AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL073098

Key Points:
- Namibian stratocumulus deck thins significantly due to the removal of southern African orography
- Atlantic ITCZ shifts south due to the increase in temperature resulting from the reduction of Namibian low clouds
- Use of a coupled model allows ocean circulation to cool the South Atlantic, which lessens and changes the structure of the ITCZ shift

Correspondence to:
S. F. Potter,
pottersf@uw.edu

Citation:
Potter, S. F., E. J. Dawson, and D. M. W. Frierson (2017), Southern African orography impacts on low clouds and the Atlantic ITCZ in a coupled model, *Geophys. Res. Lett.*, *44*, 3283–3289, doi:10.1002/2017GL073098.

Received 27 FEB 2017
Accepted 6 MAR 2017
Accepted article online 15 MAR 2017
Published online 9 APR 2017

Southern African orography impacts on low clouds and the Atlantic ITCZ in a coupled model

S. F. Potter[1], **E. J. Dawson**[2], **and D. M. W. Frierson**[2]

[1]Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, Washington, USA, [2]Department of Atmospheric Sciences, University of Washington, Seattle, Washington, USA

Abstract We examine the influence of southern African orography on the Namibian stratocumulus deck, the South Atlantic ocean-to-atmosphere energy transport, and the Intertropical Convergence Zone (ITCZ), using an atmosphere-only model and a coupled atmosphere-ocean model. For both models, a control simulation with realistic orography is compared to a simulation where the orography in southern Africa was removed. As in the previous studies, the removal of orography results in thinning of the Namibian stratocumulus deck. In the coupled model, the increased sea surface temperature in the southern Atlantic due to the reduction of low clouds forces the Atlantic ITCZ to shift southward toward the warmer hemisphere. However, changes in the ocean circulation cool the South Atlantic atmosphere, lessening the ITCZ shift and changing the structure of precipitation. These results show the importance of orography on shaping Atlantic rainfall and highlight the role of dynamical ocean processes in atmospheric dynamics.

1. Introduction

Orography plays an important role in atmospheric general circulation. *Manabe and Terpstra* [1974] used an atmospheric general circulation model (AGCM) with fixed sea surface temperature (SST) boundary conditions, parameterized radiative transfer, and moist convection to study the impact of mountains on the general circulation of the atmosphere. Comparing a control simulation with Earth orography to a flattened “no-mountain” simulation, the authors found that Earth’s mountains play a vital role in controlling both stationary and transient components of the general circulation. Since then, many orography removal experiments have studied the climatic importance of regional and continental-scale orography. African orography, the focus of this study, has been shown to be a key control of past and current climate. Using a regional general circulation model (GCM), it has been found that the uplift of East Africa played a key role in the drying of East Africa 8 Ma ago [*Sepulchre et al.*, 2006]. East African orography has also been shown to enhance the Asian Monsoons [*Ran and Xiao-Dong*, 2010; *Xu et al.*, 2010]. The Atlas Mountains of northwestern Africa have been shown to contribute to the aridity of the Mediterranean basin [*Simpson et al.*, 2015; *Rodwell and Hoskins*, 1996].

The orography of southern Africa, despite being small compared to the East African Highlands, has also been shown to have important climate impacts. The uplift of southern African orography strengthened upwelling in the Benguela current and led to a thickening of the Namibian stratocumulus deck—the low cloud deck off of the southwest African coast [*Jung et al.*, 2014]. The link between Namibian stratocumulus and African orography was explained by *Richter and Mechoso* [2004]. The authors found that southern African orography acts to increase static stability, and consequently low cloud amount, in the Namibian stratocumulus region.

Our work is an extension of *Richter and Mechoso* [2004]. In their discussion, the authors mention they expect that their results may change when their orography removal experiment is performed with a coupled GCM rather than an AGCM with fixed SST boundary conditions. We take advantage of a computationally inexpensive lower resolution Geophysical Fluid Dynamics Laboratory (GFDL) coupled model to study the coupled climate dynamics attributable to southern African orography. The remainder of the paper is organized as follows. Section 2 describes the two models we used as well as the no-orography experiment we performed. Section 3 describes the impact of removing southern African orography on key climatic fields. Lastly, we conclude with discussion of three key takeaways.

2. Methods

This study uses two models: an atmosphere-only model and a coupled atmosphere-ocean model. The atmosphere-only model is GFDL’s AM2LM2 [*Anderson et al.*, 2004] with monthly climatological mean SST

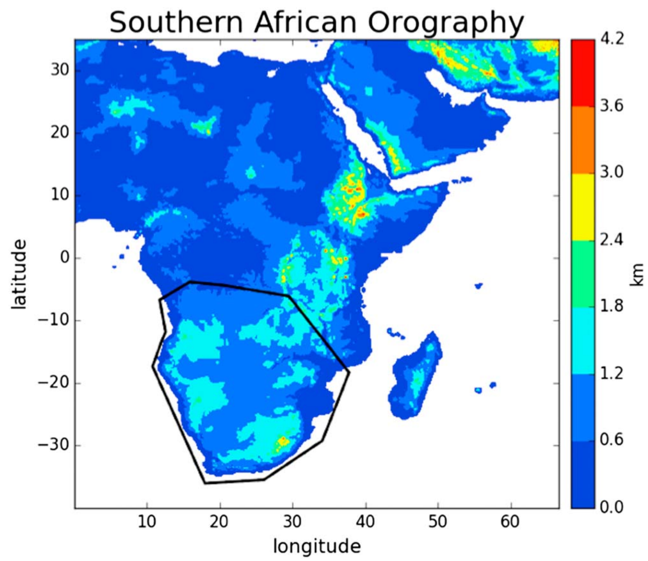

Figure 1. Orography of southern Africa showing elevation in kilometers above sea level. The polygon contains the region where orography was reset to 3 m.

boundary conditions from version 1 of the Reynolds Optimum Interpolation SST data set. AM2 has a resolution of 2° latitude by 2.5° longitude, with 24 levels in the vertical. The atmosphere-ocean model is GFDL's CM2Mc, a relatively low resolution coupled climate model [*Galbraith et al.*, 2011; *Yang et al.*, 2014]. We use the specific configuration of CM2Mc described in *Maroon* [2016]. The ocean component has 3.0° longitude spacing with varying latitude resolution, starting with 0.5° at the equator and increasing to 3.0° at the poles. The ocean model has 28 vertical levels. The atmosphere component has 3.75° longitudinal spacing and 3.0° latitudinal spacing, with 24 vertical levels. The topography has the same resolution as the atmosphere grid. The relatively coarse resolution was used because of computational limitations. Since much of the southern African topography is plateau-like, we hope that sensitivity to resolution may be modest. In the future, we hope to run similar coupled simulations at higher resolution.

Both of the models were run in two configurations: a control case ("control"), with standard orography, and a no-orography experiment ("no-orography") with the orography of the southern African continent set to three meters. The polygon used to define southern African orography is shown in Figure 1. The polygon follows the coast roughly from the mouth of the Zambezi River in Mozambique south around South Africa and north up to the mouth of the Congo River. The northern edge of the polygon approximately connects the center of the Congo Basin with Lakes Tanganyika and Malawi, and back to the mouth of the Zambezi River.

In both configurations the atmosphere-only model was run for 15 years. The first 5 years were used as spin-up, and climatologies are taken from the final 10 years. In the coupled model climatologies are taken from 600 years of steady state. The coupled model no-orography experiment was given 600 years of spin-up, but ocean temperatures almost immediately converged to the new equilibrium after the no-orography was enforced.

3. Results

We examine the effects of removing southern African orography by subtracting the control run from the no-orography run in both the atmosphere-only and the coupled models.

3.1. Precipitation and Temperature

First, we examine the effects of orography on annual mean precipitation and 2 m air temperature in the coupled model. There are no significant effects due to orography removal on these fields in the atmosphere-only model away from the removed mountains since the model has fixed SSTs. Removing orography results in a southward shift in the Intertropical Convergence Zone (ITCZ) in the equatorial Atlantic Ocean (Figure 2a). In the control, precipitation in the equatorial Atlantic is highest between 10°S and 10°N and peaked at 8 mm/d along the West African coast. There was also a smaller maximum of about 5 mm/d at about 10°S. However, in the no-orography simulation the precipitation peaks at about 15°S. This results in a maximum change in precipitation of 3.3 mm/d in the region of Salvador, Brazil.

The annual change in temperature due to the removal of orography reaches a maximum of 10 K over land where orography was flattened. Over the Atlantic just west of where the orography was altered, the SST

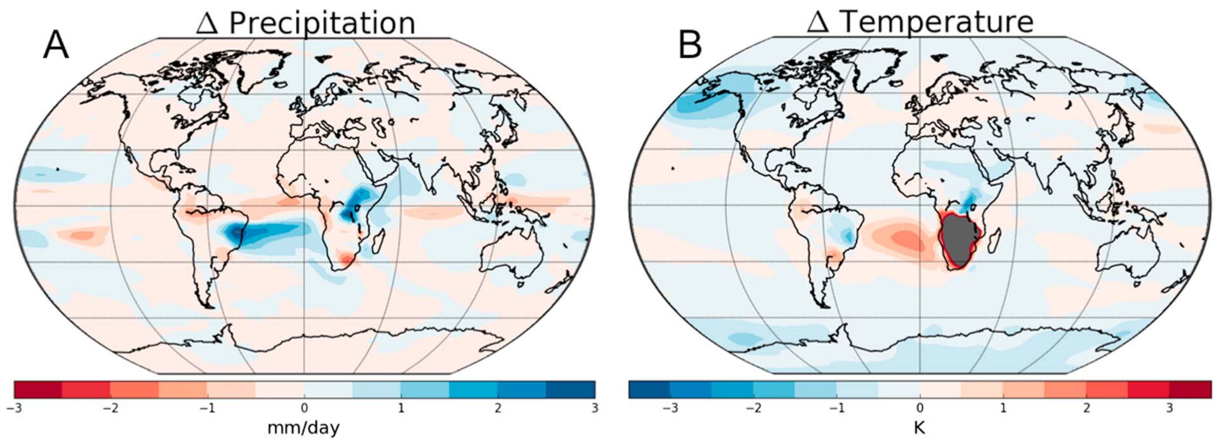

Figure 2. Annual mean difference in (a) precipitation (mm/d) and (b) 2 m temperature (K) in the coupled model, calculated by subtracting the control experiment from the no-orography experiment. The grayed out region corresponds to where the orography was removed and is not plotted here to highlight temperature changes away from the removed orography.

increases significantly, exceeding a 2 K increase over a 10° latitude × 10° longitude area. This South Atlantic Ocean temperature change is very similar to that found in Figure 4 of *Jung et al.*'s [2014] African orography removal experiment.

3.2. Cloudiness

The increase in temperature over the equatorial Atlantic corresponds to a large reduction in low clouds just west of the southern African coast. In the control, low clouds form just west of the continent due to subsiding air on the leeward side of the southern African terrain. Removing the orography results in a reduction in the amount of low clouds for both the fixed SST simulation and the coupled simulation. In the fixed SST simulation the low cloud amount reduces by more than 40% in places, from approximately 60% to 20%. In the coupled simulation, the low cloud amount decreases by slightly less than 20% in places, from approximately 35% to 15%.

Changes are larger in the fixed SST simulation largely because the control state is much cloudier to begin with. This is likely associated with the fact that the coupled simulation has a worse double ITCZ bias than the fixed SST simulation, with excessive precipitation in the South Atlantic. Less subsidence in the South Atlantic leads to a smaller low cloud fraction in the control simulation of the coupled model.

Since the SST is allowed to vary in the coupled model, an additional feedback is permitted, where warmer SSTs cause further decrease in cloudiness by reducing lower tropospheric stability [*Klein and Hartmann*, 1993]. This leads to a reduction in low cloudiness that extends further west in the Atlantic than in the fixed SST simulation.

A southward shift in high clouds can be seen from removing orography in the coupled simulation (Figure 3d). The high cloud amount increases by more than 10% at 15°S across the South Atlantic Basin, indicative of a southward shift in the ITCZ. In contrast, there is no significant shift in high clouds in the Fixed SST simulation. Again, since the SST is fixed, the ITCZ cannot shift southward.

3.3. Atmospheric Energy Balance

A large body of literature [e.g., *Yoshimori and Broccoli*, 2008; *Kang et al*., 2008, *Chiang and Friedman*, 2012] emphasizes the importance of the atmospheric energy budget in determining rainfall shifts in models where the SST is allowed to change. *Kang et al*. [2014] showed that a localized energetic forcing in the extratropics leads to a zonally symmetric shift in precipitation, while a localized forcing in the tropics shifts rainfall only in the area where there is forcing. The vertically integrated atmospheric energy budget following *Fasullo and Trenberth* [2008] is shown in equation (1). A is the total atmospheric energy, $-\nabla \cdot F_A$ is the convergence of atmospheric energy transport, R_{TOA} is the top of atmosphere (TOA) net downward radiation, and F_S is the net upward surface energy flux. Figures 4a and 4b show the change in TOA net radiation in the fixed SST and coupled runs. A positive value denotes energy into the atmosphere. The change in low cloud

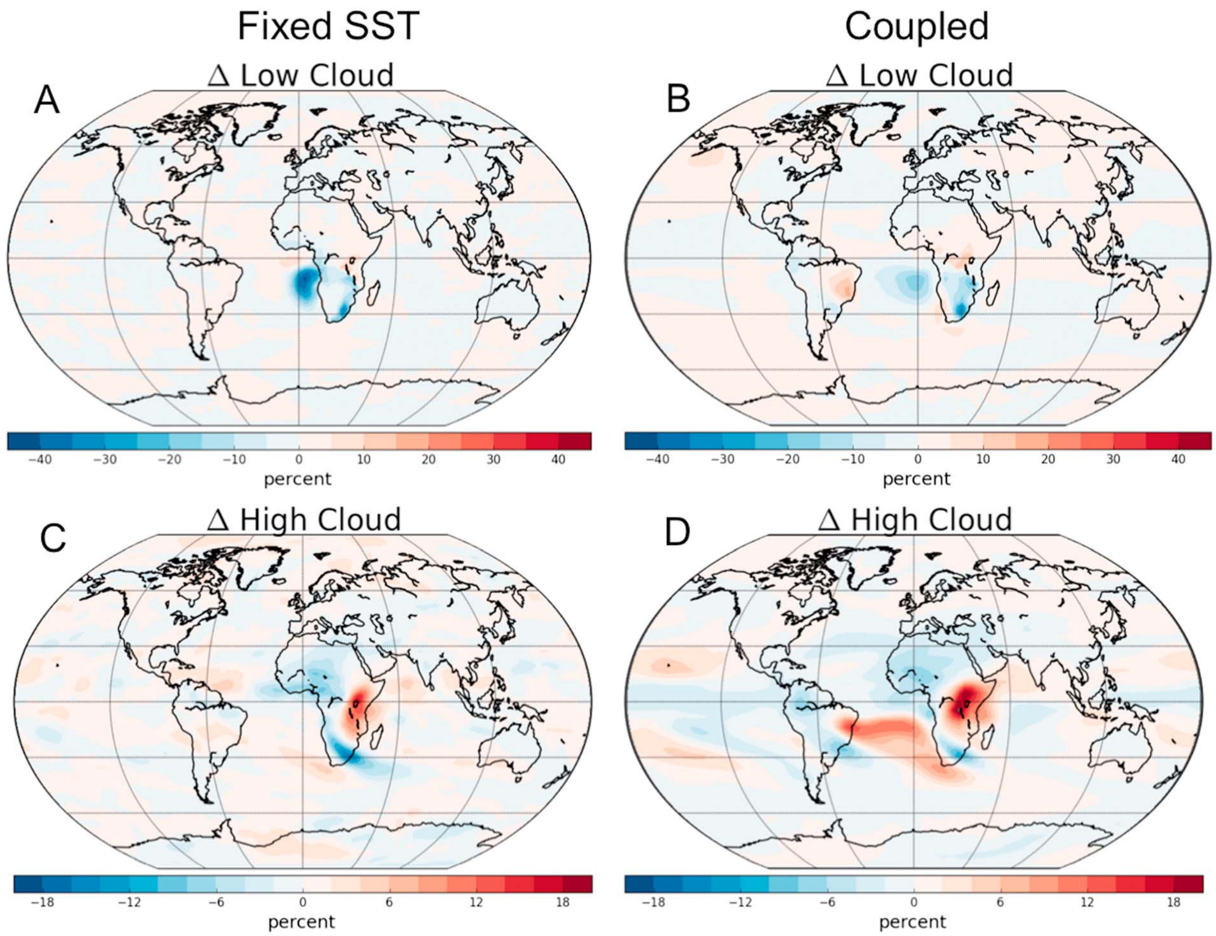

Figure 3. Comparison of cloud amount difference (no-orography minus control) for the fixed SST simulations and the coupled simulations. Cloud amount differences for the fixed SST simulations are shown in (a) low cloud amount and (c) high cloud amount. Cloud amount differences for the coupled simulations are shown in (b) low cloud amount and (d) high cloud amount.

discussed above is associated with a large change in TOA net radiation. TOA radiation increases where low cloud amount is reduced in both the fixed SST and the coupled simulations (Figures 4a and 4b). In contrast, changes in high cloud amount have less of an effect on TOA radiation. The reduction of low clouds reduces the amount of shortwave radiation reflected back to space but has significantly less impact on outgoing longwave radiation. The low cloud change is a large driver of the ITCZ shift in the coupled model.

$$\frac{\partial A}{\partial t} = -\nabla \cdot F_A + R_{\mathrm{TOA}} + F_S \quad (1)$$

3.4. Ocean Circulation

Figure 4c shows the change in surface flux (positive into the atmosphere) in the coupled model. Following *Fasullo and Trenberth* [2008], the vertically integrated oceanic energy budget is shown in equation (2). O is the total oceanic heat content and $-\nabla \cdot F_O$ is the convergence of oceanic energy transport. Equation (2) shows that a nonzero steady state surface flux change in the model ocean must be balanced by ocean heat flux convergence. Removing the orography decreases the ocean to atmosphere energy transfer in the Southern Atlantic. The extrema for surface flux and TOA net radiation (coupled simulation) do not align (Figures 4b and 4c). The ocean to atmosphere transport peaks a little above $-16\,\mathrm{W/m^2}$ at approximately 15°S, centered slightly north of the cloud-forced positive TOA signal in Figure 4b. Surface flux is about $-10\,\mathrm{W/m^2}$ where the TOA net radiation is at a maximum.

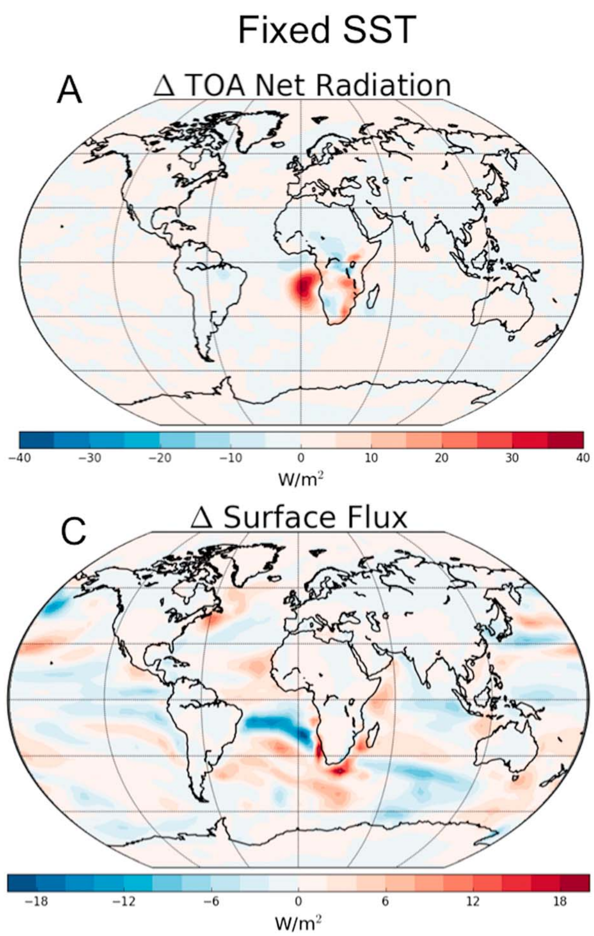

Figure 4. Energy flux (positive is into the atmosphere) changes from no-orography minus control experiments: (a) top of atmosphere (TOA) net radiation, fixed SST simulations. (b) TOA net radiation, coupled simulations. (c) Surface flux, coupled simulations. (d) Upwelling at 30 m depth.

$$\frac{\partial O}{\partial t} = -\nabla \cdot F_O - F_S \tag{2}$$

The surface flux change is associated with a change in ocean circulation. Figure 4d shows the change in upwelling at 30 m. The largest signal is again in the South Atlantic, with a dipole change in upwelling of decreased upward motion just south of the equator and increased upwelling centered near 20°S. This change in upwelling is likely a product of the shifting ITCZ. The convergent tropical easterlies shift south with the shifted ITCZ, shifting the latitude of primary upwelling and cooling the mixed layer.

4. Discussion and Conclusion

The primary result from our study is that the orography of southern Africa plays a key role in controlling both the Namibian stratocumulus deck (as previously found by *Richter and Mechoso* [2004]) and the Atlantic ITCZ. The movement of the ITCZ highlights the importance of considering a dynamic ocean in studies of atmospheric dynamics. Versus a fixed SST model, a fully coupled model allows the ocean surface to properly couple to its atmospheric forcing, which in turn allows surface temperature, precipitation, and, eventually, the general circulation to respond to changes in the Earth system. Figures 2a and 2b show large changes that do not manifest when SSTs are held fixed, despite the huge changes in TOA energy balance shown in Figures 4a and 4b. There are three main large-scale changes that occur in the South Atlantic Ocean when the southern African orography is removed. First, the Namibian stratocumulus deck thins dramatically. Second, the atmospheric column takes in more energy where the low clouds have disappeared. Lastly, the Atlantic ITCZ shifts toward the “warmer” hemisphere, following the interhemispheric energy imbalance and the theory of *Kang et al*. [2014], who found that tropical forcing leads to regional shifts in the ITCZ. The first two responses are found in both the fixed SST and coupled models. The ITCZ shift, a huge signal between 0° and 20°S in the coupled model, is not at all represented in the fixed SST model.

The ability of the coupled model to respond to the loss of low clouds and subsequent asymmetric warming of the Southern Hemisphere atmosphere only requires coupling to a slab ocean, not a fully dynamic ocean as was used in this study. Using an atmosphere model coupled to a global slab ocean, *Maroon et al*. [2015] showed that the ITCZ shifts north when Andes-like orography (which is almost entirely in the Southern Hemisphere) is added to the slab ocean. This is very similar to our coupled-ocean no-orography run, which shows that removal of Southern Hemisphere orography (in this case located in southern Africa) leads to a southern shift of the ITCZ. In contrast to *Maroon et al*. [2015], however, the ocean model used in our study can change its circulation. Figure 4d shows that the addition of a dynamic ocean acts opposite to the atmosphere-only dynamics captured by the fixed SST model. As discussed above, the thinning of the Namibian stratocumulus leads to atmospheric heating and a southward shift of the Atlantic ITCZ. The ocean, however, cools the South Atlantic atmosphere. In the absence of this ocean dynamical feedback, the southward shift of the ITCZ would be even greater and would have a different spatial structure because the upwelling and cloud changes are not collocated. Our study adds to the literature that emphasizes coupled responses of the ITCZ [*Fučkar et al*., 2013; *Singh et al*., 2016; *Deser et al*., 2015; *Kay et al*., 2016; *Hawcroft et al*., 2016].

Lastly, we would like to highlight the strong influence of orography on the atmospheric circulation despite our no-orography experiment only removing orography in southern Africa. As stated above, *Richter and Mechoso* [2004] showed that removing all African topography from an atmospheric model with fixed SST boundary conditions resulted in dramatic thinning of the Namibian stratocumulus deck. Here we have shown that this thinning occurs when only the southern African topography is removed. We performed two other fixed SST experiments (not shown), with both Eastern (roughly the Horn of Africa down through the African Great Lakes region) and southern African orography removed together and separately. The existence of the eastern African orography had no significant impact on Namibian stratocumulus: the impact of African orography on the South Atlantic basin is mostly the result of southern African topography. Conversely, the eastern African orography had large impacts on the Indian Ocean basin, while the southern African orography changes had little impact there. Our results suggest that while large-scale orography has important global-scale effects [e.g., *Held et al*., 2002], the attribution of regional effects seems to be possible with more precise orography removal experiments, even in relatively low-resolution models.

To conclude, we would like to emphasize the importance of considering a dynamic ocean even in studies of atmospheric dynamics. Until recently, it was difficult to study coupled dynamics without access to a supercomputer that potentially was prioritized to Intergovernmental Panel on Climate Change-type runs. Now with more access to computing resources and the creation of less intensive coupled models like CM2Mc, there is the possibility for many new studies of large-scale coupled atmosphere-ocean dynamics to use both comprehensive and idealized models. This study was performed with a relatively low-resolution model. In the future we would like to run this experiment with a higher resolution model as well.

Acknowledgments
This research was supported by National Science Foundation grants AGS-1359464 and PLR-1341497, and the UW Royalty Research Fund grant. We would like to acknowledge the support given by the Joint Institute for the Study of the Atmosphere and Ocean. Additionally, we would like to thank Elizabeth Maroon for her expertise on running the coupled model used for this work. The data used are available online at https://drive.google.com/folderview?id=0B0qxDq9RfX6zSnp5UzRpV3ZJNVk&usp=sharing.

References

Anderson, J. L., et al. (2004), The new GFDL global atmosphere and land model AM2-LM2: Evaluation with prescribed SST simulations, *J. Clim.*, *17*(24), 4641–4673, doi:10.1175/JCLI-3223.1.

Chiang, J. C. H., and A. R. Friedman (2012), Extratropical cooling, interhemispheric thermal gradients, and tropical climate change, *Annu. Rev. Earth Planet. Sci.*, *40*, 383–412, doi:10.1146/annurev-earth-042711-105545.

Deser, C., R. A. Tomas, and L. Sun (2015), The role of ocean-atmosphere coupling in the zonal-mean atmospheric response to Arctic sea ice loss, *J. Clim.*, *28*, 2168–2186, doi:10.1175/JCLI-D-14-00325.1.

Fasullo, J. T., and K. E. Trenberth (2008), The annual cycle of the energy budget. Part I: global mean and land–ocean exchanges, *J. Clim.*, *21*(10), 2297–2312, doi:10.1175/2007JCLI1935.1.

Fučkar, N. S., S.-P. Xie, R. Farneti, E. A. Maroon, and D. M. W. Frierson (2013), Influence of the extratropical ocean circulation on the intertropical convergence zone in an idealized coupled general circulation model, *J. Clim.*, *26*, 4612–4629, doi:10.1175/JCLI-D-12-00294.1.

Galbraith, E. D., et al. (2011), Climate variability and radiocarbon in the CM2Mc Earth System Model, *J. Clim.*, *24*(16), 4230–4254, doi:10.1175/2011JCLI3919.1.

Hawcroft, M., J. M. Haywood, M. Collins, A. Jones, A. C. Jones, and G. Stephens (2016), Southern Ocean albedo, inter-hemispheric energy transports and the double ITCZ: Global impacts of biases in a coupled model, *Clim. Dyn.*, doi:10.1007/s00382-016-3205-5.

Held, I. M., M. Ting, and H. Wang (2002), Northern winter stationary waves: Theory and modeling, *J. Clim.*, *15*(16), 2125–2144, doi:10.1175/1520-0442(2002)015<2125:NWSWTA>2.0.CO;2.

10.1002/2017GL073098

Jung, G., M. Prange, and M. Schulz (2014), Uplift of Africa as a potential cause for Neogene intensification of the Benguela upwelling system, *Nat. Geosci.*, *7*(10), 741–747, doi:10.1038/ngeo2249.

Kang, S. M., I. M. Held, D. M. W. Frierson, and M. Zhao (2008), The response of the ITCZ to extratropical forcing: Idealized slab-ocean experiments with a GCM, *J. Clim.*, *21*, 3521–3532, doi:10.1175/2007JCLI2146.1.

Kang, S. M., I. M. Held, and S. P. Xie (2014), Contrasting the tropical responses to zonally asymmetric extratropical and tropical thermal forcing, *Clim. Dyn.*, *42*, 2033–2043, doi:10.1007/s00382-013-1863-0.

Kay, J. E., C. Wall, V. Yettella, B. Medeiros, C. Hannay, P. Caldwell, and C. Bitz (2016), Global climate impacts of reduced Southern Ocean shortwave radiation bias in the Community Earth System, *J. Clim.*, doi:10.1017/CBO9781107415324.004.

Klein, S. A., and D. L. Hartmann (1993), The seasonal cycles of low stratiform clouds, *J. Clim.*, *6*, 1587–1606, doi:10.1175/1520-0442(1993)006<1587:TSCOLS>2.0.CO;2.

Manabe, S., and T. B. Terpstra (1974), The effects of mountains on the general circulation of the atmosphere as identified by numerical experiments, *J. Atmos. Sci.*, *31*(1), 3–42.

Maroon, E. A. (2016), *The Roles of Land and Orography on Precipitation and Ocean Circulation in Global Climate Models*, Univ. of Washington, Seattle, Wash.

Maroon, E. A., D. M. W. Frierson, and D. S. Battisti (2015), The tropical precipitation response to Andes topography and ocean heat fluxes in an aquaplanet model, *J. Clim.*, *28*(1), 381–398.

Ran, Z., and L. Xiao-Dong (2010), The effects of tectonic uplift on the evolution of Asian summer monsoon climate since Pliocene, *Chin. J. Geophys.*, *53*(6), 948–960, doi:10.1002/cjg2.1565.

Richter, I., and C. R. Mechoso (2004), Orographic influences on the annual cycle of Namibian stratocumulus clouds, *Geophys. Res. Lett.*, *31*, L24108, doi:10.1029/2004GL020814.

Rodwell, M. J., and B. J. Hoskins (1996), Monsoons and the dynamics of deserts, *Q. J. R. Meteorol. Soc.*, *122*(534), 1385–1404, doi:10.1002/qj.49712253408.

Sepulchre, P., G. Ramstein, F. Fluteau, M. Schuster, J.-J. Tiercelin, and M. Brunet (2006), Tectonic uplift and eastern Africa aridification, *Science*, *313*(5792), 1419–1423, doi:10.1126/science.1129158.

Simpson, I. R., R. Seager, T. A. Tiffany, and M. Ting (2015), Mediterranean summer climate and the importance of middle east topography, *J. Clim.*, *28*(5), 1977–1996, doi:10.1175/JCLI-D-14-00298.1.

Singh, H. A., C. M. Bitz, and D. M. W. Frierson (2016), The Global Climate Response to Lowering Surface Orography of Antarctica and the Importance of Atmosphere-Ocean Coupling, *J. Clim.*, *29*(11), 4137–4153, doi:10.1175/JCLI-D-15-0442.1.

Xu, Z., Y. Qian, and C. Fu (2010), The role of land-sea distribution and orography in the Asian monsoon. Part II: Orography, *Adv. Atmos. Sci.*, *27*, 528–542, doi:10.1007/s00376-009-9045-z.

Yang, S., E. Galbraith, and J. Palter (2014), Coupled climate impacts of the Drake Passage and the Panama Seaway, *Clim. Dyn.*, *43*(1–2), 37–52, doi:10.1007/s00382-013-1809-6.

Yoshimori, M., and A. Broccoli (2008), Equilibrium response of an atmosphere–mixed layer ocean model to different radiative forcing agents: Global and zonal mean response, *J. Clim.*, *21*, 4399–4423, doi:10.1175/2008JCLI2172.1.