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Viscous tidal dissipation in Enceladus's ocean

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Abstract

We compute the energy dissipation inside Enceladus's ocean using a two step approach in which we first compute the displacement induced on the planet by the periodic tidal potential caused by its nearest companion (Saturn). We then use the value of the (periodic) displacement at the ocean's boundaries as a forcing for the momentum (Navier-Stokes) equation.

1. Introduction

Enceladus has a global ocean about 40kms deep (see e.g. [Beuthe et al., 2016]). Observations of its south pole reveals the presence of geysers. The source of energy that powers those geysers is still debated. one possible mechanism is viscous dissipation within the ocean induced by tidal forcing from Saturn. Previous estimations have relied on the thin layer approximation to model the ocean as a two-dimensional surface using the Laplace Tidal Equations [Matsuyama et al., 2018]. however, the thickness of the ocean amounts to 15% of Enceladus's radius. In addition, viscous dissipation estimated from boundary layer theory neglects the contribution of internal shear layers which are likely to fill the volume of the ocean. In the present study, we do away with this approximation as we solve for the linearised momentum equation numerically. We use a new efficient linearised spectral method which allows us to reach the a value of the viscosity parameter which matches the actual value inside Enceladus's ocean. We compare our results to those obtained within the thin layer approximation.

2. Method

2.1 Displacement due to tidal forcing

We model Enceladus's ocean as a spherical shell enclosed within solid impervious boundaries that constitute the core and the crust. Saturn's motion observed from Enceladus's reference frame induces a varying gravity potential which, in turn, deforms the crust and the core, i.e, the boundaries of the ocean. The first step in our model consists in computing that motion by solving the gravito-elastic equations for a three-layer model. The resulting displacement is then imposed as a surface forcing in the next step of the model.

2.2 Momentum equation

The linearised Navier-Stokes equation in the reference frame tied to Enceladus's surface reads (in the frequency domain):

$$i\omega\vec{u} + 2(\vec{\Omega} \times \vec{u}) + \vec{\nabla}p - \text{Ek}\nabla^2\vec{u} = 0\ , \qquad (1)$$

where p is the reduced pressure and includes the gravitational, centrifugal and tidal potentials. All the dynamical effects of the tidal forcing happen via the condition that the velocity field must be continuous across the fluid's boundary.

2.3 Numerical resolution

We assume that the fluid is incompressible, $\vec{\nabla} \cdot \vec{u} = 0$, this allows to decompose the velocity field as

$$\vec{u} = \vec{\nabla} \times \vec{\nabla} \times (P\vec{r}) + \vec{\nabla} \times (T\vec{r})\ . \qquad (2)$$

We use a spectral decomposition in spherical harmonics and Chebyshev polynomials respectively in the angular and radial directions for the scalar functions P and T. We then solve simultaneously the radial projection of the curl and the double curl of Eq. (1). The discretised version of the resulting expressions together with the condition of continuity at the boundary form an algebraic problem of the type $\mathbf{A}\vec{x} = \vec{b}$. Fig. 1 shows a graphic representation of the matrix $\mathbf{A}$ at low resolution. Once the algebraic problem is solved, one can reconstruct the velocity field which can then be used to compute the total viscous dissipation

$$D \equiv \text{Ek} \int_{\mathcal{V}} d\mathcal{V}\ \vec{u} \cdot \nabla^2\vec{u}\ . \qquad (3)$$

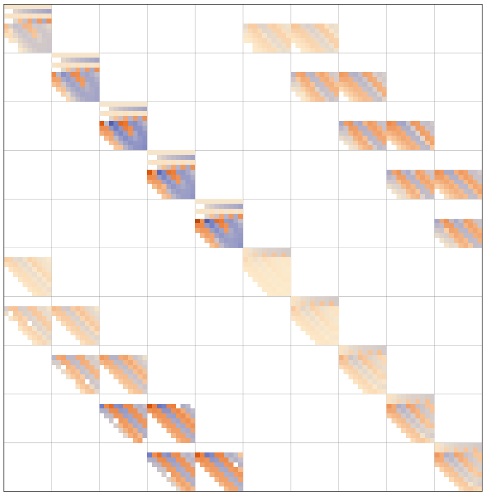

Figure 1: Low resolution illustration of the matrix used in the algebraic problem resulting from the discretisation of Eq. (1) and the condition that $\vec{u}$ should be continuous at the physical boundary.

3. Discussion and remarks

The efficiency of the spectral method used in the present study allows to solve the momentum equations at very small values of the Ekman number, Ek, that correspond to the actual value relevant for Enceladus (Ek$\sim 10^{-10}$). This is usually the most stringent limiting factor in numerical simulations of rotating fluids. In principle, it would be possible to extend our analysis to account for the non-spherical figure of Enceladus in which case it would be impossible to use such low values of Ek.

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