Supporting Information for "Tidally heated convection and the occurrence of melting in icy satellites: application to Europa"

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Text S1: General description of a tidally heated convective system

Figure S1 shows horizontal and vertical slices illustrating the characteristics of the convective fluid for four representative cases. Horizontally averaged temperature profiles from these cases are plotted in figure S2a. We first note that the heating rate field (figure S1) is a function of the viscosity (eq. 3), while viscosity is itself a function of

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temperature (eq. 1). As a consequence, the maximum heating rate H_{max} is reached within hot upwellings. By contrast, the heating rate is close to zero within cold downwellings (figure S1) and within a top layer corresponding to the stagnant lid (figure S2d). The stagnant lid can be inferred with its laterally homogeneous temperature (figure S1) and its linear change of temperature in the absence of internal heating (figure S2a), both features denoting its conductive nature. Note that the stagnant lid is also characterized by a strong viscosity increase (figure S2c). The thickness of this stagnant lid does not change significantly when we vary H_{max} (figure S2a), while increasing importantly with decreasing Rayleigh number (figure S1) or increasing viscosity contrast (not shown here). An important effect of increasing H_{max} is to increase the temperature of the convective interior, which in turn causes a decrease of the bottom heat flux (table 1). This reduction of the bottom heat flux indicates that less heat can be evacuated from the interior inducing a slower planet cooling, and therefore a longer lifetime for the subsurface ocean. Although the cooling rate of the planet is reduced, the surface heat flux is increasing (table 1), because the decreasing bottom heat flux is compensated by an increasing amount of heat internally generated (eq. 4).

The planforms of convection in figure S1 are very similar to the ones obtained for purely volumetrically heated convection (Parmentier & Sotin, 2000; Limare et al., 2015; Vilella et al., 2018). At low $Ra_{1/2}$ (figure S1a), they are composed of large, stable cold downwellings that are progressively linked with each other in a nearly isothermal background. This so-called "spoke" pattern (figure S1b), characterized by star-shaped downwellings, is only observed when internal heating is dominant. At larger $Ra_{1/2}$ (figure S1c and d), cold downwellings become cylindrical while their size is reduced and their number increases.

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Interestingly, in this regime the cold downwelling instabilities are time-dependent, as in the volumetrically heated case, but their movements are more limited and only triggered by interactions with neighboring downwellings. Another notable observation is the absence of active hot upwellings for high H_{max} (figure S1d), which is again a property of the volumetrically heated case.

The major feature of tidal heating is to increase the maximum dimensionless temperature in the convective interior up to values above 1 (figure S2b), provided that H_{max} is sufficiently high. This is of particular importance since this increase is required for the occurrence of melting within the ice layer. More precisely, the melting temperature of water ice is decreasing with increasing pressure/depth (as the Clapeyron slope of the water liquidus is negative), while by definition the temperature at the bottom of the ice layer is necessary lower or equal to the melting temperature at that depth. The melting temperature within the ice layer is thus necessary equal or larger than the bottom temperature, which is equal to 1 in our framework. This condition, i.e., temperature above 1, is required but not sufficient, since pressure and composition variations may alter the melting temperature. For instance, the freezing point at the bottom of the ice layer may be further reduced by the presence of impurities in the subsurface ocean. Therefore, the actual presence of melting should be assessed considering the composition and properties of the ice layer.
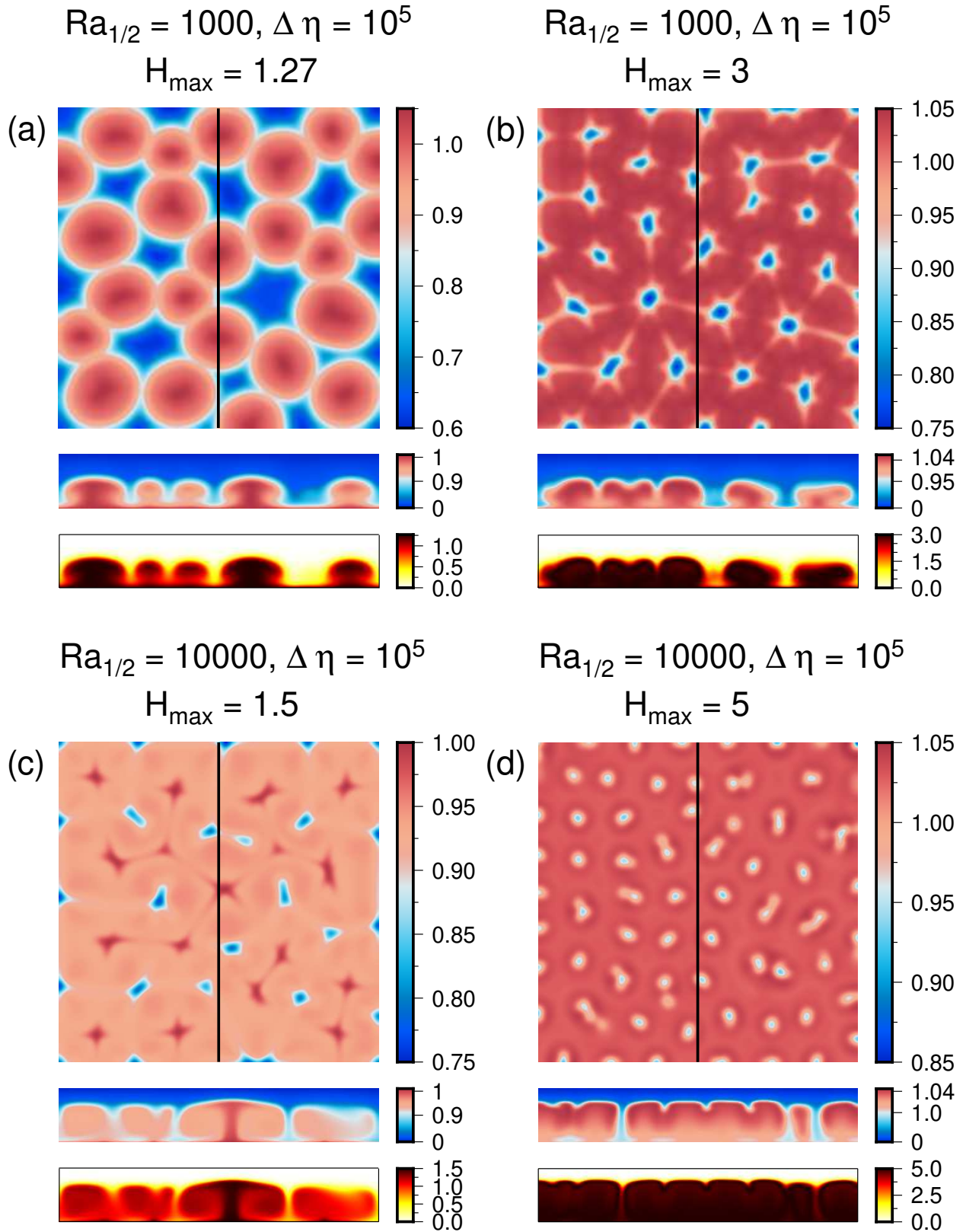
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$Ra_{1/2} = 1000$, $\Delta\eta = 10^5$
$H_{max} = 1.27$

(a)

$Ra_{1/2} = 1000$, $\Delta\eta = 10^5$
$H_{max} = 3$

(b)

$Ra_{1/2} = 10000$, $\Delta\eta = 10^5$
$H_{max} = 1.5$

(c)

$Ra_{1/2} = 10000$, $\Delta\eta = 10^5$
$H_{max} = 5$

(d)

Figure S1.   Horizontal slices of the dimensionless temperature field (T) taken at a dimensionless height 0.25, and vertical slices of the dimensionless temperature and heating rate (H) fields. For each numerical simulation, the value of the Rayleigh number ($Ra_{1/2}$), viscosity contrast ($\Delta\eta$) and maximum dimensionless tidal heating rate (H_{max}) is provided (see table 1 for other output properties). The black lines in the horizontal planforms indicate the location of the vertical slices. Note that the color scales of the vertical temperature fields are non-linear in order to enhance the contrast in the convective interior.
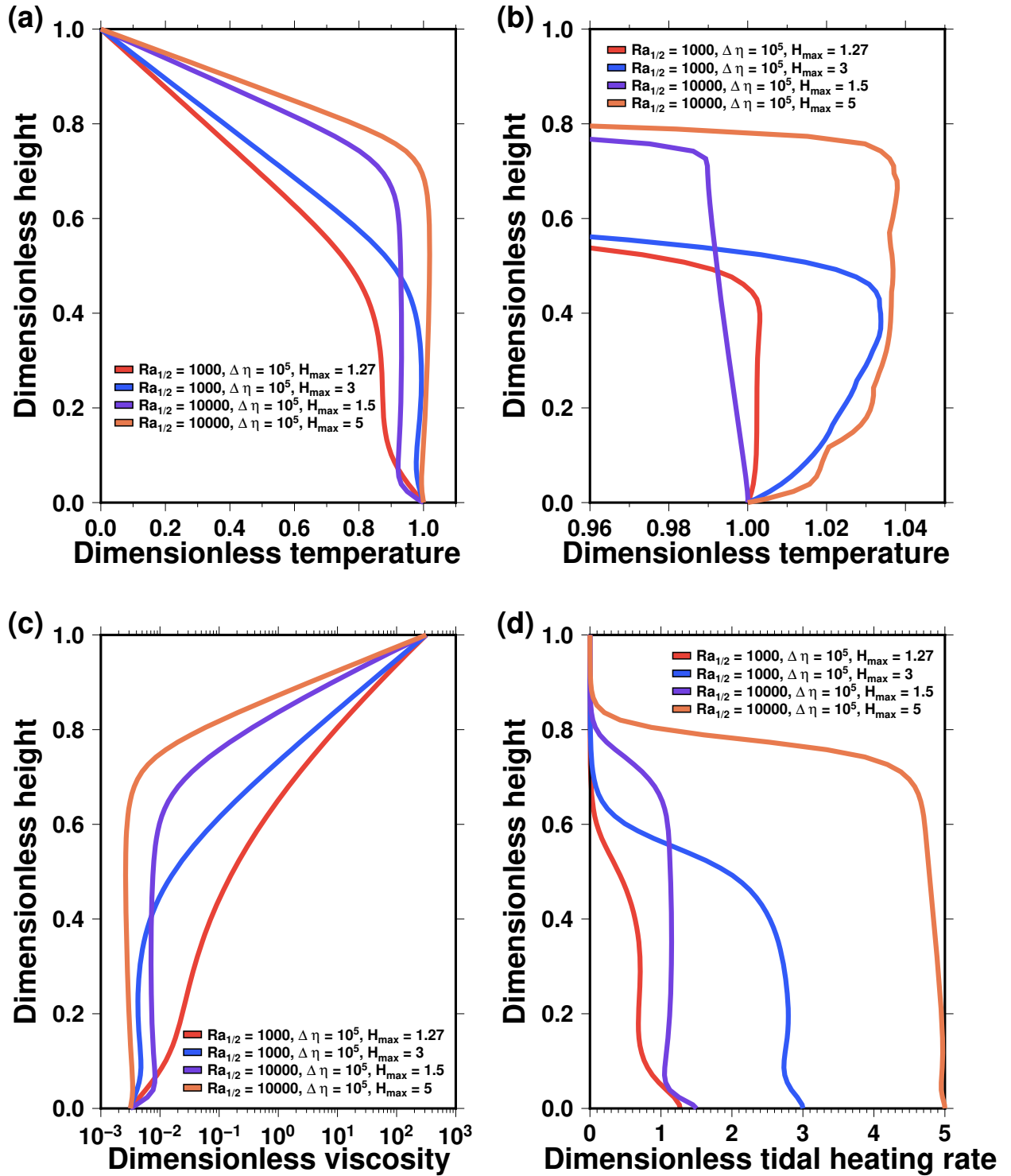
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Figure S2. Horizontally averaged dimensionless (a) temperature, (c) viscosity, and (d) tidal heating rate as a function of height for four different numerical simulations. We also show (b) the dimensionless temperature profile composed of the hottest temperature at each depth.

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