Deep Velocity Measurements in the Western Equatorial Indian Ocean

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ABSTRACT

Vertical profiles of horizontal current collected in April and June 1979 in the western Indian Ocean revealed the presence of short vertical scale (150–300 m) deep zonal jets, trapped to within 1° of the equator. Meridional velocity records displayed in general higher temporal and spatial variability and significantly less energy at the larger vertical scales as compared with zonal records. Vertical wavenumber spectra of velocity showed no statistically significant peaks. The conspicuous alternating zonal jets were identified with the slightly more energetic (as compared to background levels) 500–429 stretched meter (sm) wavelengths.

For most vertical wavenumbers, zonal currents were not significantly coherent at distances greater than 400 km downstream. At shorter zonal separations, phase lags were indistinguishable from zero. On the equator, there is an indication of upward shift of approximately 100 sm over the 500–429 sm band. Also on the equator, zonal current (u) and vertical displacement (f) were significantly coherent for the 429 sm wavelength, with f leading u with increasing depth by approximately π/2. For the same wavelength, zonal kinetic energy decayed away from the equator on scales comparable to the theoretical Kelvin wave scaling. Both these results suggested the possible presence of Kelvin waves in the records, at the 429 sm band.

Comparison of these findings with previous studies from the Indian and Pacific oceans indicates different temporal and spatial scales for the deep jets in the two basins.

1. Introduction

The equatorial ocean circulation differs in several aspects from mid-latitude flow regimes, exhibiting a variety of spatial and temporal scales and a complex pattern of mean zonal currents and countercurrents not seen at higher latitudes. The rich flow structure is not confined to the upper layers, but extends to the deep ocean as well. Deep equatorial zonal jets of short vertical scale, discovered by Luyten and Swallow (1976) in the western Indian ocean, have also been observed in the equatorial Pacific (e.g., Leetmaa and Spain 1981; Eriksen 1981; Firing 1987; Ponte and Luyten 1989) and their presence in the Atlantic Ocean has been inferred from hydrographic data (Eriksen 1982) and the recent observations of Ponte et al. (1989). These jets seem to be an ubiquitous feature of the equatorial circulation, but a complete understanding of their dynamics has remained elusive. Most theoretical studies (Wunsch 1977; Eriksen 1981; McCreary 1984; McCreary and Lukas 1986; Ponte 1988, 1989) have relied on linear equatorial wave ideas, but a lack of records extensive enough to resolve the long spatial and temporal scales of the jets has prevented any meaningful comparison between models and the data. For the same reasons, the question of whether the jets observed in the different oceans are governed by the same dynamics has not been answered.

Analyses of the most extensive records of deep equatorial currents, collected in the central Pacific, have characterized the jets in that region as narrow band currents in vertical wavenumber (300–400 m), with basin-scale zonal wavelengths (Ponte and Luyten 1989) and time scales on the order of a few years (Firing 1987; Ponte and Luyten 1989). Knowledge about the deep jets in the Indian ocean is not nearly as good. The pioneering observational work of Luyten and Swallow (1976) in the western Indian ocean did not resolve their time scales (long compared to one month) and lacked the longitudinal coverage needed to estimate their zonal scales (O’Neill and Luyten 1984).

In an effort to overcome some of these shortcomings, a more complete set of absolute velocity and CTD observations was collected in the western Indian ocean during the spring and summer of 1979 (Luyten et al. 1980), as part of the Indian Ocean Experiment (INDEX). Analysis of this dataset will be reported here. Emphasis is primarily given to the treatment of the deep zonal current records. In section 2, we describe the field work and give a qualitative description of the data. Section 3 deals with the spectral and cross-spectral analysis of the velocity records. Results are interpreted in terms of linear equatorial wave arguments in section

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4. A summary and a general discussion of results are presented in the final section.

2. The data

The INDEX dataset considered here consists of 42 vertical profiles of horizontal velocity, conductivity (salinity) and temperature, collected during two separate cruises to the western Indian ocean in April and June 1979, using the White Horse profiler described by Luyten et al. (1982). The spatial distribution of the 16 sites occupied is shown in Fig. 1. Most profiles were repeated at least once, although the zonal coverage on the first cruise was restricted to sites B, C, N, M and L (Fig. 1). A summary of the records and details on the preliminary processing of the dropsonde data can be found in Levy et al. (1982).

Zonal velocities along the equator are shown in Fig. 2, for each of the cruises (for the complete set of profiles see Levy et al. 1982). A prominent feature of the records is the short vertical scale jets present in the upper 2000 m and superposed in larger scale westward flow (especially in June). The distance between successive maxima in westward velocity ranges from 300 to 600 meters, suggesting a broad band character in vertical wavenumber. Some of the jets can be traced over several degrees of longitude and vertical shifts in time are apparent at some depths (e.g., eastward jet at 1600 m migrates upward from April to June). The meridional transect along 51°E (not shown) revealed the trapping of the shorter vertical scales to the equator.

The quantitative analysis of the data follows closely that of Ponte and Luyten (1989). The reader should refer to this earlier work for details. The vertical coordinate was stretched and the velocity amplitudes were scaled as discussed by Eriksen (1981), O’Neill (1984) and others, using a mean buoyancy frequency profile computed from the CTD data and a reference frequency $N_0 = 1.9 \times 10^{-3} \, \text{s}^{-1}$ (for this choice, the stretched and unstretched vertical coordinates are equivalent at depths of approximately 1700 m). Figure 3 shows the normalized zonal currents previously displayed in Fig. 2. Each profile looks, in general, more homogeneous in amplitude and vertical scale than its original counterpart. The stretched and scaled records were cut at 1787.5 and 4787.5 sm (approximately 400 and 4200 m in the unstretched coordinate) to a standard length of 3000 sm, and analyzed with the use of spectral methods. The data discarded at the top corresponds to the thermocline region where the stretching and scaling procedure is not valid (Eriksen 1981; O’Neill 1984). Since the largest stretched interval over the considered depth range was approximately 50 sm, vertical wavelengths shorter than 100 sm are not well resolved and will not be considered in the results.

To retain maximum vertical scale resolution, piece-averaging was used in the spectral calculations. In most cases, averaging was restricted to records taken at the same longitudes. Spectral results should be interpreted as representing the mean conditions over large sections of the observational region. Signals that are not present over a significant number of the records used in the averaging are necessarily blurred. Similar considerations underlie the use of Fourier methods, since processes which occur over large portions of the water column will be better represented in the spectral analysis.
3. Spectral and cross-spectral analysis

A major feature in the zonal velocity records is the conspicuous short vertical scale, equatorially trapped jets seen in Fig. 2. These currents will be emphasized in this section. Thus, analysis will focus primarily on the data collected within one degree of the equator.

Power spectra provide a quantitative measure of the variance associated with each vertical wavelength and reveal the presence of any dominant scale in the records. Figure 4 shows the zonal and meridional current...
power spectra obtained by piece-averaging 24 profiles collected along the equator during both cruises. Energy levels at the longer wavelengths are significantly lower for meridional current, but become comparable at smaller scales with similar vertical wavenumber dependences (close to m$^{-2}$). Both spectra are red with no statistically significant peaks at the 95% confidence level, although for zonal current an enhancement in energy is apparent at the 500–429 sm wavenumber band. These wavelengths correspond roughly to the
vertical scales of the deep jets suggested from a visual inspection of records in Fig. 3. Calculations of spectra using data from each cruise separately did not alter these results significantly. The absence of energetic peaks in zonal current contrasts with the conditions observed at 53°E in 1976 (O’Neill and Luyten 1984), when a strong signal at 720 sm and a weaker but still statistically significant one at 360 sm were present, and is also different from spectra calculated using central equatorial Pacific data (Ponte and Luyten 1989).

The existence of long time-scale periodic motions in the zonal current records was examined by computing time-lagged coherence between profiles collected at the same sites along the equator. Only a few time lags were available, ranging from one week to three months. Coherence at the shorter time lags showed significant amplitudes at zero phase for the longer wavelengths, suggesting long time scales compared to one week. Thus, casts taken a few days apart were averaged together and used in the longer lag calculations. Figure 5 shows coherence amplitude and phase computed by piece-averaging records from B, C, N, M and L sites (see Fig. 1) along the equator. The time lags for each of the five segments used ranged from two to three months, approximately. Coherence amplitude is generally below the 95% zero significance level, with only marginally significant results occurring at 1500 and 500 sm (shorter wavelengths were not in general coherent at the shorter time lag calculations and are not considered in the remaining analysis). At the 1500 sm band, coherence phase is $-58^\circ \pm 61^\circ$ (the 95% confidence error bracket is computed according to Koopmans 1974, based on ten degrees of freedom). The result at 500 sm is more relevant, since it occurs at the slightly more energetic wavenumber band associated with the jets. The coherence phase is $-74^\circ \pm 58^\circ$ (significantly different than zero) and implies an upward shift of approximately 100 sm over two/three months, for the wavelength considered. Although for the adjacent 429 sm band the coherence amplitude (0.72) was just at the level of zero significance, it is worth noticing that the calculated phase lag of $-73^\circ$ is in close agreement with the value obtained for the 500 sm band. If a single frequency wave process is responsible for the results, the implied vertical shifts correspond to upward phase propagation at periods close to one year, but the large uncertainty on the phase values and the lack of a longer time series prevent a more meaningful estimate of the time scale involved.

Correlations between zonal current and vertical displacement yield information about the presence of equatorial waves in the data. For Kelvin (Rossby) wave fields measured on the equator, $\xi$ should lead (lag) $u$ by $90^\circ$ with increasing depth (e.g., Eriksen 1982). A

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1 Since the value of $N_0$ used by O’Neill and Luyten (1984) is approximately equal to the one chosen in this study, vertical wavelengths are equivalent.
mixture of Kelvin and Rossby waves would in turn imply correlation at different phases. Vertical displacement profiles were estimated from the CTD data as described in Ponte and Luyten (1989) and treated as the velocity records (see section 2) prior to the spectral analysis. Because of the lower vertical resolution of the displacement records as compared to the velocity measurements, only results for wavelengths longer than 300 sm are considered.

Coherence between $u$ and $\xi$ using all equatorial profiles is shown in Fig. 6. Records collected one day apart were averaged and taken as a single realization in the calculation. Statistical inference is based on 32 degrees of freedom (i.e., twice the number of piece-averaged records). The strong peak in amplitude at 429 sm is significantly different than zero at the 95% confidence level, with $\xi$ leading $u$ ($-84^\circ \pm 35^\circ$) with increasing depth. The phase value for the 429 sm wavelength is consistent with the presence of Kelvin wave energy in the data. Eriksen (1981) and Ponte and Luyten (1989) found a similar relation between $u$ and $\xi$ in equatorial Pacific records, but of broader band character in vertical wavenumber.

Calculations of coherence over longitudinal separation between $u$ records yielded information on the zonal structure of power associated with each vertical scale. A number of zonal lags were possible, given the distribution of casts along the equator. To increase the degrees of freedom, station pairs at slightly different lags were grouped together. Results are contaminated by temporal effects, since profiles used in each segment are not collected simultaneously. To minimize this influence, only pairs of casts taken within one week were considered. In any case, results for the longer vertical wavelengths, which seem to have time decorrelations scales longer than one week, should not be affected. Table 1 displays the relevant findings of the coherence calculations. The records have generally short zonal decorrelation scales compared to the spatial extent of the observations. Only the 3000 sm wavelength is coherent at all the lags considered, with phases indistinguishable from zero. The 429–500 sm wavenumber band becomes decorrelated at distances longer than approximately 400 km. Since the 95% zero significance level for the three larger zonal lags is the same (0.73), there is a real drop in the coherence amplitudes at the 4° and 6°30′ lags. The near zero coherence phases observed at 1°30′ and 3° lags imply no sizable tilt of phase lines with longitude. Similar coherence analysis for meridional current suggested zonal decorrelation scales shorter than 200 km at all wavenumbers.

4. Interpreting results

The 500–429 sm bands were slightly more energetic (as compared to background energy levels) and showed a more coherent character over time and lon-

<table>
<thead>
<tr>
<th>Lags $\delta$ (sm)</th>
<th>1°30′</th>
<th>3°</th>
<th>4°</th>
<th>6°30′</th>
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<tbody>
<tr>
<td></td>
<td>$\rho$</td>
<td>$\theta$</td>
<td>$\rho$</td>
<td>$\theta$</td>
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<tr>
<td>3000</td>
<td>.88</td>
<td>$-5 \pm 23$</td>
<td>.88</td>
<td>$-18 \pm 34$</td>
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<td>500</td>
<td>.87</td>
<td>$-2 \pm 25$</td>
<td>.75</td>
<td>0 ± 68</td>
</tr>
<tr>
<td>429</td>
<td>.67</td>
<td>$-1 \pm 54$</td>
<td>.75</td>
<td>0 ± 68</td>
</tr>
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</table>
mplitude. These vertical wavelengths were identified with the conspicuous jets in Figs. 2 and 3. Spectral results at the 500–429 sm bands are thus taken to reflect the characteristics of the deep equatorial jets during INDEX.

Coherence between zonal current and vertical displacement suggests the presence of Kelvin waves at the 429 sm wavelength. A comparison of the observed meridional scaling of zonal kinetic energy with predicted values based on Kelvin wave theory seems to confirm this finding. Table 2 displays the observed and the theoretical values of the ratio between zonal kinetic energy at latitudes of 3/4°N,S to that at the equator, for the vertical scales of interest. In general, at each wavelength energy decays on scales much broader than the predicted Kelvin wave theoretical values. The only exception occurs at 429 sm, coinciding with the observed peak in coherence between $\nu$ and $\zeta$. Over this band, zonal kinetic energy near the equator is apparently dominated by Kelvin wave motions.

The Kelvin wave signature at 429 sm is absent at the 500 sm band, as indicated by the broad meridional energy scaling and the lack of coherence between $\nu$ and $\zeta$ at this wavenumber. It is unclear whether this difference, occurring between the two wavelengths most likely representative of the deep jet variability, is physically meaningful or simply arises because of the imperfect and noisy character of the data.

On the other hand, coherence over time and longitude for both the 500 and 429 sm wavelengths yielded similar results. The longer wavelength was the more coherent of the two, but both showed time scales on the order of one year and zonal decorrelation scales shorter than 500 km. The apparent time scales involved are much longer than the duration of the INDEX observations. The coverage provided by the records is thus very limited in this respect, but the following discussion may elucidate a few relevant points. If the observed upward shifts in time for the 500–429 sm wavelengths are related to vertical phase propagation of waves, one would expect phase lines to slope with longitude. For example, a Kelvin wave with a period of one year and vertical wavelength of 500 sm has zonal wavelengths on the order of 5000 km. Its presence in the records would imply phase lags as large as 40° between casts separated zonally by 500 km (periods shorter than one year would lead to larger phase estimates). Results in Table 1 do not display such lags, although the phase error bars are too large to exclude that possibility. Furthermore, the short decorrelation scales deduced from the coherence analysis seem to imply a fairly broad band process in zonal wavenumber, but the extent to which these results reflect the relatively small signal-to-noise ratio observed in the data is unclear.

Given the limited records, the interpretation of results is ambiguous. Despite the apparent contribution of low frequency Kelvin wave energy to the deep jets observed during INDEX, the details on the particular spectral composition cannot be prescribed. Coherence results seem to favor a broad band mixture of modes (perhaps including Rossby waves) in both frequency and zonal wavenumber, as opposed to a monochromatic field. The general scenario presented here is the simplest possible one in the equatorial wave theoretical framework. With the acquisition of more complete datasets, other interpretations involving completely different dynamics may be more appropriate.

5. Summary and discussion

Vertical profiles of horizontal velocity, collected during 1979 in the western Indian Ocean, revealed near-equatorial zonal currents with considerably more energy at long vertical scales and with a more coherent character over time and space than meridional currents. Deep zonal jets qualitatively similar to the features described by O'Neill and Luyten (1984) were a prominent part of the observed variability. A quantitative definition of their vertical scales was difficult, in the absence of significant peaks in wavenumber spectra. The slightly more energetic (relative to the background) and more coherent 500 and 429 sm wavelengths were taken to be representative of the jets. Zonal decorrelation scales at these wavelengths were shorter than 500 km. The 500 sm band was coherent over the duration of the records (2 to 3 months), showing an upward shift of approximately 100 sm over this period. Vertical phase propagation at periods on the order of one year could be responsible for the observed shift, but the relatively short records are not sufficient to resolve this issue. Coherence between zonal current and vertical displacement and the meridional structure of zonal kinetic energy at the 429 sm band suggested the contribution of Kelvin waves to the deep jet variability.

Pertinent issues in the wave interpretation of these long period, short vertical scale deep currents, are the forcing mechanisms responsible for their existence and how the energy reaches considerable depths, in light of the extremely small ratio of vertical to zonal group velocities of the waves considered (e.g., McCready

<table>
<thead>
<tr>
<th>$\theta$ (sm)</th>
<th>$0^\circ$45'/0$^\circ$</th>
<th>$e^{-a}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.74</td>
<td>0.34</td>
</tr>
<tr>
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<td>0.19</td>
<td>0.28</td>
</tr>
<tr>
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<td>0.24</td>
</tr>
<tr>
<td>333</td>
<td>0.99</td>
<td>0.20</td>
</tr>
</tbody>
</table>
1984). For example, on a linearly stratified ocean with
buoyancy frequency $N = 1.9 \times 10^{-3} \text{ s}^{-1}$, energy as-
associated with surface generated Kelvin waves of 1-year
period and vertical wavelength of 500 m emanating
from the African coast would reach depths of 500 me-
ters, only at distances of 5000 km from the boundary.
The paths of energy propagation in the real ocean are
more complicated due to a variety of effects (variable
$N$, critical layer absorption), but in any case, it is un-
clear how the Kelvin wave energy possibly associated
with the jets could have followed a direct path from
the surface. A more probable origin is the reflection at
the western boundary of Rossby wave energy, possibly
.injected at the surface as in Wunsch’s (1977) model.
Alternative mechanisms such as having deeper energy
sources exciting the waveguide (Kawase 1987; Ponte
1989) are more speculative, but could be important in
the Indian Ocean. Strong subthermocline currents
along the African coast have been observed near the
equator (e.g., Quadfasel and Schott 1982; Schott 1986),
and recent hydrographic measurements at $3^\circ \text{S}$ seem
to imply large geostrophic vertical shears near the
boundary, at depths below 3000 m (G. Johnson, private
communication). Variability in the system of currents
present along the slanted coast of Africa could conceiva-
ibly induce time dependent zonal motions in the
equatorial interior.

Eriksen (1979) suggested that the deep fluctuations
in dynamic height found in the Indian ocean could be
related to the jets observed by Luyten and Swallow
(1976). Calculations of dynamic height referenced to
2000 db (not shown) revealed subthermocline signals
with vertical scales too large to be related to the equa-
torial jets. It is more likely that the observed fluctua-
tions are the manifestation of lower vertical modes in
the records (e.g., Luyten and Roemmich 1982).

Observational results discussed here differ from pre-
vious analyses of similar datasets. Whether these dif-
ferences are statistically significant remains an issue,
but in any case a brief summary of the most relevant
ones is provided. O’Neill and Luyten (1984) found
significant peaks in vertical wavenumber spectra of
zonal current, based on records collected close to the
region surveyed during INDEX (the jets in their profils
were more visible than the ones shown in Fig. 2). In
addition, on the equator, vertical displacement and
zonal velocity records were not coherent at any vertical
scale, unlike what we have found here. Comparison of
the INDEX results with a study of the deep equatorial
jets by Ponte and Luyten (1989), in the central Pacific,
also unveils some important differences. Zonal current
power spectra from the two regions have comparable
background energy levels, but the jets in the central
Pacific were clearly above the background noise and
their vertical scales could be determined from the
wavenumber spectrum. The time scales for the Indian
Ocean features are apparently shorter. The different
signal-to-noise ratios found in the two studies probably
account for the more coherent character (in both time
and longitude) of the jets observed in the central Pacific.

The differences between the Pacific and Indian ocean
results may be related to a variety of reasons, but the
scales and strength of the forcing in the two oceans
(e.g., strong interannual signals in the Pacific as com-
pared to semiannual oscillations in the Indian ocean)
may be particularly important. The proximity of the
African coast to the INDEX array may also play a role
in smearing the deep jets signal, because of the higher
"eddy" kinetic energy normally present near regions
of strong currents, but the similar background spectral
levels of both datasets do not support this idea.

More deep velocity measurements of the sort ana-
alyzed here are needed, before a quantitative, more ex-
tensive comparison of the deep jet characteristics in
the various equatorial regions can be accomplished.
The picture arising from the existing records is still
vague and incomplete, but already suggests a consid-
erable variety of temporal and spatial scales, depending
on the location of the measurements. Thus, what has
come to be known in the oceanographic literature as
the "equatorial deep jets" may just be the longest time
scale, more coherent part of the overall oceanic tropical
variability associated with equatorial waves, with the
regional variations mainly reflecting the different forc-
ing characteristics.

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