

instability) must occur in the near-Gulf Stream region but the difficulties of measurement in the strong velocities that occur there has precluded quantitative estimates of the heat flux-terms. (Strong mooring motions induced by the high velocities produce fictitious temperature signals coherent with the velocity field.)

If we rule out open-sea generation by meteorology and open-sea baroclinic instability as mesoscale eddy sources, we are left only with topographic generation and generation and radiation from strong boundary currents as possible significant eddy sources. Both are difficult to evaluate quantitatively. Schmitz (1978) and Fu and Wunsch (1979) showed that the major effect of topography seems to be the spin-down of the deep ocean layers relative to the thermocline. Topography would thus more closely resemble a sink of eddy energy than its source. At the present time, then, the strong boundary currents seem the most likely *major* source of eddy energy.

These general results, coupled with the intense concentration of low-frequency energy near the western boundary currents, suggests that the eddy field may indeed be dynamically unimportant except in the immediate vicinity of the boundary currents. The presence of a strong recirculation on the flanks of the Gulf Stream System (Worthington, 1976; Stommel, Niiler, and Anati, 1978; Wunsch, 1978a; Reid, 1978; and see chapter 1) is associated with an intense barotropic eddy field (Schmitz, 1978) and a large resident population of Gulf Stream rings (Richardson, Cheney and Worthington, 1978). A discussion of the Gulf Stream System variability may be found in chapter 4 and will thus not be pursued here. But at this time the only strong evidence for the importance of the variability in the dynamics of the mean flow is in the western boundary current regions. Theories (Pedlosky, 1977) show that the interior field could be largely radiated from the Gulf Stream System and from moving Gulf Stream rings (Flierl, 1977; see also chapter 18).

The mesoscale and other spatial scales of variability become bound up with almost all other aspects of oceanography, including biological, geological, and chemical as well as physical oceanography. To the extent that the variability transports properties, nutrients and other tracers can be expected to be carried along. Eddies will scour the bottom, confusing the interpretation of sediments, and indeed will carry sediments with them from one region to another, possibly quite contrary to the overall time-mean flows. On the physical side, the variability will interact with internal waves and fine structure on the short-wavelength end of the spectrum, and there is probably an interaction between the mesoscale variability and the interannual fluctuations at the other end. We have not dealt directly here with any of these questions; to do so would

require a complete discussion of almost all aspects of oceanography and would be premature in any case.

11.3 Summary and Conclusions

The extent to which the ocean undergoes large-scale climatological fluctuations remains uncertain in the face of difficult sampling problems and the short duration over which appropriate instrumentation has existed. Given that large fluctuations exist at least in the sea-surface temperature field, we cannot really distinguish changes imposed by the atmosphere with a static ocean response from those in which large-scale oceanic dynamics are directly involved. Study of the atmospheric spectra displayed here and elsewhere suggests that the forcing and response by the atmosphere is a complex function of position and time scale. With all of the current emphasis on the question of climatic changes, we have been able to do little more than define what we do not know.

Study of the more accessible mesoscale is very much in its infancy and generalizations are dangerous because so little of the ocean has actually been appropriately sampled. At present, one can draw a few qualitative conclusions that may survive future observational programs. The mesoscale eddy field is highly inhomogeneous spatially—both in the horizontal and the vertical. Direct wind forcing and instabilities of the interior ocean are unlikely to provide much energy to the mesoscale. Much of the total mesoscale energy is found in the immediate proximity to the western boundary currents in the region where they are going seaward. It seems, therefore, that these regions are the generators of much of the eddy field energy. Detailed mechanisms are not yet known. The intense recirculations that exist on both sides of the Gulf Stream, the underlying eddy field (Luyten, 1977), and the formation and decay of Gulf Stream rings there are probably related. They suggest an intimate relation between the generation of the eddy field, the maintenance of the eastward going jet, and the transition of the jet into the comparatively quiescent interior in a complex dynamic linkage that we can only vaguely understand. One would guess that the next 10 years will find many of the keys to these puzzles.

The spectra that are displayed throughout this paper suggest that oceanic low-frequency variability does have some characteristic features independent of geography. An eddy-containing band between 50 and 150 days is a feature of most regions. Almost all the spectra show an isotropic band at frequencies higher than the eddy-containing band with a slope not far from -2 . (In the immediate vicinity of topography the isotropic band may show more structure.) The interannual band has a distinct tendency to zonality, especially in the

thermocline. These features are nearly independent of the remarkable fluctuations (two orders of magnitude) in the overall energy levels.

Although the supporting evidence is more sparse, the dominant mode of baroclinic motion in the eddy-containing band is a simple vertical translation of the thermocline with roughly isotropic horizontal velocities; lower frequencies are more zonal and confined to the upper ocean (cf. Schmitz, 1978). The isotropic band has energy levels nearly independent of depth when a simple scaling by the buoyancy frequency is made. We are totally ignorant of the deep structure on decadal and longer time scales.

The connections between medium-scale oceanic variability and the growing interest in global climate remain problematical. Despite the substantial effort that has gone into understanding the large-scale surface anomalies in the ocean and the possibility of induced changes in the atmosphere, the subject remains enigmatic. Conceivably, subtle changes in the ocean are climatologically more important. For example, one could imagine that the *changes* in regional eddy statistics induce changes in the ocean eddy heat flux (if it exists) and thus in climate. By now the reader should appreciate how far we are from being able to deduce global estimates of the eddy statistics, much less their temporal fluctuations.

Obtaining a full three-dimensional description of ocean variability has remained beyond the capability of oceanographers to this day. A few regions have been intensively studied for comparatively short periods (e.g. MODE Group, 1978; Brekovskikh et al., 1971) and use has been made of crude data sets [e.g., engine-intake temperatures (Fieux and Stommel, 1975)] to build up a qualitative global picture. But it must be admitted that despite the advances that have occurred during the past decades, perhaps our main accomplishment in studying the variability has been to come to appreciate the magnitude of the task. We now recognize the enormous discrepancy between what is required to fully describe and understand the ocean, and the tools we are actually able to bring to bear on the problem. The situation is not hopeless; improvements in moored-instrument technology, new instruments (see chapter 14), and entirely novel techniques, including the use of sound (Munk and Wunsch, 1979) and of satellite systems (Huang, Leita, and Parra, 1978), suggest that the next decade will be a period in which the descriptive oceanography of the variability field will be built up in the same way that a description of the mean was determined in the previous decades.

To conclude this chapter on a positive note we display (from Wunsch and Gaposchkin, 1980) in figure 11.16 the absolute sea-surface elevation and resulting

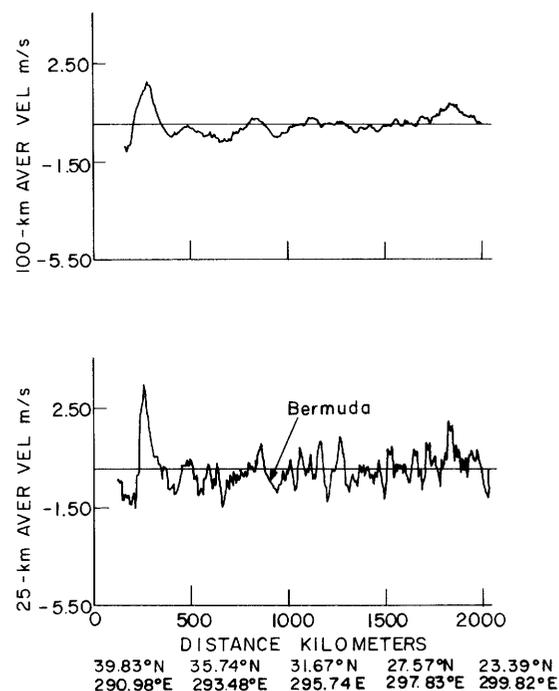


Figure 11.16 Geostrophic velocity determined by satellite altimetry along a track crossing Gulf Stream and Bermuda. Structure of the Gulf Stream seems plausible, as do amplitude and space scales of surrounding eddy field. Two different averaging intervals are displayed. (Wunsch and Gaposchkin, 1980.)

absolute surface geostrophic velocity deduced from the SEASAT-1 altimeter and the Marsh and Chang (1978) gravimetric geoid. One clearly sees the Gulf Stream, and fluctuations with the correct amplitudes and scales for mesoscale and larger eddies. Here at hand is a new tool, which along with others now under development will allow us for the first time to attack the global field of variability.