Solid Earth deformation and gravity changes due to surface loading: Status and scientific problems

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Abstract: The Earth's surface is perpetually displaced due to atmospheric, oceanic and continental water mass loads. These displacements and the associated gravity changes are increasingly important for the application of space-geodetic methods for scientific studies and operational tasks. Increasingly accurate observations of the displacements provide the means to study the loading processes involved and to validate the theory and Earth models used for the modelling as well as the input data and models used to describe the surface loads.
Here we first summarise the current status of modelling of the surface displacements induced by loading, including the basic theory used, the Earth model and the surface load data. The currently available predictions suffer from both deficiencies of the theory and the Earth models as well as the surface load observations and models.
We then identify a list of critical problems that need to be addressed in order to improve the quality of the predictions. Here we address improvements of the theory, the Earth model and the loading data.
Finally, we discuss the characteristics of the currently best possible operational prediction of the loading signal and give recommendations for a conventional approach to taking the full loading signal into account in the station motion model required for space-geodetic analyses.

1 Introduction

On 1 January 1998, the International Earth Rotation Service (IERS) established the Global Geophysical Fluids Center (GGFC) in an effort to expand IERS's services to the scientific community. Under the GGFC, seven Special Bureaus (SB) were established (see http://bowie.gsfc.nasa.gov/ggfc/). Each of these is responsible for research activities relating to a specific Earth component or aspect of the geophysical fluids of the Earth system. However, until recently, there was no specific focus on the interaction of the different components through gravitational and surface forces on the boundaries. In particular, consistent models of the deformation of the solid Earth due to loading of the atmosphere, ocean and terrestrial hydrosphere are presently not available. This is also reflected in the IERS Conventions [14], where standard models for solid Earth tides and ocean loading are discussed while no standard procedure is given for taking into account other surface loading effects.

In order to foster the development of consistent models for predicting loading signals, the IERS on 31 October 2001 issued a Call for Proposals for a Special Bureau for Loading (SBL). In this call it was stated that the *IERS conventions currently do not give comprehensive recommendations for treating the loading signals due to the full range of possible effects* and that it therefore was *timely to set up the tools that provide a basis for a future conventional treatment of loading effects in all IERS analyses.* Furthermore, it was pointed out that meeting *future requirements calls for considerable theoretical work, algorithm developments, model compilations and studies of relevant observations.*

Table 1: Current Membership of the SBL
Note also that the chairs of the existing SBs are ex-officio members of the SBL. Currently, the ex-officio members include Ben Chao (Mantle), Tim Van Hoolst (Core), Richard Gross (Oceans), Richard Ray (Tides), David Salstein (Atmospheres), Michael Watkins (Geocenter), and Clark Wilson (Hydrology).

Name	**Affiliation or Function**
Tonie van Dam	European Center for Geodynamics and Seismology (ECGS), Luxembourg (chair)
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Olivier Francis	European Center for Geodynamics and Seismology, Luxembourg
Pascal Gegout	Ecole et Observatoire des Sciences de la Terre, Strasbourg, France
Halfdan Pascal Kierulf	Norwegian Mapping Authority, Norway
Tadahiro Sato	National Astronomical Observatory, Mizusawa, Japan
Hans-Georg Scherneck	Onsala Space Observatory, Sweden
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Eventually, the SBL is expected to provide in near real-time (NRT) a consistent global solution data set describing at least the surface deformation, gravity signal and geo-centre variations due to the various surface loading processes in reference frames relevant for direct comparison with existing geodetic observing techniques.

On 1 February 2002, the SBL (see http://www.gdiv.statkart.no/sbl/) was formally established with a team of 10 members (see Table 1). The expertise of these ten members covers all areas relevant for accurately modeling surface deformations, namely, theory of Earth deformation and Earth models, observations of surface loads, computation of tidal and non-tidal loading, space-geodetic and gravimetric observations. The team also includes the 7 chairs of the already existing SB's. The chairs of the existing SB's are ex-officio members of the SBL and participate in the SBL to insure close cooperation between their SBs and the SBL. Moreover, the combined membership provide the necessary links to other geodetic services and relevant projects, such as the IGS, IVS, ILRS, and the GGP.

The accuracy of the products provided through the SBL should, as much as model limitations allow, match the accuracy and precision of the space-geodetic and gravimetric observation techniques. Achieving this ambitious goal requires major scientific advances with respect to the Earth model, the theory and algorithms used to model deformations of the Earth and the observational data of surface loading. Consequently, a scientific agenda has been establised to perform the research necessary for the development of the models and algorithms, in parallel with an operational agenda which is directed towards the provision of validated products to potential users.

In March, 2002, the SBL held its first workshop in Luxembourg to establish priorities, to discuss loading datasets, to outline areas for future research, and to define an operational timeline. The 'Action Items' and 'Recomendations' outlined in this document are the direct outcome of this workshop.

In order to meet the IERS mandate for the SBL, two separate agendas have been established, namely

- **operational:** provide in near real-time a consistent global solution data set describing at least the surface deformation, gravity signal and geo-centre variations due to the various surface loading process in reference frames relevant for direct comparison with existing geodetic observing techniques.

- **scientific:** major scientific advances with respect to the Earth model, the theory and algorithms used to model deformations of the Earth and the observational data of surface loading.

2 Overview of the basic components required for determining load responses

Figure 1 sketches the main elements required in the computation of loading predictions. The main ingredients for the computation of the mathematical tools are (1) an Earth model, which determines the geometry, the mechanical properties and, if necessary, the rheology, and (2) a mathematical model for the surface load including the boundary conditions at the Earth surface and the extension of the load. Then selected parts of the continuums mechanics (e.g. elastic theory, or linear visco-elasticity) can be used to solve the boundary value problem to obtain the system's response to a unit load. For the problem of Earth deformation, the system's response is best described by Love numbers which can be used to compute the Green's functions of the boundary problem.

For the computation of predictions of load-induced signals, actual surface load data are required for all relevant loads, such as the atmosphere, the ocean, the terrestrial hydrosphere, and the cryosphere. These loads are convolved with the system's response (either in the space or the wave number domain) to compute the loading parameters such as surface displacements, gravity variation, or goecenter displacements.

However, the Earth and load model as well as the theory selected to compute the system's response may not be adequate for describing the loading problem. In addition, the surface load data may be erroneous, inaccuracte or incomplete. Therefore, a careful validation of the predictions both through model intercomparison and through comparison to observations is required. For the latter, an additional problem arises from that fact that the observations also contain errors and, depending on the technique and data processing used, and they also may not contain the full loading signal. After a successful validation, operational processing can be set up to produce conventional products in near-real time. However, considering the present state-of-the-art both with respect to the theory of loading predictions, the quality of the surface loading signals, and the processing of space geodetic data, the need for additional loading predictions for research purposes will remain for a long time to come.

3 Theory of Deformations Induced by Surface Loading– Load Love Numbers

Here we summarise the status of computation of surface displacement, gravity variations and geocenter variations due to surface loads. The computation of load Love Numbers (LLN) for a given Spherically symetric, non-rotating, elastic, isotropic (SNREI) Earth model is done by integration from the Earth center to the surface, requiring however a starting solution at a certain depth. Pascal Gegout uses a starting solution for a homogeneous sphere of radius 100 km or no deformation at the Core-Mantle-Boundary for degrees larger than 250. Uncoupling of the core and mantle is done for degrees greater than 250 but can also be done for degrees greater than 25 at the 1 % accuracy. With this approach, LLNs can be computed for almost arbitrarily high degrees. For the core, normally a hydrostatic model is used.

For the start solution, most often a homogeneous sphere with a radius depending on the spherical degree is utilised. By selecting the starting depth as function of the degree, again the LLNs can be computed for very large

Figure 1: Sketch of the scientific and operational loading predictions.

spherical degrees. In addtion, for the core, a density profile satisfying the Adams-Williamson condition has to be used.

The LLNs can be used either to compute the required Green's function or can be used directly in the convolution with the load potential. The surface loads are approximated by a surface density (thin-load assumption), which may not be appropriate for computation of gravity variations.

The advantage of using SNREI models is that the LLNs depend on harmonic degree only (see Figure 2. For 3-D models, the LLNs also depend on the order.). For 3-D models, the available theory is based on a perturbation method [e.g. 16].

Table 2: Summary of different classes of Green's Functions.
Depending on the Earth model, the Green's function depends only on the angular distance between load and observer (SNREI), or explicitly on the load and observer positions (EREI, LHREI), or on the angular distance and the time (SNRVI) or on both positions and time (LHRVI). The theory for SNREI models [5] is widely used, while the theory for LHREI [16] has not been fully implemented yet.

SNREI	Sperically symmetric, Non-Rotating, Elastic, Isotrop $G_u = G_u(\vartheta(x, x'))$ $G_g = G(\vartheta(x, x'))$
EREI LHREI	Rotating, Elliptically symmetric, Elastic, Isotrop Laterally heterogeneous, (Rotating), Elastic, Isotrop $G_u = G_u(x, x')$ $G_g = G(x, x')$
SNRVI	Sperically symmetric, Non-Rotating, Viscoelastic, Isotrop $G_u = G_u(\vartheta(x, x'), \tau)$ $G_g = G(\vartheta(x, x'), \tau)$
LHRVI	Laterall heterogeneous, Rotating, Viscoelastic, Isotrop $G_u = G_u(x, x', \tau)$ $G_g = G_u(x, x', \tau)$

There is the need for a detailed study of the theoretical and technical details in the computation of LLNs for different classes of Earth models. With respect to visco-elastic effects, it can be concluded that this is only important for long-period surface loads, e.g. decadal to inter-decadal variations. However, the uncertainty in the surface loads derived from models and observations due to artifical trends is likely to be larger than visco-elastic effects.

It is not fully clear how the different Earth model assumptions affect the computed surface displacements, gravity variations and geocenter variations. In particular, it is not known whether different model assumptions lead to differences in loading effects that are significantly larger than differences due to different data sets for the same surface loads (i.e. European Center for Medium Range Weather Forcasts (ECMWF) versus the National Center for Environmental Prediction (NCEP) surface atmospheric pressure fields). Therefore, the following action item are proposed:

Action Item SBL-1: *Carry out a sensitivity study which shows the effect of different Earth models and surface pressure fields on computed surface displacements.*

We will initially restrict this action to SNREI models, while studies of the sensitivity to 3-D models will be performed in the future.

4 Earth models

In this section, we summarise the status of Earth models currently used in modelling deformations due to surface loads (which to a large extent also applies to Earth models used for modelling deformations due to body forces such as tidal forcing). Earth models can be characterised by the geometry (i.e. spherical or elliptical, with or without undulations of the surface and inner boundaries), the space-dependency of the mechanical properties (i.e. the functions for density, bulk modulus, and shear modulus) and the rheology (i.e. the frequency dependency of the shear modulus). The most widely used models are SNREI models. Moreover, the models are assumed to be hydrostatically prestressed. For these relatively simple models, where all mechanical properties depend on radius alone, it is often assumed that computation of LLNs is a standard procedure. However, this is not necessarily the case. First, one has to select the functions describing the depth-dependency of density, bulk and shear modulus. The Preliminary Reference Earth Model [PREM, 4] appears to be the natural choise, but the LLNs given by [5], which are based on a Bullen model, are also still in use. Using the PREM poses at least three problems which leave room for inconsistencies:

- the PREM has a global ocean of 3000 m depth, which needs to be replaced by a solid layer;
- the PREM is a visco-elastic model giving shear and bulk modulus for 1 s and 200 s. The PREM is based on the Anderson-Kanamori-rheology, which cannot be used to compute elastic values for the shear and bulk modulus;
- the numerical computation of the LLN may require some parameterisation of the depth-dependency of the mechanical properties.

Generally, differences in the LLN due to different Earth models are assumed to be of the order of 1-1.5 percent. However, comparing the LLN computed for the PREM by different groups show much larger differences (see Fig. 2 in Section 6.1). It is very important to clarify the source of these discrepancies.

The popularity of the SNREI models is due to the fact that the Green's function for such models are rather simple, depending for a given Earth model only on the angular distance between the load and the observer. For laterally heterogeneous models (i.e. models with lateral heterogeneities in the distribution of the mechanical properties, boundary undulations, or a non-hydrostatic prestress) the Green's function depends explicitly on the position of the load and the observer, complicating the computation of the response considerably. For visco-elastic models, the Green's function in addition becomes time-dependent. Even if the theory for more advanced Earth models were to be implemented, the question remains whether such Earth models are available. For the Earth' crust, a 3-D model is provided by the Reference Earth Model web site at http://mahi.ucsd.edu/Gabi/rem.html or directly at http://mahi.ucsd.edu/Gabi/rem.dir/crust/crust2.html. The newest model is specified on a 2x2 degree grid and is an update of the earlier CRUST 5.1 model. It takes advantage of a recent compilation of global sediment thickness which is defined on a 1x1 degree grid. It also includes ice thickness on the same scale. The new crustal model also takes advantage of the still ongoing effort to compile crustal thickness on a 1x1 degree scale. The current compilation available from the REM group covers most of Eurasia, North America, Australia and some areas of Africa and South America and in the oceans.

The global crustal model CRUST2.0 uses type keys to assign various types of crustal structure (such as Archean, early Proterozoic, rifts etc.) in each cell.

Compared to CRUST5.1, CRUST2.0 gives a better representation of the edges of shelves and the coastline. Some tectonic regions in the Americas and Eurasia are also adjusted. Ice thickness for CRUST 2.0 is within 250 m of the true ice thickness. Sediment thicknesses in each cell are to within 1.0 km of the true sediment thickness and crustal thickness are within 5 km of the true crustal thickness.

Concerning the Earth's mantle, the situation is not as positive. On the REM web site, five different 3-D models for the shear modulus in the Earth mantle can be found (at http://mahi.ucsd.edu/Gabi/rem2.dir/shear-models.html). Using the tools provided on that web site, model intercomparison reveals that there is very little correlation between different models for the depth range 670-1000 km. This depth interval will still have a effect on surface displacements due to low-degree loads (lower than approximately degree 30).

SNREI models are most likely not sufficient to model displacements due to surface loads with an accuracy of 1 mm or better. Moreover, treatment of SNREI models leave room for significant differences between models and groups. 3-D Earth models are developing and the transition from PREM to REM seems feasible in the near future. However, significant differences still exist for 3-D models of the shear modulus in the Earth's mantle.

Here, we did not address anisotropy and non-hydrostatic prestress. The latter may have a significant effect particularly in regions with high tectonic prestresses.

We raise the question whether it is a natural task of the SBM to interact with the REM group and to provide a standard Earth model or whether this is a task for the SBL. Considering the uncertainties in the LLN, the following action item was agreed upon:

Action Item SBL-2: *Carry out an intercomparison of Load Love Number computed by different programs/groups for the PREM model.*

5 Surface loads

5.1 Contributions from the SBs

5.1.1 Ocean

The global oceans have a major impact on global geophysical processes: Ocean currents and bottom pressure affect the Earth's rotation (LOD, polar motion, nutation), and the redistribution of oceanic mass causes temporal variations of the Earth's gravity field, affects the geocenter and loads the solid Earth leading thus to surface deformations. The IERS established a Special Bureau for the Oceans as part of the Global Geophysical Fluid Center with three goals: (1) maintain liaisons with ocean modeling groups and advocate the calculation of relevant products, (2) archive and distribute these ocean-model products, (3) facilitate research on the effect of oceanic processes on solid Earth geophysics, including geodesy and geodynamics. Core products of the SBO are the oceanic angular momentum, the oceanic center-of-mass, and ocean-bottom pressure. Extended products include time-dependent gravitational field coefficients caused by ocean-bottom pressure changes, and oceanic torques (frictional and topographic). With respect to the former it was mentioned that CHAMP and GRACE soon will measure the time-dependent gravitational field coefficients of the entire Earth and the information from ocean models will be helpful in separating the different contributions. The latter enable investigations on how angular momentum is exchanged between the oceans and solid Earth.

The SBO also provides auxiliary products such as the land-ocean mask and time-dependent oceanic mass, which are needed when imposing mass conservation upon products of Boussinesq ocean models (which conserve volume but not mass). Another auxiliary product is ocean-bottom topography, which is needed for certain calculations involving ocean-bottom pressure.

The SBO products are made available through the web site at http://euler.jpl.nasa.gov/sbo/ and the ftp site at ftp://euler.jpl.nasa.gov/sbo. The SBO team includes members from the fields of oceanography, atmospheric sciences, and Earth rotation (see http://euler.jpl.nasa.gov/sbo/ for more details). Further growth in this field strongly depends on the development of ocean models, as observations will continue to be sparse. With respect to operational activities, there appear to be only two groups that intend to update their models regularly: Mercator has the plan to have an operational global ocean model available in 2003. The Phase 3 MERCATOR prototype planned for January 2003 will include real-time routine modeling of the global ocean at medium resolution (1/4 degrees), assimilating altimetry and in-situ data. ECCO (Estimating the Circulation and Climate of the Ocean) has been formed under the US National Ocean Partnership Program (NOPP) and is a consortium formed by a group of scientists at the Jet Propulsion Laboratory (JPL), the Massachusetts Institute of Technology (MIT) and the Scripps Institution of Oceanography (SIO). The consortium intends to bring ocean state estimation from its current experimental status to that of a practical and quasi operational tool for studying large-scale ocean dynamics, designing observational strategies, and examining the ocean's role in climate variability. The ocean-bottom pressure fields available from ECCO are at 1 degree resolution (telescoping to 0.3 degree meridionally in the tropics) and are produced by an ocean model that is assimilating altimetry and in situ observations. According to Richard Gross, ECCO is planning to implement in the near future regular updates at intervals no less than monthly. The bottom pressure is available on request.

With respect to model predictions of deformations due to atmospheric and non-tidal ocean loading, results obtained by Shailen Desai and Bruce Haines show that hot-spots in variance are found in Siberia and the Antarctic circum polar ocean with maxima of 30 and 12 mm for atmospheric and non-tidal ocean loading, respectively. Comparing the predictions to GPS site displacements, Desai and Haines found that at many stations there is a reduction in variance of the radial component if atmospheric and non-tidal ocean loading is corrected. Interestingly, the reduction is larger if the seasonal cycle is not removed.

In the subsequent discussion, Gross pointed out that the ocean circulation models use Boussinesq approximation, i.e. volume but not mass is conserved. Mass conservation is typically imposed after the fact by adding a surface layer of the appropriate time-dependent thickness. Such a correction for mass conservation would need to be done to the ocean-bottom pressure fields before using them for loading calculations. The models also have a drift problem due to incomplete adjustment of the model to the forcing fields. The correction for mass conservation would also correct for the effect of this drift on ocean-bottom pressure.

The forcing of the ocean models typically includes surface wind stress, heat, and salinity fluxes, but not atmospheric pressure. However, the ocean response to atmospheric pressure could be obtained from barotropic models.

For operational purposes, model errors are important in addition to model resolution. Low degree errors might be important for high temporal resolution. It is not clear whether we know the errors for the different spatial degrees, though some work with respect to the spatial and temporal scales of the ocean-bottom pressure is being done. However, it is clear that the models need improvement. For example, no loading and self-attraction is included. It can be assumed that the modelers would benefit from feed-back from our side.

5.1.2 Atmosphere

The SB Atmosphere, which previously was called the Special Bureau for Atmospheric Angular Momentum is a cooperative effort of Atmospheric and Environmental Research, Inc. (AER) and the U.S. National Centers for Environmental Prediction (NCEP). AER provides scientific input, archives SBA parameters (see below) and maintains liaison with IERS and the wider scientific community. NCEP calculates the SBA Atmospheric Angular Momentum parameters and receives data from other centres.

Ongoing efforts of the SBA focus on the combination of atmospheric data sets, and archiving assessing torques related to Earth rotation, including the mountain and friction torque, and the interpretation of climate signals (e.g. the importance of El Nino) in Earth rotation and related parameters. Note also, that comparison of global torques indicate that friction torque is far less important on shorter time scales (¡ 20 days) than mountain torque and AAM.

Participating Centers in the SBA are the National Centers for Environmental Prediction (NCEP), the Japan Meteorological Agency (JMA), the United Kingdom Meteorological Office (UKMO), and the European Centre for Medium-Range Weather Forecasts (ECMWF).

Parameters provided by the SBA describe the atmospheric angular momentum related to Earth rotation/polar motion due to winds and mass (surface pressure). Products include:

1. Hemispheric values for the excitation functions for polar motion/axial Earth rotation (Chi1, Chi2, and Chi3) computed for the
   - wind to the top of the model,
   - wind to 100 hPa,
   - air pressure,
   - and air pressure modified for the inverted barometer response of the ocean.

   These products are provide for analyses and forecasts, using wind and pressure fields to compute them.
2. Mean surface pressure (hPa) over the globe.
3. Low-order coefficients of surface pressure.

Access to data is provided by the SBA in two modes:

- Operational mode: products derived from at least the most recent ten days and forecasts of all four participating centres are available via ftp to climon.wwb.noaa.gov.
- Delayed mode: products in delayed mode are available via ftp at ftp.aer.com on directory pub/collaboration/sba. There are products derived from NCEP/NCAR reanalyses (1948-present), which are updated every month. Moreover, records of all four centers are available. The NASA/GEOS data assimilation system covers about 1.5 decades from 1980- 1995 and will eventually cover the 1979 - EOS era from a future analysis. ECMWF reanalysis system has currently a 15-year set and will eventually be extended to 40 years.

The NCEP data sets are available within 1-2 days through the web and ftp sites. Operationally, the NCEP itself can be used. At the Climate Diagnostics Center (CDC) data can be down-loaded from http://www.cdc.noaa.gov/cdc/reanalysis/. David Salstein showed examples of Earth rotation excitation computed four times daily from wind and pressure for 2000 and discussed the surface pressure harmonics for the period 1975-2001 (monthly means). He showed various truncation of the surface pressure field. These series are available as coefficients both for the surface pressure and the pressure modified by the inverted barometer response.

5.1.3 Hydrology

Within the GGFC, the SBH is responsible to coordinate research activities related to continental water variations. The main goals include the collection and distribution of data sets and numerical model results related to the changing distribution of water over the planet, especially over land, that are of interest to the geodetic community as well as the development of working relationships with hydrological modeling groups, in order to compute geodetically interesting quantities directly during model computations. Focus is also on data sets and model results which provide generally complete global measures of water mass redistribution and to provide these sets in forms that will allow useful comparisons with variations of e.g. the Earth rotation and the gravity field.

Data currently available at the SBH include the water storage and fluxes derived from NCEP/NCAR Climate Data Assimilation Syatem I (CDAS-1), which provides soil moisture and snow for the time span 1993 - 1998 with a monthly sampling rate on a 1 x 1 degree grid.

It is expected that the data set soon will be available for the full NCEP reanalysis period 1948 - present with a temporal resolution of 1 day. For selected periods, the data will be made available for six hourly samples. Again, the data set will be interpolated to a 1 x 1 degree grid and made available as ASCII compressed file or NetCDF file.

The NASA NSIPP hydrological model is a coupled model for prediction purposes and will provide data for a period from 2010 - 2059.

Concerning the quality of the models, it has to be pointed out that the SBL needs to study the uncertainties and their effect on loading signals. Somehow, this information on uncertainties needs to be transferred to the users of SBL products.

5.2 Status of ocean tidal loading

Computation of ocean tidal loading requires two ingredients, namely ocean tidal models describing the load and Earth models, on which the load acts. Two ways of computing the loading response can be distinguished, namely the convolution in the space domain (direct convolution of the load with the Green's function in the space domain) and the summation in the wave number domain (summation of the products of Love numbers and load potential). There are specific advantages and disadvantages of the two approaches, which in principle should give identical results. In practice, this is not the case with the ocean tides. The 2-D function describing the tides presents a discontinuity at the coastlines and this generates some instabilities in the loading computation in coastal region (so-called Gibbs's effect). It is therefore recommended to work in the space domain when possible.

For the ocean tidal models, a distinction can be made between global and local/regional models. For global models, the Schwiderski model covers the main semi-diurnal, diurnal and long-period tidal constituents. There are 15-20 models available, which are derived from Topex/Posidon and which provide the main semi-diurnal and diurnal constituents. Finite Element models give quart-diurnal, semi-diurnal, diurnal and long-period tides. Local models generally provide finer grids and are likely to be superior locally. For some specific near-coast sites, a combination may be necessary.

Because the ocean models are all specified on rectangular grids, they sometimes cover land-area. The software of D. Agnew includes a land-sea database. It performs a test on the location of the ocean tide models cells with respect to the land and automatically adjusts the cell to fit the actual coastlines.

With respect to Earth models, Load Love Numbers (LLN) are in good agreement for different models (1-1.5 6.1). Concerning the software available for computation of ocean tidal loading coefficients, the following list gives most but maybe not all authors and programs:

- O. Francis: program GGP, more research type, not easy to use.
- D. Agnew: has a good representation of coasts, large number of models, including local ones; will be available on the web to give loading coefficients for arbitrary stations,
- H.-G. Scherneck: available on web, uses Gutenberg Earth model, coastline is treated very well,
- Matsumuto: available of ftp, mainly for Japanese island,
- ICET: only Schwiderski ocean tide model.

Ocean loading should be made available after validation through the SBL. However, it is not clear how validation the loading coefficients can be achieved. How can realistic estimates of uncertainties be obtained? Moreover, care should be taken in not giving too optimistic estimates.

5.3 Status of surface loads

Main focus is here on the temporal and spatial resolution required for the surface loads. Surface loads to be considered are

- atmospheric loading,
- non-tidal ocean loading,
- continental water storage.

With respect to the atmospheric data, we point out that NCEP and ECMWF show RMS differences over a month with the highest differences in the high latitudes. There, the latitudinally averaged rms difference are of the order of 2-4 hPa, though occasionally can be as high locally as 6-10 hPa. In the low latitudes, zonal mean differences are much smaller, between 0.5 and 1.0 hPa.

Concerning the ocean-bottom pressure, the space-time spectrum of the ocean-bottom pressure field is not well known. In particular, it is not clear whether high frequency variations are large enough to cause significant effects. Therefore, we propose the following action item:

Action item SBL-3: *Investigate the space-time spectrum for the ocean-bottom pressure field.*

It has to be emphasised that ocean models drift with respect to total mass and therefore, trends from ocean bottom pressure models have to be removed. In order to avoid contamination of e.g. tectonic studies, the trend biases in the surface loads need to be accounted for somehow. This appears to be a rather intricate problem.

Trends in the x- and y-component of oceanic angular momentum due to trends in the ECCO model are, in equivalent polar motion units, 0.5 mas/year, but it is not clear how this would translate into height.

For the continental hydrology models using meteorological observations as input are the only source of global information. Examples are [9], which provide monthly results for 1979-1993 and [21], which provide groundwater, soil moisture and snow for the period 1978-1998. However, uncertainties of these model predictions are rather large and their usefulness for loading computation is not fully clear.

We propose the following two action items:

Action Item SBL-4: *Study mass conservation of ocean and continental hydrosphere models.*

Action Item SBL-5: *Investigate the spatial distribution of trend in air pressure.*

Another issue is the reference level to be used for the different surface loads. Care must be taken in selecting the reference level for computing the surface load anomalies. Using biased anomalies in the computation of load-induced surface displacements and gravity variations may change the radius of the Earth or. e.g. the mean gravity on the Earth surface. We propose the following two recommendations:

Recommendation 1: *Biases in trends due to model insufficiencies need to be removed from surface loads derived from models.*

Recommendation 2: *The reference level for surface loads should be space-dependent and should be computed as average over a long time.*

However, it has to be emphasised that the corrections should not change the ITRF coordinates after they have been determined and are fixed. This may require a very special selection of the reference levels. With respect to the spatial resolution of the surface pressure field for atmospheric loading, the following recommendation is proposed:

Recommendation 3: *The spatial resolution of the atmospheric pressure field should be 2 by 2 degrees.*

The potential role of surface topography for atmospheric loading was pointed out. It can be questioned whether a resolution of 2 by 2 degrees is sufficient to represent mountain ranges. However, before committing to include the surface topography it should be investigated whether this is really necessary to obtain the desired accuracy of 1 mm or better. The following action item is proposed:

Action Item SBL-6: *Investigate effect of topography on displacements.*

It may be that in atmosphere pressure, S1 might require a separate treatment. The S1 thermal tide is a large signal in atmospheric pressure but unfortunately it is not well-represented in the atmospheric analyses. Differences between the NCEP and ECMWF analysed pressure fields at this frequency are nearly as large as the signal itself. Thus, if one wants to produce results at 6-hour intervals, the problem with the S1 tide will need to be addressed at some point. One approach would be to substitute the climatological results of [van den Dool] for the S1 tide. This may or may not be more accurate that using the NCEP or ECMWF results for this tide. It would need some study.

A related issue is semidiurnal variations in surface pressure. This has the added difficulty of being right at the Nyquist frequency of 6-hour values.

However, focus could be first on the seasonal signal. For mass conservation, the seasonal cycle has to be treated in a special way. However, for products, we should not do any filtering. The seasonal cycle might be useful in validation of models and for internal research. There are climatological signals like El Nino, which also might be interesting. However, removing trends from surface load data sets might be a problem for these phenomena.

5.4 Conclusions

The SBL should request from other SBs the input needed in terms of observations, and models. This should also including the Earth models required for loading calculations. A clear distinction needs to be made between operational products and research results or products still in research state.

It can be expected that the SBL will create new demands for products from the other SBs and thus stimulate coordination. This results in the Action Item:

Action item SBL-M1-7: *The SBL needs with respect to the other SBs should be clarified and the required input from the different SBs specified.*

6 Model Intercomparison

6.1 Love numbers

6.2 Load signal predictions

Loading responses to non-tidal surface loads are normally computed in one of two ways: 1) Point loading approach in which a gridded surface mass is convolved with Green's funtions to determine the load response; 2) Spherical harmonics approach in which the LLNs are used directly to carry out the convolution with a given surface load in the wave number domain. This approach requires the surface loads to be given as a spherical harmonic expansion.

A comparison of 3-dimensional deformations determined using the spherical harmonic approach and the Green's function approach has been performed. Preliminary results indicate that the difference in the determination of the vertical component is less than 1 mm. Horizontal differences are much smaller. Further testing needs to be done and will be reported on at the IERS meeting.

If the differences between the two approaches remains at the 1 mm level, the SBL will adopt the spherical harmonic approach for calculating the loading responses. This technique is significantly faster computationally.

In computing the load signals, special attention must be given to the reference frame [1]. One possibility is to provide the loading products in various frames, for examples, center of mass of the entire Earth system (common in SLR), center of mass of the solid Earth (Farrell assumption), center of figure frame (common in GPS). To a large extent, the frame selected depends on the degree one LLN chosen. Conversion of the degree one LLN to the appropriate frame can be done prior to the computation or the frame correction can be done at the end by applying condition equations on the gridded displacements. In any case, a clear specification of the reference frame needs to be attached to the model predictions.

In the context of the atmospheric pressure loading effects, the response of the ocean to atmospheric forcing needs to be considered. Currently, only two simple modesl are used for describing the atmosphere-ocean interaction at these time periods: 1) no oceans and 2) inverted barometer ocean. We propose to operationally generate global loading effects using both of these models. However, neither alternative results in high accuracy and, particularly for broad coastal regions, both assumptions may be insufficient. Therefore, more complex models for the ocean response to air pressure and also wind will have to be considered providing estimates of bottom pressure.

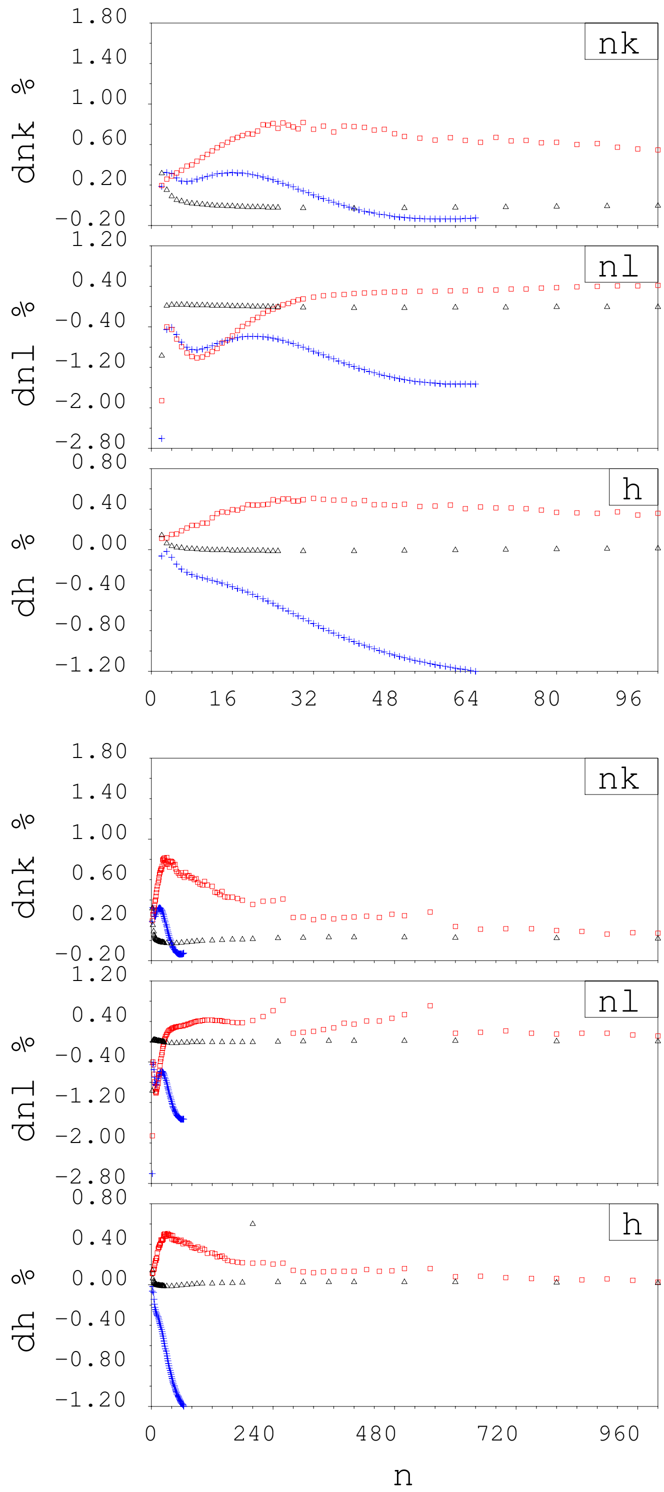

Figure 2: Differences in LLNs for PREM computed by three different programs. *The differences are given in percentage of the LLN (e.g.* $dh_n = (h1_n - h2_n)/h1_n * 100$*). Reference are the Load Love Numbers computed by P. Gegout. Red squares correspond to results obtained by H.-P. Plag, blue crosses to M. Tamisea, and black triangles to O. Francis. O. Francis and P. Gegout agree very well except for* $n = 2$*. The other two results show large disagreements particularly for higher orders.*

7 Validation of Prediction Models

The question of how to validate the model predictions is not easy to answer. However, it has to be clear that validation does not mean verification. Following [15] we emphasised that verification is not possible and that validation is a process of reaching a consensus on which model appears to represent nature (or the modelled aspect of nature) in a satisfactory way. Therefore, intercomparison of models and comparison of model predictions to observations are valuable steps to model validation. However, comparison with only a few surface displacement series certainly is not enough to draw conclusions. Rather, these comparisons will have to be done by the whole IERS community with different types of observations (rotation, gravity, surface displacement, ...) at a lot of different places. A coordinated IERS validation campaign would involve all IERS techniques (GPS, VLBI, SLR, DORIS) at all ITRF sites. It would involve a large number of users. Thus, such a campaign would provide a very broad comparison.

We suggest two action items:

Action Item SBL-8: *Carry out an internal validation by comparing model predictions for atmospheric loading computed by the different groups for a small number of selected sites.*

Action Item SBL-9: *Compute data sets for a reasonable number of sites and time interval for external validation through comparison with observations.*

8 Identification of Problems

To be addressed in the future.

9 Agenda for Improvements of Loading Predictions

9.1 Improvements of the theory

The following issues need to be addressed:

- Height dependend load
- Surface undulations
- lateral heterogeneities

9.2 Towards a 3-d Earth model

- elastic-viscoelastic,
- 3-d from seismology

9.3 Atmospheric loading

- inverted barometer/ocean response

9.4 Hydrological loads

- How to improve the models?

9.5 non-tidal ocean loading

- Combined models for complete atmospheric forcing
- Combined circulation/tidal models

9.6 Tidal loading

- Validation of models made available through the SBL umbrella

10 Towards a Conventional Treatement of Loading

10.1 Conventions for loading: the vision

This section is a draft for the new IERS Conventions

Temporal variations in the geographic distribution of atmospheric mass, load the Earth and deform its surface. The pressure variations on the order of 20 Hpa (and even larger) at mid-latitudes, are observed in synoptic pressure systems with length scales for 1000-2000 km and periods of approximately two weeks. Seasonal pressure changes due to air mass movements between the continents and oceans can have amplitudes of up to 10 Hpa in particular over the large land masses of the Northern Hemisphere. At the interannual periods, basin-wide air pressure signals with amplitudes of several HPa also contribute to the spectrum of the loading signal. Theoretical studies by [18], [19], [24], and [11] demonstrate that vertical crustal displacements of up to 25 mm are possible at mid-latitude stations due to synoptic pressure systems. Annual signals in the vertical are on the order of 1-2 mm but maximum signals of more than 3 mm are possible over large parts of Asia, Antarctica, Australia and Greenland [12; 3]. Pressure loading effects are larger at higher latitude sites due to the more intensive weather systems (larger in amplitude and more spatially coherent) found there. Effects are smaller at mid-latitude sites and at locations within 400 km of the sea or ocean due to the inverted barometer response of the ocean. In all cases, horizontal crustal deformations are about one-third the amplitude of the vertical effects.

There are two basic methods for computing atmospheric loading corrections: 1) using geophysical models or simple approximations derived from these models and 2) using empirical models based on site-dependent data.

The geophysical model approach, involves the estimation of atmospheric loading effects (vertical and horizontal deformations, gravity, tilt and strain) via Green's functions convolved with a global surface pressure model or via spherical harmonic descriptions of the global pressure field and loading Love numbers. The geophysical approach is analogous to methods used to calculate ocean tidal loading effects. However, due to the continuous spectrum of the atmospheric pressure variations, the compution of the atmospheric loading signal must be carried out in the time domain. The major advantage of the geophysical model approach is that loading effects can be computed in a standardized way for any point on the Earth's surface. As Gipson (5) points out in the Explanatory Supplement to the IERS conventions (1996) Chapters 6 and 7 [20], the geophysical approach suffers from a number of problems including: the requirement of a global pressure data set, a minimum of 24 hours in time delay in the availability of the global pressure data set, limitations of the pressure data itself (low temporal and spatial resolution), uncertainties in the Green's functions and uncertainties in the ocean response model.

Gipson favors an empirical approach for operationally correcting geodetic data for atmospheric pressure loading. In this case, site-dependent pressure loading effects are computed by determining the fit of local pressure variations to the geodetic observations of the vertical crustal motion. This approach is likely to produce better results (than the geophysical approach) for a given site but has a number of drawbacks as well. The largest limitation, is that the regression coefficients cannot be extraploated to new site (for which no data exist). Furthermore, it is uncertain that other pressure correlated geodetic signals are not being 'absorbed' into the regression estimate. So while this approach would lower the scatter on a given geodetic time series the most, one would always be uncertain whether only atmospheric loading effects were being removed with the correlation coefficient. There is also the issue that the regression coefficients at coastal sites are time dependent due to interannual changes in the regional weather pattern (H.-P. Plag, personal communication, 2002).

Based on studies of geophysical models, [19] recommend a simplified form of the dependence of the vertical crustal displacement on pressure distribution. It involves only the instantaneous pressure at the site in question, and an average pressure over a circular region C with a 2000 km radius surrounding the site. The expression for the vertical displacement (mm) is

$$\Delta r = -0.35p - 0.55\bar{p}, \tag{1}$$

where p is the local pressure anomaly with respect to the standard pressure of 101.3 kPA (equivalent to 1013 mbar), and $\bar{p}$ the pressure anomaly within the 2000 km circular region mentioned above. Both quantities are in 10^{-1} kPA (equivalent to mbar). Note that the reference point for this displacement is the site location at standard pressure. Equation 1 permits one to estimate the seasonal displacement due to the large-scale atmospheric loading with an error of less than ± 1 mm [19].

An additional mechanism for characterizing $\bar{p}$ may be applied to Equation 1. The two-dimensional surface pressure distribution surrounding a site is described by

$$p(x, y) = A_0 + A_1 x + A_2 y + A_3 x^2 + A_4 xy + A_5 y^2, \tag{2}$$

where x and y are the local East and North distances of the point in question from the VLBI site. The pressure anomaly $\bar{p}$ may be evaluated by the simple integration

$$\bar{p} = \frac{\int\int_C dx\ dy\ p(x, y)}{\int\int_C dx\ dy} \tag{3}$$

giving

$$\bar{p} = A_0 + (A_3 + A_5) R^2/4, \tag{4}$$

where $R^2 = (x^2 + y^2)$. It remains the task of the data analyst to perform a quadratic fit to the available weather data to determine the coefficients A_{0-5}.

Corrections to geodetic data based on Equation 1 are inadequate for stations located close to the coast [24]. For coastal stations, Equation 1 must be improved by adapting the coefficient on $\bar{p}$ to reflect the fact that the pressure changes over the ocean do not contribute to the loading effects at a site (W. Rabbel personal communication, 1996). The regional coefficient would thus vary from site to site depending on the land/ocean ratio within 2000 km of the site.

In using Equation 1, one must analyze the surface pressure field within 2000 km of a geodetic site. Depending on the frequency of the geodetic observations (e.g.continuous with daily estimates of site postion) and the number of geodetic sites analyzed (the more than two hundred global VLBI sites and hundreds of global continuous GPS sites, not to mention the SLR sites exist at the writing of this document), the $\bar{p}$ could only realistically be computed using global pressure fields available through either the National Center for Environmental Prediction (NCEP) or the European Center for Medium Range Weather Forecasts (ECMWF). Once the gridded pressure fields are obtained, there is no advantange in using Equation 1 over performing the global convolution.

Equation 1 is limited in that only vertical crustal motions can be estimated. To compute the 3-dimensional loading effects, a convolution between the surface pressure and the mass loading Green's Functions must be performed. [24] computed the displacements due to atmospheric loading by performing a convolution sum between National Meteorological Center (NMC) surface pressure data and Farrell's mass loading Green's Functions. Since then, a number of analyses have used this technique to compare geodetic observations of vertical crustal motion with predicted loading effects [see 23; 25; 11]. The above analyses differ in that the vanDam comparisons use NMC surface pressure data and the Manabe analyis used Japanese Meteorological Agency surface pressure data.

The alternative to computing the global convolution sum, is to use regression coefficients as mentioned above. The vertical deformation, in this case, can then be given in terms of a local pressure anomaly. The regression coefficients can be determined in one of two ways: 1) local pressure can be fit to observed vertical deformations or 2) model derived local pressure can be fit to convolution sum predictions of vertical deformation. If the regression coefficients are based on a regression of predictions from geophysical models to model derived local pressure, these these coefficients suffer from both the uncertainty in the Green's function and the quality of the air pressure data. If on the other hand, the regression is based on local observations of pressure and crustal deformation, there is a possibility that different observing techniques would give different regression coefficients for the same location.

A few investigators [11; 10; 23; 25; 22] have attempted to calculate site dependent pressure responses by regressing local pressure changes with theoretical (derived from the convolution sum approach), VLBI or GPS height variations. For example, [23] find significant site displacements in some VLBI stations which can be modeled by a simple linear regression. Using a more extensive set of VLBI observations, [7] estimated loading coefficients partly from a global convolution and partly from VLBI observations. A comparison of these coefficients with earlier results from VLBI [10] and from GPS [25], [8] determined that previously determined coefficients can be in error by as much as 20 %.

Regression coefficients for a number of VLBI sites are available through the Conventions web page
`ftp://maia.usno.navy.mil/conv2000/chapter7/atmospheric.regr`. The regression results presented in the file were computed using 18 years of the NCEP Reanalysis Data (1 Jan. 1980 to 31 Dec. 1997). The data are 6 hourly values of surface pressure given on a 2.5°× 2.5° global grid. Vertical crustal motions at a particular site are modeled by convolving Farrell's (1972) Green's functions for a Gutenberg-Bullen A Earth model. The ocean was assumed to be inverse barometric for the calculations. The regression results (mm/mbar) are determined via a linear regression between the modeled crustal displacements and the local surface pressure determined from the NCEP data set. An inverted barometer model was used in determining the ocean's response to pressure.

There is currently no clear evidence that either the convolution sum approach or the local regression coefficients is superior in reducing the scatter in geodetic position data from all geodetic sites. However, when comparing time series (either between different techniques or the same technique at different times) some standard for the loading correction must be adopted. In 2002, the IERS Governing Board accepted a proposal for the establishment of a Special Bureau on Loading (SBL) whose charge is to promote, stimulate and coordinate work and progress towards a service providing information on Earth surface deformation due to surface mass loading. In establishing the SBL the IERS is recommending that the convention for computing atmospheric loading corrections will be based on the geophysical model approach.

Up to now, most pressure loading studies have made the assumption that the response of the ocean to changes in air pressure is inverse barometric. It is likely that the ocean responds to pressure as an inverted barometer at periods of a few days to a few years. (See e.g. [2] and [17] for a summary of observational evidence for the inverted barometer response]. A local inverted barometer response is probably appropriate for periods as short as 3 or 4 days. On the other hand, the decidedly nonequilibrium diurnal ocean tides imply that the global response is certainly not an inverted barometer at periods close to a day. Profound departures from inverted barometer at periods ranging from a day to a week have also been observed at near-equatorial latitudes by [13]. It would be difficult to find a single ocean response that is optimal for all geodetic sites. The true response of the Earth to surface pressure changes is somewhere between the inverted barometer ocean model and the no ocean Earth model. The SBL will provide estimates of loading for both of these ocean model options.

The SBL will provide in near real-time a consistent global solution data set describing at the surface deformation due to atmospheric pressure variations in reference frames relevant for direct comparison with geodetic observing techniques. To date, the SBL has determined:

1) That there is no significant difference in geodetic corrections computed using the global convolution sum approach or the spherical harmonic approach

2) Deformation time series computed for 220 sites using two years of NCEP and ECMWF data indicate that the mean difference between time series computed with the ECMWF and NCEP is less than 1 mm with an RMS of 0.5 mm. Thus, either the ECMWF global pressure fields or the NCEP global pressure fields can be used to determine deformations.

3) Green's functions from a number of Earth models (Gutenberg-Bullen A (Farrell, 1972) PREM, were chosen and compared. Deformation time series for the different Green's functions differ by only a few tenthss of a millimeter, indicating that the choice of Earth Model/Green's functions among the models tested does not affect the computations of the load responses significantly

The operational products to be made available through the SLB will allow users utilizing these corrections to account for loading in a conventional way in their operational processing of space geodetic data. For more information see: http://www.gdiv.statkart.no/sbl

10.2 Products to be delivered

A key issue is the question of which products can or should be made available and when. Initially, data sets which can be used for the validation of the products against observational time series of surface displacements, gravity changes and geocenter variations should be produced. These data sets are here termed as research data sets to distinguish them from operational products. The IERS community might be interested in loading time series for all ITRF sites. Ideally, these series should cover the total period of observations, which for VLBI dates back to around 1980.

Based on the rational that the more recent observations are likely to be of higher quality, time series for initial validation purposes should be produced for the period 1995 - present. However, e.g. the GPS coordinate time series determined by different analysis centers display seasonal signals which are not present for the total time interval. This may be due to changes in the analysis strategy and would hamper the comparison with model predictions. Therefore, a much longer time interval for the loading time series could make sense.

Concerning the temporal resolution, it appears reasonable to provide the products with a high resolution of 6 hours.

10.3 Availability of data sets

For the research data sets made available for certain time intervals relevant for the comparison with observations, atmospheric data is available for NCEP and also for ECMWF. Ocean-bottom pressure and continental hydrological are also available from models as discussed above.

For operational, near-real time computations, it is not clear whether ECMWF data will be available. According to the conditions described on the ECMWF web page (see http://www.ecmwf.int/services/data/general/Conditions.html and http://www.ecmwf.int/services/forecast/additional_products.html), the data should be freely available for research purposes. NCEP data should be possible to obtain. Currently, no ocean-bottom pressure and continental hydrology is likely to be available in near-real time.

10.4 Required contribution from the SBM

Earth model

10.5 Required contribution from SBO

Ocean bottom pressure

10.6 Required contribution from SBA

Pressure at Earth surface: Gridded data and Spherical Harmonic description

10.7 Required contribution from SBH

Reliable estimates of continental water storage variability

10.8 Required contribution from SBT

Ocean tidal models

10.9 Required contribution from SBC

To be discussed

10.10 Required contribution from SBG

To be discussed

References

[1] Blewitt, G., Lavallee, B., Clarke, P., & Nurutdinov, K., 2001. A new global mode of earth deformation: Seasonal cycle detected, *Science*, **294**, 2,342–2,345.

[2] Chelton, D. B. & Enfield, D. B., 1986. Ocean signals in tide gauge records, *J. Geophys. Res.*, **91**, 9081–9098.

[3] Dong, D., Fang, P., Bock, Y., Cheng, M. K., & Miyazaki, S., 2002. Anatomy of apparent seasonal variations from GPS-derived site position time series, *J. Geophys. Res.*, **107**, 9-1 to 9-16.

[4] Dziewonski, A. M. & Anderson, D. L., 1981. Preliminary reference Earth model, *Phys. Earth Planet. Int.*, **25**, 297–356.

[5] Farrell, W. E., 1972. Deformation of the Earth by surface loads., *Rev. Geophys. Space Phys.*, **10**, 761–797.

[6] Gipson, J., 1999. Explanatory Supplement to the Section "Atmospheric Loading" of the IERS conventions(1996), in *Explanatory Supplement to the IERS Conventions 1996 Chapters 6 and 7, 1999* edited by H. Schuh, pp. 24–25.

[7] Haas, R., Scherneck, H. G., & Schuh, H., 1997. Atmospheric loading corrections in geodetic VLBI and determination of atmospheric loading coefficients, in *Proceedings of the 12 Working Meeting on European VLBI for Geodesy and Astronomy, Honefoss, Norway, 1997*, edited by B. R. Pettersen, pp. 122–132.

[8] Haas, R., 1996. Untersuchungen zu Erddeformationsmodellen fur die Auswertung von geodatischen VLBI-Messungen, PhD-thesis, Deutsche Geodatische Kommission, Reihe C, Heft Nr. 466, 103 pp., 1996.

[9] Huang, J., van den Dool, H., & Georgakakos, K. P., 1996. Analysis of model-calculated soil moisture over the united states (1931-1993) and application to long-range temperature forecasts, *J. Clim.*, **9**, 1350–1362.

[10] MacMillan, D. S. & Gipson, J. M., 1994. Atmospheric pressure loading parameters from very long baseline interferometry observations, *J. Geophys. Res.*, **99**, 18081–18087.

[11] Manabe, S., Sato, T., Sakai, S., & Yokoyama, K., 1991. Atmospheric loading effect on VLBI observations, in *Proceedings of the AGU Chapman Conference on geodetic VLBI: Monitoring Global Change*, pp. 111–122, NOAA Tech. Rep., NOS 137 NGS 49.

[12] Mangiarotti, S., Cazenave, A., Soudarin, L., & Cretaux, J. F., 2001. Annual vertical crustal motions predicted from surface mass redistribution and observed by space geodesy, *J. Geophys. Res.*, **106**, 4277–4291.

[13] Mathers, E. L. & Woodworth, P. L., 2001. Departures from the local inverse barometer model observed in altimeter and tide gauge data and in a global barotropic numerical model, *J. Geophys. Res.*, **106**, 6957–6972.

[14] McCarthy, D. D., 1996. *IERS Conventions 1996*, IERS Technical Note 21, Observatoire de Paris, 95 pages.

[15] Oreskes, N., Shrader-Freshette, K., & Belitz, K., 1994. Verification, validation and confirmation of numerical models in the earth sciences, *Science*, **263**, 641–646.

[16] Plag, H.-P., Jüttner, H.-U., & Rautenberg, V., 1996. On the possibility of global and regional inversion of exogenic deformations for mechanical properties of the Earth's interior, *J. Geodynamics*, **21**, 287–308.

[17] Ponte, R. M., Salstein, D. A., and Rosen, R. D., 1991, Sea Level Response to Pressure Forcing in a Barotropic Numerical Model, *J. Phys. Oceanogr.*, **21**, pp. 1043–1057.

[18] Rabbel, W. & Zschau, J., 1985. Static deformations and gravity changes at the Earth's surface due to atmospheric loading, *J. Geophys.*, **56**, 81–99.

[19] Rabbel, W. & Schuh, H., 1986. The influence of atmospheric loading on VLBI experiments, *J. Geophys.*, **59**, 164–170.

[20] Schuh, H., 1999. Explanatory Supplement to the IERS Conventions (1996) Chapters 6 and 7, *Report 71, presented by the IAG/ETC Working Group 6 on 'Solid Earth Tides in Space Geodetic Techniques'*, 29 pp.

[21] Shmakin, A. B. & Milly, P. C. D., 1999. Evaluation of interannual variations in runoff from large river basins (abstract), in *IUGG XXII General Assembly*, p. 36.

[22] Sun, H. P., Ducarme, B., & Dehant, V., 1995. Effect of the atmospheric pressure on surface displacements, *J. Geodesy*, **70**, 131–139.

[23] van Dam, T. M. & Herring, T. A., 1994. Detection of atmospheric pressure loading using very long baseline interferometry measurements, *J. Geophys. Res.*, **99**, 4505–4517.

[24] van Dam, T. M. & Wahr, J. M., 1987. Displacements of the Earth's surface due to atmospheric loading: Effects on gravity and baseline measurements, *J. Geophys. Res.*, **92**, 1281–1286.

[25] van Dam, T. M., Blewitt, G., & Heflin, M. B., 1994. Atmospheric pressure loading effects on Global Positioning System coordinate determinations, *J. Geophys. Res.*, **99**, 23939–23950.

[van den Dool] et al.van den Dool. H. et al., 1997. ..., *J. Geophys. Res.*, **102**, 22013–22024.