GGFC Special Bureau for Loading: Current Status and Plans

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Abstract: The Earth's surface is perpetually being displaced due to temporally varying atmospheric, oceanic and continental water mass surface loads. These non-geodynamic signals are of substantial magnitude that they contribute significantly to the scatter in geodetic observations of crustal motion. In February, 2002, the International Earth Rotation Service (IERS) established a Special Bureau of Loading (SBL) whose primary charge is to provide consistent and valid estimates of surface mass loading effects to the IERS community for the purpose of correcting geodetic time series.

Here we outline the primary principles involved in modelling the surface displacements and gravity changes induced by surface mass loading including the basic theory, the Earth model and the surface load data. We then identify a list of operational issues, including product validation, that need to be addressed by the SBL before products can be provided to the community.

Finally, we outline areas for future research to further improve the loading estimates. We conclude by formulating a recommendation on the best procedure for including loading corrections into geodetic data. Success of the SBL will depend on our ability to efficiently provide consistent and reliable estimates of surface mass loading effects. It is imperative that we work closely with the existing Global Geophysical Fluids Center (GGFC) Special Bureaus and with the community to as much as possible to verify the products.

1 Introduction

Temporal variations in the geographic distribution of surface masses load the Earth and deform its surface. Surface displacements due to atmospheric mass circulation are dominated by the effects of synoptic scale systems (1000–2000 km wavelength) with periods of approximately two weeks. Peak-to-peak vertical displacements of 10 to 20 mm are common at mid-latitudes (Figure 1) (van Dam and Wahr, 1987; Manabe et al., 1991; Rabbel and Zschau, 1985). The effects are larger at higher latitudes due to the larger amplitude pressure systems found there.

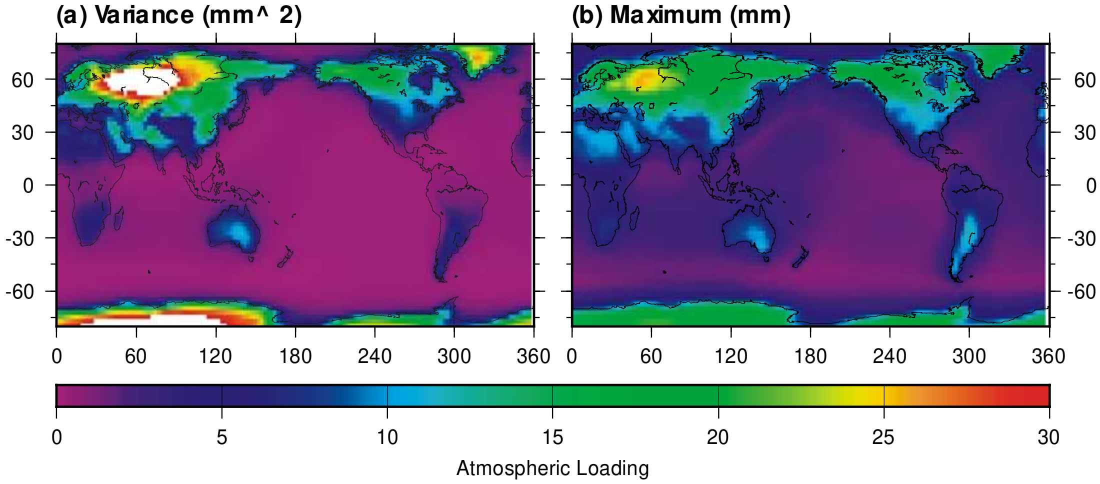

Fig. 1 Maximum range and variance in vertical crustal displacement during 1994-1998 (mm) due to changes in atmospheric surface pressure. (Figure provided courtesy of S. Desai.)

While surface displacements are largest for pressure systems with periods of approximately two weeks, annual signals are also significant having amplitudes between 0.5 and 3 mm. At annual periods, variations in continental water storage also become important. The modeled vertical displacements have root-mean-square values as large as 8 mm, with ranges of up to 30 mm (van Dam et al., 2001) (Figure 2).

Tidal and non-tidal motions of oceanic mass also contribute to the deformation spectrum at points on the Earth's surface. Variations in bottom pressure driven by uncompensated changes in sea surface height can induce vertical deformations at coastal sites of up to 20 mm with periods of approximately one month (van Dam et al., 1997; S. Desai, personal communication).

For all of these loading signals, the effects in the horizontal are approximately one-third the amplitude of those in the vertical.

Loading effects caused by the redistribution of surface masses have been observed in high-precision geodetic data for some time now (See for example, van Dam and Herring, 1994; van Dam et al., 1994; MacMillan and Gipson, 1994; van Dam et al., 2001). As these data are primarily being interpreted in terms of geodynamic processes (plate tectonics, post-glacial rebound, sea level rise, etc.), it is becoming necessary to remove loading effects from the data. Currently, however, there is no clear concensus on how this should be done.

On 1 January 1998, the International Earth Rotation Service (IERS) estab-

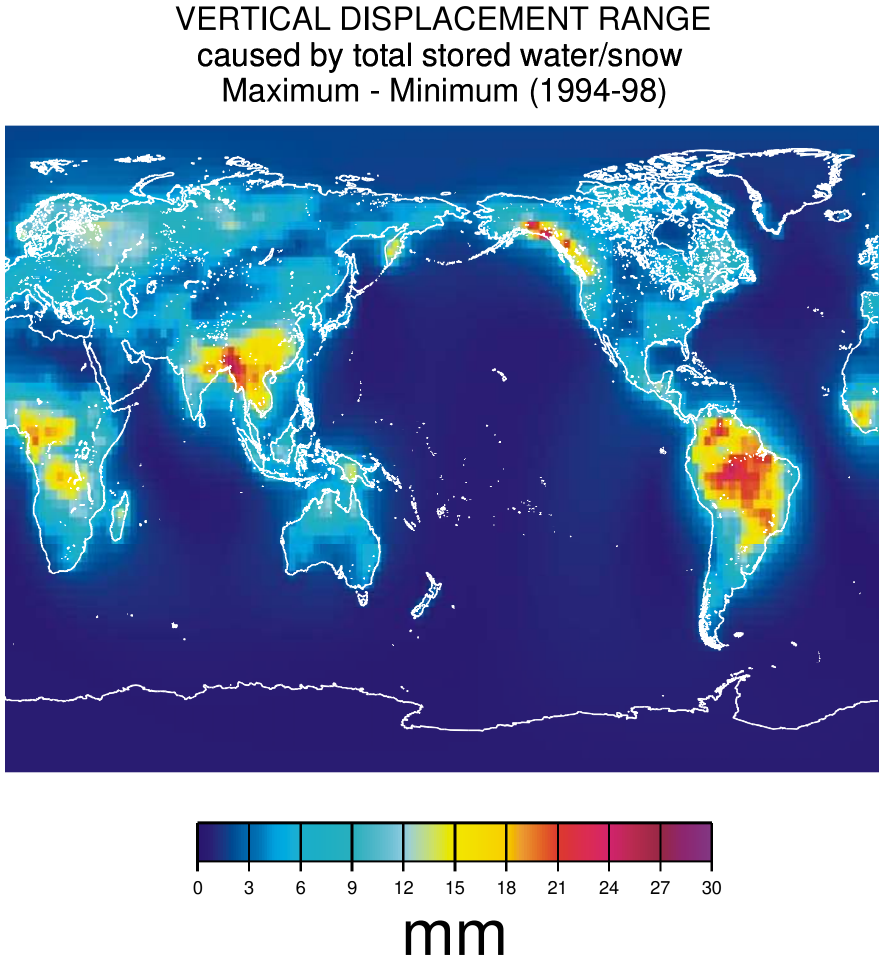
VERTICAL DISPLACEMENT RANGE
caused by total stored water/snow
Maximum - Minimum (1994-98)

Fig. 2 Maximum range in vertical crustal displacement during 1994–1998 (mm) due to changes in total continental water storage.

lished 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 <[1]>). 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 fact is reflected in the IERS Conventions (McCarthy, 1996), where standard models for solid Earth tides and ocean loading are discussed while no standard procedure is recommended for the case of other surface loading effects.

In order to foster the development of consistent models for predicting loading effects, 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 development, model compilations and studies of relevant observations.

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.

Table 1 Current Membership of the SBL. (Note 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)
Hans-Peter Plag	Norwegian Mapping Authority (NMA), Norway (co-chair)
Geoffrey Blewitt	University of Nevada, Reno, U.S.A.
Jean-Paul Boy	Goddard Space Flight Center, U.S.A.
Olivier Francis	European Center for Geodynamics and Seismology (ECGS), Luxembourg
Pascal Gegout	Ecole et Observatoire des Sciences de la Terre, Strasbourg, France
Halfdan Pascal Kierulf	Norwegian Mapping Authority (NMA), Norway
Tadahiro Sato	National Astronomical Observatory, Mizusawa, Japan
Hans-Georg Scherneck	Onsala Space Observatory, Sweden
John Wahr	University of Colorado, Boulder, U.S.A.

On 1 February 2002, the SBL (see <[2]>) 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: 1) the theory of Earth deformation and Earth models, 2) observations of surface loads, 3) computation of tidal and non-tidal loading effects, 4) and space-geodetic and gravimetric observations. The team also includes the 7 chairs of the existing SBs. These chairs are ex-officio members of the SBL and par-

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[1] http://bowie.gsfc.nasa.gov/ggfc/

[2] http://www.gdiv.statkart.no/sbl/

ticipate in the SBL to insure close cooperation between their SBs and the SBL. Moreover, the combined membership provides 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 precision of the space-geodetic and gravimetric observing 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 surface loading data of surface. Consequently, a scientific agenda has been established to perform the research necessary for the improvement of the models and algorithms, in parallel with an operational agenda which is directed towards establishing a service which provides validated loading products to IERS community.

Given that the most pressing objective of the SBL is to begin distributing reliable products, we will primarily report on the status of the operational agenda. We will report on the discussions held at the first SBL Workshop (Luxembourg, March 2002) and the 2002 IERS GGFC Workshop (Munich, November, 2002). The ‘Action Items’ and ‘Recomendations’ outlined in this document are the direct outcome of these workshops.

2 Overview of the basic components required for determining load responses

Figure 3 sketches the main elements required in the computation of loading predictions. These elements include: (1) an Earth model, which determines the geometry, with specific mechanical properties and, if necessary, the rheology, and (2) a mathematical model for the surface load including the boundary conditions at the Earth’s surface and the extension of the load. Selected parts of continuum mechanics (e.g. elastic theory, or linear visco-elasticity) can be used to solve the boundary value problem to obtain the systems response to a unit load. For the problem of Earth deformation, the system’s response is best described by Load Love Numbers (LLN) which can be used to compute the Green’s functions of the boundary problem.

For the actual computation of the loading effects, surface load data are required for all relevant loads. These loads are then convolved with the Earth’s response (either in the space or the wave number domain) to determine the loading effects (e.g. surface displacements, gravity variations, and geocenter displacements).

However, the Earth model and load data, as well as the theory selected to compute the Earth’s response may not be adequate for describing the loading problem at the precision required for geodetic data analysis. For example, it is well known that the surface load data themselves can be inaccurate or incomplete. Therefore, a careful validation of the predictions both via model intercomparisons, as well as via comparisons to observations is required. After successful validation, operational processing can be set up to produce conventional products in near-real time. It is worth noting, that given the present state-of-the-art with respect to the theory of loading predictions, the quality of the surface load data, and the processing of space geodetic data, the need for additional improvements to the components of determining the loading predictions for research purposes will remain for a long time to come.

In the following three sections, we briefly describe the current state of the components required for determining the load response of the Earth, namely (1) the status of Earth models, (2) the existing surface load data, and (3) the numerical procedures for performing the computations themselves.

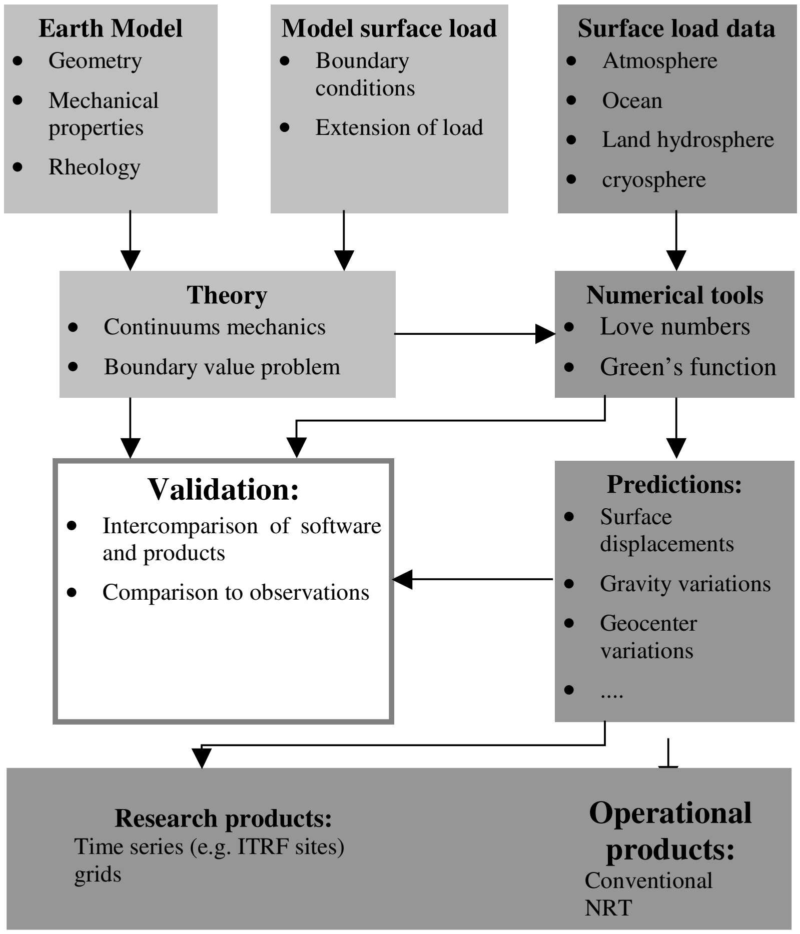

Fig. 3 Sketch of the scientific and operational loading predictions

3 Earth models

Earth models can be characterised by their geometry (i.e. spherical or elliptical, with or without undulations of the surface and inner boundaries), the space-dependency of their mechanical properties (i.e. the functions for density, bulk modulus, and shear modulus) and their rheology (i.e. the frequency dependency of the shear modulus). The most widely used models are Spherical Non-Rotating Elastic Isotropic (SNREI) models, assumed to be hydrostatically pre-stressed. 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) (Dziewonski and Anderson, 1981) appears to be the natural choice (the LLNs given by Farrell (1972), which are based on the Gutenburg-Bullen A Earth model, are also still widely in use). Using the PREM poses at least three problems which leaves 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.

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 pre-stress) the Green's functions depend explicitly on the position of the load and the observer on the Earth, complicating the computation of the response considerably. For visco-elastic models, the Green's functions additionally become time-dependent.

SNREI models are most likely not sufficient to model displacements due to surface loads with an accuracy of 1 mm or better. In the future, issues such as anisotropy, lateral heterogeneity, visco-elasticity, and non-hydrostatic prestress will need to be considered.

4 Surface loads

The primary charge of the SBL is to provide reliable estimates of loading effects due to the temporal variability of the various surface loads. Thus, the SBL will need to obtain validated surface mass fields. As the IERS GGFC has within its umbrella, Special Bureaus for 1) Oceans, 2) Atmospheres, 3) Tides, and 4) Hydrology, the SBL will rely on these components of the GGFC to validate and provide access to the appropriate mass loading data sets. In this section, we outline the surface mass data currently available through the respective Special Bureaus.

The SBL should request from other SBs the input needed in terms of observations and models. This might also include the Earth models required for loading calculations.

Action item SBL-1: *The requirements of the SBL with respect to the other SBs should be clarified and the necessary input from the different SBs specified.*

4.1 Contributions from the SBs

4.1.1 Atmosphere

The SB Atmosphere, previously 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 a liaison with IERS and the wider scientific community. AER calculates the SBA Atmospheric Angular Momentum parameters and receives data from other meteorological centres.

Ongoing efforts of the SBA focus on the combination of atmospheric data sets, and archiving 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. Participating Centers in the SBA are 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). What is important for the SBL is that the SBA uses surface atmospheric pressure to compute its products. In fact, the SBA converts the 6-hourly NCEP surface pressure into a spherical representation with and without modification for the inverted barometer ocean (harmonics for various truncations are available starting in 1975). The SBL can thus obtain the surface atmospheric pressure data as well as the spherical harmonic representation of the field from the SBA for some of the pressure fields.

4.1.2 Hydrology

Within the GGFC, the Special Bureau for Hydrology (SBH) is responsible for coordinating research activities related to continental water variations. The main goals of the SBH 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. The SBH is also responsible for developing working relationships with hydrological modelling groups, to insure that geodetically pertinent quantities are also computed during model runs. The current focus of the SBH is on data sets and model results which provide global estimates of water mass redistribution and to provide these sets in formats that will allow useful comparisons with geodetic observations, e.g. 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 System I (CDAS-1): monthly soil moisture and snow for the period 1993 – 1998 on a 1° x 1° grid.

It is expected that the 1° x 1° degree data set will be available soon for the full NCEP reanalysis period (1948 – present) with a temporal resolution of 1 day. For selected periods, the data will be made available at six hourly sampling.

The NASA NSIPP hydrological model is a coupled model developed for prediction purposes and will provide data for the period 2010–2059.

Two additional global models exist: Huang et al. (1996), which provide monthly results for 1979–1993 and Shmakin and Milly (1999), which provide groundwater, soil moisture and snow for the period 1978–1998.

There are large uncertainties in all available hydrological models. Information on the effect of these uncertainties on predicted loading signals will need to be transmitted to the SBL user community.

4.1.3 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 GGFC with three goals: (1) maintain liaisons with ocean modelling 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.

The SBL will initially rely on the SBO to provide reliable estimates of ocean bottom pressure. Two operational models currently exist: 1) Mercator, which plans to have an operational global ocean model available in 2003. The Phase 3 MERCATOR prototype planned for January 2003 will include real-time routine modelling of the global ocean at medium resolution (1/4 degrees), assimilating altimetry and in-situ data; and 2) ECCO (Estimating the Circulation and Climate of the Ocean), 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 ECCO 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° resolution (telescoping to 0.3 degree meridionally in the tropics) and are produced by an ocean model that assimilates altimetry and in situ observations.

ECCO is planning to implement regular updates to the model at intervals no less than monthly. The bottom pressure data is available on request.

Ocean general circulation models used to predict ocean bottom pressure, use the 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.) The practical consequence of the Boussinesq approximation for loading predictions is that an artificial trend in the load and subsequently the load effects exists.

The ocean bottom pressure fields could be corrected by removing a trend from the time series for each grid unit. Unfortunately, this will also remove any real trend that might be associated, for example, with an increase in mass in the oceans, and so this solution is not acceptable. We will need to continue to investigate the optimum method for correcting the data for model induced trends.

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. We currently do no understand the spatial/temporal errors of the bottom pressure fields. The data (observations of bottom pressure over a large spatial wavelength at a high degree of temporal and spatial resolution) do not exist for evaluating the reliability of the models. Ocean modellers might benefit from feed-back from the SBL.

4.2 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. The 2-D function describing the tides is discontinuous at the coastlines. This generates instabilities in the loading computation in coastal regions (so-called Gibbs's effect). It is therefore recommended that the convolution be carried out in the space domain whenever 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/Poseidon 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.

Software available for computing of ocean tidal loading coefficients includes (but is not limited to):

- O. Francis: Research type program, not publicly distributed; large number of models
- D. Agnew: Publicly distributed; good representation of coasts; large number of models, including local ones; to be set up on the web to provide loading coefficients for arbitrary stations
- H.-G. Scherneck: Web based; Gutenberg-Bullen A Earth model; Coastline is treated very well
- Matsumuto: Available by ftp; primarily for Japanese islands
- ICET: Only solutions for the Schwiderski ocean tide model.

As ocean tidal loading represents a surface load, the responsibility of computing loading effects due to ocean loading should by definition fall under the purview of the SBL. However, unlike atmospheric pressure, continental water storage, and ocean bottom pressure, different investigators have developed and provided ocean tidal loading corrections to the geodetic community for years. As such, the SBL has no interest in duplicating the excellent efforts of so many individuals. Instead, the SBL will try to find a way to validate the different products that are currently available. Once validation has been performed the SBL will link to the appropriate web pages. At this point, it is not clear how validation of the loading coefficients can be achieved.

4.3 Status of atmospheric surface loads and issues to be addressed

Initially, the SBL will operationally generate 3-d deformations due to variations in atmospheric pressure variations. (Once the technique and Earth models have been validated for atmospheric pressure data sets, other surface loads will be added.) Because the ocean response to pressure is still not completely understood, deformations calculated with and without an inverted barometer ocean model will be supplied. Historic loading time series (going back to 1980) for all IERS sites will be generated first. Global gridded results as well as time series will be generated once the SBL becomes operational.

Initially, there will be two surface pressure data sets that will be considered by the SBL: the ECMWF surface pressure and the NCEP surface pressure data sets. The ECMWF and the NCEP data are provided as 256 and 126 quasi-regular Gaussian Grids, respectively. Both data sets can also be downloaded as 2.5° x 2.5° global grids. The latency period for obtaining both data sets is between 1 and 2 days.

In this section, we will report on the atmospheric load data issues that remain to be addressed. There are primarily three topics that need to be investigated: (1) model accuracy, (2) required spatial sampling for geodetic observations and (3) required temporal sampling.

4.3.1 Accuracy

The accuracy of SBL products will be limited by (among other things) the accuracy of the surface load data. Without independent global observations of the parameters of interest, the accuracy of the data sets is impossible to determine. On the other hand, we can investigate the differences in the data sets. This method will not reveal errors that would be common to both datasets. However, it does provide some estimate of the accuracy of the loading data.

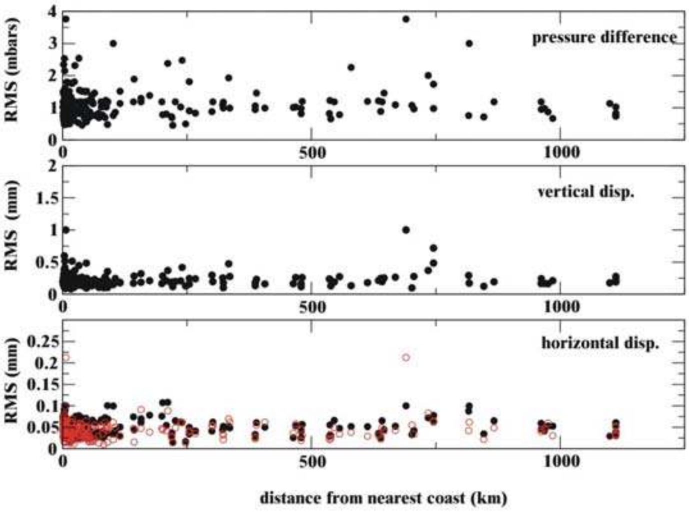

Fig. 4 RMS differences between deformations predicted using ECMWF and NCEP pressure data

A question of primary interest to the SBL is, are the differences in the deformations determined using the NCEP or the ECMWF data set, significantly larger than the current precision of the geodetic observations?

To investigate this question, predicted 3-d deformations for 225 IERS geodetic sites were determined using three years of NCEP and ECMWF 2.5° x 2.5° global surface pressure data sets. Deformations were determined for an Earth model with an inverted barometer ocean. The NCEP and ECMWF time series for each site were differenced and the RMS of the differences was determined. The results are presented in Figure 4. The results indicate that the RMS of the pressure difference is always less than 4 hPa. The RMS of the difference between the radial deformations predicted using the two surface pressure data sets is always less than 0.75 mm. On the other hand, maximum differences can be as large as 14 hPa and 3 mm in the local pressure and the radial crustal motion respectively. These differences are significant given the current precision of geodetic observations.

As we cannot determine which data set is more reliable, the SBL will produce loading effects for both the NCEP and ECMWF surface pressure data sets. The difference between the results will be reported as an error on the products.

As stated earlier, trends exist in the ocean bottom pressure and the continental water storage data. Trends may also exist in the air pressure data sets. The trends in these data affect the long term accuracy of the models. As such we propose:

Action Item SBL-2: *Study mass conservation of ocean and continental hydrosphere models.*

Action Item SBL-3: *Investigate the spatial distribution for the trend in air pressure.*

4.3.2 Spatial Resolution

The spatial resolution of the surface loads and the predicted loading should be sufficient to allow for an interpolation of the loading signals to any location on the 1 mm level or better. With respect to the spatial resolution of the surface pressure field for atmospheric loading, the following recommendation is proposed:

Recommendation 1: *The spatial resolution of the atmospheric pressure field should be 2° x 2°.*

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

Action Item SBL-4: *Investigate the effect of topography on displacements.*

4.3.3 Temporal Resolution

Concerning atmospheric pressure variations, the temporal resolution of the products will be limited by the temporal resolution of the surface pressure data themselves (currently 6 hours). In most instances, this resolution is sufficient for geodetic investigations where daily or even weekly averages of position are desired.

The S_1 thermal tide is a large signal in atmospheric pressure but is not well represented in the atmospheric analyses. Recent studies indicate that the amplitude of the S_1 is between 0.67 and 0.71 mbars (Dai and Wang, 1999; van den Dool et al., 1997) with a spatial dependence of:

$$P(\phi, t) = P_{max} * \cos^3(\phi) * \sin(t + 12^\circ)$$

P_{max} is the maximum amplitude, ϕ is the latitude and the longitudinal dependence of the function (the argument of the sine) depends on the time of the day (i.e. the position of the sun). Modelling the spatial distribution of the pressure with this function on a solid earth (no oceans were applied to maximize the effect of the load), induces a diurnal deformation at the equator of -0.8 mm. (The deformation would be significantly smaller in the case of an inverted barometer ocean Earth model.) The deformation fall's off quickly away from the equator (to approximately 0.2 mm at 40 degrees for the solid Earth model). For daily averages of the station position, this diurnal signal would average to zero.

The amplitude of the S_2 atmospheric tide is about twice the amplitude of the S_1 tide. The loading effect is proportionately larger as well, having a peak-to-peak amplitude of approximately 3 mm at the equator where it is a maximum. The deformation falls to 1.5 mm peak-to-peak at 40 degrees either side of the equator.

The fraction of the geodetic community which might be interested in sub-daily estimates of pressure loading would be those groups interpreting the GPS data in terms of water vapour changes. For these data: $PWV = 0.04 X \delta h$ and the error in the PWV estimate would be approximately 0.04 mm for a load of 1 mm. Thus, it seems unlikely that we would have to consider improving the models of the S_1 and S_2 atmospheric tides in the atmospheric pressure data sets.

On the other hand, if the community states a need for sub-daily corrections, we will need to improve the model of the S_1 and S_2 atmospheric tides in the surface pressure data, where it is currently poorly modelled (R. Ray, personal communication).

It is imperative that we understand the temporal characteristics of all surface loading data sets. For example, it would be unwise to distribute products with a data sampling rate higher than the time variability of the signal of interest. In this case, erroneous corrections might be transmitted to the community. With this in mind, we propose the following action item:

Action item SBL-5: *Investigate the space-time spectrum for all surface load data.*

4.3.4 Reference levels for surface loads

Another issue in terms of accuracy, 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. However, we emphasise that the corrections should not change the ITRF coordinates. This will require a very special selection of the reference levels.

We propose the following two recommendations:

Recommendation 2: *Biases in trends due to model insufficiencies need to be removed from surface loads derived from models.*

Recommendation 3: *The reference level for surface loads should be a space-dependent and should be computed long period average.*

5 Model Intercomparison

5.1 Love numbers

Generally, differences in the LLN due to different Earth models are assumed to be on the order of 1–1.5 percent. However, comparing the LLNs for different Earth models, much larger differences are found. Thus, Farrell's (1972) LLN's for vertical displacement computed for the Gutenberg-Bullen A Earth model differ by up to 10 % from LLNs for the PREM. Moreover, LLNs computed for the PREM by different groups show differences of the order of 1 % and more (see Fig. 5). The PREM LLNs differ due to the way the equations of motion are integrated by the different investigators and the applica-

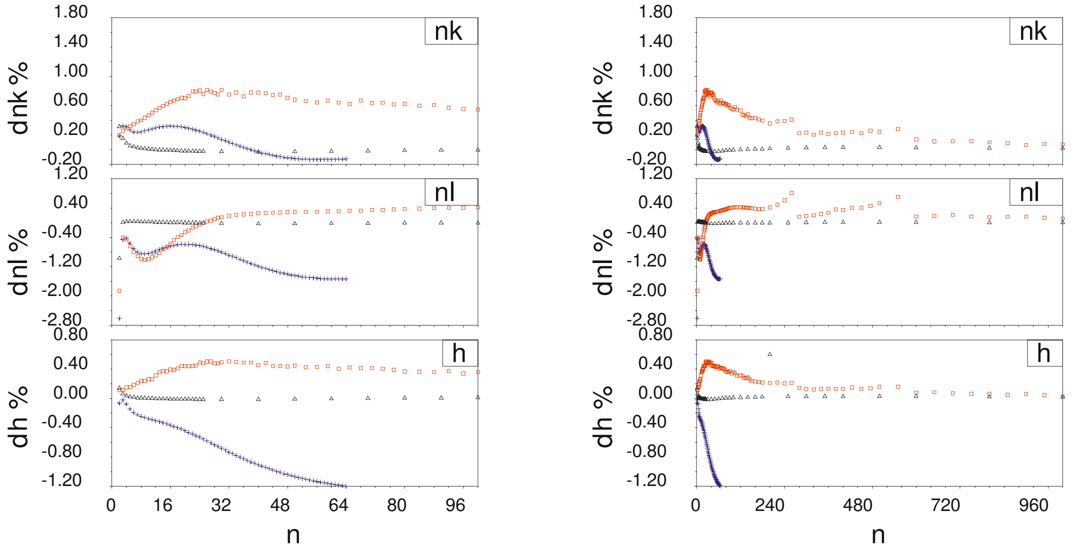

Fig. 5 Differences in LLNs for PREM computed by three different programs. The differences are given in percentage of the LLN (e.g., $dh_n = (h1_n - h2_n)/h1_n * 100$). Reference are the LLNs computed by P. Gegout. Red squares correspond to results obtained by H.-P. Plag, blue crosses to M. Tamisea, and black triangles to O. Francis. O. Francis and P. Gegout agree very well except for $n = 2$. The other two results show considerable disagreements for certain degrees.

tion of different boundary conditions.

A comparison of radial deformations determined for 4 different sets of Green's functions was performed. The Green's functions were derived from LLNs from 4 different Earth models including: 1) Gutenburg-Bullen A Earth Model (Farrell, 1972), 2) PREM (J. Zschau, personal communication), 3) PREM (P. Gegout, personal communication), and 4) PREM (H.-P. Plag, personal communication). Differences in the radial deformations determined for all the above Earth models were always less than 0.04 mm, indicating that the choice of LLNs (as long as they are for an SNREI model) will not have a significant influence on the estimated loading effects.

5.2 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 functions 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.

Clearly, the LLN approach is desired because of its computational speed. However, a potential problem arises when this approach is used for an Earth with an inverted barometer ocean. In this case, there is a discontinuity in the pressure anomaly at all the continental boundaries as the pressure anomaly

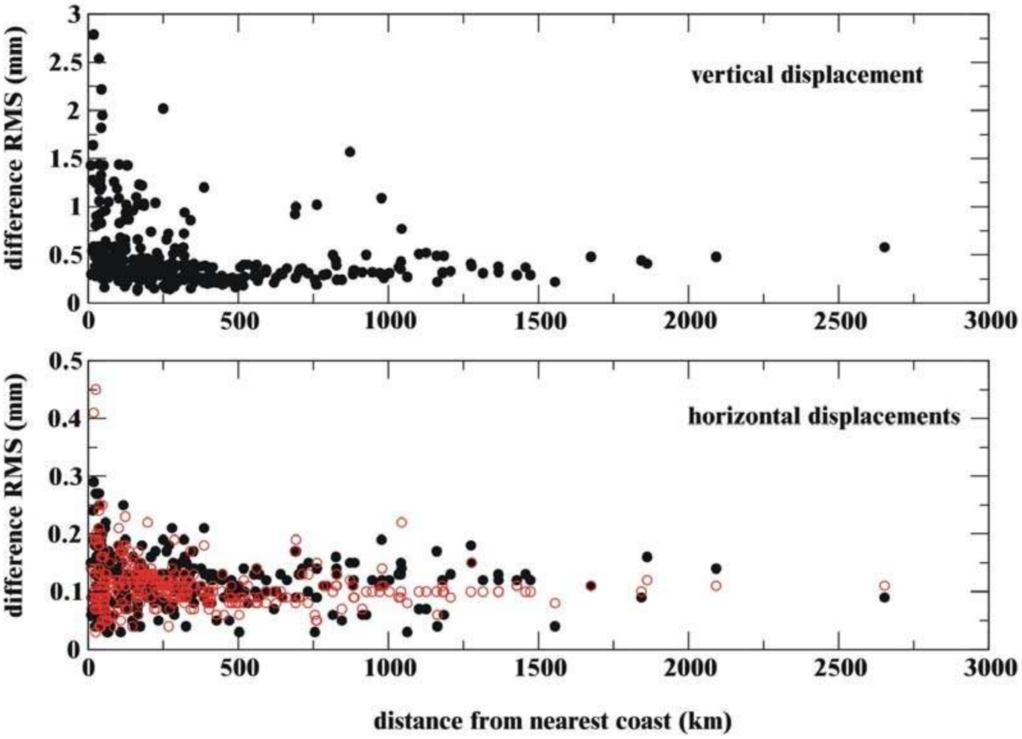

Fig. 6 A comparison of deformations obtained using the LLR approach and the Green's function approach. The RMS differences for the 360 sites are plotted as a function of distance from the nearest coastline.

goes from ambient over the continents to near zero over the oceans.

A comparison of 3-dimensional deformations determined using the spherical harmonic approach and the Green's function approach has been performed to determine what, if any, is the loss in precision from using the LLN approach versus the Green's function approach (see Figure 6). The time series from 360 IERS sites were compared using 11 years of NCEP reanalysis data. RMS differences in the estimate of the vertical can be as high as 3 mm at coastal sites. However for most sites the RMS of the differences is less than 1 mm. Individual epoch differences for a single site can be as high as 11 mm.

If the near-real time constraint can be relaxed for the SBL products, the Green's function calculation would be sufficient. However, it is more likely that the SBL will produce two products, (1) a rapid product that uses the LLN approach, and (2) a precise product that uses the Green's function approach. For the products from a solid Earth, i.e. no oceans, the LLN approach would be identical to the Green's function approach.

In computing the load signals, special attention must be given to the reference frame (Blewitt et al., 2001). 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 also needs to be considered. Currently, only two simple models 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 sufficient 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.

6 Validation of Prediction Models

The question of how to validate the model predictions is not straight forward to answer. It has to be clear that validation does not mean verification. Following Oreskes et al. (1994) we emphasise 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, intercomparisons 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, etc.) at a number of different sites. 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.

Action Item SBL-6: *Compute data sets for a reasonable number of sites and time interval for external validation through comparison with observations.*

7 Scientific Agenda for Improvements of Loading Predictions

There are many areas where model improvements might improve our estimates of the surface loading effects. Development of these models fall under the SBL's Scientific Agenda. We outline a few areas for future research here.

- Improvements of the theory
  - Height dependent load
  - Surface undulations
  - lateral heterogeneities
- Towards a 3-d Earth model
  - elastic-viscoelastic,
  - 3-d from seismology
- Surface Mass Loads
  - Atmospheric loading
    - inverted barometer/ocean response
  - Hydrological loads
    - How to improve the models?
  - Non-tidal ocean loading
    - Combined models for complete atmospheric forcing
    - Combined circulation/tidal models
  - Tidal loading
    - Validation of models made available through the SBL umbrella

8 Towards a Conventional Treatment of Loading

The IERS conventions currently do not provide a recommendation for the treatment of atmospheric pressure loading effects. We provide here a draft of a procedure which is based on the geophysical model approach for correcting geodetic data for atmospheric pressure loading.

8.1 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. For example, 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.

Other surface loads due to changes in snow and ice cover, soil moisture and groundwater, as well as ocean-bottom pressure also contribute to surface displacements. For example, at seasonal time scales, it is expected that the contribution of hydrological loads to surface displacements exceeds the one from air pressure (Blewitt et al., 2001). However, while the atmospheric load is fairly well known from global air pressure data sets, no sufficient models for ocean bottom pressure, snow and soil moisture exists at this time. Therefore, in the following, focus is on atmospheric loading. However, the discussion applies also to any other surface load.

Theoretical studies by Rabbel and Zschau (1985), Rabbel and Schuh (1986), van Dam and Wahr (1987), and Manabe et al. (1991) 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 (Mangarotti et al., 2001; Dong et al., 2002). 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 500 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.

Two basic methods for computing atmospheric loading corrections to geodetic data have been applied so far: 1) using geophysical models or simple approximations derived from these models and 2) using empirical models based on site-dependent data.

The standard geophysical model approach is based on the estimation of atmospheric loading effects (vertical and horizontal deformations, gravity, tilt and strain) via the convolution of Green's functions with a global surface pressure field. 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 computation 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 more or less instantaneously. The geophysical approach currently 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.

In the empirical approach, 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. 1.) Geodetic observations have to be available for a certain period of time before a reliable regression coefficient can be determined; this period of time may be as large as several years. 2.) The regression coefficients cannot be extrapolated to a new site (for which no data exist); 3.) The regression coefficient has been observed to change with time and with observing technique; 4.) Regression coefficients at coastal sites are time dependent due to interannual changes in the regional weather pattern (H.-P. Plag, personal communication, 2002); 5.) The regression coefficient can only be used for vertical crustal motions; and 6.) It is uncertain that other pressure correlated geodetic signals are not being 'absorbed' into the regression coefficient determination. 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.

In a hybrid method, regression coefficients determined from a geophysical model instead of geodetic observations could be used to operationally correct observed vertical position determinations from local air pressure alone. The vertical deformation caused by the change in pressure, in this case, can then be given in terms of a local pressure anomaly. The regression coefficients can be determined by fitting local pressure to the vertical deformation predicted by the geophysical model. Regression coefficients determined in this manner would still suffer from both the uncertainty in the Green's function and the quality of the air pressure data.

In February 2002, the Special Bureau on Loading (SBL) was established within the IERS. The charge of the SBL is to promote, stimulate and coordinate work and progress towards a service providing information on Earth surface deformation due to surface mass loading, including the atmosphere, ocean and continental hydrosphere. In establishing the SBL the IERS is recommending that the convention for computing atmospheric loading corrections will be based on the geophysical model approach.

At the 2002 IERS Meeting in Munich, the IERS adopted the convention that corrections for surface load variations including the atmosphere should be determined using the geophysical model approach. Further, these corrections should be obtained from the IERS SBL. The point of this recommendation is to insure that comparisons of geodetic time series between different observing techniques or within the same technique but at different times and locations have a consistent atmospheric pressure loading (and later also non-tidal ocean and continental hydrological loading) correction applied.

The ultimate goal of the SBL is to provide in near real-time a consistent global solution data set describing at the surface deformation due to all surface loads (including atmospheric pressure variations) in reference frames relevant for direct comparison with geodetic observing techniques. The SBL will provide global gridded solutions of 3-d displacements and time series of displacements for all IERS sites. Time series will be determined from 1985 to the present. Displacements will be determined for both the European Center for Medium Range Weather Forecasts and the National Center for Environmental Prediction operational pressure data sets for the inverted barometer and the non-inverted barometer ocean models. For more information see <[1]>.

Regression coefficients based on a geophysical model are available for a number of VLBI sites through the SBL web page and the IERS convention's web page <[2]>. The regression coefficients 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 modelled 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 modelled 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.

For more information on atmospheric pressure loading and geodetic time series, see the references listed in the extended bibliography.

8.2 SBL 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 will be produced. These data sets are here termed 'research' data sets to distinguish them from the 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 observation, which for VLBI dates back to around 1980.

Based on the rational that more recent observations are likely to be of higher quality, time series for initial validation purposes should be produced for the period 1995 to the present. However, GPS coordinate time series generated

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[1] http://www.gdiv.statkart.no/sbl.

[2] ftp://maia.usno.navy.mil/conv2000/chapter7/atmospheric.regr

by different analysis centers display seasonal signals which are not present for the total time interval, indicating that changes in an analysis strategy would hamper the comparison with model predictions. Therefore, a much longer time interval for the loading time series might be more appropriate.

The temporal resolution of the products will be determined by the temporal resolution of the loading data. In the case of atmospheric pressure loading, this is 6 hours.

9 Conclusion

We have outlined the issues related to operationally producing surface load effects for use in correcting geodetic data. The primary focus of the SBL at this point, is to address the issues necessary to become operational with reliable products as soon as possible. Once we become somewhat operational, the SBL will focus on the scientific agenda, i.e. the issues that will improve our estimates of the loading effects.

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