Reversing Sahelian Droughts

Authors: Katharine Ricke[1,2], Detelina Ivanova[1], Taylor McKie[1], Maria Rugenstein[3]

[1] Scripps Institution of Oceanography, La Jolla CA 92037

[2] School of Global Policy & Strategy, UC San Diego, La Jolla CA 92037

[3] Department of Atmospheric Science, Colorado State University

Corresponding author: Katharine Ricke (kricke@ucsd.edu)

Key Points:

- Earth system model simulations indicate cooling the Indian Ocean with artificial upwelling would increase precipitation in the Sahel
- Our intervention can reverse the mid-20th century Sahelian drought, but has side effects in other regions such as sub-Saharan East Africa
- The energy and infrastructure for large-scale regional artificial upwelling would likely be costly and require a major actor to implement

Abstract

Earth system modeling of climate geoengineering proposals suggests that the physical outcomes of such interventions will depend on the particulars of the implementation. Here, we present a first attempt to "geoengineer" a well-known teleconnection between sea surface temperatures (SSTs) and Sahelian precipitation. Using idealized earth system model simulations, we show that selectively cooling the Indian Ocean efficiently increases precipitation in the Sahel region, widening the seasonally migrating rainband over Africa. Applying the SST perturbations derived from the idealized experiments to observationally constrained historical ones, we find that our intervention can reverse conditions as extreme as the mid-20th century Sahelian drought, albeit less efficiently than in the idealized simulations. Side effects include changes in the seasonal distribution of Sahelian precipitation and substantial precipitation reductions in sub-Saharan East Africa. This work represents a proof-of-concept illustration of effects that might be expected with a tailored, regional approach to climate intervention.

Plain Language Summary

Climate geoengineering is the idea that some impacts of anthropogenic climate change could be reduced through deliberate, engineered intervention into the Earth system. Research on this topic has generally focused on global approaches that would have diffuse effects on the climate, but regional approaches may be more geopolitically feasible and have been little researched. We investigate whether a regional climate intervention, in this case cooling the Indian Ocean with pipes that bring deep cool water to the surface, could be designed to reverse a particular climate impact. We show that Indian Ocean cooling can increase precipitation in the Sahel region of Africa. We illustrate the implications of this by using computer simulations of our designed intervention to reverse a drought in the Sahel that happened in the 20th century. While we are able to reverse the drought, increasing precipitation in the Sahel also decreases precipitation in sub-Saharan East Africa. A feasibility assessment indicates that millions of pipes would likely be required to implement wide-scale cooling of the Indian Ocean.

1 Designing a regional climate intervention

The past ten years has seen an increasing body of research devoted to climate geoengineering technologies – approaches that would deliberately modify the earth's climate system to reduce some effects or impacts associated with global warming (Boettcher et al., 2019). While most of the proposals have aimed to make global-scale forcing interventions, a recent government-funded cloud brightening experiment off the eastern coast of Australia (Readfearn, 2020) as well as a large-scale proposed weather modification program in China (Griffiths, 2020), suggest that some decision makers are closely considering unconventional options for mitigating the risks presented by climate change. Climate geoengineering presents an imperfect opportunity to circumvent some harms from climate change if emissions reductions prove insufficient. Many planetary-scale geoengineering approaches, however, present potentially considerable physical risks and global governance challenges. While "geoengineering" has often referred only to techniques that would have a substantial effect on the global-scale climate, in theory, certain impacts could be geographically targeted using interventions that are limited in time and space. The feasibility and efficacy of regional geoengineering approaches remain largely unexplored.

Here, as a proof-of-concept, we target an extensively researched regional teleconnection between sea surface temperatures of the tropics and precipitation in the Sahel region of Africa (Biasutti et al., 2008). The Sahel is home to approximately 100 million people, a number of vulnerable and endangered species and a waypoint for many migratory birds. A multi-decadal drought in the 1970s and 80s resulted in famine, displacement and declines in regional biodiversity (Mortimore, 2010; Walther, 2016). While the consequences of climate change on mean Sahelian precipitation and frequency and severity of intermittent drought are uncertain (Giannini & Kaplan, 2019; Hill et al., 2018), the ability to protect the region from risk of future drought under global warming could have a large humanitarian and ecological impact.

A robust observational and modeling literature supports the existence of teleconnections between tropical SSTs and Sahelian precipitation(Giannini et al., 2003; Lu & Delworth, 2005). Multiple factors have been examined to explain the drivers of the 20th century drought, including a shift in the interhemispheric temperature gradients that determine the location of the intertropical convergence zone (ITCZ) and teleconnection with the tropical oceans (Michela Biasutti, 2019). Regardless of the causal mechanisms, studies have consistently identified an anomaly between Northern-Southern hemispheric ocean temperatures as a feature of Sahel drought-period climatology (Giannini et al., 2013).

Our modeled intervention mimics artificial upwelling activities, which were first proposed as a means for carbon sequestration. Previous work demonstrates that, when implemented globally, this would disrupt the thermocline and, on centennial timescales, lead to higher global mean temperatures than if artificial upwelling had not been implemented in the first place (Kwiatkowski et al., 2015). However, targeted deployment at regional and seasonal scales could be used to change climate locally.

As a theoretical exploration of what a targeted regional climate intervention with artificial upwelling could accomplish, we simulate surface cooling of the Indian Ocean and show that such targeted cooling results in a sharp increase in Sahelian precipitation which increases approximately linearly with the magnitude of regional forcing. To test the efficacy of the targeted cooling in a more quasi-realistic intervention, we then apply the cooling response derived in the idealized experiments to reverse the late 20th century Sahelian drought. While we restore annual mean precipitation during the 1970s-80s in the historical intervention simulations, we find that the seasonal and geographic distribution of precipitation is different than in the pre-drought historical period. In addition, the intervention results in substantial precipitation side effects elsewhere in the region. In particular, the full restoration of Sahelian precipitation during the late 20th century drought is accompanied by a substantial reduction in precipitation in Sub-Saharan East Africa.

2 Idealized simulations to increase Sahelian precipitation

We use the Community Earth System Model (CESM) version 1.2.2 with Community Atmosphere Model version 5 (CAM5) (Hurrell et al., 2013) to conduct four idealized numerical experiments (summarized in Table S1). For our idealized intervention simulations, we used the "slab ocean" configuration of the model, wherein grid-cell level surface ocean heat fluxes are prescribed. That is, while there is not a dynamic ocean there is still two-way energy exchange between the atmosphere and ocean, with the lateral and vertical fluxes in and out of each slab ocean grid box specified at the monthly time scale. As a result of the dynamic response of the atmosphere, the geographic pattern of the surface temperature response to this "Q-flux" perturbation does not directly correspond to the pattern of forcing.

In our reference simulations, global mean Q-flux is zero, with the forcing field mimicking the observed ocean transport of energy from the tropics to higher latitudes. To place the outcomes in our idealized Indian ocean cooling scenarios in the context of both pre-industrial and present day climate, we conducted equilibrium reference simulations with both preindustrial concentrations of atmospheric CO2 (*ref_preind*) and doubled CO2 (*ref_warm_world*). In our ocean cooling simulations, we prescribe a net downward Q-flux to mimic the surface cooling that would occur with ocean upwelling by artificially increasing transport of cold water from beneath the thermocline and associated mixing and displacement of warm surface water. Figure 1a illustrates the forcing perturbation made in our most extreme Indian Ocean cooling simulation (*io_cooled_strongly)* with a positive zonally varied Q-flux perturbation over the region pictured and reference flux (zero perturbation) elsewhere. This perturbation produces a global, annual mean forcing of 1.6 W/m2, but the peak local forcing across the center of the Indian Ocean is much higher, approximately 47 W/m2.While this is a large perturbation, the surface heat fluxes are still of a comparable magnitude to natural background fluxes in the topics, as illustrated in Figure S1. The Q-flux perturbation induces strong surface cooling over the Indian Ocean, as expected, as well as surface temperature changes elsewhere due to the dynamic response of the atmosphere (Fig 1b). While the natural background Q-fluxes vary by month, identical magnitudes of Q-flux perturbation were applied in all months throughout the simulations.

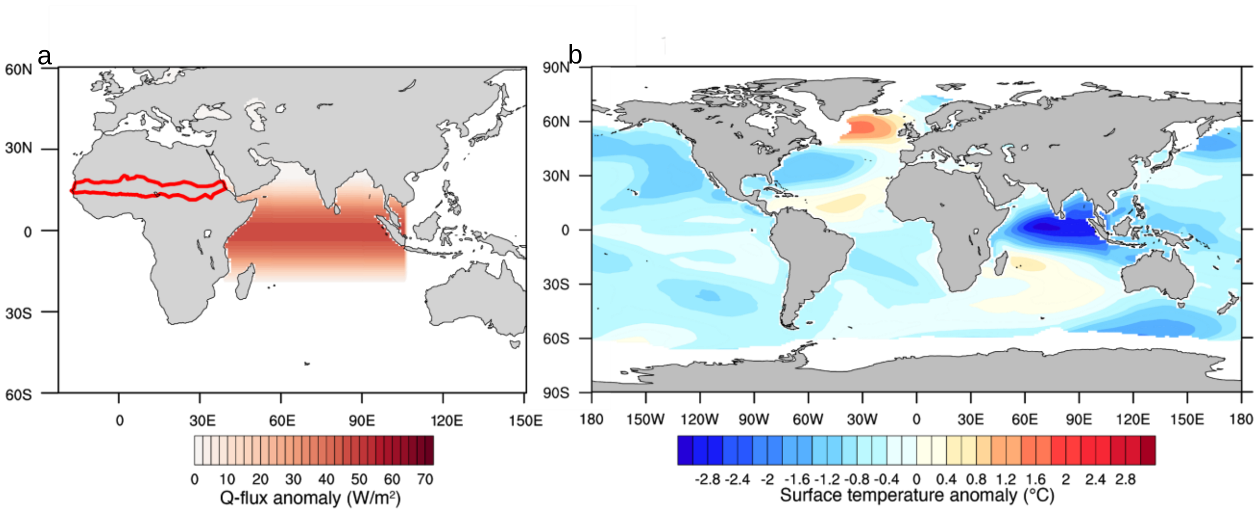

Figure 1. Simulation forcing perturbations to (a) surface heat flux (W/m^2) anomalies for *io_cooled_strongly* slab ocean experiments (anomaly is zero elsewhere) with the Sahel region outlined in red, and (b) surface temperature (°C) anomalies induced by the *io_cooled_strongly* experiment, and applied as the perturbation to inputs for the *drought_reverse* prescribed SST experiments (see Section 3).

The artificial upwelling intervention was designed to maximize increase in precipitation over the Sahel per decrease in global mean temperature. We conducted a perturbed simulation with half the Q-flux forcing (*io_cooled*) as well to examine the linearity of the forcing response. We find an approximately linear relationship between global mean surface temperature decrease, and Sahelian precipitation increase (Fig.2a). This relationship holds both in a pre-industrial (ref_preind) and in a greenhouse gas warmed world (re_warm_world). The outlined region in Figure 1a shows the region we define as the Sahel for the purposes of our efficacy analysis. Comparing first the two reference scenarios, we find that a world warmed by elevated atmospheric carbon dioxide has slightly higher, but substantially similar annual mean precipitation in the Sahel. When we increase the magnitude of heat transport into the deep Indian Ocean, and thereby cool SSTs (as illustrated in Fig 1), Sahelian precipitation increases with global temperature with an efficacy of -1.8 cm/month/°C indicating a high sensitivity of Sahelian precipitation to global cooling concentrated in this particular region. This precipitation response to global temperature is markedly different from that associated with globally diffuse, greenhouse gas driven surface warming where cooling is associated with moderate drying (Sahelian precipitation efficacy of 0.06 cm/month/°C).

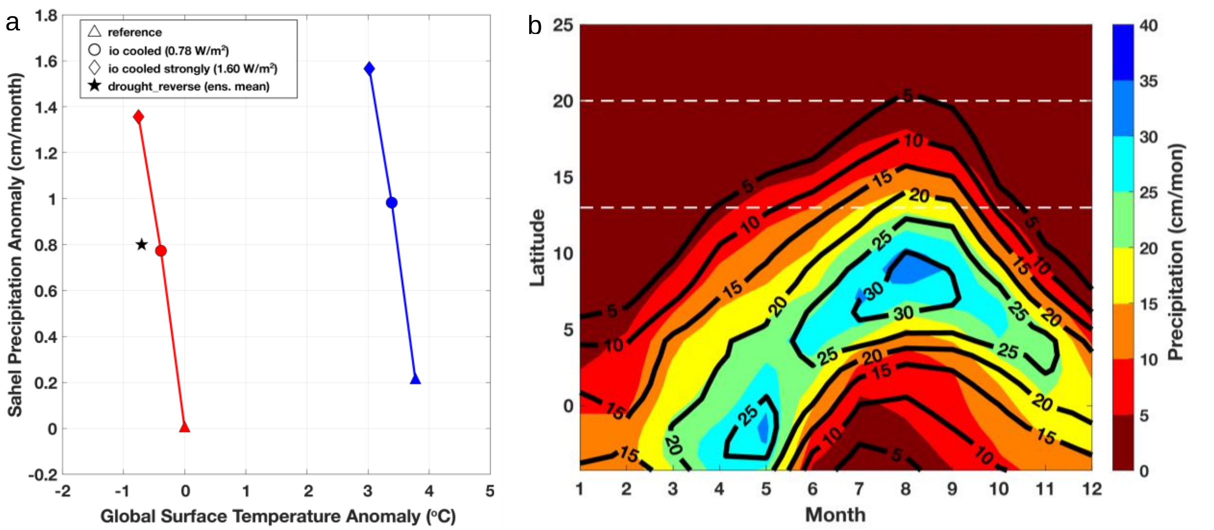

Figure 2. Results of idealized simulations: a) relationship Sahel precipitation and global surface temperature anomalies in all simulations; b) monthly precipitation (cm/month) over Africa (20°W-30°E) by latitude and month, with *ref_warm_world* results in solid color and *io_strongly_cooled* in contour. (The latitudes associated with the Sahel region, (13-20°N,) marked in white)

There are two major climatological phenomena that drive the features of the annual hydrological cycle in the Sahel: the annual migration of the Intertropical Convergence Zone (ITCZ) and the annual African monsoon. The historical drought is thought to be driven primarily by a change in interhemispheric forcing (Biasutti, 2019). Our drought restoration intervention is also achieved primarily by widening the rainband over Africa, rather than through manipulation of the ITCZ position in space and time (Fig 2b).

3 Historical drought and drought reversal simulations

To illustrate the implications of our idealized intervention, the surface temperature anomalies derived in the slab ocean experiments were superimposed on prescribed SST simulations of the 20th century historical drought in the Sahel. In these 20th century historical drought reversal simulations, we run the CESM1.2.2/CAM5 model with a data ocean, wherein SSTs –typically based on observations – are prescribed for every gridcell. Observed SSTs are based on Hadley Centre Global Sea Ice and Sea Surface Temperature (Rayner et al., 2003) We ran two three-member ensembles of prescribed SST simulations using historical observed SSTs (*historical*) and the surface temperature anomalies derived from the slab experiments above (shown in Figure 1b) for the drought reversal simulations (*drought_reverse*).

While precise definitions of the drought period vary, the 1970s and 80s are generally considered the peak time period of the late 20th century drought (Dai et al., 2004). Historical experiments using CAM5 reproduce 20th century precipitation variability in the Sahel reasonably well (Monerie et al., 2017). in our historical prescribed SST ensemble, annual mean precipitation in the region averaging 5.3 cm/month during the mid-century pre-drought period and 4.5 cm/month during the period between 1970-89, a decrease of approximately 15%. By applying the surface cooling pattern associated with the *io_cooled_strongly* experiment on top of historical SSTs, Sahelian precipitation is restored to 5.3cm/month between 1970-89 (Fig 3a).

While the annual mean precipitation over the 1970-89 period in the drought-reversal simulations matches almost exactly with the mid-century non-drought period precipitation, the seasonal distribution of precipitation is distinct from that in the pre-drought historical. In particular, the additional precipitation in the drought-reversal simulation is concentrated in the boreal spring months relative to the pre-drought historical (Fig3b). The distribution of regional climatological responses to Indian Ocean cooling is similar in the idealized slab ocean and historical prescribed SST simulations, however unlike the idealized simulations the intervention is ineffective at increasing summer precipitation in the Eastern Sahel in the fixed SST simulations (see Figure S2). This results in a substantially lower efficacy in Sahelian precipitation increase per degree of global cooling (-1.1 cm/mon/°C, see Fig 2a) than in the idealized design simulations.

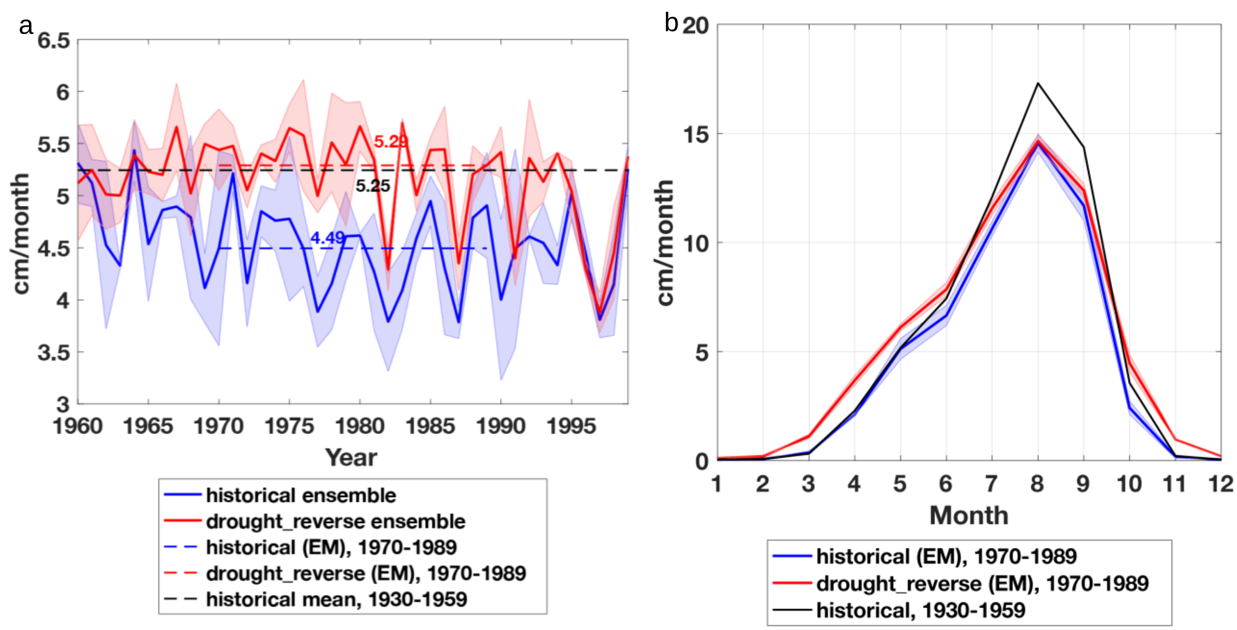

Figure 3. Sahel precipitation response in transient prescribed SST simulations: (a) time series of annual mean Sahel precipitation for the *historical* (blue) and *drought_reverse* (red) simulation ensembles, (b) annual cycles of monthly mean precipitation for the pre-drought *historical* (black), drought *historical* (blue) and *drought_reverse* (red).

A regional intervention like the one we design to mitigate drought in the Sahel is likely to have significant climatological effects beyond the target region. Indian Ocean cooling results in substantial effects on other proximate regional climates, including precipitation reductions in South and Southeast Asia, the southern Arabian Peninsula and, in particular, Sub-Saharan East Africa (Fig 4a). One might expect that substantial cooling over the Indian Ocean could have a large impact on precipitation over the Indian subcontinent through reduction of moisture availability and alteration of the monsoon dynamics. Comparing the reference simulations in

India, we find that a world warmed by elevated atmospheric carbon dioxide has higher temperature and precipitation. When we strongly cool the Indian Ocean, mean annual precipitation in India decreases with global surface temperature with an efficacy of 1.5cm/month/°C (Fig 4b). This constitutes a small and statistically insignificant reduction compared to total mean precipitation over India. Some of the most substantial precipitation reductions occur in East Africa, particularly in and adjacent to Tanzania. In Tanzania, annual precipitation decreases with Indian Ocean cooling with an efficacy of 6.9cm/month/°C, a reduction that, in terms of percentage, is of similar magnitude to the increase in precipitation in the Sahel.

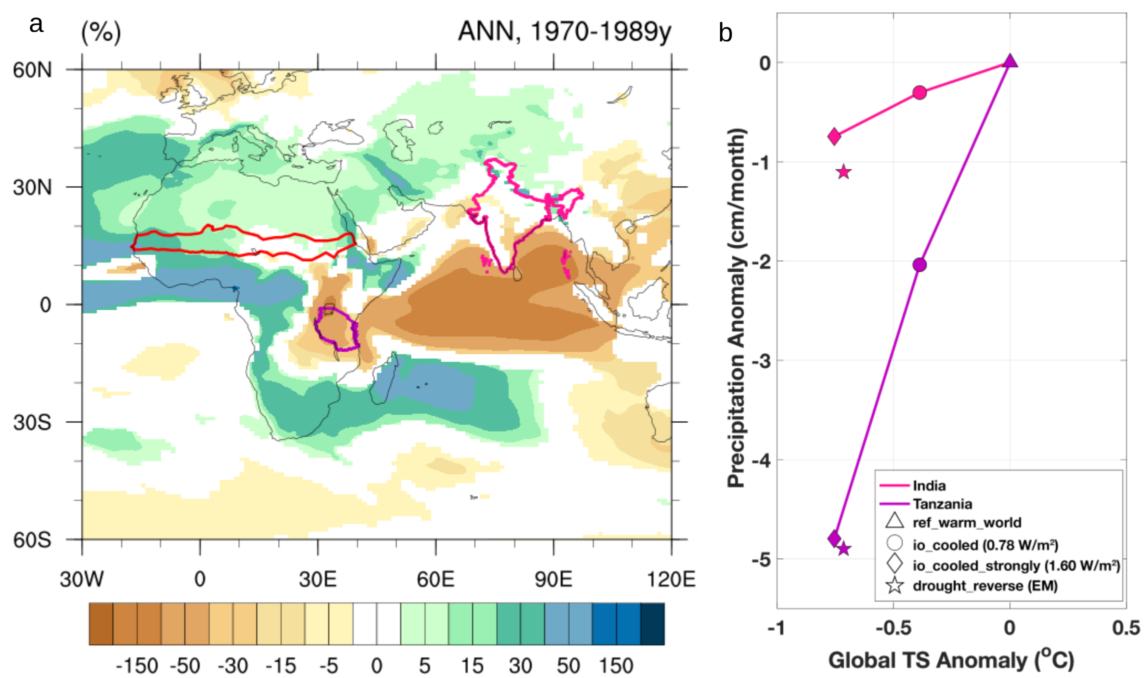

Figure 4. Distribution of precipitation anomalies associated with Indian Ocean cooling: a) Annual precipitation anomalies (%) maps from between SST prescribed experiments *drought_reverse* and *historical.* The bottom row are the differences (red-dryer, blue – wetter); b) global surface temperature vs precipitation anomalies in India (solid) and Tanzania (dashed).

4 Feasibility scoping analysis

Our modeled regional climate intervention mimics artificial upwelling (AU), which was first proposed as a means for carbon sequestration. By bringing nutrient-rich water from below the thermocline to the surface, phytoplankton blooms could be stimulated and carbon captured (Lovelock & Rapley, 2007). Earth system modeling work has suggested artificial upwelling would not be an effective carbon sequestration method, however, due to the potential for CO2 outgassing to the atmosphere from either high concentrations of dissolved inorganic carbon pumped to the surface or the termination of pipe operation (Oschlies et al., 2010; Kwiatkowski et al., 2015). These experiments do demonstrate, however, that artificial upwelling has significant thermodynamic impacts by cooling sea surface temperatures. Technologies designed to implement artificial upwelling have been field tested and demonstrate the same thermal effects (White et al., 2010). This suggests that artificial upwelling may be more plausibly deployed for its cooling effects rather than biogeochemical ones.

While there is little doubt AU is theoretically possible, to implement it at the scale simulated would require substantial investment and alteration of the physical environment. To provide a preliminary analysis of the feasibility of a regional intervention like the one presented here, we estimate energy and number of pipes required to cool the Indian Ocean by the same amount as in the *drought_reverse* simulations. To do this, we utilized a linear first order differential equation characterizing the change in heat at the surface as deep ocean water is upwelled to the mixed layer while influenced by surface energy fluxes from the simulations (see Supporting Text). The upwelling rates within a region were optimized by constraining the resulting heat loss at steady state to the grid-cell level temperature anomalies from the *drought_reverse* simulations (Fig S3). The regional upwelling rates are then constrained by typical upwelling rates of pipes and, following a method similar to that of (Fan et al., 2013), the amount of energy and number of pipes can then be determined. We estimate that cooling this region with 150m pipes with a 30% efficiency would require approximately 1,000 GW (equivalent to about 9,000 TWh, or about 35% of global electricity consumption). Using 150m pipes that are 1 meter in diameter and with

30% efficiency, this would require approximately 40 million pipes (equivalent to 5.8 million km of pipe, nearly double the total length of all pipelines in the world).

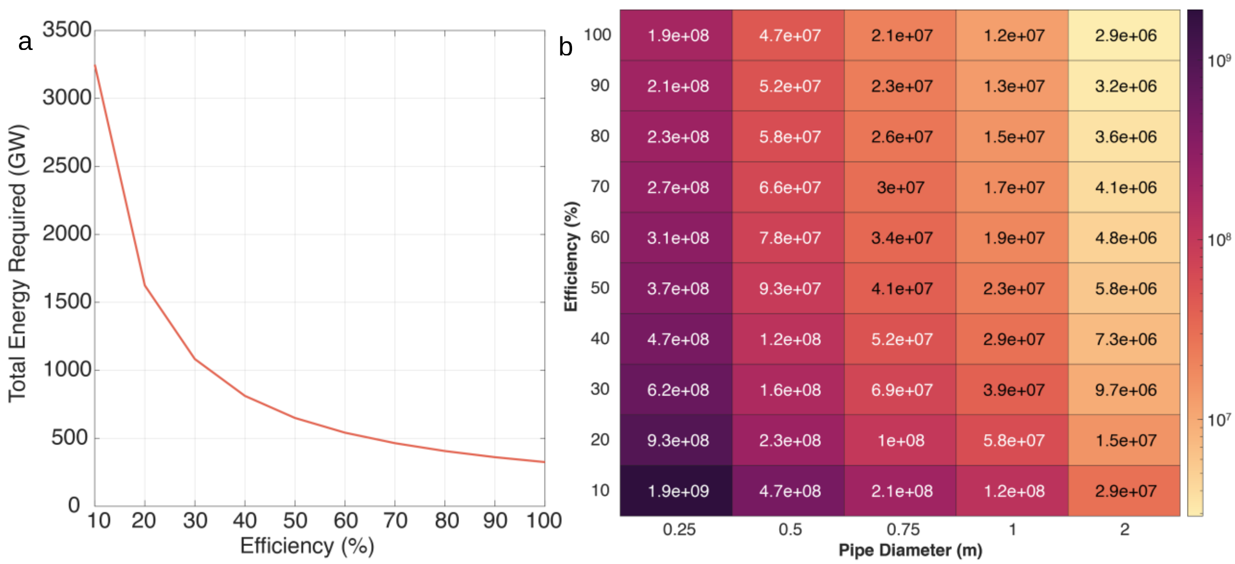

Figure 5. Efficiency-dependent estimation of (a) annual-mean power required (GW) to realize a strong cooling of the Indian Ocean and (b) number of pipes required dependent on pipe diameter.

5 Limitations, discussion and conclusions

The results above represent a proof of concept. The regional intervention was designed though exploratory analysis and, while alternative regional boundaries for ocean cooling were investigated, we did not fully optimize our intervention to increase rain in the Sahel. The intervention was also not temporally tuned; thus, it's possible one could retain the positive outcomes in the Sahel and reduce impacts elsewhere by introducing seasonality, such as reduced cooling in the period March-May when the most drastic reductions in East African precipitation occur. In the historical drought reversal experiments, we assume that the surface temperature anomalies induced in the slab ocean experiments could be approximately reproduced spatially under more realistic conditions. Notably, these experiments do not include the dynamic response of the ocean which will be an important avenue of research in follow-up studies. Increased model resolution might also change regional hydrological outcomes substantially.

To our knowledge, this is the first study that has explored the possibility of targeting a climate teleconnection with a climate intervention approach. We exploited one extensively studied regional teleconnection between SSTs and precipitation over land, but the same approach could be applicable to other dynamical systems or drought prone regions. Our approach requires some understanding of the basic climate dynamics driving the regional hydroclimate in order for regional scale interventions to be effective. Without such system understanding, the discovery of sensitivities like the one between Indian Ocean temperature and Sahelian precipitation could require infeasible amounts of trial-and-error. A lack of consideration of the dynamics could also produce side effects that are greater than expected, though as the analysis of precipitation over India reveals, whether side effects are perceived as positive or negative will depend on the baseline of comparison.

There is a large and robust literature on climate teleconnections that could guide future studies on the feasibility of targeted regional geoengineering (Liu & Alexander, 2007; Stan et al., 2017; Yuan et al, 2018). The difference between a geoengineered teleconnection and those observed and modeled in the existing literature is that natural modes of variability exhibit patterns of spatial correlation that can theoretically be broken with a technology like artificial upwelling or cloud brightening. More studies on the outcomes of interventions like the one explored in this paper will be required in order to draw any conclusions about the feasibility and implications of regional artificial upwelling interventions. The technical and political considerations that would enter into any future decisions about deploying such approaches would undoubtedly be extremely complex. However, there isn’t a physical or geopolitical basis for assuming that global rather than regional processes will determine future geoengineering activities. This suggests that regional climate interventions aimed at mitigating particular risks associated with climate change are underexplored in the geoengineering literature to date.

Acknowledgments

The CESM project is supported primarily by the National Science Foundation. We thank all the scientists, software engineers, and administrators who contributed to the development of CESM. An award of computer time was provided by the HPC@UC program at the San Diego

Supercomputer Center (SDSC). KR and DI were supported by funding from the Vetlesen Foundation. TM is supported by an NSF Graduate Research Fellowship.

Data Availability

The CESM1.2.2 source code and input data are available through subversion code repositories accessible through the model's public webpage: https://www.cesm.ucar.edu/models/cesm1.2/ . For the purposes of the review the data to produce the figures can be found here: https://drive.google.com/drive/folders/1KP_KONFRijN80HdRzBlK681fCqX8PcFX?usp=sharing. A DOI will be generated after acceptance.

References

Biasutti, M., Held, I. M., Sobel, A. H., & Giannini, A. (2008). SST Forcings and Sahel Rainfall Variability in Simulations of the Twentieth and Twenty-First Centuries. *Journal of Climate*, *21*(14), 3471–3486. https://doi.org/10.1175/2007JCLI1896.1

Biasutti, Michela. (2019). Rainfall trends in the African Sahel: Characteristics, processes, and causes. *WIREs Climate Change*, *10*(4), e591. https://doi.org/10.1002/wcc.591

Boettcher, M., Chai, F., Cullen, J., Goeschl, T., Lampitt, R., Lenton, A., et al. (2019). *High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques* (Report). GESAMP. Retrieved from http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques

Dai, A., Lamb, P. J., Trenberth, K. E., Hulme, M., Jones, P. D., & Xie, P. (2004). The recent Sahel drought is real. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 24(11), 1323-1331.

Fan, W., Chen, J., Pan, Y., Huang, H., Arthur Chen, C.-T., & Chen, Y. (2013). Experimental study on the performance of an air-lift pump for artificial upwelling. *Ocean Engineering*, *59*, 47–57. https://doi.org/10.1016/j.oceaneng.2012.11.014

Giannini, A., Saravanan, R., & Chang, P. (2003). Oceanic Forcing of Sahel Rainfall on Interannual to Interdecadal Time Scales. *Science*, *302*(5647), 1027–1030. https://doi.org/10.1126/science.1089357

Giannini, A., Salack, S., Lodoun, T., Ali, A., Gaye, A. T., & Ndiaye, O. (2013). A unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales. *Environmental Research Letters*, *8*(2), 024010. https://doi.org/10.1088/1748-9326/8/2/024010

Giannini, Alessandra, & Kaplan, A. (2019). The role of aerosols and greenhouse gases in Sahel drought and recovery. *Climatic Change*, *152*(3), 449–466. https://doi.org/10.1007/s10584-018-2341-9

Griffiths, J. (2020, December 3). China to expand weather modification program to cover 5.5 million square kilometers - CNN. Retrieved February 22, 2021, from https://www.cnn.com/2020/12/03/asia/china-weather-modification-cloud-seeding-intl-hnk/index.html

Hill, S. A., Ming, Y., & Zhao, M. (2018). Robust Responses of the Sahelian Hydrological Cycle to Global Warming. *Journal of Climate*, *31*(24), 9793–9814. https://doi.org/10.1175/JCLI-D-18-0238.1

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., et al. (2013). The Community Earth System Model: A Framework for Collaborative Research. *Bulletin of the American Meteorological Society*, *94*(9), 1339–1360. https://doi.org/10.1175/BAMS-D-12-00121.1

Johannessen, O. M., Subbaraju, G., & Blindheim, J. (1987). Seasonal variations of the oceanographic conditions off the southwest coast of India during 1971-1975.

Kwiatkowski, L., Ricke, K. L., & Caldeira, K. (2015). Atmospheric consequences of disruption of the ocean thermocline. *Environmental Research Letters*, *10*(3), 034016. https://doi.org/10.1088/1748-9326/10/3/034016

Letelier, R. M., Strutton, P. G., & Karl, D. M. (2008). Physical and ecological uncertainties in the widespread implementation of controlled upwelling in the North Pacific Subtropical Gyre. *Marine Ecology Progress Series*, *371*, 305-308.

Liu, Z., & Alexander, M. (2007). Atmospheric bridge, oceanic tunnel, and global climatic teleconnections. *Reviews of Geophysics*, *45*(2).

Lovelock, J. E., & Rapley, C. G. (2007). Ocean pipes could help the Earth to cure itself. *Nature*, *449*, 403. https://doi.org/10.1038/449403a

Lu, J., & Delworth, T. L. (2005). Oceanic forcing of the late 20th century Sahel drought. *Geophysical Research Letters*, *32*(22). https://doi.org/10.1029/2005GL023316

Monerie, P. A., Sanchez-Gomez, E., Pohl, B., Robson, J., & Dong, B. (2017). Impact of internal variability on projections of Sahel precipitation change. *Environmental Research Letters*, *12*(11), 114003.

Mortimore, M. (2010). Adapting to drought in the Sahel: Lessons for climate change. *WIREs Climate Change*, *1*(1), 134–143. https://doi.org/10.1002/wcc.25

Oschlies, A., Pahlow, M., Yool, A., & Matear, R. J. (2010). Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. *Geophysical Research Letters*, *37*(4). https://doi.org/10.1029/2009GL041961

Prasad, T. G., & Bahulayan, N. (1996). Mixed layer depth and thermocline climatology of the Arabian Sea and western equatorial Indian Ocean.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., et al. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres*, *108*(D14). https://doi.org/10.1029/2002JD002670

Readfearn, G. (2020, April 16). Scientists trial cloud brightening equipment to shade and cool Great Barrier Reef. Retrieved February 22, 2021, from http://www.theguardian.com/environment/2020/apr/17/scientists-trial-cloud-brightening-equipment-to-shade-and-cool-great-barrier-reef

Stan, C., Straus, D. M., Frederiksen, J. S., Lin, H., Maloney, E. D., & Schumacher, C. (2017). Review of tropical-extratropical teleconnections on intraseasonal time scales. *Reviews of Geophysics*, *55*(4), 902-937.

Walther, B. A. (2016). A review of recent ecological changes in the Sahel, with particular reference to land-use change, plants, birds and mammals. *African Journal of Ecology*, *54*(3), 268–280. https://doi.org/10.1111/aje.12350

White, A., Björkman, K., Grabowski, E., Letelier, R., Poulos, S., Watkins, B., & Karl, D. (2010). An Open Ocean Trial of Controlled Upwelling Using Wave Pump Technology. *Journal of Atmospheric and Oceanic Technology*, *27*(2), 385–396. https://doi.org/10.1175/2009JTECHO679.1

You, Y., & Tomczak, M. (1993). Thermocline circulation and ventilation in the Indian Ocean derived from water mass analysis. *Deep Sea Research Part I: Oceanographic Research Papers*, *40*(1), 13-56

Yuan, X., Kaplan, M. R., & Cane, M. A. (2018). The interconnected global climate system—A review of tropical–polar teleconnections. *Journal of Climate*, *31*(15), 5765-5792.

Supporting References

Cole, S. T., Wortham, C., Kunze, E., & Owens, W. B. (2015). Eddy stirring and horizontal diffusivity from Argo float observations: Geographic and depth variability. *Geophysical Research Letters*, 42(10), 3989-3997.

Fan, W., Chen, J., Pan, Y., Huang, H., Arthur Chen, C.-T., & Chen, Y. (2013). Experimental study on the performance of an air-lift pump for artificial upwelling. *Ocean Engineering*, *59*, 47–57. https://doi.org/10.1016/j.oceaneng.2012.11.014

Liang, N. K., & Peng, H. K. (2005). A study of air-lift artificial upwelling. *Ocean engineering*, *32*(5-6), 731-745.

Pan, Y., Fan, W., Huang, T. H., Wang, S. L., & Chen, C. T. A. (2015). Evaluation of the sinks and sources of atmospheric CO2 by artificial upwelling. *Science of the Total Environment*, *511*, 692-702.

Pan, Y., Fan, W., Zhang, D., Chen, J., Huang, H., Liu, S., ... & Chen, Y. (2016). Research progress in artificial upwelling and its potential environmental effects. *Science China Earth Sciences*, *59*(2), 236-248.