Reports

Upwelling: Oceanic Structure at the Edge of the Arctic Ice Pack in Winter

Abstract. *Observations taken on an expedition into the Arctic Ocean north of Spitsbergen indicated the existence of a region of wind-driven upwelling along the edge of the ice pack. Models underestimate the 12-kilometer width of the upwelling region.*

In December 1977 aboard the icebreaker M.S. *Polarsirkel*, we carried out an experiment at the edge of the polar ice pack north of Spitsbergen. The aims of the experiment were to study the upper layers of the water column near the ice edge in winter and to search for evidence of wind-generated upwelling along the ice edge. This type of upwelling is similar to the well-understood and observed phenomenon of coastal upwelling (*1*). It has been discussed theoretically only recently (*2*), and no direct observations have been reported, as far as we know.

We chose the region north of Spitsbergen (Fig. 1a) because it promised a relatively long, straight, and distinct boundary between a large area of open water and the ice pack. The existence of this ice edge was verified prior to our cruise both by infrared imagery from the NOAA-5 (National Oceanic and Atmospheric Administration) satellite and by observations from the *Polarsirkel* (*3*). Earlier studies in this region in summer (*4*) have shown that the water column consists, in general, of a layer of cold Arctic water extending to a depth of between 100 and 150 m overlying warmer and more saline Atlantic water.

During the cruise several hydrographic sections were made through and perpendicular to the ice edge at about 81°N. Each section consisted of between 12 and 20 CTD (*5*) stations separated by 1 to 5 km. The station positions of one of these sections are shown in Fig. 1b. The stations were taken as close as possible to the line 13°E, but in the pack ice the ship had to follow the most easily penetrable route and therefore stations 128 to 131 deviate from this straight line.

The predominant feature of this section, shown in Fig. 2, is the nearly homogeneous region south of the ice edge between the surface and a depth of about 140 m. This water is warmer and more saline than the water on either side and is bounded on both sides by fronts, one coincident with the ice edge and one about 12 km away from it in open water. The density anomaly (σ_θ) section (*6*) (Fig. 2c) shows that this water mass is also more dense than the adjacent waters. A comparison of Fig. 2, a to c, shows that the temperature, salinity, and density fronts coincide. Away from this feature, the structure of the water column was as expected.

We believe that this feature is the result of upwelling. Figure 2c shows that the homogeneous region has a density of about 27.86 σ_θ units. Water of the same density is found only near a depth of 150 m in the two most undisturbed stations, stations 119 and 131. The salinity distribution (Fig. 2b) is consistent with the density distribution, but the temperature of the homogeneous region is about 0.2C° cooler than at a depth of 150 m on either side. Since the air temperature was −25°C, the water was subject to intense surface cooling which probably caused convection and decreased its temperature slightly. The measured heat flux from the water surface was sufficient to have caused this amount of cooling in a few days (*7*). Thus it is probable that this structure was formed by the upwelling of Atlantic water from a depth of about 150 m, displacing the Arctic water above it.

The theoretical studies (*2*) have shown that wind blowing in the appropriate direction parallel to a relatively straight and unmoving boundary between ice-covered and ice-free regions should cause upwelling in the vicinity of the boundary. The presence of the ice edge causes an abrupt change in the effect of the wind on the surface of the water. This change causes a divergence in the wind-driven flow field of the surface layer, which in turn causes upwelling. Although we were working in a region with pack ice, not fast sea ice as supposed by the theories, the transition zone between the ice-covered and ice-free regions was usually less than approximately 100 m. This distance is much smaller than the baroclinic radius of deformation (*8*); thus the zone meets the theoretical requirements for an "ice edge."

In order that there be upwelling of water from about 150 m to the surface, the theory requires that strong winds blow for at least 2 days. Measurements from the ship showed winds from the correct direction only for the day preceding the section. These winds were too weak and of too short a duration to have caused the observed upwelling. However, weather maps show that an intense low-pressure region passed north of Spitsbergen in the 3-day period just prior to our cruise. There are no actual wind measurements from the ice edge region in that time period, but this low-pressure cell certainly could have produced the winds necessary to force an upwelling event, the results of which we observed.

The present theories of ice edge upwelling are analytical and as such require many assumptions which limit their applicability. Our observations show a situation that the theories do not adequately describe. The stratified model predicts the baroclinic radius to be the horizontal scale of the upwelling. Based on a two-layer approximation of our density profile data, this radius is about 3 km, similar to that of the frontal zones on either side of the homogeneous region but greatly underestimating the 12-km width of the upwelling feature. However, our observations showed that the ice edge was not stationary as the theories assumed but moved a number of baroclinic radii in a period of a few days. Such movement could serve to distort the upwelled region. Examination of the den-

Length Limit for Reports: The average length of individual Reports in *Science* has been steadily increasing. At the same time, the number of pages allotted to Reports has remained constant and cannot be increased. The net result has been that fewer Reports on fewer subjects are being published; many that receive excellent reviews are being rejected for lack of space. The overall rejection rate is more than 80 percent. In order to increase the acceptance rate for reports in 1979 we plan to enforce the length requirements: one to seven double-spaced manuscript pages of text, including the references and notes, and two items of illustrative material (tables and figures) which together will occupy no more than half of a published page (30 square inches). After Reports are reviewed, those that are being considered for acceptance and that exceed the length limit will be sent back to the authors for shortening before a final decision is made. Reports that initially meet the length requirements will not be subject to this delay.

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sity profiles in the middle of the homogeneous region shows much fine structure and regions of negative density gradient, an indication that the region is undergoing active convection. This mechanism may serve to completely mix a region whose stability has already been weakened by the upwelling process and hence cause an apparent broadening of the upwelled region.

During the day after the completion of this section, we measured the surface water velocity with surface drogues. They showed a mean current directed southwest, away from the ice edge. This direction of water movement could indicate the surface divergence necessary for upwelling at the ice edge.

There is a strong enough resemblance between our observations and the theories to suggest that the mesoscale structure in the vicinity of the ice edge was at least initiated by the mechanism of ice edge upwelling. We report elsewhere a more complete analysis of the phenomenon (9).

Ice edges in the world's oceans extend for many thousands of kilometers. Thus, if the theories and our interpretation of the observations are essentially correct,

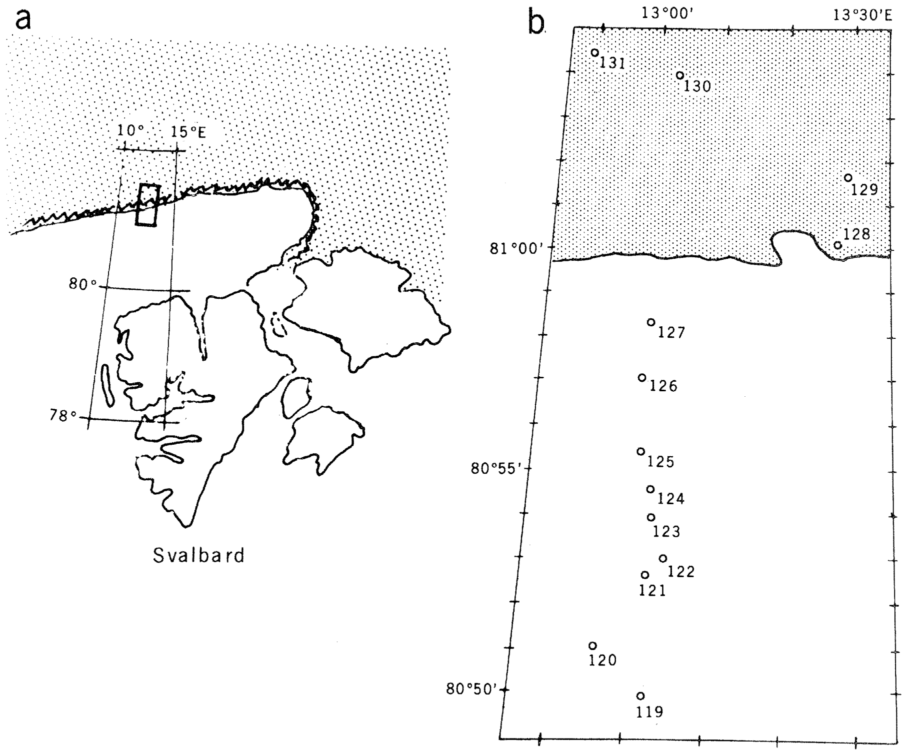
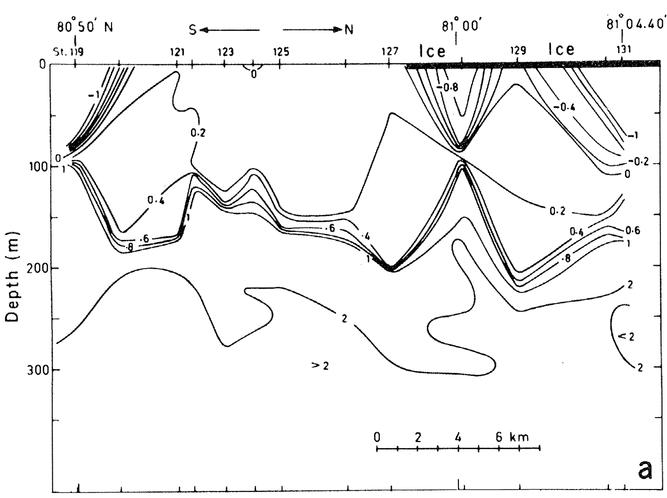
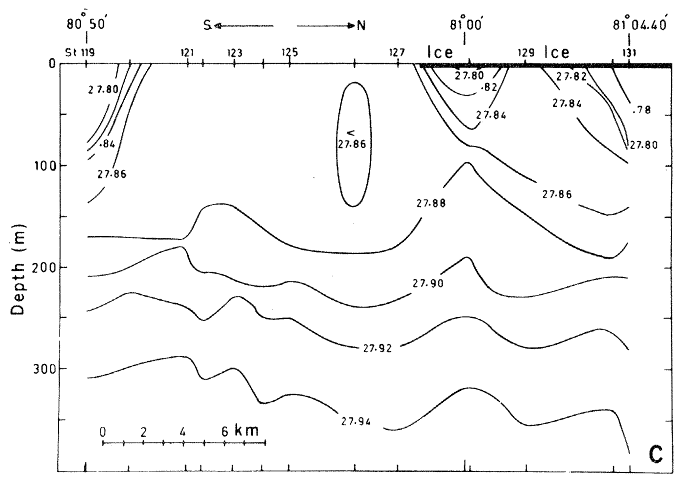


Fig. 1. (a) The location of the polar ice pack relative to Spitsbergen (called Svalbard in Norwegian) as drawn from a NOAA-5 satellite image taken in late November 1977. The shaded area represents the area covered by more than 6/8 pack ice. The small rectangle at about 81°N, 13°E is the area discussed in this report. (b) An enlargement of the small rectangular area in (a) showing the locations of stations 119 to 131, used to create the sections shown in Fig. 2. The shaded area is ice-covered.





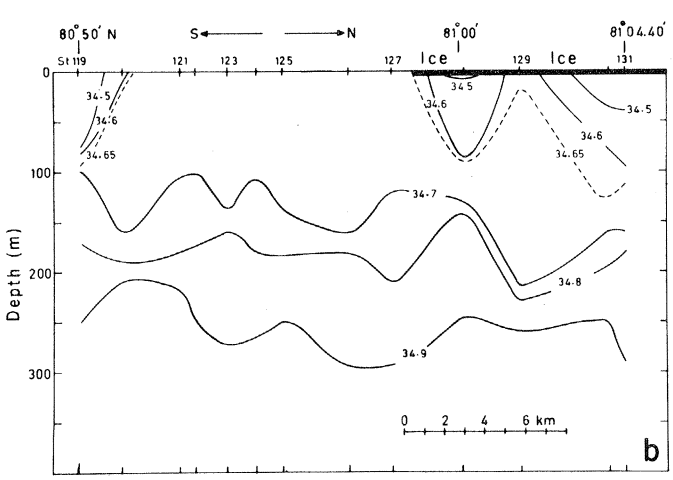


Fig. 2. Sections of properties drawn from CTD casts made at the station locations shown in Fig. 1b. Positions have been projected into the line 13°E. (a) Temperature (in degrees Celsius). (b) Salinity (per mil). (c) Density in units of σ_θ. All these measurements were made in a 12-hour period on 3 December 1977.

this hitherto unreported phenomenon may be quite widespread. In a manner similar to other forms of upwelling, this mechanism should be a means of creating oceanic fronts and for bringing nutrients to the surface waters where they will enhance biological productivity in these ice edge regions when the sunlight conditions allow. In raising the deeper, more saline waters to the surface where they will be cooled and made denser, ice edge upwelling is a mechanism for deep and possibly even bottom water formation. This process could be important for removing heat from the ocean's depths and hence may be important in determining the world's climate.

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References and Notes

1. Some descriptions of the theory and observations of coastal upwelling are given in the following: R. L. Smith, *Oceanogr. Mar. Biol.* **6**, 11 (1968); C. N. K. Mooers, C. A. Collins, R. L. Smith, *J. Phys. Oceanogr.* **6**, 3 (1976); A. E. Gill and A. J. Clarke, *Deep-Sea Res.* **21**, 325 (1974).
2. The first published work on ice edge upwelling was the presentation of an analytical, homogeneous model by T. Gammelsrød, M. Mork, and L. P. Røed [*Mar. Sci. Commun.* **1**, 115 (1975)]. A. J. Clarke [*Deep-Sea Res.* **25**, 41 (1978)] produced a stratified model. Most of the comparisons with theory in this report are based on Clarke's model.
3. In late November 1977, K. Aagaard and A. Foldvik made a cruise in this region on the *Polarsirkel*.
4. H. Mosby, *Geofys. Publ. 12* (1938).
5. A CTD is an instrument which makes continuous measurements of conductivity, temperature, and depth as it is lowered through the water. With these measurements it is possible to calculate the salinity and density of the water as well as other variables.
6. The density anomaly of seawater may be written as $\sigma_\theta = (\rho_\theta - 1)10^3$, where ρ_θ is the potential density of the water in grams per cubic centimeter. Potential density is the density a water sample would have if it were raised adiabatically from the sample depth to the ocean's surface.
7. Y. Gjessing, in preparation.
8. The baroclinic radius of deformation (internal Rossby radius) in a two-layer fluid is given by $\sqrt{(gH\Delta\rho/\rho f)}$, where g is the acceleration of gravity, $\Delta\rho$ is the density difference between the layers, ρ is the average density of the layers, H is the depth of the surface layer, and f is the Coriolis parameter, that is, twice the rotation rate of the earth multiplied by the sine of the latitude. In this formula it is assumed that the total depth of the fluid is much greater than the depth of the surface layer. Although baroclinic radii calculated from this two-layer approximation may be different from those calculated from continuous theory by as much as a factor of 2, they are of sufficient accuracy for the purposes of this report. The upwelling varies away from the ice edge as $\exp(-|x|/a)$, where x is the distance from the ice edge and a is the baroclinic radius.
9. J. R. Buckley, T. Gammelsrød, O. M. Johannessen, L. P. Røed, in preparation.
10. We thank the director of the Institute for Continental Shelf Research (IKU) in Trondheim, Norway, for providing us with their integrated navigation system, a computerized satellite position-finding and navigation unit; T. Vinje of the Norwegian Polar Institute for interpreting the satellite images; and the captain and crew of the M.S. *Polarsirkel* for making the best of working under very difficult conditions. This research was supported by the University of Bergen.
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Thermoclines: A Solar Thermal Energy Resource for Enhanced Hydroelectric Power Production

Abstract. *The solar thermal energy stored in hydroelectric reservoir thermoclines is very large and greatly exceeds the gravitational hydroenergy of the surface water, even after limitations arising from the second law of thermodynamics have been taken into account. Greatly enhanced power production can be obtained at present hydroelectric facilities if heat engines are adapted to exploit this large thermal energy resource.*

We suggest here a technique for increasing the power output of conventional hydroelectric plants. The freshwater thermoclines behind normal hydroelectric plants contain thermal energy greatly in excess of the gravitational hydroenergy. Even after one takes into account the Carnot efficiency and the reduction below Carnot efficiency for real heat engines, the convertible energy expressed in equivalent "head" can exceed the average dam height in the United States by a factor greater than 4. The presence of power-conditioning equipment and power transmission lines makes present hydroelectric facilities ideal locations for heat engines that operate on the large freshwater thermocline energy source. Furthermore, there should be no negative environmental factors associated with power production by the application of heat engines to hydroelectric dam thermoclines. Thermocline data taken from three western reservoirs (Lake Mead, Lake Shasta, and Clair Engle Lake) are presented for illustrative purposes.

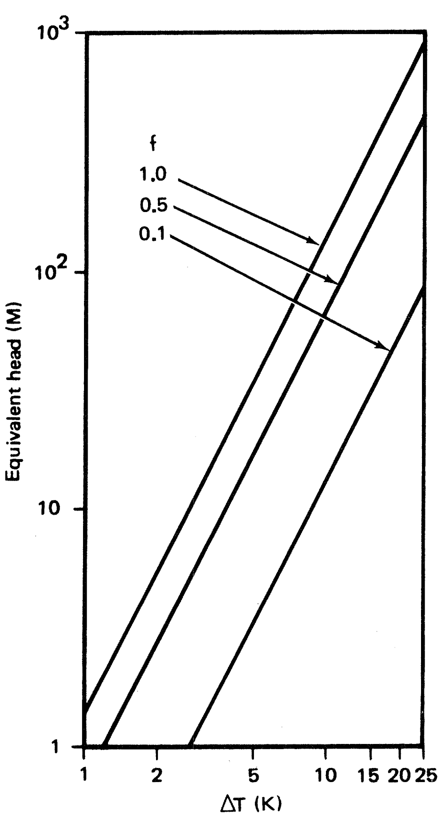
Vast quantities of absorbed solar energy are stored in the form of freshwater thermoclines behind hydroelectric dams. The mechanical equivalent of the thermal energy stored in water at a temperature difference ΔT can be expressed conveniently in terms of head if one sets the gravitational potential energy of the head, h, equal to the thermal energy

$$Mgh = MC\Delta T \qquad (1)$$

where M is the mass of water, g is the acceleration due to gravity (9.8 m/sec^2), and C is the specific heat of water (4.18×10^3 J kg^{-1} K^{-1}). Equation 1 then becomes

$$\frac{h}{\Delta T} = \frac{C}{g} = 427 \text{ m K}^{-1} \qquad (2)$$

or 778 feet per degree Fahrenheit. This value is very impressive when compared to the average head deliverable by a dam in the United States, which is only ~40



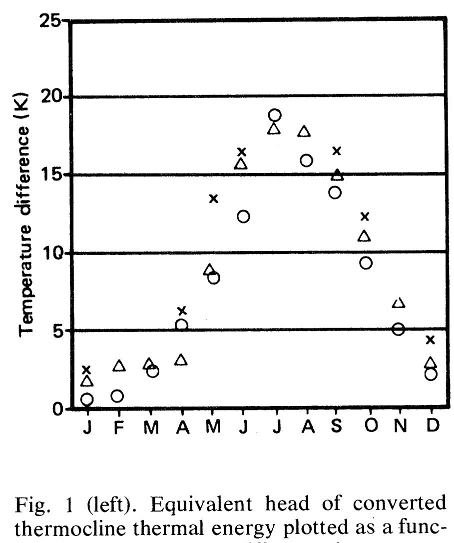


Fig. 1 (left). Equivalent head of converted thermocline thermal energy plotted as a function of the temperature difference between solar-warmed surface water and cooler deep water. The parameter f is the fraction of the maximum theoretical heat conversion efficiency (Carnot) at which a heat engine is to operate. Fig. 2 (right). Seasonal variations in the thermocline temperature difference in three western reservoirs: △, Lake Mead; x, Lake Shasta; and ○, Clair Engle Lake.

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