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.

VICTOR T. NEAL
STEPHEN NESHYBA
Department of Oceanography, Oregon State University, Corvallis
WARREN DENNER
Department of Oceanography, U.S. Naval Postgraduate School, Monterey, California

References and Notes

1. H. Stommel and K. N. Federov, *Tellus* **19**, No. 2, 306 (1967); J. W. Cooper and H. Stommel, *J. Geophys. Res.* **73**, 18, 5849 (1968); J. D. Woods, *Meteorol. Mag.* **97**, No. 1148, 65 (1968).
2. L. K. Coachman and C. A. Barnes, *J. Arctic Inst. N. Amer.* **14**, 147 (1961).
3. R. I. Tait and M. R. Howe, *Deep-Sea Res.* **15**, 275 (1968).
4. J. S. Turner, *Int. J. Heat Mass Transfer* **8**, 759 (1965); *Deep-sea Res.* **14**, 599 (1967);— and H. Stommel, *Proc. Nat. Acad. Sci. U.S.* **52**, 49 (1964).
5. Supported by ONR 1286(10), Naval Ordnance Systems Command ORD-030-005/561-1/UR104-03-01, and the Naval Arctic Research Laboratory. We thank Jack Groelle and Asa Robinson of Oregon State University and Commander Jack Geary of the U.S. Naval Postgraduate School for assistance in obtaining the measurements.

5 June 1969

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.

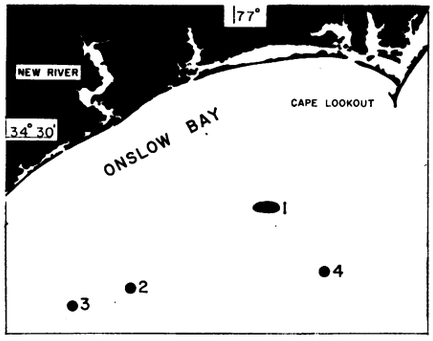

Fig. 1. Areas of reef corals in Onslow Bay off North Carolina.

Highly polished phosphorite grains are also common throughout the samples. The faunal assemblage is Upper Miocene in age (*9*).

Solenastrea hyades and *Siderastrea siderea* probably were introduced into Onslow Bay by the northerly flowing Gulf Stream waters. If the free-swimming larval stages of these two species were derived from southern Florida, it is surprising that up to now they have not been reported in shelf areas between south Florida and Onslow Bay. The low rate of sedimentation (*10*) and abundant outcrops (*11*) in Onslow Bay apparently offer suitable conditions for the establishment of these reef corals despite low winter temperatures.

Other stony corals dredged from the coral-head areas in Onslow Bay are the ahermatypic corals *Oculina arbuscula* Verrill and *Astrangia astreiformis* Milne-Edwards & Haime, both previously reported in the Beaufort area (*12*), and *Phyllangia americana* Milne-Edwards & Haime, which is being recorded from Onslow Bay for the first time, along with the two species of reef corals.

Because reef corals are usually associated with tropical waters, their occurrence in temperate waters indicates that ecological or paleoecological generalizations based on a single environmental parameter must be applied with caution.

Fig. 2. Bottom photograph of area 1 (Fig. 1) showing scattered heads of *Solenastrea hyades* (Dana) on a rock ledge having a thin sediment cover. The depth is 22 meters.

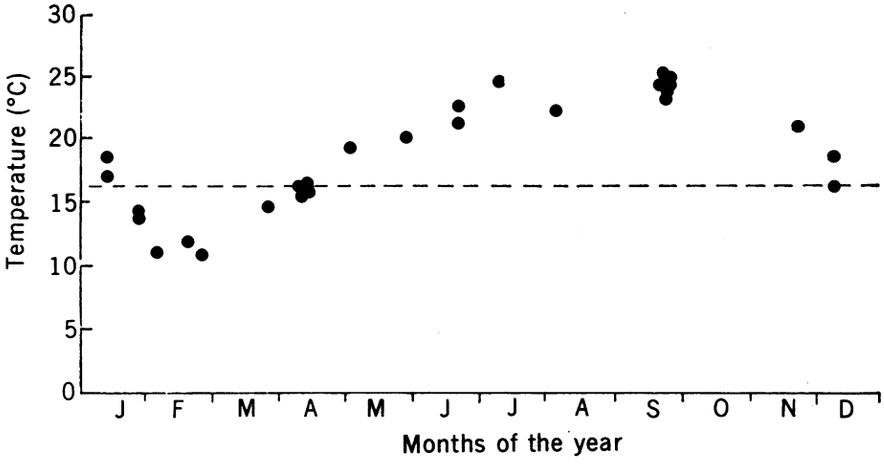

Fig. 3. Year-round bottom temperatures from vicinity of area 1 (Fig. 1). Data assembled from R.V. *Eastward* cruises for 1965–1969, and from D. F. Bumpus, 1950 and 1954. Broken horizontal line indicates previously accepted 16°C minimum temperature for survival of reef corals.

IAN G. MACINTYRE
Duke University Marine Laboratory, Beaufort, North Carolina 28516
ORRIN H. PILKEY
Department of Geology, Duke University, Durham, North Carolina

References and Notes

1. P. H. Kuenen, *Marine Geology* (Wiley, New York, 1950), p. 416; J. Gilluly, A. C. Waters, A. O. Woodford, *Principles of Geology* (Freeman, San Francisco, 1959), p. 317; J. A. C. Nicol, *The Biology of Marine Animals* (Interscience, New York, 1960), p. 16.
2. J. W. Wells, in *Treatise on Marine Ecology and Paleoecology*, J. W. Hedgpeth, Ed. (Geological Society of America, New York, 1967), Mem. 67, p. 1088; D. J. J. Kinsman, *Nature* **202**, 1280 (1964).
3. B. W. Evermann, in *Report on Inquiry Respecting Food Fishes and the Fishing Grounds.* Report of the Commissioner for year ending 30 June 1903, H. M. Smith, Ed. (U.S. Commission of Fish and Fisheries, Washington, 1905), part XXIX, p. 100.
4. L. Radcliffe, *U.S. Bur. Fish. Econ. Circ. No. 8*, 1 (1914).
5. F. G. W. Smith, *Atlantic Reef Corals* (Univ. of Miami Press, Miami, 1948), pp. 79–89.
6. J. W. Wells, *Rep. Gt. Barrier Reef Comm.* **6**, 21 (1955).
7. D. F. Squires, *Mem. Nat. Mus. Melbourne* **27**, 167 (1966).
8. A. G. Mayer, *Pap. Tortugas Lab.* **6**, 3 (1914); E. H. Edmondson, *Bull. Bernice P. Bishop Mus.* **45** (1928).
9. B. W. Blackwelder, in preparation.
10. O. H. Pilkey, *Mar. Sed.* **4**, 51 (1968).
11. W. J. Cleary and O. H. Pilkey, *Southeast. Geol. Spec. Pub.* **1**, 13 (1968).
12. A. E. Verrill, *Amer. J. Sci. Arts* **3**, 432 (1872); T. A. Stephenson and A. Stephenson, *J. Ecol.* **40**, 35 (1952).
13. We thank G. Newton (Oceanographic Party Chief, Duke University Marine Laboratory) who initiated this study by supplying a coral head collected by local fishermen; J. W. Wells (Cornell University) for identifying the corals; T. F. Goreau (University of the West Indies) and S. A. Wainwright (Duke University) for discussion and advice; the Duke University Marine Laboratory and the Cooperative Program of Biological Oceanography for the use of the R.V. *Eastward* and for the postdoctoral award to I.G.M. The Cooperative Program is supported through NSF grant GB-8189. Contribution of the Joint U.S. Geological Survey–Duke University Marine Geology Program.

19 May 1969; revised 9 July 1969