Daniel J. Vimont, Ralf Bennartz
Dept of Atmospheric and Oceanic Sciences
University of Wisconsin – Madison
Email: dvimont@wisc.edu
Email: bennartz@aos.wisc.edu

Amato Evan
Department of Environmental Sciences
University of Virginia
Email: ate9c@virginia.edu

James Kossin
NOAA NCDC
CIMSS/University of Wisconsin-Madison
Email: james.kossin@noaa.gov

June 30, 2013

RE: NOAA CVP GRANT
NA11OAR4310156

James F. Todd
Program Manager, Climate Variability and Predictability Program
NOAA Climate Program Office
1315 East-West Highway, Room 12214
Silver Spring, Maryland 20910-6223
USA

Dear James Todd,

Attached is the progress report for the NOAA CVP Grant NA11OAR4310156. This progress report is for activities that occurred from April 1, 2012 through March 31, 2013 at University of Wisconsin – Madison (PIs: Daniel Vimont, Ralf Bennartz, and James Kossin) and at the University of Virginia (PI: Amato Evan).

NOAA Grant: NA11OAR4310156

Title: The role of aerosols in Atlantic climate variability.

PIs: Daniel J. Vimont and Ralf Bennartz (U. Wisconsin – Madison), Amato Evan (University of Virginia), and James Kossin (NOAA NCDC)

Major accomplishments over the last year include *(i)* development of estimates of global surface direct radiative forcing for total, natural, and anthropogenic aerosols; *(ii)* investigation of the coupled response to dust aerosol forcing using signal-to-noise maximizing EOF analysis, and *(iii)* initial steps toward estimating the climatic response to the surface forcing described in *(i)*. These accomplishments are described below.

Please let me know if you need any additional information.

Best Regards,

Daniel J. Vimont
(Ralf Bennartz, Amato Evan, and James Kossin)

GRANT DETAILS:

Grant: NA11OAR4310156

Title: **The role of aerosols in Atlantic climate variability.**

PIs: Daniel J. Vimont and Ralf Bennartz (U. Wisconsin – Madison), Amato Evan (University of Virginia), and James Kossin (NOAA NCDC)

OVERVIEW:

Recent analyses of global and regional climate trends and variability have highlighted the difficulty in distinguishing between contributions of radiatively forced climate variations (both anthropogenic and natural forcing) and climate variations that arise due to natural variations between different components of the climate system. Of particular importance is the role of greenhouse gasses and aerosols in forcing Atlantic variability, and the potential influence of Atlantic multi-decadal variability (AMV) on regional and global temperature trends. The potential aliasing of aerosol-forced climate variability on natural and greenhouse-gas forced variations in the Atlantic – and the potential excitation of natural climate variability by aerosol forcing – has important implications for detecting and attributing anthropogenic climate change, and for understanding mechanisms of Atlantic climate variability, including AMV.

PROJECT GOALS:

This research aims to better understand the forcing mechanisms and impacts of Atlantic Multidecadal Variability, including (1) the role of natural and anthropogenic aerosols in forcing tropical and mid- to high-latitude Atlantic climate variations; (2) interactions between aerosol forcing and coupled ocean atmosphere dynamics that may give rise to long-term variations in Atlantic climate; and (3) the impact of Atlantic multidecadal variability on seasonal hurricane activity.

METHODOLOGY:

This project proposes the following three major research tasks:
  (1) Develop new climatological and transient data sets of aerosol optical depth and direct radiative forcing using satellite observations and radiative transfer models. These data sets will attempt to identify aerosol forcing from "natural" sources (e.g. dust, sea salt, volcanoes, natural sulfate and smoke) and "anthropogenic" sources (sulfate and smoke).
  (2) Identify the coupled ocean / atmosphere response to aerosol forcing, and divide the response into a "natural", "anthropogenic", and "full" response. We will identify the coupled ocean / atmosphere response through running coupled model experiments using various configurations of the NCAR CCSM.
  (3) Relate model findings to extreme event characteristics, especially tropical cyclone track and intensity.

NOAA Annual Report: April 1, 2012 – March 31, 2013
RESULTS AND ACCOMPLISHMENTS:

I. Estimates of aerosol radiative forcing in the Atlantic

Overview:

The energy balance of the Earth is the driving factor in climate dynamics, and understanding the processes by which the energy balance is altered is critical to understanding the climate system. Clouds as well as atmospheric gases and particles can have profound impacts on the energy balance in different ways and varying magnitudes. Recent analyses of global and regional climate trends and variability have highlighted the difficulty in distinguishing between contributions of radiatively forced climate variations (both anthropogenic and natural forcing) and climate variations that arise due to natural variations between different components of the climate system. Of particular importance is the role of greenhouse gasses and aerosols in forcing Atlantic variability, and the potential influence of Atlantic multi-decadal variability (AMV) on regional and global temperature trends. The potential aliasing of aerosol-forced climate variability on natural and greenhouse-gas forced variations in the Atlantic – and the potential excitation of natural climate variability by aerosol forcing – has important implications for detecting and attributing anthropogenic climate change, and for understanding mechanisms of Atlantic climate variability, including AMV.

This research aims to better understand the forcing mechanisms and impacts of Atlantic Multi-decadal Variability, including
- The role of natural and anthropogenic aerosols in forcing tropical and mid- to high-latitude Atlantic climate variations
- Interactions between aerosol forcing and couple ocean atmosphere dynamics that may give rise to long-term variations in Atlantic climate, and
- The impact of Atlantic Multi-decadal variability on seasonal hurricane activity.

Calculating global surface fluxes:

Global surface shortwave fluxes are computed using a radiative transfer model, called Streamer (Key and Schweiger, 1998). Streamer uses a two-stream, discrete ordinance approximation method with 24 shortwave bands ranging from 0.28 to 4.0 micrometers. Several important components to radiative transfer calculations are built-in to Streamer and can be specified by the user. These include seven standard atmospheric profiles ranging from tropical to arctic winter, six optical models for aerosols (tropospheric, maritime, etc), absorption of gases (hydrogen, oxygen, ozone, carbon dioxide, and trace gases), as well as spectral reflectivities for a variety of surface types (dry sand, freshwater, etc). For this experiment, we assume gaseous absorption, a tropospheric optical model, and an open ocean surface for every point on the globe. Standard atmospheric profiles are determined by the latitude and month.

Experiments performed

Four experiments are performed in Streamer for each point on a 1x1 degree global grid using an aerosol climatology developed by Kinne et al. (2003). Average monthly aerosol optical depths (AODs) are given for coarse, preindustrial, anthropogenic, and all aerosols. A control run turns

off all background aerosols and calculates the net surface shortwave flux. The same flux is then computed for three cases:

1. Total AOD
2. Anthropogenic AOD
3. Natural (coarse plus preindustrial) AOD

The optical properties of natural and anthropogenic aerosols are taken from the Optical Properties of Clouds and Aerosols (OPAC) dataset (Hess et al., 1998). Anthropogenic aerosols are assumed to be sulfates, while natural aerosols are assumed to be a combination of the accumulation and coagulation modes of sea salt. For both aerosol types, the optical properties are taken at a constant relative humidity of 80%. The global distribution of average July AODs from the climatology is shown in Figure 1.
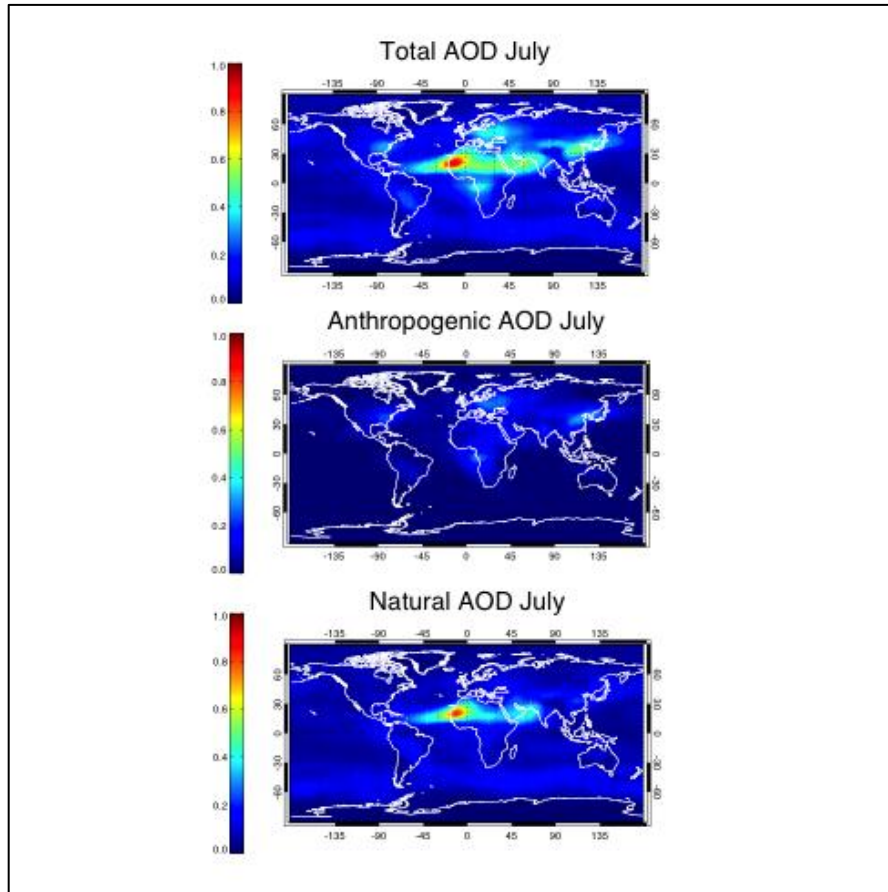

Figure 1: Global distributions of average July total, anthropogenic, and natural aerosol optical depths from the Kinne et al. (2003) climatology. The top figure shows high optical depths in northwest Africa and central China. There is a strong anthropogenic component in the aerosol optical depths in China (middle), while natural aerosols, such as dust, make up the majority of the high optical depths found in Africa (bottom).

As sulfates are typically smaller and lighter than sea salt, the layer of sulfates is placed between 2 and 4 km above sea level. The layer of sea salt is placed from 0 to 2 km. The extinction coefficient, asymmetry parameter, and single-scatter albedo of each layer is determined by the OPAC dataset, while the optical depth is determined by the Kinne et al. (2003) climatology.

Height sensitivity tests showed that the effect of changing the height of the sulfates between 2 and 6 km was negligible. All background aerosols that are in the streamer default settings are turned off. The net surface shortwave fluxes are computed for every hour on the 15th of every month. The 15th of each month was chosen in order to utilize the average zenith angle of that month, which is calculated by streamer. Figure 2 shows the average diurnal variations in surface fluxes and flux perturbations for each experiment at 24.5N 0.5W for the month of July. When the sun is at its lowest above the horizon (largest zenith angle), there is a slight decrease in shortwave radiation reaching the surface due to the presence of the sea salt, which likely scatters that radiation away. When the sun is at its highest point (lowest zenith angle), the sea salt scatters solar radiation towards the ground, accounting for a higher surface flux between 7 and 17 UTC.
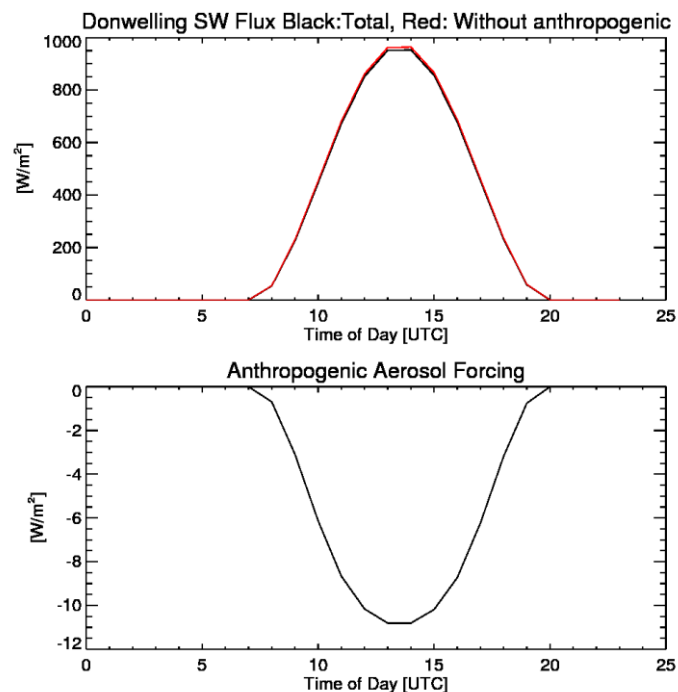

Figure 2: Average June diurnal variations in shortwave downwelling surface fluxes at 0.5N 20.5W in W m^{-2} for different aerosol scenarios. (Top) The total downwelling shortwave flux (black) and shortwave downwelling flux without anthropogenic aerosol (red). (Bottom) The resulting anthropogenic forcing calculated as the difference between the top panel's black and red curves. Positive perturbations indicate an increase in surface flux, while negative perturbations indicate a decrease in surface flux.

References:

Hess M., P. Koepke, and I. Schult, "Optical properties of Aerosols and Clouds: The software package OPAC", *Bulletin of American Meteorological Society*, **79**, 831-844 (1998).

Key, J. and A.J. Schweiger, 1998, Tools for atmospheric radiative transfer: Streamer and FluxNet, *Computers & Geosciences*, 24(5), 443-451.

Kinne, S., Lohmann, U., Feichter, J., Timmreck, C., Schulz, M., Ghan, S., Easter, R., Chin, M., Ginoux, P., Takemura, T., Tegen, I., Koch, D., Herzog, M., Penner, J., Pitari, G., Holben, B., Eck, T., Smirnov, A., Dubovik, O., Slutsker, I., Tanre , D., Torres, O., Mishchenko, M., Geogdzhayev, I., Chu, D. A., and Kaufman, Y.: Monthly Averages of Aerosol Properties: A Global compari- son among models, satellite data and AERONET ground data, *J. Geophys. Res*, 108, 4634, 2003.

II. Role of dust radiative forcing in tropical Atlantic climate variability

The response of the NCAR CCSM4 to direct radiative forcing from a typical dust aerosol outbreak was investigated. We forced the NCAR CCSM4 coupled with a slab ocean model (CCSM4-SOM) with a derived pattern of direct shortwave dust aerosol forcing. To construct the dust aerosol radiative forcing, we took a composite of direct radiative forcing from dust aerosol variations (taken as the mean difference between three years that experienced large dust outbreaks, and three years that experienced minimal dust outbreaks) and used that radiative forcing to force a version of the NCAR CCSM4 coupled with a slab ocean model (SOM). The forcing was applied from May – November, and then turned off in December. The model integration begins in April (to account for the linear ramp-up of forcing from mid-April through mid-May) and continues through the following March, well after the forcing has shut off. A 40-member ensemble was run to ensure robust results. Initial results were reported in the 2012 progress report. For reference, the forcing is shown in Fig. 3, and indicates a reduction in downward shortwave radiation over most of the northern tropical Atlantic from May through about September (though weak anomalies continue through December) of the simulation.

The SST response of the model is diagnosed using signal-to-noise maximizing EOF (SNEOF) analysis (Venske et al., 1999). SNEOF is useful when a signal is likely to be contaminated by noise that has a pre-defined structure (e.g. when there is small sample size, or natural climate variability has large variance). In our case, SNEOF is used to diagnose the dominant response structures. We define the noise covariance matrix from a long (40yr) control simulation using the CCSM4-SOM, and use the dominant EOFs from the control simulation to pre-whiten the ensemble mean response. SNEOF produces patterns and associated time series (12mo long, as each model simulation is 12mo in duration) that maximize the signal to noise ratio in the response. SNEOF is applied to the ensemble mean SST field from the forced CCSM4-SOM experiments and the leading two response time series (which are orthogonal by constraint) are used to define the response in SST as well as other fields.

The leading two SNEOFs are shown in Fig. 4 below. The leading SNEOF bears a strong resemblance to the average forcing structures from Fig. 3, with negative forcing (cooling) spanning the tropical Atlantic from about the equator and 40°W northeastward to about 30°N-20°W. The leading PC amplifies through about August, then gradually decays, similar to the overall amplitude of the forcing. As such, we interpret the leading SNEOF as the direct forced SST response in the model. The second SNEOF/SNPC has a local minimum centered in the eastern tropical Atlantic, around 10°N-10°W, that is centered slightly south of the directly forced region. SNPC2 shows that this pattern initially has negative amplitude, then turns to positive amplitude around November through March, around the time when the forcing is shut off. This depicts a southward migration of cold anomalies that occurs as a response to the directly forced SST anomalies.

The SNEOFs are constrained via the fact that they are linear combinations of the noise forcing patterns. The full evolution of the SST field can be described via regressing SST onto the associated SNPC time series and reconstructing using a subset of the SNPCs. The reconstructed SST using the leading two SNPCs is shown in Fig. 5, and confirms the equatorward migration of negative SST anomalies in the northern tropical Atlantic that was inferred from the SNEOFs in Fig. 4. We can reconstruct the associated precipitation response via the same method; we regress precipitation onto the leading two SNPCs of surface temperature, and reconstruct. The precipitation response is shown in Fig. 6, and shows that the model produces precipitation anomalies that extend well over South America. Simple composites also confirm the over-land response.

While the SNEOFs are a good way of determining the dominant forced response, there is still considerable variation of the response between different ensemble members. For example, the response in the first 20 ensemble members has a much stronger meridional SST gradient near the equator, and as such a much stronger precipitation response over South America than the response in the last 20 ensemble members. We are currently extending our analysis using the SNEOFs to determine the robustness of the response in individual ensemble members.

We have run two additional sets of sensitivity experiments to test the linearity of the response. The first ensemble experiment is identical to the dust forcing experiment described above, except the polarity of the forcing is reversed to test the linearity of the response (the NEG experiment). The second ensemble experiment reduces the forcing to one-half that used in the dust experiment described above (the HALF experiment). We found that although the response was relatively linear in the HALF experiment, it was quite different in the NEG experiment. We are currently examining the reasons for the differences.

Results from the dust radiative forcing experiments have been written up in a Master's thesis (Watkins, 2012) and in a paper to be submitted soon (Vimont et al., 2013).

Papers:

D. J. Vimont, K. Watkins, and A. T. Evan, 2012: Model simulation of the tropical Atlantic response to African dust outbreaks in the NCAR CCSM4. *In Preparation.*

References:

Allen, M. R. and L. A. Smith, 1996: Optimal filtering in singular spectrum analysis. *Phis. Lett.,* **234**, 419-428.

Venzke, S., M. R. Allen, R. T. Sutton, and D. P. Rowell, 1999: The atmospheric response over the North Atlantic to decadal changes in sea surface temperature. *J. Climate*, **12**, 2562 – 2584.
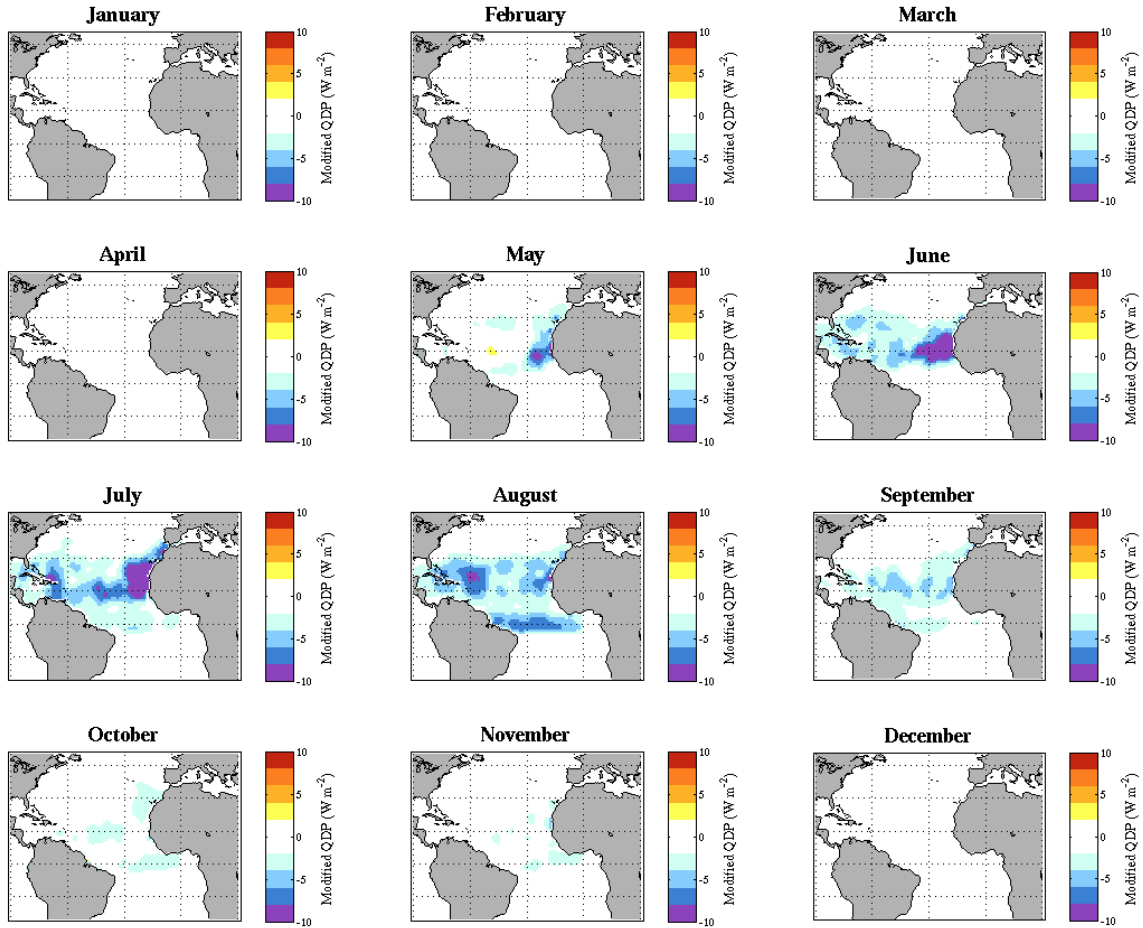
Figure 3. Downward shortwave radiation forcing used in the dust aerosol forced CCSM4-SOM experiments. Units are in W m^{-2}, and negative values imply a reduction in downward solar radiation.
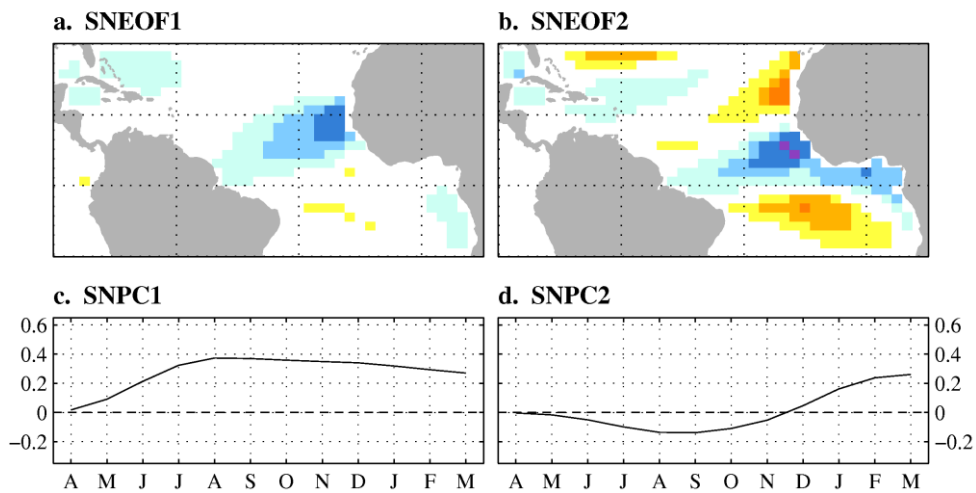

Figure 4: Leading (left) and second (right) SNEOFs (top) and associated SNPCs (bottom). Units are arbitrary.

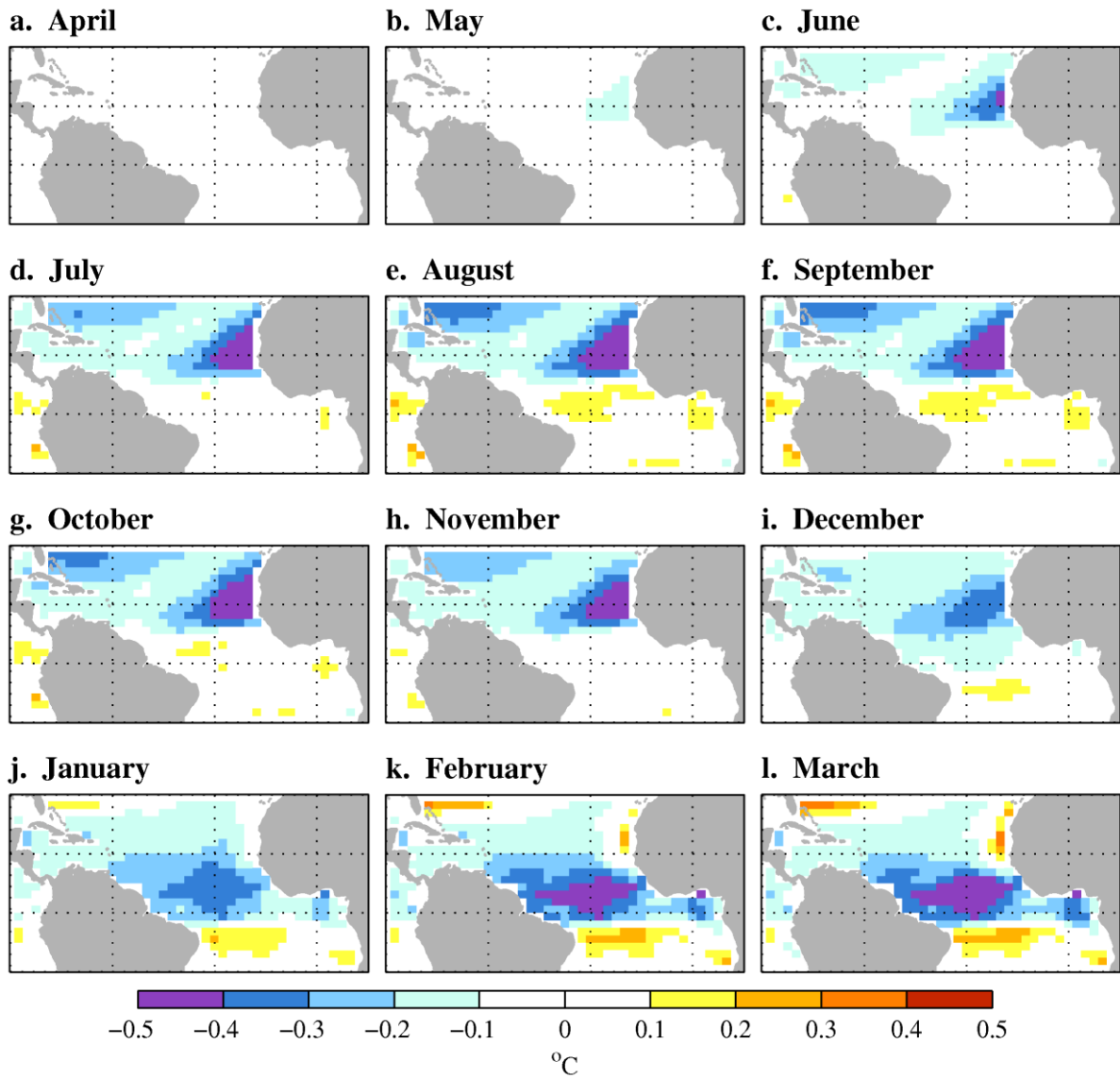# TS Monthly Response (S/N Max EOF)

Figure 5: SST response reconstructed from the leading two SNEOFs. Note the equatorward migration of negative SST anomalies from December through March, after the forcing has been set to zero.
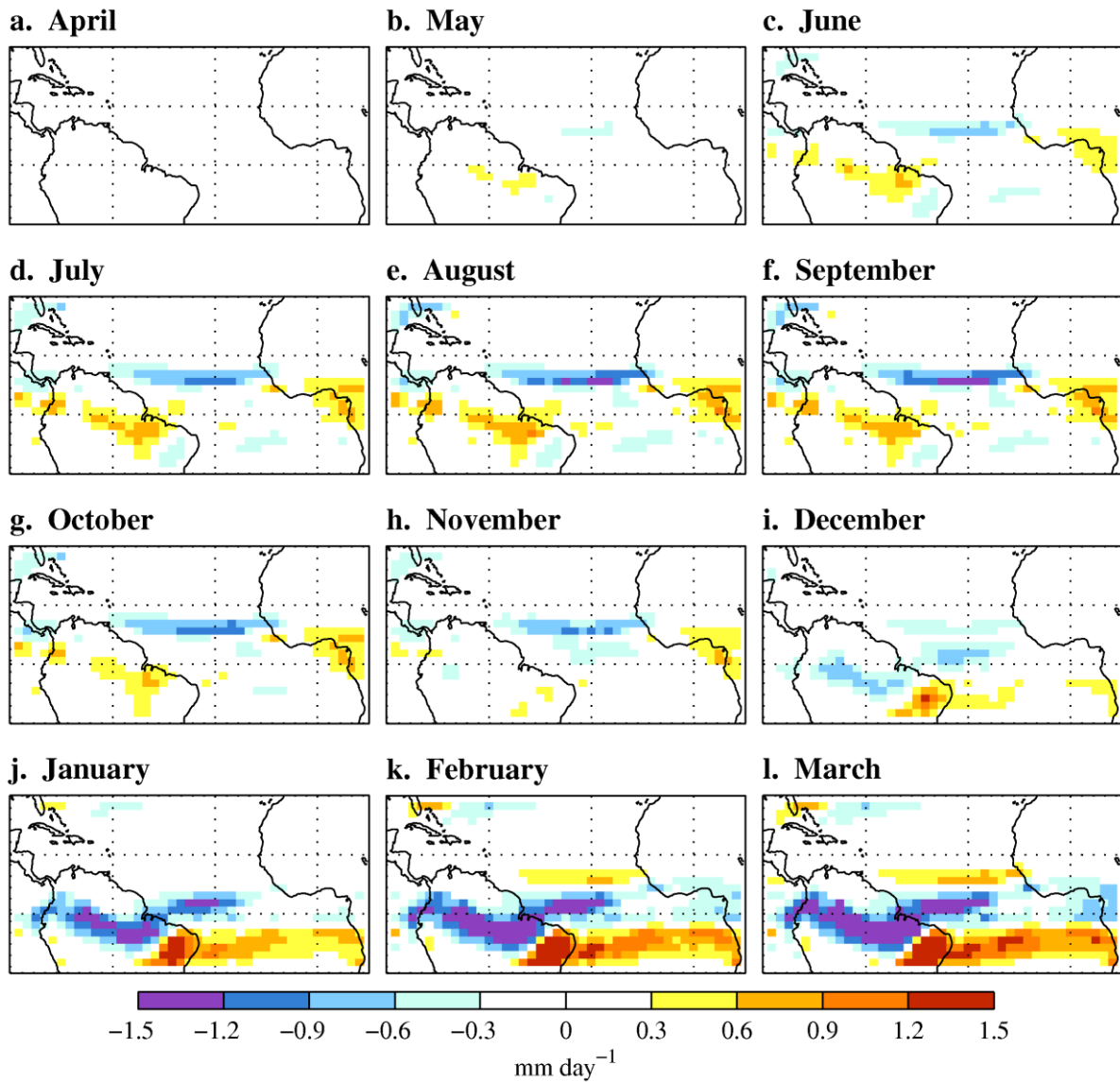
PRECT Monthly Response (S/N Max EOF)

Figure 6: Precipitation response to anomalous dust forcing. Precipitation is reconstructed using the leading two SST SNPCs (see text). Note the southward shift in the ITCZ during boreal winter, after the forcing has been shut off. Note that precipitation anomalies extend over South America.

III. Role of sulfate aerosol radiative forcing in producing climate variability

For the last year of the project, we will estimate the direct response of the ocean / atmosphere system to direct radiative forcing from natural and anthropogenic sulfate aerosols. We will run four different experiments. The first is a control experiment using CCSM4 in which all sulfate aerosols are "zeroed" out. The second experiment will use a climatological surface radiative forcing from all aerosol sources (described in part I above). Experiments three and four will investigate the response to surface radiative forcing from natural and anthropogenic aerosol radiative forcing, as described in part I above. For all experiments, direct radiative forcing will be scaled by the instantaneous albedo at a given time, as we expect that the surface radiative forcing is dominated by the shortwave response to aerosols.