SOME NEW IDEAS ABOUT THE FORMATION OF ANTARCTIC BOTTOM WATER

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In this communication, we point out two things : first, the existence of a convection process which is active when the surface water is considerably less dense than the deeper water, and, second, the importance of variations of depth on any convection which may occur. Previous theories (Brennecke, 1921 ; Mosby, 1934 ; Mosby, 1966 ; Fofonoff, 1956 ; Munk, 1966) all require the production of denser water near the surface by freezing during the winter ; in contrast, the process discussed here can be driven by melting of surface ice, and can also be active in the summer. It can explain in a natural way the measured characteristics of Antarctic bottom water, and it is supported by observations of a simple laboratory model.

In Antarctic waters south of the Antarctic convergence, the great bulk of the water, called "warm deep water", has a salinity close to 34.7°/₀₀ and temperature close to +0.5°C. The surface water above and bottom water below are presumably formed by modification of this basic water mass. The surface water is found to be fresher, colder and lighter than the deep water, its temperature is usually near the freezing point (about -2°C), and salinities cover a fairly wide range. The freshness can be ascribed to an excess of precipitation over evaporation and the discharge of ice and melt water from the Antarctic Continent. The bottom water, whose properties we seek to explain, is also cooler and fresher, but also denser, than deep water (see Fig.1).

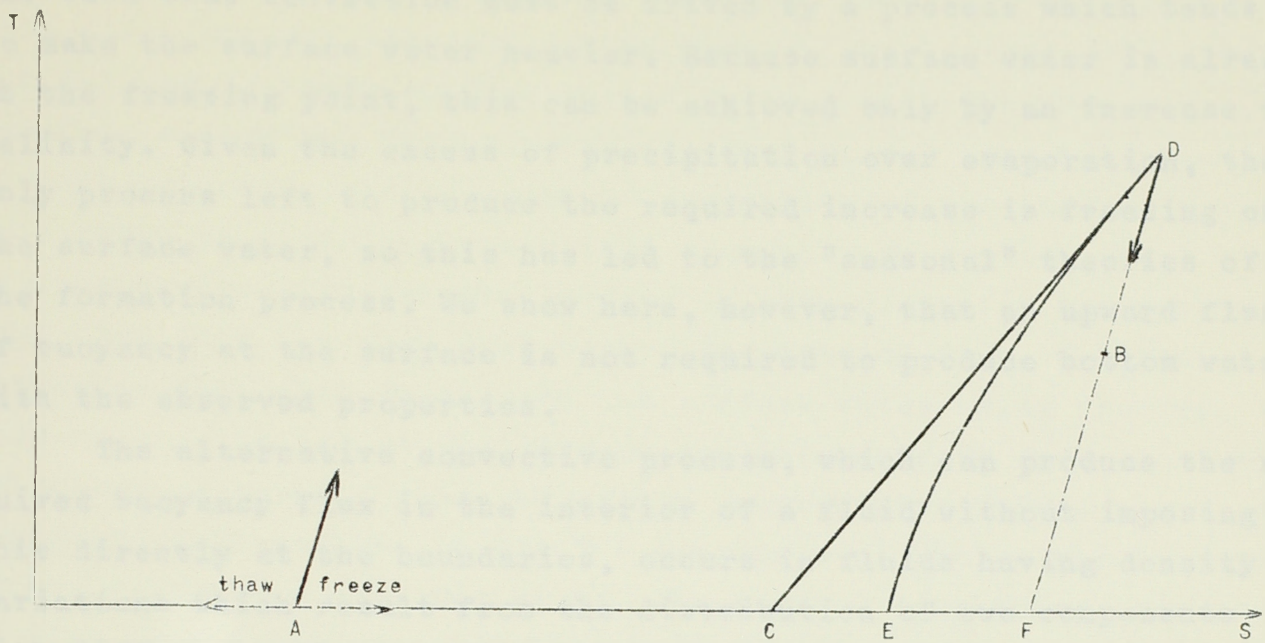

Fig. 1.- A temperature-salinity diagram showing the effect (solid arrows) of thermohaline processes on the properties of surface water (A) and warm deep water (D). The point B represents bottom water. In conditions of rapid thaw or of freezing, the properties of surface water change in the direction of the appropriate broken arrow. The line ACEF is not precisely one of constant temperature but is the freezing curve. The curved line DE is one of constant density and CD is tangent to it at D .

The old arguments about bottom water formation are based on the idea that convection must be driven by a process which tends to make the surface water heavier. Because surface water is already at the freezing point, this can be achieved only by an increase in salinity. Given the excess of precipitation over evaporation, the only process left to produce the required increase is freezing of the surface water, so this has led to the "seasonal" theories of the formation process. We show here, however, that an upward flux of buoyancy at the surface is not required to produce bottom water with the observed properties.

The alternative convective process, which can produce the required buoyancy flux in the interior of a fluid without imposing this directly at the boundaries, occurs in fluids having density variations which result from the distribution of two components with different molecular diffusivities (for example, salt and heat). If one of the components (in this case heat) has a destabilizing gradient, motions can be driven by drawing on the potential energy in the field of that component, even though the overall density distribution is statically stable. This thermohaline convection mechanism has been well documented by laboratory experiment (Turner, 1964 ; Turner, 1956), and it has been used to interpret various small scale features in lakes (Hoare, 1966) and the ocean (Tait, 1968 ; Cooper, 1968). We now suggest that there can also be important larger scale consequences of the process.

The upward flux of heat (in density units) is only partly compensated by a flux of salt, and so the density of the upper layers will decrease and that of the lower layers will increase. If a layer of shelf water with properties A overlies deep water with properties D (Fig.1), the fluxes across the interface cause the temperature and salinity to change in the directions indicated by the solid arrows. Energy considerations show that the arrow at D must always li lie between the direction AD and the vertical ; and, in fact, the relative rates of change of temperature and salinity have been determinated quantitatively in the laboratory (Turner, 1956).

A significant feature of the thermohaline process (Stommel, 1962) is that the resulting properties need not lie on the line AD, as they must after an ordinary mixing process. The modification of the deep water would produce bottom water B with the observed properties, colder and slightly fresher than D, and this will continue to hold true over a wide range of properties of the surface water. To sustain an unstable temperature gradient, of course, there must be continued cooling at the surface to compensate for the upward heat flux from the warm deep water. The special form of convection discussed here also depends on the surface water being fresher, so that melting of ice at the surface can indeed drive such convection by providing both of these necessary ingredients. Taking the surface processes into account on the T-S diagram will change the direction of the arrow at A (but not at D). The surface temperature will tend to stay near freezing, while the salinity changes in either direction along the freezing curve ; to the left in conditions of rapid thaw, and to the right in freezing conditions (with no net thawing or freezing, the arrow will point to the right because of the salinity flux from below).

The explanation of the properties of bottom water in terms of non-linear mixing effects (Fofonoff, 1956) seems, however, to put undue emphasis on surface water with the properties F (which is heavier than D), and we do not believe this to be physically sound. We agree that, in winter conditions, the surface salinity will tend to increase at least to the point C where some mixtures with deep water will be heavier than either water mass, and that this effect can cause a flow down the slope when surface salinities lie in the range between C and E. The maximum salinities produced by this kind of direct mixing, however, while still maintaining static stability, will lie on the straight line joining D and E. Before overturning occurs, therefore, only the thermohaline mechanism can produce sufficiently saline bottom water, with properties which are at the same time consistent with the observations and insensitive to the surface salinity. When the surface water reaches salinities to the right of E and it (as well as the mixtures) becomes heavier than D, mixing will take place rapidly throughout the depth, and non-linearity will play a minor part. There can certainly be an important contribution to bottom water formation at this stage, as discussed by earlier workers. The convection must then be driven entirely by a buoyancy flux at the surface, because there is no longer an "interface" across which a compensating interior flux can occur.

Our argument is not yet complete, for if conditions were uniform horizontally, no distinct bottom water would be formed ; the deep water D would merely undergo a slow change of properties (in the direction of the arrow in Fig.2, when the thermohaline process is important). Our second main point concerns the effect of variations in depth on the convection, and is independent of how this is driven, whether by an interior or a surface flux of buoyancy. Consider, for example, the situation shown in Fig.2, where a cold fresh layer overlies a warmer salty one in a container with a sloping bottom. The thermohaline process initially produces a uniform upward flux of buoyancy through the interface, but the result of this is that fluid at H becomes heavier faster than at L, because mixing occurs through a smaller depth of fluid. The fluid at H therefore sinks and gives rise to a circulation in the sense shown, an important feature of which is the current down the slope carrying colder fresher water right to the bottom under the warm salty layer. The existence of this bottom current in the summer is a definite prediction arising from the thermohaline mechanism, which seems worth testing by direct observation.

A variation of the above argument shows that in the corner G, where there is only a single layer, a uniform downward flux of salt through the surface would produce the heaviest water in the corner, leading to a current down the slope towards H. If it is sufficiently heavy it will penetrate the interface and add to the flow below H. Note that although this water may be saltier than deep water on formation (such water has been observed on the shelf), it will continually mix with fresher surface water as it runs down the slope and need not be as salty as the warm deep water when it flows underneath it.

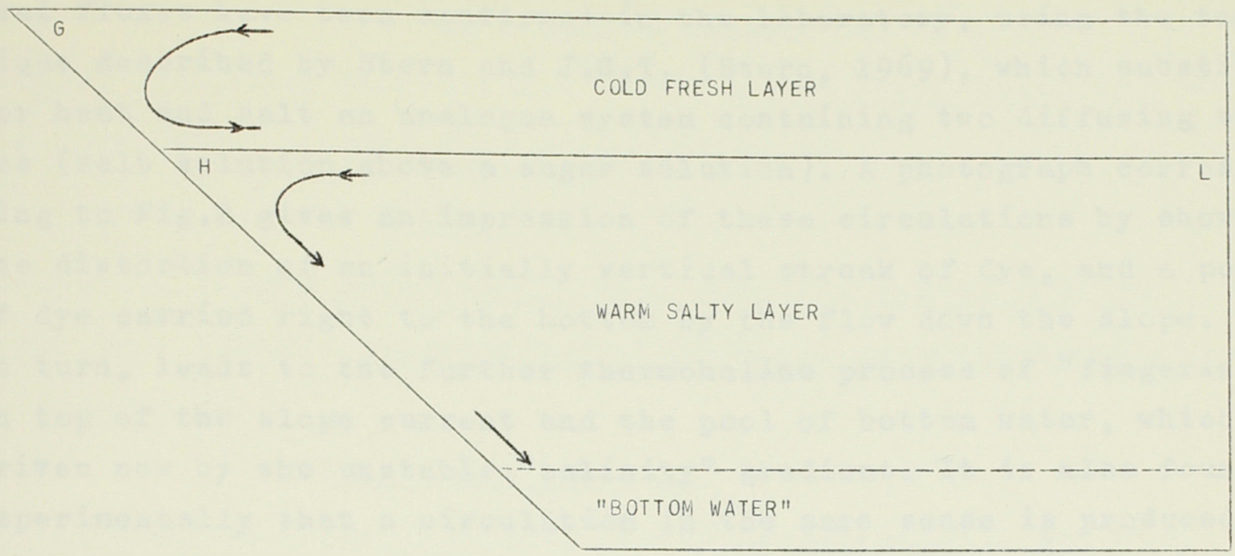

Fig. 2.- Sketch of the circulations set up by convection in a container with a sloping boundary.

The main features of the circulation driven by the interfacial fluxes have been confirmed in the laboratory, using the technique described by Stern and J.S.T. (Stern, 1969), which substitutes for heat and salt an analogue system containing two diffusing solutes (salt solution above a sugar solution). A photograph corresponding to Fig.2 gives an impression of these circulations by showing the distortion of an initially vertical streak of dye, and a pool of dye carried right to the bottom by the flow down the slope. This, in turn, leads to the further thermohaline process of "fingering" on top of the slope current and the pool of bottom water, which is driven now by the unstable "salinity" gradient. It is also found experimentally that a circulation in the same sense is produced in the upper layer, because the density difference between the layers is altered at different rates in different positions. This results in a strong shear at the interface, especially in the corner and out to the position where the layers are comparable in depth.

The sugar-salt technique is useful when it is important to avoid complications due to irrelevant heating or cooling from the room, but it is possible to illustrate the effect more simply and directly. If ice cubes are dropped into salty water at room temperature in a tilted container, a current down the slope will soon be set up, and can be made visible by adding a few drops of dye at the shallow end. This circulation is driven by the cooling and freshening caused by melting, while a thin lighter layer of melt water remains floating on the top.

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