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Mountain ranges favour vigorous Atlantic meridional overturning

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[1] We use a global Ocean-Atmosphere General Circulation Model (OAGCM) to show that the major mountain ranges of the world have a significant role in maintenance of the Atlantic Meridional Overturning Circulation (AMOC). A simulation with mountains has a maximum AMOC of 18 Sv (1 Sv = 10^6 m^3 s^{-1}) compared with ~0 Sv for a simulation without mountains. Atlantic heat transport at 25°N is 1.1 PW with mountains compared to 0.2 PW without. The difference in AMOC is due to major changes in surface heat and freshwater (FW) fluxes over the Atlantic. In the Pacific changed surface fluxes lead to a meridional overturning circulation of 10 Sv. Our results suggest that the effects of mountains on the large-scale atmospheric circulation is to force the ocean towards a state with a vigorous AMOC and with no overturning in the Pacific. **Citation:** Sinha, B., A. T. Blaker, J. J.-M. Hirschi, S. Bonham, M. Brand, S. Josey, R. S. Smith, and J. Marotzke (2012), Mountain ranges favour vigorous Atlantic meridional overturning, *Geophys. Res. Lett.*, *39*, L02705, doi:10.1029/2011GL050485.

1. Introduction

[2] The difference between the Meridional Overturning Circulation of the Atlantic (AMOC) and of the Pacific has long been noted. Deep sinking occurs in the North Atlantic, but not in the North Pacific, with resulting differences in ocean heat transport that help maintain Western Europe's relatively mild climate [*Rhines and Häkkinen*, 2003].

[3] Mountains have a significant effect on atmospheric circulation and climate. Idealized theoretical studies [*Bolin*, 1950], and more realistic atmospheric general circulation model (GCM) studies with and without orography [*Manabe and Terpstra*, 1974], show that the Rocky Mountains generate stationary waves in the westerlies and suggest that mountain effects are important in maintaining Europe's mild winters [*Seager et al.*, 2002] and the position and intensity of the Atlantic storm track [*Wilson et al.*, 2009]. Mountains produce warmer (after elimination of the lapse-rate effect), drier and less cloudy continental interiors, whereas monsoon dominated regions become cooler due to more rainfall, with a wetter land surface and more clouds [*Broccoli and Manabe*, 1992]. Studies using an atmospheric GCM coupled to a slab ocean [*Kitoh*, 1997] and to a fully coupled ocean-atmosphere GCM [*Kitoh*, 2002] demonstrate extensive effects of mountains over ocean regions including reduction in sea-surface temperatures due to stronger trade winds and increased low-level clouds. Mountains may also be responsible for maintenance of the AMOC, through control of the asymmetry between North Pacific and North Atlantic surface freshwater (FW) fluxes [*Warren*, 1983; *Emile-Geay et al.*, 2003]. Coupled ocean-atmosphere simulations with and without mountains (albeit with surface flux corrections and a rather coarse-resolution atmosphere) performed by *Kitoh* [2002] had the potential to address the role of mountains in maintaining the AMOC, but the author performed no analysis of the subsurface ocean. Following *Kitoh* [2002] we perform simulations with and without mountain ranges, but this time using a non-flux corrected coupled ocean-atmosphere model, with an atmospheric component of significantly higher resolution, sufficient to well resolve atmospheric stationary waves and transient eddies.

2. Methods

[4] We employ the Fast Ocean Rapid Troposphere Experiment (FORTE) climate model consisting of an atmosphere model with 15 vertical levels and T42 horizontal spectral resolution (~2.8° × 2.8°) coupled to a z-coordinate ocean model, with horizontal resolution of 2° × 2°, and 15 vertical levels, including isopycnal mixing and a thermodynamic sea-ice model [*Wilson et al.*, 2009]. The coupled simulation spins up to a realistic analogue of observed climate without flux corrections.

[5] Two main experiments are performed with FORTE, one with present day mountain ranges, atmospheric composition, and land vegetation ('CONTROL'), and another identical to CONTROL except with a flat land surface of 1 m height everywhere ('FLAT'). River runoff catchment areas and coastal discharge points are not changed in FLAT. CONTROL is initialised with climatological ocean temperature and salinity, zero ocean velocity and atmospheric fields from a previous atmosphere-only simulation [*Wilson et al.*, 2009]. CONTROL is integrated for 900 model years, reaching a quasi equilibrium state after ~200 years. FLAT is initialized with the ocean-atmosphere state of CONTROL at year 400, and integrated for 850 model years. One further experiment, analyzed in less detail, was conducted where mountains were reintroduced at year 500 of FLAT and the simulation was continued for another 350 years.

3. Results

3.1. Surface Air Temperature, Sea-Ice and Sea-Surface Salinity

[6] Surface air temperature (SAT, 50 year average) for CONTROL shows that FORTE simulates the main features of observed SAT (Figure 1a). Model deficiencies include

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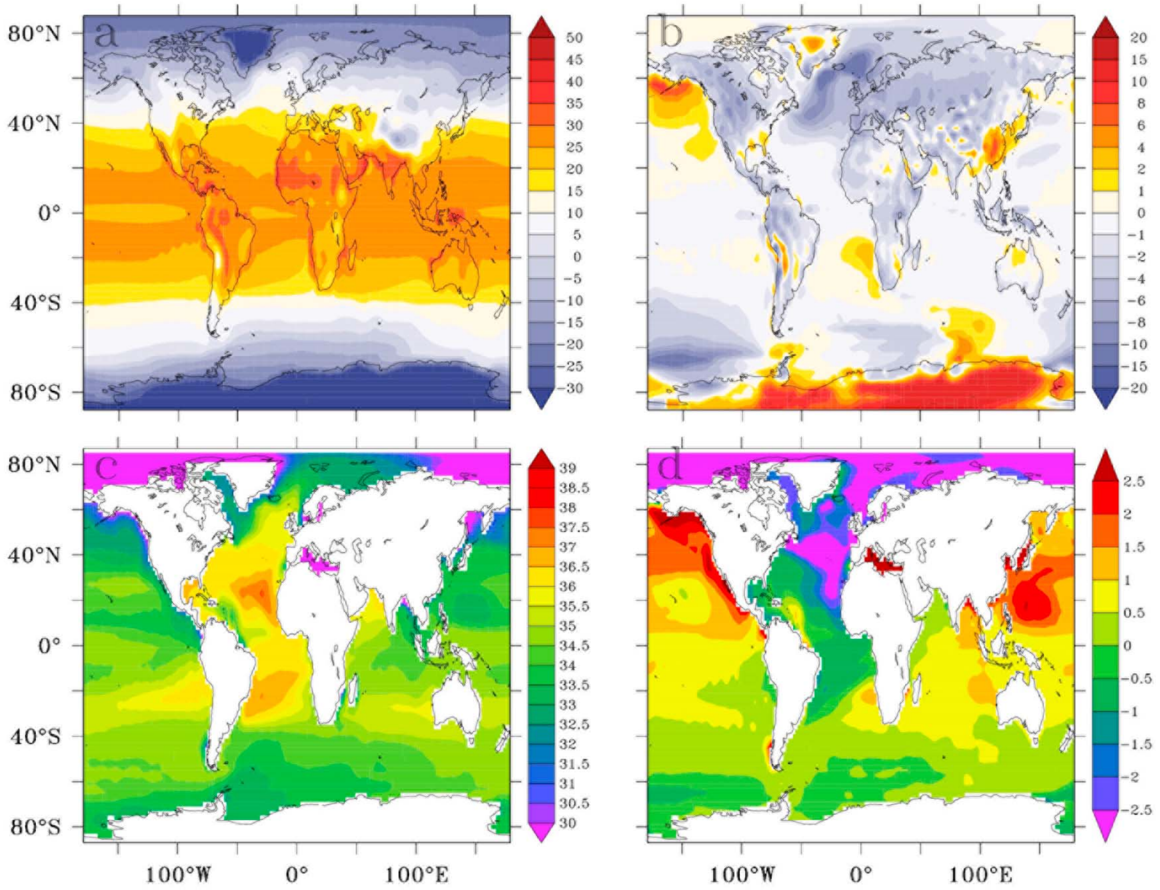

Figure 1. (a) SAT (°C) (CONTROL), (b) SAT difference (FLAT-CONTROL, lapse rate corrected) (°C), (c) SSS (PSU) (CONTROL), (d) SSS difference (FLAT-CONTROL) (PSU). SAT/SSS are averaged over the final 50 years of each simulation.

equatorial temperatures 1–2°C lower than observed and polar sea temperatures 2–3°C higher than observed. The SAT difference (FLAT-CONTROL, adjusted to mean sea level using observed lapse rates [*Stone and Carlson*, 1979] (Figure 1b)) shows large areas of Eurasia, North America, tropical Africa and South America are cooled in FLAT by up to −8°C due to the prevalence of moister, cloudier conditions [*Kitoh*, 1997, 2002]. China is warmed by up to +8°C and Antarctica warms by up to +15°C. Maritime areas with large differences are the North Pacific (up to +8°C) and the North Atlantic (up to −20°C). The South Pacific cools by up to −20°C at around 60°S.

[7] Changes in sea-ice are observed between the model runs, however the changes are not very large. Mean Northern Hemisphere sea ice extent increases by about 10% when mountains are removed. The sea ice model in FORTE is a simple thermodynamic model with no advection of sea ice, hence the model does not capture effects such as ice export from the Arctic. The importance of these effects would need to be evaluated using a more sophisticated model.

[8] With mountains (CONTROL, Figure 1c), the model predicts a ∼4 psu sea-surface salinity (SSS) difference between North Atlantic and North Pacific. This contrast is associated with the vigorous present-day thermohaline circulation (THC) and is thought to be caused by a lower exchange between subtropical and subpolar gyres in the Pacific than in the Atlantic [*Warren*, 1983]. In addition the Asian Monsoon brings precipitation to the tropical Pacific, an effect not present in the Atlantic [*Emile-Geay et al.*, 2003]. Finally, the Rocky Mountains ensure that a large part of the FW export from the Pacific to North America returns as runoff, and the Isthmus of Panama allows export of FW from Atlantic to Pacific basins by the Trade winds. North Atlantic SSS in FLAT is up to 4 psu lower than in CONTROL (Figure 1d), with largest differences around 40°N. North Pacific SSS in FLAT is 2–3 psu higher than in CONTROL, with largest differences south of Japan, and off north west America.

[9] When mountains are removed sea-surface temperature (SST) changes by a few tenths of a degree over the first year and SSS changes by order 0.1 psu. The major changes, however, appear to occur by slow changes of the ocean circulation, taking centuries to reach their equilibrium values.

3.2. Meridional Overturning Circulation

[10] The mean AMOC with mountains, (∼18 Sv, Figure 2a), is similar to that estimated from observations [*Cunningham et al.*, 2007; *Kanzow et al.*, 2010]. In the Pacific (Figure 2b) there is no meridional overturning in CONTROL. The AMOC gradually vanishes (∼0 Sv) when mountains are removed (Figure 2c), and a clockwise

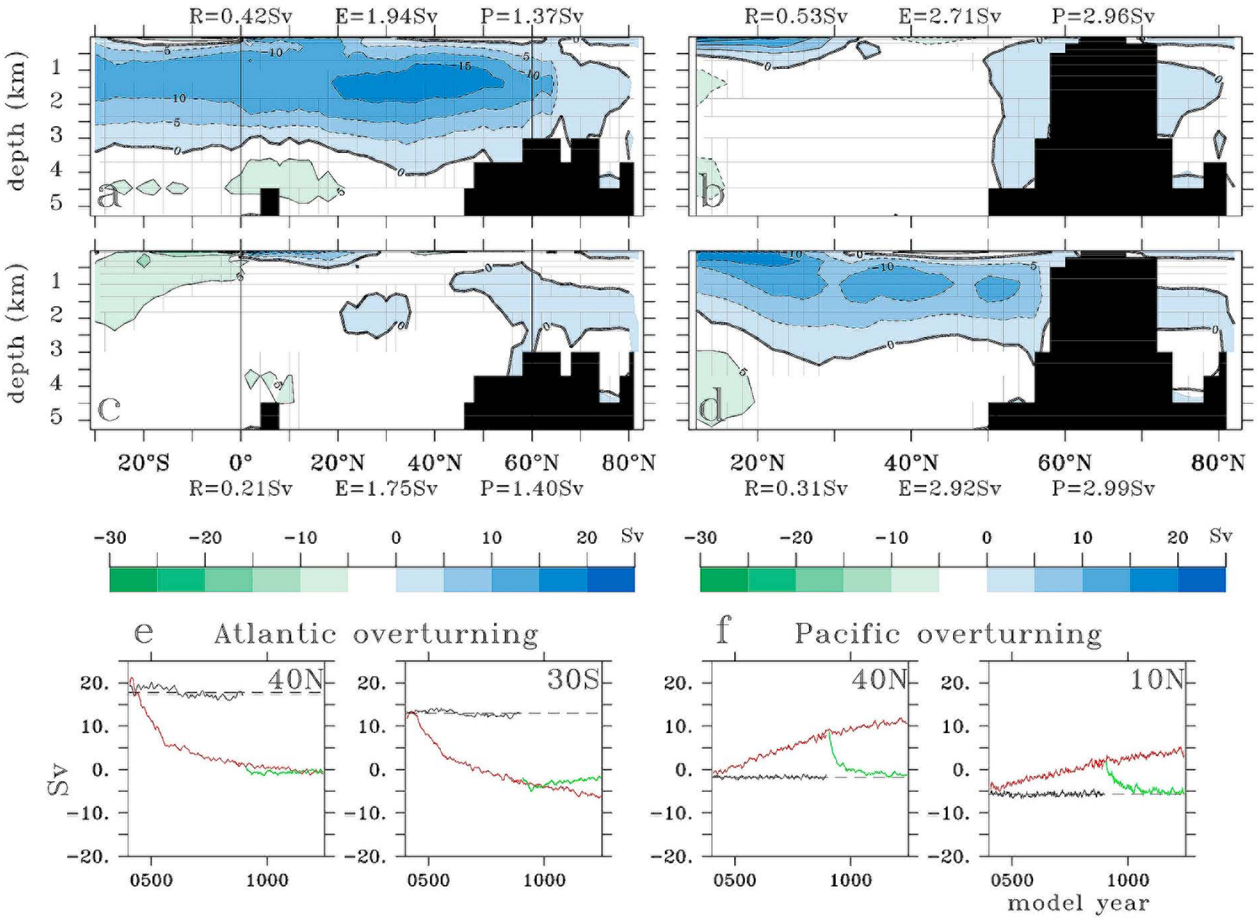

Figure 2. Meridional overturning circulation (Sv) (a) Atlantic (CONTROL), (b) Pacific (CONTROL), (c) Atlantic (FLAT), (d) Pacific (FLAT). Positive (negative) values indicate clockwise (anticlockwise) circulation. Precipitation (P), evaporation (E) and runoff (R) over the Atlantic (0–60°N) and Pacific (10–65°N) are marked. Averaging period is the final 50 years of each simulation. (e) Overturning streamfunction (12-yr running mean) at ~1360 m depth in the Atlantic at 40°N and 20°S for CONTROL (black line), FLAT (red line) and when mountains are reintroduced in FLAT (green line). (f) Similar plots for the Pacific overturning streamfunction at 40°N and 10°N colours as for Figure 2e.

meridional overturning circulation of ~10 Sv between 0 and 2 km depth develops in the Pacific (Figure 2d).

[11] AMOC changes and associated changes in SAT, heat transports and surface fluxes occur because the North Atlantic exports more FW and the North Pacific imports more FW with mountains than without, and because of changes in the wind field which modify the surface heat loss directly. Figure 2 lists the components of the annual mean surface FW flux in the North Atlantic and North Pacific. In CONTROL, the Atlantic (0–60°N) loses 1.94 Sv of FW through evaporation, partially compensated by 1.37 Sv of precipitation and 0.42 Sv of runoff giving a net export of 0.15 Sv of FW. The Pacific (10–65°N) receives a net FW input of 0.78 Sv made up of 2.71 Sv of evaporation, 2.96 Sv precipitation and 0.53 Sv river runoff. Removing the mountains reduces evaporation in the North Atlantic to 1.75 Sv, whilst precipitation increases slightly to 1.40 Sv (mainly increasing at mid-high latitudes), and runoff reduces to 0.21 Sv (mainly reducing in low latitudes) for a net export of 0.14 Sv. There is thus not a large change in the surface freshwater forcing of the Atlantic as a whole, but we will see in section 3.4 that changes to the regional pattern are more important. There is a large net reduction in FW export to the Pacific, manifested as increased evaporation and as reduced river runoff, much of it due to suppression of the Asian Monsoon in FLAT.

[12] The decline of the AMOC in FLAT (Figure 2e) occurs in three stages. The AMOC increases, by ~1 Sv over the first 5 years (at 40°N, ~1300 m depth). Thereafter it reduces at a rate of ~1 Sv/decade for the next 150 years, reaching ~4 Sv at year 570. In the final stage, the AMOC declines at a slower rate of ~1 Sv/century. Spin up of the Pacific overturning occurs as a sustained increase over about 800 years with the run becoming steadier over the last 100 years of integration (Figure 2f).

[13] The effect of reintroducing mountains into FLAT is also shown in Figures 2e and 2f. In the Atlantic the MOC initially decreases slightly but then begins a slow but steady rise (more noticeable at 30°S than at 40°N). In the Pacific the return of the mountains result in a quick collapse of the Pacific overturning within about a century.

Table 1. Heat and FW Budgets for CONTROL and FLAT for the Final 50 Years of Each Simulation[a]

	Atlantic		Pacific	
	CONTROL	FLAT	CONTROL	FLAT
	Heat (PW)			
Surface flux (25–67°N)	−0.98	−0.26	−0.82	−1.31
Advection (25°N)	+1.13	+0.23	+0.42	+1.19
Advection (67°N)	+0.06	+0.04	-	-
Diffusion (25–67°N)	−0.09	+0.05	+0.39	+0.13
	Fresh Water (SV)			
Surface flux (30–60°N)	+0.15	+0.28	+0.49	+0.32
Advection (60°N)	−0.19	−0.18	−0.01	−0.03
Advection (30°N)	−0.42	−0.46	−0.23	−0.24
Diffusion (30–60°N)	+0.07	+0.01	−0.28	−0.12
Surface flux (15–30°N)	−0.42	−0.35	−0.06	−0.30
Advection (15°N)	+0.00	+0.04	+0.10	+0.24
Diffusion (15–30°N)	+0.02	−0.14	−0.27	−0.19

[a] Negative surface flux indicates heat/FW loss by the ocean. Advective transports are positive northward. The diffusion term is a flux convergence calculated as a residual of the surface flux, convergence of the advective flux, and change of heat/FW content over the analysis period. Positive values for diffusion indicate gain of heat/FW in the specified ocean region.

3.3. Ocean Heat Budget

[14] Northward Ocean Heat Transport (OHT) across 25°N in the Atlantic and Pacific in CONTROL are 1.13 and 0.42 PW (Table 1), within the range of observational estimates [*Ganachaud and Wunsch*, 2003; *Johns et al.*, 2011]. In FLAT, Atlantic and Pacific OHT across 25°N are 0.23 and 1.19 PW respectively. Mountains cause a modest net increase of global OHT across 25°N (0.06 PW), but the balance between Atlantic and Pacific components is reversed. Surface heat loss over the North Atlantic (25–67°N) is 0.72 PW lower in FLAT compared to CONTROL with consequent cooling of Western Europe and the northern North Atlantic region. North Pacific ocean heat loss (25–65°N) is stronger without mountains (1.31 PW in FLAT compared to 0.82 PW in CONTROL). Over western North America this reduces the cooling effect of removing mountains. Diffusive heat transports are small in the Atlantic (<0.1 PW in magnitude), but are significant in the Pacific (0.39 PW in CONTROL, 0.13 PW in FLAT), consistent with a stronger meridional temperature gradient in the mid-upper thermocline in the subtropical Pacific compared to the Atlantic. The reduction in FLAT reflects a weakening of the gradient when mountains are removed. Diffusive FW transports behave similarly (section 3.4).

3.4. Ocean Freshwater (FW) Budget

[15] FW budgets (Table 1) indicate that in CONTROL there is net FW export from the surface low-latitude North Atlantic (0.42 Sv, 15–30°N) and net import at high latitudes (0.15 Sv, 30–60°N). These North Atlantic FW fluxes are consistent with a thermally forced AMOC, with salinity acting as a brake as in the Stommel two-box model [*Stommel*, 1961]. Previous studies suggest that the existence of multiple equilibria of the THC and the position on the stability curve depend on the strength of FW forcing at high latitudes as well as on the exchange of sea water properties between high- and low latitudes due to ocean gyres and diffusive processes [*Scott et al.*, 1999; *Longworth et al.*, 2005]. In FORTE the THC is also determined by zonal asymmetries of the surface forcing between Atlantic and Pacific [*Warren*, 1983; *Emile-Geay et al.*, 2003; *Saenko et al.*, 2004]. Excess precipitation in the North Atlantic is mainly balanced by southward FW transport across 30°N, which replaces FW lost by evaporation in the subtropical North Atlantic. Some of this FW feeds the North Atlantic, but most is exported to the Pacific. There is little loss or gain of FW from the North Atlantic across 15°N either by advection or diffusion (Table 1), although further south FW transport is northward and about 0.2 Sv in magnitude (not in Table). Both diffusive and advective horizontal transports are important in the Pacific, with a combined southward FW transport in the North Pacific (−0.51 Sv) across 30°N balancing FW input by surface fluxes between 30 and 60°N. These processes in combination maintain the Atlantic more saline than the Pacific, and result in a strong AMOC. Without mountains, the North Atlantic imports 0.13 Sv more FW and the North Pacific imports 0.17 Sv less. In both the Pacific and Atlantic basins, diffusive fluxes change in order to balance the reduced surface fluxes. In the end state, advective FW transports are very similar at 30°N in both CONTROL and FLAT cases (unlike the heat transport), although there are significant changes to the FW transports during the transient adjustment stage in FLAT (section 3.5). The explanation is that there is a strong east-west salinity (but not temperature) gradient in the Atlantic in FLAT, so that the gyre transport of freshwater compensates for changes to overturning transport.

3.5. Mechanism of AMOC Decline and Spin Up of Pacific Overturning

[16] In the first year of FLAT the removal of the mountains causes a ∼50% increase in the eastward windstress between 30°N and 60°N (Figure 3a), which persists for the rest of the simulation. The absence of mountains allows the atmospheric jet stream and associated low level winds to become more zonal. Standing waves associated with orography are absent, leading to less drag and stronger winds. The immediate effect of the strengthened westerlies is to increase sensible/latent heat loss (which varies with wind stress and air-sea temperature/humidity difference) (Figures 3b and 3c). There is also an instantaneous increase in precipitation over the region (by only ∼5% however, Figure 3d). This is due to the absence of the Rockies, which allows moisture-laden air to travel from the Pacific to the Atlantic. Initially, the increased sensible heat loss is the dominant effect, increasing the north-south density contrast and resulting in a slight increase in the AMOC [*Thorpe et al.*, 2001]. Over a longer timescale the sensible heat loss decreases. During the first few decades after the removal of mountains, its tendency to increase density gets outweighed by the increase in precipitation which causes a freshening of the North Atlantic with consequent reduction in density and weakening of the AMOC. This weakening induces a positive feedback, since it reduces the air-sea temperature contrast in the North Atlantic by reducing the northward OHT (Figure 3e). The saturation humidity of the atmosphere falls, resulting in reduced evaporation and further freshening of the North Atlantic (Figure 3c – this shows the latent heat flux rather than evaporation, the latter can be obtained by dividing the latent heat flux by the latent heat of vaporisation of water, $L_v = 2.5 \times 10^6$ J kg^{-1}). Corresponding

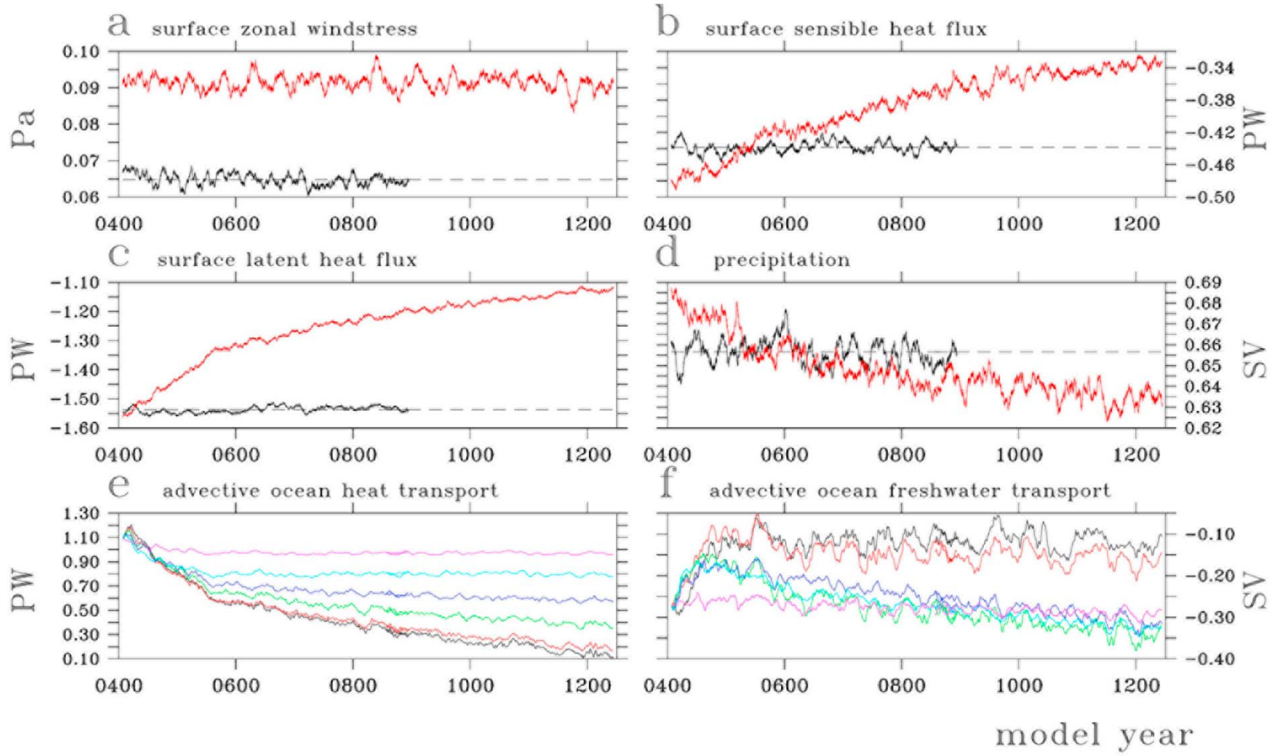

Figure 3. Average across the Atlantic basin between 30–60°N for CONTROL (black) and FLAT (red) of (a) surface zonal windstress, (b) surface sensible heat flux, (c) surface latent heat flux, (d) precipitation. Dashed black lines show the mean value for each variable in CONTROL averaged over years 401–900. (e) Advective ocean heat transport (Atlantic) in FLAT for various latitudes (black = 10°N, red = 20°N, green = 30°N, dark blue = 40°N, light blue = 50°N, pink = 60°N). (f) Advective FW transport (Atlantic). Heat and FW transports have been offset in Figures 3e and 3f so that all lines start from the same value. FLAT was initialized at CONTROL year 400. A 12-year running mean filter has been applied to the time-series.

reduction in latent and sensible heat losses (Figures 3b and 3c) have a sea-surface warming tendency, which feeds back negatively on the latent and sensible heat losses (tending to increase them again), but more importantly the warming feeds back positively on the AMOC (tending to reduce it further) by reducing the density of the north Atlantic. Subsequent reduction of surface heat flux has a much greater impact on the density flux than changes in precipitation and evaporation combined. A further positive feedback ensures rapid decline of the AMOC, namely an associated reduction of southward FW transport (Figure 3f). Increasing surface FW flux between 30° and 60°N results in less FW transport across 30°N, and since the transport across 60°N is unchanged there is more FW retained in the region, further reducing the density and in consequence the AMOC. The oceanic FW transport feedback only lasts about 100 years. After this time southward export of FW increases, and this coincides with a slowing of the rate of decrease of the AMOC. The increasing FW transport is gradually offset by reduction of diffusive input of FW (section 3.3 and Table 1).

[17] In FLAT, the tropical-subtropical Atlantic cools slightly and freshens, but to a much lesser extent than the mid-high latitudes (Figures 1b and 1d). The resultant density changes are smaller than further north, and in FLAT the Northern Hemisphere north-south density gradient declines, consistent with the decline in the AMOC. Sensible heat flux and precipitation change markedly in this region when mountains are removed (not shown). Enhanced sensible heat loss in FLAT occurs in winter and is likely due to advection of relatively cool air (compared to CONTROL) from Africa by Trade winds.

[18] Reduced Atlantic FW export makes the Atlantic fresher in FLAT than in CONTROL. In parallel, the North Pacific becomes more saline (Figure 1d). Detailed analysis presented in Figure 4 indicates that removal of the mountains results in an immediate increase in windstress (Figure 4a) over the North Pacific as in the North Atlantic. The resultant cooling due to enhanced surface heat loss (Figures 4b and 4c) coupled with salinification due to reduced precipitation (Figure 3d) results in dense water formation and overturning in the Pacific, and associated increases in heat transport into the Pacific (Figure 4e). A positive feedback (hypothesized by *Warren* [1983]) appears to take place whereby import of warm surface waters into the North Pacific results in increased evaporation, buoyancy loss and overturning. This feedback is strong enough to overcome increased freshwater transport into the Pacific (Figure 4f) and later, a small increase in the precipitation over the North Pacific (Figure 4d). As in the Atlantic, ultimately, the surface heat fluxes become much more important than the surface freshwater fluxes in controlling the surface

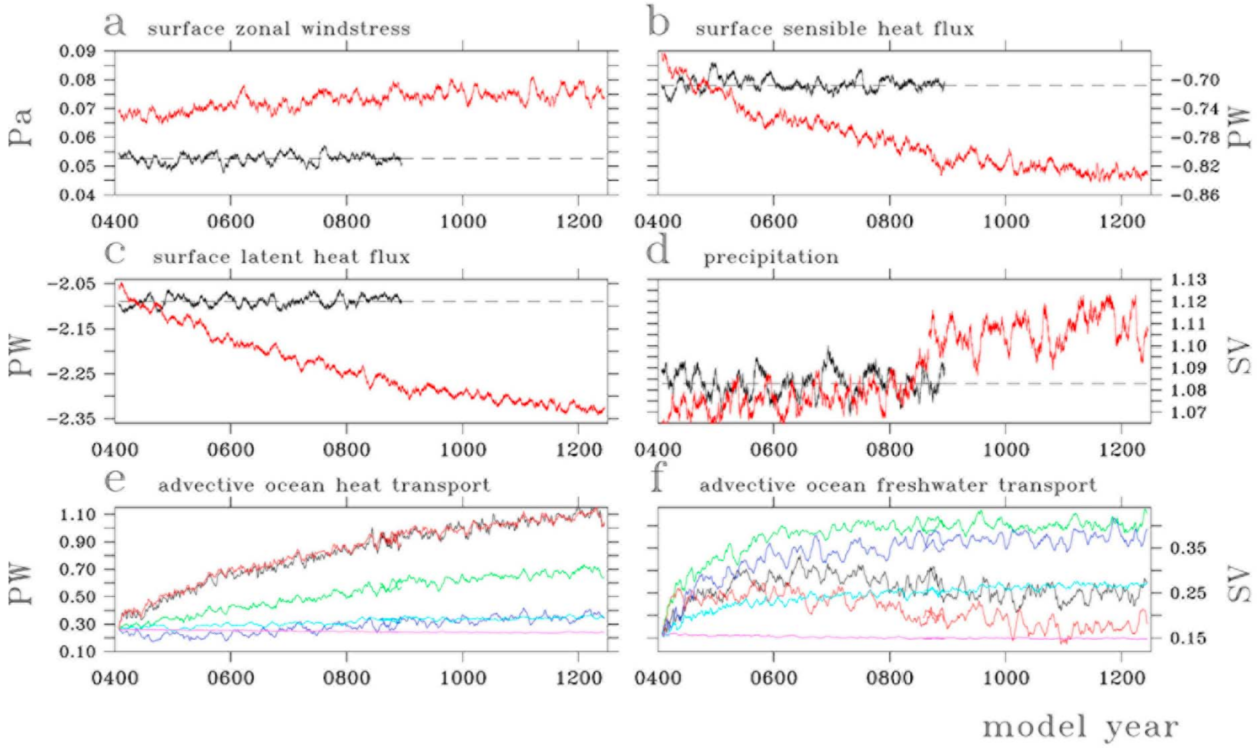

Figure 4. As in Figure 3 for the Pacific basin.

density flux. We note that the Asian Monsoon is suppressed when mountains are removed, depriving the Pacific of runoff from the Asian mainland, and this contributes to the enhanced salinity of the western subtropical Pacific in FLAT [cf. *Emile-Geay et al.*, 2003]. However, this does not appear to be the ultimate cause of the increased salinity in the North Pacific in our model.

4. Discussion and Conclusions

[19] Our experiments demonstrate that mountains are a key factor controlling the oceanic conveyor belt circulation and associated delivery of heat to the North Atlantic region. In our model, without mountains, the AMOC collapses and a strong overturning spins up in the Pacific. The changes appear to be reversible by reintroducing mountains: Pacific overturning diminishes rapidly, although the AMOC might take thousands of years to return to the same strength as in the control run. A fully dynamic ocean is required to produce this result. Previous studies [*Kitoh*, 1997, 2002; *Seager et al.*, 2002] employed lower resolution atmosphere models and used a slab mixed layer ocean, or included artificial adjustments to ocean surface heat and FW fluxes, and were unable to capture the crucial heat and FW flux feedbacks responsible for changes to the AMOC.

[20] In FORTE, removal of the mountains initially results in increased overturning, due to enhanced zonal windstress over the midlatitude Atlantic, however within a decade there is rapid reduction of the AMOC, lasting about a century, because of increased precipitation due to removal of the Rocky Mountains and positive feedback from reduced southward ocean FW transport. Subsequent slower reduction of the AMOC occurs over several centuries due to another positive feedback: midlatitude evaporation diminishes as a consequence of weakening air-sea temperature (and humidity) difference. In the Pacific, overturning is kick-started by a reduction in precipitation and runoff, but it appears that the sustained positive feedback is caused by increases in evaporation due to warming of the surface waters in the North Pacific.

[21] Our study has major implications for the present debate on the fate of the AMOC under climate change. The present day configuration of mountains ranges favours a strong AMOC and may explain why the AMOC simulated by state of the art climate models exhibits great resilience to perturbations to the FW cycle caused by increasing atmospheric greenhouse gas concentrations [*Intergovernmental Panel on Climate Change*, 2007; *Hargreaves et al.*, 2004]. Our experiments do not establish whether the AMOC is monostable, or bistable in either the CONTROL or FLAT cases with respect to surface FW flux forcing, but the results suggest that even if the AMOC is bistable, the presence of mountains pushes the system towards stability (up the stability curve and away from a transition threshold). Recent results by *Hawkins et al.* [2011] demonstrate bistability of the AMOC in a coupled ocean-atmosphere model of similar complexity and slightly lower resolution to FORTE, obtained by artificially modifying North Atlantic FW forcing. Our study suggests that mountains will act to limit the range of FW forcing that can be accessed naturally by the system.

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