Thermal Stratification in the Arctic Ocean

Abstract. *Fine scale measurements of the vertical temperature profile in an Arctic water column show the presence of several cascaded isothermal layers. Layers between the depths of 300 and 350 meters range from 2 to 10 meters in thickness, while the temperature change between adjacent layers is approximately 0.026°C. The individual layers are isothermal to within ± 0.001°C.*

Sophisticated electronic systems now being used by oceanographers to obtain continuous temperature and salinity profiles have provided sufficient data to show that the vertical temperature profile in the oceans may be quite complex. Most salinity-temperature-depth data showing fine structure have been obtained in warm-water regions where large temperature gradients exist and where reasonably calm sea conditions may be expected (*1*). However, even in calm seas vertical ship oscillations tend to obscure fine detail in continuous vertical profiles.

We experimented with expendable bathythermographs (XBT's) to see if a detailed profile of the fine thermal structure of ocean water under the Arctic Ice Island T-3 could be obtained. Although T-3 undergoes slow horizontal movements it has no vertical oscillations that interfere with short-period vertical profile measurements. T-3 was in water 2502 m deep (84°38.2′ N, 128°21.6′ W) at the conclusion of our experiments on 19 March 1969.

The free-fall rate of the XBT's was adjusted to about 2 m/sec by increasing the drag. The overall profiles we obtained are shaped much like those interpolated Arctic temperature profiles reported by Coachman and Barnes (*2*). However, we found definite stair-step temperate changes in all profiles.

We measured the small laminae more precisely by lowering the XBT unit slowly with a hydrographic winch. Records obtained with this technique show far greater detail than that obtained from freely falling XBT's. For example, we found a temperature inversion at a depth between 50 and 60 m which could not be identified on any of the free-fall records. A series of records was made by using the hydrographic winch; a portion of one such profile is shown in Fig. 1, upper right. We obtained still greater precision by using high amplification of the sensor signal while simultaneously lowering the sensor by winch at 0.4 m/sec. An example of the profiles obtained this way is shown in Fig. 1, lower left, as an expanded portion of the overall profile. Even at reduced winch speed the temperature change between layers was so abrupt that the recorder characteristically overshot; we estimate the thickness of the transition at less than 20 cm.

Each layer measured was isothermal within ± 0.001°C. The temperature change per step (between adjacent layers) was nearly constant at 0.026°C over the 34 steps between 220 and 340 m, suggesting a "minimum" temperature increment. The layer thickness, however, increased directly with depth and inversely with temperature gradient. There is also evidence that "half-steps" in temperature may occur. One such half-step is encircled in Fig. 1; it persisted unchanged during a 20-hour measurement period.

Tait and Howe (*3*) reported a thermal step structure almost as abrupt as the one reported here. They obtained their data in a section of the Atlantic where salty warm water from the Mediterranean Sea is found beneath the surface, but above cooler and fresher deep water. The steps they reported were in the lower portion of Mediterranean water where both salinity and temperature decrease with depth. In the Arctic Ocean where our data were obtained, warmer saltier water from the Atlantic is found beneath colder fresher water. The temperature steps we measured were in the upper portion of the Atlantic water where both temperature and salinity increase with depth. In both regions low static stability conditions exist, and changes in density caused by vertical fluxes of heat and salt are partially compensating. Thus, the strong layering which we found appears to be associated with weak density gradients where there are counter fluxes of density (that is, salt and heat fluxes in the same direction). Thus our field data support the labora-

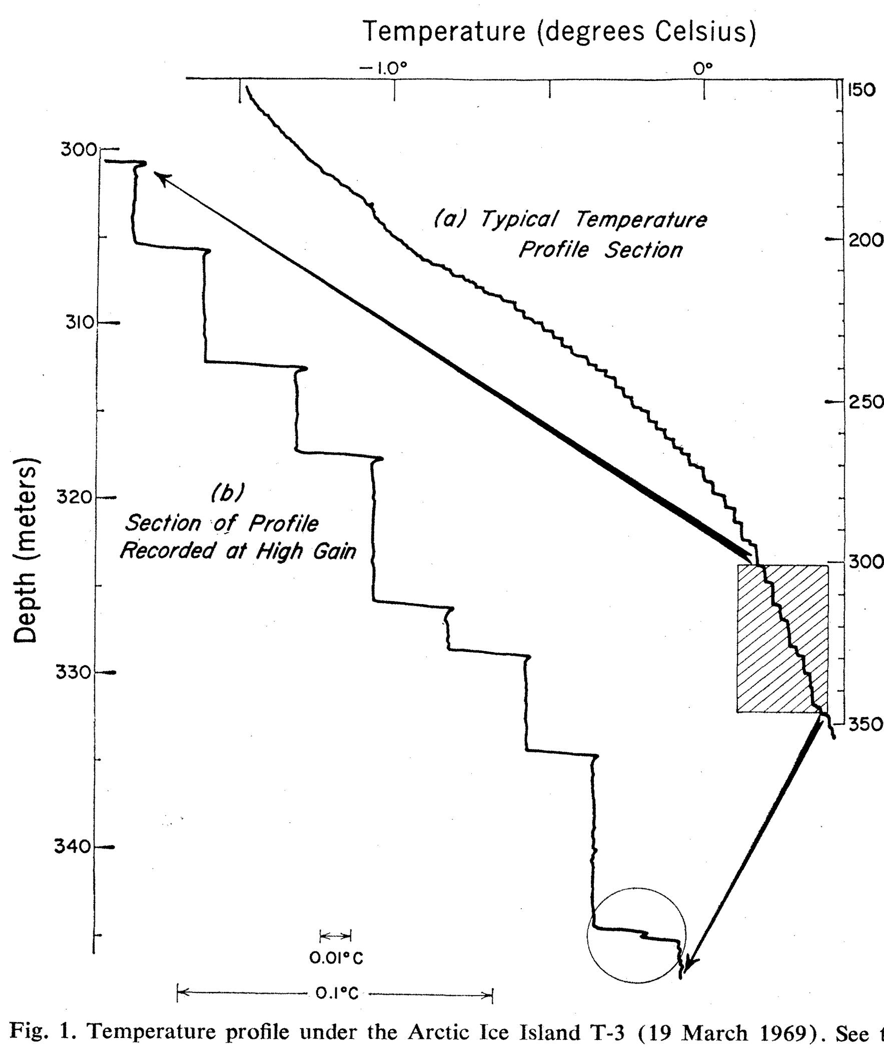

Fig. 1. Temperature profile under the Arctic Ice Island T-3 (19 March 1969). See text.

tory results reported by Turner (see *4*).

Our continuing Arctic research program will include further studies of the thermal and density structure under T-3. Longer and more detailed measurement programs will enable us to determine the geometry of the interfaces as well as the longevity of individual laminae. We are developing suitable instruments that will enable us to determine density fluxes as well as the principle mechanisms that govern these fluxes.

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Tropical Reef Corals: Tolerance of Low Temperatures on the North Carolina Continental Shelf

Abstract. *Individual heads of two species of reef or hermatypic coral,* Solenastrea hyades *(Dana) and* Siderastrea siderea *(Ellis and Solander), occur on rock outcrops on the inner continental shelf off North Carolina in waters where winter bottom temperatures are as low as 10.6°C. These temperatures are significantly lower than previously assumed minimum temperatures for the survival of tropical reef corals in their natural environment.*

Current dogma has it that reef or hermatypic corals occur only in warm tropical waters and that reef corals cannot tolerate water temperatures below 20°C (*1*). More detailed reports suggest that reef corals are able to survive only limited exposures to minimum water temperatures around 16° to 17°C (*2*). However, two species of tropical reef coral are forming coral-head patches in Onslow Bay on the inner continental shelf off North Carolina where winter bottom temperatures apparently remain well below this minimum range for several months of the year.

Individual heads of *Solenastrea hyades* (Dana) and *Siderastrea siderea* (Ellis and Solander) are present on rock outcrops at depths of 20 to 26 meters at three locations in Onslow Bay (Fig. 1) approximately 32 km offshore. A solitary head of *Solenastrea hyades* was recovered from a depth of 30 meters. Areas 1, 2, and 3 (Fig. 1) are well-known fishing grounds, and, as early as 1902, investigators from the Bureau of Fisheries dredged corals from area 1 (*3*), and in 1913 they collected corals from all three locations (*4*) but apparently never identified any of these specimens.

Solenastrea hyades, which has been reported in reef areas off Florida, the Bahamas, and in the West Indies (*5*), is abundant and flourishing in the colder North Carolina waters, where it is attaining sizes comparable to maximum sizes reported for this species in tropical waters. In Onslow Bay, this species occurs as scattered individual heads (Fig. 2), which generally are as high as they are wide at the base and taper to one or several lobes. The largest specimen collected to date is 30 cm high. The fresh porous nature of these coral heads and the lack of destruction by boring organisms both indicate healthy growth of *S. hyades* in Onslow Bay. Distinct growth lines in several coral heads are 15 to 17 mm wide, and, if annual, they may give some indication of the growth rate of *S. hyades* in this temperate environment.

Siderastrea siderea, common to coral-reef communities off Florida, the Bahamas, the West Indies, and Bermuda (*5*), is sparse in Onslow Bay. Dredged samples are no larger than 10 cm in diameter—in contrast to the masses of about 2 meters in diameter reported for this species in tropical waters. The small dense heads from Onslow Bay are all extensively bored, which indicates that this species may be just surviving in this environment.

Reef or hermatypic corals, which are characterized by the presence of symbiotic algae in their tissues, are thought to flourish best in temperatures of 25° to 29°C and to be capable of surviving limited exposures to a minimum temperature of 16°C (*2*). At the southern limit of the Great Barrier Reef region, however, six genera of reef corals survive minimum temperatures of 12° to 13°C (*6*), and, off Melbourne, two species of reef corals were reported in waters where the annual minimum temperature is 9°C (*7*). Some laboratory experiments on reef corals from Australia, Florida, and Hawaii (*8*) showed lower temperatures of endurance, but such experiments fail to indicate thermal limits at which reef corals can function normally, as they would in their natural habitat. Despite the importance of temperature in determining geographic distribution of reef corals, no detailed information has been collected on the variation of bottom water temperatures at the northern and southern limits of their distribution.

Bottom temperature data for the vicinity of area 1 (Fig. 1) in Onslow Bay were assembled (Fig. 3); bottom temperatures in this location reach a maximum of 24.7°C in September and a minimum of 10.6°C in February. Furthermore, it appears that bottom temperatures remain below the generally accepted 16°C minimum-tolerance temperature for reef corals for about 3 months of the year.

Large ripple marks, probably formed during storm-wave activity, are a common feature in bottom photographs of the coral-head areas and are a further indication of the hardiness of *Solenastrea hyades* and *Siderastrea siderea.* Not only are these corals capable of surviving the relatively wide temperature fluctuations in Onslow Bay, but they also withstand the large periodic movement of sediment that surrounds the coral heads.

The predominant rock type dredged up in association with these reef corals is a light grey to brown, fine to medium calcareous quartz sandstone. It generally has an iron-stained surface that is extensively bored by pelecypods. The characteristic matrix consists of slightly argillaceous, microsucrosic to chalky limestone which has a distinct granular texture in thin sections. The fauna includes mollusks, barnacles, bryozoans, and serpulids. Most of the rocks are leached of all aragonitic material so that the rock is characterized by abundant casts and molds of large mollusks, many of which are lined with bryozoans, barnacles, and serpulids that originally encrusted the mollusk shells.