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Evaluation of the doctoral thesis

Modelling of global ocean circulation and ocean-induced magnetic field

submitted by **RNDr. Libor Šachl**

Numerical ocean models have become indispensable tools to understand the dynamics of the oceans and their broader interplay with the physical Earth system. These models have progressed from crude representations of decades past to complex frameworks through which we can test theories, predict weather systems or study the effects of climate change. As such, modeling techniques complement, and underpin, approaches of observational inference. The field is by no means isolated; it firmly sits at the crossroads of oceanography and related geosciences (e.g., meteorology, geophysics, geodesy) which formulate practical requirements and pose scientific applications. In fact, oceanic phenomena in standard analysis of geodetic and geophysical records are frequently treated as nuisance, as they obscure more subtle target signals (e.g., seafloor deformation, gravity field changes) and thus necessitate precise correction. Yet methods and measurements furnished by these disciplines have been recognized as additional reservoir for oceanographic knowledge. Vice versa, it is not uncommon for scientists from such areas to engage in serious ocean modeling work themselves and tailor these tools to specific geophysical questions at hand.

The doctoral thesis presented by Libor Šachl is placed at this very interface. In particular, the candidate has accomplished the formidable task of completely overhauling, and extending, the somewhat dated Large-Scale Geostrophic (LSG) ocean model. These efforts were initially motivated by the necessity to model the ocean's response to changes in surface loads in the glacial isostatic adjustment (GIA) problem through a dynamic framework instead of an offline sea-level equation. However, as pointed out in the text, the emphasis shifted from paleo to present-day applications in the advanced stages of the work, more particularly to the forward modeling of the ocean-induced magnetic field (OIMF) in the context of the Swarm satellite mission. While these contrasting areas of operation exemplify the non-linear track some PhD students must take these days, they are also unified by the interdisciplinary character of Earth system science, as elucidated above.

The main text of the thesis comprises 200 pages and follows a logical structure. After a brief general introduction, Šachl lays out the physical principles of ocean models (e.g., momentum and conservation equations, frictional closures, equation of state) in Chapter 1. Chapter 2 addresses numerical implementation options one necessarily faces when translating analytical equations into their discrete form, pertaining to, e.g., vertical discretization and the treatment of advection terms. Chapters 3 to 5 – perhaps the most impressive parts of the thesis – detail the metamorphosis of the LSG model into a state-of-the-art tide and circulation model, dubbed LSOMG (Libor Šachl Model for Geophysics). The candidate makes objective choices for mixing and advection schemes and goes to significant length to describe the model's versatility regarding time-stepping and horizontal gridding techniques. An intercomparison of a wide range of bulk formulae and transfer coefficients, applied to the same atmospheric reanalysis data, provides some understanding of uncertainties in surface boundary conditions. Chapters 6 to 8 finally direct the thesis away from development aspects to scientific problems, although a taste of the former lingers. Using the barotropic component of LSMOG, Šachl adopts a multi-tiered approach to evaluate the impact of time-stepping schemes, spatial grids, and smoothing choices on the simulation of tides. Major circulation phenomena are benchmarked and extended to a full treatment on the globe, laying the groundwork for a concurrent simulation of tides and the wind-driven baroclinic circulation at 0.25° horizontal resolution. Chapter 8 rounds out the thesis with findings related to the forward modeling of the non-tidal OIMF. It particularly addresses sensitivities of the deduced magnetic field at satellite height to peculiarities in the electromagnetic induction solvers and the vertical structure of the simulated ocean currents.

The amount of thought and work that went into the development of LSOMG is staggering. The candidate must be congratulated for his achievements. Yet, in the spirit of an objective scientific assessment, some criticism is warranted. In general, I have the impression that full immersion into the inner workings of a general circulation prevented Šachl from really following the tails of his explorations, or – at least – keep an eye on the bigger picture that any doctoral thesis should convey. Both chapters 6 and 7 strive for increasingly realistic simulations of the tidally and wind-driven circulation using a well-designed suite of tests. However, these sections end in a rather abrupt manner and leave important questions unanswered: What do the results mean for the wider ocean modeling community? What are possible implications and outstanding issues? How does this particular analysis tie in with the rest of the thesis? Possibly, one or two pages of discussion after each chapter would have done the job. Likewise, the initial objective of modeling the ocean's involvement in GIA in an online fashion quickly drowns out. Although the reasons for such foundering are vocalized, it would have made sense to provide a dedicated outlook on how the huge investment into the LSG/LSOMG would have been benefited GIA modeling. I am also inclined to think that several of the more general sections (e.g., equation of state, treatment of advection and diffusion) – mostly non-essential for the later parts of the main text – would have been a better fit for the appendix. Overall, less technicality, and more discussion, would have strengthened the thesis and made it more concise.

Nonetheless, the scientific merits of the work cannot be disputed. They come in several little thrusts, each being the product of a systematic evaluation of physical and numerical modeling choices. First, the intercomparison of bulk formulae in the determination of surface boundary conditions highlights outstanding and potentially underappreciated subtleties in some widely used atmospheric forcing parameterizations. The findings corroborate current international efforts of improving atmospheric flux representations through coupled atmosphere-ocean simulations or state estimation (as practiced by, e.g., the ECCO Consortium). Second, the breakdown of different time-stepping schemes and horizontal discretizations in terms of their skill for tidal simulations will be useful for researchers working on the diverse effects of ocean tides in the Earth system. While some of the tested numerical options are known to be impractical, the more subtle energy leakages in particular schemes can be a significant source of error in paleo-simulations aiming at estimates of tidal dissipation rates. The headways made toward truly global simulations of tides are especially noteworthy. Avoiding pole singularities in settings where vertices cannot be placed on land (e.g., when continental configuration changes) remains an open issue in paleoceanography. Šachl has tested two of the more promising gridding techniques (Yin-Yang and reduced spherical coordinate grids) and illustrates that neither gives satisfactory results, with dynamical features heavily marred by grid-scale noise. Finally yet importantly, Chapter 8 establishes the importance of galvanic coupling between ocean and mantle for reliably quantifying the non-tidal OIMF in support of dedicated satellite missions such as Swarm.

All of these aspects can be considered genuine scientific advances. I therefore believe that the document submitted by Mr. Šachl meets the requirements for a PhD thesis and I warmly recommend its acceptance.

With kind regards,

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Michael Schindelegger