On the Role of the Unresolved Eddies in a Model of the Residual Currents in the Central Strait of Georgia, B.C.

RESEARCH NOTE

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ABSTRACT  A depth-independent numerical model of the Juan de Fuca/Straight of Georgia system reproduces the broad structure of the observed depth-averaged residual circulation in the Central Strait of Georgia but underestimates its magnitude (Marinone and Fyfe, 1992). Here we present some new calculations based on a re-parameterization of the unresolved eddies in terms of "statistical dynamical tendencies" instead of the previous eddy-viscosity treatment. With the new parameterization, the simulated time-mean flow is closer to the observed circulation both in structure and magnitude. While not specifically designed to do so, the new parameterization also leads to a modest improvement in the low-pass filtered component of the flow. Based on these results, the depth-averaged residual currents in the region are conjectured to involve a four-way balance between the hitherto ignored effect of "statistical dynamical tendencies" and conventional tidal, atmospheric and buoyancy forcing.

RÉSUMÉ  Un modèle numérique indépendant de la profondeur du système détroit Juan de Fuca/Straight de Géorgie reproduit la structure générale de la circulation résiduelle moyenne observée par rapport à la profondeur dans le centre du détroit de Géorgie mais sous-estime son ampleur (Marinone et Fyfe, 1992). Nous présentons quelques nouveaux calculs basés sur une reparamétrisation des tourbillons non résolus en termes de «tendances dynamiques statistiques» pour remplacer le traitement antérieur par viscosité tourbillonnaire. La nouvelle paramétrisation permet au flux moyen dans le temps d'être plus près de la circulation observée tant dans la structure que dans l'ampleur. Bien qu'elle n'est pas conçue...
Marinone and Fyfe (1992, hereafter MF) attempted to reproduce the observed depth-averaged residual flow in the Central Strait of Georgia with a depth-independent non-linear numerical model forced only by the major tidal constituents observed at the openings to the Pacific Ocean. Since the simulated residual flow in the region was found to be an order of magnitude less than observed, it was concluded that forcing agents other than tidal must be at play. Indeed, recent calculations (Marinone et al., 1994) with a multi-layer model which includes tidal, atmospheric and buoyancy forcing show a much more energetic depth-averaged residual circulation. Here we take a different approach to reconciling MF and the observations by returning to the original depth-independent model of MF and we pursue the suggestion of Holloway (1993, hereafter H) that “at least in part, this model defect may be due to the absence of statistical-dynamical tendencies that result from eddy interactions (in reality)”. Quite plausibly the residual currents in the region involve a balance between this hitherto ignored effect and conventional tidal, wind and buoyancy forcing. Here we will isolate the first two mechanisms, namely the statistical-dynamical tendency (hereafter SDT) and tidal forcing.

H suggests that the unresolved eddies in MF’s depth-averaged model should not tend to relax the resolved flow to rest, as MF had them doing via the usual eddy-viscosity (hereafter EV) parameterization, but rather should drive the flow to a state reflecting the underlying topography. Behind this idea is the fact that equilibrium statistical mechanics predicts that an unforced, inviscid and quasi geostrophic ocean filled with random eddies (without mean motion) tends to a non-zero equilibrium mean state which follows the topography (see Eq. 1). The strength (or weakness, as the case may be) of the link between idealized quasi-geostrophic dynamics and the primitive equations dynamics as used by MF is discussed in H and will not be repeated here. Suffice to say that many accepted parameterizations developed in the modelling community rest on theoretical grounds no stronger, and in many instances much weaker, than the SDT parameterization (e.g., the usual EV treatment).

Following H’s suggestion, we now parameterize the SDT by rewriting the diffusive terms in MF’s equations governing the horizontal transport components \( U \) and \( V \) to read \( \nu \nabla^2 (U - \bar{U}) \) and \( \nu \nabla^2 (V - \bar{V}) \) instead of \( \nu \nabla^2 U \) and \( \nu \nabla^2 V \), respectively (\( \nu \) is the EV parameter and \( \nabla^2 \) the two-dimensional Laplacian). These altered terms are used to relax the horizontal velocity, \( (u, v) \), toward the following equilibrium statistical mechanical solution,

\[
(\bar{u}, \bar{v}) = (\bar{U}, \bar{V})/h = f\lambda^2 k \times \nabla \ln h
\]  
(1)
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where $f$ is a constant Coriolis parameter, $\lambda$ a free parameter representing a length scale shorter than the dominant eddy scale, $k$ the unit vector in the local vertical direction and $h$ the bathymetry. The correlation length scales obtained in the observational study of Stacey et al. (1987) suggest a $\lambda$ on the order of 4 km. Since this parameterization involves several spatial derivatives of the bathymetry, an initial smoothing of the $h$ field is necessary ($h$ remaining unsmoothed elsewhere in the equations of motion). Notice that $(\bar{u}, \bar{v})$ is parallel to the smoothed bathymetry with shallow water to the right.

In the top-left panel of Fig. 1 we show $(\bar{u}, \bar{v})$ (where the overbar represents the time-mean) in the Central Strait of Georgia obtained from a six-month simulation using MF's model and the usual EV treatment for the unresolved eddies ($v = 10^6$ cm$^2$s$^{-1}$). [Note that the spatial domain of the model is much larger than indicated in Fig. 1, covering Juan de Fuca Strait, Puget Sound, Strait of Georgia and all of their connecting passages (see Fig. 1a from MF for the complete domain).] As in MF, the simulated $(\bar{u}, \bar{v})$ compares favorably in structure with the available observations in the region (see Fig. 14 from MF for the observed time-mean currents) but is an order of magnitude too weak. In the left column of Fig. 2 we show the dominant terms in the time-mean $\partial u/\partial t$ equation (see section 3c of MF for this equation). [Note that the time-mean frictional and EV terms (not shown) are negligible.] On the mainland (right) half of the domain, the balance is between the time-mean Coriolis and pressure-gradient terms (i.e., $\bar{v}$ is in near geostrophic balance there) while on the island (left) half of the domain, the balance is mostly between the time-mean pressure-gradient and advection terms.

In the top-right panel of Fig. 1, we show $(\bar{u}, \bar{v})$ obtained from a six-month simulation where the SDT, rather than EV, parameterization was used. In this case, $(\bar{u}, \bar{v})$ has reasonable structure and magnitude when compared against the observed currents. Of course this is no real surprise since, by design, $(\bar{u}, \bar{v})$ has relaxed to near $(\bar{u}, \bar{v})$, which itself mimics the observations. In the right column of Fig. 2, we show the dominant terms in the time-mean $\partial u/\partial t$ equation. Note the time-mean frictional term (not shown) is negligible (presumably because of the relatively large depths in the region) while the time-mean STD term (also not shown) nearly vanishes since $\bar{u} \approx \bar{u}$. As can be seen in Fig. 2, the dominant balance throughout the domain is between the time-mean Coriolis and pressure-gradient terms (i.e., $\bar{v}$ is in near-geostrophic balance everywhere) with nonlinear advective processes playing only a minor role.

Having established a relaxation of the time-mean flow to $(\bar{u}, \bar{v})$ with the inclusion of the SDT parameterization, we now ask how the low-frequency oscillations (i.e., motions with periods longer than a day) are affected? In the middle and bottom rows of Fig. 1, we compare the dominant principal component pattern and time-series, respectively, of the low-pass filtered $u$ and $v$ (combined) for the EV (left) and SDT (right) simulations. [Note that only every third grid point is used in this principal component analysis.] As can be seen, the magnitude of the low-frequency variability is increased (and towards the observations, not shown) with the inclusion of the SDT
Fig. 1  \((\bar{u}, \bar{v})\) and \(|\bar{u}, \bar{v}|\) (cm/s) for the EV (top-left) and SDT (top-right) simulations. First principal component pattern of low-pass \(u\) and \(v\) (combined) and \(|(u, v)|\) (with the latter normalized by its maximum absolute value) for the EV (middle-left) and SDT (middle-right) simulations (the percentage of variance explained as indicated). Corresponding principal component time-series for the EV (bottom-left) and SDT (bottom-right) simulations (with the time series normalized by their maximum absolute value). The absolute amount of variance explained by the given principal component is indicated.
Fig. 2 Time-mean $u$-tendency equation Coriolis (top), pressure-gradient (middle) and advection (bottom) terms for the EV (left) and SDT (right) simulations. For each simulation, the normalization is such that the largest absolute value taken across all terms is unity. (Note that the time-mean frictional, EV and SDT terms are negligible and hence are not shown.)
Fig. 3 First (top-left) and second (top-right) principal component patterns for the low-pass $u$-tendency difference (percentage variance explained as indicated). First (middle-left) and second (middle-right) principal component patterns for the low-pass (linear+advective term) difference. First (bottom-left) and second (bottom-right) principal component patterns for the low-pass frictional term difference. Normalization as described in the text.
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parameterization (i.e., the domain-averaged variance goes from about 0.89/0.89 = 1.0 cm² s⁻² with the EV parameterization to about 1.84/0.92 = 2.0 cm² s⁻² with the SDT parameterization). As well, the spatial and temporal characteristics are seen to change somewhat. To understand what may be driving these changes in low-frequency variability, we now perform a principal component analysis on the low-pass \( \partial u/\partial t \) equation.

In the top left of Fig. 3 we show the first principal component pattern of the low pass filtered \( \partial u/\partial t \) difference between the EV and SDT simulations, i.e.,

\[
\text{LP} \left( \frac{\partial u}{\partial t} \right)_{\text{EV-SDT}} \equiv \text{LP} \left( \frac{\partial u}{\partial t} \right)_{\text{EV}} - \text{LP} \left( \frac{\partial u}{\partial t} \right)_{\text{SDT}}
\]  \hspace{1cm} (2)

(LP representing low-pass filtering). In the middle left and bottom left of Fig. 3 we show the first principal component pattern of LP (linear + advection) \( \left| \text{EV-SDT} \right| \) and LP (friction) \( \left| \text{EV-SDT} \right| \), respectively (linear includes Coriolis, pressure gradient and either EV or SDT terms). Note that the latter are scaled in such a way that their maximum absolute values are equal to the correlation coefficient between the given-pattern time-series and the first principal component time-series of the low-pass filtered \( \partial u/\partial t \) difference (also shown is the percentage variance that the given pattern explains). These results imply that friction plays a very important role in driving the main variations in the low-pass filtered \( \partial u/\partial t \) difference. Perhaps relevant in this regard is the physical mechanism as described by Godin (1971, 1986) where an \( M_p \) enhancement in simulations of St. Lawrence river tides was seen to involve nonlinear frictional term interactions between \( K_1, O_1 \) and an increased time-mean flow. Also shown in Fig. 3 (in the right column) is the same analysis but for the second principal component of the low-filtered \( \partial u/\partial t \) difference. We conclude that the effect of friction on the second mode of variation of the low-pass filtered \( \partial u/\partial t \) difference is negligible.

We conclude that the SDT parameterization has a significant and positive effect on our simulation of the depth-averaged residual circulation in the Central Strait of Georgia over what can be obtained using a conventional EV treatment of the unresolved eddies. It would be interesting to see how the SDT parameterization fares in the more realistic three-dimensional model with wind and buoyancy forcing included.

References

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CORRIGENDUM


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