Introducing the TROPF (*T*idal *R*esponse *o*f *P*lanetary *F*luids) Software Package

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This presentation announces the initial release of a package of highly-optimized solution algorithms and integrated software (TROPF) that the author has developed in the course of studying the tidal response of a variety of planetary fluids including water oceans (e.g. Tyler, 2014), core fluid (Tyler and Kuang, 2014), global magma (Tyler et al., 2015), and atmospheres (Tyler, 2018). The forces that can be considered need not strictly be of the tidal form (i.e. derived from the gradient of a scalar) but can be more generally prescribed, provided they occur at a set temporal frequency (or can be represented this way through Fourier expansion).

The key feature distinguishing TROPF from other approaches more common in terrestrial tidal studies is the recognition that in planetary applications the required input parameters describing the media must be considered over a very large range. Because the tidal response can depend very sensitively on these parameters, millions of tidal scenarios are typically required to adequately sample the space of tidal response behaviors. This creates a practical demand for computational speed but also a potential storage challenge as each tidal scenario involves a data set describing a number of solution variables and their spatial distribution. These challenges can be regarded as resolved with TROPF. The TROPF package includes several different formulations and solution approaches to the full governing equations. In the fastest (and most recent), millions of solutions can be calculated essentially in real time on a standard computer, solving the speed challenge and also the storage problem as solutions can simply be regenerated when needed. For example, 281562 individual tidal solutions calculated (to spherical-harmonic truncation degree 500) to produce results similar to that shown in Fig. 1 take 3.94 minutes on a MacBook Pro 2.8 GHz Intel Core i7 with 16 GB RAM. (Fig. 1 in fact is four times more expensive because it superposes the solution sets for forcing on Jupiter by four different moons calculated separately.)

The TROPF solution methods are highly accurate and have been validated. The several core approaches use spherical-harmonic bases and provide results that agree to within machine precision. TROPF also includes a flux-conserving finite-volume method (entirely different from the spherical-harmonic methods). While slower than the core routines, this method was developed to provide important cross-validation (results agree to within the theoretical discretization error) and also allow applications (e.g. oceans with continents) not allowed in the core routines.

Initial versions of TROPF were aimed at applications involving thin, barotropic or equivalent-barotropic, global fluids. The software has been rewritten through several generations to allow more general applications, including potentially thick, compressible, non-hydrostatic atmospheres, as well as stratified oceans with parameterized ice-shell coupling. Dissipation processes that can be currently represented include Rayleigh drag, harmonic and biharmonic eddy viscosity, and a Newtonian radiation form which includes Newtonian cooling as well elastic-membrane ice coupling (Beuthe, 2016) as special cases. While the equations solved are strictly linear, solutions involving nonlinear terms can be included (as in Tyler, 2014) by first obtaining the solutions for a range of the linearized coefficients, then identifying in post-inspection the solutions with coefficients satisfying the nonlinear form. The primary restrictions in the TROPF approach which are probably permanent are two fold:

1. The mathematical formulations remain within the conditions for separability between horizontal and vertical dependencies. This essentially reduces as 3D problem to a set of 2D + 1D problems, with huge computational advantage. Some of the customary conditions for separability have been relaxed by using altered formulations in TROPF, but one which may remain hard to get around is the Traditional Approximation whereby the vertical components of the Coriolis force are ignored.

2. TROPF is formulated in the frequency-domain rather than time-domain.

TROPF solves equations for mass and momentum conservation and includes thermodynamics but currently application to an MHD fluid requires parameterization or coupling with the equations governing the electrodynamics.

TROPF has been developed in the Matlab/Octave programming language but the core solution algorithms have been optimized for rather generic sparse-matrix operations and can be quickly translated to other languages (e.g. Python). A large library in TROPF is included for post-processing and graphic display (including, for example, a GUI that allows a user to click on coordinates in a diagram such as Fig. 1 and the full tidal solution including a movie of the tidal response will pop up). This larger library is not as immediately translated to other languages.

The TROPF distribution is publicly available and includes a user's manual, tutorial document, and configured scripts for a variety of examples. In this initial beta release, input for improving the package is initially solicited from the user community. Those interested in using TROPF and potentially joining development efforts should contact the author to determine the appropriate site for uploading the package.

References

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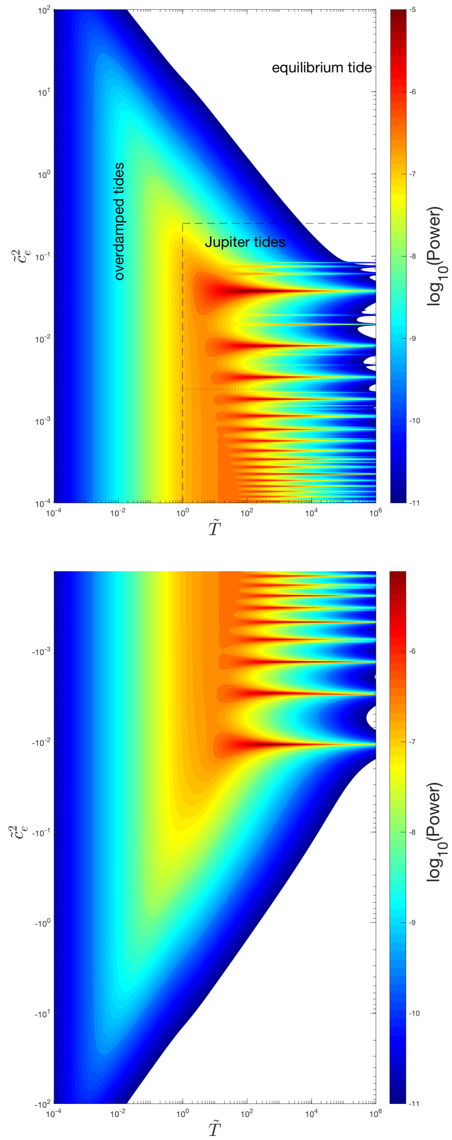

Figure 1: (Example of tidal power in Jupiter taken from Tyler, 2018): Solution space of tidal power scenarios ($\log_{10}$ scale with respect to 1 W/kg). The averaged tidal power (per unit mass) simultaneously describes the work performed on Jupiter by its moons and the dissipative heat generated. The power is shown as a function of the dimensionless dissipation time scale $\tilde{T}$ and the dimensionless squared wave speed $\tilde{c_e}^2$ (values less than 10^{-11} W/kg are off the color scale.) Because there are vertical structures that allow $\tilde{c}_e^2 < 0$ (i.e. $\tilde{c}_e$ is imaginary), the power space is continued into the lower frame. Jupiter's tidal response is expected to include modes in the region described by the dashed line and populated by resonance peaks. (Where $N > 10^{-3}\text{s}^{-1}$, the solutions are further constrained to fall above the faint dotted line.) The power levels shown reach values which should be regarded as highly significant in Jupiter's dynamics.