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DYNAMIC INTERPRETATION OF GEOID ANOMALIES

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INTRODUCTION

The NASA Geodynamics program has as two of its missions precise determination of spatial variations in Earth's geopotential (or geoid) and highly accurate monitoring of polar motion, including changes in length of day (LOD). These observations place fundamental constraints on processes occurring in the atmosphere, near the surface, in the mantle, and in the core of our planet. Short-wavelength variations in the geoid are mainly the result of density variations in the crust and lithosphere, while long-wavelength variations are primarily the result of density variations associated with mantle convection. Short-timescale ($t \lesssim 1$ yr) variations in LOD are mainly the result of interaction between the atmosphere and the solid earth, while variations in LOD on decade timescales result from exchange of angular momentum between the mantle and fluid core.

For the past several years, the PI has been using these high quality data sets provided by NASA, along with data and models from other areas of geophysics, to place fundamental constraints on the large scale dynamics of Earth and her sister planet Venus. His main approach has been using fluid mechanical models of mantle flow to predict the long-wavelength variations in the geoid. The grant under which this work was done has now expired. This is the final report describing the work done under this grant.

The fundamental physics of the generation of geoid anomalies in a convecting planet was first recognized by Pekeris (1935). Density contrasts in a convecting mantle result both in flow and in dynamically supported topography at the surface, the core-mantle boundary (CMB), and at any other interior boundaries in composition that might exist (e.g., the 670 km seismic discontinuity or the top of the D" layer just above the CMB). The mass anomalies associated with this dynamic topography are comparable in magnitude and opposite in sign to those associated with the interior density contrasts driving the flow. As a result, the geoid anomalies associated with mantle convection are relatively small differences of larger quantities.

As we showed (Richards and Hager, 1984), the distribution of dynamic topography among the boundaries of a convecting system, and the resulting geoid anomalies, depend strongly upon the distribution of viscosity with depth and the presence or absence of chemical stratification. If the density differences driving flow in the mantle can be estimated, e.g., through seismic tomography, comparison of the observed geoid with model geoids predicted by forward modeling using a variety of assumed mantle structures places useful constraints on the dynamic structure of the mantle. Using this approach, we have been able to explain ≈ 90% of the variance in the observed geoid at wavelengths longer than 4,000 km (Hager and Clayton, 1988; Hager and Richards, 1988, abstracts attached).

The flow models also predict the pattern and amplitude of the dynamic topography at the surface and at the CMB. CMB topography is particularly interesting because the coupling between the solid mantle and fluid core is strongly affected by this topography. Excess ellipticity of the CMB has been inferred from effects on nutation observed using VLBI (Gwinn et al, 1986), while interaction of bumps at the CMB with changes in the flow field in the core could explain the decade length changes in LOD (e.g., Hide, 1986). We have used models of core flow inferred from observations of variations in the magnetic field (NASA sponsored) to constrain the dynamics of the CMB (Hager, 1987).

Our initial paper on geoid anomalies in a dynamic earth (Richards and Hager, 1984) outlined the formalism for calculating the dynamic topography and geoid anomalies for a spherical, self-gravitating, incompressible planet with a spherically symmetric, but depth dependent, viscosity. The important effects of chemical layering and changes in viscosity with depth were illustrated using simple two-layer models. The formalism was applied to explaining the long-wavelength geoid anomalies associated with subducted slabs (Hager, 1984). An important conclusion of this paper was that the geoid anomalies associated with subducted slabs could only be explained in the context of mantle-wide convection (with a two-layer parameterization of viscosity) if there were a substantial viscosity increase with depth (> 30) across the 670 km discontinuity. Chemically stratified models could also explain the geoid if subducted slabs have large mass anomalies, e.g., as would result if they are about a factor of 5 more dense than inferred from our thermal model, perhaps due to phase changes (e.g. Anderson, 1987).

We were fortunate that at about this time the second generation of models of lower mantle structure from seismic tomography (Dziewonski, 1984; Clayton and Comer, 1984,) were becoming available. Using density contrasts inferred (by assuming that density and velocity anomalies were directly proportional) from these tomographic inverses as inputs to our fluid dynamical models, we were able for the first time to provide a physically based explanation of the origin of the longest wavelength (degree 2-3) variations in the observed nonhydrostatic geoid (Hager et al, 1985). Still using a two-layer parameterization of mantle viscosity, the inferred jump in viscosity at 670 km depth was a factor of 10.

Using more realistic models of viscosity variation with depth, we were able to reconcile the estimates of viscosity jump across the 670 km discontinuity based on the geoid signature of lower mantle heterogeneity and subducted slabs. Using a four-layer parameterization (lid, asthenosphere, transition zone, and lower mantle) and including the additional density contrasts inferred from upper mantle seismic tomography (Tanimoto, 1986) and delayed response to Pleistocene deglaciation, we were able to explain over 90% of the variance in the observed geoid, assuming mantle-wide flow (Hager and Clayton, submitted, 1986, still in press, 1988). The fit for chemically stratified models was not quite as good, but still acceptable, providing that the mass anomalies associated with subducted slabs are large.

Perturbations in viscosity

The above (3-D, spherical) models all assumed spherically symmetric viscosity distributions for mathematical tractability. Unfortunately, this assumption is clearly a very crude approximation for a convecting mantle. For example, the temperature variations associated with the density variations driving mantle flow also cause viscosity variations. Plate boundaries are weaker than plate interiors. Thus it is essential to determine how the assumption of viscosity that varies as a function only of depth affects inferences of mantle structure.

In his Ph. D. thesis, Mark Richards (1986) addressed this issue using both analytic (perturbation theory) and finite element approaches. His results (Richards and Hager, 1988b) show that for flow with half-wavelength greater than the thickness of the mantle, radial variations in viscosity are more important than lateral variations, while for shorter wavelengths, lateral variations are comparable in importance to radial variations. Thus the basic conclusions about mantle structure derived thus far seem sound, but further progress can be expected from including lateral variations using numerical, rather than analytical, approaches.

Empirical correlations and hotspots

In addition to our fluid dynamical modeling of geoid anomalies, we have investigated a number of empirical correlations (Richards and Hager, 1988b). These include the correlation of the long-wavelength geoid highs with both plate convergence velocities and with the distribution of hotspots. The latter correlation was investigated in detail by Richards, Hager and Sleep (1988). They found that the association of geoid highs with hotspot provinces could be explained if plumes preferentially occur in regions of above average background temperature. Plumes are also expected to neck down, becoming thinner as they enter the upper mantle.

Dynamic topography

Although the model fits to the observed geoid were excellent, we sought further tests. The dynamic topography predicted by the flow models is one important test. At the surface, the predicted dynamic topography is of order several hundred meters (Hager and Clayton, 1988). This is small compared to the topography caused by variations in crustal thickness and lithospheric age and comparable to the magnitude of estimates of residual topography, i.e., topography not associated with these two main causes. The match to estimates of residual topography is encouraging (Hager and Clayton, 1988), and more detailed comparisons are planned.

Coupling with the fluid core

Because of its high temperature, the CMB is unlikely to support static topography like that due to crustal thickness variations at the surface: it is likely that any topography at the CMB is dynamically maintained. Thus if the topography of the CMB can be constrained, it would provide powerful tests of our dynamic models. Several approaches to modeling CMB topography have been attempted in the past few years, although, as yet, the results are not straightforward to reconcile.

Probably the most accurate estimate of CMB topography is that provided by models of coupling of core and mantle nutation. The shift in resonance period of the free core nutation from that predicted using hydrostatic theory, observed using VLBI geodesy, has been interpreted as due to an excess ellipticity of the CMB of $\approx$ 500 m (Gwinn et al, 1986). This is about a factor of four smaller than that predicted by our first and second generation dynamic models and, as discussed below, motivated us to improve them by considering the effects of a chemically distinct and/or low viscosity D" layer. At this time, this VLBI technique has been used only to look at CMB ellipticity, not at any higher order component of CMB topography.

Seismological estimates of the CMB topography have had large amplitudes (~ 10 km) (e.g. Morelli and Dziewonski, 1987), but the models proposed by the three groups most active in modelling the CMB region (Harvard, MIT, Caltech) show little similarity to each other.

A third way to constrain CMB topography is to calculate the mechanical interaction between flow in the mantle and bumps on the CMB (e.g. Hide, 1986). If the temporal variation in the dynamic pressure at the top of the core can be obtained, the change in torque exerted by the flow in the core on the overlying mantle can be computed and compared to the observed changes in length of day. Unfortunately, there are many uncertainties involved in estimating the pressure field in the core. Nevertheless, we have spent substantial effort in calculating models of core-mantle coupling in the belief that, while the details of the models are probably incorrect, they can place useful bounds on CMB topography.

In order to estimate the pressure field at the top of the core, we have followed Hide (1986) in assuming that the flow there is, to a first approximation, geostrophic. The main assumption, somewhat controversial (e.g., Bloxham, 1988), is that near the boundary with the (assumed insulating) mantle, the magnetic field is small.

At the time this work was initiated, there was only one geostrophic model available (Le Mouel et al, 1985). (This model has since been shown to be only approximately geostrophic (Bloxham, 1988), but the small degree of ageostrophy, which occurs at high harmonic degree, is unimportant, given the uncertainties in the model.) Testing it against our models of CMB topography gave decade length changes in LOD an order of magnitude larger than observed (Hager, 1987).

The seismological estimates of CMB topography (Morelli and Dziewonski, 1987) gave even larger predicted variations. We are in the process of obtaining additional geostrophic flow models from C. V. Voorhies and J. Bloxham to test the robustness of our results.

Our tentative conclusion is that the bumps at the CMB predicted by our mantle flow models are an order of magnitude too large to be consistent with the observed changes in LOD. The even larger bumps inferred from tomography present an even more serious problem. Resolution of this paradox will be discussed below, and in two papers in preparation.

Models Including D"

Our seemingly too large estimates of CMB topography, as well as the *a priori* expectation that the CMB is a thermal boundary layer and might also be chemically distinct from the overlying mantle, led us to include these parameterizations in a third generation of flow models. These models, discussed in Hager and Richards (in press, 1988; abstract attached), include an additional one to two layers above the CMB, for a total of up to 6 layers. The layer above the CMB can be low-viscosity, chemically distinct, or both. Including D" in the parameterization allows nearly as good a fit to the geoid with (small) CMB topography that satisfies the constraints from nutation and LOD.

While it satisfies the geodetic constraints, this small CMB topography seems inconsistent with the estimates from seismic tomography. One resolution (Hager, 1987; Hager and Richards, 1988) is to speculate that there is a layer of molten silicate floating on the metallic core just below the solid mantle. Since dynamic topography is inversely proportional to the density contrast across an interface, the small density contrast between molten silicate and solid mantle would result in large dynamic topography, consistent with the seismological models. These "anti-oceans" of molten silicate would shield the CMB topography from flow in the metallic core, removing the problem of excessive predicted changes in LOD.

Implications of high inferred core temperature and bounds on heat flux from the core were discussed by Ahrens and Hager (1987). The indication is that D" is stably stratified against convection, otherwise the heat flux from the core would exceed the surface heat flux.

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