Earth System Implications of a Central American Seaway

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Introduction

The gradual closure of the Central American Seaway (CAS) is of interest to both the paleoclimate proxy data and climate modeling communities because it is hypothesized to have significantly changed climate and reorganized the large-scale ocean circulation and caused changes in both ocean and terrestrial ecosystems. During the time of the estimated final closure (ca. 5-2 Ma), higher benthic δ13C values and better carbonate preservation in the Caribbean (ODP Site 999) indicate stronger ventilation (Figure 1) attributed to intensification of North Atlantic Deep Water (Haug and Tiedemann, 1998). Diverging planktonic foraminifera δ18O records from the Caribbean and Eastern Equatorial Pacific (EEP; ca. 4.4 Ma) indicate a build-up of the modern Pacific-Caribbean salinity contrast and the emergence of the Western Atlantic Warm Pool (Keigwin 1982; Haug et al. 2001; Steph et al. 2006). These records are consistent with increasing foraminiferal Mg/Ca ratios at the same time indicating rising temperatures in the Caribbean (Groeneveld et al. 2008).

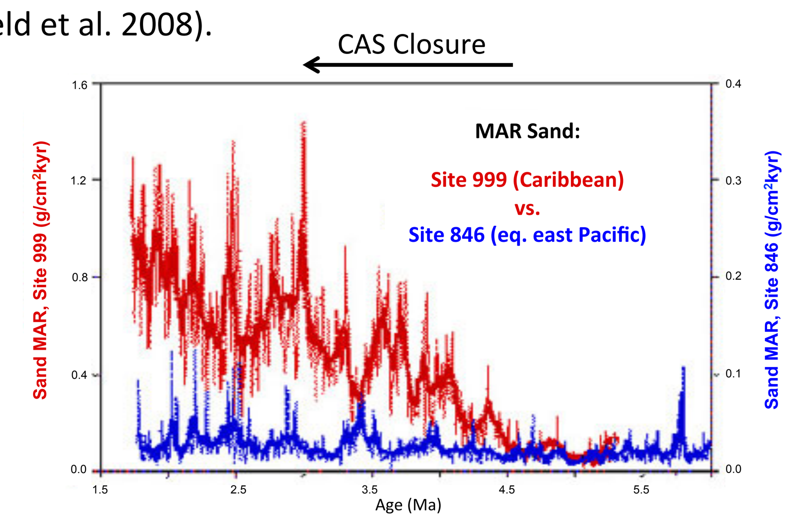


Figure 1. Comparison of carbonate sand-fraction mass accumulation rates (sand MAR) at ODP sites 999 (left axis) and 846 (right axis) (see Figure 2) plotted versus age for the period 2–5.3 Ma (Haug and Tiedemann 1998, Fig 2).

In most coupled climate models, the CAS transports relatively fresh and cool Pacific water into the Atlantic, maintained by the steric height gradient, decreasing sea surface salinity (SSS) in the Caribbean Sea and Atlantic Ocean, and either collapsed (Maier-Reimer et al. 1990; Mikolajewicz et al. 1993; Mikolajewicz and Crowley 1997; Murdock et al. 1997) or weakened (Nisancioglu et al. 2003; Klocker et al. 2005; Schneider and Schmittner 2006; Steph et al. 2006; Lunt et al. 2007; Steph et al. 2010; Butzin et al. 2011; Zhang et al. 2012; Yang et al. 2014) the Atlantic Meridional Overturning Circulation (AMOC). The difference in the simulated AMOC responses has been attributed to poorly constrained parameters that vary in models, like ocean diffusivity (Schneider and Schmittner 2006).
The impact of the seaway on the fully coupled Earth system is uncertain and has not been thoroughly evaluated.

Experiment Design

The role of the CAS gradual sill shoaling and closure on the Earth system is examined through four open and closed CAS sensitivity multi-millennial GFDL-ESM2G (Dunne et al. 2012; Dunne et al. 2013) experiments with 1860 forcing and no land use initialized from a quasi-equilibrium state after 2000 years of the CMIP5 ESM2G preindustrial 1860 control experiment (Table 1; Figure 2). The WIDE (NARROW) experiment represents the earlier (later) stages of seaway closure. The channel location for NARROW was chosen based on paleogeographic reconstructions (Kirby et al. 2008; Montes et al. 2012). Analysis was conducted on the final 100 years after quasi-equilibrium (1300 years of spinup for climate, 1700 years for carbon).
This experiment design is unique in that:

- The model's horizontal discretization allows for a very narrow 1˚ wide CAS to study the role of the seaway width on the Earth system
- The isopycnal framework of the ocean has a relatively high resolution compared to previous modeling studies; 1˚ horizontal grid up to ⅓˚ meridionally at the equator

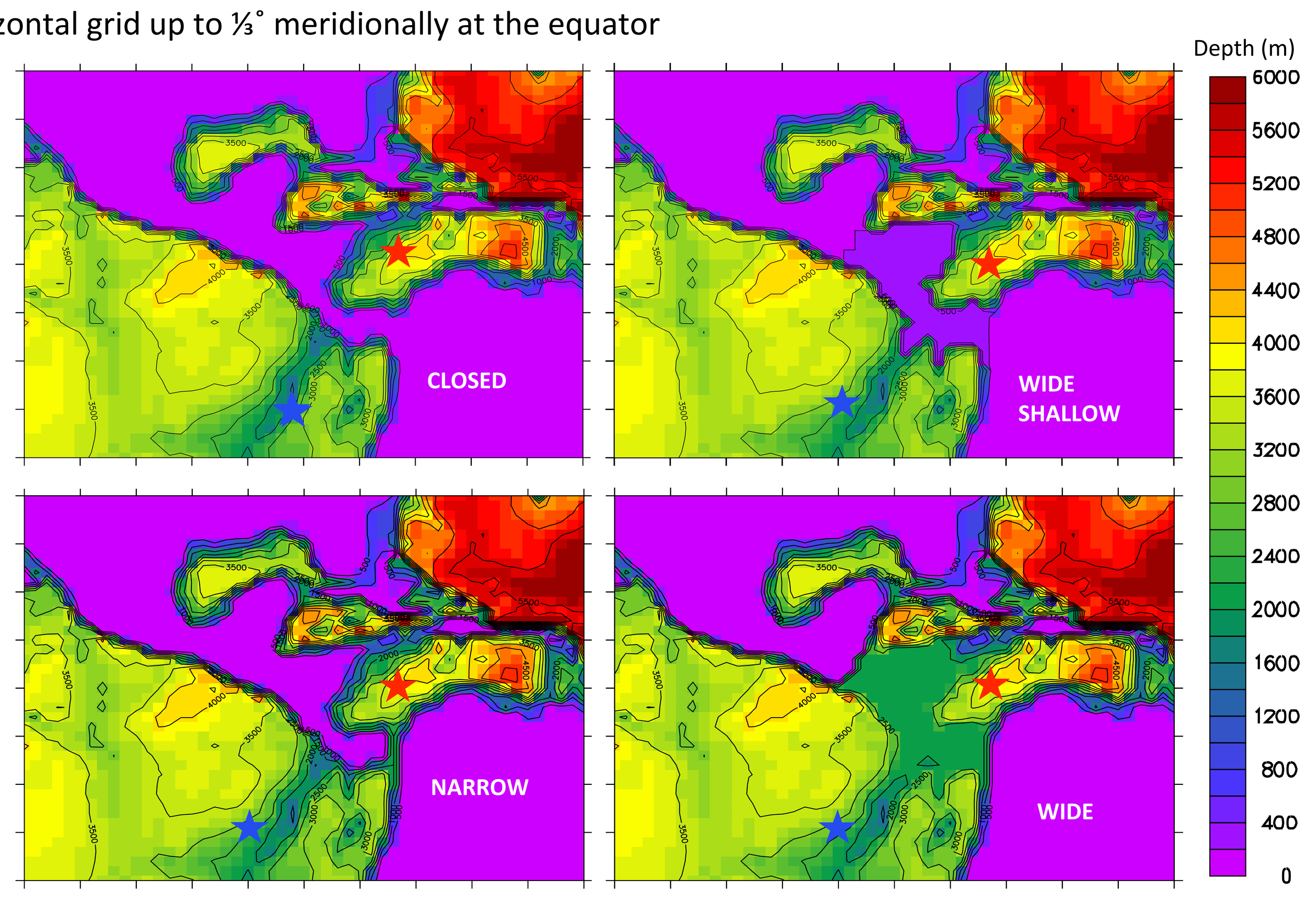


Figure 2. GFDL-ESM2G bathymetry (m) for the four CAS sensitivity experiments. Red and blue stars represent approximate locations of ODP sites 999 and 846 (Figure 1), respectively.

1. Ocean Circulation Changes with a Seaway

Water is rerouted from the ACC in the Pacific through the seaway into the Atlantic, where it splits into the North Atlantic and South Atlantic. With a wide seaway, there is two-way horizontal transport, with a westward (eastward) component in the northern (southern) part of the seaway.

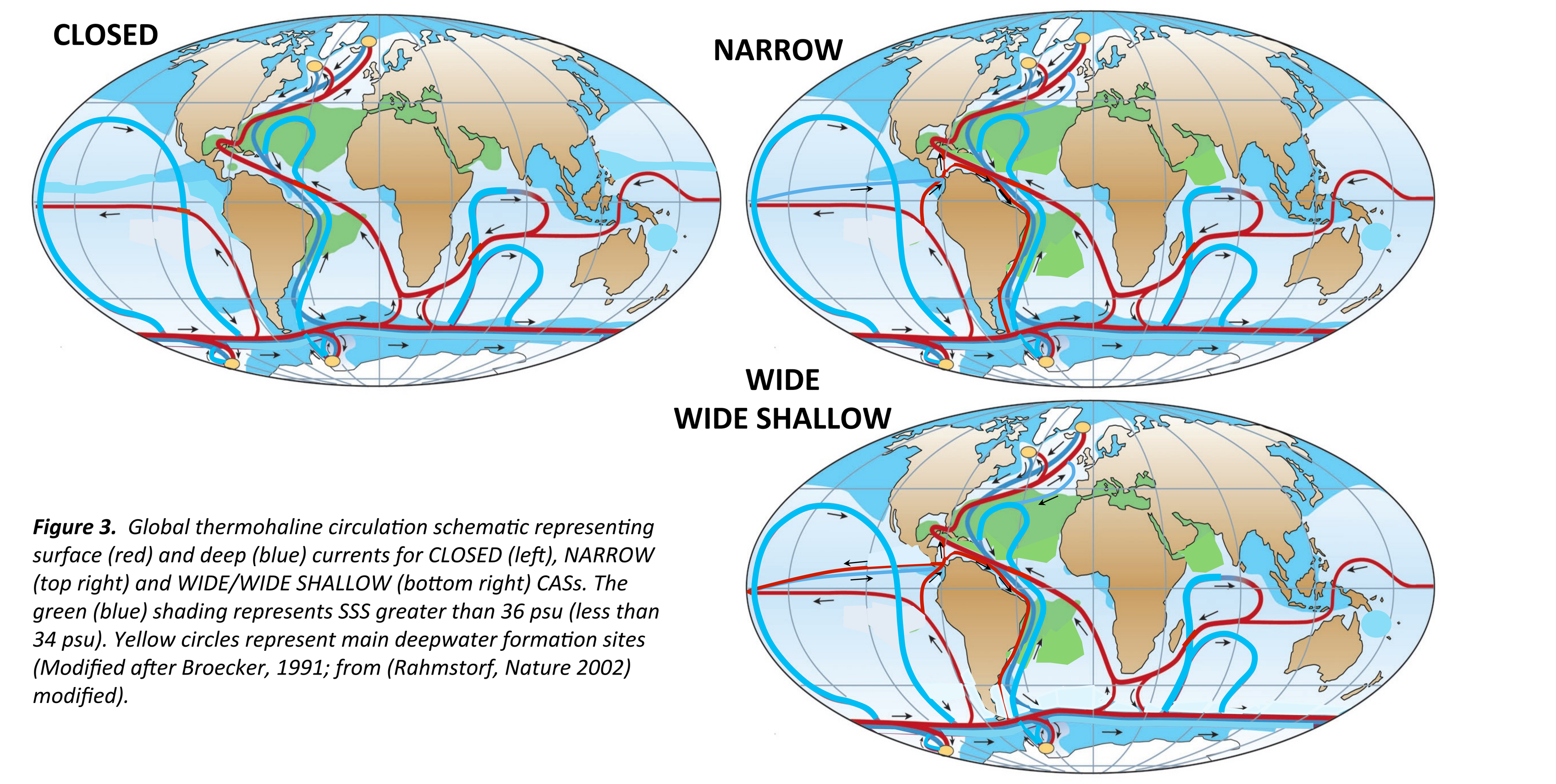
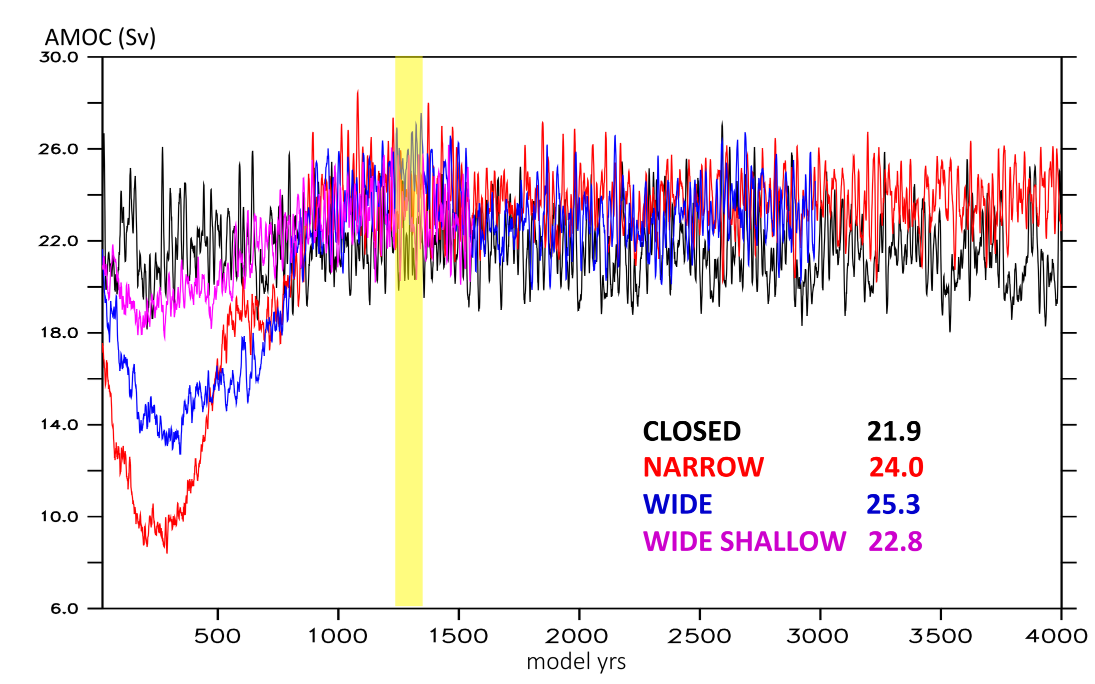


Figure 3. Global thermohaline circulation schematic representing surface (red) and deep (blue) currents for CLOSED (left), NARROW (top right) and WIDE/WIDE SHALLOW (bottom right) CASs. The green (blue) shading represents SSS greater than 36 psu (less than 34 psu). Yellow circles represent main deepwater formation sites (Modified after Broecker, 1991; from (Rahmstorf, Nature 2002) modified).

Table 1. CAS configuration specification and mass transports in Sverdrups (1 Sv=10^6 m^3 s^{-1}) [a].

Exp	CAS Width (km)	CAS Depth (m)	CAS	SAMBA 34.5S	RAPID 26.5N	Gulf Stream	Brazil Current	ITF	Drake Passage	Mozambique Channel	Bering Strait	ACC 25E	ACC 148E
OBS	-	-	-	3-39[b]	16.5[c]	94[d]	10-17.5[e]	-13[f]	136.7 ± 6.9[g]	-16.7 ± 8.9[h]	0.4-1.2[i]	N/A	100-150[j]
CLOSED	-	-	-	-19.4	20.5	50.4	-13.1	-21.1	65.1	-28.6	0.346	86.6	88.7
NARROW	~110	2000	20.5	-5.3	22.9	54.8	-23.8	-8.1	49.4	-13.7	0.183	70.2	70.9
WIDE	~2000	2000	31.1	-5.1	24.6	55.9	-20.8	-8.6	47.2	-13.4	0.158	75.5	67.1
WIDE SHALLOW	~2000	200	32.2	-6.9	21.3	53.9	-19.9	-9.4	48.9	-17.2	0.224	74.8	71.2

[a] Observational estimates and the four GFDL-ESM2G CAS sensitivity experiments. Negative values indicate southward or westward transport. Blue (red) values indicate reduced (increased) transport with a seaway. Gulf stream between 70W and 82W at 27N integrated from 0 to 1,000 m . Brazil current between 55W and 42W at 32S integrated from 0 to 1,000 m. Indonesian Throughflow (ITF) between 113.8E and 140E at 8.2S integrated from 0 to 1,000 m.
[b]Meinen et al. (2013); [c]Cunningham et al. (2007); [d]Leaman et al. (1989); [e]Stramma (1989); [f]Gordon et al. (2009); [g]Meredith et al. (2011); [h]Ridderinkhof et al. (2010); [i]Woodgate et al. (2012); [j]Knauss (1996).



Approximately 4-15% stronger (Figure 4) and 500m-1000m deeper (Figure 5) AMOC with a seaway.

Figure 4. Maximum Atlantic overturning streamfunction (Sv) between 20N and 80N for the four GFDL-ESM2G seaway experiments; CLOSED (black), NARROW (red), WIDE (blue), and WIDE SHALLOW (purple). 100-year averages for the period highlighted in yellow.

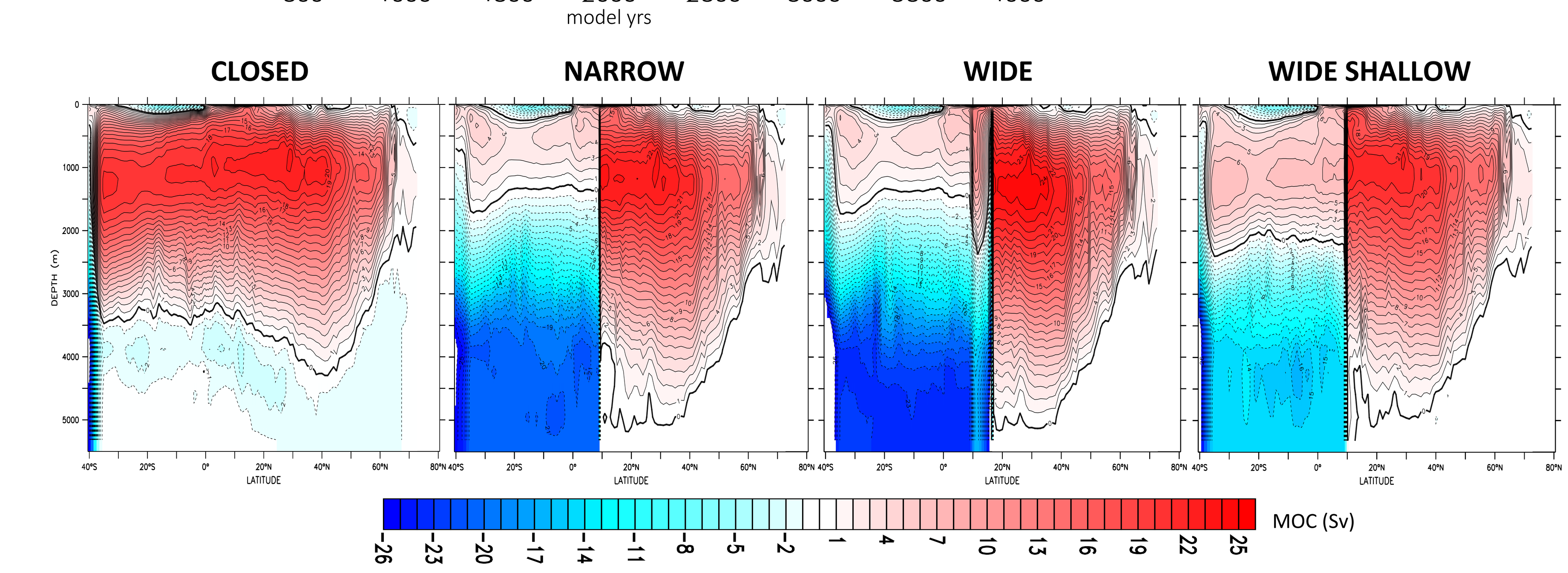


Figure 5. Atlantic (40S to 80N) meridional overturning streamfunction (Sv) vertical structure for the four GFDL-ESM2G seaway experiments.

2. Climate Impacts with a Seaway

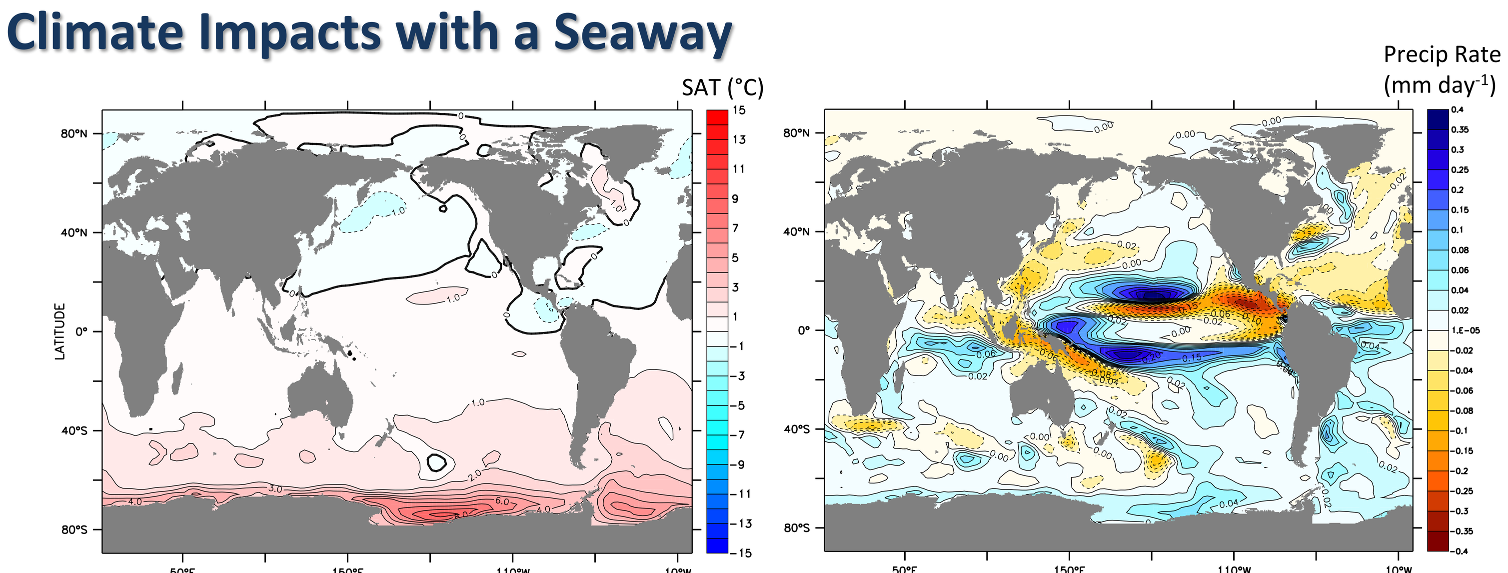


Figure 6. 100-year annual average surface air temperature, SAT (°C; left) and precipitation rate (mm day^{-1}; right) WIDE minus CLOSED differences. NARROW and CLOSED differences are similar (not shown). Inter-hemispheric bipolar temperature response with an overall warming of 0.4 °C (NARROW) and 0.7 °C (WIDE and WIDE SHALLOW) (Table 2), and a slight southward shift of the Intertropical Convergence Zone (ITCZ) towards the warmer southern hemisphere, SH.

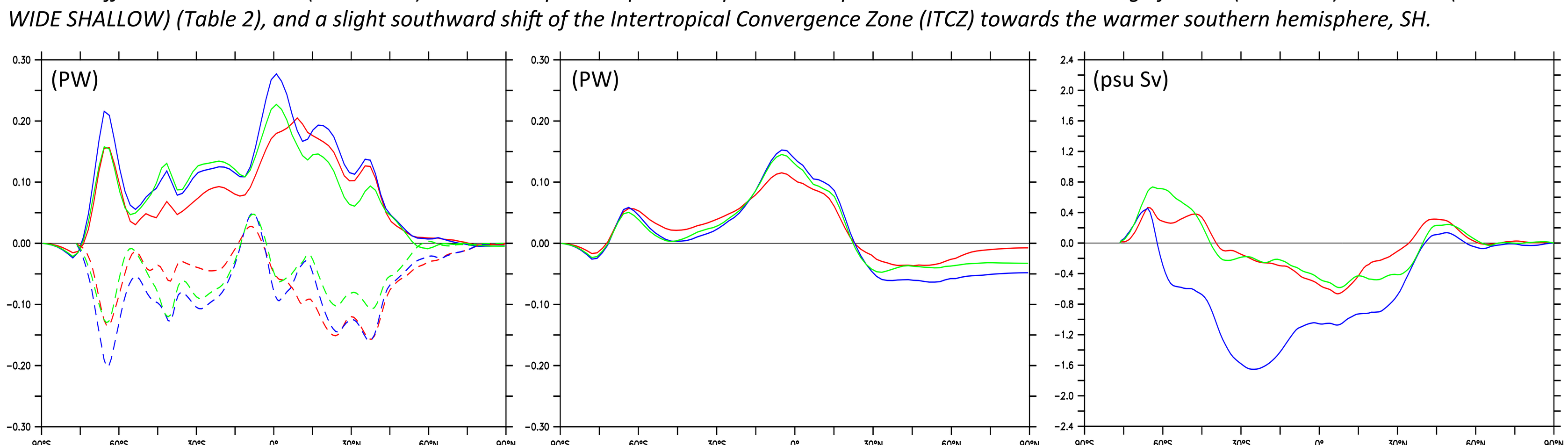


Figure 7. Vertically integrated meridional flux difference (open minus CLOSED) of heat and salt. Northward atmosphere (solid; left), ocean (dashed; left) and total (middle) heat transport (PW) and salt transport (psu Sv; right); red (NARROW), blue (WIDE), green (WIDE SHALLOW).
There is a net northward heat flux driven by the atmosphere heat flux and a net southward salt flux with a seaway.

Table 2. Global 100-yr annual average SAT, northward heat transports, and salt transports [a]

Exp	Ave SAT (K)	Ave North AHT (PW)	Ave North OHT (PW)	Ave North Total HT (PW)	Ave North Salt Transport (psu Sv)
CLOSED	286.4	-0.015	0.295	0.280	-0.044
NARROW	286.8	0.055	0.246	0.301	-0.094
WIDE	287.1	0.076	0.215	0.291	-0.616
WIDE SHALLOW	287.1	0.061	0.235	0.296	-0.096

[a] Red (blue) values indicate relative increases (decreases) with a seaway.

3. Earth System Impacts with a Seaway

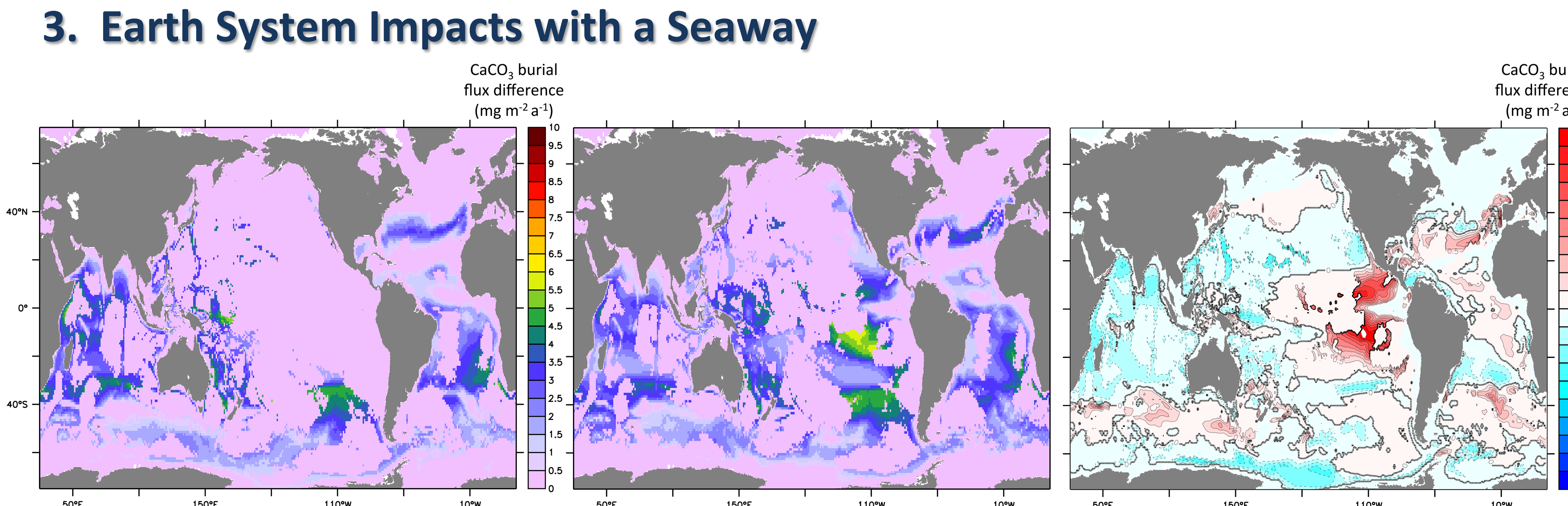


Figure 8. GFDL-ESM2G 100-yr annual average $CaCO_3$ burial flux for CLOSED (left), WIDE (middle) and WIDE minus CLOSED (right) difference (mg m^{-2} a^{-1}). NARROW and CLOSED changes are similar(not shown). With a seaway, there is decreased (increased) $CaCO_3$ sedimentation (negative values) in the Caribbean (E. Pacific) consistent with proxy data (Figure 1). Global total $CaCO_3$ burial fluxes are 0.23 (CLOSED), 0.31 (NARROW), and 0.34 PgC a^{-1} (WIDE). Optimized model $CaCO_3$ burial flux based on the 5-parameter calcite metamodel of Dunne et al. (2012).

Key Points

- Earth system implications of the Central American Seaway gradual shoaling and closure are explored through multi-millennial open and closed seaway sensitivity experiments with the GFDL-ESM2G model.
- We simulate two-way horizontal transport through the wide seaway, and a recirculating of the EEP water through the narrow and wide seaways influencing buoyancy in the Atlantic and reorganizing basin-scale circulation and overturning.
- With a seaway, there is a stronger (~4-15%) and deeper (~500-1000m) AMOC, in contrast to other modeling studies.
- The reorganization of the ocean circulation with a seaway results in overall global warming (0.4-0.7 °C) dominated by increased northward atmosphere heat transport and a slight southern shift of the ITCZ.
- There is decreased carbonate sedimentation in the Caribbean with a seaway consistent with proxy data, and increased total global $CaCO_3$ burial implying lower global ocean alkalinity at steady-state before the seaway closure.
- Changes in basin-scale overturning and circulation suggest that as the seaway gradually shoaled, there were less pathways for the circulation to act on as a result of asymmetric forcing on the system resulting in important climate and carbon cycle changes that need to be understood.