Dissipation Mechanisms and the Importance of Eddies in Model Ocean Energy Budgets

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ABSTRACT

The importance of mesoscale eddies in the basin energy budgets of closed-basin numerical model oceanic systems that attempt to resolve such motions varies greatly from calculation to calculation. In existing calculations, eddy importance has been found to depend strongly on the dissipation mechanism(s) selected. These energy budget results can be understood by examination of how eddy and mean flow kinetic energy are dissipated in the long-time mean in the different regions of the model flow. Scale analysis arguments are presented, assuming that the characteristics of the flows satisfy certain mild quasi-oceanic constraints, to investigate these dissipation terms. From these scale estimates it appears that many of the model ocean results can be understood in terms of a nondimensional parameter that measures the relative importance of horizontal and bottom friction dissipation. When horizontal friction dissipation dominates, eddies can only be of modest importance in basin energy budgets, but when bottom friction dissipation dominates, eddies generally must be important. This follows simply from the assumed flow characteristics. The implications of these results on the interpretation of present modeling results are described.

1. Introduction

The roles played by oceanic turbulence on all scales in the climatological mean ocean circulation are the subject of much observational work and theoretical speculation at present (see, e.g., Garrett, 1979). One particular set of investigations is directed toward trying to understand the interaction between mesoscale motions (periods in excess of tens of days, horizontal wavelengths of hundreds of kilometers) and the long-time averaged ocean circulation, especially in midlatitudes (see, e.g., POLYMODE, 1976). Mesoscale motions appear to dominate the energy spectrum in many parts of the ocean (Rhines, 1972) and it has often been assumed that they play some important role in the circulation. However, the paucity of data is such that even the question of whether or not they are important to the dynamics of the time-mean circulation of a given region of the ocean cannot be answered confidently at this time.

Because of the scarcity of ocean data, idealized numerical model ocean circulation experiments, whose grids allow eddy-scale motions to exist (the so-called EGCM's), have been used to investigate the character of eddy-mean flow interaction in idealized systems (e.g., Holland, 1978; Semtner and Holland 1978; Robinson *et al.*, 1977). Of particular interest has been the extent to which the model eddies are important in the dynamics of the model mean flows. The work described here examines some of the existing EGCM results about eddy importance from a perspective that reveals them to be of rather more limited interest than has heretofore been understood.

The importance of eddies in EGCM systems has basically been measured by examining their role in the model basin energy budgets. As has been noted, the model eddies are of almost no consequence in some basin budgets, are extremely important in others, and in a few cases fall in between these extremes. Further, they are found to be important only when certain types of subgrid-scale processes are included in the model physics (Harrison, 1979). Because the subgrid-scale processes provide the dissipation that permits these forced systems to come into equilibrium it is not possible to eliminate them; they are an essential part of the model system. Unfortunately, little is known about how these processes ought to be modeled in EGCM's. Since existing EGCM energy budget results show considerable sensitivity to the form of the assumed model subgrid-scale processes, it is of interest to understand why this sensitivity exists and to try to assess its effects on the conclusions that can usefully be drawn from these energy budget results.

For the EGCM experiments so far published, the importance of eddies in the basin energy budgets can be understood if the factors that determine the ratio of dissipation of mean eddy kinetic energy to that of mean flow kinetic energy, $[D']/[\bar{D}]$, can be understood. This results from the fact that $[D']/[\bar{D}]$ is

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well correlated with the various basin energy budget measures of eddy importance, for example, the ratio of the rate of conversion of mean flow energy into eddy kinetic energy to the rate of energy input into mean flow energy by the steady external forcing. Such correlation is required by energy conservation for some model systems, yet holds for others in which it is not required by first principles. See Harrison (1979) for a discussion of EGCM energetic results or if these concepts are unfamiliar.

Simple scale arguments are used here to estimate $[D']/[\bar{D}]$ for a variety of flow types, subgrid-scale processes and subgrid-scale process magnitudes, assuming that the model mean and eddy flow are what will here be called quasi-oceanic. It will be shown that in the parameter range of existing EGCM experiments, some choices of subgrid-scale processes lead to eddies being quite important in the basin energy budgets, other choices lead to the eddies being of at most limited importance, and one case is ambiguous. For the EGCM's so far published a single nondimensional parameter is identified that can roughly determine the importance of the eddies without need of further calculation.

Section 2 introduces the scale notation that will be used, the characteristics assumed by the quasi-oceanic flow requirement, and gives estimates for the mean and eddy dissipation quantities of interest. Section 3 considers the implications of Section 2 for published EGCM results, while Section 4 summarizes the results of Sections 2 and 3 and offers some discussion of the modeling consequences of this work.

2. Dissipation estimates

The most commonly used momentum equation subgrid-scale process parameterizations may be grouped into what will here be called horizontal processes and bottom drag processes. In all EGCM cases published to date the horizontal process is assumed to be a constant coefficient horizontal derivative operator {either $C_2\nabla^2 \equiv C_2[(\partial^2/\partial x^2) + (\partial^2/\partial y^2)]$ or $C_4\nabla^4 \equiv C_4\nabla^2(\nabla^2)$}. The second-order derivative form is the traditional "eddy viscosity" parameterization and the fourth-order "biharmonic" form has recently been adopted in some EGCM experiments because it is more strongly scale selective than the ∇^2 form (e.g., Holland 1978). The bottom drag form has varied from experiment to experiment; the most commonly used version is a simple Rayleigh law, $-R\mathbf{u}$, but others have used a quadratic form and some have used no bottom drag at all. Dissipation estimates for bottom drag processes will assume the Rayleigh form except as otherwise noted.

To form useful dissipation estimates it is necessary to partition the total volume of fluid into a part in which there are strong mean flows (boundary currents and internal jet systems) and the remainder. The first subvolume will be called the strong current region and the second the interior. At a minimum it is also necessary to introduce thermocline/near surface and abyssal velocity scales for the flow in each region. It will be assumed that one horizontal and one vertical length scale suffice to characterize flow variation in each region. Table 1 introduces the notation that will hereafter be used to describe the various mean and eddy flow quantities.

TABLE 1. Notation.

Quantity	Region	Mean	Eddy
Speed	Strong current:		
	thermocline	${}^sU_t$	${}^su_t$
	deep	${}^sU_d$	${}^su_d$
	Interior:		
	thermocline	U_t	u_t
	deep	U_d	u_d
Length scale	Strong current	${}^sL$	${}^sl$
	Interior	L	l
Region volume	Strong current:		
	thermocline	$H_t\,{}^sA$	$h_t\,{}^sa$
	deep	$H_d\,{}^sA$	$h_d\,{}^sa$
	Interior:		
	thermocline	H_tA	h_ta
	deep	H_dA	h_da

As indicated in Section 1, the quantities of interest are $[D']$, the net dissipation of mean eddy kinetic energy, and $[\bar{D}]$, the net dissipation of mean flow kinetic energy. Each term has two contributions, one due to horizontal stress work (HS' or $\overline{\text{HS}}$, respectively) and one to bottom stress work (BD' or $\overline{\text{BD}}$). These contributions in turn are the sum of the dissipation resulting in each of the regions of the domain identified above. Using estimates for these regional dissipation quantities it is straightforward to build up estimates of $[D']$ and $[\bar{D}]$.

Throughout it will be assumed that the flows of interest satisfy a set of quasi-oceanic constraints. Basically, these constraints require that the eddy flow be stronger than the mean flow everywhere except in the upper ocean strong current region where they may be comparable; that the eddy (mean) upper ocean flow be greater than or comparable to the eddy (mean) deep flow except in the strong current region where the mean should be stronger in the upper ocean than in the deep; that the mean (eddy) strong current length scale be smaller than (smaller than or comparable to) the interior length scale; and that the smallest eddy length scale be comparable to or greater than the strong current mean flow scale. The complete statement of constraints is given in Table 2. Model circulations

TABLE 2. Quasi-oceanic flow characteristics.

Quantity	Assumed value
${}^sU_t/{}^sU_d$	>1
U_t/U_d	$\geqslant 1$
${}^sU_t/U_t$	$\gg 1$
${}^su_t/{}^su_d$	$\geqslant 1$
u_t/u_d	$\geqslant 1$
${}^su_t/u_t$	>1
${}^sU_t/{}^su_t$	$\geqslant 1$
${}^sU_d/{}^su_d$	<1
U_d/u_d	<1
A/a	$\geqslant 1$
${}^sA/{}^sa$	$\leqslant 1$
$A/{}^sA$	>1
$a/{}^sa$	>1
H_t/H_d	$\leqslant 1$
h_t/h_d	$\leqslant 1$
h_t/H_t	~ 1
${}^sL/L$	<1
${}^sl/l$	$\leqslant 1$
${}^sL/{}^sl$	$\leqslant 1$

with flows significantly different in character from those acceptable under these conditions would have to be considered inconsistent with available ocean data; hence the quasi-oceanic label.

a. Horizontal stress work estimates

We consider first the regional contributions to $\overline{\mathrm{HS}}$. By the basin subdivisions introduced above, $\overline{\mathrm{HS}}$ has four contributions, arising from the deep and thermocline flow in both the strong current and thermocline region. Assuming that the horizontal stress process is described by an nth order constant coefficient operator in the momentum equation, these contributions may be estimated by

$$ {}^s\overline{\mathrm{HS}}_t \sim \frac{C_n\, {}^sAH_t\, {}^sU_t^2}{{}^sL^n}, \tag{1a} $$

$$ {}^s\overline{\mathrm{HS}}_d \sim \frac{C_n\, {}^sAH_d\, {}^sU_d^2}{{}^sL^n}, \tag{1b} $$

$$ \overline{\mathrm{HS}}_t \sim \frac{C_nAH_tU_t^2}{L^n}, \tag{1c} $$

$$ \overline{\mathrm{HS}}_d \sim \frac{C_nAH_dU_d^2}{L^n}. \tag{1d} $$

The relative importance of these components can be inferred from the ratios

$$ \frac{{}^s\overline{\mathrm{HS}}_t}{{}^s\overline{\mathrm{HS}}_d} \sim \frac{H_t}{H_d}\left(\frac{{}^sU_t}{{}^sU_d}\right)^2, \tag{2a} $$

$$ \frac{\overline{\mathrm{HS}}_t}{\overline{\mathrm{HS}}_d} \sim \frac{H_t}{H_d}\left(\frac{U_t}{U_d}\right)^2, \tag{2b} $$

$$ \frac{{}^s\overline{\mathrm{HS}}_t}{\overline{\mathrm{HS}}_t} \sim \frac{{}^sA}{A}\left(\frac{L}{{}^sL}\right)^n\left(\frac{{}^sU_t}{U_t}\right)^2, \tag{2c} $$

using Table 2.

So long as $H_t/H_d = O(1)$ Eqs. (2a) and (2b) suggest that ${}^s\overline{\mathrm{HS}}_t > {}^s\overline{\mathrm{HS}}_d$ and $\overline{\mathrm{HS}}_t \gtrsim \overline{\mathrm{HS}}_d$. Thus it is reasonable to scale the strong current and interior region dissipations by their thermocline contribution, irrespective of the order of the subgrid-scale process operator. Furthermore, so long as the strong current region thermocline flow is greater than its interior counterpart and also has smaller length scale of variation, Eq. (2c) suggests that ${}^s\overline{\mathrm{HS}}_t \gg \overline{\mathrm{HS}}_t$. Only if the strong current region represents but a tiny fraction of the volume of the fluid, would this result not hold for quasi-oceanic flows. The use of a higher order operator would tend to increase further this ratio. It appears that $\overline{\mathrm{HS}} \sim \overline{\mathrm{HS}}_t$ is the appropriate scaling.

We now consider the contributions to HS′. Relations precisely analogous to (1) and (2) describe the eddy flow dissipation in the mean; it is necessary only to substitute the appropriate eddy scales from Table 1 into the estimates (1) and (2) to obtain the eddy flow estimates. Unfortunately, it is not simple to identify an obvious single-scale estimate for HS′.

With a barotropic eddy field it is possible to get ${}^s\mathrm{HS}_d'$ and/or HS_d' slightly greater than ${}^s\mathrm{HS}_t'$ and HS_t', respectively, as is seen from the eddy analogs of (2a) and (2b). Furthermore, because there is no evidence that $l/{}^sl$ should be expected to differ significantly from unity, the eddy analog of (2c) is probably determined by $({}^sa/a)({}^su_t^2/u_t^2)$. From Table 2, ${}^sa/a < 1$ and ${}^su_t/u_t > 1$, so it is quite likely that ${}^2\mathrm{HS}_t'$, ${}^s\mathrm{HS}_d'$, HS_t' and HS_d' all contribute significantly to HS′ for many flows. In light of this the simplest solution is to assume that an appropriate scaling is

$$ \mathrm{HS}' \sim \frac{C_n\, {}^sah_t(u_t^+)^2}{{}^sl^n}, \tag{3a} $$

where

$$ u_t^+ \equiv \max[{}^su_t,(a/{}^sa)^{1/2}u_t] \tag{3b} $$

with the understanding that this may slightly underestimate HS′ if the eddy flow is quite barotropic. Should one be uncomfortable with the assumption $l/{}^sl \sim 1$, the definition of u_t^+ can easily be modified to incorporate an interior length scale compensation. This is felt to be an unnecessary complication for the EGCM flows.

b. Bottom stress work estimates

We consider first the mean flow estimates $\overline{\mathrm{BD}}$. There are now two components of $\overline{\mathrm{BD}}$,

$$ {}^s\overline{\mathrm{BD}} \sim R\, {}^sAH_d\, {}^sU_d^2, \tag{4a} $$

$$ \overline{\mathrm{BD}} \sim RAH_dU_d^2, \tag{4b} $$

and their ratio is

$$ \frac{{}^s\overline{\mathrm{BD}}}{\overline{\mathrm{BD}}} \sim \frac{{}^sA}{A}\left(\frac{{}^sU_d}{U_d}\right)^2. \tag{5} $$

As in (3) the area-weighted interior speed must be compared with the strong current speed; neither term is unambiguously larger than the other according to Table 2. Again the convenient solution is to define a new speed

$$U_d^{\ddagger} \equiv \max[{}^sU_d,(A/{}^sA)^{1/2}U_d] \tag{6}$$

and then the scaling is $\overline{\overline{\mathrm{BD}}} \sim R\,{}^sAH_d(U_d^{\ddagger})^2$. If a nonlinear bottom stress law is adopted, it will favor ${}^s\overline{\overline{\mathrm{BD}}}$ over $\overline{\overline{\mathrm{BD}}}$ because ${}^sU_d > U_d$ generally.

The contributions to the eddy flow bottom stress work in the mean, BD′, are obtained from the eddy analogs of (4) using Table 1. As for $\overline{\overline{\mathrm{BD}}}$, the most convenient procedure is to introduce

$$u_d^{\ddagger} \equiv \max[{}^su_d,(a/{}^sa)^{1/2}u_d] \tag{7a}$$

and take

$$\mathrm{BD}' \sim R\,{}^sah_d(u_d^{\ddagger})^2 \tag{7b}$$

as the appropriate estimate, since it is not possible to identify the relative importance of the strong current and interior contributions for all flows allowed by the quasi-oceanic constraints.

c. $[D']/[\bar{D}]$ *estimates*

By our partitioning of dissipation contributions,

$$\frac{[D']}{[\bar{D}]} = \frac{\mathrm{HS}' + \mathrm{BD}'}{\overline{\overline{\mathrm{HS}}} + \overline{\overline{\mathrm{BD}}}},$$

so that it is useful to investigate the relative importance of HS′ and BD′ and of $\overline{\overline{\mathrm{HS}}}$ and $\overline{\overline{\mathrm{BD}}}$, in hopes of reducing the number of different comparisons that must be investigated to examine $[D']/[\bar{D}]$.

From Section 2a, using Eqs. (6) and (7) we have

$$\frac{\overline{\overline{\mathrm{HS}}}}{\overline{\overline{\mathrm{BD}}}} \sim \left(\frac{C_n}{R\,{}^sL^n}\right)\frac{H_t}{H_d}\left(\frac{{}^sU_t}{U_d^{\ddagger}}\right)^2, \tag{8}$$

$$\frac{\mathrm{HS}'}{\mathrm{BD}'} \sim \left(\frac{C_n}{R\,{}^sl^n}\right)\frac{h_t}{h_d}\left(\frac{u_t^{+}}{u_d^{\ddagger}}\right)^2. \tag{9}$$

In ratio (8) there are two cases to be examined because of the presence of $U_d^{\ddagger}$; in (9) there are four cases because of u_t^+ and $u_d^{\ddagger}$. We first consider ratio (8). From Table 2, H_t/H_d is smaller than unity but O(1), while $({}^sU_t/U_d^{\ddagger})$ is probably greater than unity. It should be observed that the more barotropic the mean flow, the greater the probability that $({}^sU_t/U_d^{\ddagger})^2$ is O(1), while strongly baroclinic mean flows could produce $({}^sU_t/U_d^{\ddagger})^2 \gg 1$. Clearly, the ratio of the bottom drag decay time scale to that set by ${}^sL^n/C_n$, $C_n/R\,{}^sL^n$, can be very important in (8)—especially when $({}^sU_t/U_d^{\ddagger})^2$ is O(1). It will then effectively determine (8). It seems that the mean flow dissipation will tend to favor $\overline{\overline{\mathrm{HS}}}$ over $\overline{\overline{\mathrm{BD}}}$ if $C_n/R\,{}^sL^n$ is O(1), and $\overline{\overline{\mathrm{HS}}}$ clearly will dominate for $C_n/R\,{}^sL^n \gg 1$. Only for $C_n/R\,{}^sL^n \ll 1$ should $\overline{\overline{\mathrm{BD}}}$ be expected to be much larger than $\overline{\overline{\mathrm{HS}}}$.

Turning to ratio (9), $h_t/h_d < 1$ but still O(1), but $(u_t^+/u_d^{\ddagger})^2$ need not always be greater than or comparable to unity. For three of the four cases $(u_t^+/u_d^{\ddagger})^2 \gg 1$ but if $u_t^+ = {}^su_t$ and $u_d^{\ddagger} = (a/{}^sa)^{1/2}u_d$ then for sufficiently small ${}^sa/a$ it might be possible to get $(u_t^+/u_d^{\ddagger})^2 \ll 1$. This situation cannot arise for the EGCM experiments because they have been performed in small enough basins that ${}^sa/a$ is always O(1), but might arise in larger basins. For the present EGCM's, however, it appears that $C_n/R\,{}^sl^n$ will play as important a role in (9) as $C_n/R\,{}^sL^n$ does in (8).

Two interesting parameter regimes are thus identified. For $C_n/R\,{}^sL^n \ll 1$ we may expect $\mathrm{BD}' \gg \mathrm{HS}'$ and $\overline{\overline{\mathrm{BD}}} \gg \overline{\overline{\mathrm{HS}}}$ so that

$$\frac{[D']}{[\bar{D}]} \sim \frac{\mathrm{BD}'}{\overline{\overline{\mathrm{BD}}}} \sim \frac{{}^sah_d}{{}^sAH_d}\left(\frac{u_d^{\ddagger}}{U_d^{\ddagger}}\right)^2 \tag{10a}$$

is the correct dissipation ratio scaling. However, if $C_n/R\,{}^sl^n \gg 1$ the appropriate scaling is

$$\frac{[D']}{[\bar{D}]} \sim \frac{\mathrm{HS}'}{\overline{\overline{\mathrm{HS}}}} \sim \frac{{}^sah_t}{{}^sAH_t}\left(\frac{{}^sL}{{}^sl}\right)^n\left(\frac{u_t^+}{{}^sU_t}\right)^2. \tag{10b}$$

For $C_n/R\,{}^sL^n$ and $C_n/R\,{}^sl^n$ both O(1) it is unlikely that (10a) will apply and there is some suggestion from above that (10b) may be the appropriate estimate, but it may not be a sharp estimate. It should be noted that neither estimate (10a) or (10b) involves the specific value of C_n and/or R.

The other possible $[D']/[\bar{D}]$ estimates, $\mathrm{HS}'/\overline{\overline{\mathrm{BD}}}$ and $\mathrm{BD}'/\overline{\overline{\mathrm{HS}}}$, deserve a few remarks. These estimates are possible only when $C_n/R\,{}^sL^n$ and $C_n/R\,{}^sl^n$ are O(1) and basically require that the mean flow be strongly baroclinic and the eddy flow be strongly barotropic or vice versa. Extreme values of $a/{}^sa$ or $A/{}^sA$ in the proper combination can also lead to these estimates, in principle.

We now consider the values of (10a) and (10b), using Table 2. When (10a) applies, $[D']/[\bar{D}] \gg 1$ so long as a/A = O(1), ${}^sa/A$ not greatly less than unity, and $u_d > {}^sU_d$. These additional constraints are all met in the EGCM flows. This result holds because of the requirement that deep eddy flows be stronger than deep mean flows. The greater the increase over deep mean flow speeds, the more $[D']$ will dominate $[\bar{D}]$. Evidently eddies will be of at least modest importance in EGCM basin energy budgets whenever (10a) holds, and may be very important indeed.

However, when (10b) applies it is found that $[D']/[\bar{D}] \ll 1$ so long as $a/{}^sA$ = O(1). This situation arises because eddy speeds are assumed less than or comparable to the strong current region maximum speed and because the eddy horizontal length scales are greater than or comparable to the strong current mean length scale. Should the eddy length scales become significantly greater than ${}^sL$, $[\bar{D}]$ will quickly dominate $[D']$, particularly when a biharmonic operator is used. Evidently eddies will be of at most modest importance if (10b) describes $[D']/[\bar{D}]$.

To assess the impact of these results it is necessary to know the values of $C_n/R\,{}^sL^n$ and $C_n/R\,{}^sl^n$ in the various EGCM experiments.

3. Implications of dissipation estimates for EGCM's

In this section we assess what can be said about the dissipation ratio $[D']/[\bar{D}]$ in the various EGCM experiments that have been performed, using the results of Section 2. Typical values of $C_n/R\ {}^sL^n$ and $C_n/R\ {}^sl^n$ are evaluated and their implications examined.

For the published EGCM flows R has generally been given the value 10^{-7} s^{-1} (one case used 2.5 $\times$ 10^{-8} s^{-1}). This also appears to be a reasonable estimate for the decay time that would follow in the strong current region from the nonlinear bottom drag law used in the other experiments that include a bottom drag process. C_2 has generally been around 2 $\times$ 10^6 cm^2 s^{-1}, but always between 10^6 and 10^7 cm^2 s^{-1}, while C_4 has been between 10^{18} and 10^{19} cm^4 s^{-1}. An appropriate strong current region length scale for these flows is 5 $\times$ 10^6 cm, so $C_2/R\ {}^sL^2$ $\sim$ 0.4 to 4 and $C_4/R\ {}^sL^4 \sim 0.02$ to 0.2. It is not possible to identify a single eddy horizontal length scale appropriate for all the EGCM flows, but in every case l and ${}^sl$ are both greater than or comparable to 5 $\times$ 10^6 cm so that the corresponding ratios for the eddy flow are smaller than for the mean flow. Thus if all other flow features are equal, bottom stress dissipation will be at least 10 times more important than horizontal stress dissipation when a biharmonic operator is used instead of an eddy viscosity in these EGCM's.

With these values it appears that we may assume (10a) is the appropriate scaling for EGCM's using a biharmonic operator with a bottom drag, because $C_4/R\ {}^sL^4$ and $C_4/R\ {}^sl^4$ are much less than unity. When an eddy viscosity and bottom drag are used it appears that the appropriate ratios are O(1), no simplification is available, in general, and the dissipation estimates are sensitive to details of the flow. To the extent that $({}^sU_t/U_d^*)^2$ and $(U_t^+/U_d^*)^2$ are greater than unity, these experiments will have dissipation ratios described by (10b). Of course for those calculations using only a horizontal dissipative process (10b) is the appropriate estimate.

Two interesting observations can now be made. In the quasi-oceanic EGCM studies so far published it should be *expected* that the eddies will be at least moderately important in the basin energy budgets when a biharmonic operator and bottom drag process provide the model dissipation. Further, the eddies should be significantly less important, perhaps even unimportant, in those calculations that use only a horizontal viscous process. Eddy viscosity/bottom drag calculations also will have eddies of at most limited importance under many circumstances.

4. Summary and discussion

For EGCM flows which satisfy the quasi-oceanic constraints of Table 2, scale estimates of the basin kinetic energy dissipation ratio $[D']/[\bar{D}]$ are given by the results of Section 2. These estimates take particularly simple forms [Eqs. (10a), (10b)] if the non-dimensional parameters C_2/RL^2 and C_4/RL^4 (for L a typical flow length scale, here) are either very much smaller or larger than unity (Section 2c). Because $[D']/[\bar{D}]$ is strongly correlated to other basin energy budget measures of eddy importance (Harrison, 1979), these results can bear strongly on the proper dynamical interpretation of basin energy budget results.

In particular, if C_2/RL^2 and C_4/RL^4 are small compared to unity, Eq. (10a) applies and $[D']/[\bar{D}] \geqslant 1$; if they are large, (10b) applies and $[D']/[\bar{D}] \leqslant 1$ (Section 2c). For the former case, eddies are of at least modest importance in the basin energy budgets while they are of reduced importance in the latter case. Taking the values of C_2, C_4 and R used in existing EGCM calculations, and assuming that the length scale of importance is 5 $\times$ 10^6 cm (Gulf Stream width scale, first baroclinic radius of deformation, etc.), it is found that $C_2/RL^2 \geqslant$ O(1) while $C^4/RL^4 \leqslant$ O(10^{-1}). According to these estimates, EGCM experiments making use of biharmonic and bottom drag dissipative processes should be expected to yield basin energy budgets in which their model eddies are important. Those which employ simply an eddy viscosity dissipative process should produce eddies of at most limited importance. Experiments using eddy viscosity and bottom drag processes with these coefficients will not obviously fall into either category; different model flow regimes can lead to different dissipation ratios.

Examination of existing EGCM basin energy budget results (Harrison, 1979) reveals that they behave as predicted by these arguments, and further that eddies tend to be relatively unimportant in the predicted ambiguous case of eddy viscosity with bottom drag. This latter result is predicted so long as the model flows are modestly baroclinic in the sense defined in Section 3.

The importance of eddies in the basin energy budgets of the existing EGCM experiments thus can be largely determined by the modeler's choice of dissipative mechanisms and dissipation coefficients. To a very considerable degree, the energetic outcome of the existing biharmonic friction/bottom drag and pure eddy viscosity experiments is not a model determined result. Only if the resulting flows are not quasi-oceanic can the constraints of these dissipation results be avoided.

The modeling situation would be much simpler if more were known about the character of dissipation in the ocean. It is physically clear that there is boundary stress work whenever there is flow near a rigid boundary. But it is not known whether this dissipation occurs primarily along the abyssal floor of the ocean, along ocean ridges and seamounts, on the continental slopes and shelves, or significantly at each. Even less is known about the dissipation away from boundaries. These calculations, assuming very simple model dissipation mechanisms, suggest that the importance of eddies in ocean energy budgets may well depend primarily on where the dissipation takes place in the ocean.

The limited utility of basin energy budget measures of eddy importance has been noted before (Harrison, 1979), but this work further emphasizes their limitations. Clearly, it is important to find alternative measures of the importance of eddies in EGCM flows if these model oceanic systems are to be fully and usefully understood. Regional energy analysis avoids many of the limitations of basin energy analysis while permitting examination of eddy-mean flow interaction, but can be difficult to interpret because of ambiguities surrounding the definition of regional conversion of some types of energy into others. Furthermore, it may be difficult to carry out if the model system is strongly spatially inhomogeneous (Harrison and Robinson, 1978). Regional vorticity, heat and momentum analyses avoid problems akin to the energy conversion ambiguity but each of these fields is linear, so there is no explicit coupling term between mean and eddy fields in these equations. Also, spatial inhomogeneity presents the same difficulty for regional analysis of these quantities. Much work with alternative measures of eddy importance should be carried out; the present basin energy budget measures are inadequate.

EGCM systems, because of the large dimension of their modeling parameter space, can produce an extremely wide range of flows of interest from a geophysical fluid dynamics perspective. When constrained by the requirement that their flows be quasi-oceanic in character, they can also be used to provide examples of possible roles for eddies in the mean ocean circulation and to produce data sets that can be used to investigate the feasibility of observational programs to document or discount such roles at sea. Because of these features their results can be of considerable interest to physical oceanographers. However, the quasi-oceanic constraint can have very strong implications about which EGCM results are model-determined and which are externally determined, as has been shown here for the question of the importance of eddies in model basin energy budgets. Attention must be given to the implications of the adopted modeling constraints before apparently model-generated results are accepted for what they seem to be. To do otherwise is to risk misunderstanding the implications of model results and their potential oceanic significance.

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