Measuring Ocean Bottom Pressure Changes from Space. Report of a Meeting

C. Wunsch and V. Zlotnicki, for the Organizing Committee (C. Hughes, J. Wahr, P. Woodworth)

Abstract.

1. Introduction

The US (NASA) and German (DLR) space agencies are committed to the launch in mid-2001 of a spacecraft called the Gravity Recovery and Climate Experiment (GRACE). A summary of the goals of this experiment would be that it is intended to measure over a period of about five years the earth's global gravity field—both the time-mean and its temporal fluctuations. A general discussion of the applications of such missions may be found in National Research Council (1997).

The structure of Earth's gravity has implications for much of earth science ranging from geophysics to hydrology to oceanography. Wahr et al. [1998] have described the basic mission configuration, and many of its potential applications to geophysics and hydrology. From the point of view of physical oceanography, GRACE will produce two complementary types of results. The first result should be a significant improvement in existing estimates [e.g., *Lemoine et al.*, 1997] of the earth's geoid height. The need for an improved static geoid has come, in physical oceanography, to be conspicuous in discussions of the use of satellite altimetry for determining the absolute ocean circulation.

GRACE will however, also be able to measure the time varying gravity field of the earth, and with accuracies and precisions that are somewhat startling. Figure 1 shows the expected precision of the change in the gravity field detectable when averaged over circular areas of various diameters, over time spans of order one month. Changes in the gravity field below a spacecraft are caused by redistributions in the mass on the earth. Thus Figure 1 has been converted to the equivalent mass distribution of a layer of water. Over the oceans, the net change in the total mass would correspond to the change in bottom pressure which is just the integral,

$$p_b(\theta, \lambda, t) = \int_{z=-h}^{z=a} \rho g dz \qquad (1)$$

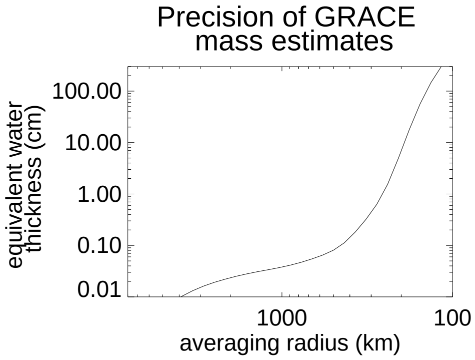

Figure 1. Figure 1. The expected precision of GRACE estimates of monthly mass variations at the earth's surface, in units of cm of equivalent water thickness. The mass is, in effect, averagedover circular regions, and the precision is plottedas a function of each region's radius.

where a denotes the top of the atmosphere (or the spacecraft altitude) $z = -h$ is the local ocean depth at position θ, λ and the density ρ varies from nearly zero at $z = a$ to the density of seawater at the seafloor. GRACE thus has the startling promise of making visible to oceanographers seafloor fluctuations in pressure as observed from space, with precisions at the sub-millimeter level. Experience with satellite missions suggests that engineering specifications tend to be somewhat conservative.

This idea, that elements of the ocean circulation manifesting themselves at the seafloor can be measured from space, has led a growing group of oceanographers and geophysicists to consider how such measurements can best be interpreted, how the data might best be analyzed, and how to optimize the results. The issues raised by these questions are varied and complicated, and as a result of the discussions of the US-GRACE Science Team, it was considered useful to convene an international meeting of some of the scientists known to be interested in GRACE and related measurements, to plan how to deal with the relevant ocean science coming from GRACE (that is, deliberately omitting most considerations of geophysics and hydrology, but with some significant exceptions). A meeting was held on the premises of the Royal Society of London on 13-15 April 1999 with partial financial support from NASA, and the UK Proudman Oceanographic Laboratory, Bidston Observatory.

2. Meeting Structure

The meeting was intended to serve both as an information vehicle—to inform the wider community about the existence of GRACE and its capabilities—and to provide a forum for discussion of problems and applications of the data. At a precision of less than 1 cm, numerous previously negligible phenomena become significant. The meeting was thus divided into several overlapping sub-sessions focussed on the following questions:

(1) What is GRACE and what will it be able to do? What are the related missions, both for gravity and altimetry which will complement it? What are the most serious technical problems the mission will face?

(2) What are the effects of the oceanic inverted barometer response and its implications for interpretation of GRACE data.

(3) What is known from *in situ* observations of the nature of oceanic sea floor pressure variations?

(4) How accurate are the analyses of atmospheric mass (pressure at the seasurface) and wind-fields? To what extent are the atmospheric tidal components present in the operational and re-analysis products adequate for quantitative use? Are hourly values from the atmospheric analyses required or even adequate?

(5) How accurate are modern models of oceanic tides, and are they adequate for de-aliasing GRACE data?

(6) What are the physical implications of measurements of oceanic bottom pressure fluctuations?

(7) How accurate are existing oceanic general circulation models, both barotropic (for high frequencies) and full baroclinic ones? What are the resolution requirements? Is the Boussinesq approximation adequate? Is the known bathymetry sufficiently adequate and parameterized properly? Can one distinguish model errors from meteorological forcing errors?

(8) Are data assimilation techniques and computer power adequate to assimilate altimetric and other data so as to de-alias GRACE at high frequencies? What will be the impact of the GRACE data when assimilated into GCMs along with other oceanographic data?

(9) What is our collective field capability, and how should we best use it to complement GRACE? How should this field capability be used to calibrate and test the GRACE system?

(10) What are the implications of GRACE and the related oceanography, to studies of earth rotation and polar motion?

In each sub-session, one or two speakers were asked to summarize their view of the state of the subject, the major issues, and to stimulate discussion. Usually there was a "respondent" to help start the discussion, and then the floor was open to all for comment and presentation. The major issues and conclusions are summarized below. Many issues were necessarily left for the future.

3. Major Points

The GRACE (Gravity Recovery and Climate Experiment) mission, was described by S. Bettadpur (U. of Texas, Austin, UT). It is optimized to measure the time variability of the earth's gravity field, approximately monthly over 5 years, at spherical harmonic degrees $n \leq 100$ (wavelengths of $\approx$400 km and longer), and the time-averaged field to $n \leq 160$ (wavelengths $\gtrsim$250 km). It is to be launched in June of 2001 and will consist of two satellites (provided by Dornier) flying with a nominally horizontal separation between 300 and 500 km, with an initial elevation of about 500 km, 87° inclination (possibly to be shifted to 90°). The key measurement is the distance between the two satellites, measured by a K-band microwave link (Jet Propulsion Laboratory, JPL) at 2.4 and 3.2 GHz. The instrument payload includes an accelerometer (manufactured by Onera) to measure non-gravitational forces and a GPS receiver (from JPL) for position, timing synchronization, and atmospheric temperature soundings. The launch vehicle will be provided by Eurockot from a site in Pletsetsk, Russia. Mission operations will be provided by the Deutsche Zentrum fur Luft-und Raumfahrt, the German Space Agency (DLR). The co-principal investigators are Professors B. Tapley (UT) and C. Reigber (GeoForschungsZentrum Potsdam, Germany, GFZ), and the mission is jointly sponsored by NASA, and DLR. The exact mission profile (inclination, height at launch, etc.) are still subject to change.

The CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and Application) mission was summarized by T. Gruber (DLR, who are responsible for this mission). To be launched in 2000, it will measure simultaneously the Earth's gravity and magnetic fields. CHAMP will use a single satellite version of almost the same platform and accelerometer as GRACE, and much of the technical and scientific work in Europe is being jointly done for both CHAMP and GRACE. Although its gravity measurement will be less accurate than GOCE (described below) or GRACE (neither of which measures the magnetic field), it will still provide a significant improvement over the best existing current gravity models at long wavelengths.

J. Johannessen (European Space Agency, ESA/-ESTEC, The Netherlands), summarized the proposed Gravity Field and Steady-state Ocean Circulation Explorer (GOCE) mission, expected to launch in 2003 or 2004. If approved, it will carry a gravity gradiometer and a GPS/GLONASS receiver, in a 250 km high orbit, over 8-16 months, to measure the gravity field with an observational requirement of 1 to 2 cm geoid accuracy at 100 km scale, and 0.1 to 0.05 cm at 1000 km. GOCE is optimized to measure the time-averaged field at higher spatial scales than CHAMP or GRACE: for spherical harmonic degrees above 60 to 80, it would be more accurate than GRACE. GOCE would be able to measure to a resolution of 80 km, albeit with 10 cm accuracy, a scale unreachable by the other two missions.

GRACE Signals

Retrieval of realistic signals from GRACE in the presence of both errors in the data and uncertainties in the fields needed to interpret the data was discussed by J. Wahr (U. of Colorado). Changes in time varying gravity can be due to: ocean; atmosphere; continental water and snow; polar ice; and solid earth, including post-glacial rebound.

Gravity at any point provides an integral property of the earth's mass, and the set of all global measurements is customarily inverted in terms of spherical harmonic coefficients. To translate these into horizontal resolution, one may convolve the spherical harmonic expansion with any weight function. In his simulations, Wahr used a Gaussian function.

One derives the vertical integral of mass over land and atmosphere, so the best atmospheric pressure (or geopotential height) estimates are needed to retrieve continental water signals. Over the ocean, atmospheric pressure contributes directly to the bottom pressure, and there is no parallel need for the atmospheric data.

Simulated GRACE signals were soil moisture and snow [from *Huang, et al.,* 1996], and ocean signals from a particular run of the Los Alamos National Laboratory POP model. The errors included the uncertainty in postglacial rebound, the error in atmospheric pressure, estimated as the difference between NCEP and ECMWF values, and expected GRACE measurement errors. In the Gulf of Alaska the dominant error source is postglacial rebound, a secular signal.

Altimetry

Because an independent geoid has been-long sought by altimeter scientists, L.-L. Fu (JPL) gave an overview of future altimetric missions. The Jason series, a collaboration of NASA and Centre National d Etudes Spatiales (CNES) France will give the highest accuracy, while ENVISAT (an ESA mission) and NPOESS (a U.S. operational series) will provide improved spatial coverage. The Jason-2 project will consider including, in addition to the classical nadir altimeter, an experimental wide-swath interferometric altimeter. This possibility is still under investigation and the final decision will not be reached until early next year.

experimental wide-swath interferometric altimeter

Aliasing in GRACE

To retrieve a reliable set of spherical harmonics, GRACE needs to combine tracking data over 15 to 30 days. Any rapid mass redistributions in the ocean and atmosphere will thus alias into the data stream. Bettadpur showed that if unmodelled, they introduce uncertainties approximately equivalent to 5 mm geoid height. (Much of the modeling discussion, described below, was directed at this problem.)

Inverted Barometer Effect and Atmospheric Forcing

The isostatic response of the ocean surface to atmospheric pressure (P), at a rate of -1 cm/mb, is termed the "inverted barometer" (IB) effect. Such compensated motions are a strong altimetric signal, but produce no ocean bottom pressure signals, apart from those due to changes in averaged P over the oceans. R. Ponte (Atmospheric and Environmental Research, Inc., USA) reviewed published work, in which the IB approximation has been found to have wide validity at different locations and different frequency bands.

From his own work [*Ponte and Gaspar*, 1999] using altimetry and model results, he reported a response from -(0.8-1) cm/mb at mid and high latitudes to -(0.4-0.8) cm/mb at low latitudes, with IB-like behavior at periods longer than 30 days. He also displayed a plot by F. Bryan, showing little difference in the sea level response to P inferred from barotropic and baroclinic ocean models.

Because a barotropic model requires hourly or more frequent atmospheric forcing, the ability to obtain such samples from the operational meteorological centers arose. H. Van den Dool [see *van den Dool,* 1997] showed that by subsampling output at 6-hourly intervals and using a simple formula that the high frequency structure could be recovered.

Observed Barotropic and Baroclinic Motions

Results of the Pacific tomographic experiment (ATOC) were reviewed by W. Munk (Scripps Institution of Oceanography, USA). When combined with altimetry, the two methods permit an observational separation of barotropic and baroclinic contributions [see *The ATOC Group*, 1998].

D. Luther (U. of Hawaii, USA) showed a particularly interesting plot of BEMPEX bottom pressure with the same quantity simulated by F. Bryan using the POP model, with coherence exceeding 0.8 at all periods longer than 2 days at zero-phase. However, the difference in spatial gradient between POP and the observations was larger than the pressure difference between two bottom pressure recorder (BPR) locations separated by 250 kilometers, so the error in modelled bottom current would be large.

BPRs and their accuracies were described by I. Vassie (POL). From the close match of atmospheric pressure spectra and BPR spectra, he concluded that suitably corrected BPR records are accurate over seasonal periods and shorter. The tidal estimates from BPRs and inverted echo sounders in the Greenland sea are essentially the same. The three moorings at Tristan da Cunha, on a triangle some 300 km on the side, show high coherence. In the ACC, BPRs separated by 1000 km show very high coherence. Most of the POL moorings include two or three instruments in the same mooring in order to remove drift. Very few individual records are longer than 1 year (a notable exception being the POL five-year long MYRTLE record).

Worldwide, the community has about 70 instruments of varying capability for oceanic bottom pressure measurements. Many of these instruments should be available for all or part of the duration of GRACE, but there are no existing plans for a coordinated effort. (Following the meeting, this situation has begun to change.)

Meteorological Center Products. Atmospheric Tides.

P. Janssen (European Center for Medium Range Weather Forecast, (ECMWF, UK) judged the accuracy of wind (and pressure) fields produced by the ECMWF model, by its ability to forecast wind waves using a numerical wave model. Because waveheight is proportional to wind-speed squared, small inaccuracies in wind speed yield large inaccuracies in waveheight. Radar altimetry provided the data on significant waveheight and comparison data on wind speed. He concluded that ECMWF wind speed is good to about 1.5 m/s in the equatorial region.

H. van den Dool (National Centers for Environmental Prediction, (NCEP, USA) discussed the accuracy with which atmospheric pressure is retrieved in the NCEP model, by using the differences between model guess and incoming data at different locations. Data coverage is excellent over the American, European and Asian continents and the North Atlantic, but is significantly less good in the N. Pacific and Indian Oceans and over Africa. It is even poorer in the South Pacific and South Atlantic basins, and very poor in the Southern Ocean and over Antarctica. The discrepancy between 6 hour forecasts and observations of surface pressure is about 1.5 mbar, a number that appears surprisingly constant between land and ocean (studied separately), and NH and SH. NCEP's model had tides with good phase but probably too large amplitude in the semidiurnal component especially. There may be a tidal error in the NCEP model because prediction for 12 and 18 hours is slightly worse than for 24 hours in some areas. If given a choice regarding resources, meteorological centers would rather assimilate more wind data at jet stream level than more pressure data, but if given more pressure data they would use it (NCEP does assimilate wind speed data over the oceans from multiple sources like airplanes, satellite cloud track winds and the Defense Meteorological Satellite Programs Special Sensor Microwave Imager). The NCEP data assimilation system ingests tendencies because for some data types whose mean may be inaccurate, the time derivatives (tendencies) are used, rather than the absolute value, whose mean may be inaccruate.

As part of this discussion, D. Stammer showed a plot of the sea surface temperature used in an atmospheric model: the map displayed ringing patterns, which he said were also present in the wind and other fields. T. Hollingsworth (ECMWF) explained that all spectral models have those effects, which are Gibbs phenomena mostly caused by the Andes, due to the truncated spherical harmonic expansion of the topography. Stammer argued that since the effect is in the mean, it can and should be removed from the analyses. Another point of discussion focussed on the future availability of pressure data over the oceans, because deployment of some drifting buoys with pressure sensors will be curtailed due to funding cuts.

Ocean Tides

Tidal models were discussed by F. Lyard (CNES). His plot of model accuracy versus time asymptotically approached 1 cm RMS, which prompted a discussion of the ultimate predictability of tides. The consensus was that there is a limit near 1 cm owing to random components in the tidal signals.

D. Cartwright (Southampton Oceanography Centre, UK, SOC) emphasized the different parts of tidal signals seen by altimeters, tide gauges, and bottom pressure recorders. For example, odd-order baroclinic modes have an inverse relationship in bottom pressure and sea surface height data; earth tides are not visible in bottom pressure recorders, but would be in the bottom pressure retrieved by GRACE, etc.

Physics of Ocean Bottom Pressure Fluctuations. Models

D. Marshall (U. of Reading, UK) reviewed several published results on how bottom topography transfers energy from turbulence into the mean flow, and from decaying turbulent barotropic modes into baroclinic ones. He also described the estimation of vertical velocity from bottom pressure and topography, and the propagation of coastally trapped waves around basins. The question was raised as to whether measuring bottom pressure monthly can give bottom velocity, because of the difference between the horizontal pressure gradient and pressure gradients along the bottom topography; even for time changes one would need to consider the time changes of bottom density.

The role of bottom pressure in the ocean circulation was further described by C. Hughes (POL). A net meridional transport in the Ekman layer causes a geostrophic deep return flow whose interaction with the bottom topography produces bottom pressure torques (spin torques) which alter the Sverdrup balance. When zonally integrated, the spin torques can balance the wind stress curl without the need to invoke a viscous boundary layer to do so. Using the OCCAM model Hughes found that in the Antarctic Circumpolar Current, the main balance is between the integral of pressure and topography against the wind stress, a balance that occurs in a few days, with other terms being much smaller. Friction removes wind energy, but wind angular momentum is passed to the solid earth through the topographic torques. Bottom pressure appears to be crucial in understanding the circulation

F. Bryan (National Center for Atmospheric Research, USA) discussed the ability of ocean general circulation models to reproduce bottom pressure. He presented results from a version of the POP model, in both barotropic and baroclinic configurations, with wind only or wind and pressure forcings. The model is volume conserving, so a correction is made by an artificial layer to conserve mass at each instant.. He recapitulated the BEMPEX comparisons and in general, the model motions are too weak. The difference between barotropic and baroclinic model results at one BEMPEX site is about 0.5 mb At a point near the equator, there is an annual cycle in the difference between the barotropic and baroclinic models. Globally the RMS difference between barotropic and baroclinic sea level is about 0.5 centimeters, but reaches 4-5 centimeters in shallow water (possibly due to coastal waves). Model resolution, and the details of the representation of topography have a significant zero-order impact on the realism of the model results.

The OCCAM model was further discussed by D. Webb (SOC). Runs carried out with 6-hourly ECMWF fields with and without atmospheric pressure forcing, showed that pressure is mostly compensated, the resulting rms variability in the deep ocean being generally below 1 hPa. The effect of the wind field is much larger, producing an rms bottom pressure variability of up to 7 hPa in the South Pacific and South Indian Oceans.

Errors introduced by the Boussinesq approximation were described by R. Greatbatch (Dalhousie University). One of these arises from the turbulent flux of density in the averaged mass conservation equation. Setting the velocity divergence to zero means that the averaged tracer equation can be in error by as much as 30 percent according to McDougall and Garrett [1992]. He argued that a simple transformation of variables $\hat{u} = \rho u/\rho_0$ allows all the current Boussinesq formulae to be applied to $\hat{u}$. In the ensuing discussion, it was argued that each improvement in numerical models, such as eliminating the Boussinesq approximation, takes extra CPU time, so the need for resources needs to be balanced against other improvements such as higher resolution.

Peter Killworth (SOC) reviewed a comprehensive list of errors in the physics, in the numerics, and in the forcing of ocean general circulation models. Among the physical simplifications he included the hydrostatic approximation, the Boussinesq approximation, the representation of levels versus layers, the absence of a Stokes tidal representation (which will leave internal tides present, but with unmodelled effects); horizontal versus isopycnic diffusivity; changes of gravity with latitude; rigid lid versus free surface; resolution—including the change in topography— and the effect of no-slip versus free-slip conditions on vertical topographic surfaces. Among the numerical issues he included grid-scale noise, which is some models can reach 15 Sv. In the ensuing discussion, D. Webb pointed out that internal tides can cause internal bores, which can lead to instability when resolution is low.

Assimilation

D. Stammer (Massachusetts Institute of Technology, USA, MIT) discussed a version of the MIT ocean model with adjoint assimilation: after assimilation of TOPEX/POSEIDON and other data, and allowing for errors in the forcing, the models surface fluxes were changed by up to 80 W/m^2, and the wind stress by up to 0.05 N/m^2. He also described the ability of a barotropic version of the same ocean model to de-alias unobserved short-period variability in altimetry and gravity observations: the fast signals produced by the model, when sampled as TOPEX/POSEIDON would, give a characteristic trackiness pattern, and removing the models sea level from the observations decreases the variance of the residuals.

Results from assimilation using a coarse resolution, global model were described by J. Schröter (Alfred Wegener Institut für Polar und Meeresforschung, Germany). Adjustments to the surface forcing derived from the adjoint method were similar to those reported by Stammer. After temporal adjustment, bottom pressures were analyzed for space/timescales accessible to GRACE. The seasonal cycle is about 1 mb and distinctly different from the surface signature.

Earth Rotation and Polar Motion

The accuracy and applications of earth rotation observations were reviewed by J. Dickey (JPL). The uncertainty in our knowledge of the Earth's orientation in space is equivalent to less than a 1 cm change in the position of an observer on the equator. Length-of-day (LOD) changes are dominantly caused by changes in the angular momentum of atmospheric winds with atmospheric pressure changes contributing about 5to the observed LOD changes. Including oceanic angular momentum (OAM) significantly improves the coherence between the LOD and the atmospheric angular momentum (AAM) and helps close the angular momentum balance between the atmosphere, oceans, and solid Earth. The effect of the recent 1997-98 ENSO event is clearly evident in the LOD observations which are highly correlated with the Southern Oscillation Index and interannual AAM variations. Unlike LOD, atmospheric pressure changes are nearly as important as changes in the angular momentum of atmospheric winds in exciting polar motion, but only about half of the observed polar motion excitation power can be explained by atmospheric sources. Including oceanic angular momentum significantly improves both the angular momentum balance and the coherence between the equatorial components of the angular momentum of the atmosphere, oceans, and solid Earth. To better understand the origin of Earth orientation changes, it would be desirable to have better measurements of the state of the oceans (especially ocean-bottom pressure measurements) as well as to be able to assimilate these measurements into oceanic general circulation models. Because length-of-day changes and polar motion excitation are both sensitive to changes in oceanic angular momentum, LOD and polar motion observations can potentially be used to discriminate between models of OAM.

R. Gross (JPL) discussed the geodetic benefits of having measurements of the Earth's time-varying gravitational field. Besides the benefit to Earth rotation studies discussed by J. Dickey, better knowledge of both the displacement of stations caused by ocean loading and of the changing location of the solid Earth's center-of-mass would be derived from these measurements.

Calibration, Validation, Verification. Field Observations

A discussion of the major issue of calibrating GRACE was led by J. Wahr. There are three possible sources of error: measurement error; incomplete parameterization in gravity solutions; aliasing of short period signals. He then asked whether these errors depend on signal strength, because if not, then a place with an expected near-zero signal would be a good calibration site. Coupled climatic/hydrologic simulations by A.J. Broccoli (GFDL/NOAA), K.A. Dunne (USGS), and P.C.D. Milly (USGS) show RMS mass values that are typically larger than 2-3 cm over most continental regions, with values as large as 30 cm in a few places. Subcentimeter signals in the POP model can be found over much of the oceans or over the Sahara. Wahr suggested the Sahara would make a good calibration site, leading to a discussion of the relative merits of calibration sites having small signals versus those of large. In all cases, it is necessary to instrument a sufficiently large area so that the GRACE 500 km average can be realistically approximated from the calibration data. He also discussed aliasing of GRACE signals over the oceans by fast, mostly barotropic motions. W. Munk described the concept of calibration by employing a "Navy Acre"—a heavily instrumented oceanic region in an area of large signals.

P. Woodworth (POL) listed the known owners/-operators of BPRs. In the ensuing discussion, issues were raised concerning the ability to make accurate multiyear measurements, i.e. how well drift rates are understood. C. Wunsch argued that consistency with derived quantities, such as geostrophic velocities obtained by strings of current meters, would be necessary to convince users of the validity of the data, especially in view of F. Bryan's observation of the accuracy with which pressure is reproduced in the model, but not the pressure gradient.

4. Recommendations

As a result of this wide-ranging discussion, the last part of the meeting was devoted to seeing if a consensus existed for recommendations to the various space agencies and science teams. Many issues were left unresolved for the Teams to consider.

In particular, the science teams must work through the relative merits of global scale versus regional calibration exercises. For the latter, the trade-offs between quiet and active sites, be they land or ocean must be better understood. GRACE and related science will need an improved understanding of the accuracies of the operational meteorological products, both pressure and winds. Cooperation of the meteorological centers will be required to do this.

De-aliasing of GRACE (and the altimetric missions) will definitely be required, spanning the entire range of motions from hours to the overall Nyquist period, and including tides (both atmospheric and oceanic), oceanic barotropic motions, and a full range of atmospheric phenomena. Oceanic barotropic models appear to have considerable skill for this purpose, but much more testing will be required.

A mechanism needs to be found for coordinating the groups which are interested in making direct in situ measurements of pressure and velocity in conjunction with GRACE and a more efficient means of communication between the US and European science teams is necessary. The meeting was followed immediately by a joint meeting of the US and European Science Working Teams for GRACE, held at the Society for Chemical Industry, London, 16-17 April. This group began the process of responding to the discussions reported here.

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