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Gulf Stream System: The Average Temperature Field at a Depth of 450 m

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Abstract

The mean temperature field of the Gulf Stream system at a depth of 450 m was determined by averaging hydrographic and XBT data in one degree squares and contouring the results. This temperature distribution is well correlated with the dynamic topography of 100 db relative to 1500 db and is interpreted as giving the mean, near-surface, baroclinic, geostrophic velocity field. The results show that: 1) the Gulf Stream is deflected approximately 100 km southeastward over the New England Seamounts, 2) a narrow zone of westward recirculation is found south of the Stream along 35-37°N from 42-57°W and an eastward flow south of this, and 3) three interconnected subgyres are embedded within the main Gulf Stream subtropical gyre, the main Sargasso Sea gyre centered at 33°N 72°W, the recirculation gyre at 37°N 52°W, and the northern gyre at 42°N 44°W.

Introduction

Attempts to map the mean dynamic topography of the near-surface Gulf Stream system have encountered two difficult problems. First, there are few reliable hydrographic and CTD stations that can be used to accurately calculate density and dynamic height. Second, the strong variability of the Gulf Stream, the meanders, rings, and eddies have made interpreting the available measurements problematic. In the presence of energetic eddies, the mean is difficult to measure with few samples.

To circumvent these problems the large number of 450 m temperature measurements from hydrographic stations and XBTs were used to smooth the time variability. Then, a subset of the data, the reliable stations, was used to show that this horizontal distribution of temperature can be interpreted within a high degree of precision as the dynamic topography of the 100 db surface relative to 1500 db. Approximately 90 percent of the variation in dynamic height across the Gulf Stream in the upper 4000 m is given by this 100 db-1500 db contribution. Assuming geostrophy, the dynamic topography and temperature field provide the distribution of baroclinic, near-surface velocity.

The motivation for this work was to try and resolve the mean circulation patterns of the Gulf Stream as it flows over the New England Seamounts and Newfoundland Ridge and in the zone of recirculation, areas of strong mesoscale activity. Although several maps of temperature, density, and dynamic topography already exist (Iselin, 1936; Wüst and Defant, 1936; Fuglister, 1954; Schroeder, 1963; Dantzler, 1977; Reid, 1978; Stommel, Niiler, and Anati, 1978), it was thought that a new map of the mean temperature field using a larger data base would overcome some of their deficiencies.

Data and Methods

The horizontal temperature distribution was determined by calculating the average temperature at a depth of 450 m in each one-degree square, and by contouring the results (Fig. 1). The 450 m depth was chosen because it is deep enough to usually lie within the main thermocline of the North Atlantic and yet shallow enough to contain the large number of recent XBTs (mainly 450 XBTs). A total of 90,000 observations obtained from NODC were used, an average of 50 per square. The highest density of observations was located in the Gulf Stream region between Bermuda and the United States East Coast where several squares contained over 1000 observations. The lowest density was located in the east and south where occasionally there were no observations in a square. The one degree average temperatures range from the coldest, near 4.4°C in the southward flowing Labrador Current off the Grand Banks, up to 17.4° near 33°N 72°W, the center of the subtropical gyre at this depth.

The dynamic topography over different layers in the North Atlantic calculated from carefully chosen stations has been described by Stommel, Niiler, and Anati (1978). Using these stations within the latitude band 20-50°N, dynamic height values (100-1500 db) were correlated with the interpolated temperatures at a depth of 450 m (T_{450}). The result (Fig. 2) shows that dynamic height values have a very close linear relation with T_{450}. The correlation coefficient is $r = .98$ and the standard error is $\pm.06$ dynamic m about the regression line ΔD (dynamic meters) $= 0.33 + 0.072\ T_{450}$ (°C). The tight linear relation between ΔD and T_{450} suggests that within a small error the mean temperature distribution at 450 m can be interpreted to be the distribution of dynamic topography of the 100 db surface relative to the 1500 db surface.

Results

The strongest temperature gradient is located in the western Gulf Stream, a region of tightly packed isotherms (Fig. 1). The central isotherms in the Stream, 9-14°C, remain closely spaced as they arc out towards the New England Seamount Chain. In front of the seamounts the isotherms (10-14) make a small southward dip and then change direction to run northeastward over the seamounts.

The northern isotherms (9-10°C) crest near 58°W and then dip southward near 54°W in front of the Fogo Seamounts near 52°W. The isotherm pattern suggests that, in the mean, the Gulf Stream is deflected approximately 100 km southeastward near the line of seamounts. "Deflection" means a shift in position and direction of the isotherms from smooth interpolated curves passing through this region connecting the Gulf Stream west of 70°W to the Stream east of 60°W. The implication is that in the absence of the seamounts the Gulf Stream would run more nearly parallel to the path shown by the 8° isotherm. This deflection also has been seen on earlier maps of mean temperature field at a depth of 200 m (Fuglister, 1954; Schroeder, 1963).

Beginning at the New England Seamounts is a significant spreading of the isotherms (9-14°C), chiefly a result of the northern isotherms (9-11°C) which continue northeastward until reaching 58°W. This spreading is interpreted to be the result of the large amplitude meanders in this region. West of the seamounts the width of the mean Gulf Stream (9-14°C) is approximately 100 km; east of the seamounts the width increases to 350 km. These isotherms become closer together, 200 km, as they approach the southeast Newfoundland Ridge which seems to confine the Gulf Stream flow to a narrow band along 50°W.

The axis of the high speed (instantaneous) near-surface Gulf Stream frequently coincides with the intersection of the 15°C isotherm and 200 m depth (Fuglister and Voorhis, 1965). Because of the vertical temperature gradient in the Gulf Stream, usually one degree per 50 m, the axis of the instantaneous Stream nearly coincides with the intersection of the 10°C isotherm and 450 m depth. Of course the map is an average of many different Gulf Stream configurations including meanders and eddies, so the 10° isotherm is only an approximation of the mean Gulf Stream axis.

North of the Stream and west of the Grand Banks is located a mean westward flow (north of 7-8° isotherm). The westward flow is detected in the drift of rings, water property distributions, and current meter records; it cannot be determined from temperature distribution alone.

The northern isotherms of the Gulf Stream (9-11°C), merge with the 5-8° isotherms and form a second tightly packed region near the Grand Banks; these isotherms pass around the Grand Banks and up to 50°N before peeling off in an eastward direction. This region of tightly packed isotherms is partially caused by southward movement of cold water in the Labrador Current next to Grand Banks. This current turns and flows northeastward along the northern edge of the North Atlantic Current. The southern isotherms in the Stream (12-15°C) continue eastward until they reached 38°N 45°W where they rapidly diverge much like the bottom topography in this location (Uchupi, 1971).

South of the Gulf Stream is a wedge-shaped area of cold water which projects westward along 35°N from near 42°W to the New England Seamounts (57°W). The Gulf Stream recirculation flows southwestward along the north side of this wedge between 35-37°N (Fig. 3). On the south side of this wedge is an eastward flowing current which extends eastward across the Atlantic in the latitude band 30-35°N. The recirculation has been observed with current meters (Schmitz, 1980), ship drift data (U.S.N.O.O., 1978), hydrographic stations (Reid, 1978; Wunsch, 1978) as well as in numerical models of the general circulation (Holland and Lin, (1975); Semptner and Mintz, 1977).* Schmitz (1980) reports that along 55°W the recirculation is weakly depth-dependent and has mean long-term velocities of 6-10 cm/sec over the depth range 600-4000 m. The 16° isotherm in this cold wedge almost meets the smaller cold ridge overlying the seamounts, suggesting the possible presence of a closed gyre centered near 37°N 52°W and containing relatively warm temperatures. This warm water gyre forms part of an eastward directed wedge of warm water which appears to be traceable eastward to 42°W, then northward around the Grand Banks and up to 50°N. The presence of another partially closed gyre is suggested by a local maximum in temperature in the region near 42°N 44°W where Worthington (1976) shows his northern gyre. An embedded gyre has also been observed on individual synoptic surveys of this region (Mann, 1967; Clarke, Hill, Reiniger, and Warren, 1980). All three of the gyres which appear in the 450 m temperature map (the Sargasso Gyre 33°N 72°W, the recirculation gyre 37°N 52°W, the Northern gyre 42°N 44°W) also appear in maps of the dynamic topography of the deeper water (Stommel, Niiler and Anati, 1978). It appears that the New England Seamount Chain and Newfoundland Ridge break the Gulf Stream into three partially connected gyres.

Extending southward from the Gulf Stream along 65.5°W and 73.5°W are two relatively cool areas. These are due to the large number of XBTs taken in Gulf Stream rings (Fuglister, 1972, 1977; Cheney and Richardson, 1976). Although rings are frequently found in these regions (Parker, 1971, Lai and Richardson, 1977), the calculated mean temperature is biased and is probably one to two degrees colder than the real long-term, unbiased mean. The cold tongue (11-14°) extending southeastward on the north side of New England seamounts is located where meanders and attached rings have been observed frequently with ship surveys (Fuglister and Worthington, 1951; Fuglister, 1963), drifting buoys (Richardson, Wheat, and Bennett, 1979), and satellite IR images.

Discussion

Although the mean temperature map has considerable noise due to meanders and eddies, it does exhibit several features which can be interpreted to be characteristic of the real long-term mean--the Gulf Stream deflection over the seamounts, the pattern of recirculation, the

*The earliest observations of surface currents in the recirculation go back over 150 years (Rennell, 1832). Reid (1978) has reviewed early maps of dynamic height in the recirculation and discussed the eastward current south of it.

embedded subgyres. It is encouraging to see that mean currents from long-term current meter deployments (Schmitz, 1980) agree with the recirculation along 55°W seen in the mean temperature field. It should be noted that the instantaneous temperature and velocity field will not look much like the mean; averaging the data smooths and broadens the high gradient regions. The Gulf Stream front and zone of recirculation appear much sharper on synoptic maps than the spacing of isotherms displayed on the mean map.

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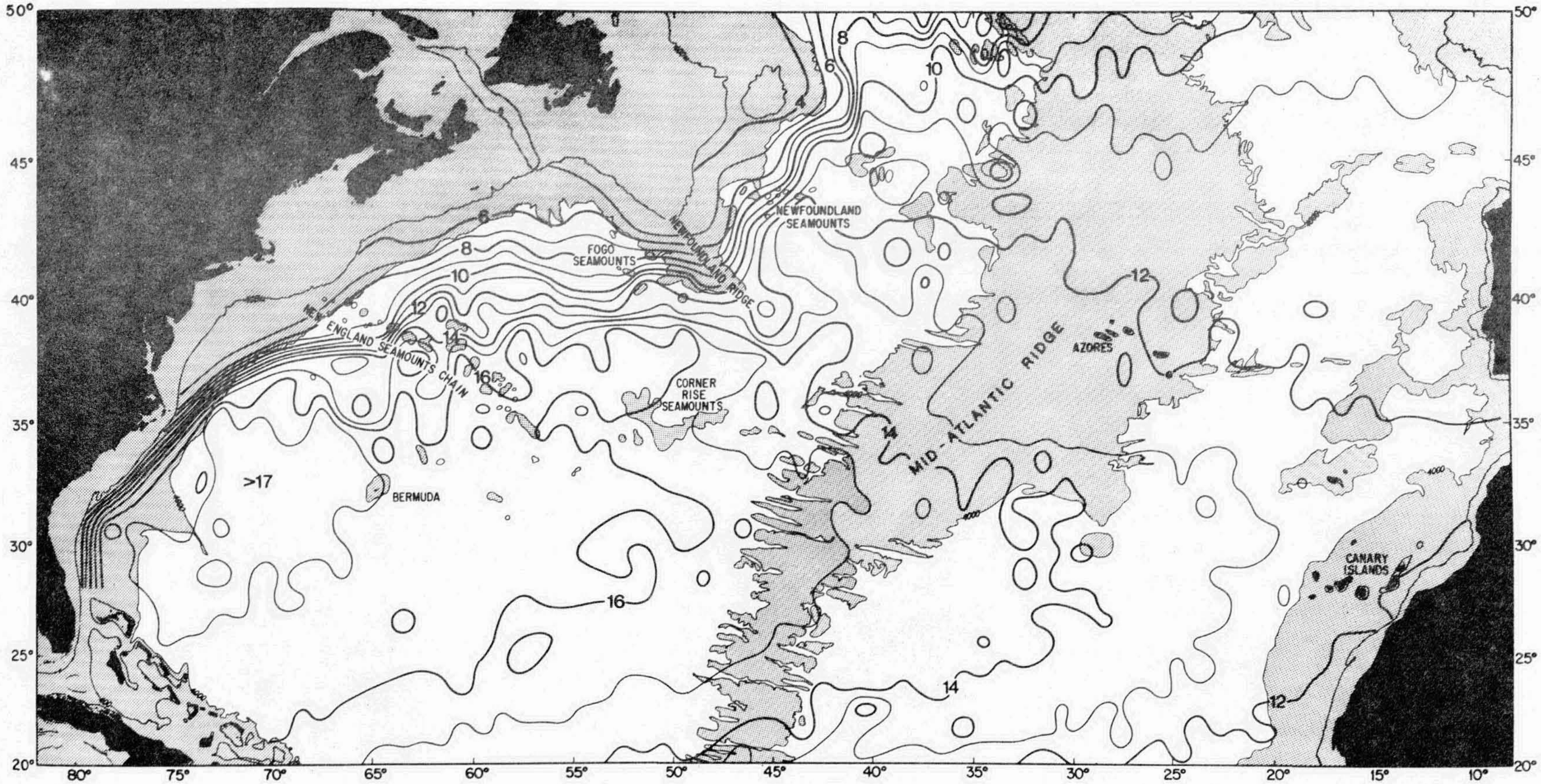

Figure 1. Temperature distribution at a depth of 450 m. Average temperature values were calculated for each one degree square using the NODC data file.

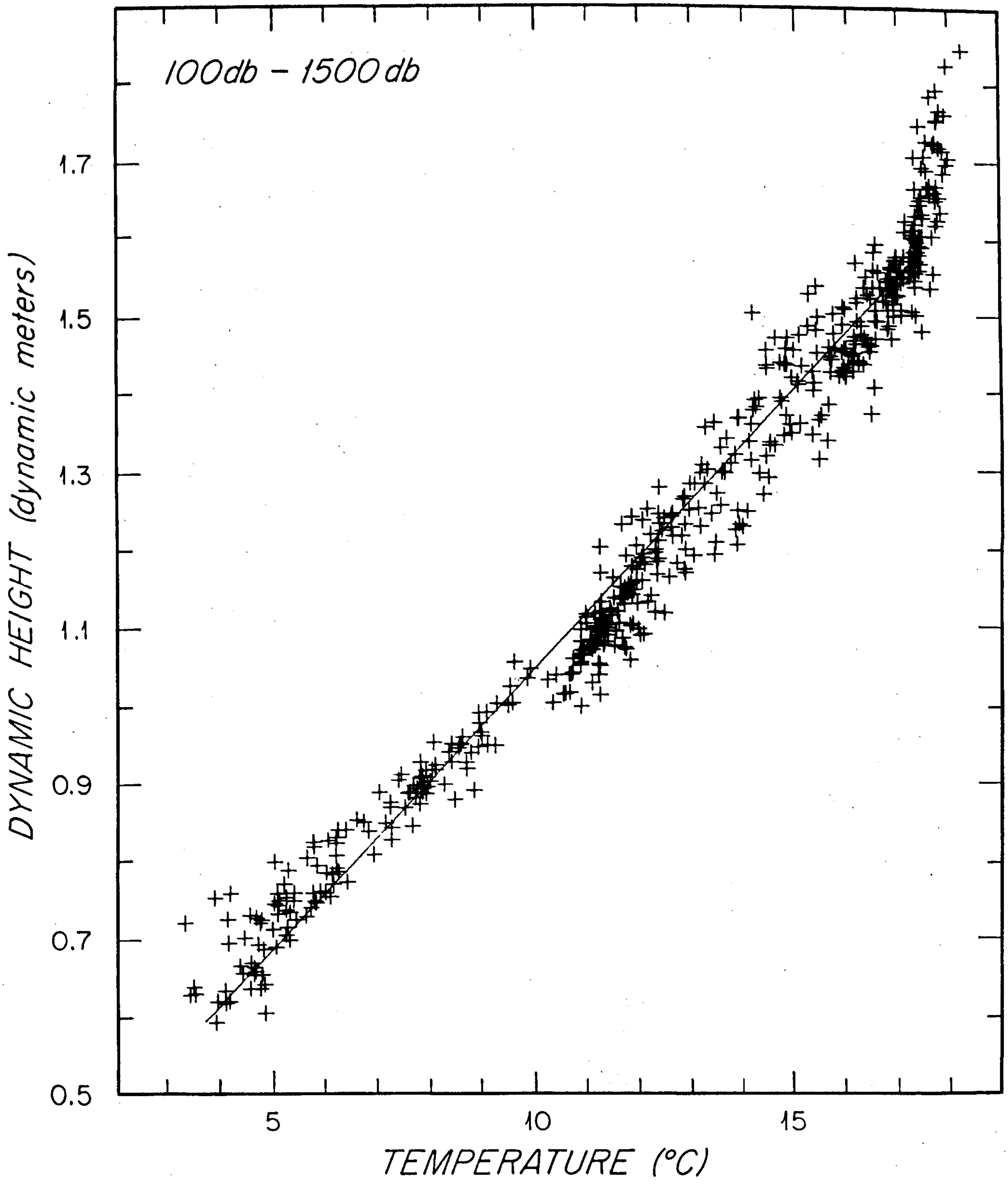

Figure 2. Scatter plot of dynamic height (dynamic meters) of 100 db relative to 1500 db as a function of the temperature at 450 m. Five hundred and seventeen stations within the latitude band 20-50°N were used; the station locations are shown in Stommel, Niiler, and Anati (1978).

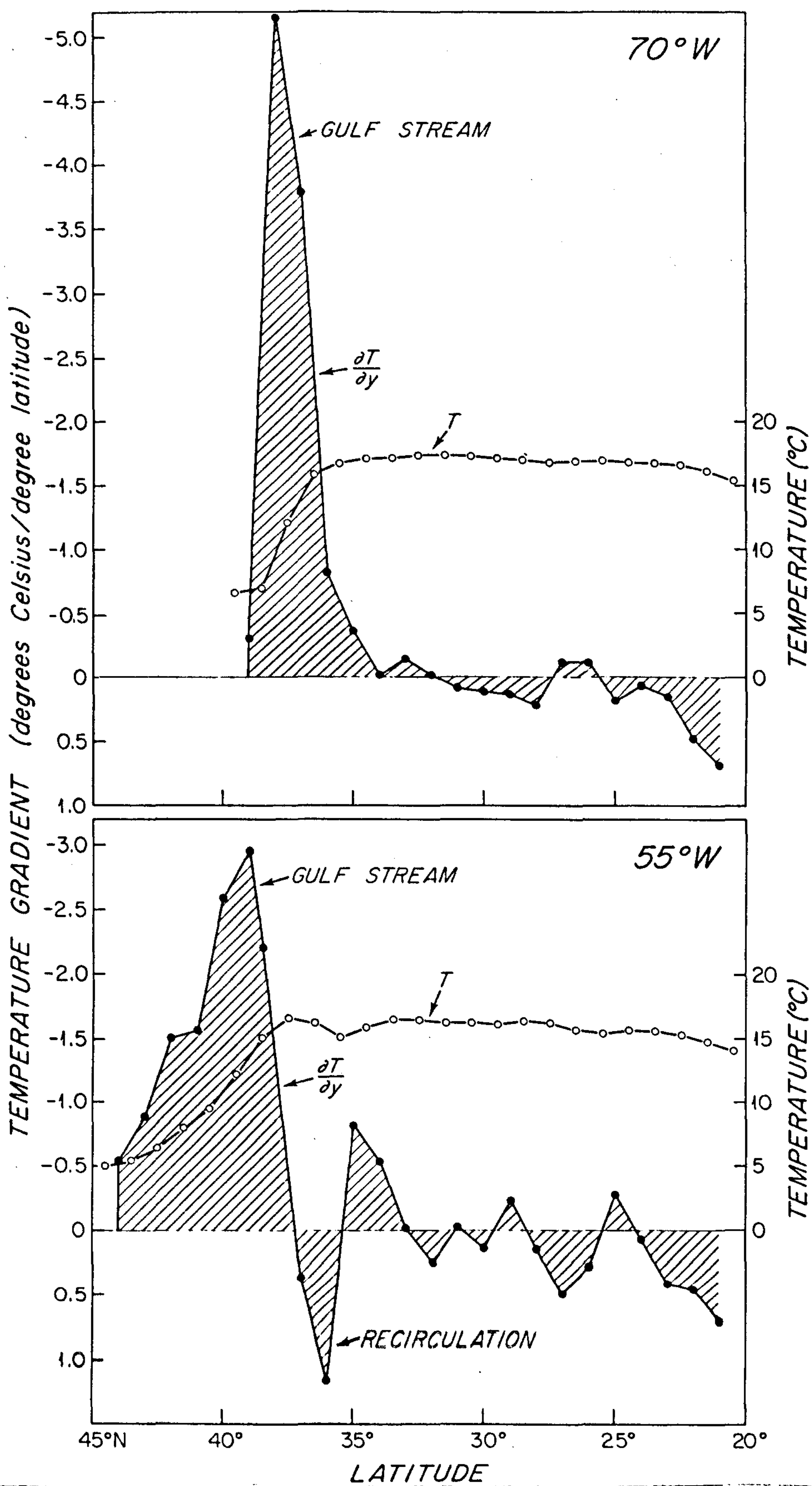

Figure 3. Temperature and temperature gradient along 70°W (69°–71°) and 55°W (54°–56°). Geostrophic velocity of the 100 db surface relative to 1500 db is proportional to temperature gradient via the geostrophic relation and the dynamic height-temperature relation (Figure 2).