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Review report on a doctoral thesis entitled
"Modelling of global ocean circulation and ocean-induced magnetic field"
by Libor Šachl

This PhD candidate has made very intensive studies on ocean general circulation models (OGCMs) and developed a new comprehensive OGCM named LSOMG. Furthermore, ocean-induced magnetic fields (OIMFs) were also calculated precisely based on a combination of the candidate's own achievement in OGCM through this study and an existing OIMF solver (ElmgTD). Because this referee isn't specialized in physical oceanography, it had been definitely tough to follow and appreciate the candidate's achievement in the part of OGCM, which this referee managed to complete. However, as for OIMF, it was intriguing even for an expert in this field, though the amount of its description is limited to one chapter alone at the very end.

This thesis starts with a very comprehensive review on OGCM followed by description on the new OGCM code, LSOMG. The last part is dedicated to realistic numerical simulations of both ocean circulation and ocean-induced electromagnetic (EM) fields. The majority of the present thesis is occupied by description and numerical performance of LSOMG apart from Part I and the very last chapter.

LSOMG is a very elaborate OGCM newly developed by the candidate himself. It is COMPREHENSIVE in the sense that it supports not only two-dimensional (2-D) barotropic circulations but also 3-D baroclinic ones. It allows several forcing with quite different spatio-temporal scales such as tides and winds. Boundary conditions for the real ocean are complicated not to mention to those at the lateral and bottom, i.e., the ocean-continent distribution as well as bathymetry of certain complexity, boundaries. The surface boundary is another important issue here, which the candidate handled skillfully allowing a few conditions including the 'free-surface' to enable kinetic tsunami simulations by LSOMG. The candidate even expanded the code to contain sea ice if desired, which may be of use especially in applications of LSOMG to climatology.

This referee has to state clearly it again that he is neither a specialist in physical oceanography nor an expert in numerical simulation, although he started his research career in an ocean research institute of University of Tokyo and has spent more than two thousand days at sea while engaging marine geophysics. However, I can understand the candidate's sincere efforts to construct a new OGCM almost from the first principle. I was also impressed by his ability in numerical calculation that definitely demands a considerable amount of time as well as labor to acquire. There's no doubt in his possession of pertinent literacy to perform very

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complicated simulations that are likely to fail without concentration and/or good command over computing facilities.

Proper handling of LSOMG indeed requires a lot of consideration over the items below:

- Time stepping: explicit vs. implicit
- Numerical grids: horizontal (Arakawa) and vertical (z, σ or ρ) discretization, global curvilinear grids (YY or RSC)
- Conversion of temperature to potential temperature
- Heat fluxes: long wave, short wave, latent and sensible
- IWD and SAL in tidal modeling
- Friction: horizontal and bottom
- Advection and its limiter: QUICK, LW and DST3, Smith and Superbee

The candidate seemed to succeed in installing all the desirable options into LSOMG. The ability of LSOMG manifests in the successful reproduction of tsunamis, ocean tides, Munk Problem for western boundary currents and Ekman spirals described in Chapter 6. In Chapter 7, the candidate also claimed that the world's strongest wind-driven currents (ACC) would have never been reproduced even in their realistic simulation of the global ocean without 3-D baroclinity of LSOMG.

In the last chapter, the thesis describes the result of OIMF simulations. It starts with comparison of three existing motional induction solvers. Two of them are in time domain and one of the three is unimodal in the sense that there isn't any galvanic coupling with the conducting Earth beneath the seafloor. The comparison was followed by four tests from A to D in order of complexity, viz., adding 1-D earth, galvanic coupling and self-indction. ElmgTD alone was used in the final realistic run for global OIMF to find the importance galvanic coupling of OIMF resulting from wind-driven ocean circulation. It was a good surprise to see the small but significant self-induction effect in reproducing the power spectra of OIMF even at time scales of wind-driven ocean circulations. It is unfortunate, however, that OIMF by tsunamis is absent in this thesis in spite of the fact that LSOMG is proved capable of tsunami simulations as well.

In summary, LSOMG turned out to be a useful tool with high-spirit ambitions of application of it to various unsolved geophysical problems such as those in paleo oceanography/glaciology as well as detection of OIMF at satellite altitudes in global induction studies, both of which are unprecedented. The code has been parallelized already using MPI or OpenMP environments for practical use in, say, data assimilation. However, this referee thinks that there is still a

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room for discussion in this thesis as follows:

1. It is good news that LSOMG can be used for a wide range of spatio-temporal scales. On the other hand, however, it is true that there is no perfect or almighty numerical code that can simulate every phenomenon of the real world. Therefore, not only the ability but also the limitation of LSOMG should be addressed clearly. Specifically, it is desirable to illustrate which parameterization is good for LSOMG in order to simulate a specific problem in physical oceanography. This referee hasn't been convinced the merit or the reason to have tidal and wind-driven forcing at the same time in a code. It is often chosen to make the numerical code divided into modules by disabling one feature after another to enhance the numerical accuracy of the code in concern, as aptly done by the candidate himself in the case of LSOMG-BT and Baroclinic LSOMG. For instance, Figure 7.18 clearly tells us that having both forcing just give us a bias between tides and winds in SSH with a very small baroclinic contribution.

2. It is necessary to state new findings by realistic simulations by LSOMG together with the candidate's own contribution in Chapter 6 apart from Einšpigel's.

3. Chaper 8 is also a result from collaborations with other institutes such as GFZ. Clarify the candidate's contribution in studying OIMF with a reference to the role of LSOMG in researches of OIMF. It is somewhat strange to see the attached paper that the candidate himself is listed as the 2nd author.

4. I'd like to know the future perspective of possible researches using LSOMG and related tools.

This referee would like to listen to how the candidate will address the questions listed above and will give my final decision on this doctoral thesis after hearing the oral defense presented by the candidate himself. I enclose an annotated manuscript of the thesis with this evaluation letter. It's my great pleasure if it is of any use for the candidate in preparation of his final defense.

Place: Kyoto, Japan
Date: August 31st, 2020
Reviewer's Name: Hiroaki Toh
Reviewer's Signature: