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Feedback between thermal convection and tidal dissipation: The example of Enceladus

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Abstract

Anelastic dissipation of tidal forces likely contributes to the thermal budget of several satellites of giant planets. In order to address how the tidal heating influences the thermal evolution of such bodies, we present a new numerical tool [1] that solves simultaneously the mantle convection and the tidal deformation in a three-dimensional spherical shell. Since both mechanisms are associated to strongly temperature-dependent rheological properties, the two processes are coupled and a strong feedback is expected. We show an application for Enceladus and we compare the tidal strain rates for the fully 3D method and a commonly used 1D method.

1 Model

For the numerical solution of the problem mentioned above, the following scheme is proposed: First, the rheological properties for the anelastic tidal deformation are computed for the three-dimensional distribution of the temperature. Using these properties, the tidal deformations and dissipation are evaluated. The dissipation rate is then averaged over a tidal cycle and this average is imposed as an instantaneous source of the volumetric heating for the thermal convection. Then the next time step of the long-term convection is evaluated and the temperature field is updated.

1.1 Mantle convection

For the long-term flow a purely viscous material is considered since the characteristic scales are much longer than the Maxwell time. The classical Boussinesq approximation is employed. The viscosity is supposed to be temperature dependent:

$$\eta(T) = \eta_b \exp\left(-a_{\mathrm{vis}}\frac{T-T_b}{\Delta T}\right), \qquad (1)$$

where a_{vis} is viscosity parameter, η_b and T_b are the viscosity and the temperature at the bottom of the domain and ΔT is a temperature contrast through the spherical shell. In this case, the energy budget is determined by in- and out-flow through boundaries and heterogeneous internal sources of energy including heating due to anelastic tidal deformations. Numerically, the solution is computed in a 3D spherical shell and the finite volume method [2] is employed.

1.2 Tidal deformation

For tidal visco-elastic deformations, an incompressible Maxwell-like formalism is used and the effective viscosity $\hat{\eta}$ is introduced in order to reproduce a given dissipation factor Q_b^{-1} at a reference temperature and a given frequency ω_{E}

$$\hat{\eta}_b = \sqrt{Q_b^2 - 1}\,\frac{\mu}{\omega_{\mathrm{E}}}, \qquad (2)$$

where μ is the shear modulus and ω_{E} is the forcing angular frequency. The shear modulus is considered either constant or depth-dependent. Analogically to Eq. (1), the temperature dependence of the effective viscosity is taken into account

$$\hat{\eta}(T) = \hat{\eta}_b \exp\left(-\hat{a}_{\mathrm{vis}}\frac{T-T_b}{\Delta T}\right). \qquad (3)$$

Note that, in general, parameters η_b and $\hat{\eta}_b$ as well as a_{vis} and $\hat{a}_{\mathrm{vis}}$ differ, especially for excitation periods shorter than the Maxwell time. The visco-elastic problem is treated in the time domain. A combined spectral and grid-based spatial discretization [3] is used.

2 Enceladus

The enormous power ($15-21\,\mathrm{GW}$ [4]) emitted on the southern polar region of Enceladus is more than one order of magnitude higher than the value expected

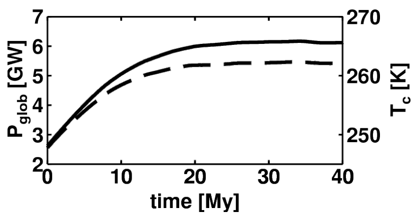

Figure 1: Time evolution of the global dissipation (solid line) and the mean temperature at the mid-depth (dashed line).

from the radiogenic heating. The method described above is applied to the case of Enceladus in order to evaluate the conditions under which such a huge heat power can be generated. We assume a shell consisting of ice I that is decoupled from the silicate core by a global liquid layer. The global dissipated power exceeds $5\,\mathrm{GW}$ (Fig. 1, solid line) if the effective viscosity is $10^{13}\,\mathrm{Pa\cdot s}$ for the temperature near the melting point. Additionally, a positive feedback (Fig. 1) is observed between the global dissipation and the temperature field. Due to the presence of the decoupling layer, the tidal dissipation rate is enhanced in the polar regions (see Fig. 2). Hot upwellings thus tend to concentrate at high latitudes whereas cold downwellings are mostly located in the equatorial region. Also, the heat flux at the base of Enceladus' ice shell is strongly reduced at the poles, thus favoring the preservation of a liquid reservoir at depth.

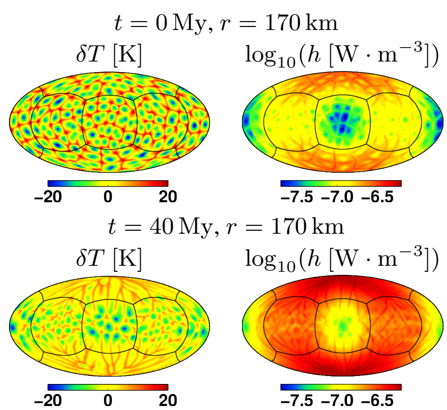

Figure 2: Temperature anomalies δT and dissipation rate h for statistical steady states without the tidal dissipation (first row) and with the tidal dissipation (second row).

In comparison with traditional method based on radially layered interior models, the tidal strain rates are strongly enhanced in hot anomalies for the 3D models. As a consequence, the classical methods locally underestimates the tidal dissipation rate within the hot anomalies, in the cases we performed, the global difference may reach 25% of the global power for steady-state results.

3 Summary and Conclusions

We presented a new numerical tool which allows to describe the coupling between the mantle convection and the tidal dissipation in a 3D spherical shell. For Enceladus, we demonstrate the feedback between the two processes and how the orbital parameters, decoupling layer and convective instabilities influence the dissipation pattern. Based on our simulations, no difference can arise between the north and south poles. Other ingredients have to be taken into account in order to explain the observed dichotomy [5].

Acknowledgements

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