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Supporting Information for

Reversing Sahelian Droughts

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Text S1. Artificial Upwelling Energy Calculation

Approximating the amount of energy it would take to accomplish the targeted cooling of the Indian Ocean involved major assumptions and their associated design parameters. A majority of artificial upwelling literature focuses on carbon sequestration and biological productivity, therefore the data collected and design parameters of artificial upwelling systems are not applicable for systems designed for ocean cooling. Additional studies aiming to investigate the physical and thermodynamic implications of upwelling cold and dense deep ocean water (DOW) to the surface regionally are necessary for understanding the feasibility of ocean cooling. The temporal scale at which a region would cool would also need to be addressed in these experimental studies. Utilizing the limited available literature, it is assumed that the upwelled deep ocean water (DOW) is adiabatically transferred to the surface and mixes thoroughly between the surface and the density interface (Fan, 2013; Fan, 2015).

To estimate the amount of energy that would be required to upwell deep ocean water and cool the surface of the ocean to the extent reflected in the slab-ocean model, the steady state solution of a simple, first order ordinary differential equation was used with boundary conditions reflective of the surface energy flux diagnostic outputs from the numerical simulations. The spatial extent of the simple model was determined by eddy horizontal diffusivity rates (Cole et. al., 2015), in which our upwelling region is considered well-mixed on the order of seconds. This is demonstrated by

$$\frac{dH}{dt} = \frac{Q(H_{DOW} - H) + F}{V}$$

in which H is the total heat within the upwelling region, H_{DOW} is the heat of the upwelled water, F is the annually-averaged radiative forcing, Q is the upwelling rate for the region, and V is the volume of the mixed layer within the upwelling region bounded by the approximate sinking depth of the dense deep water (Pan et. al., 2015). The heat of the upwelled water was calculated using the temperature of the deep ocean water and the initial condition for heat in **Equation dH/dt** was calculated using the temperature at the surface.

Constraints were applied using the temperature anomalies from the slab-ocean model, and the upwelling rate for each region was optimized then scaled to the resolution of the slab-ocean model as shown in Fig S3. This upwelling model tested 3 different pipe lengths, 150, 350, and 600 meters, with 150 meters proving to be the least energy intensive. Using the total upwelling rate, the number of pipes and the flow rates of individual pipes were optimized to discrete pipe diameter sizes and the total energy was computed by

$$E_K = \frac{1}{2}\rho_{DOW}\frac{Q^3}{\pi^2\left(\frac{D^4}{16}\right)}$$

$$E_O = glQ\frac{\rho_{DOW}}{\rho_{SURF}}(\rho_{DOW} - \rho_{SURF})$$

$$E_{TOT} = \frac{1}{\eta}n(E_O + E_K)$$

where ρ_{DOW} is the approximate density of the upwelled water, ρ_{SURF} is the approximate density of the surface water, l is the length of the pipe, g is gravity, D is the diameter of the pipe, n is the total number of pipes (Liang and Peng, 2005; Fan et. al., 2013; Pan et. al., 2016) and η is the pipe efficiency. These energy estimates disregard any frictional losses, which are parameterized as a component of η.

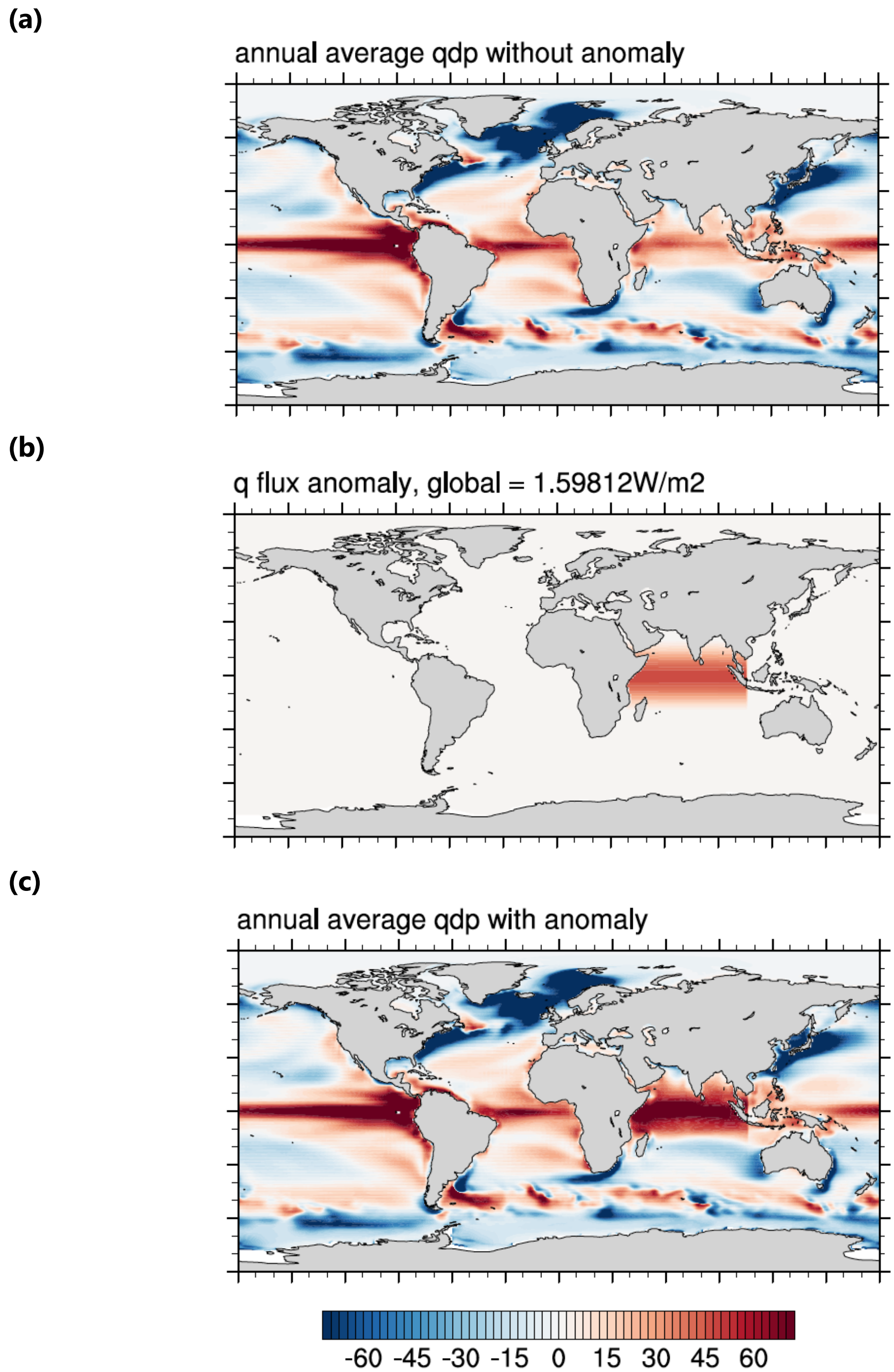

Figure S1. Prescribed surface heat fluxes in slab ocean experiment: (a) pre-industrial background (applied in control experiments), (b) Q-flux perturbation designed for t4 simulation, and combined perturbation and background q-fluxes (applied in t4 slab ocean simulations). The t3 simulations use the same control Q-fluxes and the same pattern of perturbation but at approximately half the magnitude.

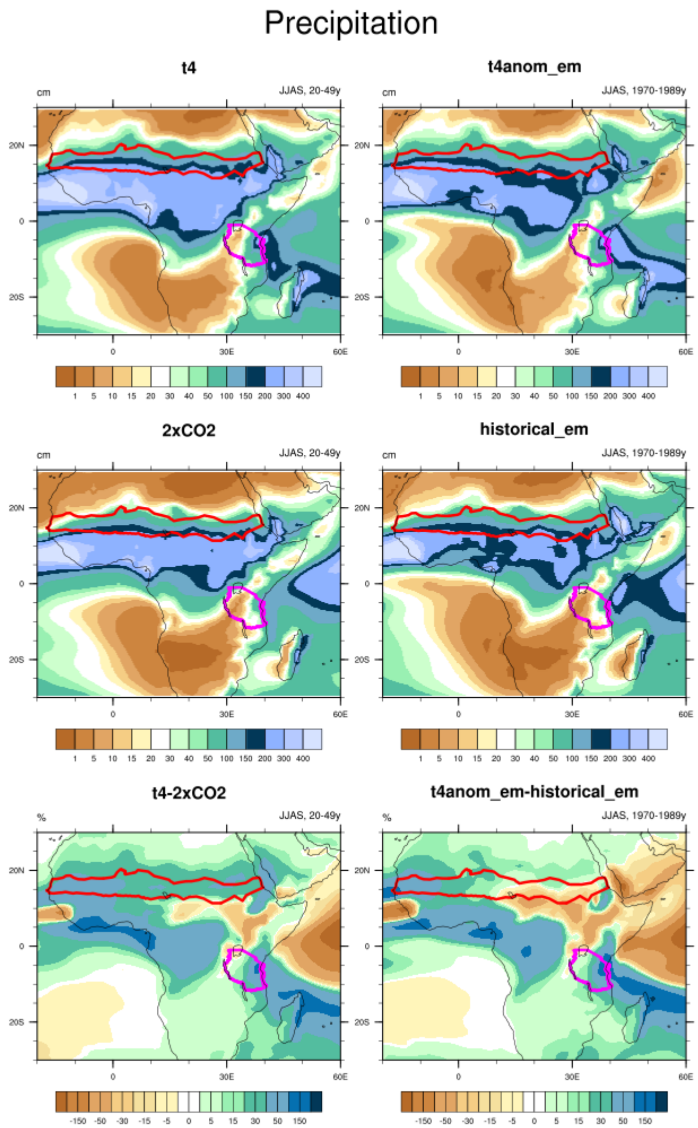

Figure S2. Precipitation over Africa in the idealized slab ocean simulations and historical prescribed SST experiments.

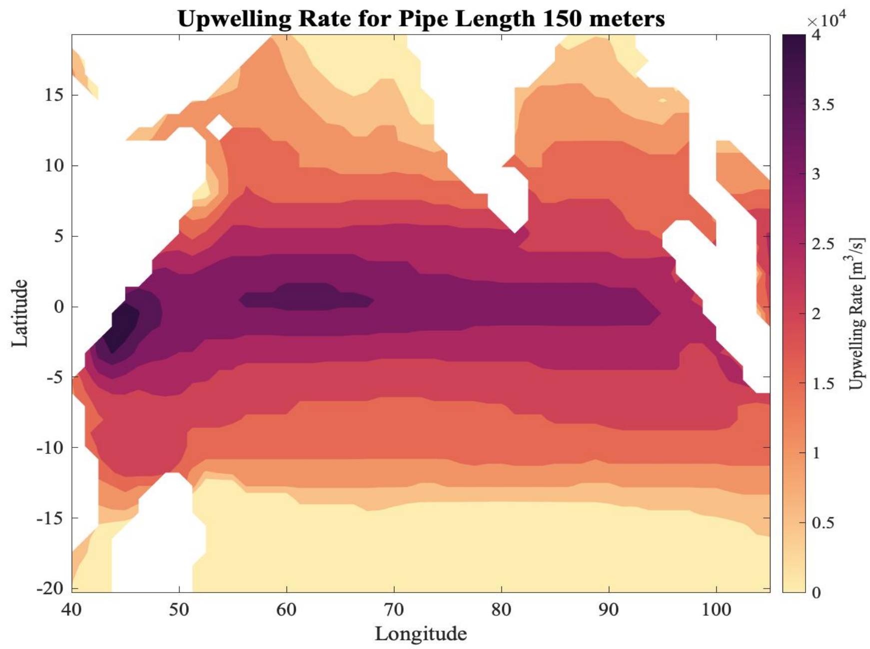

Figure S3. Derived upwelling rate (m3/s) for 150m pipes to cool Indian Ocean as in the drought_reverse simulations.

Short Name	Description
Slab ocean (SOM) simulations	
ref_preind	Pre-industrial CO2 levels of 286ppm; Reference set up.
ref_warm_world	Doubled CO2 levels of 562 ppm ; Reference set up.
io_cooled_strongly	Large magnitude of Indian ocean cooling with 2xCO2 forcing
io_cooled	Small magnitude of Indian ocean cooling with 2xCO2 forcing
SST prescribed simulations	
historical	Time varying SST prescribed from 1930 – 2000 based on Hadley Centre Global Sea Ice and Sea Surface Temperature (HADISST v1.1)
historical branch 1 ***historical branch 2***	branches from 1960 of the historical
drought_reverse	3-member ensemble with branches from 1960 of the historical with perturbation ***io_cooled_strongly*** - ***ref_warm_world*** monthly climatology cycling applied from 1965 to 1995

Table S1. Numerical experiments descriptions