Geodynamics of Icy Satellites: Effects of Latitudinal Surface Temperature Variations and Yielding in Thin Shells. M. B. Weller\textsuperscript{1}, L. Fuchs\textsuperscript{2}, T. W. Becker\textsuperscript{1,3}, and K. M. Soderlund\textsuperscript{4}\textsuperscript{*}; \textsuperscript{1}Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX (mbweller@ig.utexas.edu, twb@ig.utexas.edu, krista@ig.utexas.edu), \textsuperscript{2}Johann-Wolfgang Goethe Universit"{a}t, Frankfurt, Germany (fuchs@geophysik.uni-frankfurt.de), \textsuperscript{3}Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX

Introduction: The surfaces of the icy satellites in our solar system indicate a wide range of geologic activity, from relatively undeformed Callisto and Dione to highly deformed Ganymede, Miranda, Enceladus, and Europa, with the latter two being currently active [e.g., 1-9]. Unraveling how heat is transferred through convection and deformation in the outer ice shells is of key importance for understanding the thermal and dynamic evolution of icy bodies. Their long term evolution controls the existence as well as the longevity of any potential subsurface ocean and, consequently, is a significant factor for the possibility for life on these worlds.

An important process for these bodies is that of latitudinally variable surface temperature ($T_s$), due to differences in solar insolation [e.g., 10], which for the icy satellites may reach a significant fraction of the basal ice shell temperature. Different modes of tectonics have been suggested for some satellites, indicating yielding to be a potentially important process [e.g., 11]. Here we use 3D numerical experiments of global thin ice shell convection to address the effects of latitudinally variable $T_s$ and yield strengths on the convective vigor, surface deformation, and planform of convection.

Numerical Methods: The governing equations of mass, momentum, and energy conservation, assuming infinite Prandtl number and Boussinesq fluid approximation, are solved using the benchmarked finite element code CitcomS [e.g., 12 – 14]. The Rayleigh number ($Ra$), internal heating rate ($Q$), and temperature-dependent viscosity $\eta(T)$ are defined:

\begin{equation}
Ra = \frac{g \rho \alpha \Delta T d^3}{(\kappa \eta)}
\end{equation}

\begin{equation}
Q = \frac{H d^4}{(\kappa \Delta T)}
\end{equation}

\begin{equation}
\eta(T) = \eta_0 \exp\left(A(T + 1)^{1 - 0.5}\right)
\end{equation}

where $\alpha$ is thermal expansivity, $\rho$ is density, $g$ is gravity, $\kappa$ is thermal diffusivity, $d$ is convecting layer depth, and $H$ is the volumetric heating rate. The dimensional reference viscosity at the base of ice shell ($\eta_0$) is estimated to be $\sim 10^{15}$ to $\sim 10^{17}$ Pa\cdot s [e.g., 15]. The rheological parameter, $A$, is chosen to give a variation in viscosity, from the base of the domain to the surface, of $10^2$ – $10^3$. The $Ra$ at the base of the ice shell is taken as $3 \times 10^5$ or $3 \times 10^4$ for $\eta_0 = 10^{15}$ and $10^{14}$ Pa\cdot s, respectively. Uniform internal heating rates range from a maximum value of $Q = 49$ to a minimum of $Q = 10$ (where $Q = 0$ represents basal heating conditions), which correspond roughly to $2.3 \times 10^8$ and $\sim 10^7$ W kg\textsuperscript{-1}, respectively [10]. We currently neglect variations in tidal heating rates for simplicity. Total ice shell thickness is taken as 60 km as an upper bound (giving a core fraction of ~0.76). For models exploring plastic yielding, a non-dimensional yield stress is set to $1 \times 10^5$ – $1 \times 10^7$ (corresponding to ~3 kPa – 3 MPa, in agreement with estimates of ice strengths of ~1 MPa [16]), and viscosity contrasts are set at $3 \times 10^4$ – $1 \times 10^5$. The modeling domain consists of $65 \times 65 \times 65$ nodes for each of the 12 spherical caps of CitcomS.

We have modified CitcomS to allow for continuous variation in the surface temperature boundary conditions from pole to equator (basal non-dimensional temperature of unity, equatorial temperature set nominally to 16.5% of the basal temperature, and polar temperatures of zero). The base of the ice shell may reach temperatures of ~273 K (assuming a pure water ocean [17]).

Results: We find that variation in insolation favors a global flow pattern of upwelling centers focused near equatorial regions and downwelling zones near polar regions. This results in a poleward transport of material that is robust under a variety of conditions tested, from basal and mixed heating, isoviscous and varying degrees of temperature-dependent viscosities, different vigors of convection, and different amplitudes of $T_s$ variations (> 0).

For low viscosity contrast regimes (Fig. 1), the surface temperature gradient results in a “Hadley cell” style of convection, with two hemispheric scale convective cells anchored near the equator (indicated by strong $l = 2$ signals in the poloidal velocity power spectrum). Downwellings become elongated, and oriented nearly perpendicular to the equator. Heat flow is enhanced equatorward, and reduced poleward. Surface stresses in the parameter ranges tested increase substantially as compared to constant surface temperature conditions (~3.3x increase).

For intermediate viscosity contrasts, larger scale plume structures emerge that are focused on the equator. Heat flow is hemispheric-scale, with antipodal enhanced, plume-dominated and suppressed, downwelling hemispheres. For stagnant lids (high viscosity contrast), a hemispheric scale internal convective cell op-
erating under the thick lid forms, similar to the Hadley-like cells found for the low viscosity contrast cases. At the surface due to the local reduction in viscosity (higher surface temperatures along the equator) a poleward orientated flow develops, but is limited to the equator and mid latitudes and does not penetrate deeply into the lid. Heat flow is generally similar to previous cases. Maxima are focused in discrete upwelling plumes that are more common along the equator and less common near the poles. Outside of these plumes, heat flux is negligible, illustrating that heat flow is highly heterogeneous.

Next, we consider the effects of plastic yielding (Fig. 2). For constant \( T_\tau \) cases, a stagnant lid occurs for yield strengths \( \geq 10^7 \). Here, strain-rates are uniformly distributed, reflecting small-scale convection beneath the lid. In contrast, the variable \( T_\tau \) case remains mobile for the same yield strength (due to increasing stress; e.g., Fig. 1). For cases that are mobile, degree-1 structures become established, with upwelling and downwelling hemispheres (both \( T_\tau \) cases), similar to intermediate viscosity contrasts. Activity is largely restricted to quasi-circular subsumption zones, or Geographically Centered Circular-failure (GCC) regions. The GCCs are focused near/on one pole and cross the equator. The GCC regions are spatially and temporally once established, and encircle 25-40% of the surface area of the satellite, though lower yield strengths show more diffuse patterns of deformation.

Within the GCC’s, linear upwellings with high heat flow occur (~90 mW/m²). These regions exhibit high strain rates of \( \dot{\varepsilon} \left( 10^{14} \right) s^{-1} \), similar to strain rates estimated previously for Enceladus’ South Polar Terrain [17]. The active subsumption creates sheet-like downwellings that isolate the interior of the GCC from the rest of the ice shell. An additional large upwelling zone occurs antipodal to the GCC. This mass redistribution due to the GCC may be significant enough to trigger a reorientation of the ice shell [e.g., 18] which would change the relative driving forces. Interestingly, these results may indicate the existence of large-scale anisotropic ice properties that could be detectable with future seismic or electro-magnetic observations.

![Figure 1: Example results showing surface velocity field, heat flux, strain rate, and the log of the poloidal velocity power spectra for constant (top row) and latitudinally variable (bottom row) surface temperatures. The basal \( Q_0 \) is fixed at 3⋅10⁸, \( \Delta\eta \) = 10², \( Q = 0 \), and the average surface temperatures for each model are the same. Arrows denote surface flow direction.](image1)

![Figure 2: Strain rate results for a yielding case showing mobile and stagnant lid states for constant (top row) and latitudinally variable (bottom row) surface temperatures. The basal \( Q_0 \) is fixed at 3⋅10⁸, \( \Delta\eta \) = 3⋅10³, \( Q = 49 \), and the average surface temperatures for each model are the same. Arrows denote surface flow direction.](image2)