Towards Understanding Hemispheric variations in Enceladus’ Ice Shell: Variable Surface Temperatures, Convection, and Yielding. M. B. Weller, L. Fuchs, T. W. Becker, and K. M. Soderlund, Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX (mbweller@ig.utexas.edu, lfuchs@ig.utexas.edu, twb@ig.utexas.edu, krista@ig.utexas.edu)

Introduction: Despite Enceladus' small size, observations reveal it as one of the more geologically active bodies in the Solar System. Its surface is heavily deformed, including ridges, grooves, grabens, rifts, and folds that cover a significant fraction of the planet [1-3]. Notably at a hemispheric scale, there is evidence of a dichotomy between the south (the so-called South Polar Terrain – SPT), and the remainder of the icy satellite. While the origin of the SPT has spurred significant debate, ranging from internal convective processes [e.g., 4-9], oceans and tides to impacts [e.g., 10-11], its existence suggests some form of localization process(es). Here, we use the mantle convection code CitcomS to address the effects of latitudinally variable surface temperature (due to differences in solar heating) for a range of internal heating rates (as proxy for active bodies in the Solar System). Its surface is heavily and planform within Enceladus' ice shell.

Numerical Methods: The governing equations of mass, momentum, and energy conservation, assuming infinite Prandtl number and Boussinesq fluid approximation, are given in non-dimensional form by:

\[ u_{i,j} = 0 \]  
\[ -P_{j} + \eta(u_{i,j} + u_{j,i}) + RaT\delta_{ij} = 0 \]  
\[ T_{j} + u_{i}T_{i} = T_{aw} + Q \]  

where \( u \) is the velocity, \( P \) dynamic pressure, \( \eta \) the viscosity, \( Ra \) the Rayleigh number, \( T \) the temperature, \( \delta_{ij} \) the Kronecker delta, \( Q \) the heat production rate, \( i \) and \( j \) represent spatial indices, \( r \) is a unit vector in the radial direction, \( t \) is time, and the form \( X_{ij} \) represents the derivative of \( X \) with respect to \( y \). Repeated indices imply summation. Eqs. (1-3) are solved using the well benchmarked finite element code CitcomS [e.g., 12-14].

Subsets of our models include temperature-dependent viscosity, which follows as:

\[ \eta(T) = \eta_{0} \exp\left[A \left(\frac{1}{T + 1} - \frac{1}{2}\right)\right] \]  

Here, \( \eta_{0} \) is the pre-exponential factor and is set to unity. The dimensional reference viscosity at the base of the ice shell is taken as \( 3 \cdot 10^{5} \) or \( 3 \cdot 10^{6} \) for \( \eta_{0} = 10^{15} \) and \( 10^{14} \) Pa·s, respectively. Internal heating rates are varied from \( -49 \) to \( -0 \) (corresponding to heating rates between \( 2.3 \cdot 10^{-9} \) W kg\(^{-1}\) and \( -10^{-11} \) [6] \( (Q = 49 - 2) \), as well as additional pure basal heating conditions). Internal heating rates are currently uniform in the model domain. Total ice shell thickness is taken as 60 km as an upper bound (giving a core fraction of \( ~0.762 \) for these models). Some models allow for plastic yielding of the surface, with non-dimensional yielding values set from \( 1 \cdot 10^{-5} \) to \( 1 \cdot 10^{-1} \), (corresponding to yield strength values of \( ~3 \) kPa – \( 3 \) MPa, in agreement with estimates of ice strengths of \( ~1 \) MPa [15]). The modeling domain consists of \( 65 \times 65 \times 33 \) nodes for each of the 12 spherical caps.

The surface temperature \( (T_{s}) \) of Enceladus varies due to solar insolation from equator to poles. The base of the ice shell may reach temperatures of \( ~273 \) K (assuming a pure water ocean [16]). We have modified CitcomS to allow for continuous variation in the surface temperature boundary conditions from pole to equator (a basal non-dimensional temperature of unity, equatorial temperature of 0.165, and a polar temperature of zero).

Results: To isolate the effects of a pole to equator variation in \( T_{s} \), we first consider models that start isoviscous for variable \( Q \) and subsequently add temperature dependent viscosity variation of up to \( 10^{5} \) for both cases of constant and variable \( T_{s} \) (\( Q = 0 \) cases shown in Figure 1A: isoviscous, 1B: temperature-dependent viscosity). Both cases are designed to operate at the same effective \( Ra \) (average \( T_{s} \) is identical for each case).

With regard to the isoviscous cases (Figure 1A), for all \( Q \) ranges, the application of variable \( T_{s} \) tends to disrupt the planform of convection compared to constant \( T_{s} \) cases. The equatorial region favors warm upwellings, while polar regions favor cold downwellings, leading to a thinning equatorial and thickening polar boundary layer, respectively.

Additionally, polar (\( z \)-axis) oriented downwelling zones may develop (downwelling velocity low along \( +y \)-axis limb, Figure 1A). Bulk system velocities are effectively identical between both systems (< 0.5% misfit), indicating the effective \( Ra \) is nearly identical, and that applying variable \( T_{s} \) results in the reorientation of convective cells to reflect the changing driving forces of the boundary conditions (from variable \( T_{s} \)).
We lastly consider the effects of plastic yielding (Figure 2). A non-dimensional yield strength of $10^7$ (3 MPa) was chosen to allow for stagnant-lid behavior for the constant $T_s$ case. The same yield strength in the variable $T_s$ system results in continuous hemispheric scale downwelling, encircling ~30–40% of the surface, with a linear upwelling zone, comprising ~8–12% of the surface area and oriented near but offset from, the $+z$-axis. The downwelling zone roughly correlates to, and is suggestive of, the along polar ($z$-axis) oriented downwelling zones in the isoviscous case in Figure 1A, suggesting that orientations of convective cells can become oriented pole-ward, and facilitate failure near polar zones (throughgoing failure zone through polar region, Figure 2). The size and general orientation of this hemispheric scale feature is evocative for the formation mechanism of the SPT. Future work will explore additional yielding at variable $Q$ as well as strain tracking, which will allow for a strain accumulation, or “memory”, within the ice shell.