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Topographic Stress in the Oceans

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The influence of seafloor topography on ocean circulation has long been a subject of research and speculation. Recent attention to this topic has shown that the interaction with currents is both more complicated and (possibly) more influential than may have been supposed.

An important question is whether inadequate representation of topographic effects in numerical ocean models may be a significant source of model infidelity. On the other side, direct observation of momentum exchange between the ocean and variations of seafloor elevation remains a daunting challenge. To focus on these and related issues and to consider possible avenues for future research, the workshop Topographic Stress was held January 23-25, 1989, at Keahou Bay, Kona, Hawaii, drawing on numerical modelers, oceanic observers, theorists, atmospheric scientists and laboratory modelers.

Concern for the role of topography in oceans can readily be appreciated by comparison with the atmospheric case. Topographic variance at any given length scale is roughly the same for typical seafloor and land-surface topographies. Yet the ocean is only a few kilometers deep, and so experiences topographic variation through a large fraction of its depth, not counting continental margins, whereas land-surface topography typically penetrates a smaller fraction of the atmospheric density scale height.

The ocean is also more weakly stratified than the atmosphere, so that Taylor-Proudman penetration ($Z=fL/N$) in the ocean may be an order of magnitude or more greater, where Z is the height to which a Taylor cap extends, f is Coriolis parameter, L is a horizontal length scale of topographic variation, and N is the stability frequency.

Oceanic N, especially in the deeper ocean, tends to be at least an order of magnitude smaller than typical atmospheric N. Moreover, relative vorticity (ζ) in the ocean is smaller so that potential vorticity anomalies (fh/H) due to topography are relatively more dominant, where h is the height of a topographic feature while H is a mean depth of the ocean. Weak nonlinearity ($\zeta H/fh<1$) in the ocean implies that even modest topography (O(100 m)) may present a significant obstacle for abyssal circulation.

An illustrative "back of envelope" calculation is to estimate a possible amplitude for pressure-slope form stress ($-p\nabla h$), where p is pressure and ∇h is bottom slope. Integrating by parts (to $h\nabla p$ plus lateral boundary contributions) and using geostrophy to estimate $\nabla p=fv$, the amplitude of form stress is fvh, where v is an abyssal flow speed. For abyssal currents of 1 cm s^{-1}, bottom features of 100 m height and Coriolis parameter 10^{-4} s^{-1}, the product fvh may be of order 10^{-4} m^2 s^{-2} or 1 dyne cm^{-2}. Larger values for v and, certainly, for h could be used in this calculation. On the other hand, a priori, we don't know the amplitude or even the sign of a correlation coefficient between fluctuations of v and of h.

Although the forces may be large, the sense of such forces is not simple. In particular, topographic irregularities often may not act to oppose the mean flow, that is, may not take the simple role of a "form drag." With this ambiguity in mind, we refer to the interaction more generally as "topographic stress."

For the moment, the preceding calculation only cautions us that the possible amplitude of topographic stresses may be large with respect to other forces that act on and in the ocean. The caution is more urgent because the amplitudes of v and h are so slight that they may be overlooked in observations or omitted entirely in numerical models.

The preceding two paragraphs could lead us to ask, "How does the ocean manage to circulate at all in the presence of its topography?" One answer may be that the ocean is forced mainly from above and is energetically stratified, currents being more intense near the upper surface. Hence seafloor topography would be less influential because it tends to be buried in a relatively less active deeper ocean. Larger N in the upper ocean tends to shield near-surface flows from bottom topographic effects. Yet even here there is a "chicken and egg" question: Is it just the roughness of the seafloor that may cause the ocean to maintain greater energetic stratification? Given that most observations are from the upper ocean, do we fail to appreciate how influential is topography with respect to mid-depth and abyssal circulation?

Beyond such questions and speculations, what is to be done? An ever growing array of observational techniques, together with ever increasing computer power for numerical modeling, offer new opportunities to tackle these old issues. Can we learn what role topographic variations play by observing the actual ocean and from numerical, laboratory or theoretical "oceans"?

A Catalog of Initial Questions

A number of questions were posed at the outset:

1. Where and at what scales is topographic stress likely to be most important?
2. How can we address question 1? from models? from observations? from lab studies? from theory?
3. Is it useful to decompose topographic stress into two parts, a gravity wave drag and "vorticity stress," based upon internal gravity wave radiation and potential vorticity (PV) dynamics, respectively?
4. If the decomposition at question 3 is sensible, then how much of oceanic topographic stress is "vorticity stress"? How much is gravity wave drag?
5. What can be learned from quasigeostrophic models? Which ageostrophic effects may be most important? What are the advantages of different model formulations?
6. Are there feasible approaches to direct observation of topographic stress? The vorticity stress part? The gravity wave drag?
7. What key similarities or differences are there between the roles of topography in the ocean and atmosphere?
8. How much of seafloor topography must be treated deterministically? How much statistically? What statistics are most important?
9. What is a plausible long-term outlook for possible representation of topographic stress in global ocean climate models?

Implications at Large Scales

One of the cornerstones for understanding ocean circulation is consideration of contours of potential vorticity. In the simplest idealization of a homogeneous ocean with weak mean flow, such contours follow f/H, with f the Coriolis parameter and H the total depth. The contours provide characteristics along which to carry lateral boundary condition information and to integrate effects of surface forcing. Already, if one contemplates actual seafloor topography, a problem arises: almost all contours close on themselves. Hence, to proceed with the classical sort of solution along characteristics, one is obliged to smooth away all but the very largest (basin) scales of topography.

In the density-stratified ocean, mean flow fields deform PV contours in ways that may tend to compensate underlying topography. Nonetheless, the influence of broad features of topography can be seen to be quite effective as in model studies showing the role of a gentle East Pacific Rise, which turns back an impinging flow from the west. As well, topographic slopes set up benthic Ekman layers with instabilities leading to modifications of interior density and velocity fields, according to P. Rhines of the University of Washington, Seattle.

Certain aspects of topographic influence on large scales have been explored in numerical models, including the influence of continental slopes at western boundaries, the interaction between large-scale bottom slopes and baroclinic density fields, and the sensitivity of overall transport in a channel to the presence of a transverse ridge that partly blocks the flow. Already one observes surprising outcomes. W. Holland of the National Center for Atmospheric Research (NCAR) in Boulder, Colo., reported that the transverse ridge case may enhance total transport, apparently because topographic torques set up pressure differences that over-compensate for the blocking presence of the ridge.

Channel Models: "The Case of the ACC"

The Antarctic Circumpolar Current (ACC) may be one of the clearest situations in the world ocean where topographic stress must play an essential role. A mean eastward wind stress supplies momentum, which, in statistically steady state, must find a compensating resistance. Neither lateral eddy transport nor bottom friction appear to be sufficient to resist the wind stress. Indeed, inverse calculations described by D. Olbers of the Alfred Wegener Institut, Bremerhaven, Federal Republic of Germany, suggest that near bottom flow may be substantially westward so that the sense of friction would be to supply a further source of eastward momentum. Apparently, if only by elimination, some manner of topographic stress is implicated.

Two model studies based upon QG formulation were reported. A 3-layer model employed steady eastward wind stress forcing together with realistic topography to examine overall momentum budgets. In particular it was seen how interfacial form drag accomplished the downward transfer of momentum, which was then taken up by the model topography, Olbers said.

Another layered QG model, by A. M. Treguier of the Centre Océanologique de Bretagne, Brest, France, run at fine resolution (13-km grid), revealed a number of important features:

- Wavenumber spectral decomposition of the stress (pressure-slope correlation) indicates that stress is supported by the largest available scales—as given either by external forcing or domain geometry. Vertical penetration of topography is seen more clearly at larger scales, roughly following *fL/N* scaling.
- Although the large scales bear most of the stress, that stress is sensitive to the presence (or absence) of smaller scales, which appear to mediate the stress through nonlinear coupling.
- A significant component of the time-averaged flow consists of stream function (or vorticity), which is correlated with the topographic fluctuations, denoted ψh. The component of ψ that correlates with h provides no topographic stress but greatly aggravates the question of possibly observing topographic stress (vh) in a field program. At smaller scales, vorticity (ζ) is anticorrelated with h. Both the large and smaller scale correlations are seen in Figure 1.
- Dependence of mean flow upon model parameters, such as β and height of topography, is complicated and not easily characterized.

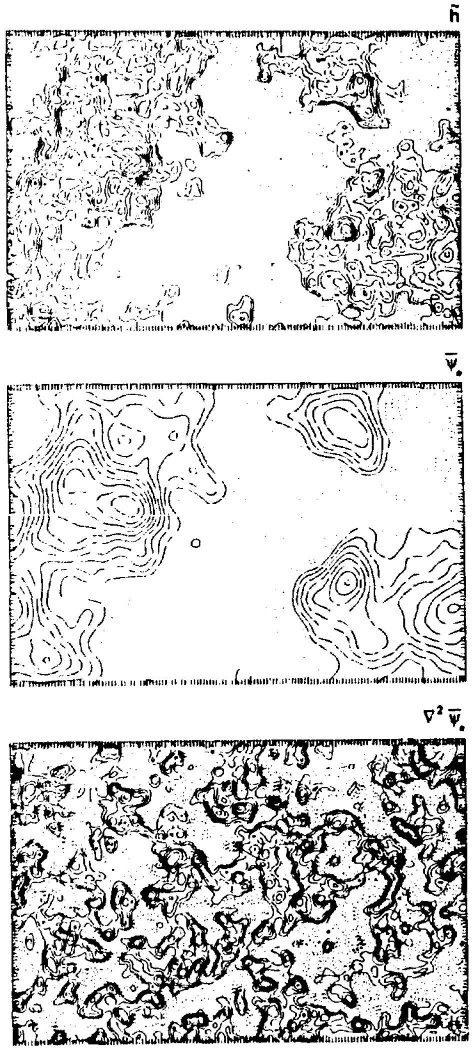

Fig. 1. A 3-layer quasigeostrophic channel flow is forced by steady zonal winds. *Top*, topography. *Middle*, time-averaged streamfunction in the lower layer, with zonal mean streamfunction removed. *Bottom*, time-averaged vorticity in the lower layer. From Treguier.

Basin Scale Models

Advances in available computing resources are making possible model studies with ever greater detail. Although a WOCE (World Ocean Circulation Experiment) Community Modeling Effort has provided a high resolution, primitive equation (PE) modeling exercise for a realistic North Atlantic Ocean, the role of topography remains to be examined in this model output. Other model studies however have clearly shown the importance of topography. Eddy-resolving quasigeostrophic (QG) models of the Gulf Stream region show that inclusion or omission of topography dramatically alters the flow regime. A fine-mesh, 8-layered, QG model of the California Current embedded in a coarser-resolution North Pacific Ocean, by Holland, shows that inclusion of topography causes the flow to become organized with poleward deep flow.

The adequacy of QG dynamics for topography of finite amplitude is always a concern, although it does appear that QG offers a kind of "analog correctness" even when bottom slopes are large compared with Rossby number, D. Haidvogel of the Chesapeake Bay Institute, Baltimore, Md., reported. Indeed it is a history of such QG studies of eddy topography interaction that has guided much of present thinking. It may be, for example, that eddy interaction with bottom roughness helps Lagrangian particles to "forget" their PV history, thereby promoting homogenization of PV. High-resolution shallow-water equation models are making it possible to extend some of these ideas. A study of flow interacting with an isolated topographic bump, by M. Kawase of the University of Washington, Seattle, suggests that ageostrophic effects impede the homogenization of PV.

In terms of overall budgets, the role of topographic stress in basins is not so clear as in the case of the ACC. Wind-supplied momentum may be balanced, for example, by pressure differences across a basin. It is not clear, though, that the relative angular momentum budget in a basin can be closed realistically by frictional retardation alone, according to G. Holloway of the Institute of Ocean Sciences in Sidney, British Columbia, Canada. Attention to this question may yet reveal a paradox similar to the zonal momentum budget issue in ACC channel geometry.

Theoretical Analyses

Analytical models provide further insight, detecting subtleties that may be misrepresented by numerical models depending upon detail of numerical method. A study of an internal Kelvin wave encountering a transverse ridge, by P. Killworth of Oxford University, Oxford, U.K., reveals how sensitive is the fraction of energy transmitted to the question whether the ridge penetrates the resting level of an isopycnal. It may be that such questions of penetrative-nonpenetrative topography will prove especially vexing.

Observability of Topographic Stress in the Ocean?

Disturbances to thermohaline structure near seamounts are readily and dramatically observed, for example in the case of flow impinging upon the Emperor Seamount chain, reported by G. Roden, University of Washington, Seattle. However, a corresponding observation of systematic momentum exchange eludes us. In some cases, such as the zonal momentum of the ACC, it appears that topographic stress can be estimated as a residual. But how might one devise an experiment for direct observation of the topographic stress?

Numerical model studies by J. McWilliams, NCAR, tend to show that pressure-slope correlation ($p\nabla h$) exhibit a smaller spatial scale of structure than does $h\nabla p$. The difficulty in leveling p appears also to discourage the $p\nabla h$ approach. Either approach will suffer from the large correlation between ψ and h, as noted by Treguier. An effort by Olbers to estimate the stress $h\nabla p$ has yielded ambiguous results based upon available data; more complete datasets (to be acquired) may refine this estimation. However, strong vertical momentum transfer within the modeled oceans suggests that consideration be given to attempting to estimate vertical momentum transfer in the interior of the water column, where isopycnal "topography" may be of larger horizontal scale.

The analogy to hydraulic critical phenomena, drawn by L. Pratt of Woods Hole Oceanographic Institution (WHOI) in Woods Hole, Mass., suggests that aspects of topographic stress might be inferred from observable changes in the width of jetlike flows as they cross ridges. M. Briscoe of the Office of Naval Research, Washington, D.C., remarked also on the possibility that Doppler and in situ profilers might be capable of detecting gravity wave drag, although it was not clear where best to attempt such observations.

Observability in the Laboratory?

Direct measurement of forces on objects in channel-flow tanks is an accomplished capability. Investigations of topographic effects in rotating table experiments are also ongoing. In particular, for experiments that simulate a β-plane, K. Helfrich (WHOI) found that the presence of a radial topographic ridge in a polar β-plane induces a marked asymmetry between spin-up and spin-down. Without topography, spin-up and spin-down follow linear viscous scaling. With topography, spin-up (that is, pseudo-eastward acceleration) continues to follow nearly the linear viscous scaling whereas spin-down, or pseudo-westward acceleration, is markedly enhanced, as seen in Figure 2. An interesting observation is that such spin-down experiments with topography tend to reverse the sense of mean flow, that is, to drive pseudo-westward flow even when the sense of flow is pseudo-westward. The laboratory permits visualization of a wave-like flow with eddies in spin-down experiments.

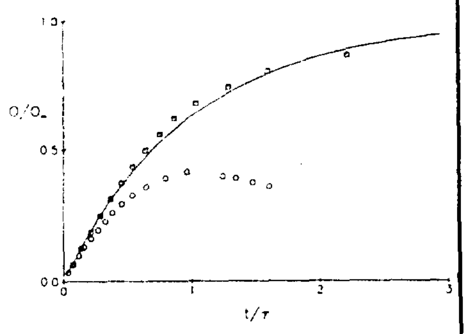

Fig. 2. Laboratory experiments showing a strong asymmetry between spin-up (□) and spin-down (○) on a polar β-plane (a cylindrical tank with a conical bottom) including a radial ridge. Plotted is the zonal average azimuthal displacement, θ, of fluid at one-half the tank radius as a function of time, *t*. Also shown is the linear viscous theory (the curve) for no radial ridge topography. θ_∞ and τ are the maximum displacement and spin-down time, respectively, from the theory. $|\Delta\Omega|/\Omega \approx 0.14$ and topography height/water depth ≈ 0.15 for both experiements. From Helfrich.

Experience from Atmospheric Sciences

Because vorticity-topography stress in the atmosphere tends to occur at sufficiently large scales to be resolvable by numerical models, most research is focused on the gravity wave interaction part. D. Fritts of the University of Alaska, Fairbanks, has observed that stratospheric gravity wave variance is enhanced over orographic regions in comparison with regions over oceans or plains. On account of decreasing density with height, gravity waves grow in amplitude until a breaking saturation limit is reached. Momentum is thereby transferred from ground-level topography to the middle atmosphere, with wave energy given up to mixing.

Detailed model studies by D. Durran, University of Washington, Seattle, supply many details of the topographic gravity wave generation and resulting mean flow modification. For the most part, Coriolis effects are omitted while attention is focused on development of lee-wave resonances and downslope winds. However, N. McFarlane of Canada Climate Centre in Downsview, Ontario, Canada, said that important modifications to the general circulation are seen when parameterizations of the gravity wave drag and momentum transfer are incorporated into global atmospheric models. Especially, it has been noted that, in the absence of such parameterization, models systematically predict upper-level flows that are too strongly eastward. The gravity wave drag correction appears to give encouraging results from a physically motivated justification. (See Figure 5 in "Parameterization of Small-Scale Processes," by Peter Müller and Greg Holloway, *Eos, 70,* 820, 1989.) However, substituting oceanic values into McFarlane's parameterization, F. Henyey of Arete Associates, La Jolla, Calif., estimates that the oceanic gravity wave drag is very small.

Conclusions

Presentation of research results and ensuing discussions raised many new and fascinating questions without resolving the initial set of questions. However, certain points did emerge.

- Separation into a vorticity stress part and a gravity wave drag appears to provide a useful conceptual framework at least for the present. For the oceans, it appears that vorticity stress is dominant.
- Model results have indicated that the largest available scales tend to dominate the vorticity stress. It was suggested that this scale dependence will be influenced by large planetary β or effective bottom slope. Although smaller spatial scales made less direct contribution to stress, their role appeared to be important in the model studies. Gravity wave drag will be generated by scales of bottom roughness between U/f and U/N, where U is an abyssal flow speed and N is an abyssal stability frequency. For oceanic parameters, these scales are roughly from 100 m to 1 km.
- Direct observation of the vorticity stress in the oceans presents daunting obstacles with some consideration given to possible mid-depth observation of vertical transfer of horizontal momentum. Estimation of vorticity stress as a residual appears to be more promising under circumstances where other forces may be adequately estimated or otherwise eliminated. Numerical model studies appear to play a central role, at least with respect to oceanic vorticity stress, while theoretical studies serve both as cautions and to suggest possible alternative observations.

Laboratory experimentation appears to offer the most direct approach to observing both vorticity stress and gravity wave drag in the context of actual fluids.

- Differences among model formulations were not considered in great detail, though this is seen as a matter that remains to be better understood. Likewise the statistical or determinisitic representations of seafloor topography were not made a focus for discussion. Sometimes a spectrum of topography is assigned for process model studies. In reality, seafloor topography includes isolated seamounts, seamount chains, ridges and fracture zones, which are not expressed by random synthesis from a spectrum.
- As presently foreseen, the outlook for parameterizing unresolved vorticity-topography stress in large-scale ocean models seems doubtful. Model results suggest complicated dependences on parameters. One thing that does seem clear is that parameterization in terms of a drag law (linear, quadratic or otherwise) cannot succeed insofar as a growing body of results point toward topographic stresses that are sometimes systematically of the sense to accelerate flows. Parameterization of oceanic gravity wave drag is more feasible, as in atmospheric applications. In the longer term, it appears that adequate representation of the vorticity stress will be essential to obtaining dependable large-scale ocean models.

Acknowledgments

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