GSA DATA REPOSITORY 2014232 Lowry et al.

A. Model Details

GENESIS is composed of an AGCM coupled to both a land-surface model and a slab ocean model with diffusive heat transport. Ocean heat transport is calculated as linear diffusion down the local ocean-temperature gradient. The AGCM has a T31 (3.75º×3.75º) spectral resolution with 18 vertical levels, while the land-surface grid has a 2º×2º resolution (Pollard and Thompson, 1995).

BIOME4 is a terrestrial vegetation model that simulates the equilibrium distribution of 28 modern biome types, each with specific albedo, leaf area index (LAI), and canopy conductance (Kaplan et al. 2003). BIOME4 was run with a surface resolution of 2º×2º, matching the land-surface model. Biome types are updated annually using monthly climate data passed from the GENESIS AGCM.

The three-dimensional thermo-mechanical ice sheet model has a resolution of 1º×2º and is based on the vertically integrated continuity equation for ice mass (Deconto and Pollard, 2003). Mass balance, basal melting, and ice flow determine the evolution of ice geometry. Internal ice temperatures are calculated to account for their effect on rheology and basal sliding. A time constant of 5000 years is used for the local bedrock response to ice loading as a relaxation toward isostacy; lithospheric flexure is modeled by linear elastic deformation. Ice shelves are not simulated in this version of the model, and ice cannot advance into ocean-covered areas.

B. Asynchronous Coupling Technique

An asynchronous coupling technique, which consists of alternating integrations of the AGCM and ice-sheet model, is implemented to couple the climate and ice sheet model following methods presented in Horton et al. (2010) and Herrington and Poulsen (2011). First, GENESIS is integrated for 30 years to produce a steady-state climatology. Second, mean monthly meteorological fields (i.e. surface air temperature, evaporation, and precipitation) from the last 10 years of the integration are passed to the ice sheet model. Third, each ice sheet experiment is run for 500 years. Fourth, the resultant ice sheet geometry is used to update the GCM boundary conditions such that the ice sheet feedbacks are felt by the climate system. This asynchronous coupling process is repeated for 10 iterations for a total of 5000 years in order to evaluate the potential for the AGCM simulated climate to initiate continental-scale glaciation. After 5000 years of asynchronous coupling, we then run the ice sheet model an additional 45,000 years to estimate the total equilibrium volume.

C. Synchronous Coupling Technique (for Solar luminosity and Vegetation Sensitivity experiments)

Similar to the previous approach we ran a 30-year simulation in GENESIS and selected the final 10 years for use in the ice sheet model. In contrast to the previous methodology, we used these climate inputs to run the ice sheet model for 5000 years (rather than 500) and did not feed the new ice sheet geometry back into the GCM. This alternate approach, which does not involve coupling between the AGCM and ice-sheet model, was used for the sole reason that it is more efficient, requiring less computation time. In comparisons of our coupled and uncoupled methods, we found no differences in whether ice sheets were initiated, justifying use of the uncoupled method in this inception analysis (Fig. DR1). The synchronously coupled simulations had minimally lower ice volume at the $4xCO_2$ level than the asynchronously coupled simulations, with the largest difference less than 28% (261,044 km^3). All other time-slices are within a 13% difference. While the total magnitude of this ice volume difference becomes larger at lower pCO_2 levels when larger ice sheets are simulated, our sensitivity experiments are conducted at higher pCO_2 (4x and $8xCO_2$), which at most only produce small glaciers. The purpose of these sensitivity experiments is to test the initiation of ice sheets under different scenarios of vegetation and solar luminosity, rather than a comparison of total ice volume. As a result, this alternative, time-efficient, coupling technique is reasonable.

D. Vegetation/Grassland Sensitivity Experiments

Since land plants did not originate until approximately 450 Ma and grasslands had not evolved in the Paleozoic (Strömberg, 2011), we conducted two additional suites of sensitivity experiments testing influence of vegetation on ice-sheet initiation. In the first suite, the land surface was specified to be bare ground (free of vegetation). We used alternate coupling technique in which we ran GENESIS for 30 years and used the climate output for a 5,000 year run in the ice sheet model. These experiments were conducted at the $4{\times}CO_2$ level and a constant solar luminosity of 97.5% reduced from modern, which allowed us to test whether or not vegetation could cause or prevent the initiation of ice formation, since minimal ice is expected at high pCO_2 levels. To test the effect of grasses, we used the same alternate coupling technique to compare simulations where Biome4 incorporates grasses and simulations where no grass exists. These experiments were conducted at the 2× and 3× CO_2 levels in order to see if the presence or absence of grasses significantly altered the volume and surface area of the ice sheets and minimal ice volume is expected at the 4× CO_2 level.

Comparison simulations using BIOME4 with prescribed bare ground indicate that ice sheet initiation is sensitive to vegetation. In all $4{\times}CO_2$ cases, ice volume and surface area are lower when vegetation is present due to increased surface temperatures, although the extent of this difference varies between experiments (Fig. DR2). The largest differences are observed in the 370, 340 and 250 Ma simulations. The 370 Ma simulation has a 50.8% reduction in ice volume and 49.3% reduction in ice surface area, while 250 Ma simulation had a 43% reduction in ice volume and 37.1% reduction in ice surface area. At

340 Ma, no ice was present with vegetation; removing vegetation allowed for a modest amount of ice to form due to decreased temperature.

Removing grass from BIOME4 had little influence on ice volume or surface area in most cases (Fig. DR2). Ice volume and surface area change by less than 12% for the majority of the simulations. The only large difference was at 480 Ma for the 3×CO_2 level, which had an 84.3% difference in volume. This large relative difference is due to the fact that the ice sheet was small, causing minor changes in volume to have a larger impact. In most cases, the simulation without grasses led to an increase in ice sheet volume and surface area, although in some instances this effect was reversed.

Our vegetation sensitivity experiments show differences between simulations using BIOME4 and simulations with prescribed bare ground, but little difference between simulations with grasslands and those without.

E. Effect of Continental Configuration on Meridional Heat Transport

In order to assess the role of continental configuration on heat transport, we calculated the implied meridional heat transport using the radiation at the top of the atmosphere for each time-slice. The northward movement of continental blocks into the high mid-latitudes of the Northern Hemisphere, starting at 310 Ma, causes a doubling of meridional heat transport of both the atmosphere and ocean due to the setup of strong seasonal temperature gradients between the land and ocean (Fig. DR3). Seasonal contrasts disrupt the zonal flow of winds and cause strong northerly surface winds in the summer, and southerly surface winds in winter, advecting cool air southward and warm air northward (Fig. DR4). As a result, the North Pole warms in the Late Carboniferous and Permian simulations (310, 280, and 250 Ma; Fig. 1).

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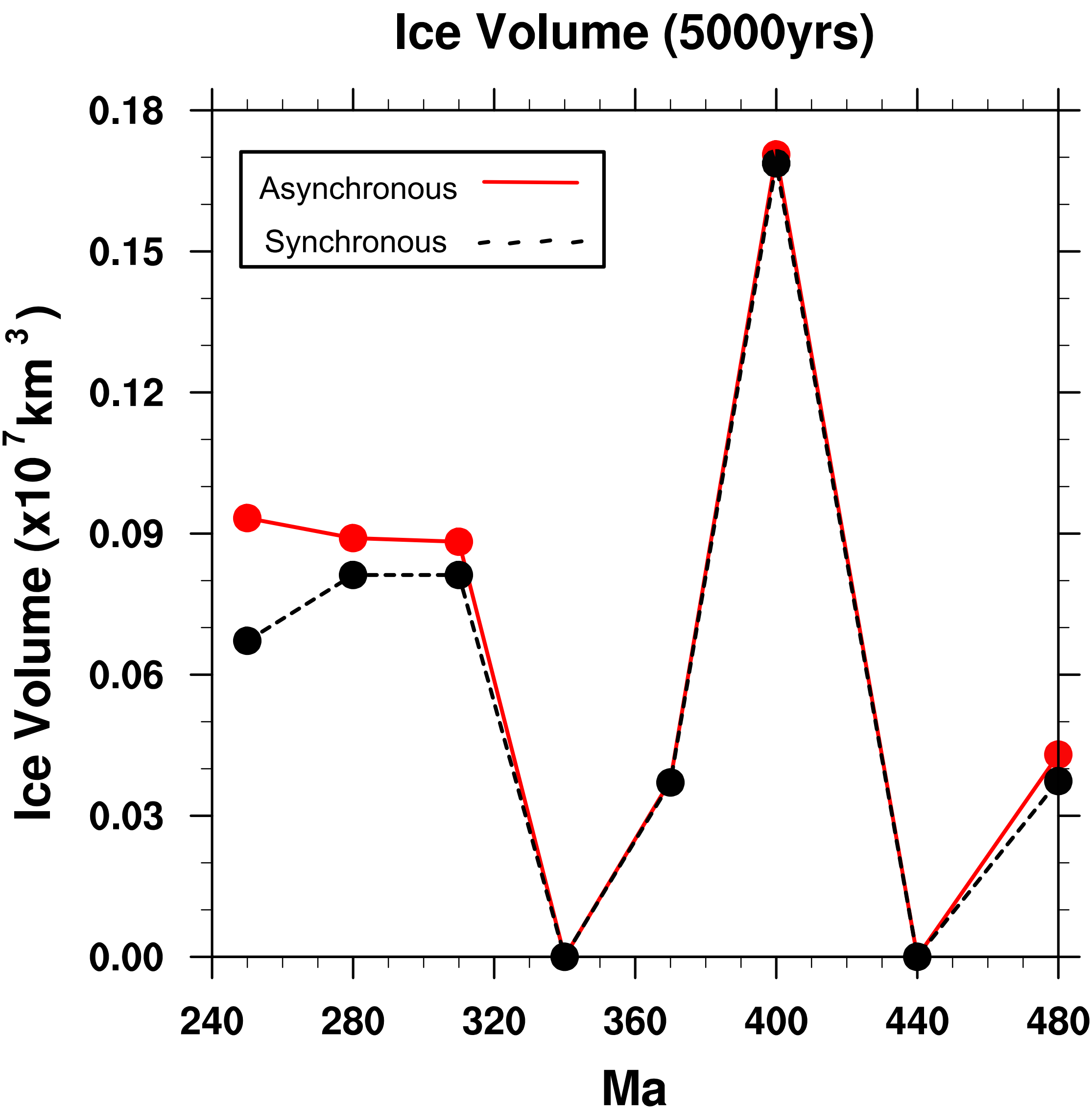
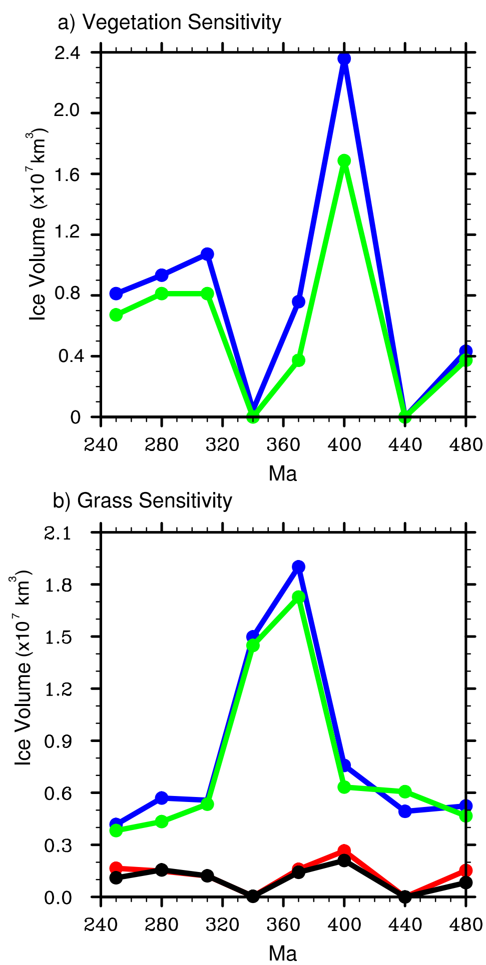
Figure DR1. (a) Ice volume (10^7 km^3) after 5000 years of ice sheet simulation for time slices spanning the Paleozoic at 4×CO_2 with constant solar luminosity and a SHCS orbital configuration using asynchronous coupling (red line) and synchronous coupling (black line).

Figure DR2. Ice volume (10^7 km^3) for a SHCS orbital configuration after 5000 years of ice sheet simulation for time slices spanning the Paleozoic. A. Barren ground (blue line) and vegetated (green line) simulations at 4×CO_2. B. Simulations at 2×CO_2 that include grasslands (green line) and exclude grasslands (blue line) and at 3×CO_2 that include grasslands (black line) and exclude grasslands (red line).

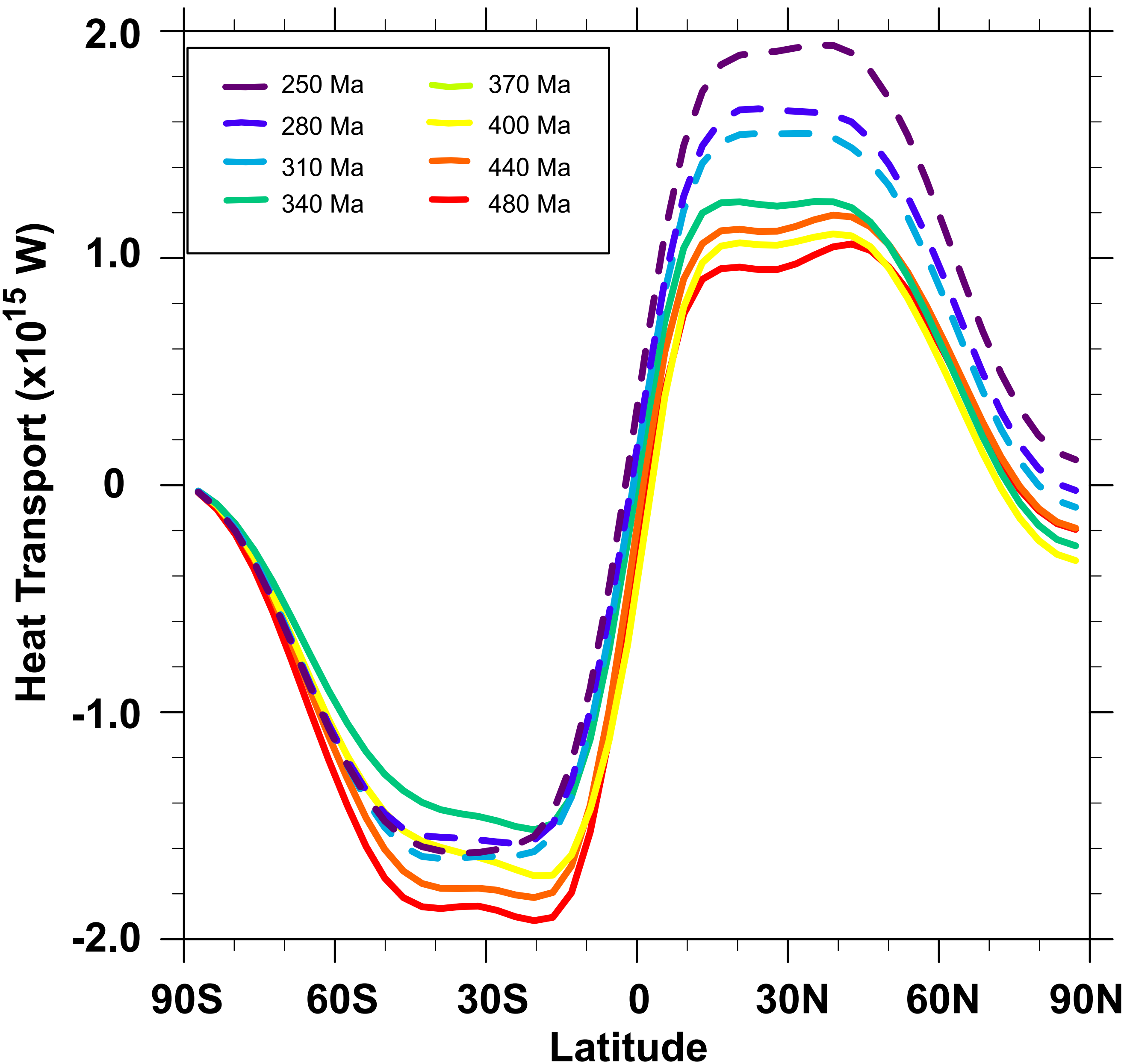
Figure DR3. Total meridional heat transport for a SHCS orbital configuration prior to ice sheet simulation at 2×CO_2 for eight Paleozoic time slices: 250 Ma (purple), 280 Ma (dark blue), 310 Ma (light blue), 340 Ma (dark green), 370 Ma (light green), 400 Ma (yellow), 440 Ma (orange), and 480 Ma (red). Lines are dashed for time slices that occur after the formation of Pangaea.

Figure DR4. Seasonal average surface winds (m/s) for (a) Late Permian (250 Ma) summer, (b) Late Permian (250 Ma) winter, (c) Late Ordovician (440 Ma) summer, (d) Late Ordovician (440 Ma) winter.

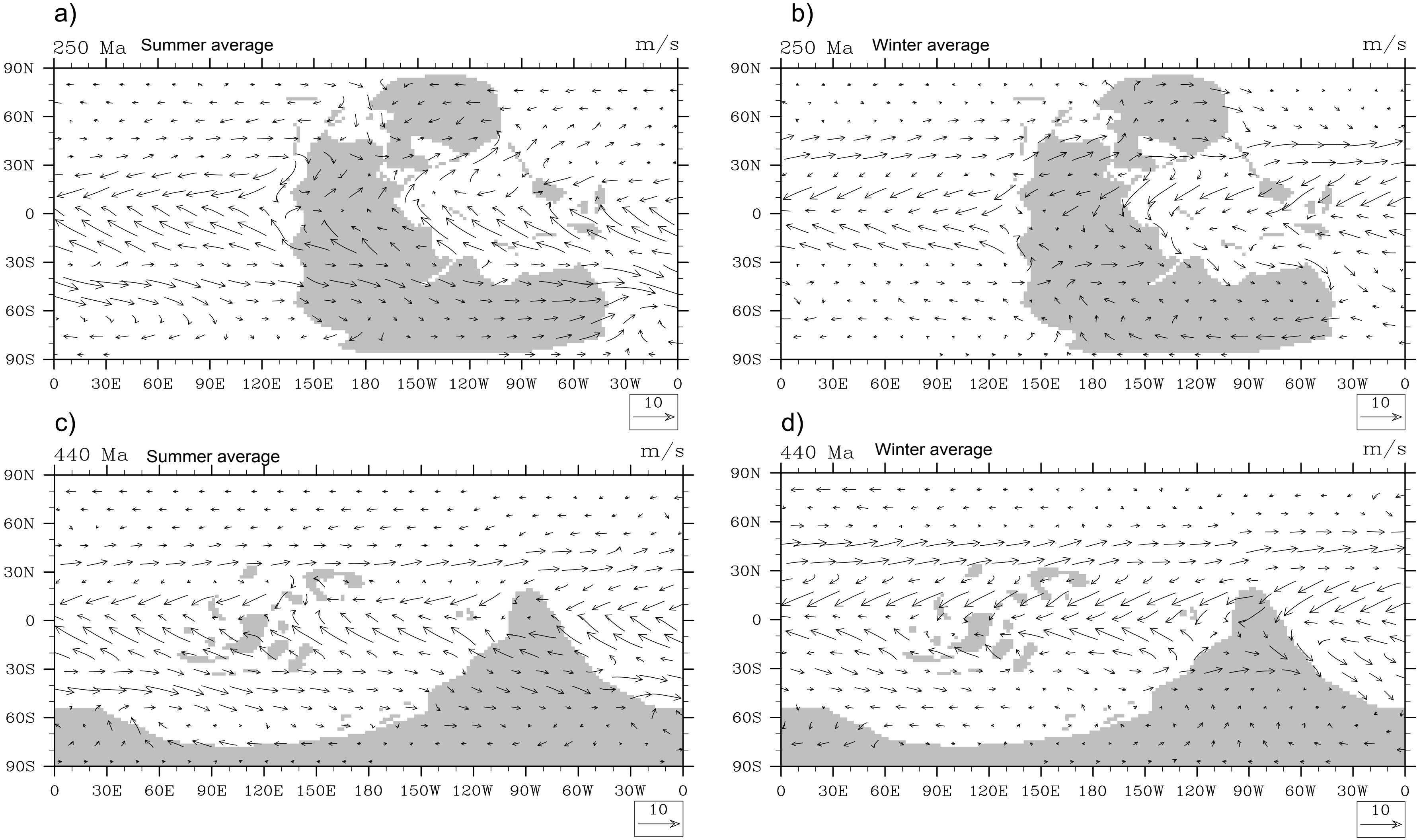

Ice Volume (5000yrs)
Asynchronous
Synchronous
Ice Volume (x10 ^{7} km ^{3})
0.18
0.15
0.12
0.09
0.06
0.03
0.00
240
280
320
360
400
440
480
Ma



a) Vegetation Sensitivity
Ice Volume (x10^7 km^3)
2.4
2.0
1.6
1.2
0.8
0.4
0
240
280
320
360
400
440
480
Ma
b) Grass Sensitivity
Ice Volume (x10^7 km^3)
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
240
280
320
360
400
440
480
Ma



250 Ma
280 Ma
310 Ma
340 Ma
370 Ma
400 Ma
440 Ma
480 Ma
2.0
1.0
0
-1.0
-2.0
Heat Transport ($\times 10^{15}$ W)
90S
60S
30S
0
30N
60N
90N
Latitude


a)
250 Ma Summer average
m/s
b)
250 Ma Winter average
m/s
c)
440 Ma Summer average
m/s
d)
440 Ma Winter average
m/s
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
10