GLOBAL OCEAN TIDES THROUGH ASSIMILATION OF OCEANOGRAPHIC AND ALTIMETER SATELLITE DATA IN A HYDRODYNAMIC MODEL

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We have developed a new hydrodynamic model and a method for assimilating in situ and altimeter data into the model. We have produced two sets of tidal solutions:

- **FES94.1, purely hydrodynamic,**
- **an improved product obtained by assimilating T/P derived solutions into the hydrodynamic solution.**

For the Jason 1-cm challenge, it is important to assess the scope for improving tidal corrections. More improvements are expected, from reprocessing T/P data combined with enhanced assimilation methods, and determining the long-period tidal components.

Use of assimilation techniques with a hydrodynamic model

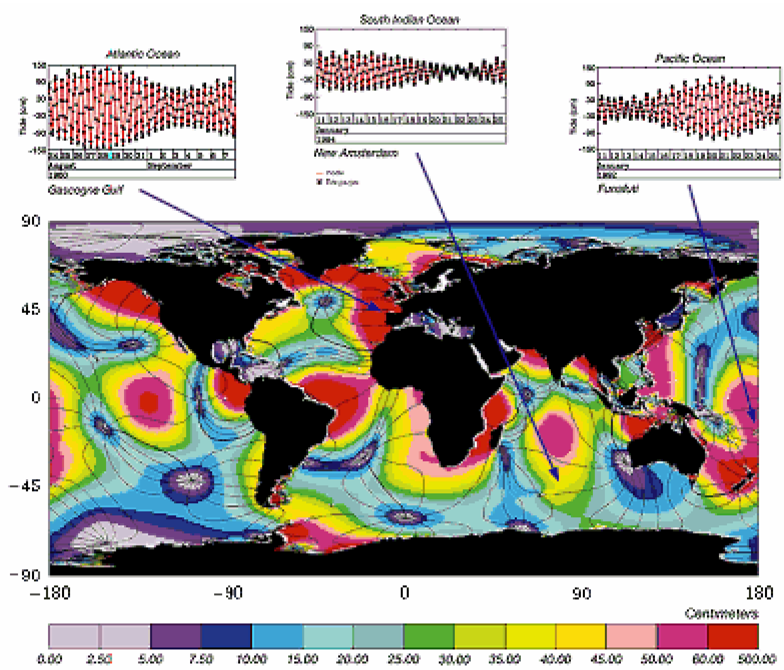
About the hydrodynamic model

The hydrodynamic model was finished in 1993, and the results published by Le Provost et al [1994]. These solutions (called FES94.1, for Finite Element Solutions) were produced with the aim of providing the science community with altimetry-independent predictions of the tides under the satellite tracks. The model is global, from the Arctic to Antarctica, including the under-ice shelf areas of the Weddell Sea and Ross Sea, and most of the shallow seas. Eight components were simulated: M2, S2, N2, K2, 2N2, K1, O1, Q1. Five secondary components were deduced by admittance from these eight major ones: Mu2, Nu2, L2, T2 and P1. The resolution of the model varies spatially with a finite element grid refined over shelves and along the coasts, up to 10 km [see figure 1 of Le Provost et al, 1994]. This high resolution concentrated over the major topographic features allows the model to capture local characteristics of tidal waves unresolved in conventional coarse hydrodynamical ocean tide models: see as illustrations Le Provost and Lyard [1991], for the Kerguelen Plateau, and Genco et al [1994], for the Weddell Sea and Falklands. We projected the solutions onto a 0.5° x 0.5° grid, for distribution via our anonymous ftp site (meolelc.hmg.inpg.fr).

FES94.1 and FES95.2 tide models

The accuracy of FES94.1 has been estimated by reference to a standard ground truth data set, and compared with the new solutions derived from the first year of TOPEX/POSEIDON [see Le Provost et al, 1995]. Although the accuracy of these hydrodynamic solutions is clearly better than previous solutions available in the literature, comparison of FES94.1 to the Schrama and Ray [1994] T/P solutions revealed that the former contained large scale errors, of up to around 6 cm in amplitude for M2 [see Figure 3, Le Provost et al., 1995], and a few centimetres for the other major components.

In 1995, a new set of solutions was produced, derived by assimilating the empirical T/P CSR2.0 tidal solution into the hydrodynamic model. F. Lyard's assimilation procedure [1997] uses a representer method, as put forward by Egbert et al. [1994]. The CSR2.0 solutions were computed by the University of Texas from two years of T/P data and with JGM-3 orbits. The data set used in the assimilation is a CSR2.0 sample on a 5° x 5° grid for ocean depths greater than 1000 m. The assimilation was applied over the Atlantic, Indian, and Pacific oceans. The solutions were complemented by adding the Mediterranean Sea [from Canceil et al., 1995], the Arctic Ocean from Lyard [1997] and Hudson Bay, English Channel, North Sea and Irish Sea from FES94.1. [see Le Provost et al, 1997]. The standard release of these new solutions, under the code name FES95.2, is again a 0.5° x 0.5° gridded version of the full resolution finite element solutions (Figure 1).



(119 Kb)

Figure 1

Amplitudes and phases of the major lunar tide M2 from Global Ocean Tides model FES95.2. This model predicts tidal sea level variations at any time and point in the deep ocean to within around 3 cm rms. Cophase lines are drawn with a 30° interval (0° phase has thicker lines)

The associated tidal prediction model includes 26 components. Among them, only the eight major components are from the hydrodynamic model: three diurnals (K1, O1, Q1) and five semi-diurnals (M2, S2, N2, K2, 2N2). These components are corrected by assimilation, except K2 and 2N2. The other 18 components are derived by admittance from these eight major components. Among these secondary waves are M1, J1, OO1, epsilon2, lambda2, eta2.

Quality of solutions

The quality of these solutions has been evaluated by Le Provost et al [1997] by reference to the standard sea truth data set. It shows that the rms differences between these solutions and in situ data are significantly reduced after the assimilation process is applied, compared with similar rms differences in both the a priori hydrodynamic solutions and the T/P solutions used as a priori data for assimilation. The rms evaluated over the 8 major components is reduced from 3.8 cm for FES94.1 to 2.8 cm for FES95.2. The performance of the prediction model is evaluated in two ways. Test 1 compares tidal predictions with observations at 59 pelagic or island sites distributed over the world ocean. Test 2 looks at the variance in the sea surface variability observed by the T/P altimeter at its cross-over points, which is explained by the tidal predictions. These two kinds of evaluation lead to the same conclusion: that the new model is much better than the one based on FES94.1, due to the correction of the major components by assimilation and increasing the number of components from 13 to 26. Test 1 estimates the rms residual in ocean tide predictions as 3.86 cm (the same test for CSR3.0 yields 3.48 cm).

Recall that:

- FE95.2 is for ocean tides only (excluding earth tides),
- FES95.2 is derived from the hydrodynamic FES94.1 solutions, of particular interest for their resolution over the continental shelves. However, in the FES95.2 solutions the assimilation led to spurious resonances in a few local areas: these areas are shown on figure 1 of the read-me introduction to the model on the ftp site above indicated. Beware of the degraded accuracy of FES95.2 in these areas.

Present status for ocean tide predictions

How close to reality are our tide prediction models?

The present status of ocean tide predictions now available for altimetry has been recently reviewed by Shum et al [1997]. A comparison of tidal models to the standard sea truth points to rms discrepancies of about 2.5 to 2.9 cm. Additional comparisons to 59 time series of hourly high-pass filtered tide-gauge observations, at islands and pelagic locations from the WOCE network and IAPSO data bank, computed by Le Provost et al [1997], find global RMS discrepancies on the order of 3.5 cm in the best cases. These rms values range from 1.7 cm at Rikitea (for which the variance level of the signal over 10 years is 21 cm^2), to 4.5 cm at Pohnpei (variance of 29 cm^2 for 8 years of records). This is probably a good indicator of present-day accuracies in the tide model predictions for the deep ocean.

Where are the major discrepancies?

- **In the deep ocean:**
  Globally, an analysis of the residual variance of altimeter data after correcting with the CSR3.0 and FES95.2 models (including load tides) reveals a slight preference for the CSR according to the Fisher-Snedecor significance (residual variance of 5.58 cm for CSR3.0, t.b.c., to 5.75 cm for FES95.2). However, without the tide-load- correction, neither ocean-tide model is favored over the other [Le Provost et al, 1997].
  Regionally, a mapping of the differences in cross-over residuals between CSR3.0 and

FES95.2 (for cycles 1 to 141) shows where each model supplies better predictions [see figure 8 of Dorandeau et al, 1996]. Typically, FES is, for example, recommended for the Southern Ocean and CSR for high northern latitudes.

- **On shelves and in coastal seas:**
  A test of residual variance over shelf areas, using 5 different tide models with Geosat, ERS-1, and T/P data, is inconclusive: the T/P data favor CSR3.0 (rms 10.05 cm); the ERS-1 data favor the AG95.1 model (rms 10.59 cm); the Geosat data favor the RSC94 model (rms 13.49 cm), see Li et al, [1996]. Further comparisons to tide-gauge data (about 530 stations along continental coastlines) find rms differences (over the 5 largest tides) of 10.5 cm (for SR95.0 and FES95.2) and higher values for other models [Le Provost et al, 1996].

How can we improve these tide prediction models?

It is not presently clear how much empirical tide correction will improve with more data, particularly given the aliasing of K1 and SSA in T/P data. Several questions have to be addressed, such as how orbit errors, environmental corrections, and inverse barometer effects in the aliased tidal frequency bands contribute to the altimeter signal.

Improvements in assimilation methods have been reported recently by Egbert [1997] and Lyard [1997]. With Lyard's revised assimilation method, new finite-element solutions will soon be computed. We will assimilate the latest empirical T/P solutions and alongshore gauge data. Boundary problems apparent in the earlier global FES solutions should now be overcome, and solutions over the continental shelves improved.

What about the long period components?

Several new solutions for the long-period tides are forthcoming, from direct analysis of the T/P data (for example from Desai and Wahr, personal communication), and from new numerical models [Wunsch et al, 1997; Lyard and Le Provost, 1997]. New FES solutions have been produced for the semi-monthly component Mf (13.66 days), with maximum equilibrium amplitude 2.94 cm at the pole and 1.7 cm at the equator, and for the monthly component Mm (27.55 days), with maximum equilibrium amplitude 1.54 cm. The accuracy of these components, at 74 island stations, is 0.2 cm.

From these new results, it appears that the semi-monthly tides are significantly different from the equilibrium response, in contrast with the monthly and longer period tides which seem to be closer. However, the semi-annual and annual components are mixed with the seasonal ocean signal, and thus, there would be no point in trying to investigate the part of these components consistent with tidal potential forcing.

Limits to the deterministic prediction of tides

Within the Jason 1 cm challenge, the fundamental limits to the deterministic prediction of tides need investigating. The key issue is how robust the concept of stability of the harmonic (or orthotide) description of the tides is. One revealing fact can be found by computing the rms difference between hourly high-pass filtered tide-gauge observations and hourly tide predictions based on harmonic constants determined from those same tide-gauge observations. This has been done for 45 stations at islands and pelagic locations, from the WOCE network and IAPSO data bank. The rms difference varies from 1.5 cm to 4 cm, far exceeding the 1-cm requirement cited above. These fundamental limitations on prediction must be due to contributions from meteorological forcing, nonlinear coupling between tides and storm surges and ocean circulation, and contributions from internal tides. To further improve tidal predictions, especially for the use of altimeter these non deterministic contributions need investigating. But we do not know yet whether it is reasonable to expect more improvements.

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