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IB and NIB Hypotheses and Their Possible Discrimination by GRACE

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Abstract. The NASA, the GFZ and the DLR plan the GRACE satellite mission to obtain an accurate gravity field after every 2–4 weeks. Because of its extreme high precision, GRACE is expected to determine the temporal variations of the gravity fields due to time varying geophysical phenomena. Among them, the effects of the atmospheric surface pressure have the largest signals and we investigated its effects mainly from the viewpoint of degree amplitudes. Behaviour of atmospheric variations over oceanic areas is unknown. The response of the ocean is essentially important not only for the corrections of the atmospheric effects on gravity fields, but also for many other studies such as satellite altimetry, crustal deformation and the Earth rotations. We proposed and applied several ocean response models, i.e., IB, NIB, and intermediate ones, and evaluated the degree power differences between each one of them. The results show that almost all the differences are distinguishable by GRACE.

Introduction

Recently, new space geodetic technologies have found application on board Earth orbiting satellites. Microwave radar interferometer, precise accelerometer and the Global Positioning System (GPS) promise an effective low-orbit Satellite-to-Satellite tracking (SST) configuration [*NRC*, 1997]. Such a configuration will be used for the Gravity Recovery And Climate Experience (GRACE) missio scheduled for launch in 2001 by NASA, GeoForschungZentrum (GFZ) and Deutsche Forschungsanstalt fur Luft und Raumfahrt (DLR). Under this configuration, this satellite will provide measurements directly relatable to the Earth's gravity field. The resulting data, after subsequent analysis, will yield a series gravity models, produced over periods of 2 to 4 weeks, having accuracies of about one or two orders of magnitude better than the present, state-of-the-art, "static" gravity model. Consequently the data collected by GRACE is expected to capture the temporally varying gravity field with high spatial resolution.

Geophysical processes commonly result in planetary mass redistribution, and this redistribution is manifested in changes of the gravity field. Measurements associated with mass redistribution of the Earth can provide useful physical information about the gravitational effects of mass transport processes. However, the observed signals from GRACE will involve the integration of all the effects of mass redistributions. Hence we have to carefully remove signals from known redistribution sources for the purposes of studies involving other, unknown, mass redistribution sources. We assume that certain geophysical phenomena are known better than others being sought after. Then the knowledge of their characteristics (amplitude, frequency and phase for cyclic terms, and trend for secular changes) can be used to eliminate their effects from the integrated gravity signals.

In this paper, we consider the measurable effects of atmospheric mass redistribution. Compared to other surface mass redistributions, air mass or surface pressure is one of the best measured quantities. However, it has unknown processes such as its behavior over oceanic areas. The differences in the handling of these processes yield different proposed models; inverted barometer (IB), non-inverted barometer (NIB) and some intermediate models, as discussed later. These differences and their possible discrimination by GRACE are the main topic of this work. Once the response is determined by the coming GRACE mission, we will be able to remove the atmospheric effects fairly well.

Data

We used atmospheric pressure data for creating models of the possible oceanic responses. The data set employed was the surface pressure from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project [details in *Kalnay et al.*, 1996]. We used twenty years of surface pressure data, spanning 1978 to 1997.

In this work, the sensitivity of the GRACE satellite is approximate. Instead of an overall GRACE accuracy analysis, we used expected accuracy values of geoid height recovery resulting from this mission, as 0.001-0.1 mm for resolution of 5000-500 km, and 0.1-10 mm for resolution of 500-100 km. These values are definitely innaccurate, however they are good enough for the purpose of this work. An overall analysis have done by *J. B. Thomas*, [1999].

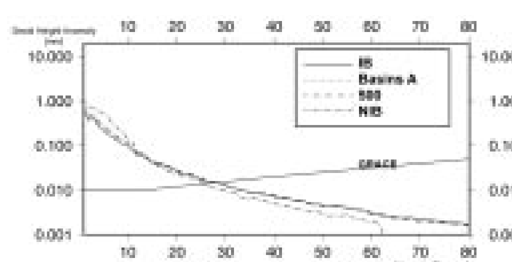

Figure 1. Geoid height anomalies for IB and NIB models and for two intermediate models between them, as a function of spherical harmonic degree l. The other intermediate models are between the shown intermediate cases. The figure also shows the expected resolution of the GRACE.

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Table 1a. Time-averaged atmospheric pressure over the ocean for each model used in this study.

IB	Hemispheres		Shallow waters	
	northern	southern	2000	500
100994	101164	100865	101121	101083

Table 1b. Time-averaged atmospheric pressure over the ocean for each model used in this study.

	Arctic	Atlantic	Pacific	Indian
Basins A	101295	101148	101166	100978
Basins B	101239	101125	101131	100915

Formulations and computations

If we know the density distribution of the Earth, the spherical harmonic coefficients (Stokes coefficients) of the Earth's external gravitational fields can be written as followed [e. g. *Chao and Gross*, 1987]

$$\begin{pmatrix} C_{l,m} \\ S_{l,m} \end{pmatrix} = -\frac{1}{MR^l} \times \int \rho(r,\theta,\lambda) r^l P_{l,m}(\cos\theta) \begin{pmatrix} \cos m\lambda \\ \sin m\lambda \end{pmatrix} dV \quad (1)$$

where, $C_{l,m}$ $S_{l,m}$ are the Stokes coefficients of degree l and order m, M and R the Earth's mass and mean radius; $\rho(r,\theta,\lambda)$ is the density, r is the radial distance, θ and λ are the colatitude and east longitude, $P_{l,m}$ is the associated Legendre function, $dV(dr, d\theta, d\lambda)$ is the volume element. The integration is over the entire volume of the Earth, including its fluid envelope, i.e. oceans and atmosphere as well.

Temporal variations of the density $\rho(r,\theta,\lambda)$ results in temporal variations of the Stokes coefficients, $\Delta C_{l,m}(t)$ and $\Delta S_{l,m}(t)$. Practically, we used fully normalized coefficients, $\Delta\overline{C}_{l,m}(t)$ and $\Delta\overline{S}_{l,m}(t)$. Let the temporal variation of surface pressure be Δp, which is given as a departure from a mean state value. Assuming $r \approx R$, sustituting $\rho = M/V$ and $V = 4R^3\pi/3$, assuming a hydrostatic profile in the atmosphere, then $\Delta\overline{C}_{l,m}(t)$ and $\Delta\overline{S}_{l,m}(t)$ become [e. g. *Chao and Au*, 1991]

$$\begin{pmatrix} \Delta\overline{C_{l,m}}(t) \\ \Delta\overline{S_{l,m}}(t) \end{pmatrix} = \frac{1}{4\pi}\frac{1+k_l'}{2l+1}\frac{3}{R\rho g} \times \int_\sigma \Delta p(\theta,\lambda,t) P_{l,m}(\cos\theta) \begin{pmatrix} \cos m\lambda \\ \sin m\lambda \end{pmatrix} d\sigma. \quad (2)$$

where $\overline{P}_{l,m}(cos\theta)$ is the normalized associated Legendre polynomial, k_l are the Earth's load Love numbers [*Farell*, 1972]; g is the average gravitational acceleration, the integration is over the unit sphere with surface element $d\sigma = \sin\theta d\theta d\lambda$.

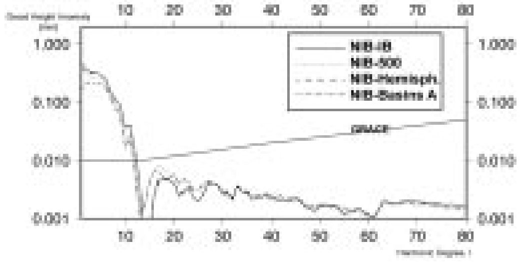

Figure 2. Differences of the geoid height anomalies of the atmospheric models, as a function of spherical harmonic degree l. This frame shows the comparison of the NIB and IB-type models. The not shown IB-type models are similar to the shown cases. The figure also shows the expected resolution of the GRACE.

The resolution of the model differences was analyzed using degree amplitude spectra to observ wether it could be detected by the GRACE. The degree amplitudes, σ_l were derived from Stokes coefficients $\Delta\overline{C_{l,m}}(t)$ and $\Delta\overline{S_{l,m}}(t)$ as follows [*NRC*, 1997].

$$\sigma_l = a\sqrt{\sum_{m=0}^{l}(\Delta\overline{C_{l,m}}^2 + \Delta\overline{S_{l,m}}^2)}. \quad (3)$$

Ocean response models

The basic ocean response models we used correspond to two extreme cases: 1) IB, which assumes that ocean responds to the change of atmospheric mass loading instantaneously so as to compensate it; and 2) NIB, which assumes the change of the atmospheric pressure directly affects the mass loading at the sea bottom. The reality may lie between the IB and the NIB cases, so we attempted to create intermediate models by mixing these two cases. For shorter variation, such as diurnal term, the NIB maybe reasonable, because of the slowness of the current flow for the time frame. For secular the term, on the other hand, the IB is much more realistic because of the quickness of current flow for secular time frame.

As intermediate models we assumed the following cases; 1) differentiating ocean current flow in the northern and the southern hemispheres; 2) treating the shallow water areas as NIB, and the deeper ocean as IB; and 3) separating the natural basins supposing that there is no flow between them. Practically, the first case supposes independent IB responses in the southern and the northern hemispheres and the third case, independent IB responses in each of the natural basins. Hereafter, we refer to these models as the hemisphere model, shallow water model and basin model, respectively. And below are brief explanation about each models.

Hemisphere model

We tried to differentiate the oceanic currents in a very rough way. Assuming separation of currents along the equator, we suppose the response of the ocean has independent IB reactions in the hemispheres. Although the characteristics of the oceanic currents follow a south-north separation, this assumption is clearly not realistic. It allows us, however, to estimate whether its separation has any notable effects on the gravity signal or not.

Shallow water models

There are several studies about the dynamics of geophysical fluids in shallow water areas [e. g. *Pedlosky*, 1979]. Around coastal areas, there is not enough depth to dissipate

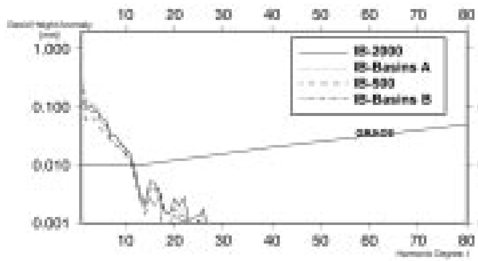

Figure 3. Same as figure 2, but cases of IB compared with other IB-type models. (Hemispheric-IB on figure 4.)

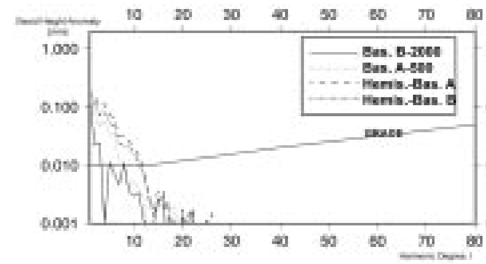

Figure 5. Same as figure 2, but intermediate cases compared to each other.

any pressure disturbance by flows. Most of the pressure signal reaches the bottom of the ocean. Thus, in shallow water, the NIB is preferable to IB. There is no clear depth to divide the shallow and the deep waters. We tried two values of 500 m and 2000 m. Hence we assumed NIB in shallower depth and IB in deeper depth.

Basin models

The flows in the ocean can provide IB compensation of pressure differences; consequently, an IB response is possible within the basin. Supposing a 100 percent through-flow between every basin means a global IB, while zero through-flow results in basin by basin IB reactions. Several works consider, for instance, the efficiency of the Indonesian throughflow. The way of handling it yields notable differences in the gravitational field [e. g., *Hirst and Godfrey*, 1993].

In our work, we separated four basins: Indian Ocean, Atlantic Ocean, Pacific Ocean and Arctic Ocean. We used the shallow water model (as described above), for depths of 500 m and 2000 m. In case of the 2000 m model, the separation of the basins have been done in consideration of the main seafloor topography at depths of 3500 m, while in the case of the 500 m model, we used a 500 m depth topography for separation. In the case of a very shallow model (500 m), we assume implicitly that the water is so viscous that it can manage IB reactions even in very shallow areas. We can surely suppose that topographic features lower than 3500 m can not stop its flow. In case of a 2000 m deep NIB shallow water model, we suppose that the bottom features can impede the water's slow motion. Hereafter these closed-basins-models will be denoted as "basin A" model and "basin B" model for the models divided at 2000 m and at 500 m depths, respectively. We use the "2000" and "500" labels for the shallow water models.

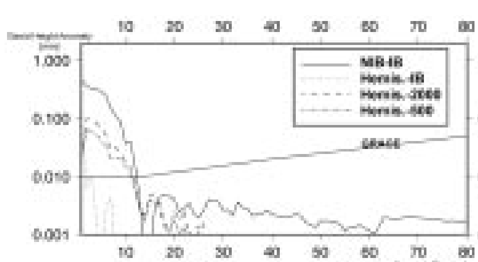

Figure 4. Same as figure 2, but cases of hemispheric model compared with others. (The comparison with the basin models are on the figure 5. However, they are between the two shallow water cases shown in this figure.) This figure also shows the NIB-IB difference to reflect the order of magnitude differences.

Results and discussion

Average surface pressure

In the original data set, the pressures over the oceans were generally larger (min. 86835 Pa/ max. 107994 Pa) than over the land (min. 50139 Pa/ max. 104533 Pa). Using the IB model, the average oceanic pressure obtained 100994 Pa (Table 1a and 1b.). The hemispheric separation yielded a slight difference between the averages of the northern and the southern oceans. When the 500 m depth criterion is used to define shallow water, the average of the pressure is slightly smaller than in case of the 2000 m criteria. Even this negligible difference of the shallow water method has a visible effect on the related basin-models. In both basin-models, the tendencies of the differences are same. It is interesting to note that the largest oceans, the Atlantic and the Pacific, have nearly the same values. It suggests that shallow water and basin models will yield similar gravitational effects. The other notable feature is that the difference becomes more obvious by setting the dividing depth deeper.

Geoid height anomalies

Using equations (2) and (3), we obtained degree variances of geoid height anomalies. Figure 1 shows the total effect of geoid height anomalies based on the models and the estimated error level of GRACE. (The cases of hemisperic, basin B and 2000 models are not plotted but these cases lie between the plotted intermediate models.) It can be seen that all of the models are detectable until about degree 25. This result is quite similar to what is found in previous other works [e. g., *NRC*, 1997].

Figure 2 shows the comparison between the NIB and the other models. All the models have nearly the same characteristics over the expected resolution of the GRACE mission (NIB-basin B and NIB-2000 are not shown), crossing at the 11th or 12th degree. This means that the IB and the NIB models are clearly distinguishable on the long wavelength

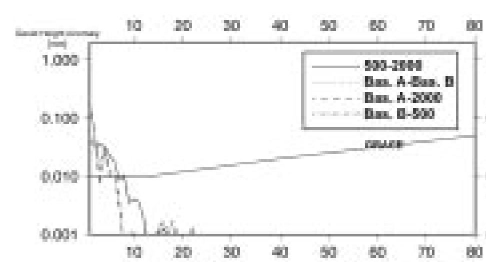

Figure 6. Same as figure 2, but intermediate cases compared to each other.

part of the coefficients (spatial resolution of about 3600 km).

The next figures show the differences between intermediate and IB models. These models exhibit characteristics that more consistent with the IB than the NIB, henceforth we consider the intermediate models to be IB-type. Figure 3 and Figure 4 show the comparisons between the IB and the IB-type models. Most of the models differ from IB until degree 11 with only exception being in the hemispheric model. A very slight difference with IB of the hemispheric model at all degrees is notable. As a result, comparing the hemispheric model with the others (Figures 4, 5) gives nearly same results as comparing them with the IB (figure 3). One exception is the 1st degree, which is much smaller in the hemispheric case. The slight difference of these two models is a consequence of the slightly different pressures in the northern and the southern hemispheres (discussed previously).

The comparison of the intermediate models to each other gives diverse results. In the case of the shallow water models and the basin models, the straight comparison (Figure 6) shows similar differences and characteristics. The case by case results can be summarized: 1) basin A & B, and 500 & 2000 comparisons are detectable until about degree 6, 2) basin B & 500, and basin A & 2000 comparisons differ until degree 6 with a weakness in the 3rd degree. The cross comparisons (Figure 5) are surprising. For basin B & 2000 models the difference is very small. The detectable part is just the first three degrees. The degree amplitudes of the basin A & 500 models strongly differ until degree 8.

Atmospheric mass conservation

In our IB model (and IB-type models), we have used the pressure differences of the spatial average $p(t)$ and its 20 years temporal average $\widetilde{p}$. Thus the atmospheric pressures over the ocean were treated as spatially independent, but temporally variable. Other works [e. g., *Wahr et al.*, 1998] chose an average zero IB-field (time independent). But since the atmospheric mass over the ocean is not constant, we preferred to use the temporally varying IB-field assumption.

We determined the temporal variation of the spatially constant atmospheric pressures over the ocean. Their values were always below 200 Pa. The temporally varying oceanic atmosphere has an annual periodicity, as expected. This annually varying signal was fitted to a sine function, which yielded an amplitude 65.31 Pa. Since the global (land plus ocean) annual amplitude was 291.5 Pa, the oceanic component of the annual amplitude amounts to about 20% of the total variation.

Conclusions

The main differences of the atmospheric pressure models should be detectable by GRACE on the longest wavelengths, although the atmosphere will be considered as a correction term for other geophysical signals. The IB and NIB appear to be distinguishable until degree 11. The intermediate models are also distinguishable from the IB and NIB until the 11th degree, with the exception of the case of the hemispheric separation, which is very similar to the IB. The distinction between other intermediate models gives detectable differences until degree 6-7. The similarity of the theoretically independent basin B and 2000 models, or the weakness of the 3rd degrees of the straight comparisons, shows that the intermediate models are very close to each other, they are indistinguishable.

From their slight differences it follows that in case of these IB-type models much more effective discrimination results from redefining the ratio of IB-NIB areas (e. g., change from 500 to 2000), than from spatially varying the IB theory with more accurately defined borders. The hemispheric model, despite its simplicity, is acceptable, because of the spatial insensibility of the IB-type hypothesis. Another possible way of improving the concepts is by increasing the number of separated IB responses, by increasing the resolution of oceanic areas.

Some of the models employed in this study may appear a little artificial. But an important point is that a very slight difference of the models causes of what should be a detectable level of effects sensible by the measurement systems on board GRACE. Much attention to the ocean response models is necessary for various applications. We also expect that the appropriate models will be determinable after completion of the GRACE mission.

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