Comments on "The Effect of Bottom Topography on the Speed of Long Extratropical Planetary Waves"*

RÉMI TAILLEUX

LMD, UPMC, Paris, France

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1. Introduction

Recently, Killworth and Blundell (1999, hereinafter KB99) used the ray approach of Wentzel–Kramers–Brillouin (WKB) theory to investigate the question of whether the large-scale topography could by itself speed up the long extratropical planetary waves of linear standard flat-bottom theory in a way consistent with the observational findings of Chelton and Schlax (1996, hereinafter CS96). By considering particular rays excited along the eastern boundary at the annual frequency in ocean basins with realistic topographies [obtained from a highly smoothed version of the ETOPO5 dataset (National Geophysical Data Center 1988)], they show that the wave speed along a ray is alternatively faster and slower than that of the standard flat-bottom first baroclinic mode, with the slower (faster) propagation occurring on the eastern (western) flanks of hills. They also find the rays' meridional excursions to remain quite small in general; that is, the propagation remains predominantly westward, suggesting that the steering effect of the topography is considerably smaller for baroclinic waves than for barotropic waves in a homogeneous ocean. From this, they conclude that, although the topography can locally have large effects on the speed of the first internal mode topographic waves, these cancel out when averaged over the basin scale.

The first intriguing point of KB99 is that their conclusions are at odds with early results from two-layer models showing that the speed of baroclinic Rossby waves can be systematically faster by the factor H/H_2 over a steep (Rhines 1977; Veronis 1981) as well as over a rough (Samelson 1992) topography; here, H_2 and H are the lower-layer thickness and total depth, respectively, and are extended to the continuously stratified case by Tailleux and McWilliams (2001, hereinafter TM01).

The second confusing point comes from that the ray approach of KB99 is presented implicitly as methodologically equivalent to the local approach of Killworth et al. (1997, hereinafter KCS97) and others, as both come under the label "WKB theory," whereas it is not. In fact, the two approaches are based on different premises, and thus lead in general to different conclusions. Specifically, the strategy in the ray approach is to chose the eigenvalues to lie a priori on a given dispersion surface that is a continuous function of its defining parameters (α and H in KB99; see definitions in section 2a), and which includes the standard first baroclinic mode of a particular case (for $\alpha = 0$). The underlying assumption is therefore that all the observed waves originate from the eastern boundary, that their properties are determined according to single-mode WKB theory,[1] and that other dispersion surfaces are either not relevant to account for some of the observed waves or not excited. In contrast, the strategy in the local approach is to select the eigenvalues yielding elevated phase speeds, if there are any, for *fixed values* of the defining parameters (the zonal background mean flow in KCS97). It is thus perfectly possible to jump from one dispersion surface to another as the defining parameters are varied in the local approach, whereas one is bound to stay on a given dispersion surface in the ray approach. The local approach therefore implicitly assumes that all waves supported by the system are excited and thus are potentially observable in the sea surface height (SSH). In KB99, the difference between the local and ray approaches arises because there is a dispersion surface yielding elevated phase speeds in the parameter regime

* Current affiliation: EGS, CSAG, University of Cape Town, Rondebosch, South Africa.

Corresponding author address: Dr. Rémi Tailleux, LMD-UPMC Paris 6, Case Courrier 99, 4 Place Jussieu, F-75252 Paris Cedex 05, France.
E-mail: tailleux@lmd.jussieu.fr

[1] Single mode refers to the assumption of no energy exchange between rays. This is not necessarily verified in the ocean, particularly over topography, see Hallberg (1997) and Tailleux and McWilliams (2002).

$\alpha > 0$ where KB99 find propagation slower than standard, as discussed in section 2. Arguably, the existence of this dispersion surface, overlooked by the authors, must be accounted for to properly assess the role of topographic effects on baroclinic Rossby wave propagation. This comment discusses the issue extensively.

Our last objection concerns the overall conclusion of KB99 that the local topographic effects cancel out when averaged over the basin scale. We find it a very ambiguous statement in view of all the assumptions it relies on, which strangely enough introduces a basin-averaged viewpoint, whereas the common view so far was to examine the too-fast Rossby wave issue from a local viewpoint. Clearly, this basin-averaged viewpoint tends to minimize the role of topographic effects in favor of the background mean flow effect advocated by KCS97 and many others; yet, a conclusion of KB99 and TM01 is also that the bottom boundary condition alone may have a dramatic impact on the properties of the eigensolutions. In this respect, topography appears to be at least equally important as the mean flow in setting the local propagation characteristics of Rossby waves. Arguably, the local viewpoint is the only one that is mathematically well defined and nonambiguous. Furthermore, one should recall that the dependence upon the mean flow and the bottom boundary condition is nonlinear in nature, so one must be cautious about making definitive statements from the study of one particular effect taken in isolation in absence of a clear understanding of how the various relevant effects interact in more complex models [as, for instance, the one recently considered by Killworth and Blundell (2003a,b)].

The purpose of this comment is to reexamine the eigenvalue problem studied by KB99 in order to clarify the above issues. To that end, we shall first express in mathematical terms the different strategies underlying what we referred to as the local and ray approach to the too-fast Rossby wave issue. We will then compare the predictions of each approach and show that they are different because of the existence of the pseudobarotropic mode $n = 0$, which is always faster than standard first-baroclinic Rossby waves. Although the barotropic mode is commonly thought to be too fast by several orders of magnitude to match the observed speeds of propagation, we show that the topography can slow it down or speed it up in the same way that it does on the first baroclinic mode, and that in its slow regime its phase speed can become comparable with those observed. The final section summarizes and discusses the results.

2. Formalization of the local and ray approaches

a. The local WKB eigenvalue problem

In WKB theory, the dispersion relation for the topographically modified long Rossby waves in absence of any other effects can be written in dimensionless form as follows:

$$\omega = -\frac{k_\lambda \gamma^2}{\sin^2\phi}, \tag{1}$$

where γ^2 is obtained by solving the following locally defined eigenproblem:

$$\frac{d^2F}{d\sigma^2} + \frac{\nu^2}{\gamma^2}F = 0 \tag{2}$$

$$F(0) = \epsilon\gamma^2\frac{dF}{d\sigma}(0) \tag{3}$$

$$F(-h) = \mu\frac{dF}{d\sigma}(-h), \tag{4}$$

where

$$\mu = -\frac{\alpha}{\delta}; \qquad \alpha = -\tan\phi\left(\frac{k_\phi}{k_\lambda}\frac{\partial H}{\partial\lambda} - \frac{\partial H}{\partial\phi}\right). \tag{5}$$

The above problem is the dimensionless equivalent of that studied by KB99 with the difference that, instead of the rigid-lid approximation[2] made by the latter authors, we retained the exact linearized free-surface boundary condition (3), (e.g., Gill 1982) for reasons clarified below. Although our notations differ somewhat from that of KB99, note that the important parameter α retains the same meaning in both studies. Dimensionless quantities are

$$\sigma = \frac{z}{\delta}; \qquad \nu = \frac{N(z/\delta)}{N_0}; \qquad \omega = \frac{2\Omega R^2}{N_0^2\delta^2}\omega_0;$$
$$h = \frac{H}{\delta}; \qquad \epsilon = \frac{N_0^2\delta}{g}. \tag{6}$$

The notations used are p is the pressure divided by a reference density ρ_0, $\mathbf{u}$ is the horizontal velocity, w is the vertical velocity, $N^2(z) = -\rho_0^{-1}gd\overline{\rho}/dz$ is the squared Brunt–Väisälä frequency, where $\overline{\rho}(z)$ is the background density assumed to be function of depth only, g is the gravitational acceleration, 2Ω is 2 times the earth's rotation rate and R is the earth's radius, $N_0 = N(0)$, δ is a length scale characterizing the depth variations of N, H is the total ocean depth, and ω_0 is 2π times the dimensional frequency of the waves; k_λ and k_ϕ are zonal and meridional wavenumbers defined from a phase function Σ (λ, ϕ) by $k_\lambda = \partial\Sigma/\partial\lambda$ and $k_\phi = \partial\Sigma/\partial\phi$, where λ and ϕ denote longitude and latitude, respectively. In general, $\epsilon \ll 1$ for typical ocean values.

b. Strategies for the ''too fast'' Rossby waves issue

To investigate the too-fast Rossby wave issue, it is necessary to define the measure of propagation one

[2] The rigid-lid approximation can be recovered by taking the limit $\epsilon = 0$.

wishes to compare with the observations of CS96. Arguably, the most relevant choice (e.g., Tailleux 2003a), is the zonal phase speed

$$c_p = \frac{\omega}{k_\lambda} = -\frac{\Gamma}{\sin^2\phi}, \tag{7}$$

which was also used in KCS97, where $\Gamma = \gamma^2$. Since the eigenproblem (2)–(4) depends only upon the parameters α/H and h, formally $\Gamma = \Gamma(\alpha/H, h)$ [e.g., see Tailleux 2003b, manuscript submitted to *J. Phys. Oceanogr.*, hereinafter T03) for details]. In the context of the too-fast Rossby wave issue, one thus wishes to understand the behavior of the following ratio

$$r_n\left(\frac{\alpha}{H}, h\right) = \frac{\Gamma_n(\alpha/H, h)}{\Gamma_1(0, h)}, \tag{8}$$

where $\Gamma_1(0, h)$ refers to the flat-bottom value of Γ for the first baroclinic mode, while n is the index of the mode considered. In practice, Γ usually depends much less on h than on α/H so that the interesting physics is essentially contained in the latter parameter. With the above notations, it is possible to define formally the local approach as seeking to determine the values of n for which $r_n > 1$ for fixed values of α/H and h.[3] The ray approach, on the other hand, consists in studying the ratio r_1 along a ray, the values of α/H and h being then determined from the integration of the ray equations. To compare the predictions of the local and ray approaches, it is therefore necessary to understand the qualitative properties of the ratios r_n for all n.

c. Qualitative properties of the eigensolutions

To understand the qualitative properties of the ratios r_n, recall first that the eigenproblem (2)–(4) which is similar to the standard eigenproblem in nature, admits an infinite number of discrete eigensolutions, which can be ordered such that for fixed values of α/H and h, $\Gamma_{n+1}(\alpha/H, h) < \Gamma_n(\alpha/H, h)$; that is, the phase speeds decrease with increasing n. For each particular mode, one may show (e.g., T03) that $1/\Gamma_n$ is an increasing (decreasing) function of $\alpha(h)$. This results in the qualitative picture of Fig. 1 showing both the rigid-lid case (Fig. 1a) and free-surface case (Fig. 1b). For comparison, we also show the results of a computation using an exponential buoyancy frequency profile in Fig. 2.

Figure 1 makes it clear that the rigid lid has a profound impact on the structure of the pseudobarotropic mode $n = 0$. In the rigid-lid case, the pseudobarotropic mode $n = 0$ combines with the bottom-trapped mode [the mode $n = -1$ in the free-surface case, first described by Rhines (1970)], and is defined only for $\alpha >$ 0. Furthermore, Γ_0 becomes infinite for $\alpha = H$.[4] In the free-surface case, the pseudobarotropic mode is defined for all values of α, and its propagation speed remains finite for all finite values of α (but one shows that $\Gamma_0 \to +\infty$ when $\alpha \to -\infty$). These remarks are important for future study of the pseudobarotropic mode $n = 0$ in case it is further confirmed to be relevant to the too-fast Rossby wave issue; one will then have to decide whether the structural differences between the rigid lid and free surface are important or not in order to construct a more appropriate model than the planetary geostrophy (PG) system for its study. In contrast, the first-

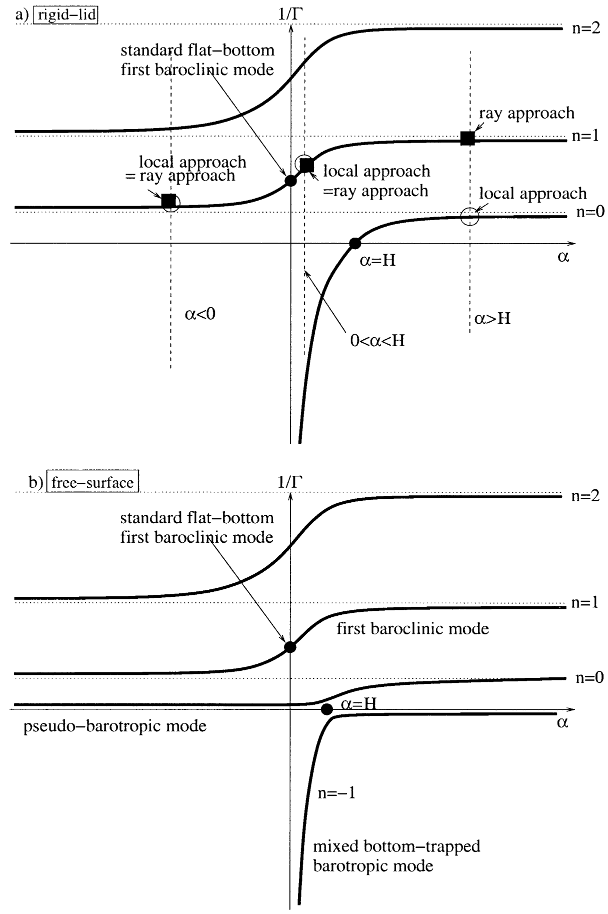

FIG. 1. Schematic dispersion curves for long Rossby over topography depicting the quantity $1/\Gamma$, i.e., the inverse of the squared gravity wave speed, as a function of the parameter α, in the (a) rigid-lid case and (b) free-surface case; (a) also illustrates the difference between the local and ray approaches for three different values of α visualized by the three vertical dashed lines. In the ray approach, illustrated by a black square, the relevant value of Γ is systematically chosen to lie upon the curve $n = 1$; in the local approach, illustrated by circles, values may be picked up on other curves if they yield a higher ratio than unity.

[3] Of course, nothing forbids one to also study the cases $r_n < 1$ if one is interested in a more general understanding of the effect studied.

[4] To see this is the case, set $\Gamma = \infty$ in (2). This yields $F'' = 0$; hence $F = Az$ to satisfy the rigid lid, with A being an arbitrary constant. The bottom boundary condition (4) then imposes $\alpha = H$.

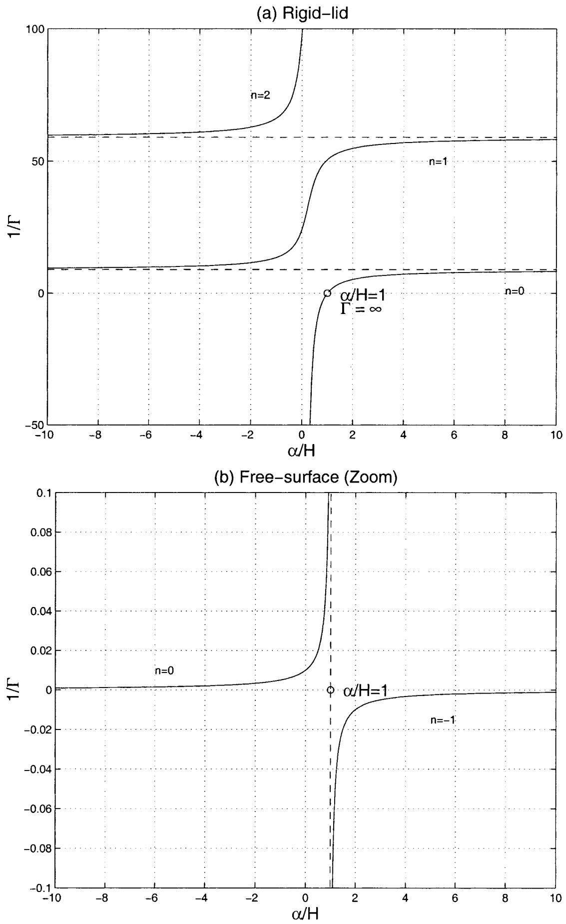

FIG. 2. As in Fig. 1 but for an exponential stratification, with the differences that $1/\Gamma$ is here plotted as a function of α/H instead of α, and (b) is a zoom of the free-surface case near $\alpha = H$ and $1/\Gamma \ll 1$. To help to assess the differences between the rigid-lid and free-surface cases, we also depicted the dispersion curve for the rigid-lid mode $n = 0$ as a dashed line in (b). Locally, the dashed line appears to be an asymptote to the dispersion curves for the modes $n = 0$ and $n = -1$.

baroclinic mode $n = 1$ studied by KB99 is largely unaffected by the rigid-lid approximation.

d. Consequences for the too-fast Rossby wave issue

Since $1/\Gamma$ is a strictly increasing function of α, it follows that the ratio r_1 studied by KB99 will be

- slower than unity, meaning propagation slower than standard, for $\alpha > 0$;
- faster than unity, meaning propagation faster than standard, for $\alpha < 0$.

Furthermore, this ratio will be bounded by its upper and lower limits at $\alpha = \pm\infty$; that is,

$$\frac{\Gamma_1(-\infty, h)}{\Gamma_1(0, h)} < r_1\left(\frac{\alpha}{H}, h\right) < \frac{\Gamma_1(+\infty, h)}{\Gamma_1(0, h)}. \qquad (9)$$

TABLE 1. Comparison of the phase speed for the local rigid-lid and free-surface approach vs the ray approach.

	$-\infty < \alpha/H < 0$	$0 < \alpha/H < 1$	$1 < \alpha/H < +\infty$
Local approach, rigid lid	Faster $r_1 > 1$	Slower $r_1 < 1$	Faster $r_0 > 1$
Local approach, free surface	Faster $r_1 > 1$, $r_0 \gg 1$	Faster $r_0 \gg 1$	Faster $r_0 > 1$
Ray approach	Faster $r_1 > 1$	Slower $r_1 < 1$	Slower $r_1 < 1$

Here we note that the upper and lower bounds for Γ are solutions of the eigenvalue problem using the bottom pressure compensation boundary condition $F'(-h) = 0$ studied in TM01. In particular, the upper ratio $r_1(+\infty, h)$ is the one considered in the latter study and compared with good agreement with the observed amplification factors of CS96 using hydrological data. We therefore expect the upper values of r_1 computed by KB99 to be comparable with the enhanced phase speed ratio computed by TM01. Using realistic stratification, KB99 finds this upper ratio to lie within the range (1.75, 2.25), which is indeed consistent with the values found by TM01.

As argued in the introduction, the existence of the mode $n = 0$ causes the predictions of the ray approach to differ from those of the ray approach. Table 1 summarizes these differences by showing 1) whether there are any elevated phase speeds for fixed values of the defining parameters and 2) how the elevated phase speeds, as measured by the ratio r_n, compare with the standard case; specifically, $r \gg 1$ means values are very far from observations, whereas $r > 1$ means that they are much closer to observations.

This shows that the three approaches coincide over the interval $\alpha < 0$, but that otherwise they all yield different predictions. It is therefore important to reason on the most general and physical case, which in the present context is the local approach retaining a free surface. This approach predicts modes faster than standard for all values of α. For $\alpha < 0$, both the ratios r_0 and r_1 are greater than unity, but for $\alpha > 0$ this is true only of r_0. These results are consistent with the findings of KB99 that the ratio r_1 is slower than unity for $\alpha > 0$ and greater than unity for $\alpha < 0$.

e. Observational restrictions on the pseudobarotropic mode n *= 0*

From a local viewpoint, the above analysis demonstrates that there are modes with elevated phase speeds for all values of α/H and h. We should not conclude, however, that all of these modes are necessarily relevant to the interpretation of the observed amplification ratios of CS96, which are bounded from above by a maximum value of about 4–5. To clarify this point, it is useful to depict the ratio r_0 and r_1 as a function of α/H along

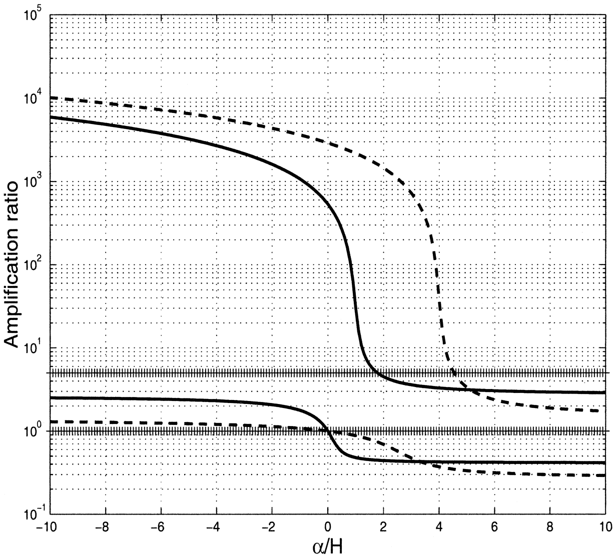

FIG. 3. The ratio $r_0(\alpha/H, h)$ (upper curves) and $r_1(\alpha/H, h)$ (lower curves) as a function of α/H for an exponential stratification $N(z) = N_0 e^{z/\delta}$. The calculations use the values $H = 4500$ m and $N_0 = 10^{-2}$ s^{-1}. The dashed and solid lines correspond respectively, to $h = H/\delta = 4$ and $h = H/\delta = 1$, respectively. The horizontal lines (marked "+") delineate the observational domain of interest, chosen to lie between the amplification factors 1 and 5.

with an admissible observational domain. This is done in Fig. 3 for two particular instances of exponential buoyancy frequency (to show the sensitivity to the choice of the e-folding depth) with an observational domain chosen here to lie within 1 and 5 (indicated by the two horizontal lines marked with "+").

Not surprisingly, r_1 lies within the observational domain only for $\alpha/H < 0$. In the latter interval, r_0 is also greater than unity, but orders of magnitude too large to fit in. For $\alpha/H > 0$, only the ratio r_0 is greater than unity. However, it enters the observational domain only beyond some critical value α_c/H depending upon the e-folding scale δ. For the examples chosen, $\alpha_c/H \approx 2$ for $H/\delta = 1$ and $\alpha_c/H \approx 4$–5 for $H/\delta = 4$.

It is here possible to conclude that r_0 should systematically overestimate observed amplification ratios without the need for estimating the corresponding values of α_c for a realistic stratification. This stems from the conclusions of TM01 that the ratio $r_0(+\infty) = r_1(-\infty)$ overestimates observations, which implies that $r_0(\alpha)$, which is always greater than $r_0(+\infty)$ for all finite values of α, should overestimate observations even more. [In contrast the ratio $r_1(\alpha)$, smaller than $r_1(-\infty)$ for finite $\alpha < 0$, could potentially improve the comparison with observations.] While this may seem to build a strong case against the pseudobarotropic mode, we believe nevertheless that this is not all the story in view of the following.

- Topographic effects do not act alone in reality, but in combination with the background mean flow. In the full eigenproblem, as considered for instance by Killworth and Blundell (2003a,b), the eigenvalues are expected to depend in a strongly nonlinear way upon both effects; it is therefore not implausible to imagine that the mean flow may act to further slow down the pseudobarotropic mode $n = 0$, although of course this should be substantiated by precise calculations that remain to be done.
- Planetary geostrophy is a dubious approximation to study the dynamics of the pseudobarotropic mode, as dispersive effects are likely to be important; as a first guess let us assume that these remain roughly as predicted by standard quasigeostrophic theory (e.g., Pedlosky 1987); if so, the expected consequence is that they reduce the ratio r_0 by the factor $1 + R_0^2\|\mathbf{k}\|^2$; they would then help to bring r_0 closer to observed amplification ratios.
- Small-scale topography could be an important effect, as they can potentially increase values of α and thus help reduce the ratio r_0; the question, however, is whether the present framework remains physically meaningful to infer conclusions about this effect, a priori excluded by construction. A rigorous assessment of this effect remains a challenge in physical oceanography.

3. Summary and conclusions

In this comment, we sought to clarify the following conceptual issues arising from the conclusions of KB99 regarding the role of topographic effects on baroclinic Rossby wave propagation.

1) Discrepancy between two-layer studies and KB99: In two-layer models, the reason for the systematic speed-up of the waves over steep/rough topography is well-understood and attributed to the surface intensification of the waves.[5] This mechanism of surface intensification is often encountered in the literature and has an observational basis that forms the starting point of Samelson (1992). It was extended to the continuously stratified case by TM01, in which the faster surface-intensified modes are linked to the solutions of the standard eigenproblem using a bottom boundary condition of vanishing pressure instead of one of vanishing vertical velocity; that is $F'(-H) = 0$ instead of $F(-H) = 0$. From the viewpoint of the eigenproblem studied by KB99, which uses the bottom boundary condition $F'(-H) = -\alpha F(-H)$, the faster modes studied by TM01 can be regarded either as the first baroclinic mode $n = 1$ in the limit $\alpha = -\infty$, or as the pseudobarotropic

[5] The speed of long surface-intensified Rossby waves is $-g'\beta H_1/f^2$, while that of the standard flat-bottom waves is $-g'\beta H_1 H_2/(f^2 H)$. The notations are that g' is the reduced gravity, f is the Coriolis parameter, $\beta = df/dy$ is the latitudinal derivative of f, and H_1 is the upper-layer thickness.

mode $n = 0$ in the limit $\alpha = +\infty$. In other words, one needs to consider two distinct dispersion surfaces in the continuously stratified case to recover the results of two-layer models over steep/rough topography; this is impossible in KB99 because their focus is only on the dispersion surface corresponding to the first baroclinic mode $n = 1$.

2) Differences between the local and ray approach: In order to determine whether any particular effect can potentially contribute to the the propagation speedup observed by CS96, it seems natural to study all eigensolutions associated with phase speeds comparable in magnitude with that of the first-mode baroclinic mode, regardless of which dispersion surface they are evolving on. Indeed, although the waves observed by CS96 are usually interpreted as too-fast first-mode baroclinic Rossby waves, nothing preclude them a priori to be potentially too-slow barotropic waves, as first suggested by Zang and Wunsch (1999). In this study, we find support for the latter hypothesis in the parameter regime $\alpha > 0$, provided that α can become large enough. This possibility is missed by the ray approach of KB99, because of the a priori restriction to the dispersion surface corresponding to the first-baroclinic mode $n = 1$.

   Although we find that the pseudobarotropic mode $n = 0$ may have propagation speeds comparable in magnitude to those observed in the regime $\alpha > 0$, we also find that the latter are bound to remain too fast in the context of PG dynamics and in absence of other effects. Nevertheless, plausible arguments suggest that both dispersion and/or small-scale topography could help bring the phase speeds closer to those observed. In any case, we believe that the dynamics of the pseudobarotropic mode $n = 0$ warrants further study, which we hope to report on later.

3) Topographic versus mean flow effects on Rossby wave propagation: On the basis that both KB99 and TM01 demonstrate a strong local effect of the bottom boundary condition on the properties of the eigensolutions of the linear standard theory, we must expect the same to be true for the eigenproblem including both the mean flow and topographic effects recently considered by Killworth and Blundell (2003a,b). In other words, we believe that the present published evidence provides no convincing indication that the topography is less important than the background mean flow in setting the properties of the eigensolutions. In any case, separating the respective impacts of the two latter effects on Rossby wave propagation is complicated by the nonlinear nature of the problem. We do not see that any firm conclusions can be drawn from the study of each effect in isolation, unless one can also provide convincing arguments that the nonlinear interactions between the two effects are negligible, which remains to be done.

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