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BENEFITS TO STUDIES OF GLOBAL SEA LEVEL CHANGES FROM FUTURE SPACE GRAVITY MISSIONS

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Abstract. Global sea level rise will present a major scientific, environmental and socio-economic challenge during the 21st century. This paper reviews the main oceanographic and geophysical processes which contribute to sea level change, with particular emphasis on the ability of space gravity missions to contribute to an enhancement of our understanding of the various processes, and ultimately to a better understanding of sea level change itself. Of special importance is the need to understand better the ocean circulation, and the contribution of ocean thermal expansion to sea level change.

Keywords: Climate change, gravity field, ocean circulation, sea level changes

1. Introduction

The study of long-term changes in sea level is of great scientific interest and considerable practical importance to the environmental and economic infrastructure of coastal zones. The recent reports of Church et al. (2001) and Woodworth et al. (2004) have provided overviews of the scientific issues connected to, and the coastal impacts of, the sea level changes of the past century and of the next 100 years.

Previous working groups have demonstrated the potential for space gravity missions to provide information on the spatial and temporal dependence of the Earth's gravity field, which can lead to improvements in the scientific understanding of a number of processes contributing to sea level changes. In particular, Balmino et al. (1999) presented the benefits of the considerably improved knowledge of the geoid from the GOCE spatial gravity mission to studies of the ocean circulation, solid Earth, glaciological processes, geodesy and satellite orbit determination, which together should lead an improved understanding of sea level change. The case for a temporal gravity mission such as GRACE was also constructed partly around the topic of sea level change, by providing better understanding of the global hydrological cycle and of the ocean thermohaline circulation together with processes in the solid Earth, notably Glacial Isostatic Adjustment (GIA, see NRC, 1997; GRACE, 1998). The spatial and temporal accuracies which these missions are expected to achieve in order to meet their scientific objectives are summarised in Rummel (2003).

Although the cases for these two missions were based to a great extent around the need for greater understanding of sea level change, it is important to realise that, just as sea level change occurs as a result of many changes in the earth's climate and geosphere (e.g. see Figure 1), so the benefits of space gravity to sea level science will be realised only after each of the above-mentioned science issues has benefited individually. Therefore, it is difficult to state quantitatively at the moment just how great the benefits to sea level studies will be.

Nevertheless, we can be confident about one aspect of future sea level change in that it will contain a significant contribution from climate change ("global warming") resulting in the thermal expansion of the ocean. Processes such as thermal expansion are modelled within Atmosphere Ocean General Circulation Models (AOGCMs). From the Intergovernmental Panel on Climate Change Third Assessment Report (IPCC TAR) (Church et al., 2001), we learn that AOGCMs predict a sea level rise of between 9 and 88 cm between 1990 and 2100, with a central value of 48 cm. This wide range is obtained because a full set of emission scenarios were used by the TAR, together with a number of AOGCM formulations. The mid-range estimate represents a rate of rise in the 21st century of approximately 2–4 times that of the past 100 years.

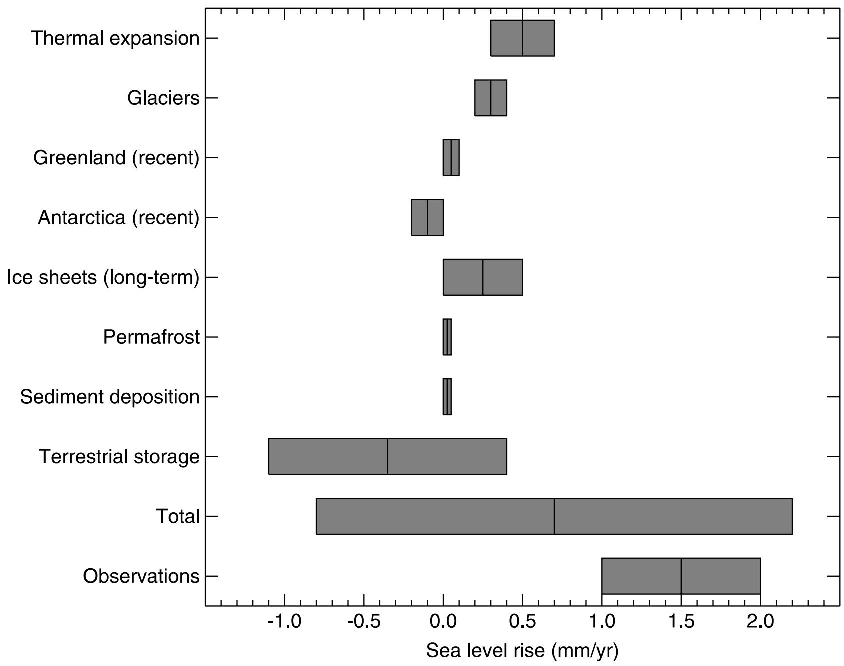

Figure 1. Ranges of uncertainty for the average rate of sea level rise during 1910–1990 and the estimated contributions from different processes (Church et al., 2001).

Figure 2 is an updated and corrected version of Figure 11.11 of Church et al. (2001). It demonstrates the wide range of predictions from AOGCMs (see also other figures and tables in Church et al., 2001 and Woodworth and Gregory 2003). However, even though their predictions differ greatly, the majority of the future rise in each is due to thermal expansion. For example, from the HadCM3 AOGCM one predicts a thermal ezxpansion for 1990–2100 of 24 cm for the IS92a scenario, which will occur within an overall rise of between 18 and 46 cm if all contributing terms are considered.

Consequently, the first difficult but most important question is, how will the sea level predictive capability of Atmosphere Ocean General Circulation Models (GCMs) improve, and the range of uncertainty narrow, as a consequence of the gravity missions, and, in particular, how will their predictions of thermal expansion improve? This issue was addressed most recently by Woodworth and Gregory (2003).

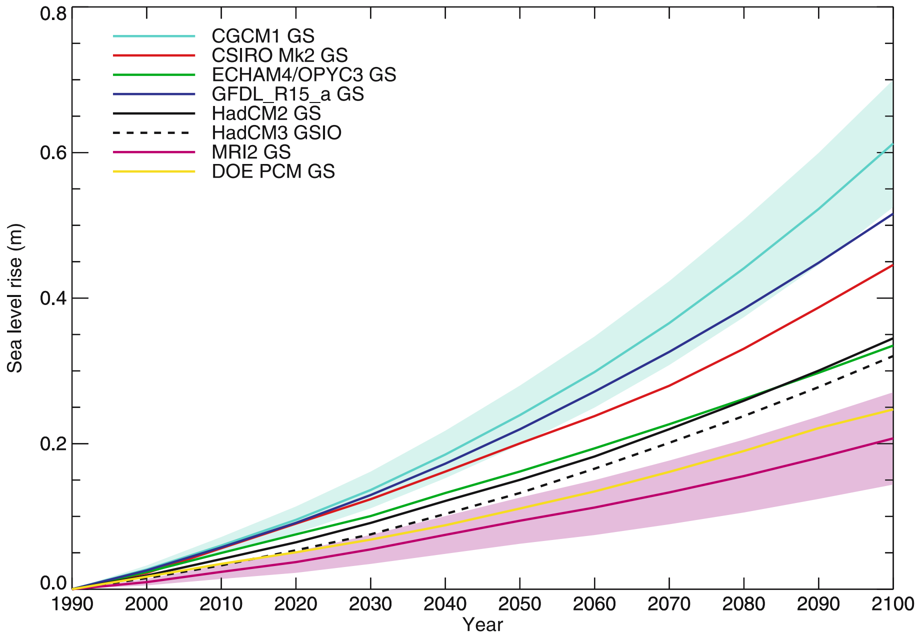

Figure 2. Global average sea level rise 1990–2100 for the IS92a emission scenario, including the direct effect of sulphate aerosols. Thermal expansion and land ice changes were calculated from AOGCM experiments, and contributions from changes in permafrost, the effect of sediment deposition and the long-term adjustment of the ice sheets to past climate change were added. For the models that project the largest (CGCM1) and the smallest (MRI2) sea level change, the shaded region shows the bounds of uncertainty associated with land ice changes, permafrost changes and sediment deposition. Uncertainties are not shown for the other models, but can be found in Table 11.14 of Church et al. (2001). The outermost limits of the shaded regions indicate the range of uncertainty in projecting sea level changes for the IS92a scenario.

Another conclusion from the IPCC TAR modelling is that a future sea level rise from either all the contributing terms, or from thermal expansion alone, will not be spatially uniform, but will vary regionally as the ocean circulation attempts to adjust to the changing fluxes. This may have important consequences for particular regions, if they experience significantly greater rises than the global-mean. Unfortunately, while the various AOGCMs agree that major spatial variations will occur, they disagree on the exact geographical pattern.

In summary, two conclusions can be drawn from Church et al. (2001) and Woodworth and Gregory (2003):

- Global-mean thermal expansion needs to be very well understood for predicting the sea level rise of the next 100 years, and in particular for the second half of the 21st century as the effects of climate change become progressively more important. To achieve that, we first have to understand much better how the ocean works.
- Sea level rise will not be spatially uniform, but will vary regionally as the ocean circulation attempts to adjust to the changing heat and freshwater fluxes, again pointing to the need to understand the ocean better.

However, one need not be too pessimistic. Woodworth and Gregory (2003) gave two examples of differences between AOGCMs which imply that, with a better understanding of the ocean from missions such as GOCE and GRACE, AOGCM formulations may be modified and the wide spread in sea level predictions between models might be reduced.

2. Future Spatial and Temporal Gravity Missions

Although there are many reservations concerning the quantification of the benefits to sea level studies from GOCE and GRACE, it is of interest to speculate how a further generation of spatial and temporal gravity missions might benefit the field. Following the examples of Balmino et al. (1999) and NRC (1997), we must once again consider the benefits to each of the terms which contribute to sea level change.

2.1. Benefits from improved resolution of a spatial gravity mission

The steady-state ocean circulation

The case for GOCE was constructed around its ability to provide a measurement of the geoid with centimetric accuracy down to spatial scales of 100 km half-wavelength, which corresponds to a typical deep ocean Rossby

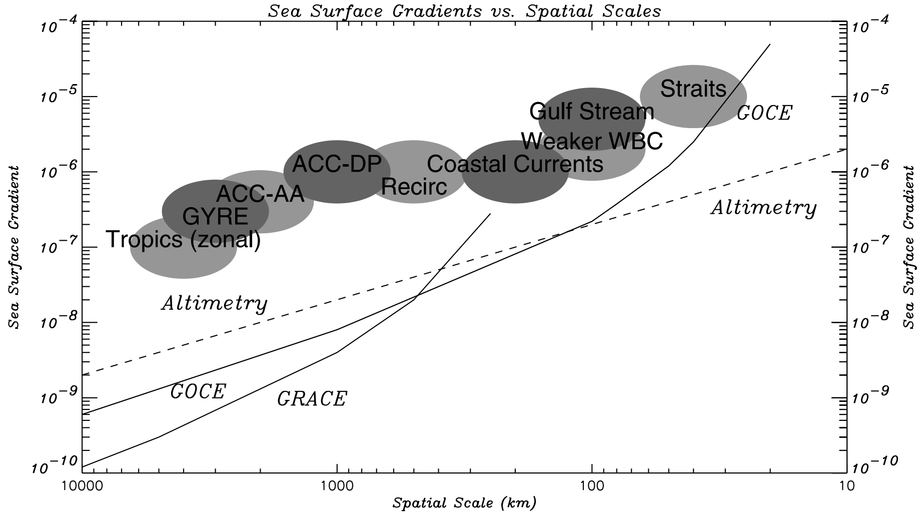

Figure 3. Highly schematic illustration of sea surface gradients (relative to the geoid) of several components of the ocean topography compared to mean sea surface slope accuracy from altimetry (dashed line) and to geoid slope accuracy from space gravity missions such as GOCE (thick line) and GRACE (thin line). "Gulf Stream" represents the stronger deep ocean fronts including those of the Gulf Stream itself and of, for example, the Antarctic Circumpolar Current. "Recirc" represents the Gulf Stream recirculation. "Weaker WBC" represents the weaker Western Boundary Currents (e.g Brazil Current) with spatial scales of order 100 km and gradients of order few 10^{-6}. "ACC-DP" and "ACC-AA" represent a major current such as the ACC at Drake Passage or at the wider African and Australian choke points respectively. "GYRE" represents a typical 1 m ocean gyre over 3000 km scale. "Coastal currents" represents the myriad of coastal currents, flows through longer straits and meridional equatorial signals with space scales of order 100 km and gradients of 10^{-6}. "Straits" represents flows through short straits which are at the limit of spatial resolution. Note that at very long wavelengths, where GRACE accuracy is superior to that of GOCE, remaining altimeter orbit and other systematic uncertainties are still significant. (from Woodworth et al., 1998).

radius of deformation. The case was made that spatial scales of the steady-state ocean surface circulation larger than the radius can be considered to be in approximate geostrophic balance with the sea surface topography measured by means of an altimetric mean sea surface from which a precise geoid can be subtracted. Therefore, the steady-state circulation can be determined from the two data sets relatively straightforwardly. The 100 km scale was also chosen on the basis that in present deep ocean models one observes relative little steady state circulation at spatial scales shorter than the 100 km (cf. Figure 3.11f of Balmino et al., 1999; see also Woodworth et al., 1998; Le Provost and Bremond, 2003).

GOCE should indeed provide a measurement of the geoid which will be good enough for deep ocean studies down to that scale. However, one might now revisit the benefits to knowledge of the circulation through improvements towards even shorter deep ocean scales and towards shallower areas of the ocean. For example, while there is relatively little steady state deep ocean circulation at these short scales in models, it clearly does exist (see above references) even if it is probably not well represented in present models. The existence of shorter scale features (meanders, fronts) is also known from a range of deep ocean observations. As higher resolution models are developed, the quality of simulation of shorter scale features should improve significantly.

Notable amongst the shorter scale features of the steady state deep ocean circulation which do exist and which are undoubtedly important is flows through straits (e.g. Gibraltar, Florida, Skagerrak). Such flows play major roles in the adjacent deep ocean (e.g. Mediterranean deep outflow in the North Atlantic) and have dimensions which are at the limit of the anticipated GOCE range (Figure 3 taken from Woodworth et al., 1998).

The steady-state circulation of continental slope currents has received relatively little attention in the context of space gravity, primarily owing to it also being at the spatial limit of GOCE, with currents typically several 10s-km wide. However, most continental slopes have currents with transports of several Sv (1 Sv = 10^6 m^3 s^{-1}). This is small in comparison to the approximately 100 Sv transports of the Gulf Stream and the other deep ocean systems. However, they together comprise a major component of the global ocean circulation and are of local importance with regard to shelf-deep water fluxes. An example of the possible improvement in oceanographic knowledge of the NW European slope current from satellite altimetry together with state-of-the-art geoid models was provided by Haines et al. (2003). Flows on the continental shelves can also be of interest. For example, in the North Sea the effective Rossby radius can be very short (several to 10s km) with flows from rivers (notably the Rhine) onto the shelf being essentially steady state at this spatial scale and with a sea surface topography signature of order 10 cm.

While these short-wavelength signals could be significant within discussions of the overall benefits of a new spatial gravity mission, especially with regard to regional ocean modelling, it is less clear how importantly this aspect of the steady state circulation might benefit sea level studies.

Ice sheets (Greenland and Antarctica). Balmino et al. (1999) referred to the limited benefits to knowledge of ice sheet dynamics, and consequently of mass balance, from GOCE, given that a $<$ 50 km resolution bed geometry was needed via measurement of the geoid at that scale for study of Antarctic ice streams. In addition, there was little benefit to knowledge of the bed geometry of Greenland which is well-known from radar sounding. Therefore, a new spatial gravity mission would have to provide a resolution of order 20 km to be of use.

Glacial isostatic adjustment. Balmino et al. (1999) implied that the spatial gravity provided by GOCE would be as specified by the science requirements for anticipated GIA studies. Therefore, there is as yet no case for a further, higher resolution spatial gravity mission for this topic.

Tectonics. Balmino et al. (1999) demonstrated that understanding could be increased of mechanisms of active tectonics in areas such as Italy and the Adriatic, with data from GOCE enabling the accurate determination of rates of vertical land movement from tectonics, to which rates from GIA can be added, for comparison to rates observed from GPS or tide gauge data (Di Donato et al., 1999; Woodworth, 2003). The modelling of such tectonic processes would clearly benefit from higher resolution spatial gravity information.

Hydrology. The uncertainty in the net contribution of hydrological processes to global sea level change during the 20th century is very large and is a major point of discussion when considering the combination of various terms which make up the observed 20th century sea level rise (Figure 1). However, a spatial gravity mission such as GOCE or its successor is not suited to address this issue.

Glaciers. Similarly, Balmino et al. (1999) did not consider that GOCE could contribute to studies of mass balance of mountain glaciers, the understanding of which it was considered would be undertaken by various forms of altimetry and other types of remote sensing in future.

Bathymetry. Balmino et al. (1999) noted that, at the 10-500 km spatial scale, spatial gravity can be directly related to ocean bathymetry. A lack of knowledge of the bathymetry of the global ocean is a major factor in the construction of ocean numerical models and bathymetric information recovered to 10 km resolution from spatial gravity would be very desirable.

Geodetic issues. There are a number of sea level-related geodetic issues such as the need for a geoid to use within "GPS-levelling" between tide gauges, and the need to remove gravity field errors in the orbits of altimeter satellites. The former was discussed by Balmino et al. (1999). The need for local *in situ* gravity in an area approximately 50 km around tide gauges, in addition to data from GOCE, is noted if geoid omission errors are to be removed to the cm level, as required for GPS-levelling between gauges. Balmino et al. (1999) considered that the gravity field errors in altimeter orbits would be essentially zero after GRACE and GOCE.

2.2. Benefits from improved spatial/temporal resolution of a temporal gravity mission

Deep ocean circulation. NRC (1997) and GRACE (1998) have demonstrated the potential for GRACE to provide monthly maps of gravity changes with an accuracy corresponding roughly to a millimetric disk of water of spatial scale typically 700 km. A temporal gravity mission such as this will be of major benefit to ocean circulation studies by providing a monitor of mass transports, complementing the monitoring of sea surface height by altimetry. Recent papers have also demonstrated the importance of understanding ocean mass transfers to studies in geophysics, such as in accounting for recent variations in J2 (Dickey et al., 2002).

Discussion of the utility of temporal gravity to oceanography beyond GRACE is provided elsewhere in this volume. The insight into ocean circulation gained will eventually be included in AOGCMs to the particular benefit of the thermal expansion component of sea level studies as discussed above.

Coastal ocean circulation. Benefits in this area are not so clear. The effective spatial resolution would need to improve over GRACE by an order of magnitude, while preserving a similar temporal resolution. While further studies could be undertaken from a purely coastal oceanography perspective, it is unlikely that benefits would extend directly to sea level studies.

Glacical isostatic adjustment. Wahr and Velicogna (2003) have discussed the decoupling of GIA from other processes within GRACE data (e.g. decoupling the Greenland GIA signal from the present-day elastic term, and from neighbouring ocean mass changes). The authors conclude that effective decoupling will result in improved estimates of the Earth's viscosity profile, although errors in ice history models remain a major issue. Higher resolution would benefit the decoupling.

Hydrology. As discussed above, hydrological changes was a major issue in discussion of reasons for 20th century sea level change (Church et al., 2001; Woodworth and Gregory, 2003; Cazenave et al., 2003). During the 2002 Bern Symposium on Space Gravity, Wahr discussed the spatial dealiasing of GRACE data in order to provide time series of groundwater mass for (large) drainage basins. Higher resolution would benefit the construction of such hydrological time series.

Ice sheets (Antarctica and Greenland) and Glacier Groups (e.g. Alaska). Ice sheet mass changes should be observable from a mission such as GRACE to the same spatial/temporal resolution as for ocean or atmospheric mass and hydrology. Interpretation in terms of sea level change will take place in combination with altimetric measurements. Low latitude glaciers contain ice equivalent to approximately 40 cm of sea level. Alaska's glaciers, which can be considered as comprising a small ice sheet, are known to be melting fast and contributing to current sea level change (Arendt et al., 2002; Dickey et al., 2002). Once again, the effective monitoring of such mass changes, in combination with altimetry, would benefit sea level studies.

In addition to considering the sea level-equivalent of melt water from ice sheets and glaciers, the signal observed in tide gauge records from the melting will include a solid earth loading term (Tamisiea et al., 2001). To model loading well, the spatial distribution of mass change needs to be known as well as possible. Consequently, the 'fingerprint methods' such as those of Tamisiea et al. will benefit from higher temporal gravity resolution.

Global-mean mass monitoring. Nerem and Leuliette (2003) presented simulations showing that GRACE should be able to monitor non-secular, monthly average changes in ocean mass of approximately 3 mm water-equivalent with a spatial resolution of order 500 km, comparable to previous estimates. They also suggested that GRACE would be able to monitor changes in global-mean ocean mass to approximately 1 mm.

These simulations are very encouraging, but the authors stress that secular signals from GIA and melting polar ice result in major difficulties with regard to determination of secular ocean mass change, and such ambiguity would be reduced with a higher resolution mission. Multiple satellites, and combined analyses with altimetry, could reduce such aliasing in time series. The capability of providing millimetric accuracy time series of global-mean ocean mass (an order of magnitude more precise than current time series of global-mean sea level) would clearly be an important addition to sea level studies.

3. Conclusions

It can be seen that both a higher resolution spatial gravity mission and a higher resolution temporal gravity mission would provide benefits to sea level studies beyond those anticipated from GOCE and GRACE. However, in spite of the undoubted benefits of an improved gravity field from a spatial gravity mission (to, say, 1 cm accuracy over 20 km half-wavelength rather than 100 km from GOCE), an improved temporal gravity mission would appear to have higher priority. As explained by Rummel (2003), we need to understand mass transports between atmosphere, oceans, hydrology, glaciology etc., with the study of sea level change forming part of that wider requirement, and that can be addressed best in the medium term by further temporal gravity missions, with an enhanced spatial gravity mission later (the GOCE studies resulted in a recommendation for missions of the GOCE type to be repeated at perhaps decadal intervals).

Finally, we can return to the major question posed by Woodworth and Gregory (2003), and ask how the predictability of sea level changes within AOGCMs will benefit from the new missions. This is still a difficult question to answer quantitatively. However, if we knew global fluxes significantly better than we know them now, then we would be able to parameterise them better in the coarse resolution AOGCMs, and thermal expansion in particular should be handled much better.

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