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Comments on "The sea surface pressure formulation of rigid lid models. Implications for altimetric data assimilation studies" by N. Pinardi, A. Rosati and R. Pacanowski

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In a recent article, Pinardi et al. (1994) reviewed, in the perspective of altimetric data assimilation, several aspects of the computation of the barotropic mode of a primitive equation, rigid lid, global ocean model. In the framework of the rigid lid approximation, the surface pressure p_s is related to the ocean surface elevation η by $p_s = p_a + \rho_0 g \eta$, where p_a, ρ_0 and g denote the atmospheric pressure at sea level, a reference value of the density of sea water and the gravitational acceleration, respectively. Pinardi et al. (1994) considered a simple assimilation procedure consisting in "blending" the surface pressure derived from altimetric measurements and that predicted by the model when unconstrained by data. They considered forcing the barotropic momentum equation by the "blended" surface pressure in the hope that the resulting barotropic velocity would be closer to reality than that obtained by ignoring data.

As shown by Pinardi et al. (1994), this method is ill-designed, for the conservation of mass precludes any modification of the ocean surface elevation in a rigid lid model. This conclusion, though correct, stems from two rather restrictive hypotheses. First, it is assumed that the barotropic continuity equation, stating that the transport (i.e., the depth-integral of the horizontal velocity) must be divergenceless, has to be rigorously enforced. Second, the barotropic momentum equation is considered exact. Lifting at least one of those hypotheses would permit implementing a simple "blending" method. We feel that it might not be safe to violate the mass conservation equation. Thus, we would suggest disposing with the second condition.

Herein, a variational method is outlined, the essence of which is to introduce minimal perturbation in the momentum equation of the barotropic mode. Details about of our method may be found in Deleersnijder (1994).

The time discretization of the barotropic mode equations may be as follows

$$\nabla \cdot \boldsymbol{U}^{n+1} = 0, \tag{1}$$

$$\frac{\boldsymbol{U}^{n+1} - \boldsymbol{U}^{n}}{\Delta t} + \frac{\omega}{\Delta t} \boldsymbol{e}_z \times \boldsymbol{U}^{n+1} + \frac{\tilde{\omega}}{\Delta t} \boldsymbol{e}_z \times \boldsymbol{U}^{n} = -\frac{h}{\rho_0} \nabla p_s^{n+1} + \boldsymbol{E}^{n}, \tag{2}$$

where $\mathbf{U}$ denotes the transport; subscript n is associated with time discretization, the increment of which is Δt; ∇, $\mathbf{e}_z$ and h represent the horizontal "gradient operator", the vertical unit vector and the ocean depth, respectively; $\mathbf{E}$ collects the depth-integral of the pressure force term due

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to the horizontal density variations, as well as advection, diffusion and bottom/surface stress terms. As emphasized by several authors (Bryan, 1969; Semtner, 1986; Dukowicz et al., 1993), it is important that the Coriolis force be discretized with some degree of "implicitness" $\beta (0 \leqslant \beta \leqslant 1)$. Accordingly, we set $\omega = \beta f \Delta t$ and $\omega + \tilde{\omega} = f \Delta t$, where f is the Coriolis parameter.

Evaluating the divergence of Eq. (2) and taking Eq. (1) into account allows determining the model surface pressure field, $p_{s,m}^{n+1}$, i.e., the surface pressure field predicted by the model without any influence of data.

If $p_{s,d}^{n+1}$ is the surface pressure field derived from altimetric measurements, one may define the "blended" pressure field as $p_{s,b}^{n+1} = \alpha p_{s,d}^{n+1} + (1-\alpha) p_{s,m}^{n+1} (0 \leqslant \alpha \leqslant 1)$. It is then tempting to introduce this "blended" pressure field into Eq. (2) so as to update the transport. But, doing so, one would obtain a transport field $\mathbf{U}^*$ having non-zero divergence, for it is only when $\alpha = 0$ that the updated transport is divergenceless.

As a result, it is generally believed impossible to directly introduce altimeter data into the barotropic mode of a rigid lid model. This difficulty may however be overcome without resorting to a sophisticated method.

It is suggested seeking the divergenceless transport that is closest to $\mathbf{U}^*$, which will be considered the updated transport $\mathbf{U}^{n+1}$. The latter achieves the minimum of the functional

$$J = \int_{\Omega} \left| \boldsymbol{U}^{n+1} - \boldsymbol{U}^* \right|^2 \mathrm{d}\Omega, \tag{3}$$

where Ω represents the computational domain, which is assumed to be limited by impermeable boundaries only — as is the case in the World Ocean.

This method for updating the transport may be interpreted in another way. Suppose that a perturbation to Eq. (2), $\mathbf{r}$, is introduced to account for all the errors affecting the computational representation of the momentum budget. If the "blended" surface pressure is used, $\mathbf{U}^{n+1}$ corresponds to the minimum of a global quadratic measure of $\mathbf{r}$.

A streamfunction, ψ, is called on so as to ensure that $\mathbf{U}^{n+1}$ is actually divergenceless, i.e., $\mathbf{U}^{n+1} = \mathbf{e}_z \times \nabla \psi$. Expressing that the first order variation of J must be zero, we obtain

$$\nabla^2 \psi = \boldsymbol{e}_z \cdot (\nabla \times \boldsymbol{U}^*). \tag{4}$$

The impermeability of the boundaries requires that ψ be ascribed to constant values along them. Poisson Eq. (4), together with the impermeability boundary conditions, form an elliptic partial differential problem, the solution of which must achieve the minimum of J.

Upon defining $a = -\Delta t / [\rho_0 (1 + \omega^2)]$ and $b = 1/(1+\omega^2)$, one may write

$$\begin{aligned} &\nabla \times \boldsymbol{U}^{n+1} - \nabla \times \boldsymbol{U}_m^{n+1} \\ &\quad = \alpha a \nabla h \times \left[(1 - \omega \boldsymbol{e}_z \times) \nabla \left(p_{s,d}^{n+1} - p_{s,m}^{n+1} \right) \right] \\ &\qquad - \alpha a h \nabla \omega \cdot \nabla \left(p_{s,d}^{n+1} - p_{s,m}^{n+1} \right) \boldsymbol{e}_z \\ &\qquad - \alpha a h \omega \nabla^2 \left(p_{s,d}^{n+1} - p_{s,m}^{n+1} \right) \boldsymbol{e}_z, \end{aligned} \tag{5}$$

where $\mathbf{U}_m^{n+1}$ is the transport that would be obtained without introducing data, i.e., by merely solving Eqs. (1), (2).

Eq. (5) shows that, in general, $\mathbf{U}^{n+1}$ is different from $\mathbf{U}_m^{n+1}$, which is the least to be expected from the present assimilation method! It is thus through the interaction of the depth gradient with the pressure gradient and through the implicit treatment of the Coriolis acceleration that the "blending" of the model and surface pressure induces modifications into the curl of the transport.

To summarize, the method outlined here consists in solving two elliptic problems, the one for determining the pressure field independent of the data, $p_{s,m}^{n+1}$ and the other for updating the transport.

It is suggested that numerical experiments be carried out in order to assess the actual potential of the present approach.

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