezing at the lead. In figure 4, we present predictions from this model showing the eddy depth (that of the centroid) and radius as a function of the lead freezing rate. We note that the penetration depth is independent of discharge time, while the eddy radius increases as $t_s^{1/2}$. Owing to the large density gradient at the base of the mixed layer, there is a sizeable range of freezing rates (e.g. $7\times10^{-7} < \dot{z} < 3\times10^{-5}$m/s for a 100m wide lead) for which plumes are trapped near the pycnocline. Our calculations suggest that in order for a plume to penetrate the pycnocline, the freezing rate would need to be unrealistically high.

Discussion

In developing our simple model, we have neglected the influence of ambient currents. The influence of background flow is negligible provided the Lead number, $L = Q_0 D/(C_d U^3)$ (based on the buoyancy flux per unit area Q_0, the mixed layer depth D, the drag coefficient at the ice-water boundary C_d and the ice-drift velocity U), is sufficiently large; for most leads $L \gg 1$, so that the plume-induced convection dominates the influence of ambient currents [*Morison et al.* 1992] .

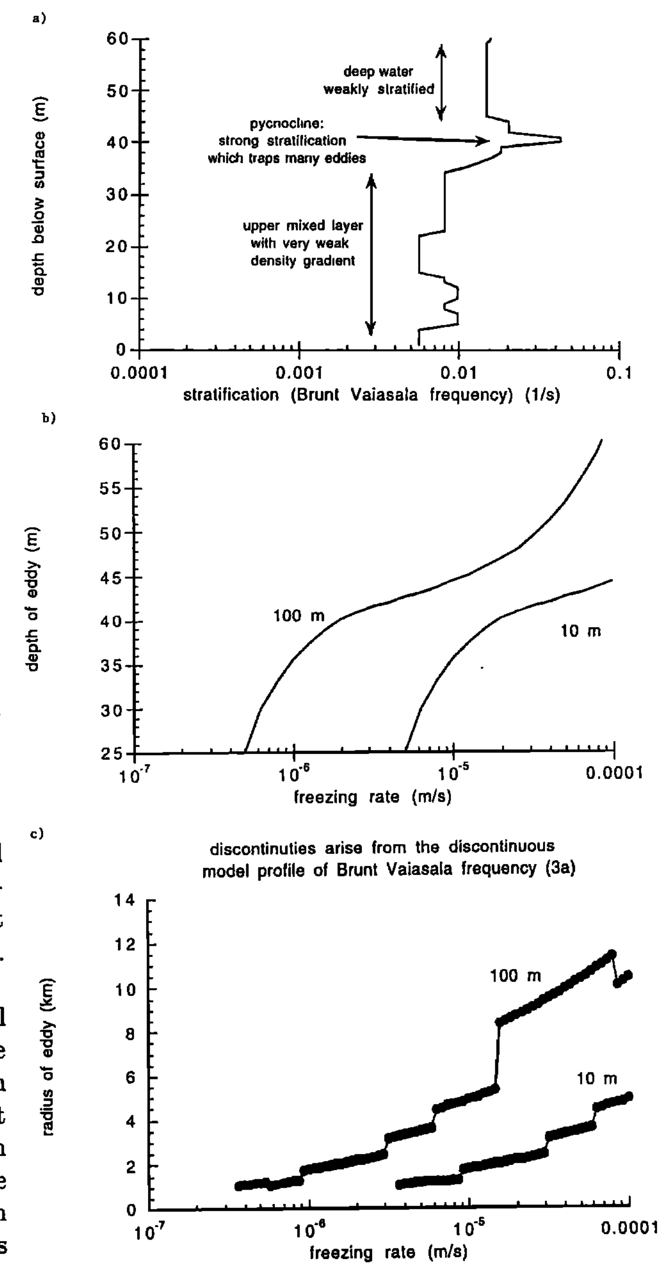

Figure 4. (a) Model of the approximate stratification in a polar ocean, based on data from the Leadex Experiments. The pycnocline, at a depth of about 40-45m which divides the upper mixed layer from the deep water is a region of very high stratification; (b,c) Calculation of the depth and radius of an eddy formed from a line plume as a function of the freezing rate at the lead. The source is assumed to persist for a time $100/f$. Owing to the large stratification at the pycnocline, plumes produced by a wide range of freezing rates are confined to depths of 40-45m. Only the most vigorous plumes produced by the highest freezing rates can penetrate the pycnocline. Curves are shown for 10 and 100m wide leads.

Nevertheless, we expect that situations will arise where vigorous background flows will disperse the plume fluid to such an extent as to preclude the generation of coherent vortices.

In order to model the generation of eddies by leads more accurately, it would be necessary to consider the influence of the finite width W of the lead source on the buoyancy flux at the intrusion depth H. In particular, a recent numerical study [*Smith and Morison* 1993] has suggested that for $W > H$, the convection may be characterized by the descent of a number of discrete plumes, in which case the volume flux impinging on the pycnocline is expected to be significantly different from that beneath a simple line plume. Finally, while our model assumes explicitly that the buoyancy flux is constant in time, it is straightforward to consider a source with buoyancy flux of the form $B_0 t^\alpha$. Doing so would allow one to make more sophisticated predictions for the properties of the coherent structures generated by leads, whose buoyancy flux necessarily decreases with time [*Wettlaufer et al.* 1997].

Our experiments and theoretical calculations suggest that lead-induced thermohaline convection provides a robust mechanism for generating anticyclonic geostrophic vortices at the base of the mixed layer. However, we conclude that this mechanism is unlikely to be responsible for the generation of the majority of the large, deep arctic eddies which have been observed on field expeditions. First, our model suggests that the plumes generated by refreezing leads will not typically be sufficiently vigorous to penetrate to great depths beneath the pycnocline, and so to account for the deepest observed eddies. Second, while the observed eddies were predominantly anticyclonic, two of seven were cyclonic [*Manley and Hunkins* 1985]. It is noteworthy that situations arose in our experiments where the anticyclonic eddies spun-up a cyclonic pair, thus forming a dipolar vortex which propagated away from the source [*Bush and Woods* 1999]; however, the mechanism by which a cyclonic eddy might arise in isolation is not clear. Finally, our model indicates that an alternate generation mechanism must be sought for ageostrophic eddies, characterised by relatively small dimensions and large internal velocities, for which fluid inertia plays a significant role in the dynamics [*Manley and Hunkins* 1985].

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