The *Journal of Marine Research* is an online peer-reviewed journal that publishes original research on a broad array of topics in physical, biological, and chemical oceanography. In publication since 1937, it is one of the oldest journals in American marine science and occupies a unique niche within the ocean sciences, with a rich tradition and distinguished history as part of the Sears Foundation for Marine Research at Yale University.

Past and current issues are available at journalofmarineresearch.org.
Sources of eddy energy in the Gulf Stream recirculation region

by Harry L. Bryden

ABSTRACT

Array measurements of current and temperature made for 15 months in the main thermocline of the Gulf Stream recirculation region near 31N, 69° 30'W are analyzed to determine the energy sources for low-frequency fluctuations or eddies and the effect of these eddies on the mean circulation in the region. Eddies are found to gain energy by converting available potential energy contained in the mean circulation at a rate of $3.3 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$ with an estimated error of $1.7 \times 10^{-6}$. The signature of this energy gain is an eddy heat flux directed down the mean horizontal temperature gradient. The eddies lose energy in their interaction with the mean currents at a rate of $1.5 \times 10^{-5}$ erg cm$^{-2}$ s$^{-1}$ with an estimated error of $0.9 \times 10^{-5}$. The signature of this energy loss is an up-gradient eddy momentum flux. While the eddies lose energy in interacting with the mean currents, there is no local conversion of eddy energy into mean kinetic energy, hence the eddies do not locally drive the mean flow. Indirect estimates of the divergence of eddy energy flux across the open boundaries of the array suggest that the net import or export of energy from this region is less important than the local energy conversions in the energetics of the eddies. While comparisons with numerical model results are difficult, the signs of the observed energy conversions tend to be in agreement with those in Holland and Lin's (1975) model and in disagreement with those in Robinson et al.'s (1977) model.

1. Introduction

As long-term current meter records have been obtained from many regions of the world ocean during the past 5 years, current fluctuations with characteristic periods longer than a day have been observed to be much larger than time-averaged currents nearly everywhere. Because most emphasis has been placed on kinematic descriptions of the observed fluctuations or eddies (e.g., MODE Group, 1978), basic questions as to the origins of these eddies and their effects on the mean circulation remain unanswered. Various mechanisms for eddy generation have been proposed including forcing by variable wind stress (Veronis and Stommel, 1956), radiation from strong current regions such as the Gulf Stream (Flierl et al., 1975), and open-ocean baroclinic instability (Gill et al., 1974). Also, various hypotheses

1. Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, 02543, U.S.A.
have been advanced for the effects of eddies on the mean circulation, particularly for an eddy-driven circulation in or near the Gulf Stream (Stommel, 1966). Only near the Gulf Stream where significant eddy momentum fluxes have been reported (Schmitz, 1977; Webster, 1965) and in Drake Passage where significant eddy heat fluxes have been reported (Bryden, 1979) have eddies been observed to affect the mean circulation directly.

The generation mechanism for mid ocean eddies and the effects of eddies on the mean circulation are examined here by estimating the energy flow between mean and eddy, kinetic and potential energies using oceanic observations. Diagrams of such energy flow have provided effective summaries of the energetics of atmospheric circulation and of numerical model ocean circulation (e.g., Lorenz, 1967; Holland, 1978). The best observations from which to estimate such energy flows are those from the Polymode Local Dynamics Experiment. While these measurements were designed primarily for analysis of the vorticity and heat balances for mid ocean eddies (McWilliams and Heinmiller, 1978), they also offer an opportunity to investigate the energetics of eddies. Thus, it is the purpose of this work to estimate the flow of energy during the Local Dynamics Experiment in order to determine the sources of eddy energy and the effects of eddies on the mean circulation.

The Local Dynamics Experiment measurements were made in the main thermocline over an approximately 50 km square area centered at 31N, 69° 30'W for 15 months from May, 1978 through July, 1979 (Fig. 1). Owens et al. (1982) have shown that this region is one of generally southwestward flow, considered to be part of the Gulf Stream recirculation region (Worthington, 1976). The analogue of this recirculation region in an eddy-resolving numerical model exhibits large eddy variability and qualitatively the eddies appear to grow in this region. The energy source for these eddies varies with numerical model: in Holland and Lin's (1975) model, eddies grow by converting available potential energy contained in the mean circulation; while in Robinson et al.'s (1977) model, eddies grow by converting kinetic energy of the mean flow. The first objective of this work is to determine whether there is a local energy source for the eddies in the Gulf Stream recirculation region and to estimate the rates of energy conversion from available potential energy and kinetic energy of the mean flow into eddy energy. Since it has been suggested that eddies may drive part of the mean circulation in the western North Atlantic, particularly near the Gulf Stream (Thompson, 1971), the second objective of this work then is to determine whether the eddies act to maintain the kinetic energy of the mean flow in the Gulf Stream recirculation region. Because Harrison (1979) has suggested that the type of energy exchange between eddies and mean flow in a numerical model is a direct consequence of the modeler's choice of forcing and dissipative mechanisms, such estimates of energy exchange from ocean measurements may also provide a primary test of the applicability of various numerical models.
Estimates of energy flow from Local Dynamics Experiment measurements are necessarily for a local region without solid boundaries. Because such an open ocean region may have substantial energy fluxes across the open boundaries, the net local energy exchange between eddies and mean flow need not balance. Also, as Harrison and Robinson (1978) showed for a numerical model, the regional energetics need not be representative of the energetics of the entire ocean basin. Nevertheless, the Local Dynamics Experiment measurements which are spatially intense and of long duration, provide a unique opportunity to investigate the interaction of eddies and mean flow in a region where substantial energy exchange is expected on the basis of numerical model results. Estimates of energy flow from these measurements provide
an effective summary of the local interaction of eddies and mean flow which should establish the role of eddies in the Gulf Stream recirculation region and should allow critical comparisons between numerical model results and oceanic observations.

2. Measurements

Current and temperature measurements were made on 9 moorings deployed for 15 months in a mid ocean region southwest of Bermuda (Fig. 1) as part of the Polymode Local Dynamics Experiment during 1978 and 1979 (Mills et al., 1981). This array was designed to provide good horizontal information in the main thermocline between 600 and 850 m depth for analysis of the vorticity and heat balances of mid ocean eddies. Owens et al. (1982) have described the mean flow and eddies observed by this array and Owens (in preparation) has analyzed the vorticity and heat balances. For the purposes of this work, all measurements have been put through a low-pass filter to eliminate high-frequency internal-inertial motions and subsampled daily. Also, temperatures have been corrected for depth variations due to mooring motion as measured by pressure recorders on each mooring. Because of instrument malfunctions at various times during the experiment, the effective data period of this experiment varies with the type of information required for a particular analysis. For example, there is good vertical information available on mooring 1 from 269 m depth to 5332 m depth (20 m above the ocean bottom) for the entire 447-day deployment which McWilliams (1983) has used to examine the mean heat and potential vorticity balances. Because energy estimates require good horizontal information, the common data period of 225 days from 13 May to 23 December 1978 for current meters on all 9 moorings is the basic time period chosen for the analysis reported here.

Energy analysis requires estimates of velocities, heat fluxes, momentum fluxes, and temperature variance (Table 1), their derivatives and associated errors. In this work an overbar, $\bar{\cdot}$, denotes a time-averaged quantity and a prime, $'\cdot'$, denotes an eddy quantity which is the deviation of a daily averaged value from its time-averaged value. The 225-day average velocities in the main thermocline are generally toward the west (Fig. 2), heat fluxes are generally toward the south (Fig. 3), the principal axes for the momentum fluxes are oriented northnortheast-southsouthwest (Fig. 4) and the temperature variability is smallest in the northern part of the array. To estimate errors, 225-day averaged velocities, momentum fluxes, heat fluxes and temperature variances from the 9 moorings are fit in a least squares sense with a plane of the form $A + Bx + Cy$ where $x$ and $y$ are eastward and northward distances and $A$, $B$ and $C$ are constants determined by the fit. Because of the depth dependence evident in Table 1, each quantity is adjusted to a common depth of 637 m on each mooring by linear interpolation using the average vertical gradient between 615 and 835 m nominal depths on moorings 1, 2 and 3 before the fits are
<table>
<thead>
<tr>
<th>Mooring</th>
<th>Depth (m)</th>
<th>$\bar{u}$ (cm s$^{-1}$)</th>
<th>$\bar{v}$ (cm s$^{-1}$)</th>
<th>$\bar{u}'T'$ ($^\circ$C cm s$^{-1}$)</th>
<th>$\bar{v}'T'$ ($^\circ$C cm s$^{-1}$)</th>
<th>$\bar{u}'u'$ (cm$^2$ s$^{-2}$)</th>
<th>$\bar{u}'v'$ (cm$^2$ s$^{-2}$)</th>
<th>$\bar{v}'v'$ (cm$^2$ s$^{-2}$)</th>
<th>$TT'$ ($^\circ$C$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>616</td>
<td>-1.51</td>
<td>-.32</td>
<td>.50</td>
<td>-3.12</td>
<td>41.9</td>
<td>23.5</td>
<td>81.8</td>
<td>.444</td>
</tr>
<tr>
<td>2</td>
<td>839</td>
<td>-1.18</td>
<td>-.31</td>
<td>1.10</td>
<td>-1.92</td>
<td>23.0</td>
<td>13.1</td>
<td>45.4</td>
<td>.470</td>
</tr>
<tr>
<td>3</td>
<td>611</td>
<td>-1.61</td>
<td>+.05</td>
<td>.37</td>
<td>-3.46</td>
<td>44.4</td>
<td>24.6</td>
<td>95.2</td>
<td>.428</td>
</tr>
<tr>
<td>4</td>
<td>830</td>
<td>-.96</td>
<td>-.07</td>
<td>.52</td>
<td>-2.06</td>
<td>31.6</td>
<td>15.4</td>
<td>49.0</td>
<td>.367</td>
</tr>
<tr>
<td>5</td>
<td>619</td>
<td>-2.41</td>
<td>-1.34</td>
<td>.64</td>
<td>-2.88</td>
<td>51.6</td>
<td>30.3</td>
<td>75.0</td>
<td>.462</td>
</tr>
<tr>
<td>6</td>
<td>839</td>
<td>-1.13</td>
<td>-1.00</td>
<td>.74</td>
<td>-2.24</td>
<td>27.1</td>
<td>12.6</td>
<td>45.9</td>
<td>.426</td>
</tr>
<tr>
<td>7</td>
<td>567</td>
<td>-2.02</td>
<td>.00</td>
<td>1.17</td>
<td>-2.22</td>
<td>56.9</td>
<td>31.6</td>
<td>101.2</td>
<td>.347</td>
</tr>
<tr>
<td>8</td>
<td>728</td>
<td>-1.44</td>
<td>1.08</td>
<td>1.11</td>
<td>-1.72</td>
<td>32.1</td>
<td>15.8</td>
<td>69.4</td>
<td>.390</td>
</tr>
<tr>
<td>9</td>
<td>617</td>
<td>-1.60</td>
<td>-2.48</td>
<td>.19</td>
<td>-2.17</td>
<td>48.9</td>
<td>30.9</td>
<td>62.0</td>
<td>.430</td>
</tr>
<tr>
<td></td>
<td>587</td>
<td>-2.67</td>
<td>-1.72</td>
<td>.74</td>
<td>-.83</td>
<td>39.4</td>
<td>23.9</td>
<td>76.4</td>
<td>.421</td>
</tr>
</tbody>
</table>
Figure 2. Time-averaged current vectors in the main thermocline for each mooring. Time-averages are done over 225 days from 13 May to 23 December 1978. Mooring number is indicated beside each vector. Deeper velocities on moorings 1, 2 and 3 are indicated by dashed vectors.

calculated. An error for each quantity (Table 2) is then estimated from the sum of the squares of the residuals from the plane fit. As described by Fofonoff and Bryden (1975), errors can also be estimated for horizontal derivatives $B$ and $C$ of each quantity; however, errors in horizontal derivatives can most simply be calculated by dividing the error in any quantity by the horizontal scale of the array: 50 km in eastward distance, 70 km in northward distance. The errors in Table 2 are meant to be measurement errors in 225-day averaged quantities, and not errors in long time-averaged means. An averaging period of 225 days is surely not long enough to estimate mean quantities, since Schmitz (1977) suggested averaging periods of order 500 days are necessary to obtain stable mean quantities in the western North Atlantic and Flierl and McWilliams (1977) suggested averaging periods of order decades are necessary to estimate mean quantities. In this work, where estimates of energy conversions during a 225-day period are made, estimates of measurement
errors in 225-day averaged quantities are required to determine errors in energy conversion estimates.

3. Conversion of available potential energy into eddy potential energy

The equation for conservation of eddy potential energy is derived by multiplying the eddy heat conservation equation by $g\alpha T'/\bar{\partial}_z$ and averaging over time to yield:

$$\frac{d}{dt} \frac{g\alpha T'^2}{2\bar{\partial}_z} + \frac{\partial}{\partial x} \frac{u' g\alpha T'^2}{2\bar{\partial}_z} + \frac{\partial}{\partial y} \frac{v' g\alpha T'^2}{2\bar{\partial}_z} + \frac{\partial}{\partial z} \frac{w' g\alpha T'^2}{2\bar{\partial}_z}$$

$$= -\frac{g\alpha}{\bar{\partial}_z} \left( u' T' \frac{\partial T}{\partial x} + v' T' \frac{\partial T}{\partial y} \right) - g\alpha w'T' - \text{Dissipation} \quad (1)$$

where $(u, v, w)$ are velocities in the $(x, y, z) = (\text{eastward}, \text{northward}, \text{upward})$ directions; $t$ is time, $T$ is temperature, $g$ is the vertical component of gravitational acceleration; $d/dt$ is defined to be equal to $\partial/\partial t + \bar{u} \partial/\partial x + \bar{v} \partial/\partial y$; $\bar{\partial}_z$ is the
Figure 4. Principal axes of the current fluctuations for the 225-day averaging period at each mooring. Dashed principal axes are for deeper records on moorings 1, 2 and 3.

Table 2. Measurement errors in 225-day averaged velocities, momentum fluxes, heat fluxes and temperature variance.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Measurement error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{u})</td>
<td>cm s(^{-1})</td>
<td>.45</td>
</tr>
<tr>
<td>(\bar{v})</td>
<td>cm s(^{-1})</td>
<td>.68</td>
</tr>
<tr>
<td>(\bar{u}'u')</td>
<td>cm(^2) s(^{-2})</td>
<td>5.01</td>
</tr>
<tr>
<td>(\bar{u}'v')</td>
<td>cm(^2) s(^{-2})</td>
<td>3.21</td>
</tr>
<tr>
<td>(\bar{v}'v')</td>
<td>cm(^2) s(^{-2})</td>
<td>6.92</td>
</tr>
<tr>
<td>(\bar{u}'T')</td>
<td>°C cm s(^{-1})</td>
<td>.27</td>
</tr>
<tr>
<td>(\bar{v}'T')</td>
<td>°C cm s(^{-1})</td>
<td>.62</td>
</tr>
<tr>
<td>(\bar{T''})</td>
<td>°C(^2)</td>
<td>.082</td>
</tr>
</tbody>
</table>
vertical gradient of potential temperature and $\alpha$ is the correlation coefficient between fluctuations of density and temperature. One reason for choosing the thermocline for these measurements was the tight correlation between temperature and salinity (Fofonoff, 1973) and hence density which allows temperature fluctuations to be related to density fluctuations:

$$
\rho' = \frac{\partial \rho}{\partial T} T' + \frac{\partial \rho}{\partial S} S' = \left( \frac{\partial \rho}{\partial T} + \frac{\partial \rho}{\partial S} \frac{dS}{dT} \right) T' = -\alpha T'.
$$

With eddy potential energy defined to be $\frac{g\alpha T'^2}{2\delta_z}$ (Bray and Fofonoff, 1981), this equation relates the time change of eddy potential energy following the mean flow,

$$
\frac{d}{dt} \frac{g\alpha T'^2}{2\delta_z}
$$
to the divergence of the eddy flux of eddy potential energy,

$$
\frac{\partial}{\partial x} u' \frac{g\alpha T'^2}{2\delta_z} + \frac{\partial}{\partial y} v' \frac{g\alpha T'^2}{2\delta_z} + \frac{\partial}{\partial z} w' \frac{g\alpha T'^2}{2\delta_z},
$$
to the conversion of available potential energy into eddy potential energy,

$$
-\frac{g\alpha}{\delta_z} \left( u'T' \frac{\partial T}{\partial x} + v'T' \frac{\partial T}{\partial y} \right), \quad (2a)
$$
to the exchange between eddy kinetic energy and eddy potential energy, $-g\alpha w'T'$, and to dissipation which denotes the loss of eddy potential energy to smaller scale fluctuations such as internal waves. The objective of this section is to estimate the conversion of available potential energy which by using the thermal wind equations can be rewritten in the form:

$$
\frac{\rho_0 f}{\delta_z} \left( v'T' \frac{\partial \bar{u}}{\partial z} - u'T' \frac{\partial \bar{v}}{\partial z} \right), \quad (2b)
$$
where $f$ is the Coriolis parameter and $\rho_o$ is the density of sea water.

The conversion of available potential energy as given by 2b depends on the cross-product of eddy heat flux and the vertical shear of horizontal velocity. Maximum conversion efficiency occurs when the eddy heat flux is directed $90^\circ$ counterclockwise from the direction of vertical shear of horizontal velocity, which by the thermal wind relations is directed $90^\circ$ counterclockwise from the horizontal gradient of time-averaged temperature. Hence, maximum conversion into eddy potential energy occurs when the eddy heat flux is directed down the mean horizontal temperature gradient according to 2a.

For each of moorings 1, 2, 3, 4, and 5 which had current meters at 600 and 820 m nominal depths, the vertical shear of horizontal velocity between the two
Table 3. Conversion of available potential energy in eddy potential energy.

<table>
<thead>
<tr>
<th>mooring</th>
<th>225-day average depth (m)</th>
<th>Vertical shear magnitude ($\times 10^{-6}$ s$^{-1}$)</th>
<th>Eddy heat flux magnitude ($^\circ$C cm s$^{-1}$)</th>
<th>Difference in direction ($D_{V8} - D_{HP^*}$) ($^\circ$)</th>
<th>Conversion of available potential energy ($\times 10^{-8}$ erg cm$^{-3}$ s$^{-1}$)</th>
<th>Error ($\times 10^{-8}$ erg cm$^{-3}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>616-839</td>
<td>1.50</td>
<td>269.1</td>
<td>2.64</td>
<td>162.3</td>
<td>106.8</td>
</tr>
<tr>
<td>2</td>
<td>611-830</td>
<td>3.00</td>
<td>281.0</td>
<td>2.80</td>
<td>170.8</td>
<td>110.2</td>
</tr>
<tr>
<td>3</td>
<td>619-839</td>
<td>6.02</td>
<td>255.1</td>
<td>2.66</td>
<td>164.9</td>
<td>90.2</td>
</tr>
<tr>
<td></td>
<td>Average of 1, 2, 3</td>
<td>615-836</td>
<td>3.42</td>
<td>264.5</td>
<td>2.69</td>
<td>166.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>98.4</td>
<td>3.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mooring</th>
<th>Record length average record length (days)</th>
<th>depth (m)</th>
<th>Vertical shear magnitude ($\times 10^{-6}$ s$^{-1}$)</th>
<th>Eddy heat flux magnitude ($^\circ$C cm s$^{-1}$)</th>
<th>Difference in direction ($D_{V8} - D_{HP^*}$) ($^\circ$)</th>
<th>Conversion of available potential energy ($\times 10^{-8}$ erg cm$^{-3}$ s$^{-1}$)</th>
<th>Error ($\times 10^{-8}$ erg cm$^{-3}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>445</td>
<td>616-839</td>
<td>5.51</td>
<td>239.2</td>
<td>2.36</td>
<td>200.4</td>
<td>38.8</td>
</tr>
<tr>
<td>2</td>
<td>236</td>
<td>611-830</td>
<td>2.50</td>
<td>276.1</td>
<td>2.63</td>
<td>170.9</td>
<td>105.2</td>
</tr>
<tr>
<td>3</td>
<td>375</td>
<td>619-839</td>
<td>6.09</td>
<td>263.7</td>
<td>2.73</td>
<td>213.3</td>
<td>50.4</td>
</tr>
<tr>
<td>4</td>
<td>181</td>
<td>634-858</td>
<td>2.14</td>
<td>151.8</td>
<td>2.18</td>
<td>143.2</td>
<td>8.6</td>
</tr>
<tr>
<td>5</td>
<td>108</td>
<td>567-789</td>
<td>4.86</td>
<td>315.1</td>
<td>1.67</td>
<td>185.4</td>
<td>129.7</td>
</tr>
</tbody>
</table>

Error

2.88  3.04  3.16  1.73
current meters and the average eddy heat flux was estimated for the total record length and for the 225-day period when available (Table 3). In each case, the eddy heat flux is directed between 0 and 180° counterclockwise from the direction of vertical shear, that is in each case the eddy heat flux has a down-gradient component, and conversion of available potential energy into eddy potential energy is occurring. From values of $\bar{\theta}$ calculated from a spatially-averaged CTD station (Bryden and Millard, 1980), the rates of conversion of available potential energy according to 2b are estimated to vary between 0.25 and $5.75 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$, with errors of about $3 \times 10^{-5}$, which are due principally to the error in estimating vertical shear of horizontal velocity. To make an overall estimate of conversion of available potential energy for the 225-day period, eddy heat fluxes and vertical shears for moorings 1, 2 and 3 are averaged and an average conversion of available potential energy is estimated to be $3.27 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$ with an error of $1.73 \times 10^{-5}$. This conversion persists for the entire duration of the measurements at approximately the same rate as indicated by record-length average conversion over 445 days at mooring 1 of $2.93 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$.

4. Conversion of mean kinetic energy into eddy kinetic energy

The equation for conservation of eddy kinetic energy is derived by multiplying the eastward and northward eddy momentum equations by eastward and northward eddy velocities respectively and averaging over time to yield:

$$\frac{d}{dt} \frac{u'^2 + v'^2}{2} + \frac{\partial}{\partial x} \frac{u'}{2} \frac{u'^2 + v'^2}{2} + \frac{\partial}{\partial y} \frac{v'}{2} \frac{u'^2 + v'^2}{2} + \frac{1}{\rho_o} \left[ \frac{\partial}{\partial x} u' p' + \frac{\partial}{\partial y} v' p' + \frac{\partial}{\partial z} w' p' \right]$$

$$= - \left[ \frac{\partial}{\partial x} u'^2 + \frac{\partial}{\partial y} u' v' \left( \frac{\partial}{\partial y} + \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y} v'^2 \frac{\partial}{\partial y} \right] + g \alpha w'^2 \bar{T}' - \text{Dissipation}$$

where $p$ is pressure and $(u'^2 + v'^2)/2$ is eddy kinetic energy. This equation relates the time change of eddy kinetic energy following the mean flow,

$$\frac{d}{dt} \frac{u'^2 + v'^2}{2}$$

to the divergence of the eddy flux of eddy kinetic energy

$$\frac{\partial}{\partial x} \frac{u'}{2} \frac{u'^2 + v'^2}{2} + \frac{\partial}{\partial y} \frac{v'}{2} \frac{u'^2 + v'^2}{2}$$

to the divergence of eddy pressure work,

$$\frac{1}{\rho_o} \left[ \frac{\partial}{\partial x} u' p' + \frac{\partial}{\partial y} v' p' + \frac{\partial}{\partial z} w' p' \right],$$
Table 4. Conversion of mean kinetic energy into eddy kinetic energy.

A. 225-day average

<table>
<thead>
<tr>
<th>Momentum flux</th>
<th>Error</th>
<th>Horizontal velocity gradient</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{uu'}$</td>
<td>44.4</td>
<td>$\partial \overline{u}/\partial x$</td>
<td>+.03</td>
</tr>
<tr>
<td>$\overline{uu'}$</td>
<td>26.2</td>
<td>$\partial \overline{u}/\partial y$</td>
<td>.03</td>
</tr>
<tr>
<td>$\overline{vv'}$</td>
<td>77.3</td>
<td>$\partial \overline{v}/\partial x$</td>
<td>.53</td>
</tr>
<tr>
<td>$\overline{vv'}$</td>
<td>77.3</td>
<td>$\partial \overline{v}/\partial y$</td>
<td>-.01</td>
</tr>
</tbody>
</table>

$$- \left[ \overline{u'^2} \frac{\partial \overline{u}}{\partial x} + \overline{u''v'} \left( \frac{\partial \overline{v}}{\partial x} + \frac{\partial \overline{u}}{\partial y} \right) + \overline{v'^2} \frac{\partial \overline{v}}{\partial y} \right] = -1.52 \pm .88 \times 10^{-5} \text{ erg cm}^{-3} \text{ s}^{-1}.$$  

B. 426-day average

<table>
<thead>
<tr>
<th>Momentum flux</th>
<th>Horizontal velocity gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{uu'}$</td>
<td>$\overline{uu'}$</td>
</tr>
<tr>
<td>$\overline{uu'}$</td>
<td>$\overline{uu'}$</td>
</tr>
<tr>
<td>$\overline{vv'}$</td>
<td>$\overline{vv'}$</td>
</tr>
<tr>
<td>$\overline{vv'}$</td>
<td>$\overline{vv'}$</td>
</tr>
</tbody>
</table>

$$- \left[ \overline{u'^2} \frac{\partial \overline{u}}{\partial x} + \overline{u''v'} \left( \frac{\partial \overline{v}}{\partial x} + \frac{\partial \overline{u}}{\partial y} \right) + \overline{v'^2} \frac{\partial \overline{v}}{\partial y} \right] = -2.94 \times 10^{-5} \text{ erg cm}^{-3} \text{ s}^{-1}.$$  

Estimates of momentum fluxes, $\overline{u'^2}$, $\overline{u''v'}$ and $\overline{v'^2}$, are made by averaging momentum fluxes for the 225-day period adjusted to 637 m and estimates of horizontal gradients of velocity are calculated from least squares plane fits to the 225-day averaged velocities for all 9 moorings (Table 4). From these values, the conversion of mean kinetic energy into eddy kinetic energy is estimated to be $-1.52 \pm .88 \times 10^{-5} \text{ erg cm}^{-3} \text{ s}^{-1}$, that is the eddies are losing energy in their interaction with the mean flow. This loss of eddy energy is principally due to eastward transport of northward momentum, $\overline{u''v'}$, up the eastward gradient of time-averaged northward velocity, $\partial \overline{v}/\partial x$. This loss of eddy energy persists for the entire duration of the
measurements as indicated by the loss of eddy energy over 426 days calculated from moorings 1, 6, 8 and 9 of $-2.94 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$.

Adding equations 1 and 3 which eliminates the exchange between eddy kinetic and potential energies, $g\alpha w'T'$, yields the equation for the conservation of eddy potential energy, $E'$, plus eddy kinetic energy, $K'$:

$$\frac{d}{dt} E' + K' + \frac{\partial}{\partial x} u' (E' + K' + p'/\rho_o) + \frac{\partial}{\partial y} v' (E' + K' + p'/\rho_o) = \frac{\partial}{\partial z} w' (E' + K' + p'/\rho_o) + \frac{\partial}{\partial z} w' (E' + K' + p'/\rho_o)$$

$$= -\frac{g\alpha}{\delta} T' \left[ \frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} \right] - \left[ \frac{1}{2} \frac{\partial u'^2}{\partial x} + \frac{\partial v'^2}{\partial y} \left( \frac{\partial T'}{\partial y} + \frac{\partial T'}{\partial x} \right) \right] - \text{Dissipation}$$

(4)

where $\partial w'K'/\partial z$ is included for symmetry even though it is formally an order Rossby number smaller than the other terms. For these measurements, the sum of eddy potential plus kinetic energy increases due to conversion of available potential energy at the rate of $3.27 \pm 1.73 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$ and decreases due to negative conversion of mean kinetic energy at a rate of $1.52 \pm .88 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$. Although these individual conversions are larger than their estimated errors, the net conversion into eddy potential plus kinetic energy of $1.75 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$, determined by the sum of individual conversions, is smaller than its estimated error of $1.94 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$. Thus, the net conversion into eddy energy during this 225-day period is not significantly different from zero.

5. **Effect of eddies on the kinetic energy of the mean flow**

The equation for conservation of the kinetic energy of the mean flow is derived by multiplying the time-average eastward and northward momentum equations by time-averaged eastward and northward velocities respectively to yield:

$$\frac{d}{dt} \frac{\bar{u}^2 + \bar{v}^2}{2} + \frac{1}{\rho_o} \left[ \frac{\partial}{\partial x} \bar{u} \bar{p} + \frac{\partial}{\partial y} \bar{v} \bar{p} + \frac{\partial}{\partial z} \bar{w} \bar{p} \right] =$$

$$- \left[ \bar{u} \left( \frac{\partial}{\partial x} \bar{u} \bar{u}' + \frac{\partial}{\partial y} \bar{u}' \bar{v}' \right) + \bar{v} \left( \frac{\partial}{\partial x} \bar{u}' \bar{v}' + \frac{\partial}{\partial y} \bar{v}' \bar{v}' \right) \right] + g\alpha \bar{w} T$$

where $(\bar{u}^2 + \bar{v}^2)/2$ is the kinetic energy of the mean flow. This equation relates the time change of mean kinetic energy following the mean flow,
\[
\frac{d}{dt} \left( \frac{\bar{u}^2 + \bar{v}^2}{2} \right),
\]
to the divergence of the pressure work by the mean flow,
\[
\frac{1}{\rho_0} \left[ \frac{\partial}{\partial x} \bar{u} \bar{p} + \frac{\partial}{\partial y} \bar{v} \bar{p} + \frac{\partial}{\partial z} \bar{w} \bar{p} \right],
\]
to the production of mean kinetic energy by the eddies,
\[
- \left[ \bar{u} \left( \frac{\partial}{\partial x} \bar{u}' \bar{u}' + \frac{\partial}{\partial y} \bar{u}' \bar{v}' \right) + \bar{v} \left( \frac{\partial}{\partial x} \bar{u}' \bar{v}' + \frac{\partial}{\partial y} \bar{v}' \bar{v}' \right) \right]
\]
and to exchange between mean kinetic energy and available potential energy \(\gamma \bar{w} T\). It is the objective of this section to estimate the production of mean kinetic energy by the eddies.

Horizontal gradients of momentum fluxes during the 225-day period are estimated from least squares plane fits to momentum fluxes adjusted to a common depth of 637 m for all 9 moorings. The average velocities, \(\bar{u}\) and \(\bar{v}\), are estimated by averaging 225-day averaged velocities over all 9 moorings. The production of mean kinetic energy by the eddies then is estimated to be \(-0.09 \pm 0.23 \times 10^{-5}\) erg cm\(^{-3}\) s\(^{-1}\) (Table 5). This production is small because the horizontal gradients \(\partial \bar{u} \bar{u}' / \partial x\) and \(\partial \bar{v} \bar{v}' / \partial y\) and \(\partial \bar{u} \bar{v}' / \partial x\) and \(\partial \bar{v} \bar{v}' / \partial y\) tend to be of similar magnitudes but of opposite signs so that their sums are small. The production of mean kinetic energy for the 426-day duration of the measurements on moorings 1, 6, 8 and 9 is also small, only \(-0.04 \times 10^{-5}\) erg cm\(^{-3}\) s\(^{-1}\). Hence, within estimated error, there is no production of mean kinetic energy by the eddies in this region of the Gulf Stream recirculation.

For a region with solid boundaries, the sum of the production of mean kinetic energy by eddies in equation 5 plus the conversion of mean kinetic energy into eddy energy in equation 3 would be zero. For this open ocean region, this sum need not be, and indeed is not, zero. These two terms differ by a divergence of energy flux across the open boundary,
\[
\frac{\partial}{\partial x} (\bar{u} \bar{u}' \bar{u}' + \bar{v} \bar{u}' \bar{v}') + \frac{\partial}{\partial y} (\bar{u} \bar{u}' \bar{v}' + \bar{v} \bar{v}' \bar{v}') .
\]
For these measurements, the eddies lose kinetic energy in their interaction with the mean flow but there is no local production of mean kinetic energy in the process. The loss of eddy energy is exported from this open ocean region; that is, this region is doing work on the rest of the ocean. Since the rest of the ocean has solid boundaries, in some other region there must be a production of mean kinetic energy or a production of eddy kinetic energy which balances the loss of eddy kinetic energy in this local region.

The fact that the sum of mean plus eddy kinetic energies need not be conserved
Table 5. Production of mean kinetic energy by eddies.

A. 225-day average

<table>
<thead>
<tr>
<th>Horizontal gradient of momentum flux ((\times 10^{-6} \text{ cm s}^{-2}))</th>
<th>Error ((\times 10^{-6} \text{ cm s}^{-2}))</th>
<th>Horizontal velocity ((\text{cm s}^{-1}))</th>
<th>Error ((\text{cm s}^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\delta u'u'/\delta x)</td>
<td>-0.96</td>
<td>.97</td>
<td>(\bar{u})</td>
</tr>
<tr>
<td>(\delta u'v'/\delta x)</td>
<td>-1.40</td>
<td>.62</td>
<td>(\bar{v})</td>
</tr>
<tr>
<td>(\delta u'v'/\delta y)</td>
<td>0.78</td>
<td>.44</td>
<td></td>
</tr>
<tr>
<td>(\delta v'v'/\delta y)</td>
<td>0.81</td>
<td>.95</td>
<td></td>
</tr>
<tr>
<td>(- \left[ \bar{u} \left( \frac{\partial}{\partial x} u'u' + \frac{\partial}{\partial y} u'v' \right) + \bar{v} \left( \frac{\partial}{\partial x} u'v' + \frac{\partial}{\partial y} v'v' \right) \right] = -0.09 \pm 0.23 \times 10^{-6} \text{ erg cm}^{-3} \text{ s}^{-1}.)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B. 426-day average

<table>
<thead>
<tr>
<th>Horizontal gradient of momentum flux ((\times 10^{-6} \text{ cm s}^{-2}))</th>
<th>Horizontal velocity ((\text{cm s}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\delta u'u'/\delta x)</td>
<td>-1.87</td>
</tr>
<tr>
<td>(\delta u'v'/\delta x)</td>
<td>0.47</td>
</tr>
<tr>
<td>(\delta u'v'/\delta y)</td>
<td>0.22</td>
</tr>
<tr>
<td>(\delta v'v'/\delta y)</td>
<td>1.36</td>
</tr>
<tr>
<td>(- \left[ \bar{u} \left( \frac{\partial}{\partial x} u'u' + \frac{\partial}{\partial y} u'v' \right) + \bar{v} \left( \frac{\partial}{\partial x} u'v' + \frac{\partial}{\partial y} v'v' \right) \right] = -0.04 \times 10^{-6} \text{ erg cm}^{-3} \text{ s}^{-1}.)</td>
<td>(\bar{u} = -2.98)</td>
</tr>
</tbody>
</table>

for an open ocean region led Harrison and Robinson (1978) to conclude that energy flow diagrams are useful only for regions where this sum is conserved, that is for regions where the divergence of energy flux across the open boundaries (6) is zero. Here, the different view is taken that consistent conservation equations for an open ocean region can be written for eddy potential energy (1), eddy kinetic energy (3) and mean kinetic energy (5) and local energy conversion can be defined and estimated as described above. It is not appropriate, however, to label these energy conversions as energy exchanges between mean and eddy energies unless the sum of mean plus eddy energy is shown to be conserved within the open region. Thus, local energy conversions, and not energy exchanges, are presented here.

6. Changes in kinetic and potential energies following the mean flow

It would be useful if all terms in equations 1, 3 and 5 could be evaluated from these Local Dynamics Experiment measurements, but at this time it is not possible to evaluate terms involving pressure or vertical velocity or the eddy fluxes of eddy potential and kinetic energies. Terms involving pressure cannot be simply evaluated because pressure and depth are not measured independently in the ocean. When all
Local Dynamic Experiment measurements, including these moored current and temperature measurements, CTD measurements, and SOFAR float current measurements, are combined into maps of streamfunction or pressure as a function of $x$, $y$, $z$ and $t$, it may be possible to evaluate the divergence of pressure work in equations 3 and 5. At this time, terms involving pressure cannot be evaluated. Since vertical velocity is not measured, terms involving $w$ cannot be simply evaluated. While there are methods to infer $w$ from current and temperature measurements (Bryden, 1976, 1980), the reliability of such estimates of $w$ must first be established by their use in vorticity balance calculations (Owens, in preparation). Although it is possible in principle to evaluate eddy fluxes of eddy potential and kinetic energies from these measurements, attempts to estimate the divergence of eddy fluxes are dominated by errors which are thought to be due to the necessary but uncertain adjustment for variations in measurement depths on different moorings. Thus, the only additional terms in equations 1, 3 and 5 which can be evaluated with relatively small errors are the time changes of eddy kinetic energy, eddy potential energy and mean kinetic energy following the mean flow.

For very long averaging periods, stable estimates of mean quantities would not change with time and local time changes, $\partial / \partial t$, of eddy potential energy, eddy kinetic energy and mean kinetic energy would be zero. Comparison of these energies for 426-day and 225-day averaging periods indicates an increase with time in all energies at rates of $0.05$ to $0.15 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$, suggesting the 225-day averaging period is not long enough to obtain stable mean energies. Because these rates of energy increase are small compared with estimated conversions and because they should be zero for long enough averaging periods, they are neglected in estimating the time changes of energy following the mean flow.

The time changes of energy following the mean flow, $u \partial / \partial x + v \partial / \partial y$, are estimated from the average velocity for all 9 moorings and from the horizontal gradients of energy obtained from least squares fits to energies for all 9 moorings (Table 6). The time change of eddy potential energy following the mean flow is $1.18 \pm 0.76 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$, indicating perhaps that some of the conversion of available potential energy into eddy potential energy estimated above is used to increase the eddy potential energy along the path of the mean flow. The time change of eddy kinetic energy following the mean flow is $-0.84 \pm 0.18 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$, indicating that some of the loss of eddy kinetic energy in the interaction with the mean flow estimated above is reflected in a decrease in eddy kinetic energy along the path of the mean flow. The time change of mean kinetic energy following the mean flow is $+0.09 \pm 0.05 \times 10^{-5}$ erg cm$^{-3}$ s$^{-1}$ which is within the error of the production of mean kinetic energy by eddies estimated above.

7. Discussion

This analysis of the Local Dynamics Experiment measurements shows that eddies
Table 6. Changes in kinetic and potential energies following the mean flow.

\[ \tilde{u} \frac{\partial}{\partial x} + \tilde{v} \frac{\partial}{\partial y} (\times 10^{-5} \text{erg cm}^{-3} \text{s}^{-2}) \]

<table>
<thead>
<tr>
<th>EPE</th>
<th>( \frac{g \alpha \tilde{T}^{2}}{2 \tilde{\nu}} )</th>
<th>1.18 ± 0.76</th>
</tr>
</thead>
<tbody>
<tr>
<td>EKE</td>
<td>( \frac{u'^{2} + v'^{2}}{2} )</td>
<td>−0.84 ± 0.18</td>
</tr>
<tr>
<td>MKE</td>
<td>( \frac{\tilde{u}^{2} + \tilde{v}^{2}}{2} )</td>
<td>0.09 ± 0.05</td>
</tr>
</tbody>
</table>

gain their energy by conversion of available potential energy at a rate of 3.3 \( \times 10^{-5} \) erg cm\(^{-3}\) s\(^{-1}\) and lose their energy by a negative conversion of mean kinetic energy at a rate of 1.5 \( \times 10^{-5} \) erg cm\(^{-3}\) s\(^{-1}\). In addition, Brown and Owens (1981) have used these measurements to show that eddies lose energy in their interaction with internal waves at a rate of 1.2 \( \times 10^{-5} \) erg cm\(^{-3}\) s\(^{-1}\). This provides an estimate of the dissipation of eddy energy in equation 4. Thus, an energy flow diagram can be made for eddies during the Local Dynamics Experiment in which each of the conversion rates is larger than its estimated error (Fig. 5). The eddies gain a net amount of energy from the potential and kinetic energies contained in the mean circulation and lose energy in their interaction with high frequency internal waves. If the increase in eddy potential plus kinetic energy following the mean flow of 0.3 \( \times 10^{-5} \) erg cm\(^{-3}\) s\(^{-1}\) is also considered, then the eddy energy balance is nearly complete with only a net increase of eddy energy at a rate of 0.2 \( \times 10^{-5} \) erg cm\(^{-3}\) s\(^{-1}\) unaccounted for. The error, however, in this net increase of eddy energy is quite large, of order 2.1 \( \times 10^{-5} \) erg cm\(^{-3}\) s\(^{-1}\). The smallness of the residual in the energy balance does suggest that the divergence of eddy energy fluxes in equation 5, which could not be estimated, is not of overwhelming importance in the eddy energy balance for this region.

These results are consistent with results in the atmosphere (Lorenz, 1967) where eddies grow in a baroclinic instability process by converting available potential energy contained in the mean density distribution and then feed their energy into the kinetic energy of the mean flow. While this analysis shows that eddies lose energy in their interaction with the mean flow but do not locally feed their energy into the kinetic energy of the mean flow, these results are consistent with the concepts of down-gradient eddy heat flux or positive eddy diffusivity and of up-gradient mo-
Figure 5. Energy flow diagram for eddies observed during a 225-day period in the Gulf Stream recirculation region. APE denotes available potential energy and MKE denotes mean kinetic energy contained in the mean circulation. EPE denotes eddy potential energy, EKE eddy kinetic energy, IWPE internal wave potential energy and IWKE internal wave kinetic energy. Energies are presented in units of erg cm$^{-3}$ and conversion rates in units of erg cm$^{-3}$ s$^{-1}$. The value of APE is calculated by Bray et al. (1981).

momentum flux or negative eddy viscosity. For these observations, the eddy diffusivity of heat is estimated to be:

$$K_H = \frac{-\bar{v}'T'}{\partial T/\partial y} = 1.1 \times 10^8 \text{ cm}^2 \text{s}^{-1};$$

and the eddy viscosity is estimated to be:

$$A_H = \frac{-\bar{u}'v'}{\frac{\partial \bar{v}}{\partial x} + \frac{\partial \bar{u}}{\partial y}} = -0.9 \times 10^8 \text{ cm}^2 \text{s}^{-1}.$$

While these values are large, comparisons between linear stability analysis and results of eddy-resolving general circulation models (Haidvogel and Holland, 1978)
suggest that large fluxes and hence large eddy coefficients are expected where the mean flow is unstable, which occurs when the vertical shear exceeds $5 \times 10^{-5} \text{ s}^{-1}$ or the horizontal shear exceeds $3 \times 10^{-6} \text{ s}^{-1}$. Since these measurements exhibit mean vertical shears close to Haidvogel and Holland's (1978) critical value (Table 3), a large down-gradient heat flux and hence a large eddy diffusivity might be expected. Also, this large value of eddy diffusivity is in reasonable agreement with Price's (1982) direct estimate of diffusivity from SOFAR float measurements at 700 m during the Local Dynamics Experiment.

It is of interest to compare these measurements with results from eddy-resolving numerical models. While kinematic comparisons such as those by Schmitz and Holland (1982), and dynamical comparisons, such as those suggested by Rhines and Holland (1979) and Holland and Rhines (1980), would also be worthwhile, energetic comparisons are explored here. Such comparisons are difficult because these results are for a local region while model results are usually summarized by a basin-averaged energy flow and Harrison and Robinson (1978) have shown that local energy conversions are generally different from basin-averaged energy conversions. On a basin-averaged basis, Harrison (1979) reported that every model exhibits conversion of mean kinetic energy into eddy energy, which is opposite to that found here, and every model except one exhibits conversion of available potential energy, which is consistent with that found here. For the recirculation region, Robinson et al. (1979, Table 3) noted that the eddy production mechanism is due to conversion of mean kinetic energy in the Robinson et al. (1977) model and is due to conversion of available potential energy in the Holland and Lin (1975) model. Harrison and Robinson's (1978) local energy analysis for the recirculation region in the Robinson et al. (1977) model confirmed a strong conversion of mean kinetic energy into eddy energy and a weaker conversion of eddy energy into mean potential energy which is directly opposed to the results presented here for the Gulf Stream recirculation. The direction of energy conversion, however, appears to be sensitive to the amount of mixing in the model. When Semtner and Mintz (1977) reduced friction and mixing in the Robinson et al. (1977) model by using a biharmonic form to parameterize subgrid scale turbulent processes, the eddies gained energy both by conversion of available potential energy and by conversion of mean kinetic energy. The conversion of available potential energy in the recirculation region of Holland and Lin's (1975) model (which is similar to experiment 1 of Holland, 1978) agrees at least in sign with the results presented here. Because the regional energetics of these models has not been reported, it is difficult to make comparisons of their basin-averaged energy conversion with the local energy conversion estimated here. An attempt is made, however, to compare the time period for eddy growth, calculated by dividing the sum of eddy kinetic plus potential energy by the conversion of available potential energy, for the model and observations. For the basin-averaged energy flow presented by Holland and Lin (1975), this growth
time scale of 67 days is in reasonable agreement with the growth time scale of 54 days for the Local Dynamics Experiment observations.

While detailed comparisons between these results and numerical model results are not possible at this time, it should be clear that, with appropriate calculations, observed and model energy conversions can be compared. For the observations, conversion of available potential energy, which is proportional to the cross-product of eddy flux and mean vertical shear of velocity, can be estimated wherever current measurements at 2 depths are made on a mooring; and conversion of mean kinetic energy into eddy energy, which is proportional to the product of eddy momentum fluxes and mean horizontal gradients of velocity, can be estimated wherever an array of current measurements on 3 moorings is deployed. For comparison, modellers should present maps of conversion of available potential energy,

$$\frac{\rho_0 f}{\partial z} \left( \frac{\nu T' \partial \bar{u}}{\partial z} - \frac{u' T' \partial \bar{v}}{\partial z} \right),$$

and of conversion of mean kinetic energy into eddy energy,

$$- \left[ \overline{u'^2 \frac{\partial \bar{u}}{\partial x}} + u' v' \left( \frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right) + \frac{\partial^2 \bar{v}}{\partial y} \right],$$

where mean is defined as a time-average and eddy as a deviation from time-average in the same manner as defined by experimentalists.

Finally, it is notable that the observed eddy heat flux is directed southward in opposition to the net northward ocean heat transport expected across this latitude in the Atlantic (Hall and Bryden, 1982). If this southward eddy heat flux of 2.3°C cm s$^{-1}$ is typical of even a 1000 km zonal distance and of the upper 1 km of the ocean, it would be an important factor in Atlantic heat transport. That the eddy heat transport is directed down the local horizontal temperature gradient and not down the global scale temperature gradient suggests that the eddies are related to local rather than global conditions.

Acknowledgments. This analysis was supported by the Office for the International Decade of Ocean Exploration of the National Science Foundation under Grant OCE 77-19403. The high quality current and temperature measurements made during the Local Dynamics Experiment are due to the careful preparation and post-calibration of instruments by the W.H.O.I. Buoy Group. Carol Mills and Ellen Levy made most of the calculations reported here and Audrey Williams meticulously typed the manuscript. Criticism of an earlier draft by Nancy Bray, Bach-Lien Hua, James McWilliams and James Price helped improve the error analysis and clarify the text. Woods Hole Contribution Number 4948.

REFERENCES


Received: 1 July, 1981; revised: 23 August, 1982.