Interactions of North African dust with tropical and subtropical Atlantic coupled ocean-atmosphere processes

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Recent work has suggested that North African dust variability over the tropical and subtropical North Atlantic can account for a large fraction of decadal changes in SST anomalies. The response of monthly SST anomalies to dust outbreaks on interannual and decadal timescales is characterized by comparing two Community Earth System Model (CESM) simulations with and without interannual variability of dust. These comparisons show an increase in SST variance in the interactive (interannual dust variability allowed) run over the tropical and subtropical North Atlantic, suggesting that fluctuations of North African dust can drive regional changes in SST variability. The leading mode of coupled SST/wind variability in the tropical Atlantic (the Atlantic Meridional Mode (AMM)) is examined. Although the observed SST spatial pattern associated with the AMM appears as an out-of-phase cross-hemispheric dipole pattern, latent heat flux coupling to the surface horizontal wind only occurs in the Northern Hemisphere. In addition, strong cross-equatorial wind flow normally associated with an interhemispheric SST gradient is present in the CESM interactive simulation, but absent in the prescribed simulation. These results indicate that modeled interannual dust variations influence deep tropical WES dynamics. Strong positive anomalies of summertime dust burden over the subtropical North Atlantic are associated with strong negative values of the coupled SST MCA principal components, indicating that interannual variability of North African dust changes the spatial loading of summertime SST associated with the AMM.
1. Introduction

The variability of Atlantic basin sea surface temperature (SST) has substantial impacts on regional and global climate change, and therefore on human life and property. Long term fluctuations in North Atlantic SST can perturb the near-surface atmosphere, altering the associated surface air temperature and shifting storm tracks and precipitation patterns across Europe and the Mediterranean (Buchan et al., 2014; Cattiaux et al., 2011; Sutton and Hodson, 2005; Trigo et al., 2002; Rogers, 1997; Hurrell, 1995). These SST-related changes in regional climate have spawned deadly heat waves (Cassou et al., 2005) and cold winters (Buchan et al., 2014) across Europe. Increases in tropical North Atlantic SST, along with reductions in vertical wind shear, are directly tied to increases in tropical cyclone frequency (e.g. Goldenberg et al., 2001) and Sahel rainfall (e.g. Folland et al., 1986), especially on multidecadal timescales (Booth et al., 2012; Mohino et al., 2011; Wang et al., 2012; Zhang and Delworth, 2006; Giannini et al., 2003). Both local and remote economic conditions are greatly affected by the relationship between Atlantic SST variability and these resulting climate patterns.

Interannual Atlantic SST observations show both natural and remotely forced components. For example, both central and eastern Pacific El Niños have been shown to significantly impact tropical Atlantic SST (Enfield and Mayer, 1997; Amaya and Foltz, 2014). On decadal and multidecadal timescales, Atlantic SST has been thought to be mainly impacted by natural variability of both ocean dynamics and near-surface layer atmospheric circulation (Enfield et al., 2001; Kushnir, 1994; Schlesinger and
Ramankutty, 1994; Cayan, 1992), while external or remote forcing has been shown not to project strongly onto the observed SST anomaly patterns on these timescales (Ting et al., 2009). However, many of the models used to identify physical mechanisms associated with the observed Atlantic SST variability did not include external forcings such as atmospheric aerosols, which a plethora of studies have identified as important modulators of atmospheric circulation and mixed layer ocean characteristics (Allen et al., 2012; Evan et al., 2009; Zhu et al., 2007). Indeed, studies that have sought to explain Atlantic SST variability using climate models with a greater number of relevant physical processes (e.g. interactive aerosol variability with meteorology and microphysics) have suggested that aerosols can explain up to 76% of simulated decadal and multidecadal Atlantic SST variability (e.g. Booth et al., 2012).

One region within the Atlantic basin where aerosols are omnipresent is over the tropical and subtropical North Atlantic basin, where large quantities of mineral dust are advected from the North African continent year-round (e.g., Prospero et al., 1970). Because of its effectiveness as both a scatterer and absorber of solar radiation, dust has been shown to impact both sea surface temperature and cloud fraction due to direct and semi-direct radiative effects (DeFlorio et al., 2014; Doherty and Evan, 2014; Evan et al., 2009). Booth et al. (2012) showed that aerosol-cloud microphysical interactions, which were omitted from previous modeling studies, dominated the spatial pattern of aerosol forcing on North Atlantic SST variability during the 20th century.

The Community Earth System Model (CESM), which is included in the Coupled Model Intercomparison Project Phase 5 (CMIP5), contains state-of-the-art parameterizations for aerosols which allow species such as dust to interact with
modeled meteorology and cloud microphysics. This is one of the models used in studies such as Booth et al. (2012). Aerosol-cloud microphysics interactions were absent in CMIP3 models, and in many of the model studies used previously to analyze Atlantic basin SST variability on decadal timescales. The inclusion of these interactions, along with better aerosol parameterizations relevant to aerosol-radiation interactions, provides a unique opportunity for utilization of CESM (and other CMIP5 models that include these aerosol processes) to investigate the relationship between North African dust outbreaks and tropical Atlantic SST.

In addition to the Atlantic Multidecadal Oscillation (AMO) (Schlesinger and Ramankutty, 1994), the Atlantic Meridional Mode (AMM) is a tropical Atlantic cross-hemispheric variation of SST that varies on interannual and decadal timescales (though the AMM can intermittently destruct on monthly timescales), and is the dominant source of coupled ocean-atmosphere variability in this region (Vimont and Kossin, 2007; Chiang and Vimont, 2004). In particular, the AMM can play a large role in modulating the seasonal march of the Intertropical Convergence Zone (ITCZ), significantly impacting Northeastern Brazil rainfall and the associated agricultural communities that rely on it (Foltz et al., 2012; Xie and Carton, 2004). Additionally, the AMM has been shown to impact tropical cyclone development (Vimont and Kossin, 2007).

It has been suggested that dust-forced variability of SST in the tropics is of comparable magnitude to the observed variability (Evan et al., 2012). Therefore, it is important to discern whether interannual- and decadal-scale dust outbreaks can modulate AMM activity, as shown in an idealized modeling framework in Evan et al.
In this study, we seek to clarify the role of North African dust outbreaks in exciting the AMM on these timescales by comparing two CESM simulations: one with interactive aerosols which are free to interact with modeled meteorology and vary on interannual and decadal timescales, and one with a prescribed seasonal cycle of aerosol concentration and no interannual and decadal variability.

2. Model description and data used

Two model simulations are compared in this study. Both are CESM 1.0.3 150-year pre-industrial control simulations run at a horizontal resolution of 2.5° longitude (lon) x 1.9° latitude (lat). The only difference in the configuration of the two simulations is that one contains fully interactive dust concentration (free to vary interannual and decadally), while the other prescribes the seasonal cycle of dust concentration using the climatology of the interactive run, such that there is no interannual or decadal variability of dust in the model. For more information regarding these specific simulations, see DeFlorio et al., 2016, DeFlorio et al., 2014, Hurrell et al., 2013, Liu et al., 2012, and Zender et al., 2003.

For model evaluation, we use monthly mean skin temperature (TS), 10-meter horizontal winds, and the net surface latent heat flux from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Reanalysis (Kalnay et al., 1996) from January 1948 to December 2014. The skin temperature was chosen to be consistent with model outputs and because it has the
added benefit over low-level surface air temperature in that it is exactly the SST over ocean grid points.

All fields have been linearly detrended at each grid point and we apply a 3-month running mean to the data used in all figures except Figures 8 and 9. We also linearly regress out the influence of the El Niño Southern Oscillation (ENSO), since we are not interested in the influence of tropical Pacific SST on tropical Atlantic SST variability. We follow Chiang and Vimont (2004) and define ENSO using the cold tongue index (CTI) over the domain 6°S to 6°N, 180°W to 90°W. Monthly anomalies in observations are relative to the climatology 1980-2010; the model anomalies are computed from a long-term monthly mean climatology which includes all months.

3. Dust and tropical Atlantic TS interannual variability

The time evolution of dust burden over West Africa (central Mauritania; 10°W, 20°N) for both the interactive and prescribed CESM simulations is shown in Figure 1. There is clearly interannual and lower frequency variability in the interactive simulation, while we have allowed no interannual or lower frequency variability in the prescribed simulation.

Dust burden peaks in magnitude during boreal summer between 5°N and 20°N over the North Atlantic in CESM (see Figure 6 of DeFlorio et al. (2014)). The variability of July TS monthly anomalies in observations and both CESM simulations is shown in Figure 2. Standard deviation levels in observations and the interactive CESM simulation are substantially higher over the climatologically high dust burden regions.
than in the prescribed CESM simulation. This suggests that interannual-decadal
variability of North African dust can drive changes in tropical Atlantic TS. A
probability density function (PDF) of TS anomalies during the top 5% “dustiest”
months in the interactive CESM simulation reveals that 64% of these high-dust months
are concurrent with negative TS anomalies over the tropical North Atlantic downstream
of North Africa ($40^\circ W$ to $20^\circ W$, $10^\circ N$ to $20^\circ N$). This, coupled with the negatively
skewed PDF towards cooler TS anomalies, reinforces the notion that increased
dustiness can cool TS through radiative effects (Figure 3).

The leading and second modes of tropical Atlantic TS variability and their
associated temporal evolution are shown in Figures 4 and 5. The leading mode of
variability is the Atlantic Niño (Xie and Carton, 2004). We are most interested in the
second mode of variability (Figure 5), which displays a spatial structure and interannual
to decadal variation over time that is reminiscent of the AMM. Consistent with other
CMIP5 models summarized in Flato et al. (2013), the AMM is too weak in magnitude
in both interactive and prescribed CESM (middle, bottom panels), especially in the
northern hemisphere, though the spatial structure agrees reasonably well with
observations (top panel).

4. **Representation of the Atlantic Meridional Mode in CESM**

Though the cross-equatorial dipole pattern associated with the AMM can be
seen as the second EOF mode of tropical Atlantic TS anomalies (Figure 5), an
alternative approach is to define the AMM as the leading mode of coupled variability
between horizontal surface winds and TS anomalies (Chiang and Vimont, 2004). This definition encompasses the cross-equatorial wind flow associated with shifts in the position of the ITCZ that are thought to externally force the TS anomalies associated with the AMM pattern through WES feedback processes (e.g., Nobre and Shukla, 1996; Xie et al., 1993a,b).

We investigate this inquiry by using Maximum Covariance Analysis (MCA) (Bretherton et al., 1992) on tropical Atlantic horizontal surface wind and temperature anomalies to calculate the AMM in observations (Figure 6, top row). The MCA technique is analogous to Empirical Orthogonal Function (EOF) analysis, but instead requires a singular value decomposition of the cross-covariance matrix of horizontal surface wind and TS anomalies. The resulting left and right singular vectors are then projected onto the original data fields to obtain spatial structure and temporal evolution of TS and winds.

The TS and wind spatial structures in the northern hemisphere are reasonably simulated in the leading CESM MCA modes, but the out-of-phase cross-hemispheric TS gradient is not captured. In observations and both CESM simulations, the second mode of coupled variability (not shown) is distinctly reminiscent of the Atlantic Niño (Zebiak, 1993). The correlation coefficients (i.e. the coupling strength) between the leading TS and wind principal components (PCs) for NCEP, CESM interactive, and CESM prescribed are 0.70, 0.49, and 0.48, respectively.

The erroneous spatial structure of the southern hemisphere coupled TS and wind field MCA in CESM may be related to the well-known tropical Atlantic SST biases in CMIP5 models discussed in Toniazzo and Woolnough (2013). This bias is
present in our CESM simulations as well (not shown) and could potentially affect the representation of the Wind-Evaporation-SST (WES) feedback in this region, which is thought to be an important element of sustaining the AMM in reality. This lack of realism is emphasized by the much weaker correlation coefficient between the leading TS and wind PCs in CESM interactive (0.49) and CESM prescribed (0.48) compared to observations (0.70). Such a low coupling strength for the CESM simulations implies that the leading mode of TS and surface winds may not be the most useful technique to characterize model AMM variability. Therefore, we explore auxiliary methods to capture model TS and wind coupled variability in the following sections.

5. Coupled variability of horizontal winds and latent heat flux

An important coupled ocean-atmosphere heat budget term which links SST and horizontal surface winds is latent heat flux (Cayan, 1992). Indeed, it has been shown that the WES feedback in the tropics manifests itself through latent heat flux anomalies forced by the horizontal surface winds (e.g., Xie et al., 1993a,b).

MCA analysis of the leading mode of surface wind and latent heat flux anomalies is shown in Figure 7. The convention for the latent heat flux is such that a negative anomaly corresponds to the atmosphere losing heat to the ocean. The correlation coefficients between the leading latent heat flux and wind principal components for NCEP, CESM interactive, and CESM prescribed are 0.71, 0.84, and 0.80, respectively.
It is clear from the observed leading spatial pattern (Figure 7, top left) that latent heat flux and wind coupling is much stronger in the northern hemisphere than in the southern hemisphere. Strong southwesterly wind anomalies override a basin-scale swath of negative latent heat flux anomalies from 15°N-30°N. This is consistent with a weakening of the climatological trade winds, which leads to a reduction in evaporation at the surface and flux of latent heat energy from the atmosphere into the ocean (negative latent heat flux anomalies). Therefore, the negative latent heat flux anomalies seen in Figure 7 are consistent with a warm phase AMM (Figure 6, top panel).

The leading spatial patterns of latent heat flux and winds in CESM interactive and prescribed (Figure 7, middle left and bottom left, respectively) are very realistic and similar to each other in the northern hemisphere. However, the interactive simulation contains a cross-equatorial wind pattern and the classic C-shaped turn of the winds that we normally associate with interhemispheric SST gradients and the AMM. This is comparable to the observed leading latent heat flux and wind MCA, which displays a similar, albeit weaker, cross-equatorial flow and C-shape turn of the winds (top row, Figure 7). On the other hand, the prescribed simulation does not have this cross-equatorial flow (bottom row, Figure 7). This suggests that interannual variability of dust can modulate the magnitude of latent heat flux and wind coupling near region of the AMM. Understanding why the interactive simulation produces a much stronger cross-equatorial flow is beyond the scope of this study and should be the focus of future modeling efforts.
6. Can summertime North African dust storms excite the AMM on interannual timescales?

Though we have shown that interannual variations in North African dust can project onto subtropical North Atlantic TS variability, it remains unclear whether dust can influence the spatial structure and magnitude of the coupled Atlantic Meridional Mode, which has been suggested in idealized modeling studies by Evan et al. (2011) and others. Climatological dust burden is highest during June and July over the subtropical North Atlantic (DeFlorio et al., 2014 and others). Therefore, we repeat the MCA calculation shown in Figure 6, but limit the analysis to only July months. We also limit our MCA analysis to north of the equator in an effort to isolate the TS-wind coupled variability most strongly associated with North African dust variations and to limit the influence of the equatorial and South Atlantic regions on the leading modes.

The “July months only” MCA analysis for TS and horizontal winds reveals that interannual variability of dust has a significant impact on the TS spatial loading in the tropical North Atlantic (Figure 8). The correlation coefficients between the leading TS and wind principal components (PCs) for NCEP, CESM interactive, and CESM prescribed are 0.61, 0.66, and 0.81, respectively. The magnitude of this spatial pattern is higher in the CESM simulation with interannually varying dust by a factor of two compared to CESM prescribed (Figure 8, middle and bottom row). Indeed, the TS principal components from the TS/wind MCA analysis are negatively correlated with subtropical North Atlantic dust burden in CESM interactive during both June and July (Figure 9).
However, the observed horizontal wind pattern is poorly simulated in both the CESM interactive and prescribed simulations during July (Figure 8, wind vectors). In particular, strong equatorial horizontal divergence normally associated with the Atlantic Niño appears in both CESM leading modes, but is absent in observations. The meridional component of the horizontal winds over the subtropics is also too weak in the CESM simulations. This is a physical shortcoming of the coupled SST and wind fields in CESM which may explain why the AMM is too weakly represented in CESM (Figures 5-6).

In spite of this, the stark difference in the magnitude of TS MCA spatial loading patterns between CESM interactive, which closely matches observations, and CESM prescribed, which is roughly two times weaker than observations, provides evidence that interannual variability of North African dust not only projects strongly onto tropical-subtropical North Atlantic TS variability, but onto the TS spatial structure of the coupled Atlantic Meridional Mode.

7. Summary and discussion

We use observations and two coupled climate model simulations (with and without interannual variability of dust concentration) to examine the interaction between North African dust fluctuations and interannual variability of tropical Atlantic SST and coupled SST/wind processes.

Our CESM interactive aerosol simulation provides clear evidence that increased dustiness over the tropical North Atlantic decreases co-located SST and increases year-
to-year SST variance, especially during boreal summer. The probability distribution of SST is negatively skewed on the dustiest months over the subtropical North Atlantic; indeed, 64% of the dustiest months are concurrent with negative surface temperature anomalies in this region.

Though the Atlantic Meridional Mode is weaker in both CESM simulations than in observations, analyses confined to boreal summer and the northern hemisphere (when/where dust loading is high over the subtropical North Atlantic) reveal that interannual variability of North African dust projects strongly onto the SST spatial structure in the Northern Hemisphere associated with the AMM. This builds on previous idealized modeling studies (e.g. Evan et al. (2011)) which also found that interannual variability of dust could excite the AMM.

Latent heat flux and surface wind coupling is only an important forcing term for the observed AMM in the northern hemisphere (Figure 7). There is no clear signal in the southern hemisphere of this coupling, which could be due to the fact that the southern hemisphere lobe of the AMM is thought to be independent of the northern hemisphere lobe and can act on different timescales (e.g., Mehta and Delworth, 1995; Enfield et al., 1999). Therefore, the southern hemisphere coupled interactions between latent heat flux and surface wind could be found in a higher order MCA mode not presented in this study.

It is also shown that modeled interannual variability of North African dust can modulate the magnitude of latent heat flux and surface wind coupling over the tropical Atlantic. Indeed, this coupling is much weaker throughout the tropical Atlantic in the prescribed CESM simulation with no interannual variability of dust concentration,
especially in the equatorial and southern hemisphere regions (Figure 7). Although it remains unclear whether this enhanced latent heat flux and wind coupling alone can substantially influence the SST spatial structure and magnitude of the AMM in CESM as defined by the SST/wind coupling, the interactive CESM simulation’s ability to reproduce a strong cross-equatorial flow that is typically associated with interhemispheric SST gradients is an indication that interannual dust variations influence deep tropical WES dynamics.

The AMM and other coupled ocean-atmosphere processes in this region are of vital socioeconomic interest because of their well-documented impacts on surrounding precipitation and tropical cyclogenesis. Consequently, we feel it is critical that future modeling efforts build on the results shown here and focus on understanding and ultimately reducing the strong CMIP5 bias in tropical Atlantic SSTs such that a more realistic representation of coupled ocean atmosphere processes in this region may be obtained. Such efforts could allow for a better representation of the AMM in climate models, and can help better constrain the role of dust forcing in exciting and/or sustaining the AMM.

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FIGURE CAPTION LIST

Figure 1: Dust burden (kg/m²) over central Mauritania (West Africa) in CESM interactive aerosol (top) and prescribed aerosol (bottom) simulations for 50 (left) and 10 (right) year subsets of the 150-year simulation.

Figure 2: Standard deviation of detrended July tropical Atlantic TS monthly anomalies in NCEP/NCAR (top), interactive CESM (middle), and prescribed CESM (bottom).

Figure 3: Probability density function of monthly TS anomalies in interactive CESM over the tropical-subtropical North Atlantic (40°W to 20°W, 10°N to 20°N), on the top 5% dustiest months. 64% of the dustiest months are concurrent with negative surface temperature anomalies in this region.

Figure 4: Leading EOF and associated PC of tropical Atlantic TS monthly anomalies in NCEP/NCAR (top), interactive CESM (middle), and prescribed CESM (bottom). The percentage variance of the total signal explained by each mode is indicated in parentheses. Note the different x-axes for the observed and model PCs.

Figure 5: as in Figure 4, but for second EOF. Note the different x-axes for the observed and model PCs.

Figure 6: Leading maximum covariance analysis (MCA) heterogeneous mode and associated temporal evolution of coupled TS (K) and wind (m/s) variability in NCEP
Figure 7: Leading maximum covariance analysis (MCA) heterogeneous mode and associated temporal evolution of coupled latent heat flux (W/m²) and wind (m/s) variability in NCEP (top row), CESM interactive (middle row), and CESM prescribed (bottom row). The percentage covariance of the total signal explained by each mode is indicated in parentheses. Note the different x-axes for the observed and model PCs.

Figure 8: Leading “July months only” maximum covariance analysis (MCA) heterogeneous mode and associated temporal evolution of coupled TS (K) and wind (m/s) variability in NCEP (top row), CESM interactive (middle row), and CESM prescribed (bottom row). The percentage covariance of the total signal explained by each mode is indicated in parentheses. Note the different x-axes for the observed and model PCs.

Figure 9: Scatterplots of vertically integrated subtropical North Atlantic dust burden anomalies (40°W to 20°W, 10°N to 20°N) and MCA surface temperature (left column) and horizontal wind (right column) principal components during June (top row) and July (bottom row).
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