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Final Report

This is the final report of all work done under NASA grant NAG5-485 awarded to the University of Colorado, from the inception of the grant in December, 1985, until the grant termination. The principal investigator is John Wahr.

The abstract for the original 1985 proposal (see the attached science statement) separated the proposed work into 3 tasks. Here, we summarize our work into 4 main sections, the first 3 roughly corresponding to the 3 tasks in the original abstract, and the 4'th section describing work which didn't fit into any one of those tasks.

(I) (a) We modeled the deformation of the earth caused by variations in atmospheric pressure. We found that large synoptic-scale storms can displace the earth's surface radially by up to 1-2 cm peak-to-peak at mid-latitudes, and by up to 3 cm at higher latitudes. Storms of this severity occur about once per month at those latitudes. We concluded that to adequately remove the effects of this deformation from Crustal Dynamics measurements, it is necessary to know the pressure field over at least 1000 km of the station. The amount of deformation near coasts is sensitive to the nature of the oceanic response to the pressure.

(b) We used GEOSAT altimeter data and PSMSL tide gauge data to test whether the oceanic response to atmospheric pressure is inverted barometer, and at what periods. The PSMSL data suggest the response is inverted barometer at periods greater than a couple of months (see below). Our GEOSAT analysis involved a least-squares-fit of pressure data to sea level along the altimeter tracks. We consistently obtained a least-squares-fit value for single tracks of -.6 cm/mbar, rather than the -1.0 cm/mbar expected if the inverted barometer assumption were valid. We also found a clear dependence of the fit results on latitude. The magnitude of the fit parameter is only slightly smaller than 1.0 cm/mbar at high-latitudes, dropping steadily to values nearer 0 cm/mbar as the latitude approaches the equator, and then rising back up close to 1 cn/mbar in the near-equatorial region. It is not clear what the implications of this are - whether this is a true non-inverted barometer response to pressure, or whether it is due instead to the response of the oceans to winds which are, themselves, correlated with pressure.

(c) We constructed Green's functions describing the perturbation of the geoid caused by atmospheric and oceanic loading and by the accompanying load-induced deformation. We found that perturbation of up to 2 cm are possible.

(II) (a) We used ice mass balance data for continental glaciers to look at the glacial contributions to time-dependent changes in polar motion, the lod, the earth's gravitational field, the position of the earth's center-of-mass, and global sea level. We looked both at linear trends and at interannual variations. We estimated similar time-dependent contributions from global changes in sea level, using the PSMSL tide gauge data. One conclusion from this work was that the rate of sea level rise due to melting continental glaciers has been substantially smaller since 1965 than it had been in previous decades.

(b) We found that there can be lateral, non-hydrostatic structure inside the fluid core caused by gravitational forcing from the mantle, from the inner core, or from topography at the core/mantle or inner core/outer core boundaries. We developed differential equations to describe the structure, and we considered the possible implications of this structure on the VLBI and earth tide constraints for the shape of the core/mantle boundary. Those constraints suggest that the non-hydrostatic ellipticity of the boundary is around 1/2 km. We find that although the 1/2 km is probably right, it would be possible to accommodate a value of up to about twice as large if there was a thin, low density fluid layer just beneath the boundary.

(c) We modeled the nutational and tidal response of a non-hydrostatic earth with a solid inner core. The presence of the inner core causes the earth to have a new nutational normal mode, with a prograde inertial space period of about 470 days. The effect of this mode on the forced nutations is larger than the present uncertainty in the VLBI observations - at least for the prograde 6-month nutation. But, it will be some time before nutation observations can be used to infer a bound on the ellipticity of the inner core. In addition, the effects of this mode on the nutations depends on all non-hydrostatic components of the inner core/outer core and core/mantle boundaries. This could complicate any future inversions for the inner core boundary shape. The effects of non-elliptical topography are not likely to be as important for the 1/2 km core/mantle boundary result presently inferred from VLBI data.

(III) We used monthly, global tide gauge data from the Permanent Service for Mean Sea Level (PSMSL) in Bidston, England, to look at the following items:

(a) the 18.6-year ocean tide: we find the tide to be within about 20% of equilibrium.

(b) the 14-month pole tide: we find the tide to be within about 30% of equilibrium in the deep ocean, and we conclude that the apparently non-equilibrium tide in the North Sea region could, instead, represent the response of that region to meteorological forcing.

(c) the oceanic response to pressure: we find that the globally-averaged response is within about 5% of the inverted barometer response at periods between 2 months and several decades.

(d) the linear trend and inter-annual variability in the earth's gravity field and center-of-mass motion, due to changes in global sea level.

(e) the global sea level rise, and the effects of post glacial rebound: we find good agreement with existing rebound models. We obtain a rise in sea level, after the effects of post glacial rebound have been removed, of between 1.4 mm/yr and 2.6 mm/yr, with a preferred value of 1.75 mm/yr.

(IV) (a) We modeled the effects of mantle anelasticity on nutations, earth tides, and tidal variation in the lod. Our results can be (and have been) used with Crustal Dynamics observations to look at the anelastic dissipation and dispersion at tidal periods. Our estimates suggest that the effects of anelasticity on nutations and on tidal variations in the lod are larger than the current observational uncertainties.

(b) We studied the possible effects on the earth's C21 and S21 gravity coefficients of a relative rotation of the core with respect to the mantle. We concluded that observations of those coefficients put useful bounds on the relative rotation between the core and mantle about equatorial axes. The gravity results can also be used to put bounds on the torque between the core and mantle about equatorial axes, and on the $l=2$, $m=1$ spherical harmonic components in fluid pressure at the top of the core.

(c) We modeled the effects of surface topography on various components of crustal deformation.

(d) We developed numerical models of post glacial rebound. Our initial contribution was to include in the model the deformation caused by the post-glacial-induced polar drift. We found that this additional deformation was small, although it could have a significant effect on estimates of the lithospheric thickness in regions close to the original ice sheet margins. More recently, we have discovered two results: (1) that the relaxation spectrum for a realistically-stratified earth includes sets of infinitely-dense modes, that considerably complicate the analysis; and (2) that we can adjust the spatial and temporal characteristics of the Laurentide ice load to simultaneously match the observed free air gravity anomaly over northern Canada and all sea level curves from around Hudson Bay, so long as we assume the lower mantle viscosity is approximately 50 times larger than the upper mantle viscosity. Result (2) is particularly important. Previously, people had concluded that the gravity and sea level data could not be satisfied simultaneously, and that the preferred earth model was one where the viscosity is nearly uniform throughout the mantle. We have also looked at the possibility of constraining viscous anisotropy in the upper mantle, using post glacial rebound observations. We have concluded that this is not yet feasible.

(e) We have extended numerical models of internal loading problems to include radial stratification and internal phase boundaries. We find that the effects of radial stratification are not particularly important. Effects of phase boundaries, however, can be extremely important. We believe that future seismic models of internal boundaries (such as the 670-km discontinuity), combined with geoid information, could provide valuable evidence about whether certain internal discontinuities are phase transition- or chemical-boundaries.

(f) We "stacked" data from the IDA network to constrain the FCN resonance in the gravity tide. We obtained a period for the FCN that agreed well with the VLBI nutation estimates. But, our solution for the damping time is much smaller than that inferred from the nutations. It is likely that uncertainties in the ocean tide are still affecting our tidal results, but, until the issue is resolved, the results counsel caution when interpreting the observed VLBI damping time in terms of dissipation inside the earth.

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