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# 1 The climates of Earth's next supercontinent: effects of 2 tectonics, rotation rate, and insolation

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## 11 **Key Points:**

12 • The climate of a distant future Earth is modeled for two different supercontinent  
13 scenarios.

14 • Location and topographic height of the supercontinents are critical to mean sur-  
15 face temperatures assuming a modern Earth atmosphere

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**Abstract**

We explore two possible Earth climate scenarios, 200 and 250 million years into the future, using projections of the evolution of plate tectonics, solar luminosity, and rotation rate. In one scenario, a supercontinent forms at low latitudes, whereas in the other it forms at high northern latitudes with an Antarctic subcontinent remaining at the south pole. The climates between these two end points are quite stark, with differences in mean surface temperatures approaching several degrees. The main factor in these differences is related to the topographic height of the high latitude supercontinents where higher elevations promote snowfall and subsequent higher planetary albedos. These results demonstrate the need to consider multiple boundary conditions when simulating Earth-like exoplanetary climates.

**Plain Language Summary**

We investigate two tantalizing Earth climate scenarios 200 and 250 million years into the future. We show the role played by plate tectonics, the sun's increase in brightness, and a slightly slower rotation rate in these future climate scenarios. In one case the present day continents form into a single land-mass near the equator, and in the other case Antarctica stays put, but the rest of the present day continents are mostly pushed well north of the equator. The difference in the mean surface temperatures of these two cases differ by several degrees Celsius, while also being distinct in the total surface area in which they maintain temperatures allowing liquid water to exist year round.

**1 Introduction**

Earth's near-future climate has been extensively explored via the IPCC and associated CMIP studies (e.g. Collins et al., 2013). Earth's ancient climate has also been studied at various levels of detail, including the Cretaceous greenhouse (e.g., Huber et al., 2018), the Neoproterozoic Snowball (Pierrehumbert et al., 2011), and on the supercontinent Pangea (e.g., Parrish, 1993; Dunne et al., 2021). Some authors have explored Earth's deep time future climate by looking at increases in CO<sub>2</sub>, solar insolation through time (e.g., Sagan & Mullen, 1972) or looking at the future carbon cycle (e.g. Franck et al., 1999). Yet few have investigated climate effects induced by additional changes in topography and land/sea masks (e.g. Davies et al., 2018).

The geological formations on the ever-changing surface of the Earth have a strong influence on our climate. The transition to a cold climate in the Cenozoic, including the glaciation of Antarctica, was induced by the opening of ocean gateways and reduced atmospheric CO<sub>2</sub> concentrations (Barker, 2001; DeConto & Pollard, 2003; Smith & Pickering, 2003). The development of the Caribbean arc and closing of the Panama Isthmus allowed the Gulf Stream to form, with major consequences for global climate (Montes et al., 2015), whereas the closure of the Strait of Gibraltar led to the Messinian Salinity Crisis (Krijgsman et al., 1999). Furthermore, the Himalayas, a consequence of the India-Eurasia collision, allows for the monsoon (Tada et al., 2016). Recently, Farnsworth et al. (2019) showed that the climate sensitivity for the period 150–35 million years ago is dependent on the continental configuration, particularly ocean area. Schmittner et al. (2011) investigated the effects of mountains on ocean circulation patterns of present day Earth and concluded that the current configuration of mountains and ice sheets determines the relative deep-water formation rates between the Atlantic and the Pacific Oceans.

The continents on Earth aggregate into supercontinents and then disperse on a cycle of 400-600 million years – the supercontinent cycle (Davies et al., 2018; Pastor-Galán et al., 2019; Yoshida, 2016; Yoshida & Santosh, 2018). The latest supercontinent Pangea formed around 310 million years ago and started breaking up around 180 million years ago. The next supercontinent will most likely form in 200–250 million years, meaning

65 Earth is currently about halfway through the scattered phase of the current supercon-  
66 tinent cycle (Davies et al., 2018).

67 There are obvious and strong links between large-scale tectonics and climate. It  
68 would be interesting to know what Earth's climate could be like in the distant future when  
69 continental movements will have taken Earth away from the current continental config-  
70 uration (Davies et al., 2018). Here, we investigate what a climate may look like on Earth  
71 in a future supercontinent state. In particular we focus on changes to land/sea mask,  
72 topography, rotation rate and insolation. We do not delve into details of the future car-  
73 bon cycle or speculations about changes to the Earth's biosphere or atmospheric con-  
74 stituents into the deep future, we keep the latter near modern values. A secondary ap-  
75 plication of climate modelling of the deep-time future is to create a climate model of an  
76 Earth-like exoplanet using the parameters known to sustain habitability and a stable bio-  
77 sphere (Earth). Using the Deep-time future Earth as a basis for exoplanetary climate  
78 studies allows us to establish sensitivity ranges for the habitability and climate stabil-  
79 ity of the future Earth and its distant cousins in our galaxy.

## 80 2 Methods

### 81 2.1 Tectonic maps

82 Maps of the future Earth were produced based on two plausible scenarios for fu-  
83 ture Earth: Aurica (forming around 250 million years from now; Duarte et al., 2018)  
84 and Amasia (forming around 200 million years from now; Mitchell et al., 2012) – see  
85 Davies et al. (2018) for a summary. In both cases the ocean bathymetry was kept as in  
86 Davies et al. (2020), with continental shelf seas 150 m deep, mid-ocean ridges 1600 m  
87 deep at the crest point and deepening to the abyssal plains within 5°, and trenches 6000  
88 m deep. The abyssal plain was set to a depth maintaining the present day ocean volume.  
89 Each topographic file was generated with a 1/4° horizontal resolution in both latitude  
90 and longitude.

91 We generated three subsets of maps for each of the two supercontinent scenarios  
92 (see Table 1):

- 93 1. CTRL: Low mean topography (land close to sea level, 1–200 m), without moun-  
94 tains
- 95 2. PD: Higher mean topography (land close to present day mean topography, 1–4000  
96 m) without mountains
- 97 3. MNTS: Low topography (1–200 m) with mountains (land close to sea level 1–200  
98 m interspersed with mountains 2000–7000 m high)

99 The first subset of maps serve as a control (CTRL), allowing us to test the effect  
100 of the position and geometry of the continents without the influence of high topographies  
101 and particular features such as mountain ranges. It could also simulate a supercontinent  
102 that has existed long enough to have been almost fully eroded. The land here has been  
103 assigned topography with a normal distribution (mean = 1 m and standard deviation  
104 = 50 m) equivalent to white noise in x-y, yielding topographic heights varying from 1  
105 to 200 m.

106 The second set of maps assume mean topographic values close to those of present  
107 day (PD) Earth but with no significant variation (e.g., no high mountains). This was  
108 made by applying a random topography following a normal distribution with mean and  
109 standard deviations closer to those of present day Earth's topography (i.e., mean of 612  
110 m and standard deviation of 712 m). The resulting topography varies between 1 and 4000  
111 m in height.

**Table 1.** A summary list of the simulations & results.

Sim	Name	Topography	Ins <sup>a</sup>	LoD <sup>b</sup> (hrs)	Runtime (years)	T <sup>c</sup> (C)	Balance (Wm <sup>-2</sup> )	A <sup>d</sup> (%)	SnowFr <sup>e</sup> (%).	Hab <sup>f</sup> (%).
Aurica 250Myr into the Future										
01	Aurica	CTRL	1.0260	24.5	2000	20.5	0.2	30.5	0.5	1.000/1.000
02	"	PD	"	24.5	2500	20.6	0.1	30.1	0.6	0.955/0.956
03	"	MTNS	"	24.5	2000	20.6	0.2	30.3	1.5	0.974/0.983
Amasia 200Myr into the Future										
04	Amasia	CTRL	1.0223	24.5	3000	19.5	0.3	30.2	5.0	0.932/0.983
05	"	PD	"	24.5	3000	16.9	0.2	31.3	10.2	0.862/0.901
06	"	MTNS	"	24.5	3000	20.2	0.2	30.0	4.7	0.926/0.976
Modern Earth										
07	Earth #1		1.0	24.0	2000	13.5	-0.1	31.1	9.3	0.869/0.953
08	Earth #2		1.0	24.5	2000	13.3	0.2	31.0	9.5	0.865/0.951
09	Earth #3		1.0260	24.5	2000	17.7	-0.0	30.6	6.4	0.930/0.974

<sup>a</sup> Insolation, where  $1.0 = 1361 \text{ W m}^{-2}$  (Modern Earth).<sup>b</sup> LoD = Length of Day in hours.<sup>c</sup> Global mean surface temperature in degrees Celsius from an average over the last 10 years of the model run.<sup>d</sup> Planetary Albedo.<sup>e</sup> Snow and Ice, global fractional area.<sup>f</sup> Habitable fraction (Spiegel et al., 2008)  $T > 0 / T > -15^\circ$ . For an explanation see Section 3.

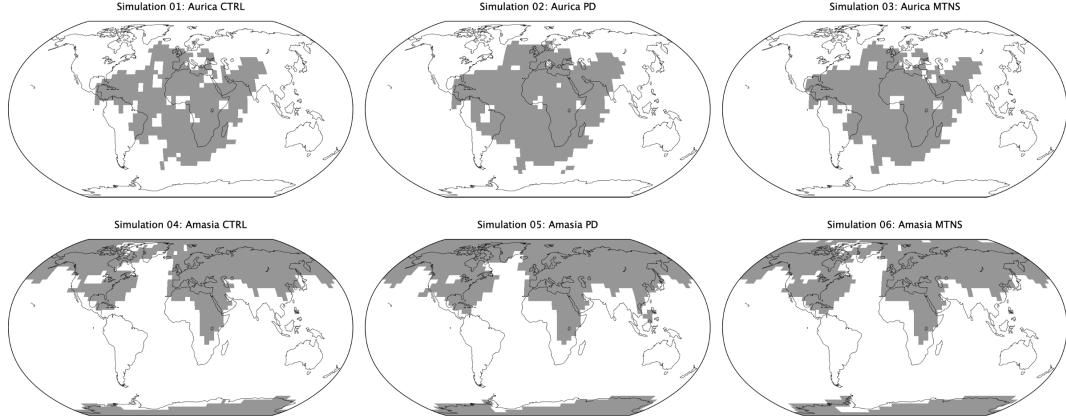
In the third set mountain ranges (MTNS) are included. The land of the supercontinent was first given a random topography similar to the control map (varying randomly between 1 and 200 m), after which mountains were added manually. The mountains are of three types: 1) Himalaya-type, which result from the collision of continents during the formation of the supercontinent, with an average peak elevation of 7500 m; 2) Andes-type, located at the margins of the continents along major subduction zones, with an average peak elevation of 4000 m; and 3) Appalachian-type, which correspond to eroded orogens that were formed and then partially eroded during the supercontinent cycle, with an average peak elevation of 2000 m. In all cases, the width of the mountains is 5° from peak to base.

## 2.2 Rotation changes

Day-length for the future was computed based on the simulated tidal dissipation rates presented in Green et al. (2018); Davies et al. (2019). The average dissipation during the remaining part of the supercontinent cycle is approximately half of the present day value (Green et al., 2018; Davies et al., 2019), leading to a change in day length that cannot be ignored. Consequently, we expect a change in daylength at approximately half the rate of present day, or about  $1 \times 10^{-3}$  s per 100 years (Bills & Ray, 1999) over the next 200 My. This leads to a day at the supercontinent state being  $\sim 30$  minutes longer than today, and this length of day (24.5 hours) was consequently used in all of the Future Climate General Circulation Model simulations discussed below.

## 2.3 General Circulation Model set up

The ROCKE-3D General Circulation Model (GCM) version Planet 1.0 (R3D1) as described in Way et al. (2017) is used for this study. A fully coupled dynamic ocean is utilized. Using data generated via Claire et al. (2012) we use an insolation value of  $1361 \times 1.0223 = 1391.3 \text{ W m}^{-2}$  for the Amasia simulations (04–06) 200 Myr into the future. We use a value of  $1361 \times 1.0260 = 1396.4 \text{ W m}^{-2}$  for the Aurica simulations (01–03) 250 My into the future. We do not change the solar spectrum as the changes for such a small leap into the future will be minimal in terms of its effect on the planet's atmosphere.



**Figure 1.** Land (grey) and Ocean/Lake (white) masks used in experiments of Table 1. Present day Earth continental outlines are shown for reference.

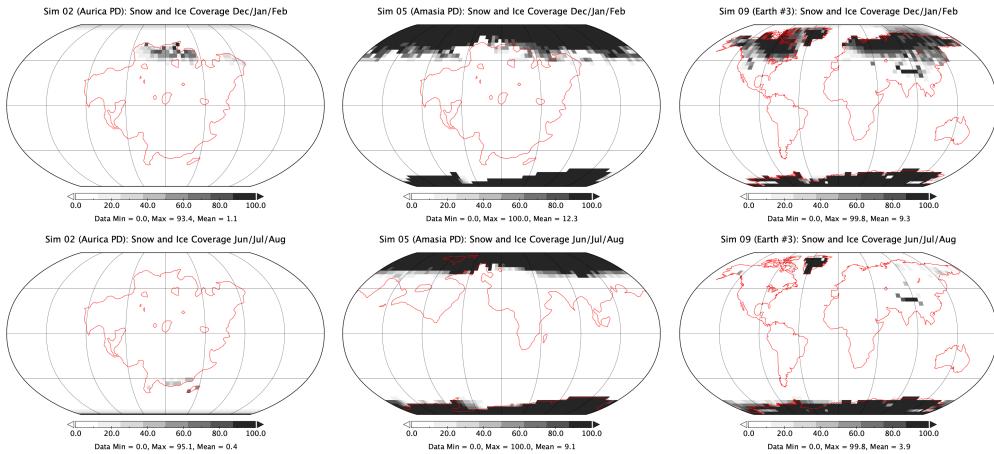
141 We use a 50/50 clay/sand mix for the soil given that we have no constraints on what  
 142 the surface will be like in the deep future and is a value commonly used in the exoplanet  
 143 community (e.g. Yang et al., 2014; Way et al., 2018). In a 3D-GCM the soil is impor-  
 144 tant for its albedo and water holding capacity, see Section 2 of (Del Genio et al., 2019)  
 145 for details on the latter. 40 cm of water is initially distributed into each soil grid cell.  
 146 We use a ground albedo of 0.2 at model start, but the albedo will change via snow de-  
 147 position (brighter), or from rainfall (darker) as the GCM moves forward in time.

148 The original topography resolution of  $1/4^\circ \times 1/4^\circ$  from the tectonic maps discussed  
 149 in Section 2.1 is down-sampled to a resolution of  $4^\circ \times 5^\circ$  in latitude by longitude, which  
 150 is the default R3D1 resolution. The standard deviation from the down-sampling is used  
 151 to set the roughness length of the surface in each grid cell. River flow direction is based  
 152 on the resulting topography and exits to the ocean when possible. Large inland seas (typ-  
 153 ically less than 15 contiguous grid cells) are defined as lakes rather than ocean grid cells.  
 154 The GCM allows lakes to expand and contract as dictated by the competition between  
 155 evaporation and precipitation. The same holds for the possible creation and disappear-  
 156 ance of lakes. This allows the model to handle inland surface water in a more sophisti-  
 157 cated manner than making all surface water defined as ocean grid cells. This is highly  
 158 desirable because ocean grid cells cannot be created or destroyed during a model run.

159 Any ocean grid cell with a depth less than 150 meters (from the down-sampled  $4^\circ \times$   
 160  $5^\circ$  data) was set to have a value of 204 meters (the mean depth of ocean model level 6).  
 161 This is especially important at high latitudes where shallow ocean cells may freeze to the  
 162 bottom causing the model to crash due to its inability to dynamically change surface types  
 163 from ocean to land ice.

164 The down-sampling has a side effect in that the land-sea mask will differ slightly  
 165 between the three topographic types (CTRL, PD, MTNS). For example, in a case with  
 166 a collection of ocean or lake grid cells adjacent to a number of high elevation land to-  
 167 polography grid cells the down-sampling may change the combined ocean + land grid cells  
 168 into a land grid cell, or vice-versa if the mean depth of the ocean grid cells is larger than  
 169 the height of the land grid cells. This is why the land/sea masks differ between CTRL,  
 170 PD and MTNS in Figure 1, even though their  $1/4^\circ \times 1/4^\circ$  parents had exactly the same  
 171 land-sea mask.

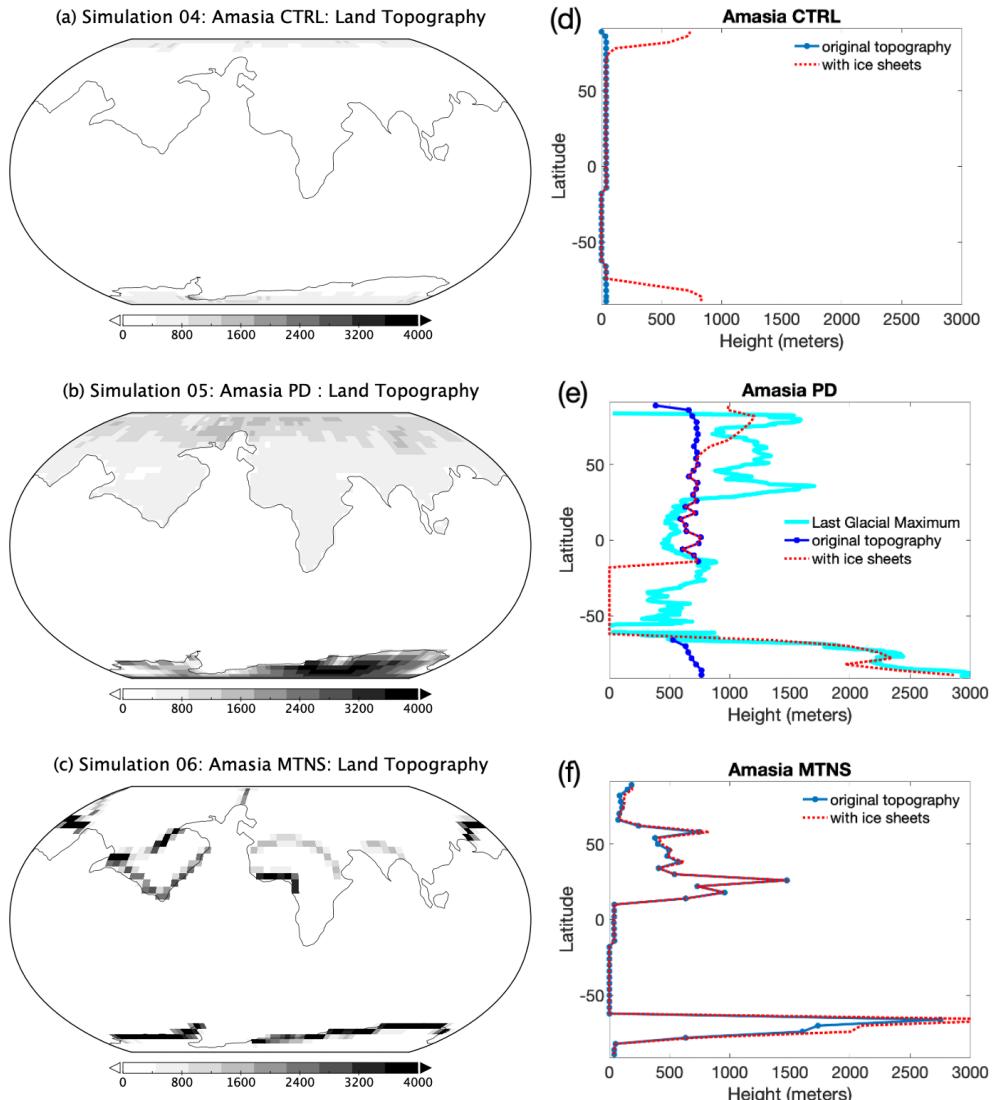
172 One side-effect of having quite distinct land elevations and a lack of oceans in po-  
 173 lar regions in the Amasia runs (sims 04–06) is that snow accumulation can result in the



**Figure 2.** Individual grid cell snow+ice fractional amounts. For simulation 02 (Aurica PD) (left), simulation 05 (Amasia PD) (middle) and simulation 09 (Earth #3) (right) for a 50-year climatological mean (from the last 50 years of each run) of the months of December, January and February (top) and June, July and August (bottom).

growth of ice sheets akin to that of Earth's last glacial maximum (LGM) when the Earth was cooler than present day (Argus et al., 2014; Peltier et al., 2015). The increase in ice sheet height can influence the climate as there may be substantially more snow accumulation at higher elevations, whereas rain would normally fall at lower elevations, due to differences in the lapse rate. Because R3D1 does not have a dynamic ice sheet model we adopt the following approach to deal with these snow accumulations. To accommodate the possibility of such ice sheets we ran models with the original Amasia topography (sims 04–05) and allowed snow to accumulate unhindered. Once these runs reached equilibrium we then used these snow accumulations as the bases for modified production runs. Fifty year climatological averages of snow accumulation (see Figure 2 middle panels) over N. Hemisphere summer months (June, July & August) were used to increase the land elevations where necessary. We choose summer months since those minimum northern hemisphere accumulations work well to allow accumulation in the Fall/Winter months and evaporation in the Spring/Summer months. The same procedure is used in the southern hemisphere with 50 year climatological averages over the months of December, January & February. We then perform small areal averages over the highest latitudes to simulate the effect of ice sheet movement. These summer minima with snow accumulations are then labeled as permanent ice sheets (with appropriate albedo) in the model topography boundary condition files. An offline ice sheet model would be preferred as is typical in LGM studies (Argus et al., 2014; Peltier et al., 2015) but is beyond the scope of the present exploratory work. Figure 3 includes original topography plus snow accumulations (denoted as 'with ice sheets' in red dotted lines) versus the original topography (blue solid lines). For comparison purposes Figure 3e over plots the LGM data from Argus et al. (2014); Peltier et al. (2015). Recall that the LGM was at a time of lower solar insolation and differing orbital parameters from our future Earth scenarios. We believe that Figure 3e with the LGM over plotted demonstrates that our approach to dealing with the ice sheets is not unreasonable. The south polar cap is reproduced with high fidelity, while the north polar cap (on average) also mimics the LGM pretty well.

The atmosphere is set to roughly Earth constituents in the year 1850: Nitrogen dominated with 21% Oxygen, 285 ppmv CO<sub>2</sub>, 0.3 ppmv N<sub>2</sub>O, and 0.79 ppmv CH<sub>4</sub>. No aerosols or Ozone (O<sub>3</sub>) are included. For the minor species (CO<sub>2</sub> and CH<sub>4</sub>) this is perhaps the simplest choice given the variability in the past (e.g. Ramstein, 2011), and long-term un-



**Figure 3.** Amasia topography comparison: (a) Simulation 04 (Amasia CTRL): Area weighted mean height =  $40 \pm 11$  m ‘original topography.’  $90 \pm 30$  m ‘with icesheets.’ (b) Simulation 05 (Amasia PD): Area weighted mean height =  $702 \pm 218$  m ‘original topography.’  $921 \pm 224$  m ‘with icesheets.’ (c) Simulation 06 (Amasia MTNS): Area weighted mean height =  $520 \pm 542$  m ‘original topography.’  $568 \pm 593$  m ‘with icesheets.’ (d) Simulation 04: Area weighted mean land height per latitude. e.) Simulation 05: Area weighted mean height per latitude for Sim 05 and Earth Last Glacial Maximum (cyan). f.) Simulation 06: Area weighted mean height per latitude.

certainties associated with human generated climate change and the subsequent uncertainties associated with the long-term evolution of the carbon cycle (e.g., Franck et al., 1999). For the second most abundant species in Earth's atmosphere ( $O_2$ ) the choice is consistent with recent estimates by Ozaki and Reinhard (2021) who set a  $1\sigma$  limit of the longevity of Earth's 21% oxygenated atmosphere of  $\sim 1 \times 10^9$  years. For comparison purposes with related work (Way et al., 2018) we include a modern Earth-like land/sea mask in Earth #1—#3 (sims 07–09) (Table 1) with these same atmospheric constituents and a bathtub ocean. The Earth-like land/sea mask used in these simulations is described in Way et al. (2018) and shown in Figure 8 of that paper. These changes to the land/sea mask do not greatly effect the mean surface temperature and the bathtub ocean makes the model more resistant to crash conditions often associated with shallow ocean cells freezing to the bottom as would be likely in some of the cases herein. To better understand the possible effects of rotation rate and insolation (given such parameters used in the Aurica & Amasia sims 01–06) we take the same Earth #1 model (sim 07) and slow the rotation rate in Earth #2 sim 08 to be the same as in the Aurica and Amasia sims 01–06, and then increase the insolation in Earth #3 sim 09 to be the same as that of the Aurica sims 01–03 as shown in Table 1 (the higher of the two insolations used at 200 and 250 Myr into the future).

### 3 Results

Let's first attempt to disentangle any effects of the slower rotation rate. We do this by looking at the modern Earth #1—#2 (sims 07—08). Table 1 shows a minimal difference between the mean surface temperature between our Earth-like world with modern rotation rate (Earth #1 sim 07) and the 24.5 hour rotation for Earth #2 sim 08 that is used by our Aurica and Amasia simulations (01–06). Planetary Albedo and snow+ice fraction are also nearly the same. In Figure 4a visible high latitude regional temperature differences ( $\sim 5^\circ\text{C}$ ) are seen between Earth #1 & #2 (sims 07 & 08) even if mean difference is only  $0.2^\circ\text{C}$ .

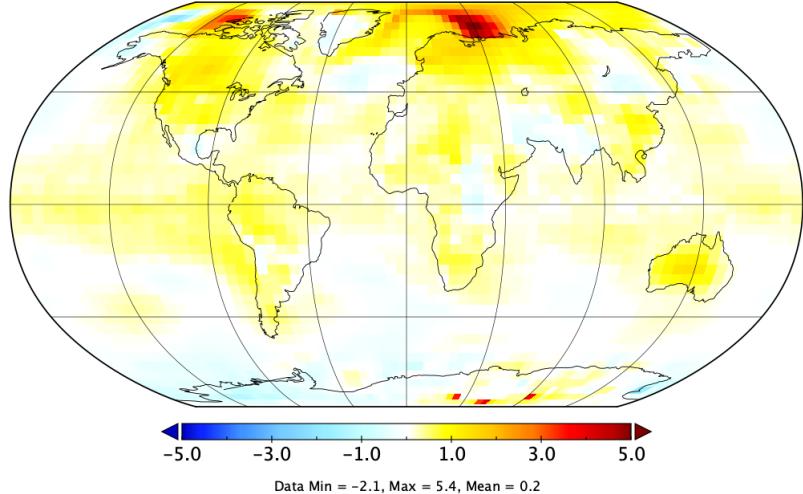
Looking at Figure 5 (left panels) we see that Earth #1 & #2 (sims 07 & 08) also have very similar atmospheric, ocean and total meridional transport. If one compares the min and max stream functions in the tropics in Figure 6a and 6b (Earth #1 & #2, sims 07 & 08) the differences are small:  $-9.1 \times 10^{10} / -9.2 \times 10^9 \sim 1\%$ ,  $1.2 \times 10^{11} / 1.19 \times 10^{11} < 1\%$  (values are also noted below each figure).

We find very little evidence that the additional 30 minutes in the length of day has any appreciable effect on the climate dynamics. Work by Showman et al. (2013, Figure 5) has shown that pole to equator temperature differences should decrease as rotation rate slows. There is a marginal difference at high northern latitudes that in fact goes in the opposite direction (Figure 7a). With the slower rotating Sim 08 having a very small increase in equator-to-pole temperature difference. Note that the Showman et al. (2013) result is for much larger changes in rotation rate. Finally in Figure 7b we plot the eddy energy transport fluxes for Earth #1 & #2 (sims 07 & 08). One can see that the mid-latitude eddy energy flux in Earth #1 (sim 07) is slightly larger than that of Earth #2 (sim 08), which would be consistent with that of Showman et al. (2013), but again the differences are marginal.

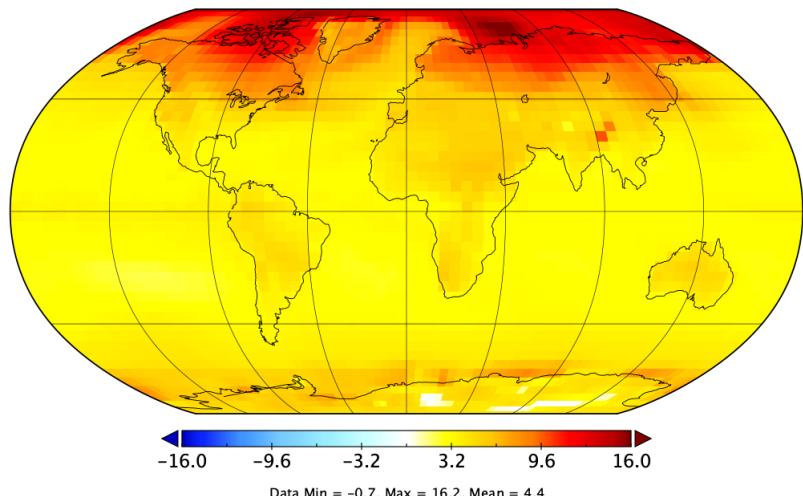
Next the rotation rate is fixed at 24.5 hours, but the insolation is increased from Earth #2 sim 08 ( $1361 = \text{W m}^{-2}$ ) to Earth #3 sim 09 ( $1361 \times 1.0260 = 1396.4 \text{ W m}^{-2}$ ). The differences are much clearer here with a  $\sim 5^\circ\text{C}$  difference in the mean surface temperature. The planetary albedo has decreased  $\sim 0.5\%$  which tracks the decrease in Snow+Ice fraction of  $\sim 3\%$ .

It should be noted that previous work has shown that some ancient Earth super-continent phases, which are comparable to our Aurica simulations 01–03, have had more

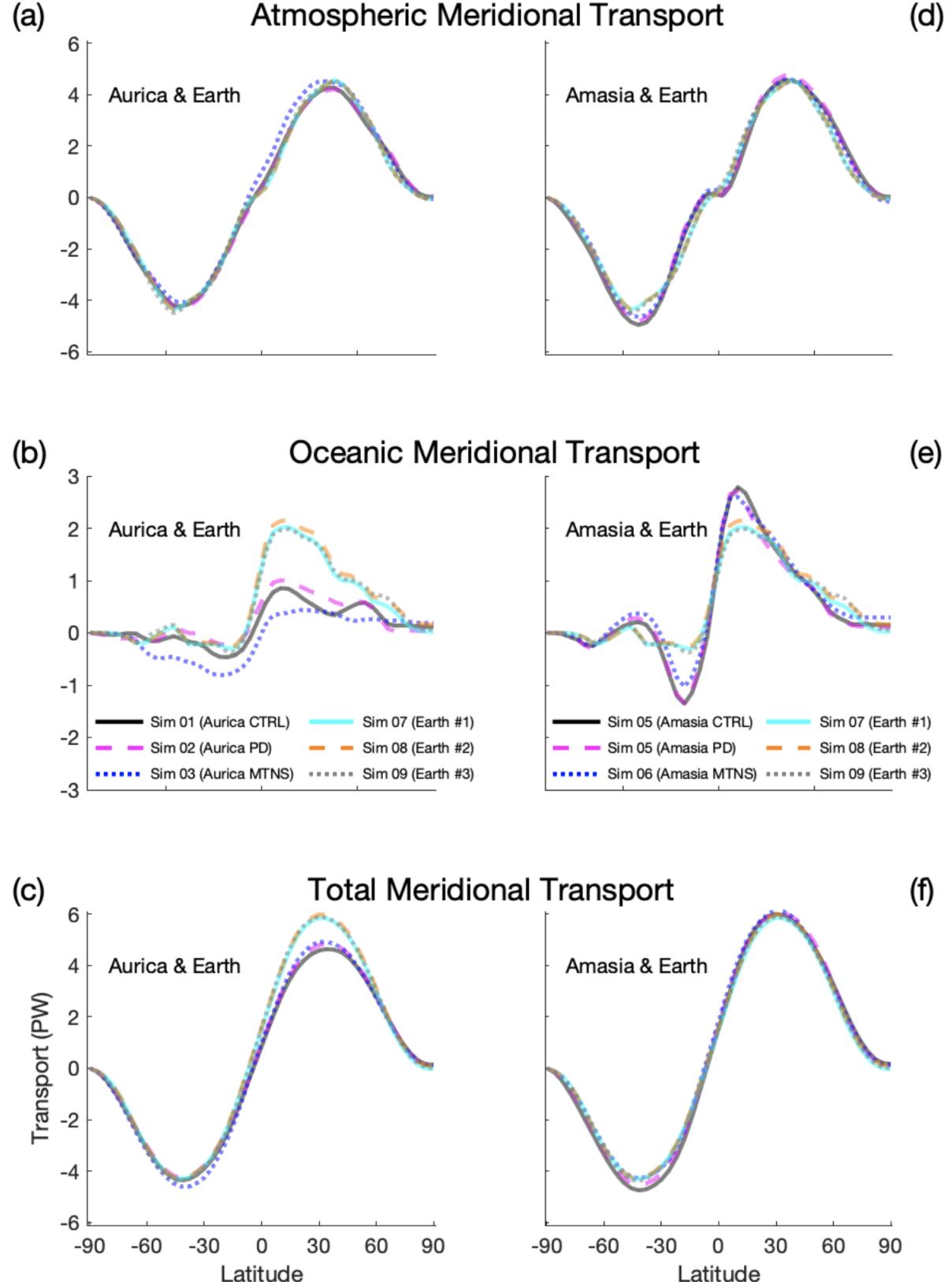
(a) Sim 07 (Earth #1) – Sim 08 (Earth #2) Mean Surface Air Temperature



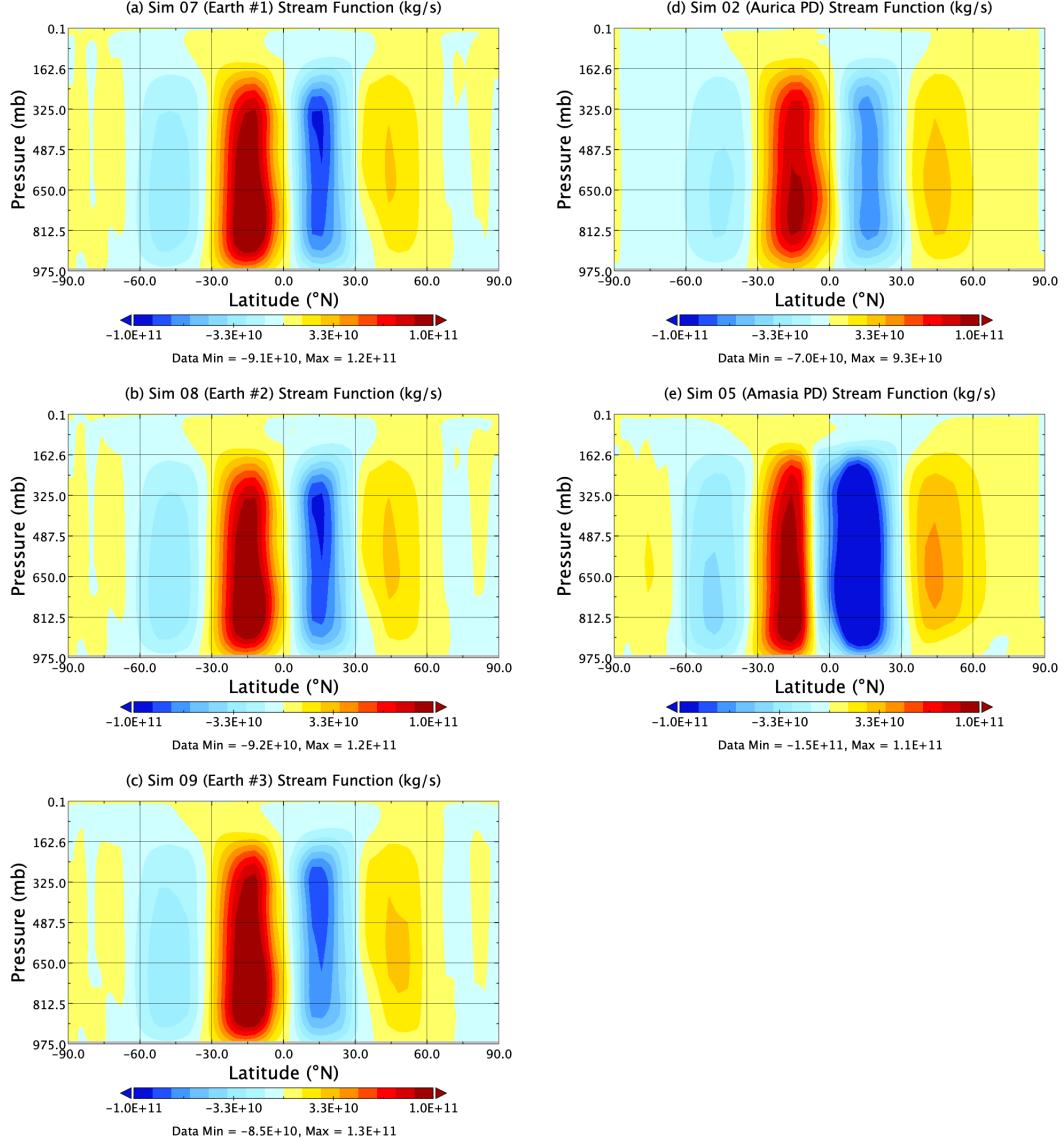
(b) Sim 09 (Earth #3) – Sim 08 (Earth #2) Mean Surface Air



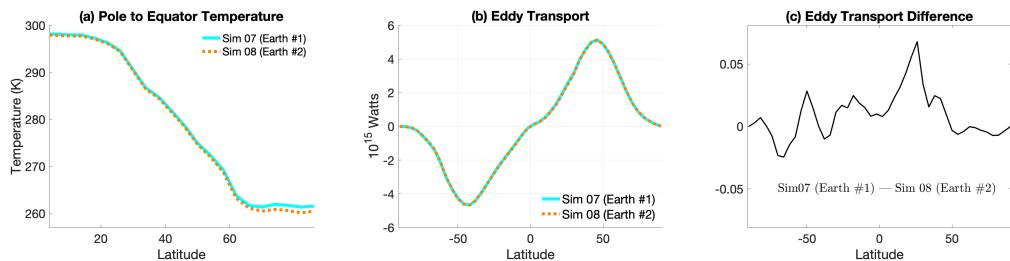
**Figure 4.** Differences in 10 year mean surface temperature (a) Simulation 07 (Earth #1) — Simulation 08 (Earth #2) and (b) 09 (Earth #3) — 08 (Earth #2). Note color bounds both straddle zero equally (cool blue colors below zero, zero white, yellows/reds above zero), but have different limits in each plot.



**Figure 5.** Atmospheric, Oceanic and Total Meridional Transport in PetaWatts (PW) =  $10^{15}$  Watts. Note that the ordinate limits for the middle panels are half those of the upper and lower panels to make the differences more readily discernible.



**Figure 6.** Stream Function for (a) Sim 07 (Earth #1), (b) Sim 08 (Earth #2), (c) Sim 09 (Earth #3), (d) Sim 02 (Aurica PD), (e) Sim 05 (Amasia PD).



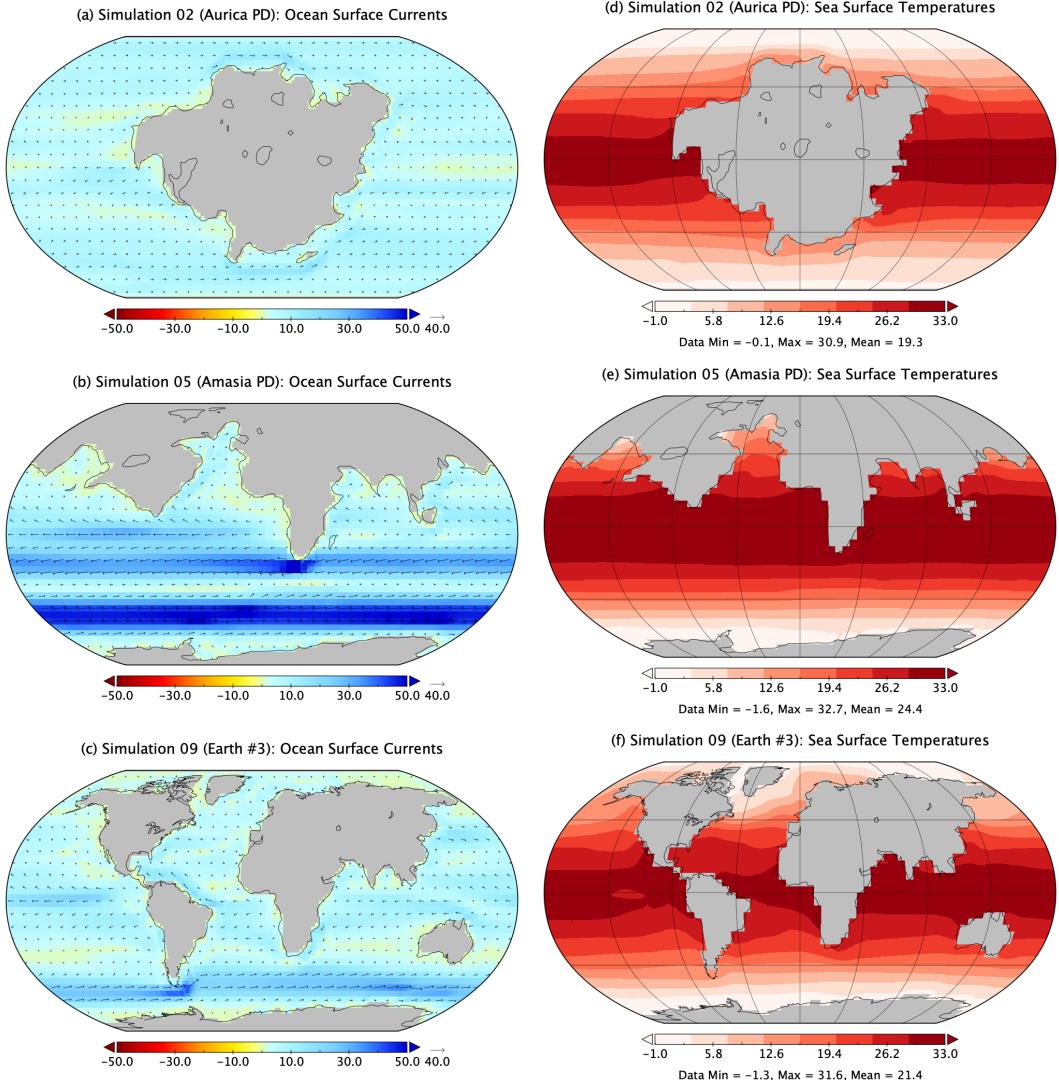
**Figure 7.** (a) Plotting pole to equator temperature contrast in Kelvin as per Figure 5 in Showman et al. (2013). (b) Eddy energy fluxes for simulation 07 (Earth #1) and simulation 08 (Earth #2) and (c) their difference.

256 arid interiors where weathering effects and CO<sub>2</sub> draw down may have been less efficient  
 257 (e.g. Jellinek et al., 2019). This would increase surface temperatures as the balance of  
 258 CO<sub>2</sub> would tend to be larger than present day because volcanic outgassing (sources) would  
 259 likely remain constant while CO<sub>2</sub> drawdown (sinks) would decrease. However, there are  
 260 other climatic effects to consider. For example, the Amasia reconstruction is essentially  
 261 an arctic supercontinent with an independent and isolated antarctic continent, mean-  
 262 ing both poles are covered by land, and much of that is covered by ice. Amasia is thus  
 263 in essence a shift to consolidate the present day domination of northern latitude land masses  
 264 even further north.

265 This increase in land masses at northern latitudes means that there is less ocean  
 266 heat transport to melt the ice in the northern hemisphere summers as happens on mod-  
 267 ern Earth. Some of the heating differences can be seen in the middle right panel of Fig-  
 268 ure 5 where the oceanic meridional transport for the modern Earth #1—#3 simulations  
 269 (07–09) is lower at lower latitudes than the Amasia simulations (04–06). This is because  
 270 there are no southern low latitude continents (e.g. S. America or S. Africa) and the north-  
 271 ern hemisphere continents are now pushed to higher northern latitudes in the Amasia  
 272 runs. At the same time in Figure 8 we see that there are active ocean currents in the mod-  
 273 ern Earth #3 sim 09 (bottom panels) near the northern polar regions (and in the Au-  
 274 rica sims at high latitudes - top panels), but none are possible in the Amasia PD sim 05  
 275 run (middle panels).

276 The lack of a northern polar ocean means that more ice resides on land and in lakes  
 277 all year round near the north pole, as we see in present day Antarctica, for the three Ama-  
 278 sia simulations (sims 04–06). This is the well known ice-albedo climate feedback and ex-  
 279 plains why the Amasia simulations tend to be cooler than the Aurica ones. Amasia PD  
 280 (sim 05) is the coolest of the Amasia simulations. This is because its mean topographic  
 281 height is higher (especially near the north polar regions) than in Amasia CTRL & MTNS  
 282 (sims 04 and 06). See Figure 3e versus 3d and 3f. The higher relief means the Amasia  
 283 PD (sim 05) lapse rate is lower on average and as discussed in the Methods section above  
 284 it is cooler and hence instead of rainfall we tend to get snowfall at high latitudes. This  
 285 fact is also born out in Figure 2 where grid snow+ice fractional amounts are quite high  
 286 in the northern hemisphere winter months (top center) and southern hemisphere win-  
 287 ter months (bottom center) in comparison with the modern Earth #3 simulation 09 with  
 288 the same rotation rate and insolation. Note that Earth #3 (sim 09) coverage on Green-  
 289 land in the northern hemisphere summer. This is because we have not adjusted the height  
 290 of Greenland assuming it no longer has an ice sheet, so it will accumulate snow and main-  
 291 tain it because of its higher altitude. In reality it would likely not be snow covered at  
 292 this higher insolation as its topographic height would surely be far lower, although one  
 293 would also have to consider the effects of any land rebound height from the removal of  
 294 the ice sheets.

295 It is informative to contrast Aurica PD (sim 02) with Amasia PD (sim 05). Au-  
 296 rica PD (sim 02) has land at lower latitudes and uses the same “present day” (PD) to-  
 297 topographic height values for inputs as Amasia PD (sim 05) where the landmasses reside  
 298 at high latitudes. In Table 1 we give their mean surface temperatures, planetary albedo,  
 299 fractional snow & ice coverage and “Habitable Fraction.” The snow & ice coverage as  
 300 illustrated in Figure 2 is clearly related to the planetary albedo and mean surface tem-  
 301 peratures in Table 1. In Table 1 it is clear that the snow & ice fractions are much higher  
 302 for the Amasia runs (04–06) compared to the Aurica runs (01–03), and highest for Ama-  
 303 sia PD (sim 05) in particular. Amasia PD (sim 05) has the highest snow fraction amount  
 304 corresponding directly to the lowest mean surface temperature of the Aurica and Ama-  
 305 sia simulations (01–06). This coldest of the future climates Amasia PD (sim 05) is nearly  
 306 1°C cooler than its corresponding modern Earth #3 simulation (09). We see a lower frac-  
 307 tional snow+ice coverage for Earth #3 (sim 09) in Figure 2 versus that of Amasia PD  
 308 (sim 05). This in turn is related to the fact that Earth #3 (sim 09) maintains open ocean



**Figure 8.** Ocean heat transport in first layer of the ocean (a b c) and sea surface temperatures (d e f) for Aurica PD (sim 02), Amasia PD (sim 05) and (Earth #3) (sim 09).

309 at the northern pole which prevents the year round land ice seen in Amasia PD (sim 05)  
 310 (see Figure 8). Hence Amasia PD (sim 05) has 10.2% for the snow+ice versus a mere  
 311 6.4% for Earth #3 (sim 09) at the same rotation and insolation.

312 The general effect of the different land/sea masks between the Aurica (sims 01–  
 313 03) and Amasia (sims 04–06) simulations and how they compare with the modern Earth  
 314 #1–#3 simulations (07–09) are seen in Figures 5, 6, and 8. In Figure 5 The largest dif-  
 315 ferences are seen in the oceanic meridional transport between the Aurica & Earth #1–  
 316 #3 simulations. The weaker values seen for Aurica simulations (01–03) are likely explained  
 317 by the large low latitude landmass restricting meridional heat transport over a large lon-  
 318 gitudinal range (left middle panel). In the right middle panel of Figure 5 we see how hav-  
 319 ing larger low-latitude open-ocean increases the oceanic meridional transport for the Ama-  
 320 sia simulations (04–06) versus the modern Earth #1–#3 simulations (07–09). Total (at-  
 321 mosphere + ocean) meridional heat transport is very similar between simulations where  
 322 the only discernible differences manifest themselves in the larger northern hemisphere  
 323 transport for Earth #1–#3 versus the Aurica simulations, which are certainly related  
 324 to the differences in oceanic transport as discussed above.

325 These general trends are repeated in Figure 6 where we plot the stream function  
 326 which indicates the strength of the Hadley circulation. The Aurica PD (sim 02) stream  
 327 function (Figure 6d) is the weaker of the three as we saw in Figure 5 (lower panels). Look-  
 328 ing at Amasia PD (sim 05) versus Earth #3 (sim 09) the northern hemisphere values  
 329 (Figures 6e versus c) are very similar, but the southern values differ likely because of the  
 330 low–mid latitude south American, south African, and Australian continents in Earth #3  
 331 (sim 09) that do not exist in Amasia PD (sim 05).

332 Work by Spiegel et al. (2008) uses a metric of “climatic habitability” that defines  
 333 the amount of surface area of a planet that can host liquid water (e.g., surface temper-  
 334 atures in the range  $0 < T < 100^{\circ}\text{C}$ ) at modern Earth atmospheric pressures. In the right–  
 335 most column of Table 1 the left values are given using this metric, while the right val-  
 336 ues utilize a larger temperature range since life on Earth has been found to thrive in tem-  
 337 peratures as high as  $121^{\circ}\text{C}$  and as low as  $-15^{\circ}\text{C}$  (e.g. NRC, 2007, Table 3.1). These met-  
 338 rics are calculated from 10 year averages (post-equilibrium) of the ground and sea tem-  
 339 peratures. From Table 1 it is clear that the Aurica simulations (01–03) have the largest  
 340 surface habitable fraction amongst all of the simulations. Since none of our simulations  
 341 approach the boiling point of water in any region Aurica’s high habitability is clearly due  
 342 to the lack of high-latitude continents found in the Amasia and Earth simulations (04–  
 343 09) that manifest below freezing temperatures not widely present in the Aurica ones (sims  
 344 01–03). Earth #1 & #2 (sims 07 & 08) have large areas with temperatures below freez-  
 345 ing – not unexpected given their lower insolations and high latitude land masses com-  
 346 pared to the Aurica simulations. The habitable fraction values for Amasia PD (sim 05)  
 347 are lower than the Earth #1 & #2 simulations (07 & 08) at lower insolation. As noted  
 348 above, this is attributable to the large ice sheets in the high latitude northern and south-  
 349 ern hemispheres. Even though Amasia PD (sim 05) has a higher mean surface temper-  
 350 ature than Earth #1 & #2 (sims 07 & 08) the higher global snow fraction appears to  
 351 influence this metric more than may be expected. However, caution is warranted when  
 352 using this habitability metric as other work (e.g. Sparrman, 2021) has shown that ap-  
 353 plying the Spiegel et al. (2008) temperature definition in a 3–D sense reveals little dif-  
 354 ference in “climatic habitability” between worlds that otherwise appear quite climati-  
 355 cally distinct. On Earth life has been found to withstand pressures beyond those of deep  
 356 sea trenches on Earth (e.g. Sharma et al., 2002; Vanlint et al., 2011), at the bottom of  
 357 thick ice sheets (e.g. Griffiths et al., 2021) and in extremely deep mines (e.g. Lollar et  
 358 al., 2019; Drake et al., 2021). Given enough time life has found a way to fill nearly ev-  
 359 ery ecological niche on the modern Earth. While a habitability metric like that used herein  
 360 may be imperfect it can still provide us a simple way to compare the surface climates  
 361 of different worlds.

362 **4 Conclusions**

363 The supercontinents of the future can provide us some guidance on how surface tem-  
 364 peratures will increase or decrease depending on how the continents are distributed, with  
 365 implications for exoplanet climate and habitability. But there are other factors to con-  
 366 sider related to weathering rates and volcanic outgassing (e.g. Jellinek et al., 2019), not  
 367 to mention the related role of atmospheric pressure (Gaillard & Scaillet, 2014). We have  
 368 also used a fixed atmospheric CO<sub>2</sub> concentration in this paper to avoid introducing a fur-  
 369 ther parameter that can add climate variability and, interesting as it would be, exploring  
 370 the climate with a dynamic carbon cycle is left for future work.

371 The 30 minute increase in the length of day between simulations 07 and 08 appears  
 372 to play little to no role in the climate dynamics as there is little discernible difference  
 373 in the strength or distribution of the Hadley or eddy transport diagnostics. This implies  
 374 the same for simulations 01–06 with their 30 min longer day lengths than present day  
 375 Earth.

376 While we discuss the future climate of Earth we do not touch on the future of life.  
 377 There are many uncertainties, but recent work provides some guidelines (Mello & Friaça,  
 378 2019). The reduced tides during the supercontinent stage (Davies et al., 2020) will lead  
 379 to reduced vertical mixing rates, i.e. a reduced vertical diffusivity in the abyssal ocean  
 380 (Munk, 1966; Wunsch & Ferrari, 2004). This may have implications for ocean ecosys-  
 381 tems, and biodiversity. At the same time it appears that the formation of Pangea had  
 382 little effect on the global biodiversity of marine animals (Zaffos & Peters, 2017) and Pangea  
 383 was in a very weak tidal state (Green et al., 2017).

384 It would be interesting to compare the GCM derived climates for the superconti-  
 385 nent at low latitude in the Aurica runs with previous work on Pangea (e.g. Chandler et  
 386 al., 1992; Chandler, 1994; Fluteau et al., 2001; Gibbs et al., 2002; Roscher et al., 2011).  
 387 Unfortunately it is difficult to make a proper comparison for a number of reasons. First,  
 388 all of these previous works use either atmosphere only GCMs (i.e., no ocean) or shallow  
 389 mixed layer oceans with either prescribed horizontal heat transport or none at all. Sec-  
 390 ondly, unlike Aurica, Pangea spanned not only lower latitudes (like Aurica), but also high  
 391 southern latitudes where ice/snow forms easily (e.g. Chandler et al., 1992, Figure 5). Fi-  
 392 nally, there are different reconstructions for different time periods and not all are directly  
 393 comparable to those we simulate herein. This makes a direct comparison with Pangea  
 394 complicated and we leave such an analysis for the future.

395 These new reconstructions may prove useful for exoplanetary researchers who will  
 396 have a larger library of topographies and land/sea masks to chose from when estimat-  
 397 ing the probability of surface habitability on neighboring worlds.

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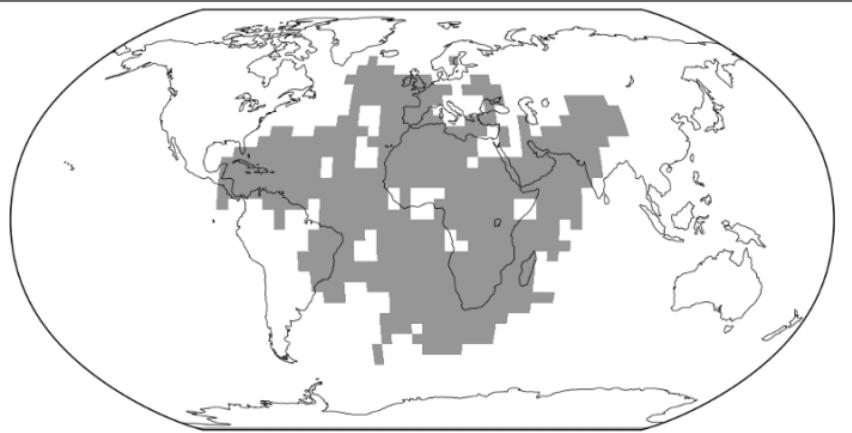
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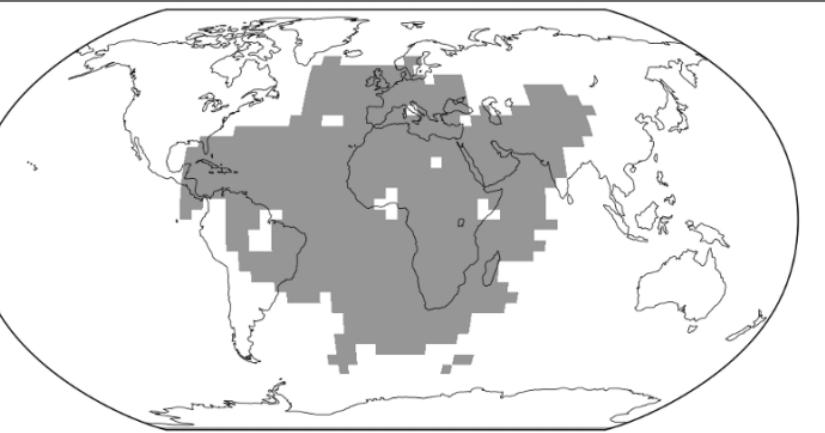
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603 (SPECIAL ISSUE: Frontiers in geoscience: A tribute to Prof. Xuanxue Mo)  
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607 <https://www.pnas.org/content/114/22/5653> doi: <https://doi.org/10.1073/pnas.1702297114>

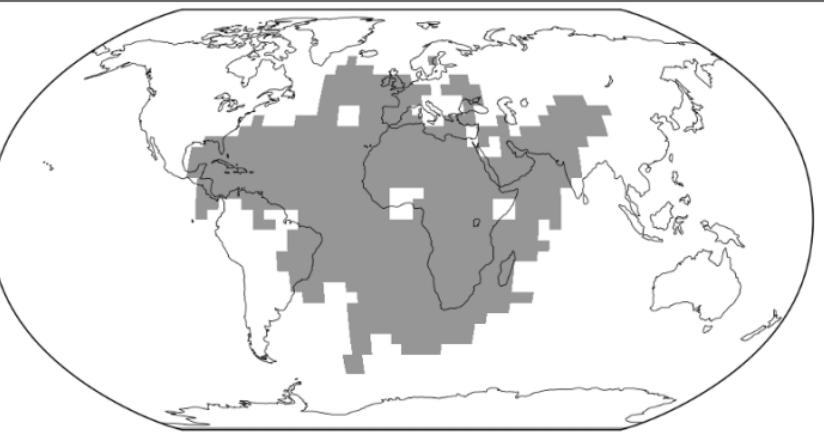
**Figure 1.**



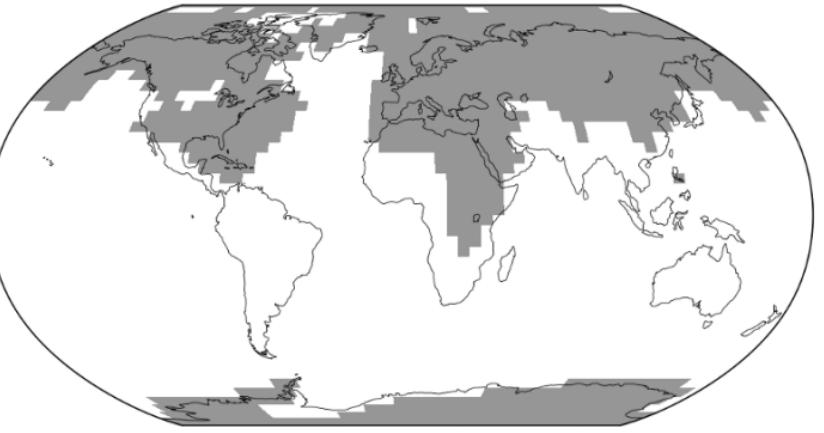
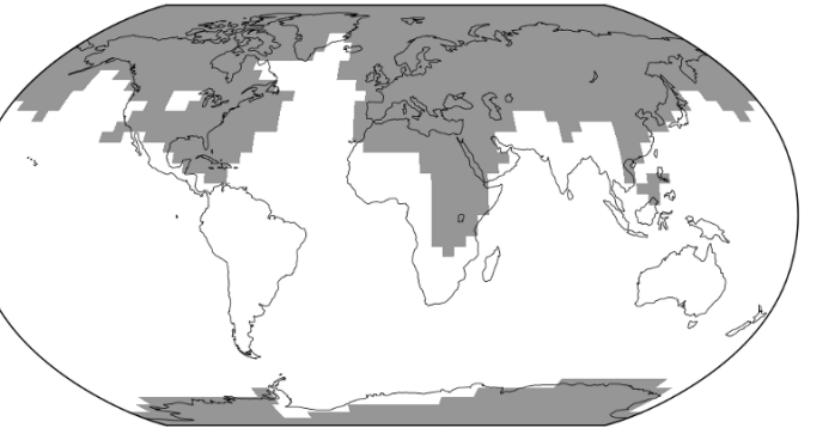
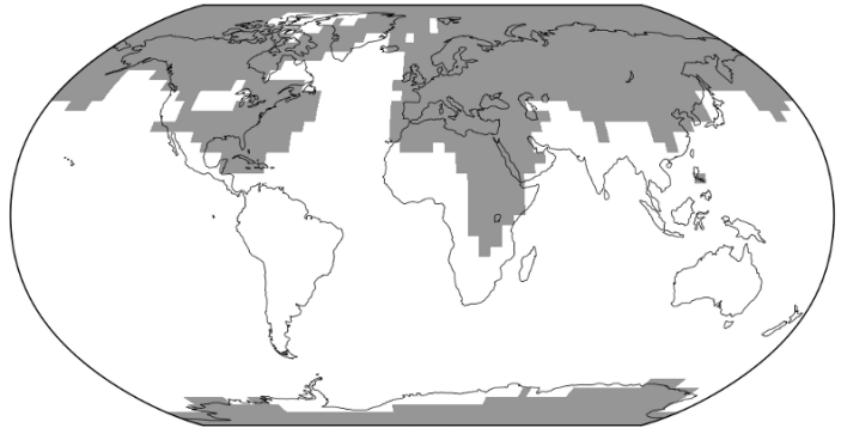
Simulation 04: Amasia CTRL



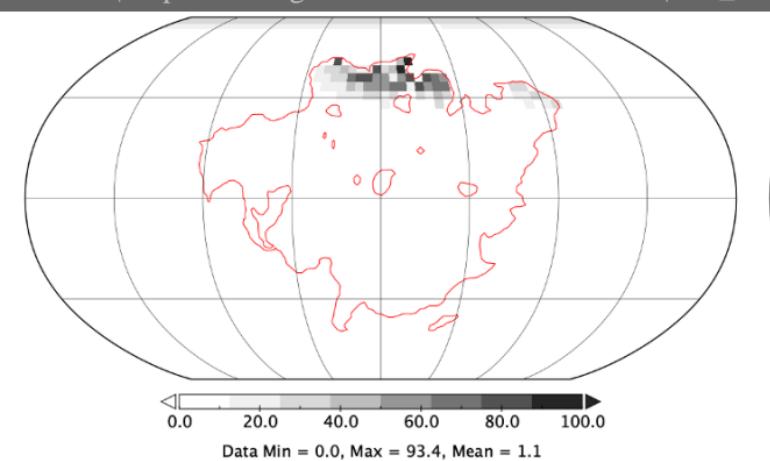
Simulation 05: Amasia PD



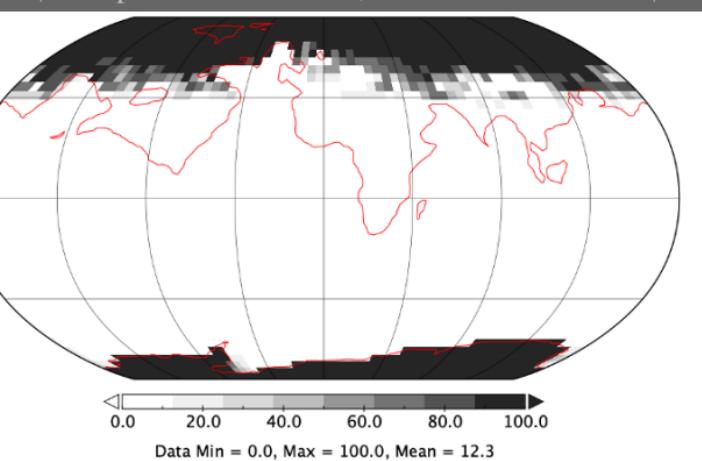
Simulation 06: Amasia MTNS



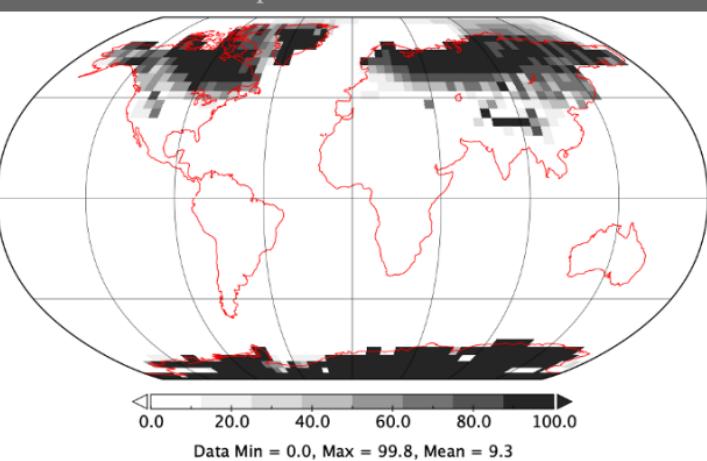
**Figure 2.**



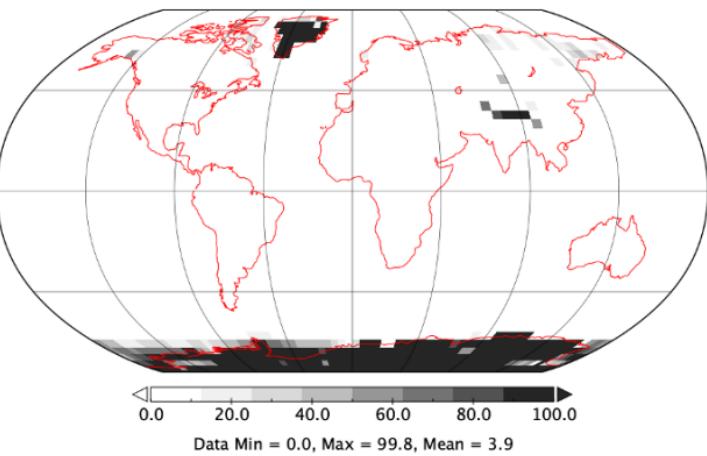
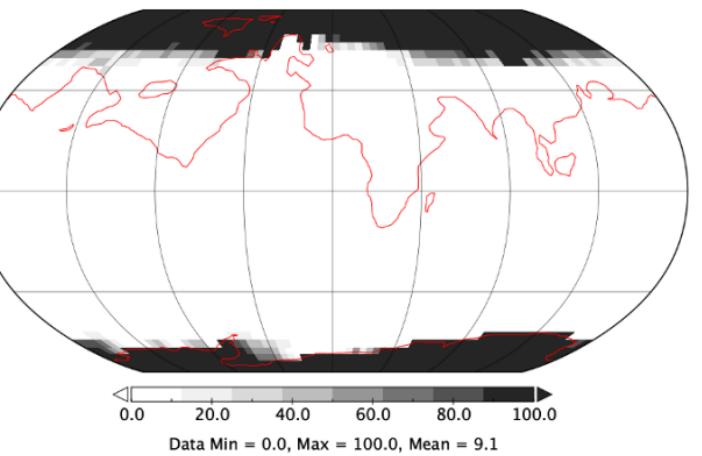
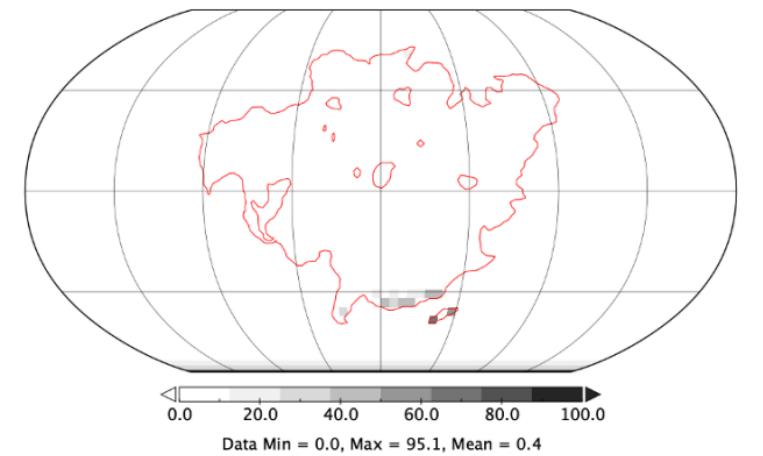
Simulation 02: Snow and Ice Coverage Jun/Jul/Aug



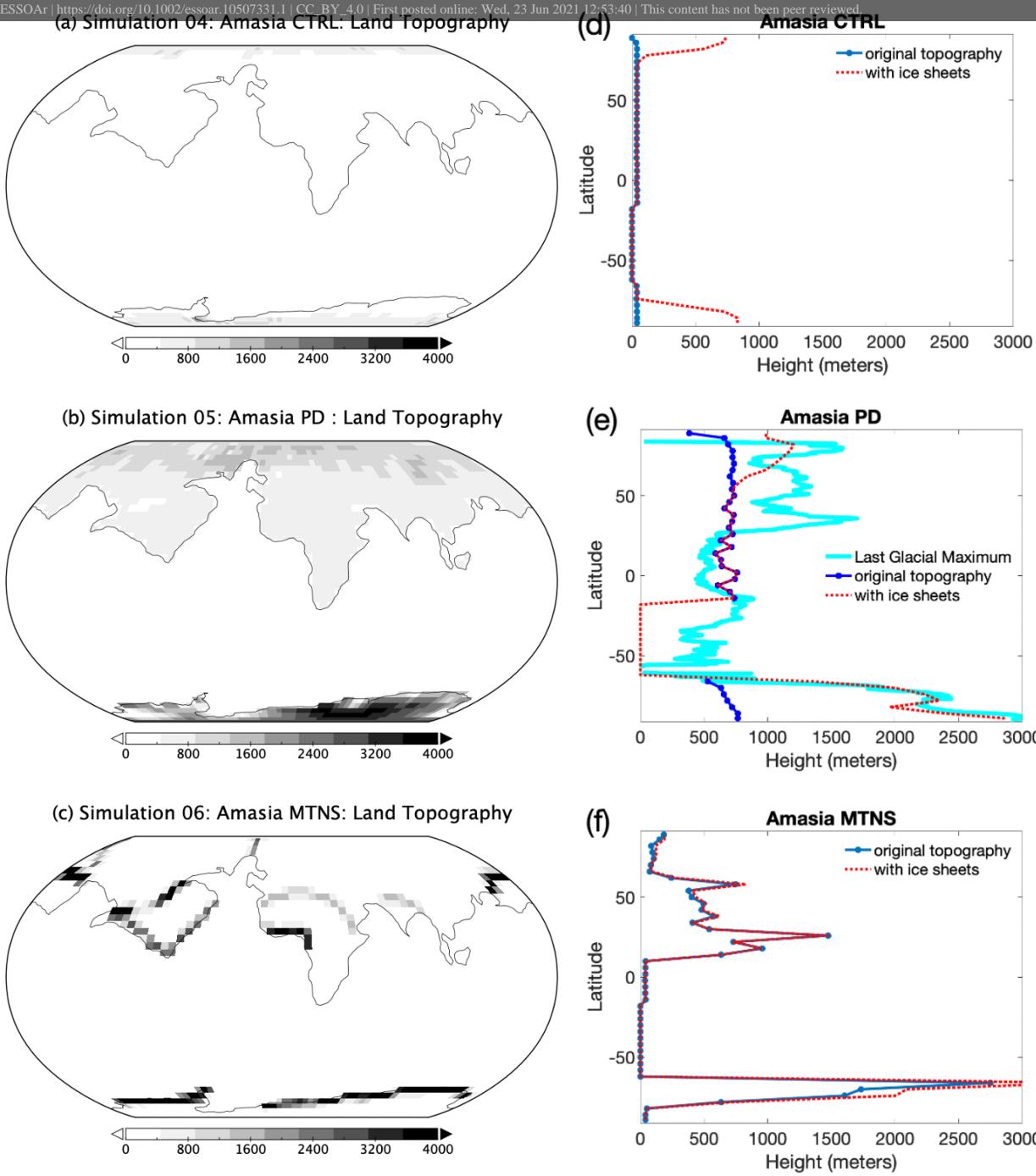
Simulation 05: Snow and Ice Coverage Jun/Jul/Aug



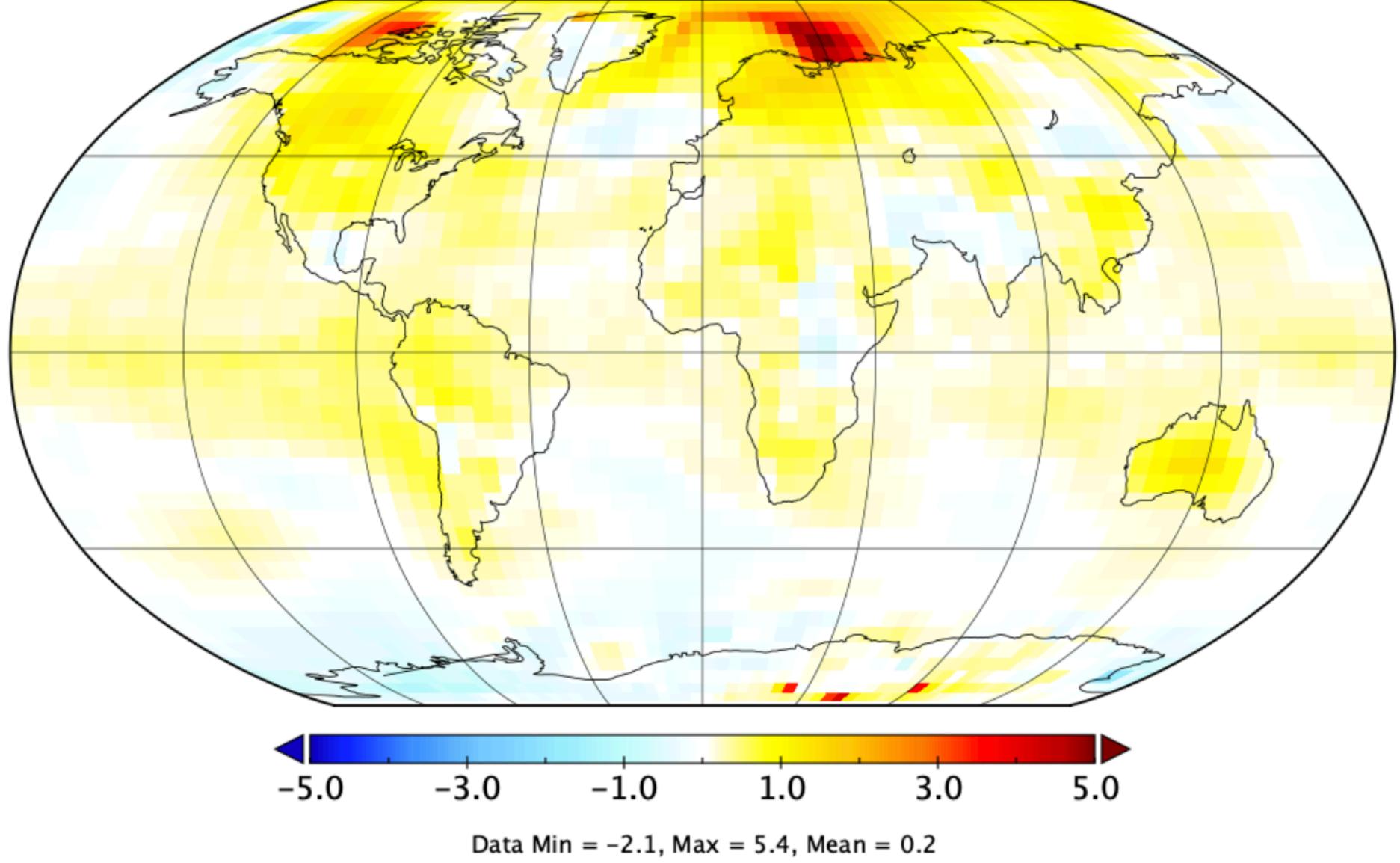
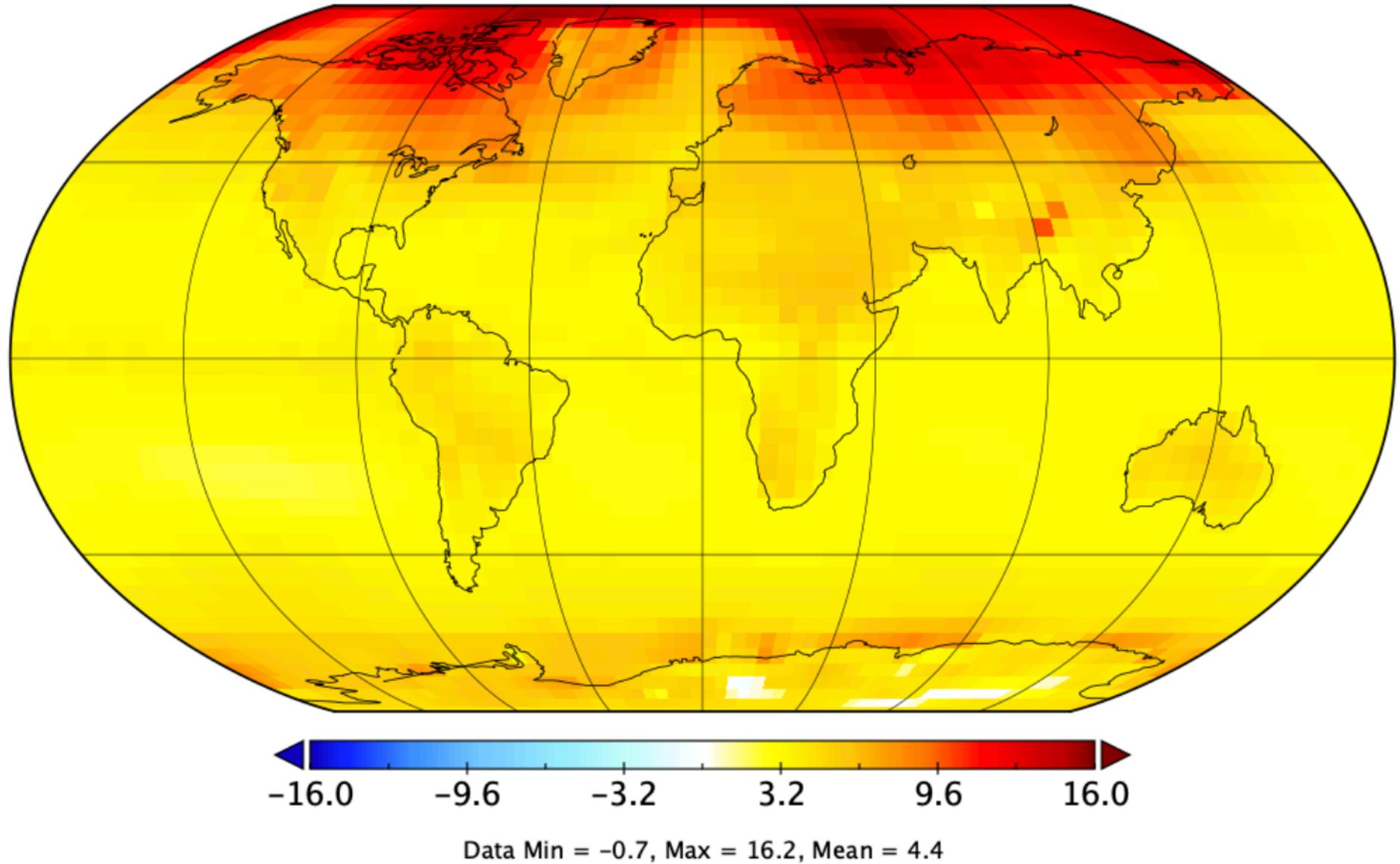
Simulation 09: Snow and Ice Coverage Jun/Jul/Aug



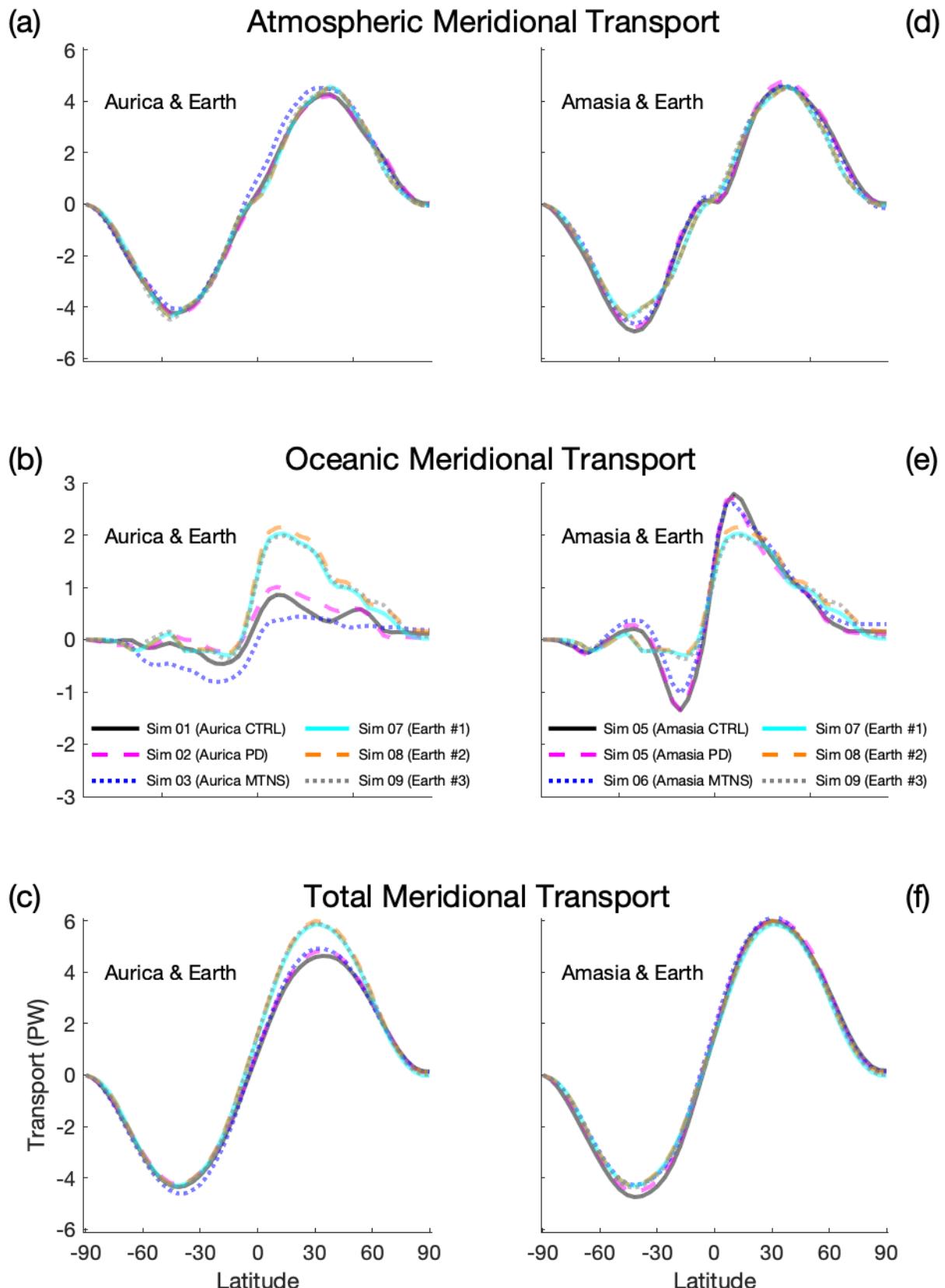
**Figure 3.**



**Figure 4.**

**(a) Sim 07 (Earth #1) – Sim 08 (Earth #2) Mean Surface Air Temperature****(b) Sim 09 (Earth #3) – Sim 08 (Earth #2) Mean Surface Air**

**Figure 5.**

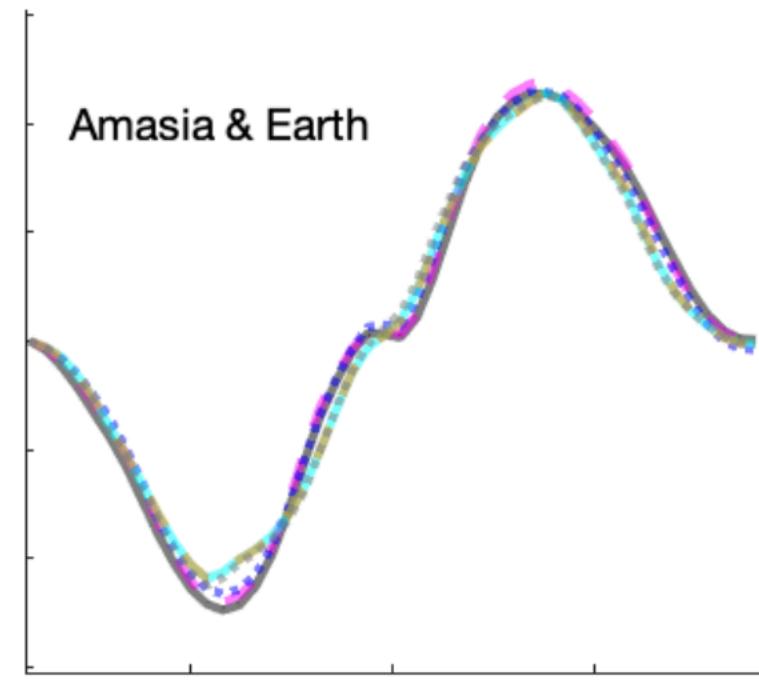
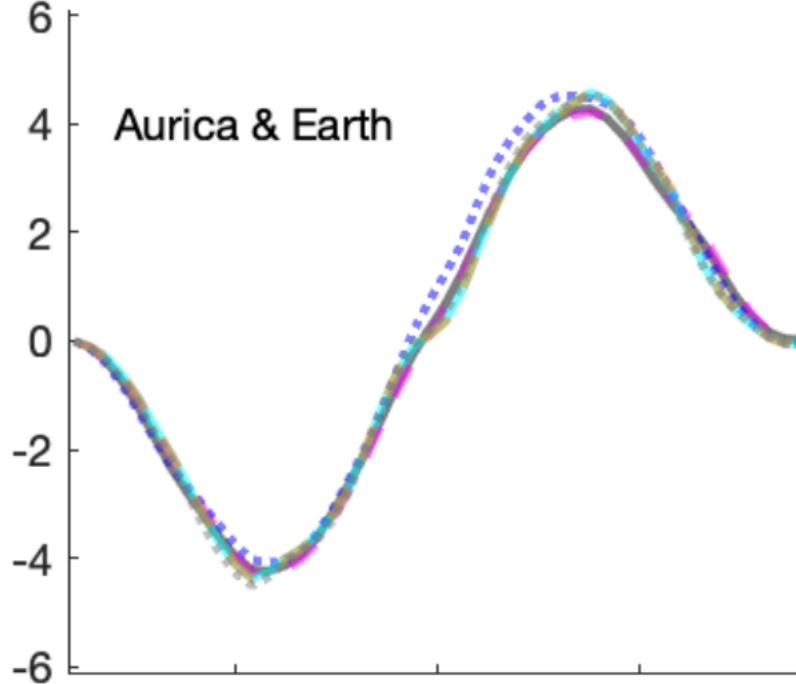


**Figure 5.**

(a)

**Atmospheric Meridional Transport**

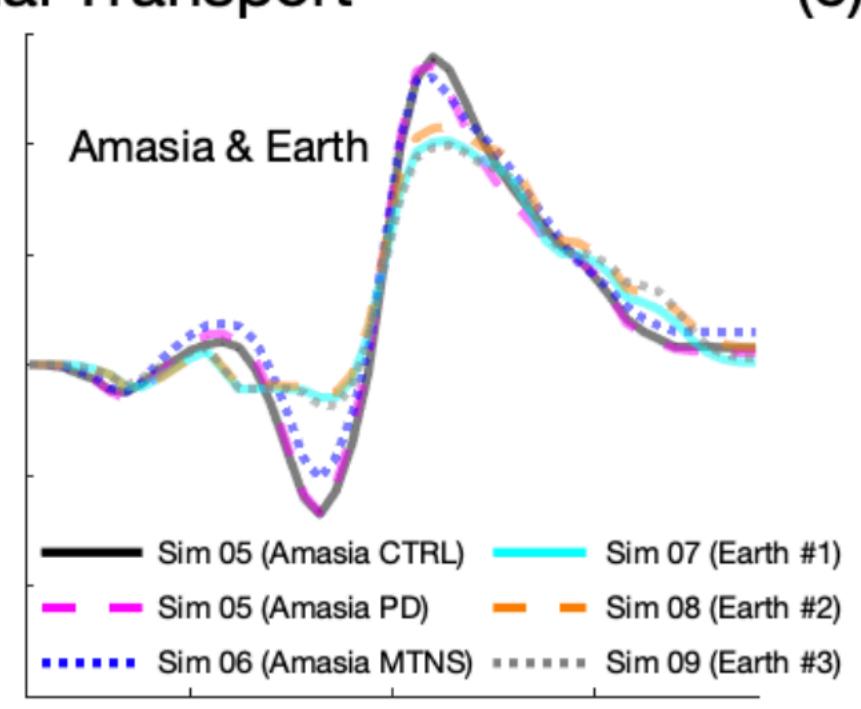
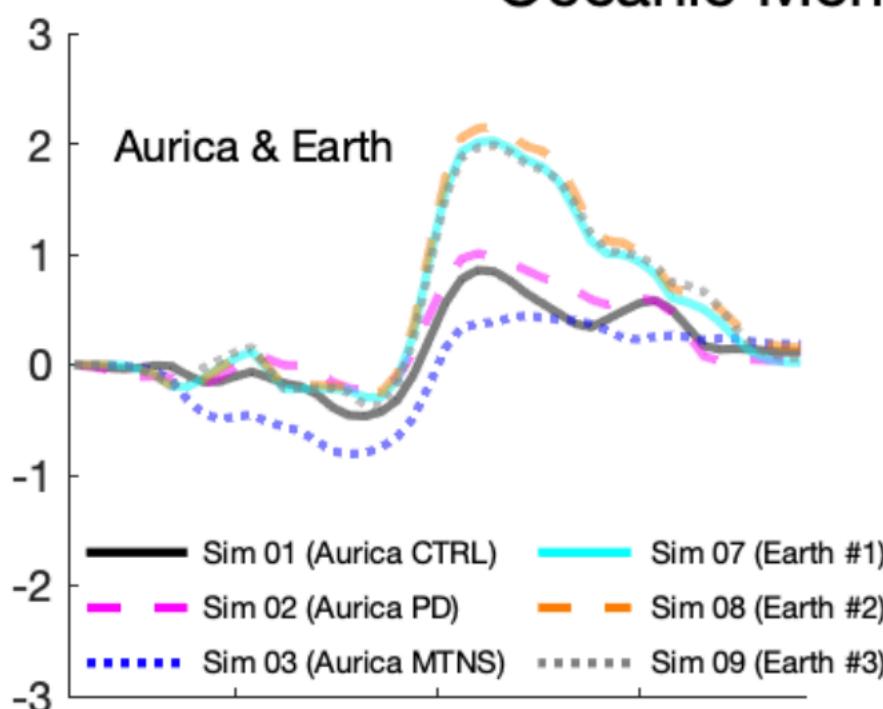
(d)



(b)

**Oceanic Meridional Transport**

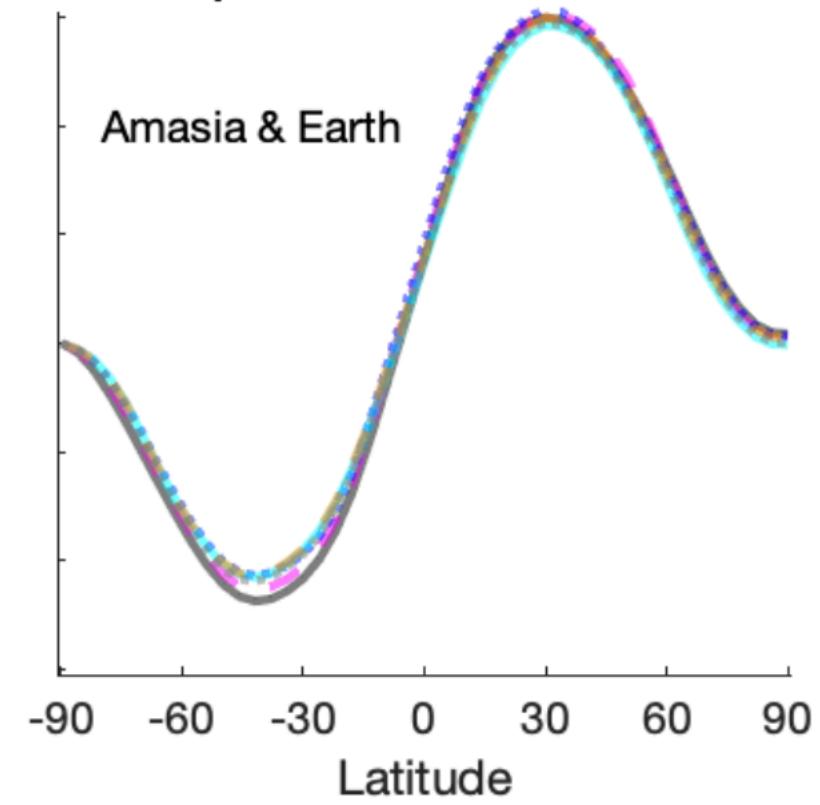
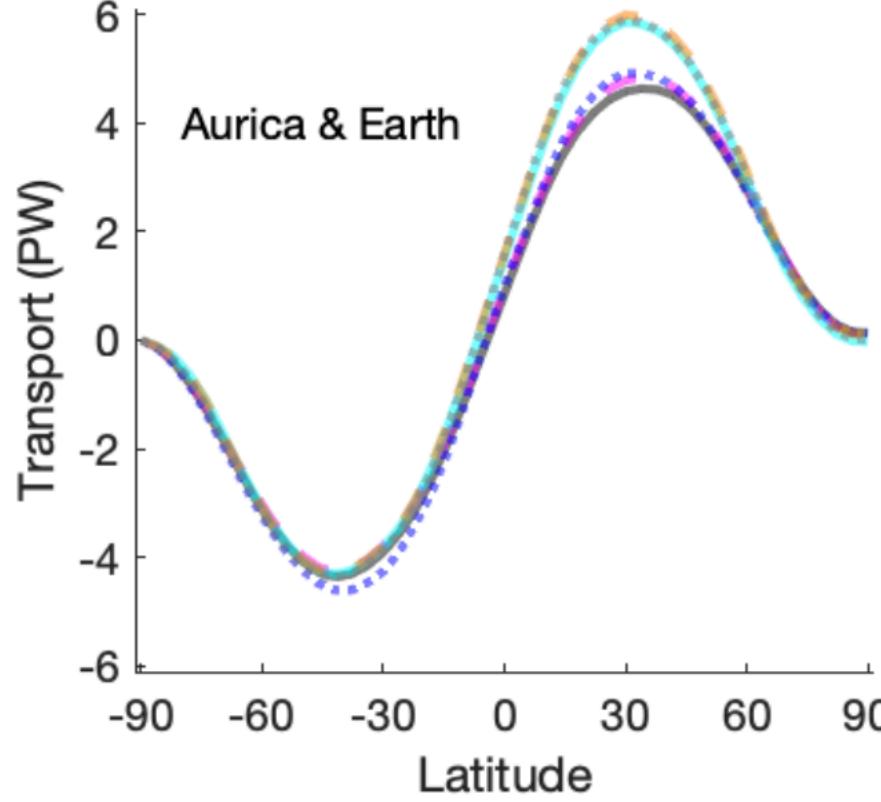
(e)



(c)

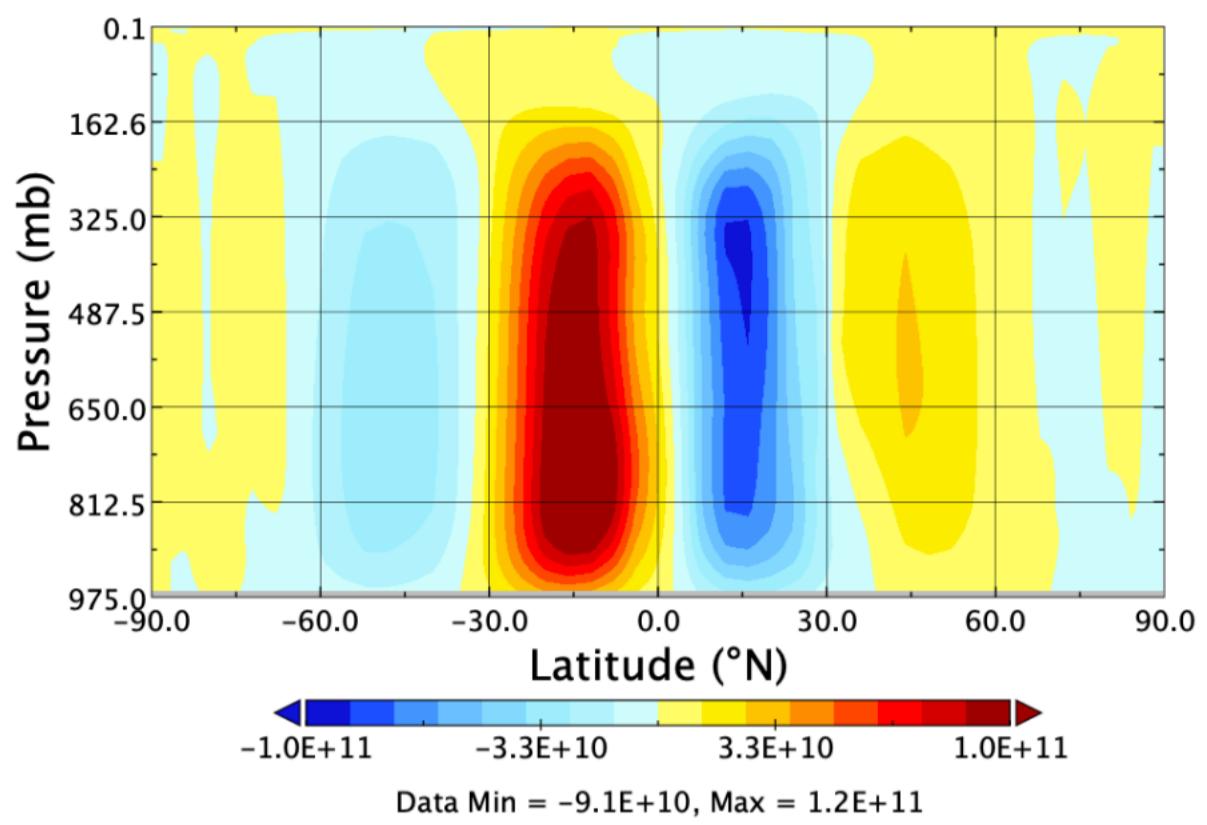
**Total Meridional Transport**

(f)

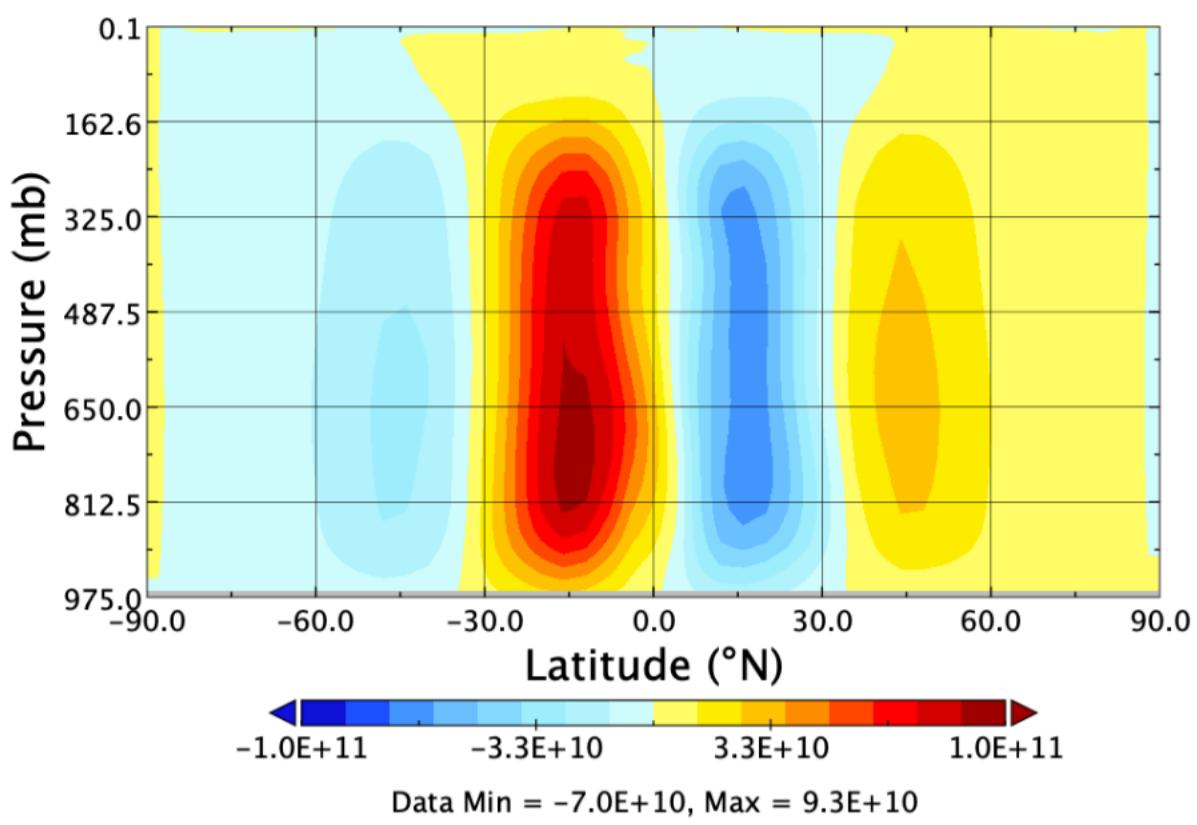


**Figure 6.**

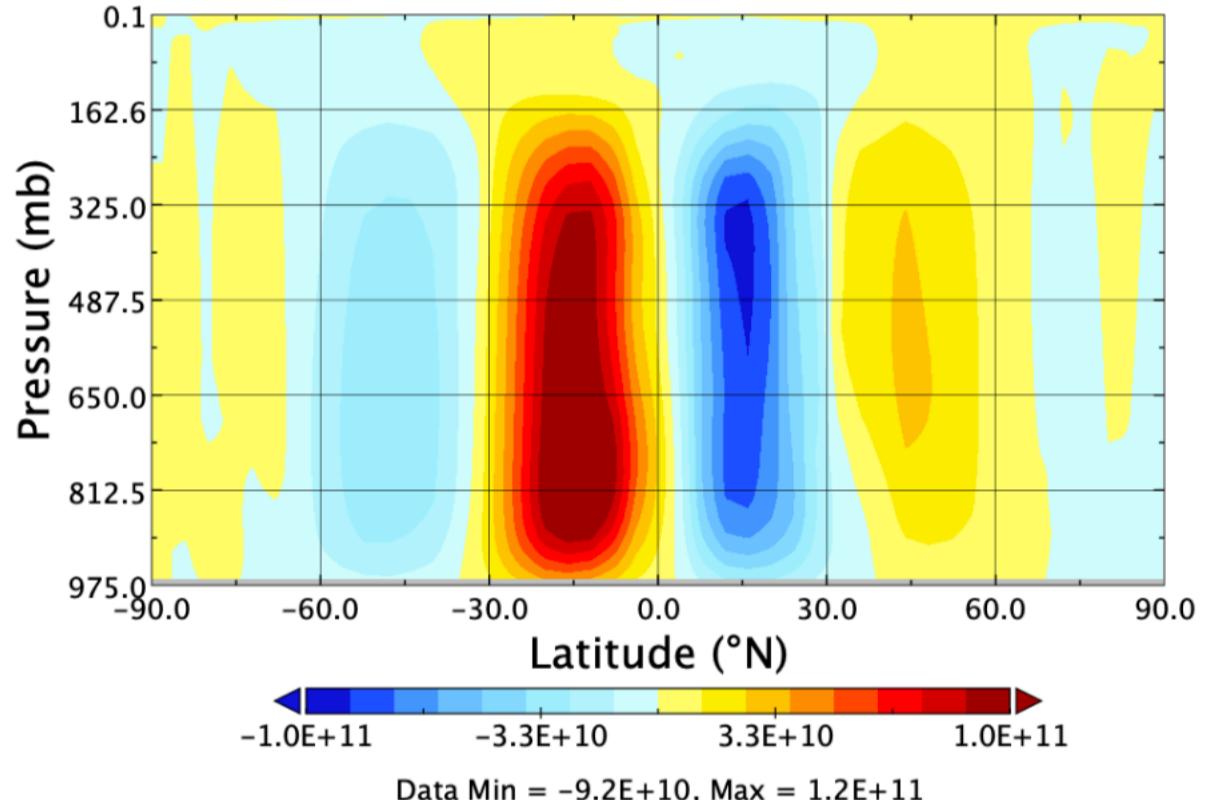
(a) Sim 07 (Earth #1) Stream Function (kg/s)



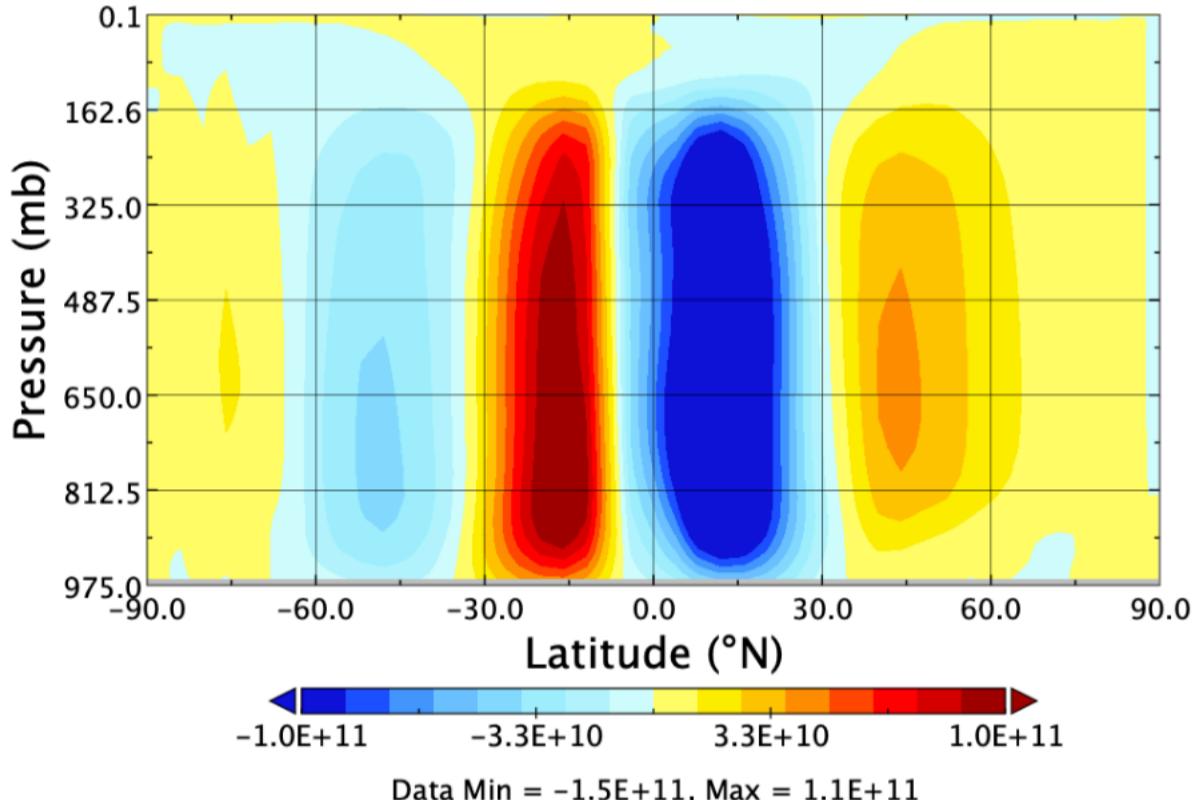
(d) Sim 02 (Aurica PD) Stream Function (kg/s)



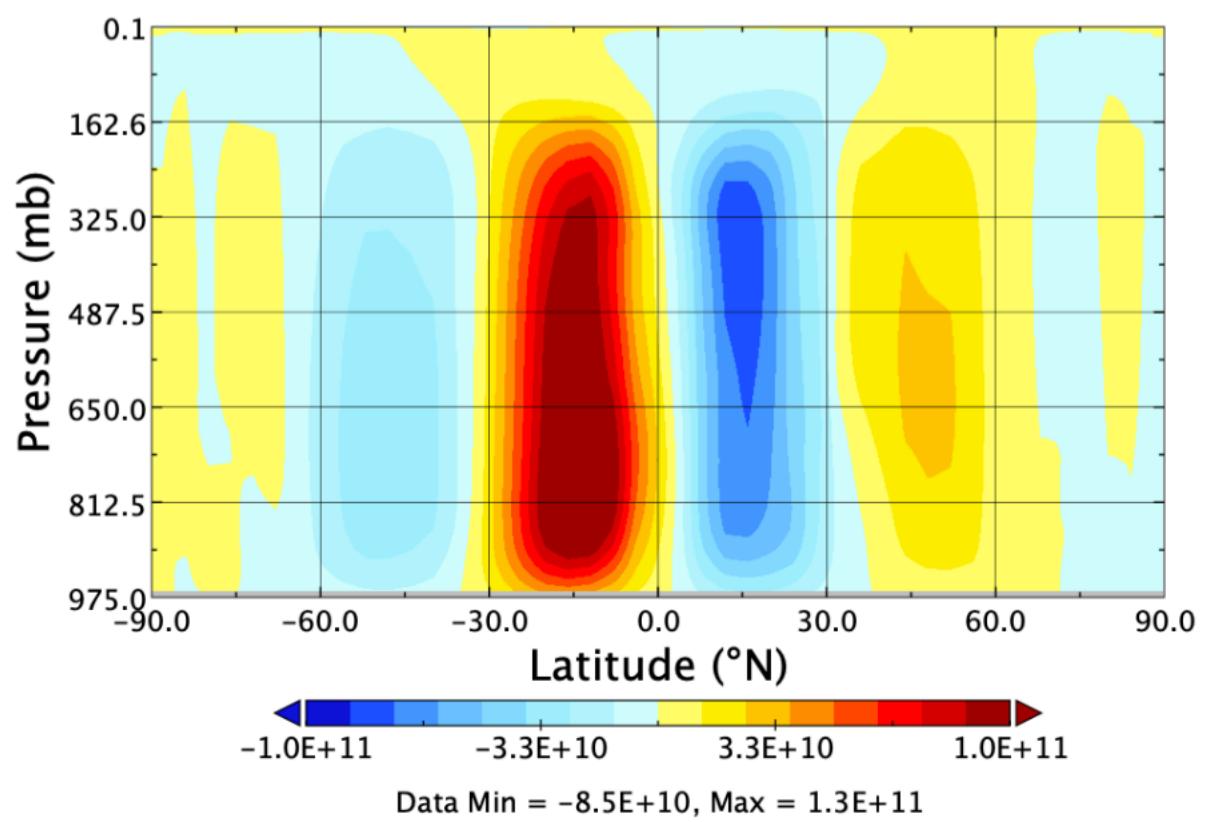
(b) Sim 08 (Earth #2) Stream Function (kg/s)



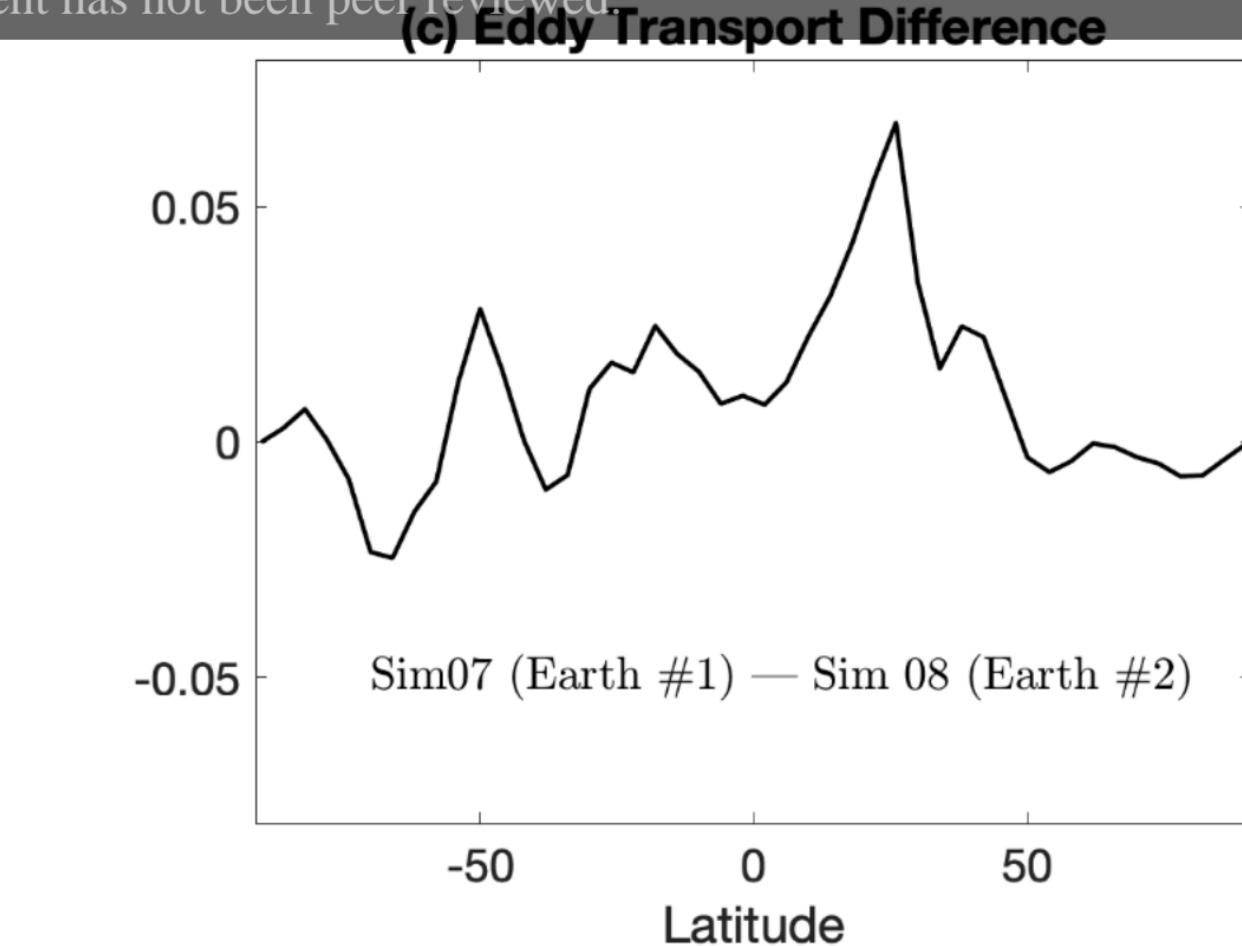
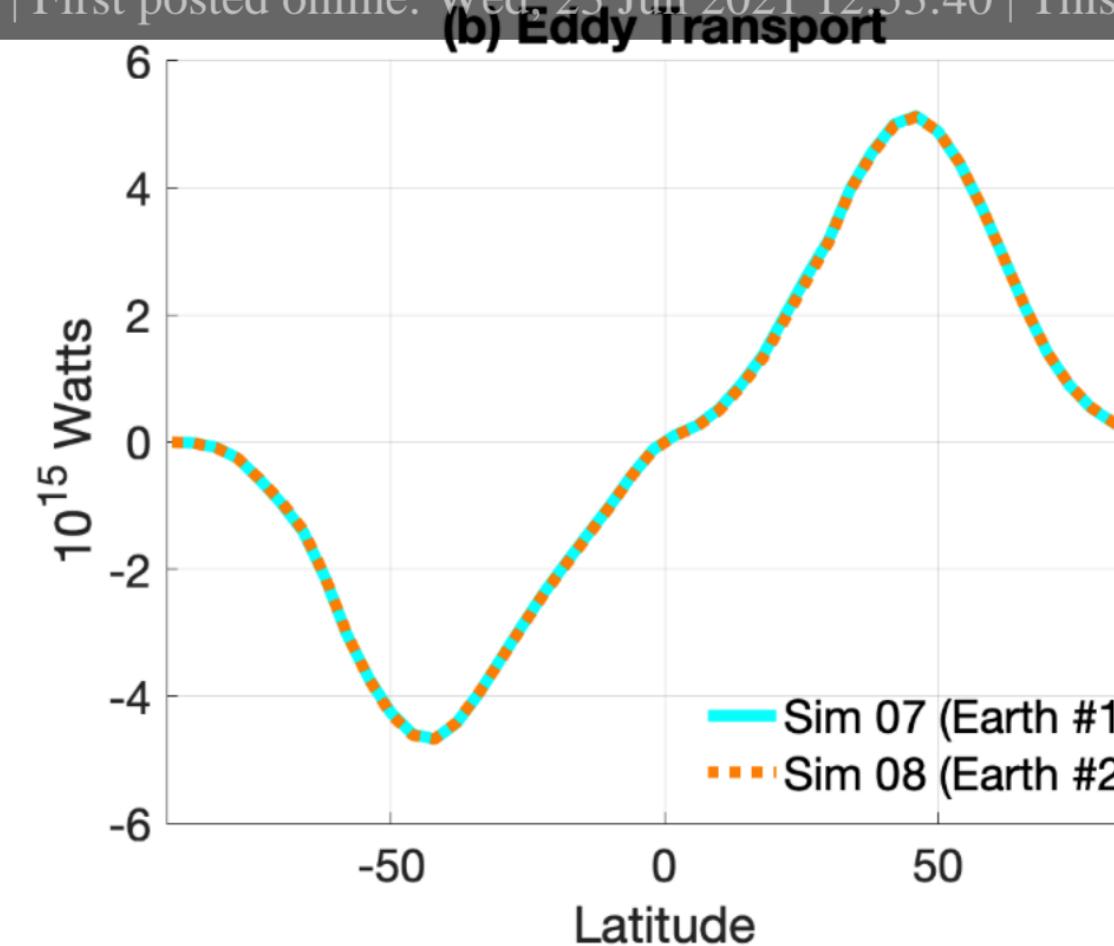
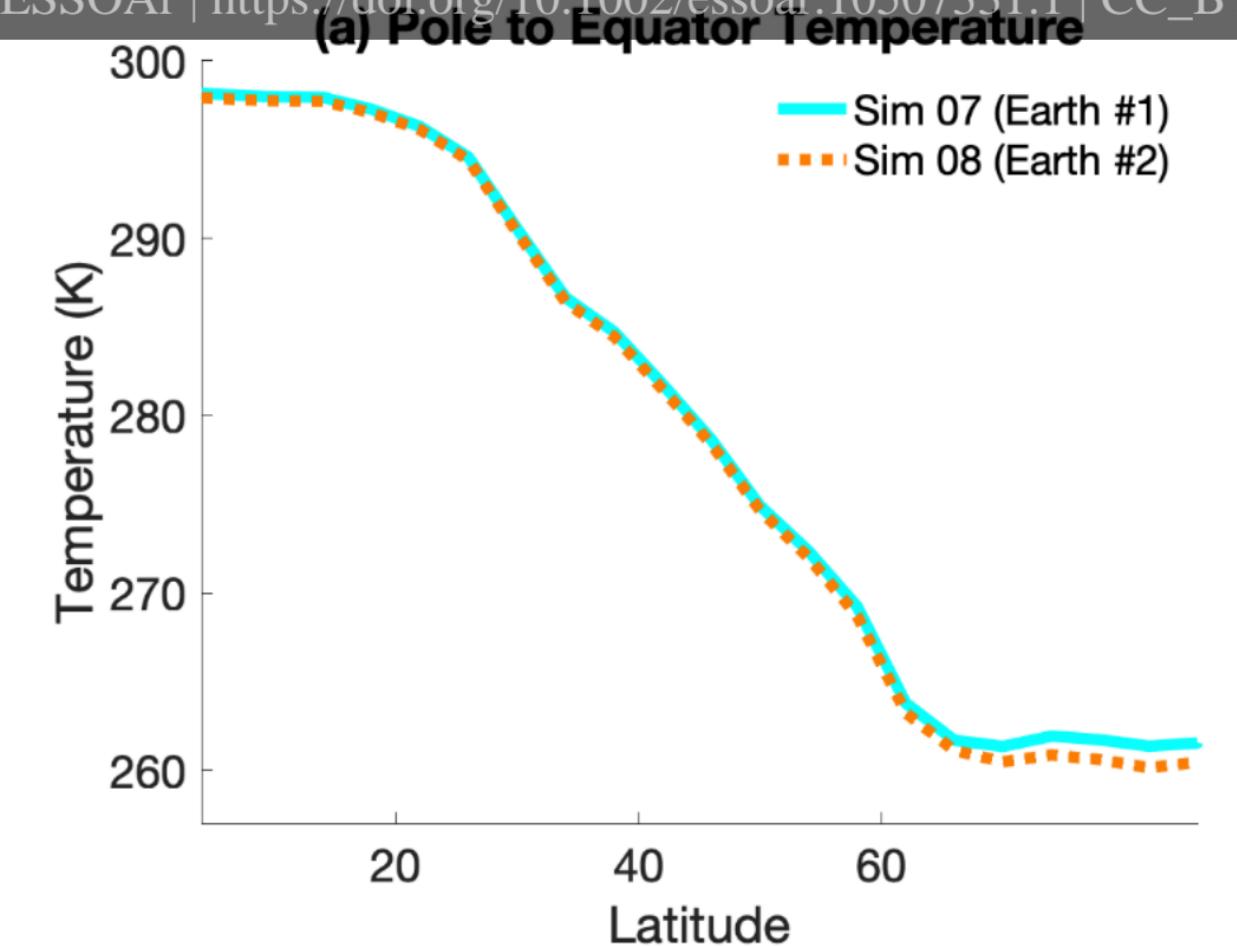
(e) Sim 05 (Amasia PD) Stream Function (kg/s)



(c) Sim 09 (Earth #3) Stream Function (kg/s)

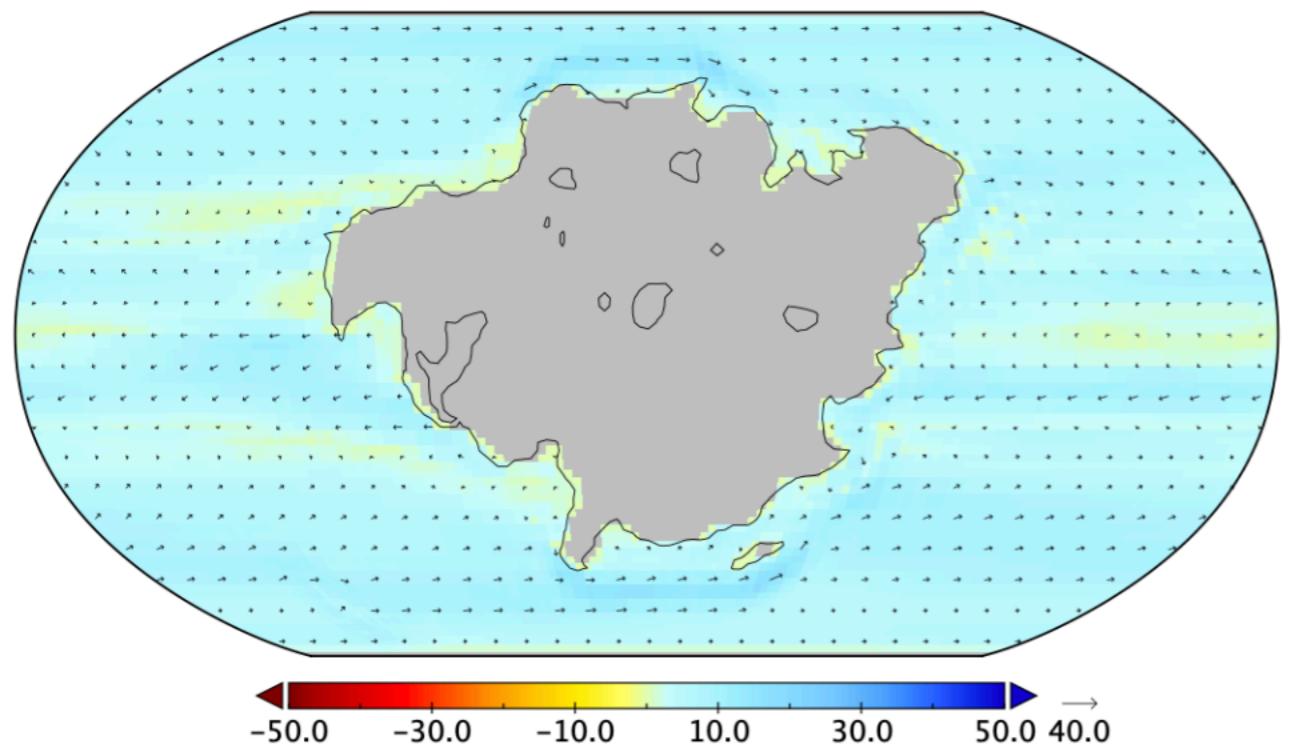


**Figure 7.**

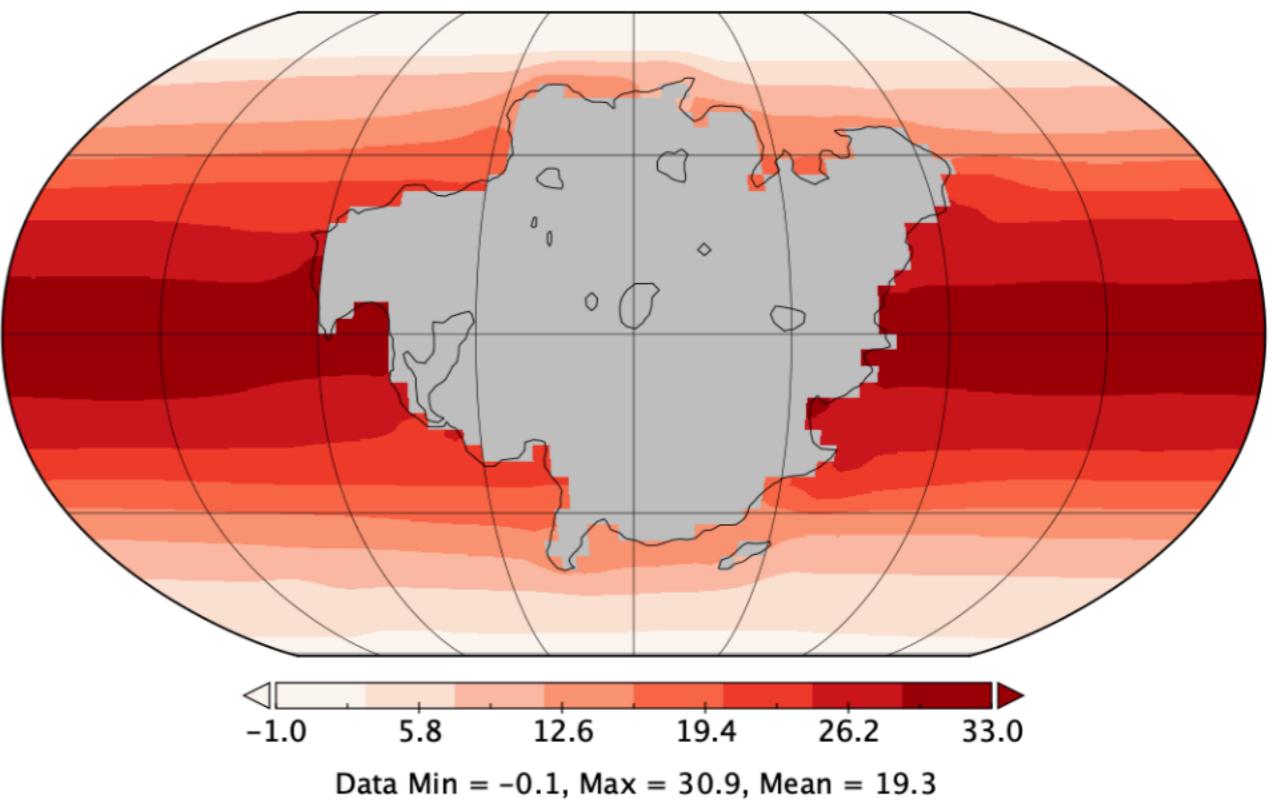


**Figure 8.**

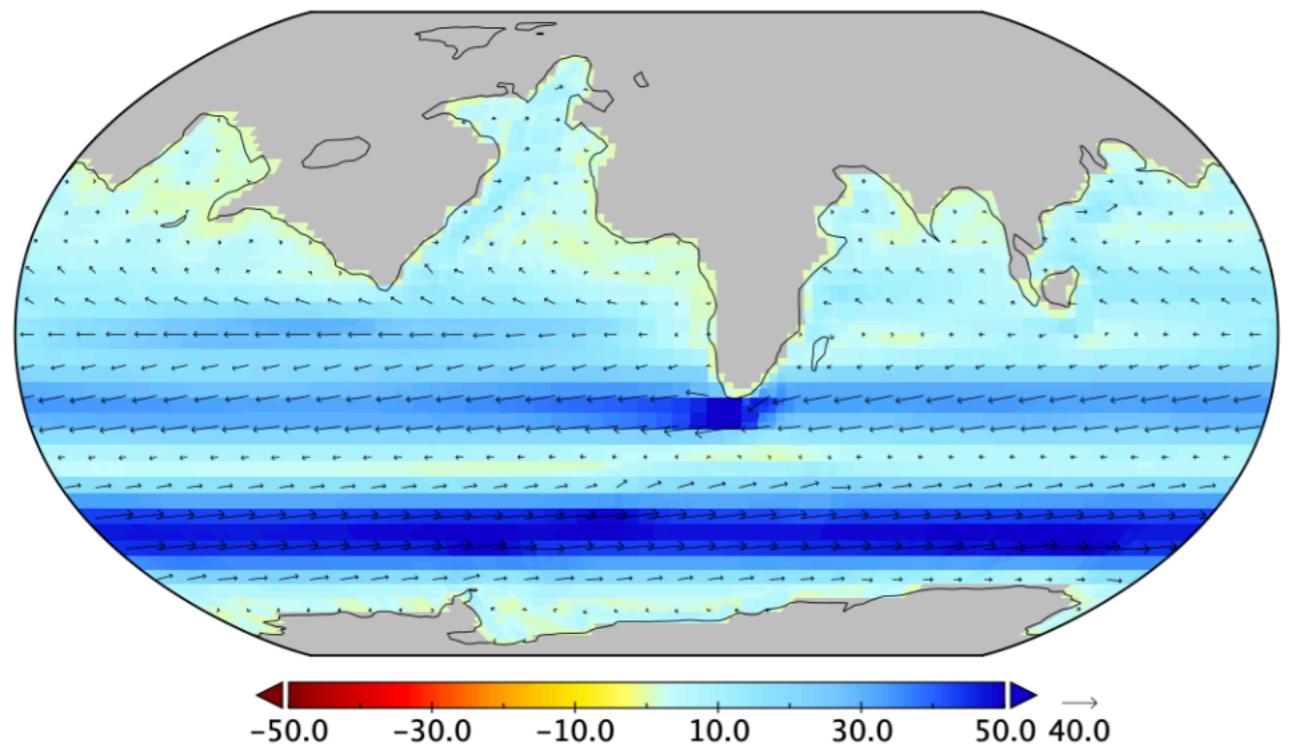
(a) Simulation 02 (Aurica PD): Ocean Surface Currents



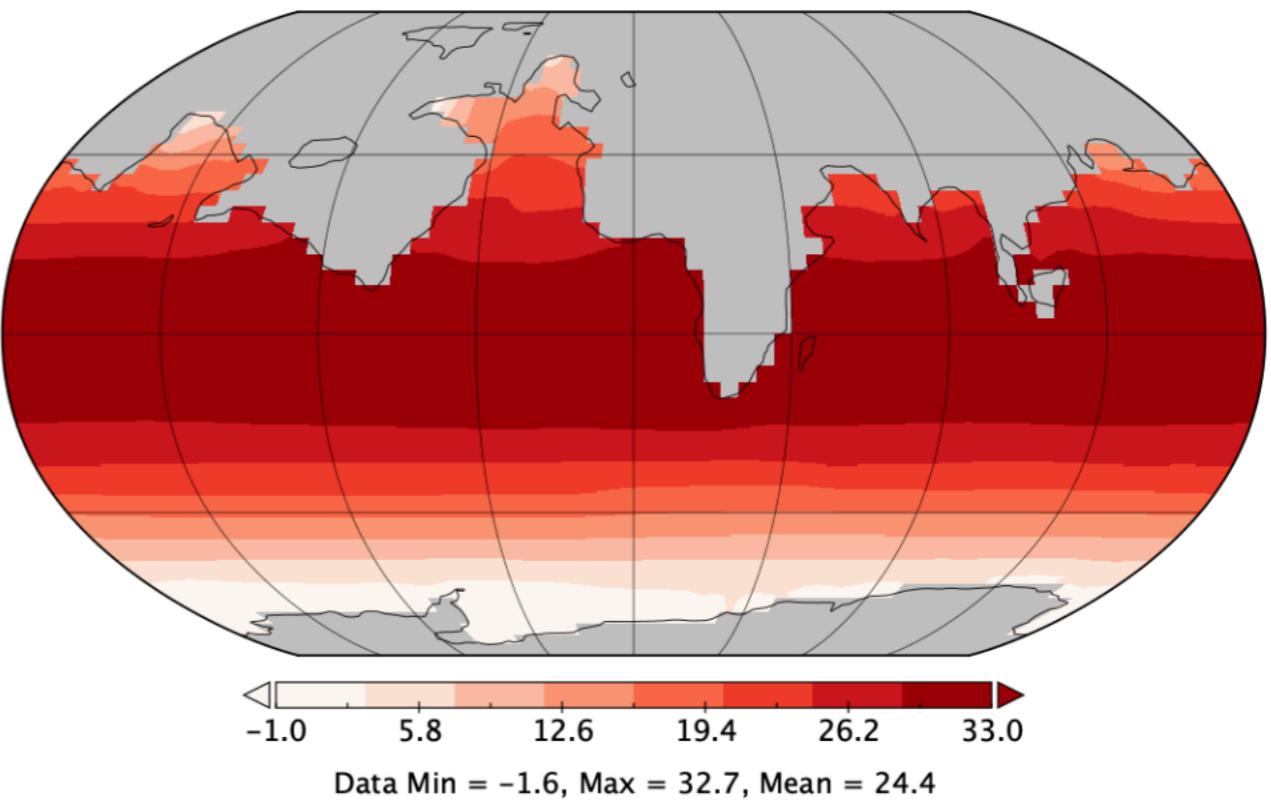
(d) Simulation 02 (Aurica PD): Sea Surface Temperatures



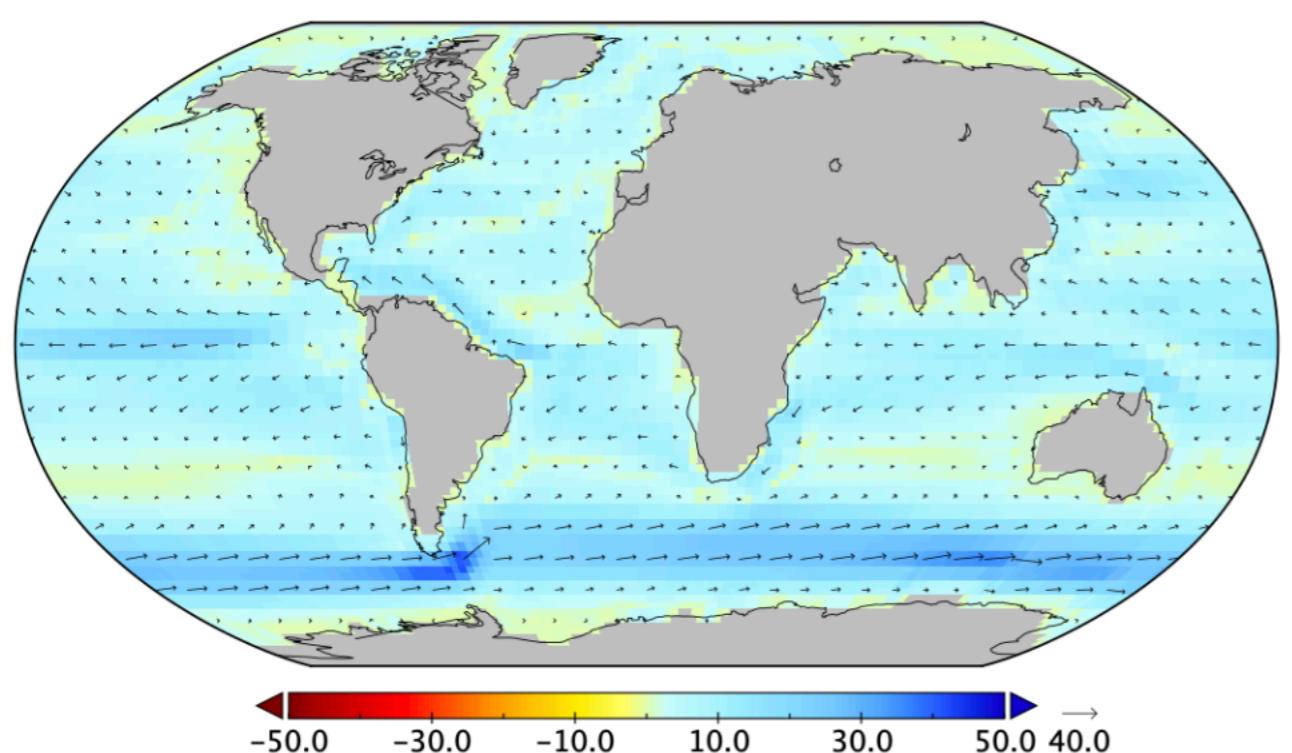
(b) Simulation 05 (Amasia PD): Ocean Surface Currents



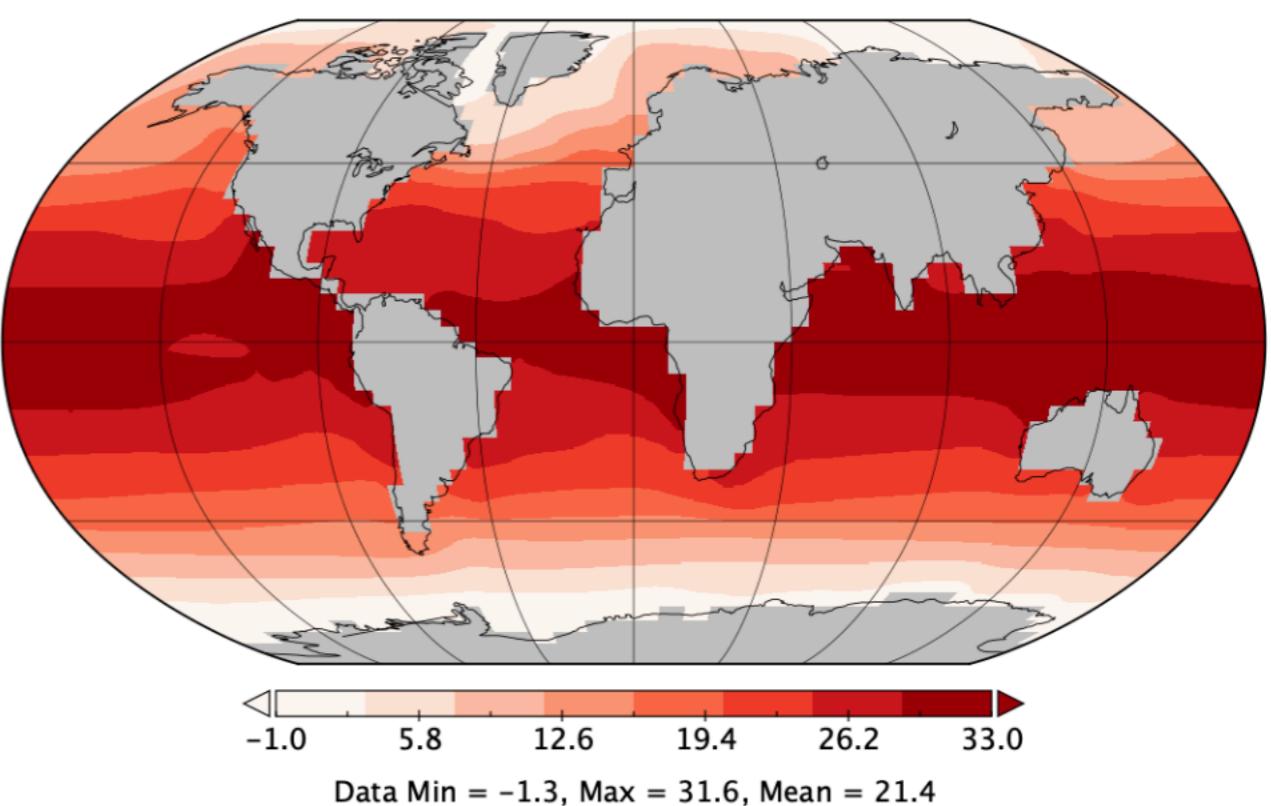
(e) Simulation 05 (Amasia PD): Sea Surface Temperatures



(c) Simulation 09 (Earth #3): Ocean Surface Currents

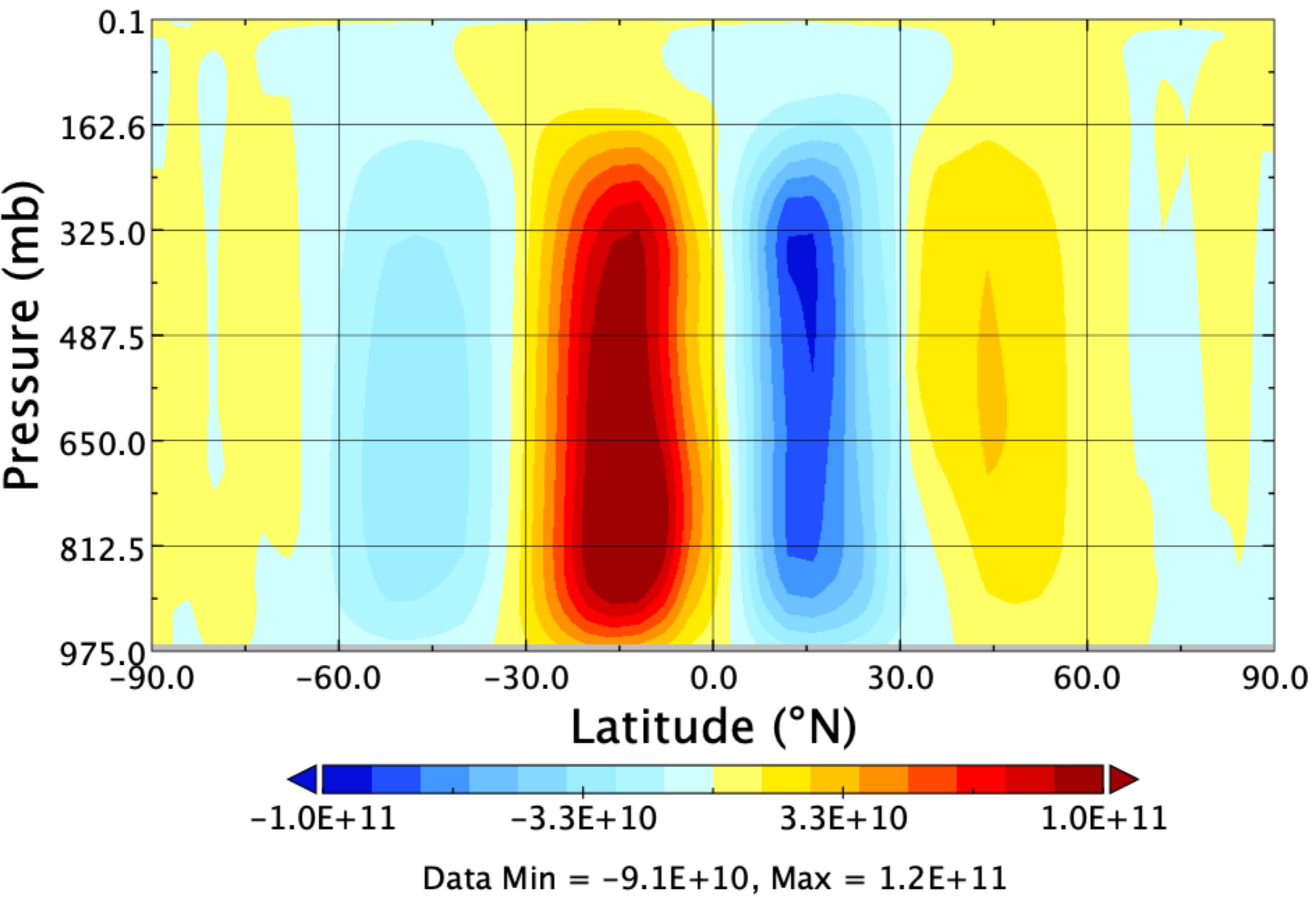


(f) Simulation 09 (Earth #3): Sea Surface Temperatures



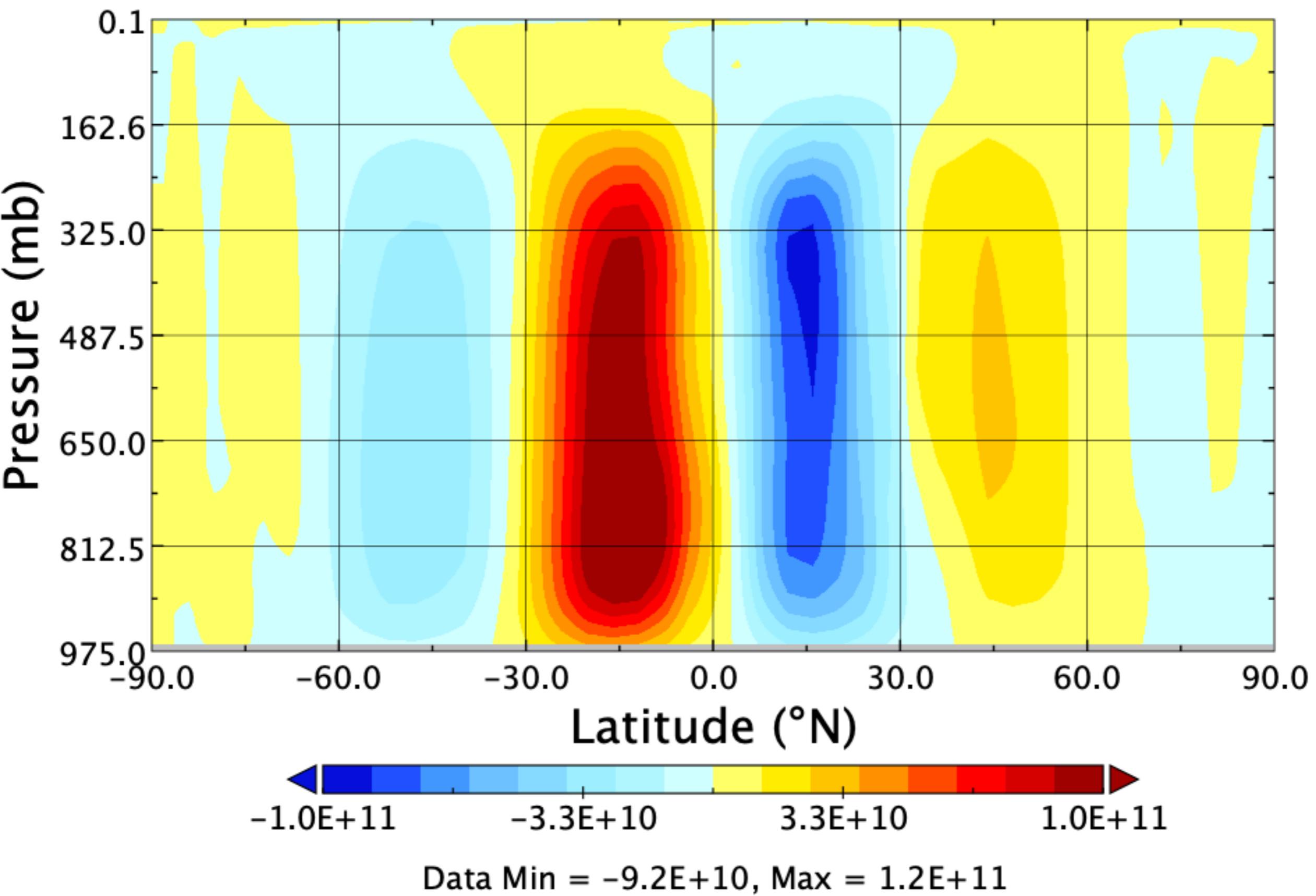
**Figure 6a.**

## (a) Sim 07 (Earth #1) Stream Function (kg/s)



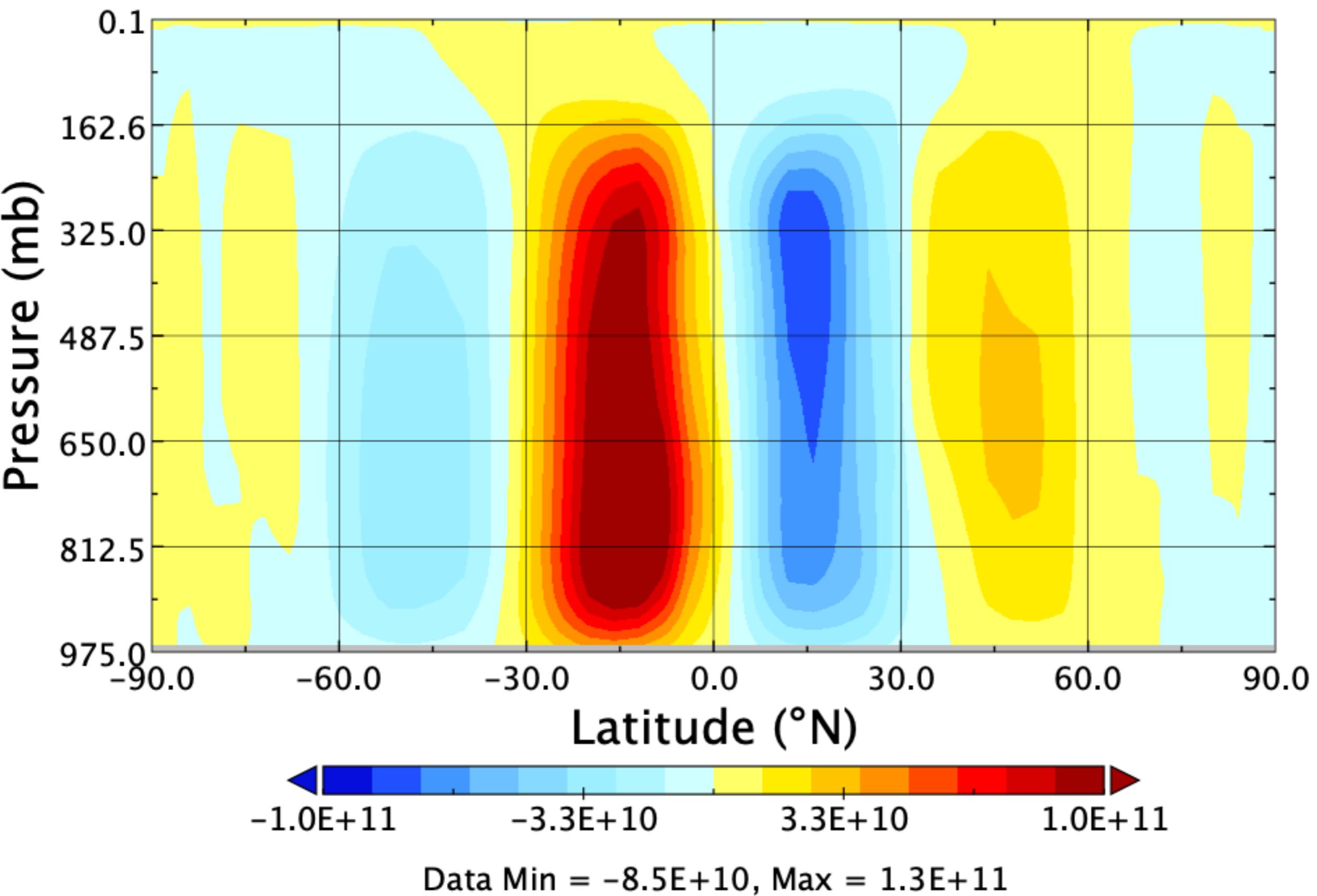
**Figure 6b.**

## (b) Sim 08 (Earth #2) Stream Function (kg/s)



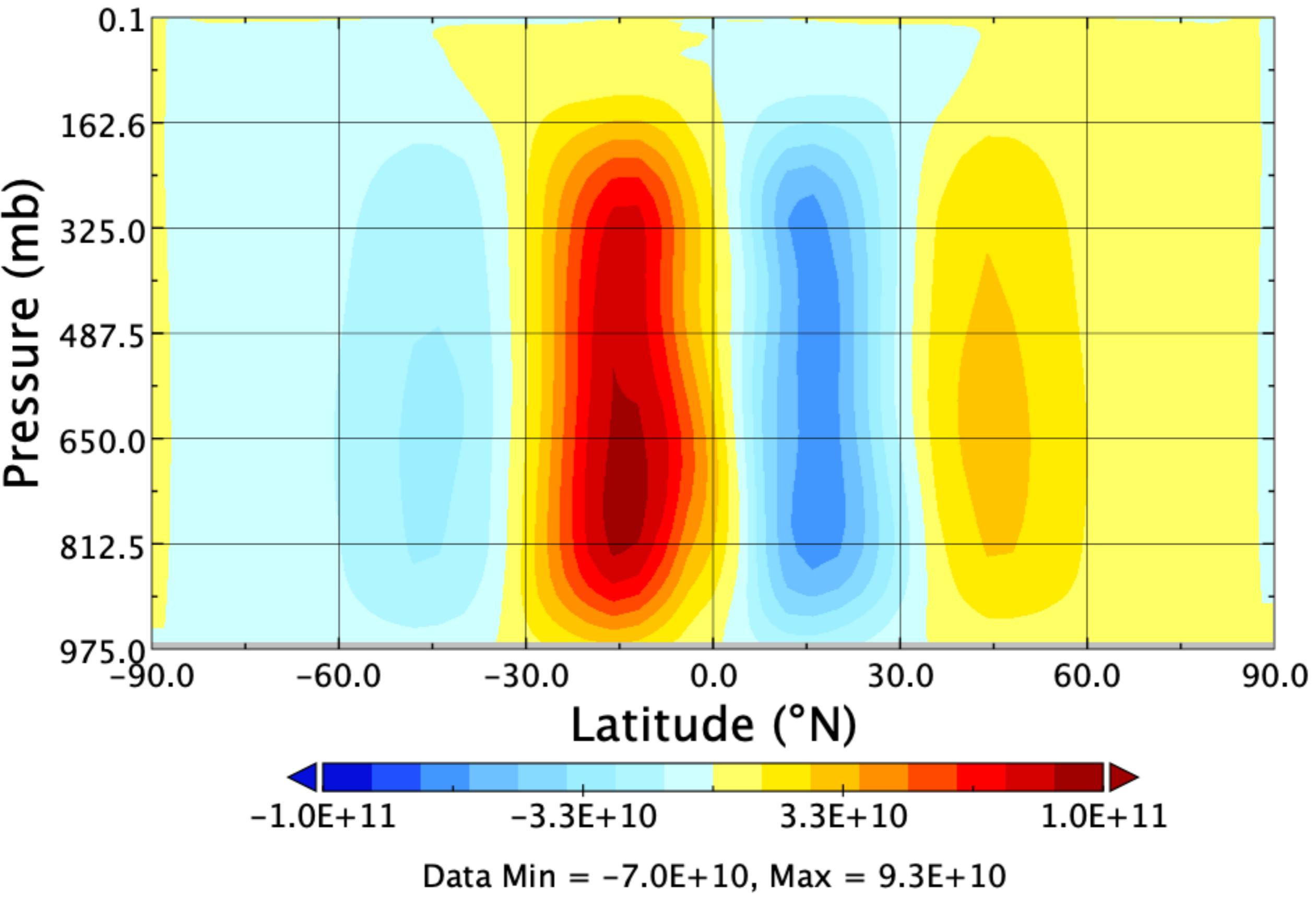
**Figure 6c.**

## (c) Sim 09 (Earth #3) Stream Function (kg/s)



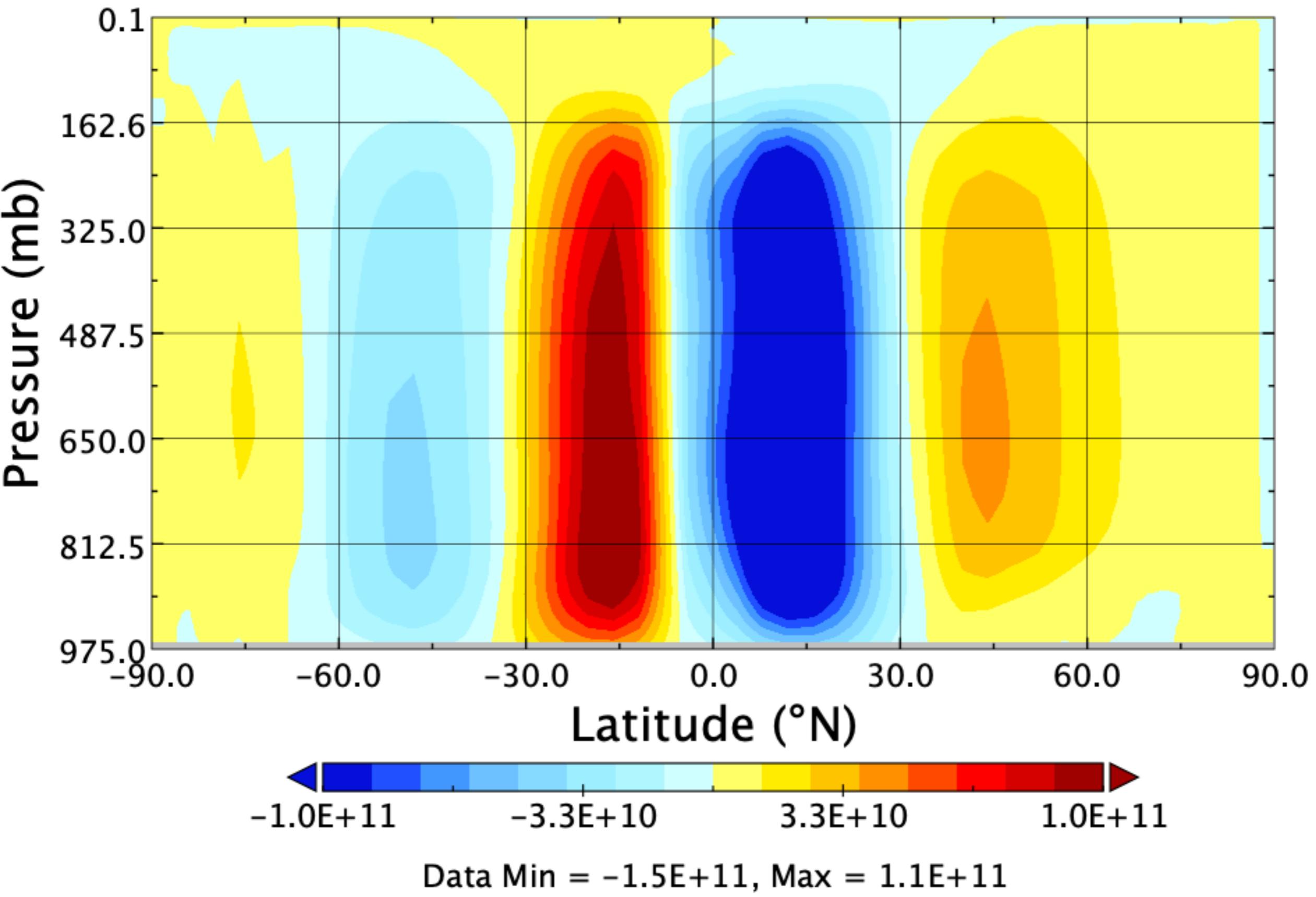
**Figure 6d.**

## (d) Sim 02 (Aurica PD) Stream Function (kg/s)



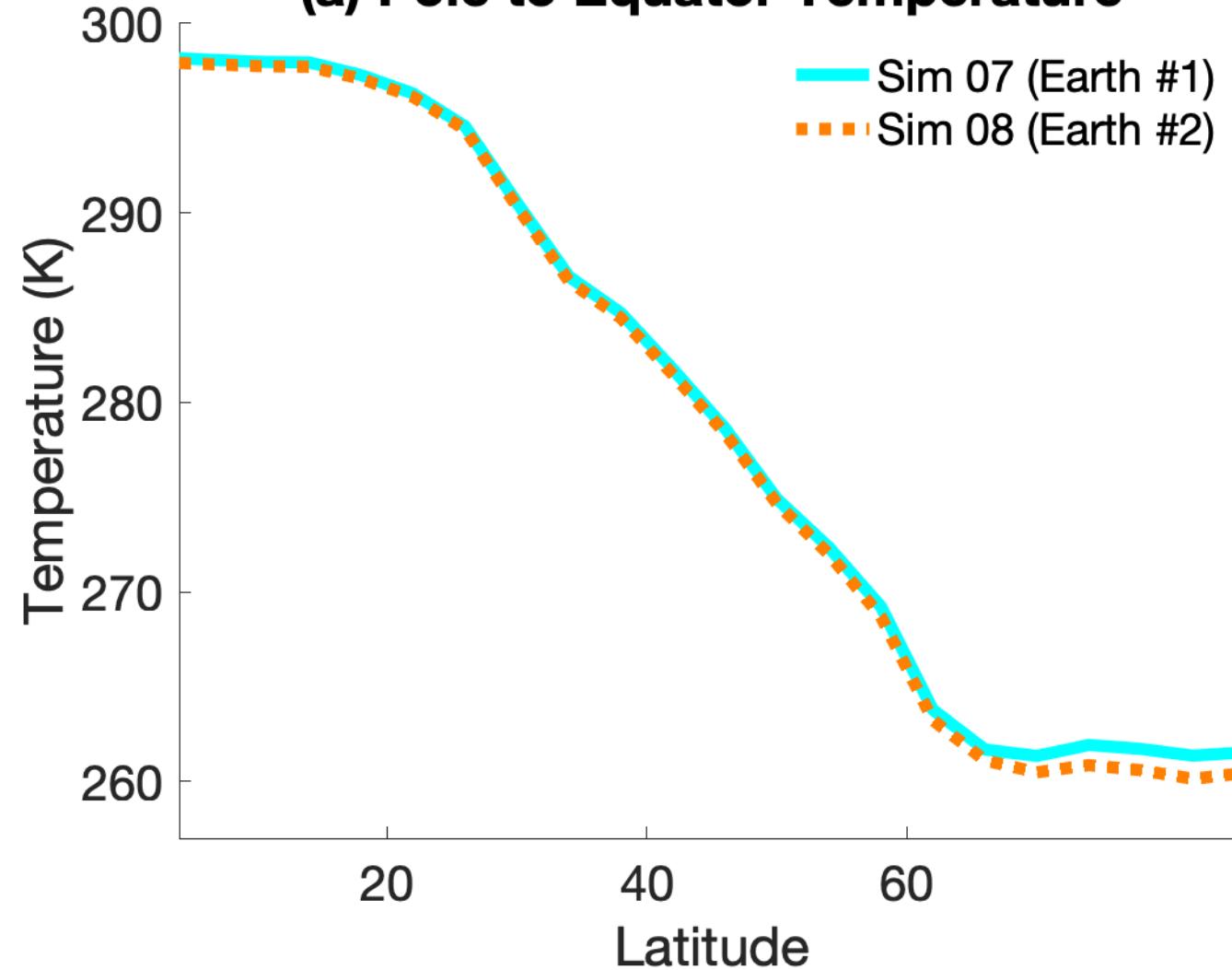
**Figure 6e.**

## (e) Sim 05 (Amasia PD) Stream Function (kg/s)

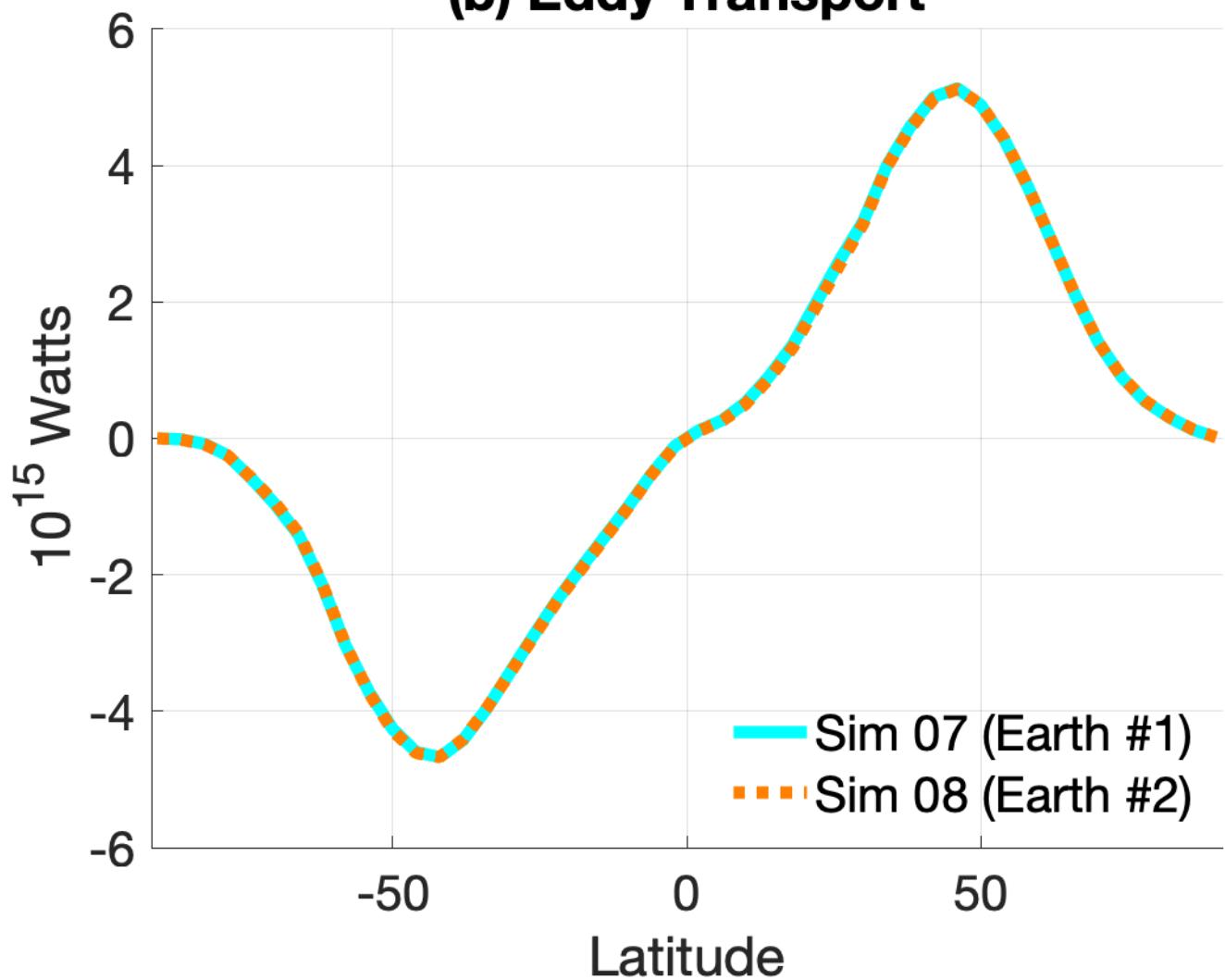


**Figure 7a.**

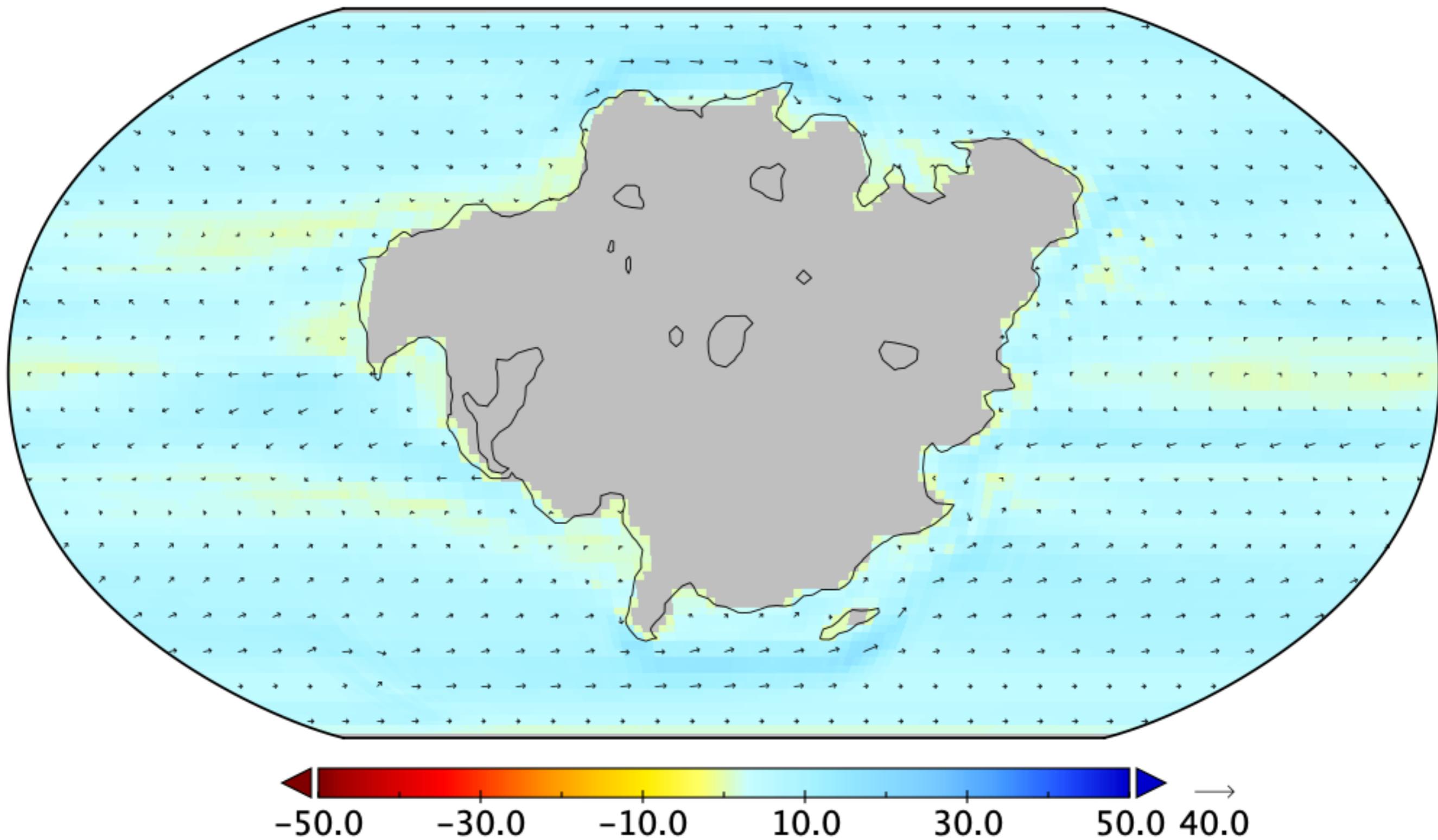
# (a) Pole to Equator Temperature



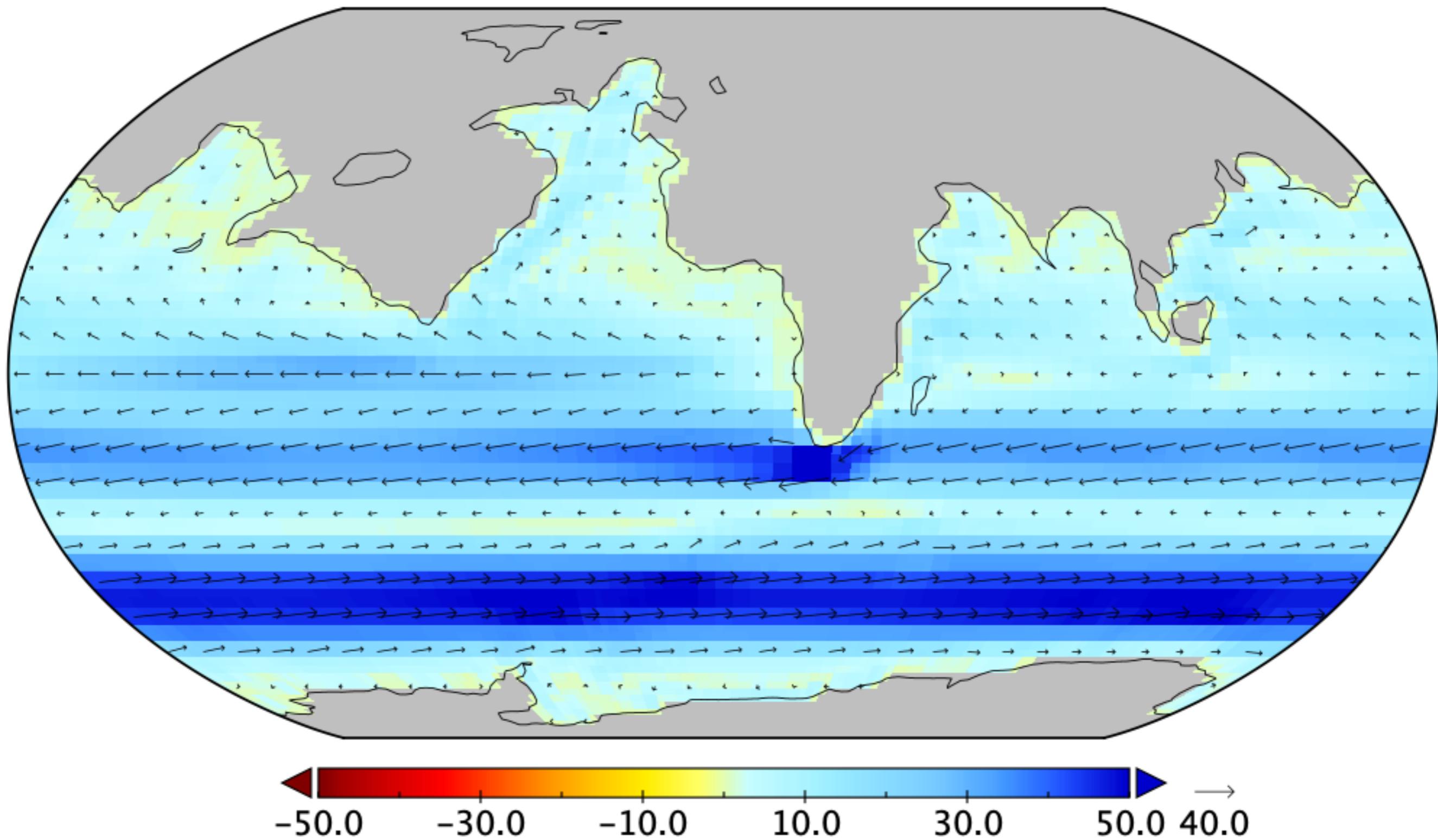
**Figure 7b.**

**(b) Eddy Transport**

**Figure 8a.**

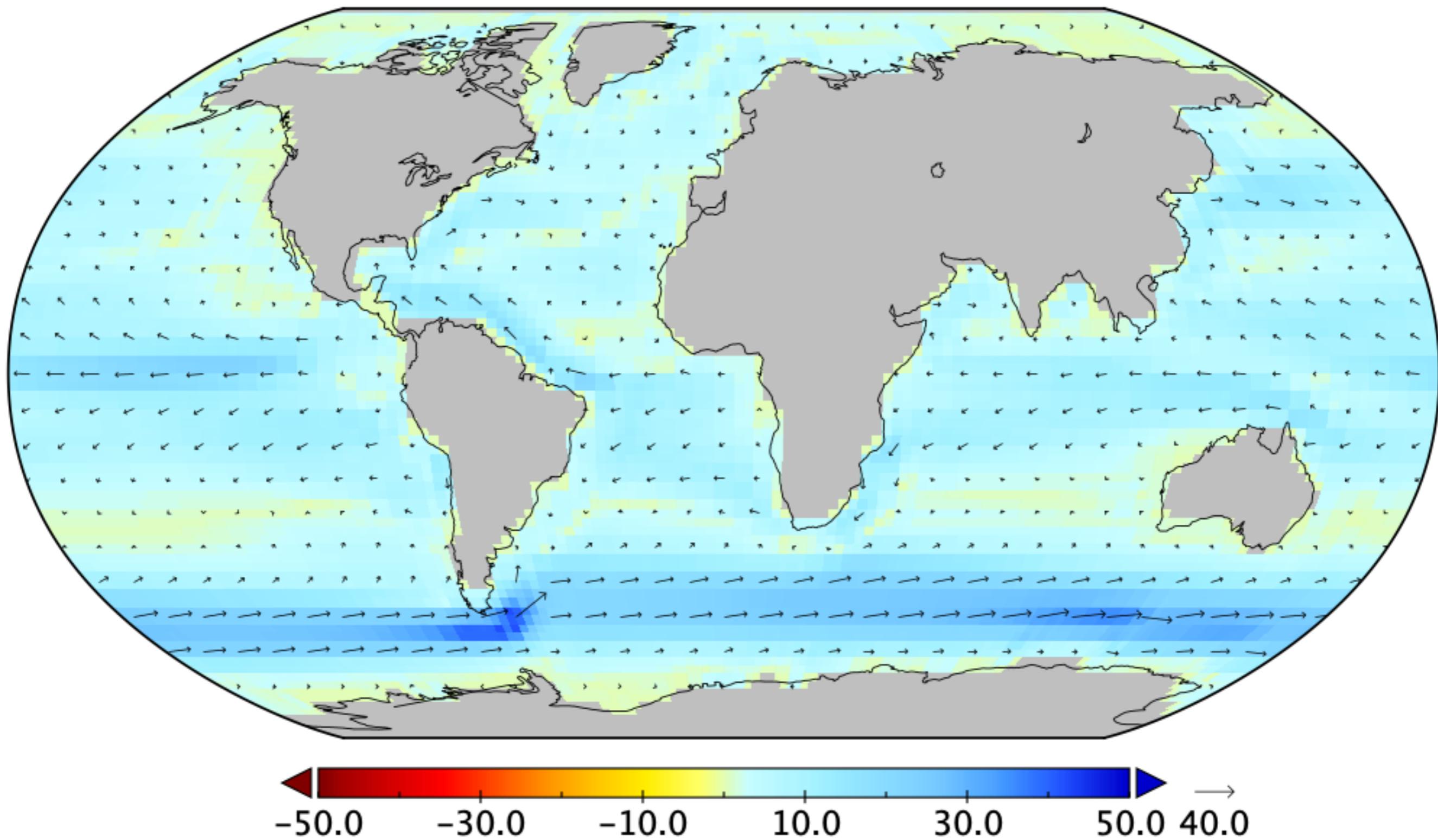
**(a) Simulation 02 (Aurica PD): Ocean Surface Currents**

**Figure 8b.**

**(b) Simulation 05 (Amasia PD): Ocean Surface Currents**

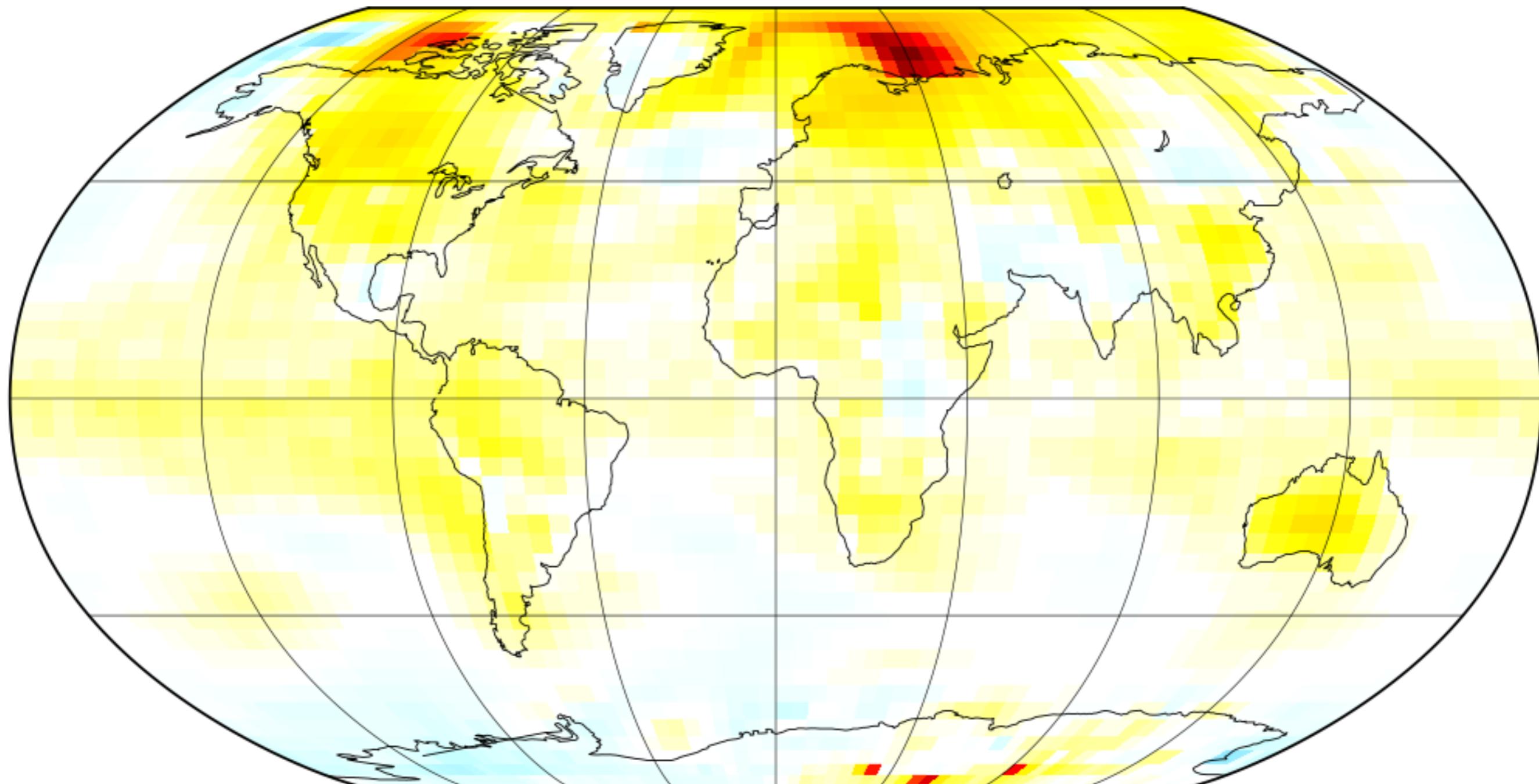
**Figure 8c.**

### (c) Simulation 09 (Earth #3): Ocean Surface Currents



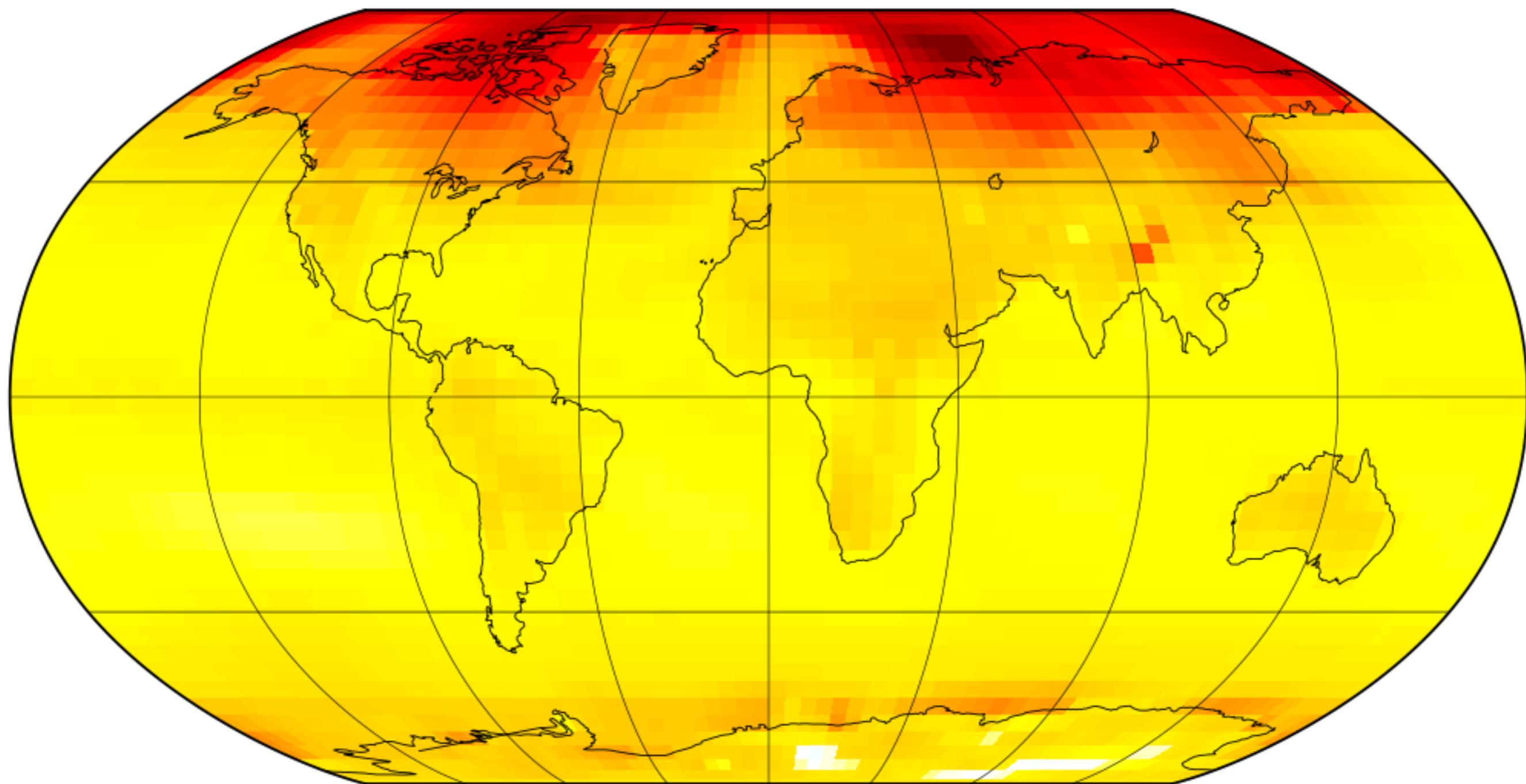
**Figure 4a.**

## (a) Sim 07 (Earth #1) – Sim 08 (Earth #2) Mean Surface Air Temperature



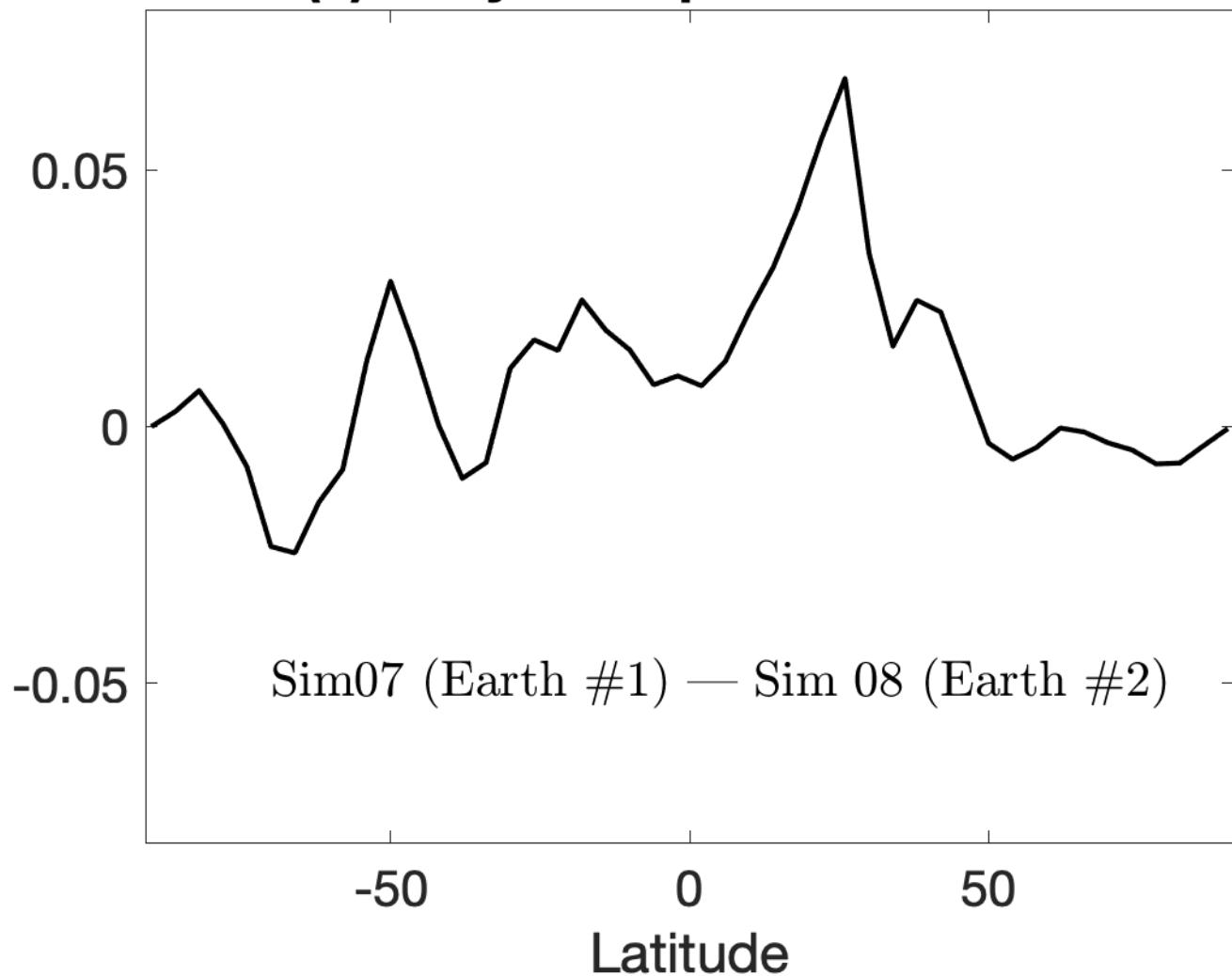
Data Min = -2.1, Max = 5.4, Mean = 0.2

**Figure 4b.**

**(b) Sim 09 (Earth #3) – Sim 08 (Earth #2) Mean Surface Air**

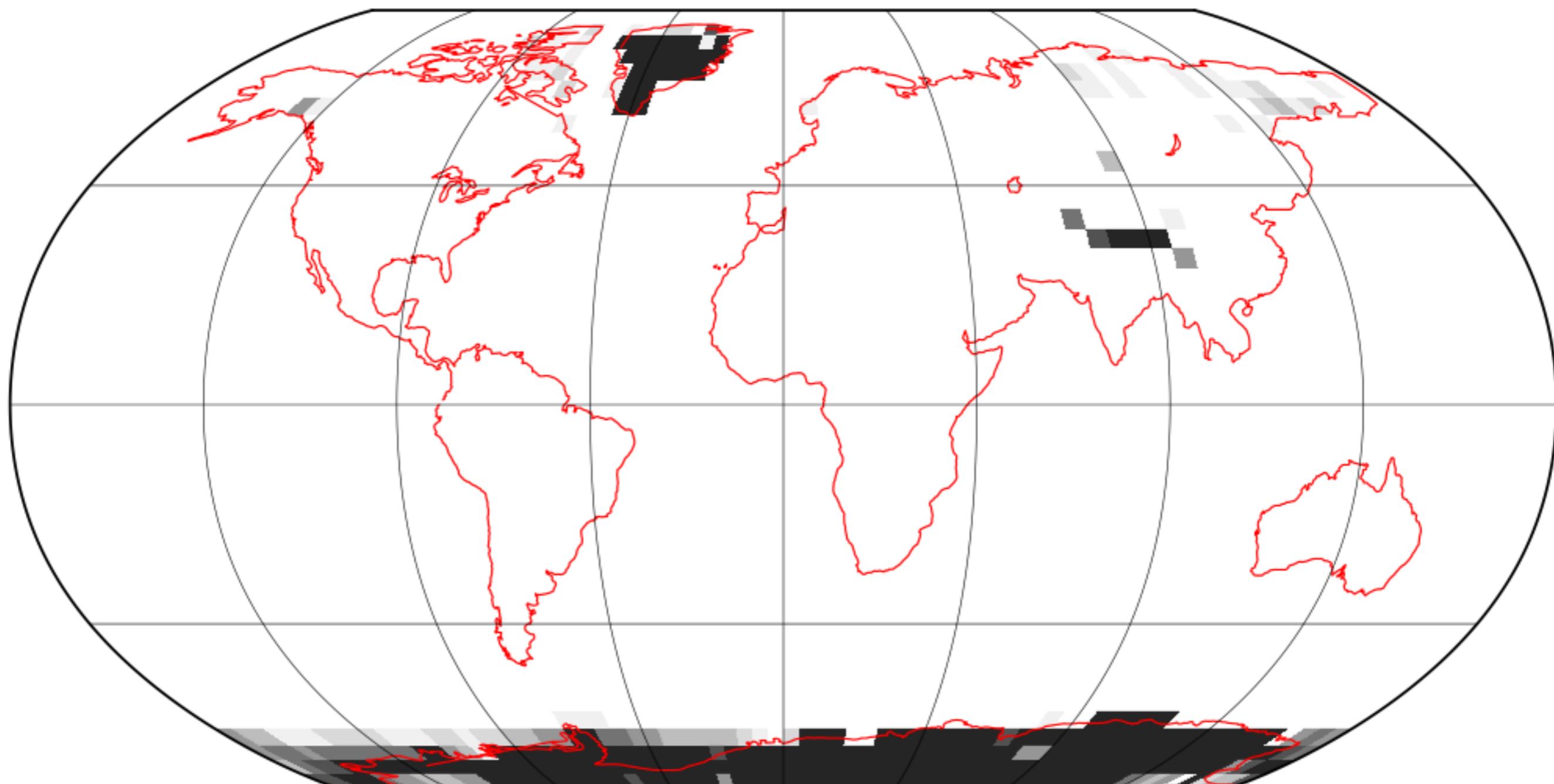
Data Min = -0.7, Max = 16.2, Mean = 4.4

**Figure 7c.**

**(c) Eddy Transport Difference**

**Figure 2f.**

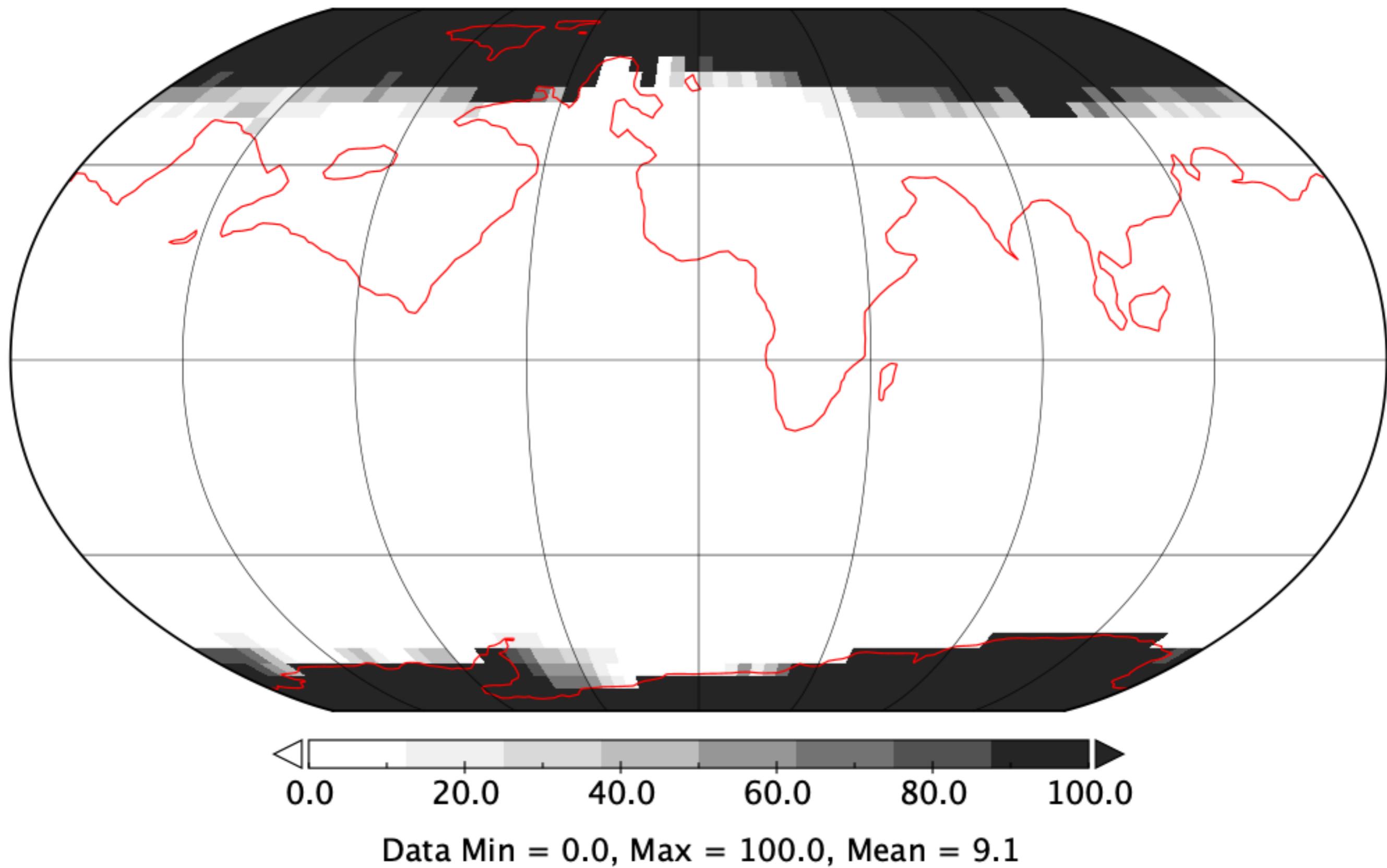
## Sim 09 (Earth #3): Snow and Ice Coverage Jun/Jul/Aug



Data Min = 0.0, Max = 99.8, Mean = 3.9

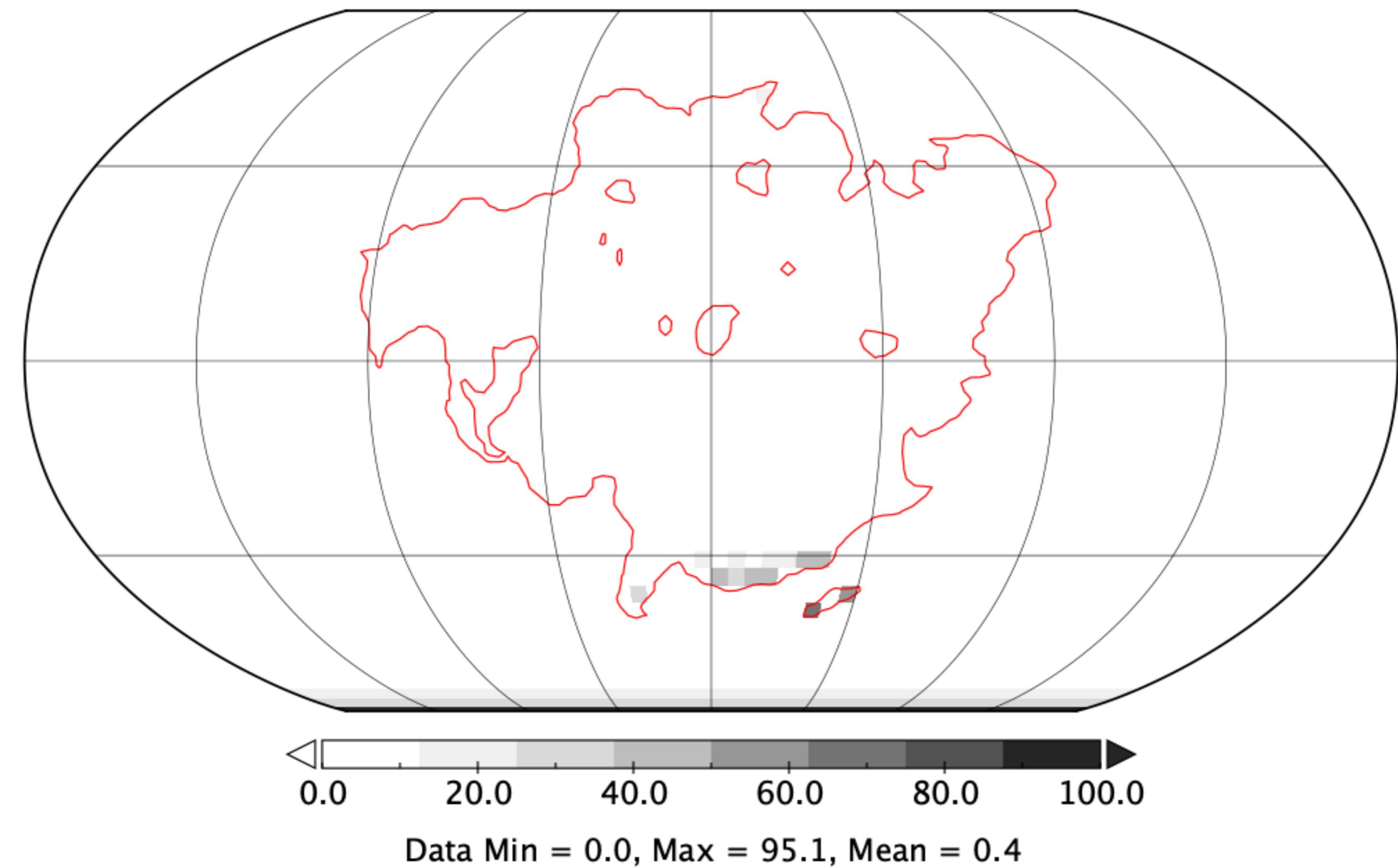
**Figure 2e.**

## Sim 05 (Amasia PD): Snow and Ice Coverage Jun/Jul/Aug



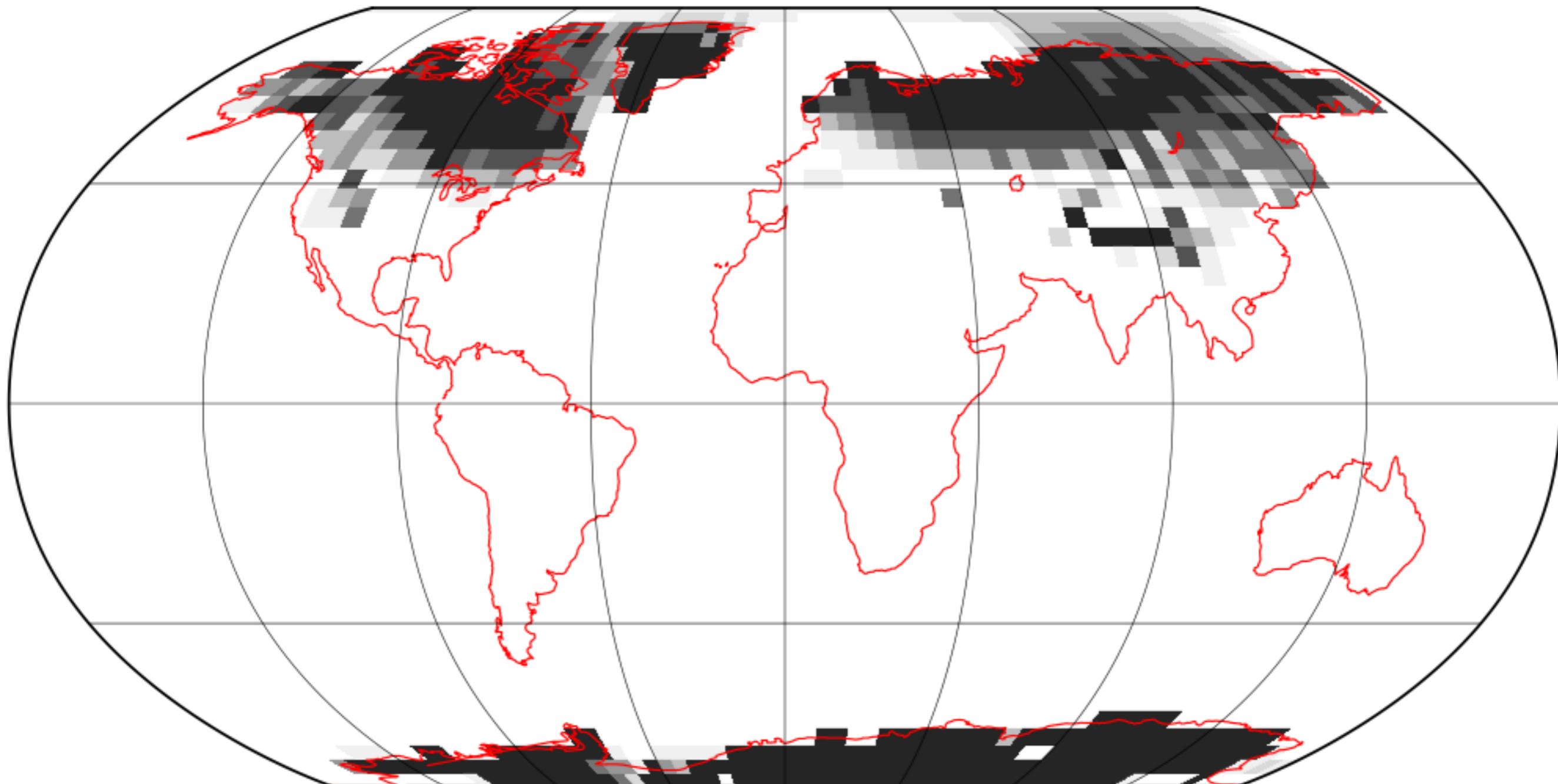
**Figure 2d.**

## Sim 02 (Aurica PD): Snow and Ice Coverage Jun/Jul/Aug



**Figure 2c.**

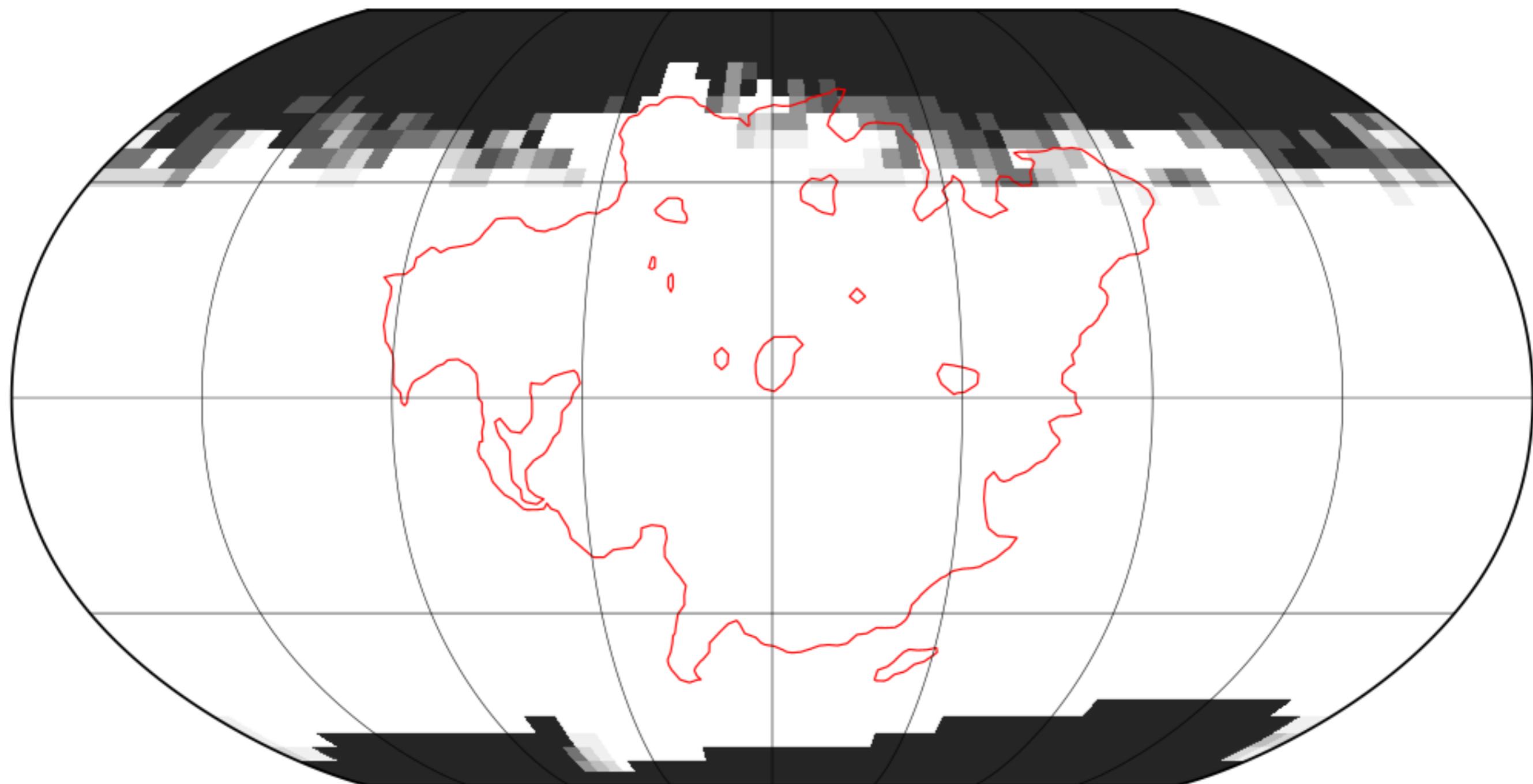
## Sim 09 (Earth #3): Snow and Ice Coverage Dec/Jan/Feb



Data Min = 0.0, Max = 99.8, Mean = 9.3

**Figure 2b.**

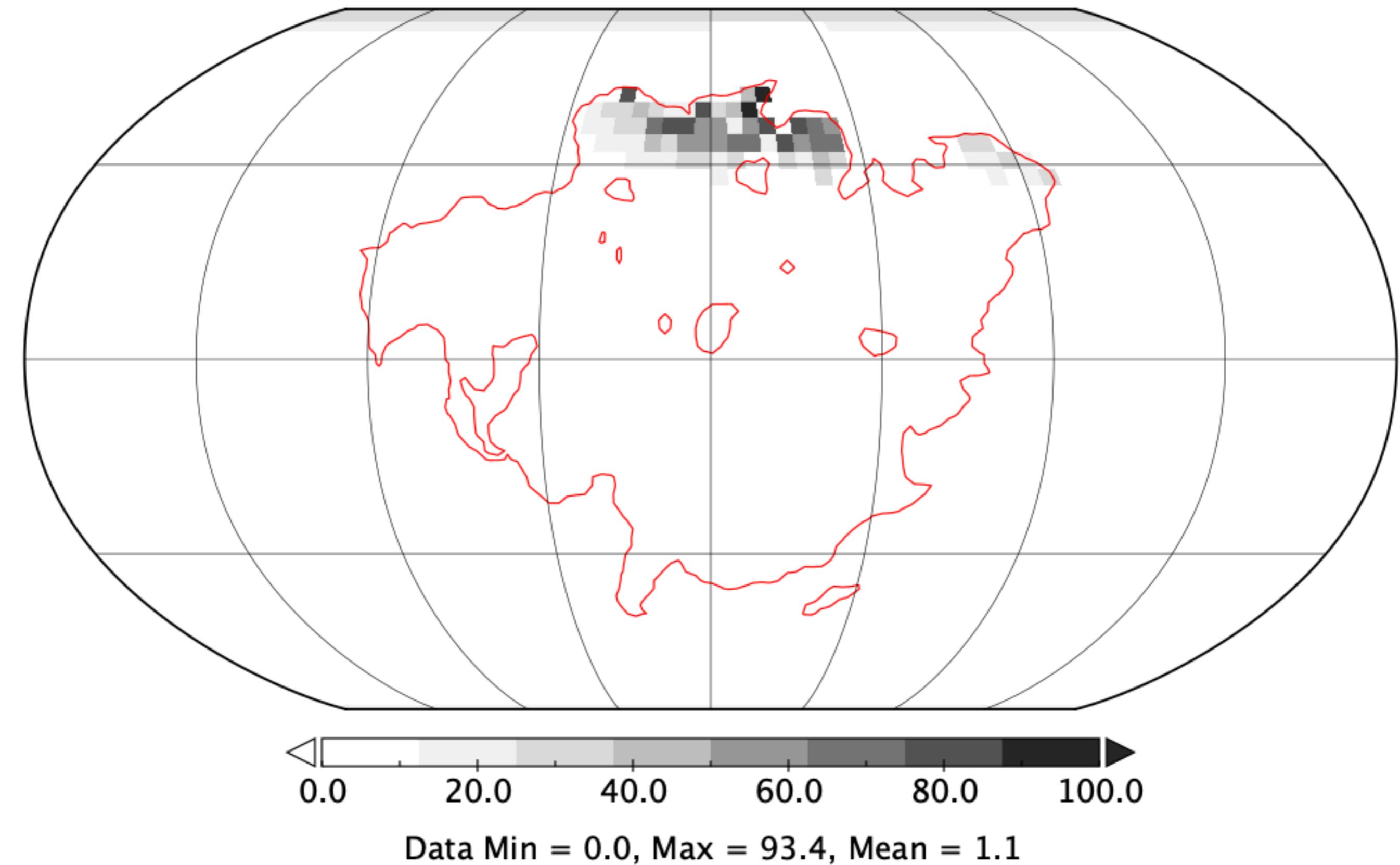
## Sim 05 (Amasia PD): Snow and Ice Coverage Dec/Jan/Feb



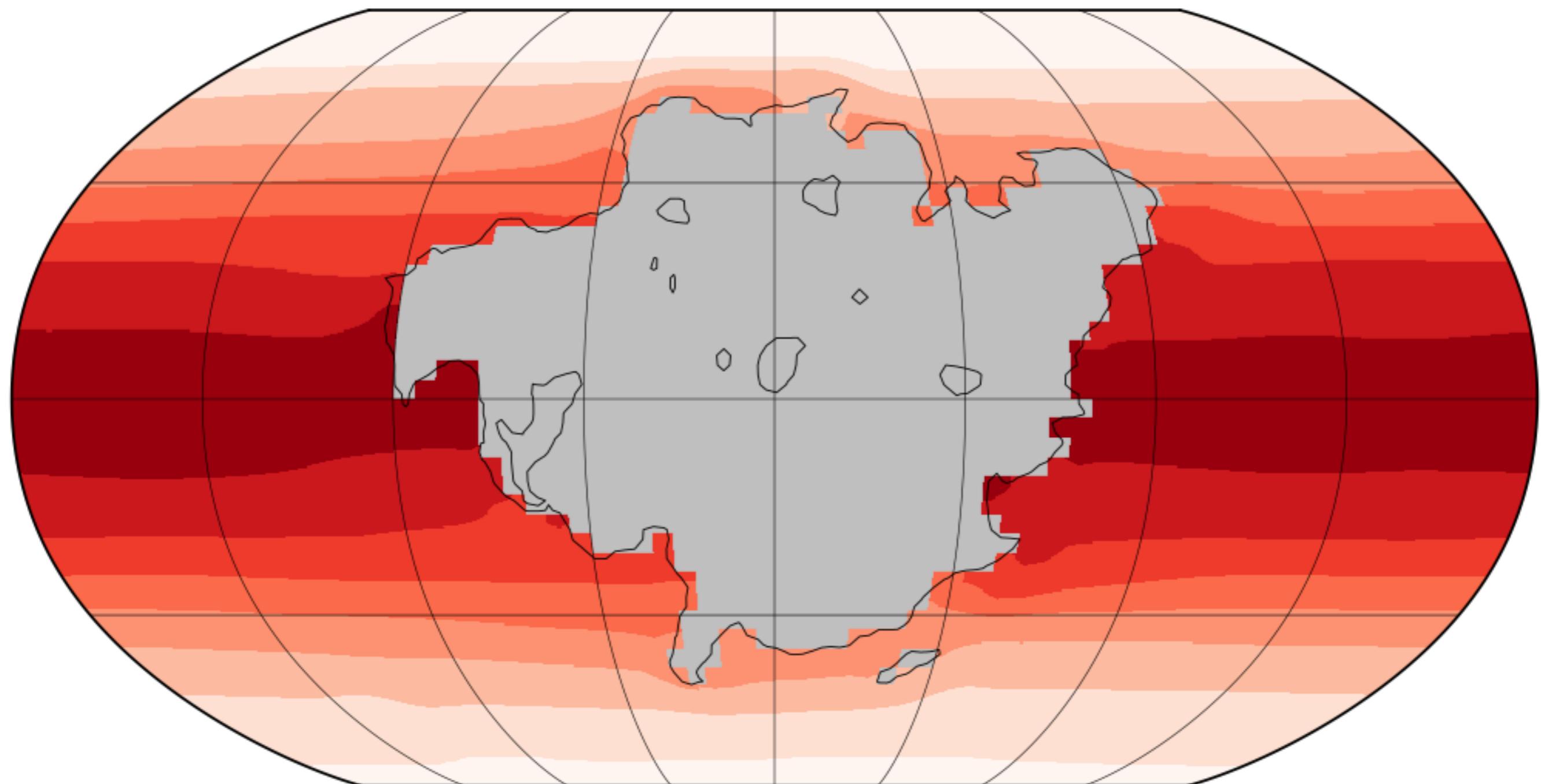
Data Min = 0.0, Max = 100.0, Mean = 12.3

**Figure 2a.**

## Sim 02 (Aurica PD): Snow and Ice Coverage Dec/Jan/Feb



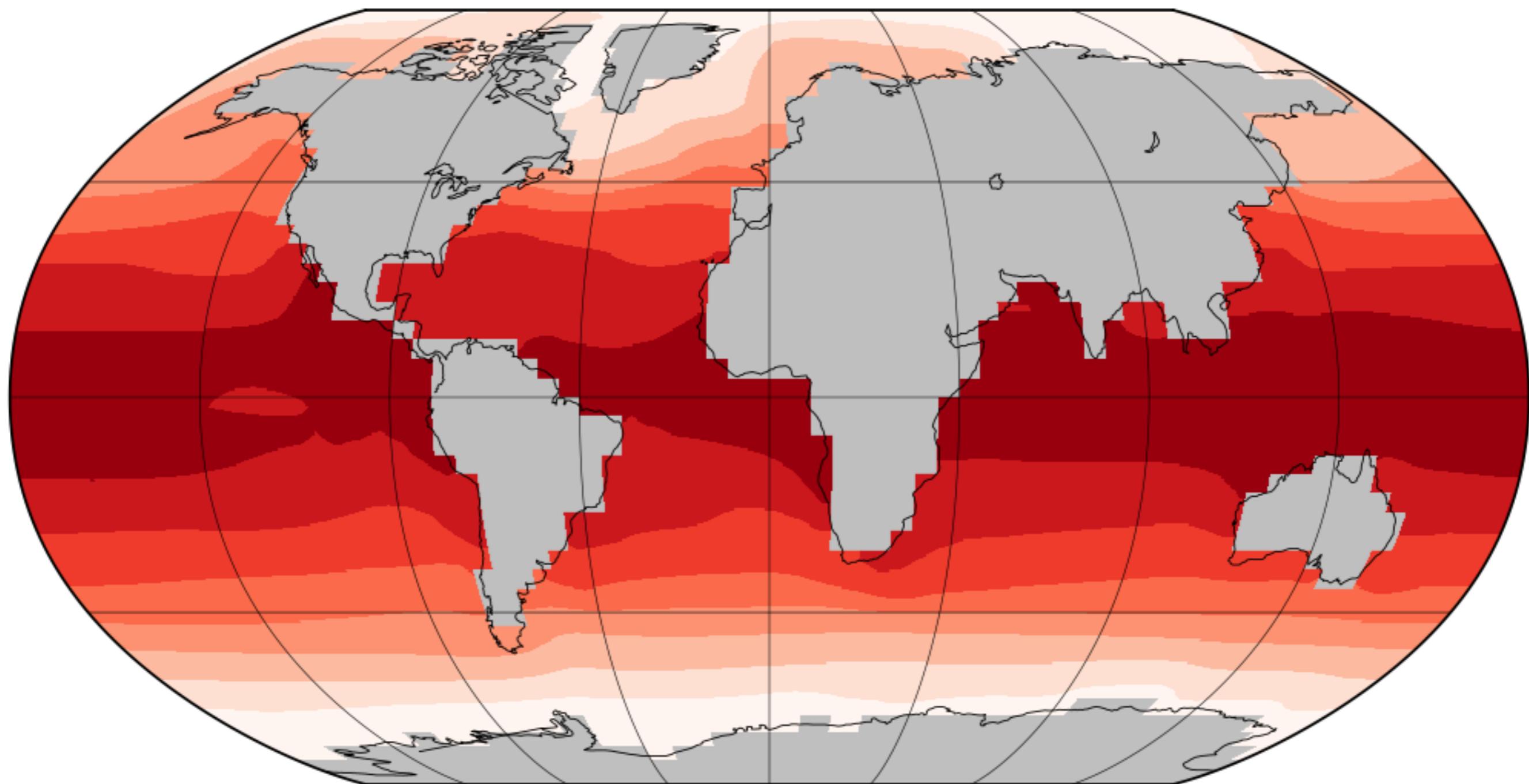
**Figure 8d.**

**(d) Simulation 02 (Aurica PD): Sea Surface Temperatures**

Data Min = -0.1, Max = 30.9, Mean = 19.3

**Figure 8f.**

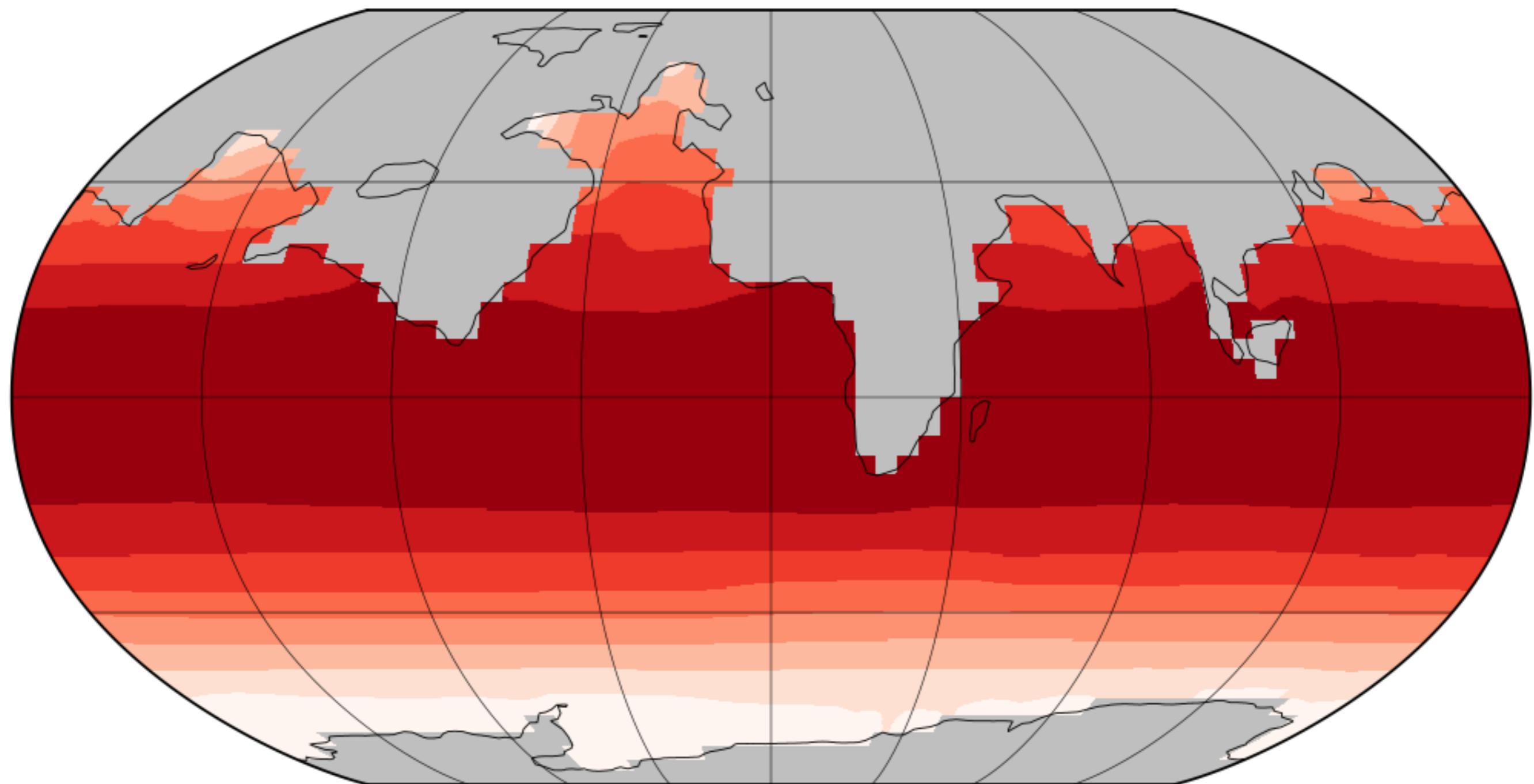
## (f) Simulation 09 (Earth #3): Sea Surface Temperatures



Data Min = -1.3, Max = 31.6, Mean = 21.4

**Figure 8e.**

## (e) Simulation 05 (Amasia PD): Sea Surface Temperatures



Data Min = -1.6, Max = 32.7, Mean = 24.4