A PHYSICALLY CONSISTENT SYSTEM MODEL FOR THE STUDY OF THE EARTH'S ROTATION, SURFACE DEFORMATION AND GRAVITY FIELD PARAMETERS

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ABSTRACT. The coupling of models of different subsystems of the Earth forms a necessary step towards a dynamic Earth system model which is physically consistent with respect to Earth rotation, gravity and surface deformation. In a cooperative project with contributions from meteorology, oceanography, hydrology and geodesy the fluxes of momentum, energy and mass between atmosphere, ocean, continental hydrosphere and rigid Earth have been jointly simulated for centennial periods. The corresponding variations of the Earth's rotation, gravity and shape have been calculated and compared with satellite data. This paper and the following four ones are closely linked.

1. INTRODUCTION

This article gives an overview about a series of projects which studied the Earth's rotational parameters (ERP) angular momentum, tensor of inertia as well as related variables of the Earth's gravitational field. A system view has been taken by trying to incorporate the contributions from the various subsystems of the Earth system in a physically consistent way. These subsystems concern the atmosphere, the continental hydrosphere, the ocean and the rigid Earth; accordingly the next four papers are presenting the respective contributions from the fields of meteorology, hydrology, oceanography and geodesy.

We started from a couple of stand-alone models for the subsystems: ECHAM for the atmosphere (Roeckner et al., 1992), HDM for the continental hydrosphere (Hagemann & Dümenil, 1998), OMCT for the ocean (Thomas et al., 2001) and DyMEG for the Earth's dynamics (Seitz, 2004). We did know from previous runs of these models that

- decadal scale variations in axial relative angular momentum variations do exist in the ECHAM simulations which are obviously forced by sea surface temperature (SST);
- the same holds for OMCT and the oceans contribution. We got first indications that the interaction of ocean currents and tides might be important;
- the length-of-day variations on time scales from a few days to several years could be almost completely explained by atmospheric torques (Seitz, 2005);
- the Chandler wobble is excited by temporally stochastic but spatially coherent modes (Seitz et al., 2004).

Our main objective in the recent working phase was the step from stand-alone simulations to a representation of subsystems within one coupled Earth system model. Such a model would exchange the mass-, energy- and stress-fluxes interactively between the atmospheric, oceanic and any other necessary submodel conserving those fundamental quantities. Even the global climate models used in the last IPCC assessment report (No.4 in 2007) are only coupled in their energy and water cycles but not with respect to angular momentum. Lastly, it had become clear that the Earth rotation components determined by astrometrical-geodetical methods are the only measurable globally integrated variables of the Earth's systems. This is in contrast e.g. to the globally mean surface temperature which has to be aggregated from individual pointwise measurements using specific model assumptions. Therefore one has to admit

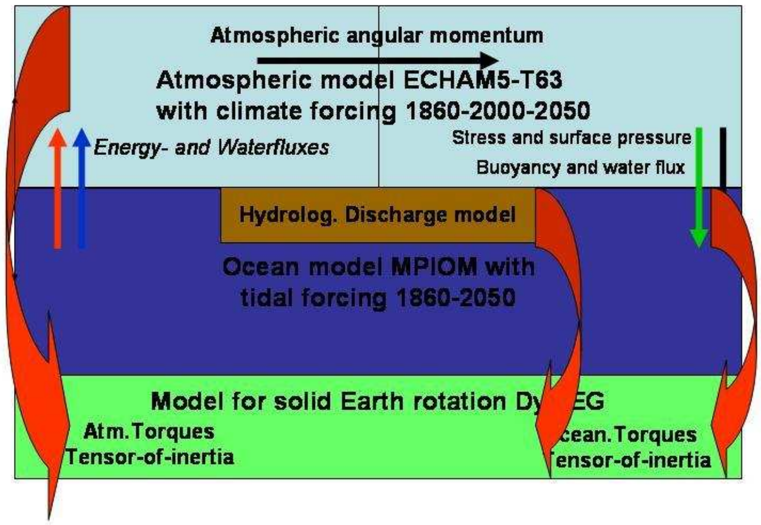

Figure 1: Symbolic layout of the modelling approach.

that the ERP have the potential for monitoring specific changes of the Earth system related to global climate change. However, as the measured ERP are variables of the solid Earth, the conclusions from the monitored ERP signal with respect to the atmosphere or the ocean require a modelling approach to disintegrate the measured signal. Therefore a prerequisite question for quantifying the monitoring potential are modelling studies using fully coupled atmosphere-ocean-land surface models to derive the changes due to anthropogenic and natural climate forcing influences on the atmospheric and oceanic torques and integrate them using the dynamic rotational model of the solid Earth. These are in effect the aims of the project which will be reported here:

- The development of a fully and self-consistently coupled atmosphere-ocean model ECOCTH based on the state-of-the-art ECHAM5-T63 atmosphere and the MPIOM ocean model including ephemeridical tidal forcing (Jungclaus et al., 2006).
- A detailed land surface hydrology model fitted into the fluxes of the internal ECHAM5/MPIOM hydrological discharge model HDM for calculating offline the sub-terrain water levels and their contributions to the tensor of inertia.
- Simulations of the 20th century under observed climate forcing from anthropogenic and natural sources of the coupled model as well as the atmospheric model ECHAM5/T63 forced with the observed SST/SIC and climate change simulations for the 21th century with the coupled model under the assumed A1b scenario for the future man-made climate forcing.
- Calculation of the influence of atmosphere and hydrosphere on rotation, shape and gravity of the Earth.
- Comparison with satellite data.

The type of modelling approach is sketched in Fig. 1.

Partners cooperating in the project are: in the field of meteorology Andreas Hense and Timo Winkelnkemper from the University of Bonn, in the field of hydrology Maik Thomas, Claudia Walter and Robert Dill from the Geo Research Centre Potsdam, in the field of oceanography Jürgen Sündermann, Xueen Chen and Malte Müller from the University of Hamburg, in the field of geodesy Hermann Drewes from the German Geodetic Research Institute Munich and Florian Seitz from the Technical University of Munich.

2. MODELS OF SUBSYSTEMS

First, it should be reemphasized that the main objective of the project was to develop an integrated model of the subsystems atmosphere, ocean and continental hydrosphere (ECOCTH). Thereafter, on the basis of the obtained spatial and temporal data fields the dynamical Earth model DyMEG should calculate the respective rotation parameters, the gravity field and the shape of the Earth and their variabilities (see Fig. 1). Only such a coupled model can guarantee the mass, energy and momentum fluxes between the subsystems to be steady and the Earth system parameters to be consistent. Differently from the singular treatment of a subsystem (where the influence of another subsystem will be prescribed by observed boundary values) the integrated approach does not use data assimilation; so principally the approximation of real nature might be somewhat inferior. On the other side, the fundamental physical properties are conserved in the coupled system and this is necessary for a consistent calculation of Earth system parameters. Moreover, only such a model can be run in a prognostic way for decades, because it does not need boundary conditions at interfaces (with the exception of the solar radiation, emission scenarios and the gravitational influence of Moon and Sun which, of course, must be prescribed).

Nevertheless, for different reasons a preceding or partially simultaneous treatment of separate subsystems made still sense. Firstly, the pioneering development of a free coupled model including ephemeridic tides represented a certain risk while the submodels had been already successfully tested. Indeed, initial difficulties arose when applying the OASIS coupling code. Together with the high computational effort for the five 200 years runs this delay allowed a common analysis and evaluation of results only in the final phase of the project. Moreover, one scientific attraction of the study was just the comparison of the classical stand-alone models of the atmosphere, the continental hydrosphere and the ocean with the new integrated model, with respect to both, specific meteorological, hydrological and oceanographical parameters, and simulations with the DyMEG model. So specifically the working groups meteorology and hydrology performed own experiments with the submodels ECHAM and HDM. The working group oceanography has focused its activities on the coupled model ECOCTH.

3. MAIN RESULTS

The results of the subsystem studies are given in the following four papers. Here some major findings will be noted.

Tidal mixing

For a long time it has been assumed that barotropic ocean tides have minor influence on the general circulation. During the last 10-15 years it has been recognized that tides induce small-scale mixing processes and therefore interact substantially with thermohaline ocean currents. Baroclinic tides are generated at topographical barriers as deep sea trenches, middle oceanic ridges and islands and breaking internal waves are causing vertical mixing. This mechanism has been mostly ignored in global ocean circulation models, sometimes it has been roughly parameterized. ECOCTH is the first model of the World Ocean's thermohaline and wind driven motion which explicitly contains the astronomical tides. The tidally induced vertical current shear enters the Richardson number of the flow modifying locally the vertical exchange of momentum, heat and salt. In the Atlantic Ocean this mechanism leads to a significant improvement in modelling the North Atlantic Current. This subsequently has influence on the structure of climate changes in scenario simulations of climate changes in the North Atlantic. Presently it is discussed whether future IPCC model runs should include ocean tides.

Anthropogenic impact on atmospheric angular momentum

Basing on the ECOCTH runs and on an ensemble of simulations with the coupled atmosphere-ocean model ECHO-G (Legutke & Voss, 1999) the possible anthropogenically induced variation of the axial component of the atmospheric angular momentum AAM has been investigated. With both models an increase of AAM due to higher mean zonal wind velocities is obtained corresponding to an increase in length-of-day (see Figure 4 in the following article by Winkelnkemper & Hense). Comparable effects have been shown also by other coupled models, but with quite different amplitudes. It is an open question whether oceanic torques and their changes - caused by a redistribution of mass from lower to higher latitudes - can compensate this effect.

Chandler wobble excitation by white noise forcing

The dynamical gyro-model of the solid Earth DyMEG has been forced by the simulated torques (matter and motion term) of the geo-fluids atmosphere, ocean and continental hydrosphere aimed at an explanation of the permanently existing Chandlerian motion of the angular momentum vector. Without these external variations of the atmospheric and oceanic angular momentum the Chandler wobble would disappear within 30-40 years due to rheological damping in the Earth's interior. This is not observed, and consequently there must be a continuous process which feeds in energy in the spectral band of the Chandlerian motion (period 430 days). Until now quasi-periodic processes in the atmosphere and the ocean close to the resonance period of the free Chandlerian oscillation have often been assumed as forcing. Now the analysis of the excitations obtained from the ECOCTH simulations have shown that the stochastic part of the forcing (mainly the variations of the off-diagonal elements of the tensor of inertia) in the period range of 400-460 days represents the essential component for the conservation of the Chandler wobble. It even turned out that a white noise forcing with an amplitude similar to the calculated geo-fluid torques is sufficient to conserve the Chandlerian motion over 1000 years, and this with characteristics as observed in 1900-2000. That means that random fluctuations of atmospheric and oceanic bottom pressure could be identified as forcing factors of the simulated by DyMEG Chandler wobble (see Figure 4 in the following article by Seitz).

4. CONCLUSIONS AND OUTLOOK

The project performs considerable progress in connecting integral parameters of the Earth as vector of rotation, surface shape or gravity field and their temporal variability with small-scale processes within the Earth system proper. Terrestrial and satellite observations provide the first mentioned planetary quantities, geological data from the atmosphere, ocean and solid Earth the variable state of the globe. It was and is the general objective of the research programme to understand and quantify this fundamental interconnection by means of model conceptions learning thereby from the total system about its components and vice versa (see Figure 1 in the following article by Seitz). From the view point of physics, we consider fluxes of momentum and energy between the Earth and extraterrestrial bodies as well as between the geophysical system parts of the Earth itself (for the latter ones also mass fluxes exist). This exchange happens on different time scales ranging from geological periods (eons) down to tidal and weather dynamics (hours). The above formulated balance must be always fulfilled.

Naturally at the beginning of the research work about forty years ago we firstly considered the long time scales (Brosche & Sündermann, 1978). Existing geological data (growth rhythms of fossil organisms; time range 500 mio years) and astronomical observations (eclipses, orbits of planets; time range 3000 years) have been used and interpreted in terms of geophysical processes on the Earth. Within the last decades more and more new astronomical and geodetical data (LLR, VLBI, altimetry, gravity) became available. They have achieved meanwhile a high degree of accuracy and density allowing analysis from the decadal and annual scale down to seasonal, daily and tidal signals. The planetary data have firstly been focused on Earth rotation parameters (mainly LOD) and supplemented in recent years by measurements of the shape and the gravity of the Earth and their variations. At the same time modelling has been advanced from separate and rough studies of the system parts to high-resolving and coupled simulations of the total Earth system.

In the current project some major progresses have been achieved on the sketched way: For the first time a free, coupled model of the partial systems atmosphere, ocean and terrestrial hydrosphere has been realized and applied. The global ocean model comprises the wind- and thermohaline driven circulation as well as ephemeridic tides and their nonlinear interaction. Basing on this data a physically consistent dynamic Earth model is run and provides simultaneously rotation parameters, surface deformation and gravity field of the Earth. The numerical results are directly compared with satellite data. 'Free' model means that on the rotating Earth with real topography - like in nature - only solar radiation and gravitational potential of Moon and Sun are acting. Atmosphere and ocean circulations as well as the hydrological cycle are freely developing under this forcing. No observational data are assimilated resulting in an independent numerical data set. This set is physically consistent in the sense that momentum, energy and mass are conserved in the total system and that fluxes between the system parts are steady.

The developed model type is necessary for the synthetical interpretation of existing and newly gained geophysical, geodetical and astronomical data, although it still may have some deficiencies for operational use. Restricted spatial resolution, insufficient parameterisation of processes or numerical artefacts must cause inaccuracies which may be greater than in a 'bounded' (by data assimilation) model. Nevertheless, for the theoretical interpretation of remote sensing data, its correction and for deducing information on the geophysical system parts, specifically for future scenarios, our model type is the only appropriate approach.

Further research activities could now focus on

- refinement of the model resolution;
- improvement of process parameterisations;
- simulations of the past millennium to assess secular changes;
- scenario runs under global change.

The last item includes the monitoring of climate change. There are strong indications that climate change is reflected in time series of planetary parameters (e.g. LOD). This opens the innovative possibility of an integral climate monitoring - independent of local geophysical observations.

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