NOTES AND CORRESPONDENCE

Internal Waves, Dynamic Instabilities, and Turbulence in the Equatorial Thermocline: An Introduction to Three Papers in this Issue

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ABSTRACT

Appearing in this issue of the *Journal of Physical Oceanography* are three papers that present new observations of a distinct, narrow band, and diurnally varying signal in temperature records obtained in the low Richardson number shear flow above the core of the equatorial undercurrent. Moored data suggest that the intrinsic frequency of the signal is near the local buoyancy frequency, while towed data indicate that the horizontal wavelength in the zonal direction is 150–250 m. Coincident microstructure profiling shows that this signal is associated with bursts of turbulent mixing. It seems that this narrowband signal represents the signature of instabilities that ultimately cause the turbulence observed in the equatorial thermocline. Common problems in interpreting the physics behind the signature are discussed here.

The first intensive and systematic observations of turbulence at the equator were made in 1984 at 140°W (Moum and Caldwell 1985; Gregg et al. 1985). Attempts to confirm previous indications of a meridional peak in the rate of turbulent kinetic energy dissipation, ϵ, were hampered by a strong diurnal variation in ϵ (Moum et al. 1986; Peters et al. 1989). A surprising aspect of the diurnal variation in ϵ was the occurrence of intermittent bursts of turbulence below the surface layer in the well-stratified, low Richardson number (Ri) shear zone above the Equatorial Undercurrent (EUC) core (Peters et al. 1988; Moum et al. 1989). Locally generated internal waves were suggested as a mechanism for stimulating these bursts in the thermocline, although no direct observations of internal waves were available. The importance of learning more about this phenomenon was illustrated by a calculation indicating that the vertical transport of momentum required to close a zonal momentum budget could not be accounted for by turbulent transport alone (Dillon et al. 1989); internal waves were suspected to carry the missing momentum. From further cruises and moored observations in 1987, evidence began to accumulate that supported the existence of wavelike features in the high shear zone. Some of this evidence is presented in three papers that appear in this issue.

The new evidence arises from three types of observations:

1) *moored temperature observations* from 0°, 140°W. During the period 12 May–11 June 1987, temperature records from depths of 30–46 m showed that for a band of frequencies slightly greater than the local buoyancy frequency (N), averaged temperature variance levels were as much as three times greater at night than during the daytime (e.g., Fig. 1a from McPhaden and Peters 1992). Episodes of elevated variance did not occur every night. McPhaden and Peters suggest that the intrinsic frequency of these fluctuations is more likely to be nearer to N when the effect of Doppler shifting due to the current structure is accounted for.

2) *towed thermistor-chain observations* made from 140° to 132°W along the equator during the period 14–18 April 1987. These show a narrow band of wavelengths (150–250 m) in which the signal is ten times larger at night than in the daytime (Fig. 1b from Moum et al. 1992). Again, this peak did not occur every night but was confined to periods of sustained and moderate westward winds. Detailed examination of the record revealed that the signal was intermittent in nature, lasting several minutes to several hours.

3) *microstructure profiles* taken simultaneously with the towed thermistor observations. These show the existence of energetic turbulent overturns associated with packets of wavelike activity (Hebert et al. 1992) and, in particular, show a correlation between the magnitude of ϵ and the variance in the 150–250-m band derived from towed thermistor chain observations (Fig. 2 from Moum et al. 1992).

Taken together, these pieces of evidence seem to indicate that wavelike motions of frequency near N and

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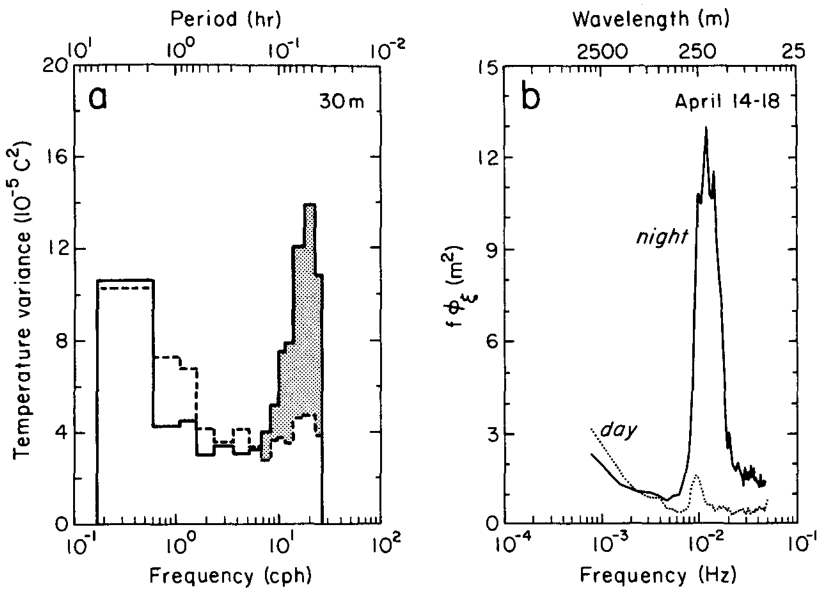

FIG. 1. (a) Variance-preserving temperature spectra computed from a *moored* temperature record at 30-m depth located at 0°, 140°W covering the period 12–27 May 1987. Nighttime variance levels (solid line) were as much as three times greater than daytime levels (dashed line) at frequencies greater than the local buoyancy frequency (~2–4 cph) (from McPhaden and Peters 1992). (b) Variance-preserving displacement spectra computed from a *towed* temperature record at 28-m depth covering the period 14–18 April 1987 and the longitudes 140°–132°W along the equator. Since the data are recorded as time series, frequency spectra are computed; however, since the record was obtained while moving at 5 kt over the surface, it is more appropriate to think of the data as a spatial series and hence these spectra as wavenumber spectra. The equivalent wavelengths are shown at the top of the figure. Nighttime variance levels (solid) exceeded daytime levels (dashed) by almost a factor of ten in the narrow wavelength band bounded by 150–250 m (from Moum et al. 1992).

zonal wavelengths of 150–250 m are associated with bursts of turbulence in the low Ri thermocline above the EUC core.

Our success at identifying a distinct and apparently important component of the small-scale physics is limited by our present inability to determine the mechanism(s) by which the observed signal was generated. We believe that two classes of phenomena could be responsible for the observed signal. On the one hand, almost free, horizontally propagating and vertically propagating or standing waves could be generated by free convection at the base of the nighttime mixed layer in the presence of strong mean vertical shear. On the other hand, the observed signal could represent a forced mode resulting from local shear instability of the mean flow. Our observations suggest that a combination of the two phenomena was present. With the mean flow having Richardson numbers barely above critical, the addition of internal waves may locally reduce Ri enough to cause shear instability. Also, the process of shear instability at fairly large vertical scales as observed could lead to the radiation of internal waves away from the region of instability. The confusion about the source of the observed signal has lead to a semantics problem. Although we have generally referred to the signal as "internal waves" in our papers, this is meant to be a generic term, implying neither purely free waves nor purely forced modes.

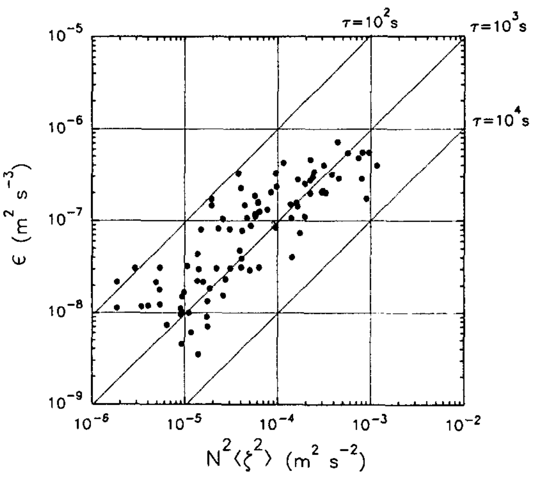

FIG. 2. Scatterplot of turbulent kinetic energy dissipation, ϵ, versus potential energy of the fluctuations, $N^2\langle\zeta^2\rangle$, associated with the peaks in the spectra of Fig. 1 (28-m depth, hourly averaged values of each parameter; from Moum et al. 1992).

Nonetheless, distinguishing between primarily forced localized modes and propagating waves is important with respect to the dynamics of small-scale processes.

As discussed by Dillon et al. (1989), one needs to determine whether an anisotropic field of internal waves can develop near the equator and transport mean momentum downward. If so, this represents a very different form of vertical momentum transport whose characteristics differ significantly from those of turbulent mixing. The wave-induced transport does not follow a flux-gradient process and cannot be detected by microstructure measurements. Alternatively, forced modes resulting from shear instability of the mean flow would break down to turbulence locally and, without further generation of propagating waves, would simply cause local mixing without transporting momentum very far vertically. Again, we suspect that there is actually a combination of the two processes at work.

This distinction between processes is important with respect to the larger-scale dynamics, as well, since the details of how the ocean transports momentum vertically affect our ability to accurately parameterize subgridscale physics in numerical models of the large-scale circulation. Parameterizations of small-scale vertical momentum transport are most often based on the assumption of downgradient turbulent fluxes and, at best, crudely approximate the true bulk transports even under the most ideal circumstances. The possibility that both waves and turbulence are important near the equator makes determination of the total vertical momentum flux more difficult, and its parameterization even more challenging.

Further progress in unravelling the complex set of interactions that take place along the equator will require a more complete set of measurements than we have at present. We really need to observe the flow field in three spatial dimensions over a sufficiently long period of time and with enough detail to distinguish between freely propagating internal waves in the presence of a mean flow and locally forced shear instabilities. To understand the mechanisms by which the waves break down to create three-dimensional turbulence, observations of wave velocities and phase speeds are required (Moum et al. 1992). We also need to better understand the role of local atmospheric forcing (wind and surface fluxes) in mediating the diurnal cycle of wave and turbulence generation. Is there a relationship, for example, between the intermittency observed in turbulent dissipation in the thermocline and the intensity of the surface forcing? What factors (oceanic and/or atmospheric) determine the narrow wavenumber/frequency band over which the enhanced diurnal cycle of internal wave variability is observed?

Data from a recent cruise may help. In October–December 1991, the equatorial station at 140°W was occupied for more than 40 consecutive days, first by a group from Oregon State University with J. Moum as chief scientist and then by a group from the University of Washington with M. Gregg as chief scientist. Microstructure devices, meteorological instruments, and shipboard thermistor-chains were deployed near the NOAA mooring that M. McPhaden had equipped with fast-sampling temperature recorders. Although that expedition was designed to observe the effects of tropical instability waves on internal waves and turbulence, the data, obtained under a variety of wind conditions, should give us a better look at the processes discussed here.

We suspect that the insights gained from our equatorial studies may be of more general applicability, since the dynamics of wave breakdown are probably similar elsewhere in the world ocean. At the equator, however, the signal levels for both internal waves and turbulence are larger and easier to detect than elsewhere. Under similar large-scale hydrodynamic conditions (e.g., in inertial shear layers at the base of the seasonal thermocline, at the top of the atmospheric boundary-layer inversion, or in laboratory experiments of stratified shear flows), the same physical processes should be important.

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