Exploring the Impact of Dust on North Atlantic Hurricanes in a High-Resolution Climate Model

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Abstract The relationship between African dust and the climatology of tropical cyclones (TCs) in the North Atlantic is explored using the Community Atmosphere Model at a global horizontal resolution of 28 km. A simulation in which the aerosol model is modified to significantly reduce the amount of airborne dust is compared to a standard simulation. The simulation with reduced dust increases TC frequency globally, with the largest increase occurring in the North Atlantic. The increase in TC activity in the North Atlantic is consistent with an environment that is more conducive for the genesis and intensification of storms. TCs are more frequent (27%) and on average significantly longer lived (13%) in the low dust configuration but only slightly stronger (3%). This results in a 57% increase in accumulated cyclone energy per hurricane season on average. This work has implications for projections of future climate and resulting changes in TC activity.

Plain Language Summary Dust from the Sahara desert in Africa can impact hurricane formation and development in the North Atlantic. Carried by the wind over the North Atlantic and around the globe, the dust contributes to dry and stable air that can make it harder for thunderstorms over the ocean to develop into stronger tropical cyclones or hurricanes. In this study, we look at how this effect shows up in a climate model with sufficient resolution to represent hurricanes. After the control experiment (1980–2012), we reduced the amount of airborne dust in the model over the same historical period as a low dust experiment. In the low dust simulation, tropical cyclone frequency increases globally. In the North Atlantic where storms can be impacted directly by African dust, storms become more frequent, longer lived, and slightly stronger, increasing their destructive potential. Understanding how dust interacts with tropical cyclones in climate models will help us understand and prepare for the potential changes in hurricanes of the future.

1. Introduction

High-resolution (Δx < 30 km) climate models are becoming a valuable tool for investigating the potential impacts of climate change on global and regional tropical cyclone (TC) activity. In particular, recent studies have explored the potential influences of a warming climate on global TC activity using general circulation models (GCMs) at such resolutions using prescribed sea surface temperature (SSTs) and have suggested a global decrease in TC frequency in the future under a variety of warming scenarios (Bacmeister et al., 2018; Murakami et al., 2012; Wehner et al., 2015, 2018). The results of these works are consistent with studies that use dynamically downscaled approaches from lower resolutions GCMs (Δx = 50–100 km) to explore future TC activity that also project a decrease in global storm frequency (e.g., Knutson et al., 2015). Similar studies, both global high resolution and downscaled from GCMs, indicated a decrease in the North Atlantic ocean basin as well (e.g., Bacmeister et al., 2018; Knutson et al., 2013), though others suggest an increase in storm activity depending on the model version (Murakami et al., 2012) or downsampling techniques (Emanuel, 2013). It is understood that large uncertainties in the future SST warming patterns complicates future projections of TC activity globally and regionally (Bacmeister et al., 2018; Knutson et al., 2015; Zhao et al., 2009).

Another potential complicating, but less understood, factor impacting future TC activity in the North Atlantic is the potential influences of atmospheric dust on storms in the region. Dunion and Velden (2004)
argued that TC activity in this region could be influenced by a dry, warm layer with dust called the Saharan Air Layer. At times the Saharan Air Layer is advected from Africa over the North Atlantic Ocean (Carlson & Prospero, 1972). Dunion and Velden (2004) hypothesize that the Saharan Air Layer may decrease TC formation or intensity through the inhibition of convection, increased vertical wind shear, and increased atmospheric stabilization through a strengthening of the trade wind inversion. Work by Evan et al. (2006) explored this topic using observations from 1982 to 2005 and found a strong inverse relationship between North Atlantic TC activity and mean dust coverage in the region. This work was corroborated by Wang et al. (2012), which found a similar relationship between dust and TCs using a longer record back to the 1950s. Furthermore, a recent study by Strong et al. (2018) using a coupled GCM at Δx ≈ 50 km also demonstrates a decrease in TC activity in the North Atlantic due to dust. Contrary to these findings, other observational work has suggested that the convection necessary to support TC development can still exist during interactions with the Saharan Air Layer (Braun, 2010) and modeling case studies of individual storms support this to some extent (Centeno Delgado & Chiao, 2015). Finally, modeling work by Bretl et al. (2015) suggests that African dust and the Saharan Air Layer likely have both inhibiting and supporting impacts on the environment in which TCs develop, highlighting the complexity of the TC-dust interaction.

Adding to the complexity of potential changes in North Atlantic TCs, projections of regional wind patterns for northern Africa suggest a decrease in African dust emission in a future climate (Evans et al., 2016). It is proposed that this decrease in dust emissions is related to potential changes in atmospheric circulation patterns in the tropics and that these dust feedbacks may not be represented in current-class climate models. Nonetheless, Evan et al. (2016) hypothesize that decreased dustiness over the North Atlantic would enhance warming of the tropical North Atlantic and therefore enhance TC formation and growth. Globally, anthropogenic aerosols in the atmosphere to date have been shown to cancel increases in potential intensity of TCs due to increases in greenhouse gases (Sobel et al., 2016), suggesting that aerosol impacts on TC activity extend beyond TC-dust interactions. Aerosol impacts on TCs have also been suggested by high-resolution GCM work of Wehner et al. (2018), which noted that the impact of aerosol forcing changes in future climate projections complicates future projections of TC activity.

The goal of this study is to explore this potential impact of African dust on North Atlantic storm formation and intensity using a state-of-the-art, high-resolution GCM. The Community Atmosphere Model, version 5 (CAM5), is configured with a fully prognostic aerosol model, which can be altered to limit the amount of atmospheric dust. In particular, a recent climate control simulation is compared to an additional simulation in which the amount of airborne dust is significantly limited. The difference in the relationship between global TC activity and varying amounts of atmospheric dust, but with a focus on the North Atlantic, is explored. CAM5 has been demonstrated to produce a reasonable distribution of TC activity in the North Atlantic compared to other GCMs (Bacmeister et al., 2014; Shaevitz et al., 2014; Wehner et al., 2014; Zarzycki & Jablonowski, 2014). Relevant details of the model design and experimental setup are provided in section 2. The model simulations are compared and analyzed in section 3, and the implications of this work are explored in section 4.

2. Experimental Design

This work uses CAM5, the atmospheric component model of the Community Earth System Model used for conventional long-term climate simulations (Hurrell et al., 2013), at a TC-permitting, quasi-uniform grid spacing of approximately 28 km globally. CAM5 consists of two main components: the physics parameterization suite and the dynamical core. This study implements the default CAM5 physics parameterizations, which include a fully prognostic Modal Aerosol Model (Easter et al., 2004; Ghan & Easter, 2006) with dust emissions modeled according to Mahowald et al. (2010), that is described in detail in Neale et al. (2012). The parameterization suite is coupled to the spectral element (SE; Dennis et al., 2012; Taylor & Fournier, 2010) dynamical core, which incorporates a fourth-order accurate continuous Galerkin method on a cubed-sphere mesh designed for use in next-generation high-resolution climate models (see Lauritzen et al., 2018, for a more recent documentation). Previous work has demonstrated the ability of CAM5-SE to simulate TCs at 28-km grid spacings in idealized (Reed & Chavas, 2015; Reed et al., 2012; Zarzycki et al., 2014) and more realistic decadal climate (Bacmeister et al., 2018; Reed et al., 2015; Zarzycki & Jablonowski, 2014) configurations. For the purposes of this work, TC detection is performed identically to that in Reed et al. (2015) and Bacmeister et al. (2018) using Zhao et al. (2009) tracking algorithm on 3-hourly instantaneous model output. In section 3 TC observations from the International Best Track Archive for Climate Stewardship (IBTrACS
The CAM5 boundary conditions (SST, sea ice extent, greenhouse gas concentrations, etc.) are configured according to the Atmospheric Model Intercomparison Project (AMIP; Gates et al., 1999) for the time period of 1980 to 2012. Note that the control CAM5 AMIP simulation is identical to that used in Reed et al. (2015) and Bacmeister et al. (2018) and more detailed information on the simulation design and a comparison of the simulation to observations can be found in these studies. In addition to the control AMIP simulation, two additional ensemble members of CAM5 AMIP simulations have been performed as part of the analysis in Bacmeister et al. (2018) and will be used to provide some context of uncertainty. Since the purpose of this study is to explore the impact of airborne African dust on TC formation and development in the North Atlantic region, an additional simulation is performed by modifying the prognostic aerosol formulation to inhibit dust emissions. Consequently, dust erodibility is reduced by over a factor of 3 compared to that in the control simulation, which has the effect of significantly limiting the amount of airborne dust globally. This additional simulation is referred to as AMIP Low Dust and is completed for the same 1980 to 2012 time period as the control AMIP simulation. The result of this alteration in the dust emission factor for the AMIP Low Dust simulation on the climatological average aerosol optical depth (AOD) of dust is shown in Figure 1 and compared to that of the control AMIP simulation. From Figure 1 a large reduction in dust AOD is observed in all major dust emitting regions around the globe, particularly emissions associated with the Sahara desert. The largest reduction over the ocean, where TCs that originate from African easterly waves often develop and track, is over the North Atlantic and thus the focus of this study. Note that dust emission in the AMIP Low Dust simulation is nonzero and there are still small concentrations of airborne dust globally. However, much of this remaining dust is constrained locally to emission sources, and therefore, a comparison of AMIP and AMIP Low Dust simulations offers a unique opportunity to explore dust impacts in the North Atlantic. Moreover, as expected the AMIP simulation better represents the general climatology of observed dust AOD, including over the North Atlantic, compared to the AMIP Low Dust simulation (not shown).

3. Results
3.1. Storm Counts
To quantify the impact that reducing dust has on TC activity in CAM5, we first compare simulated global storm counts. The control AMIP configuration simulates approximately 71.2 storms globally per year from 1980 to 2012, which is noticeably less than the 89.8 storms per year observed during the same time period. Note that the TC climatology and known biases, such as storm frequency, in CAM5 have been explored in detail in other studies (i.e., Bacmeister et al., 2018, 2014; Reed et al., 2015; Wehner et al., 2014) and is not the focus of this work. In AMIP Low Dust, the global number of simulated TCs increases by over 5 to 76.7 storms per year. The global TC counts in the control AMIP and AMIP Low Dust, simulations are different at the significance level of 0.1 using a two-sided Student’s $t$ test. Given that the general simulated CAM5 climate in both AMIP and AMIP Low Dust is very similar in terms of the global energy budget (not shown), this marks a significant increase in TCs globally in the simulation with reduced amounts of airborne dust.

As shown in Figure 1 the North Atlantic is the ocean basin that is most impacted by the reduction in dust emissions. Not surprisingly, this is the ocean basin with the largest increase in TC frequency, about 2.1 more
3.2. Regional Distribution

In order to shed light on the potential relationship of African dust with TC activity in the North Atlantic, Figure 3 compares common indices used to explore the impact of the environment on TC activity to distributions of TC genesis and track densities (defined to be the number of storms to track/form within 5° of a given location every year). To quantify the impact of the environment of TC intensity, we calculate the potential intensity as defined by Bister and Emanuel (2002), and references therein, from monthly average model output and display the average annual maximum potential intensity (first row in Figure 3). The analytical expression of the attainable intensity of a TC in a given thermodynamic environment is derived from a Carnot cycle analog and assumes dissipative heating of the atmosphere, with a ratio of surface exchange coefficients set to 0.7. In our implementation of potential intensity we make an additional adjustment that accounts for the average height of the lowest CAM5 model level throughout the tropics and effectively reduces the wind speed to a 10-m level. Furthermore, we calculate the annual genesis potential index from Emanuel (2010), which combines the monthly average potential intensity and midlevel entropy deficit with the dynamical contributions of absolute vorticity and vertical wind shear to approximate how conducive the average environment is to TC genesis (second row in Figure 3). When compared to the control AMIP simulation, the AMIP Low Dust configuration simulates an increase in both the maximum potential intensity and genesis potential index throughout most of the North Atlantic. This increase in the environmental indices basin wide is matched by an increase in genesis and track density (third and fourth rows in Figure 3, respectively) in the AMIP Low Dust simulation. In particular, the main development region directly off the African coast simulates an increase in TC genesis, as well as the subsequent tracks, which is supported by a general increase in genesis potential and potential intensity in the region.

This analysis provides strong evidence that the increase in TC counts (Figure 2) in the North Atlantic in the AMIP Low Dust simulation is linked to either a modification of the incipient tropical disturbances or changes in the large-scale environment in the region where airborne dust has been greatly reduced (Figure 1). It remains unclear whether the TC-dust interaction that leads to this increase in TC genesis in the simulation with reduced airborne dust simulation is due to direct or indirect effects and is beyond the scope of this study. Understanding the relative role of radiative impacts and aerosol-cloud interactions remains the focus of future research, requiring additional simulations to explore these effects individually, as well as additional high temporal model output of relevant fields (dust concentrations, radiation, microphysical properties, etc.) to augment what is currently archived in standard AMIP simulations.
3.3. Storm Characteristics

The analysis thus far suggests a relationship between simulated airborne African dust in the North Atlantic and TC activity in CAM5, but how does this relationship impact the characteristics of the simulated storms themselves? To explore this question, Figure 4 compares the probability density function of lifetime maximum intensity, duration, and accumulated cyclone energy (ACE; Bell et al., 2000) for all simulated storms in the control AMIP and AMIP Low Dust configurations. Compared to the control simulation, the lifetime maximum intensity distribution in the AMIP Low Dust simulation has shifted toward higher wind speeds, with an average lifetime maximum wind speed that is 1.4 m/s (or ∼3.5%) stronger than in the control AMIP configuration. Note that the median lifetime intensity is over 2.4 m/s stronger, suggesting an increased likelihood of the stronger storms, which is consistent with the increase in potential intensity throughout much of the basin in Figure 3. However, it is important to mention that it is well understood that climate models underestimate the intensity of the most intense storms at horizontal resolutions used here (Davis, 2018). Storm duration in the AMIP Low Dust simulation also shifts toward longer storm lifetimes compared to the control
AMIP simulation. While this shift appears subtle in Figure 4, there is a large increase in the probability of storms lasting longer than 13 days, resulting in an increase of just under a day (or 13%) in the average simulated lifetime of TCs in the AMIP Low Dust configuration. This increase in average lifetime may be linked to the fact that the increase in TC frequency in the AMIP Low Dust simulation is associated with TC genesis in the main development region, including the eastern portion, where TCs can track and develop for many days without moving over cooler waters while curving to the north or moving over land to the west. The differences between the control AMIP and AMIP Low Dust simulation shown Figure 4 are significant at a level of at least 0.1 using the Kolmogorov-Smirnov test, with the difference in ACE significant at the 0.01 level.

ACE quantifies the combined effect of changes in intensity and duration. Given the increase in TC intensity and duration in the AMIP Low Dust simulation, it is no surprise that the distribution of ACE in Figure 4 shows a shift toward higher energy values on a per storm basis. The probability of a simulated storm reaching an ACE over $18 \times 10^4$ kn$^2$ increases significantly in AMIP Low Dust, so much so that the average storm ACE is almost $2.7 \times 10^4$ kn$^2$ larger, or 23%. When the increase in frequency (Figure 2) is taken into account, the CAM5 configuration with reduced dust simulates on average a North Atlantic hurricane seasonal ACE value that is over $51 \times 10^4$ kn$^2$ larger than in the control AMIP simulation. This equates to a 57% increase in annual ACE in simulations where there is less African dust over the North Atlantic region.

4. Conclusions

This work explores the relationship between African dust and TC activity in the North Atlantic through a set of high-resolution CAM5 experiments. In particular, a novel CAM5 simulation in which the aerosol formulation is adjusted to inhibit the emission of dust globally is compared to more conventional AMIP simulations from previous studies (Bacmeister et al., 2018; Reed et al., 2015). In a world in which the amount of airborne dust is significantly reduced, the number of TCs increases globally, with the largest increase occurring in the North Atlantic where airborne dust commonly overspreads large areas of the basin. This increase in TC activity in the North Atlantic is consistent with an environment, as quantified by the potential intensity and genesis potential index, that is more conducive for the genesis and intensification of storms. Analysis shows that the simulated storms in the AMIP Low Dust configuration are on average slightly stronger (3%) and significantly longer lived (13%), which when combined with the increased frequency (27%) in the North Atlantic region results in a substantial increase of 57% in ACE in the basin. Such a large increase in cyclone energy would, on average, increase the destructive potential for any individual storm, as well as hurricane seasons as a whole, in the event of a dramatic reduction in airborne dust over the North Atlantic. Finally, in the North Atlantic the correlation of simulated storm counts with observations is degraded in the AMIP Low Dust configuration, further implying some relationship between airborne African dust activity and TC genesis in the region. However, additional ensemble simulations would be needed for a more detailed investigation of this potential relationship.

This work may have implications for future projections of climate change. As mentioned in section 1, work by Evan et al. (2016) suggests a decrease in African dust emission (albeit of smaller magnitude than our idealized decrease in dust emissions explored in this study) in a future climate. If this is indeed the case, and even in the absence of warming, this may have a nonnegligible effect on TC activity in the North Atlantic,
possibly resulting in more frequent, more intense, and longer-lived storms. While uncertainty in regional projections of SST in climate change projections leads to uncertainty in future changes in TC frequencies and distributions (Bacmeister et al., 2018; Zhao et al., 2009), additional uncertainty in TC activity may exist in dust concentrations over the North Atlantic in the future, especially if important dust feedbacks are not fully incorporated in climate models (as suggested by Evan et al., 2016). This work demonstrates that high-resolution climate models with fully prognostic aerosol models offer a critical scientific tool for exploring TC-dust interactions, both direct and indirect, on decadal time scales. As computing power increases, these modeling tools could be configured to more thoroughly investigate the radiative effects of dust on TC activity, by fully accounting for air-sea interactions, a limitation of this current study as SST is prescribed in AMIP-style simulations. Furthermore, controlled experiments in which the interaction of dust with parameterized convection and microphysics is examined through mechanism denial experiments are now possible in current generation climate models and should be a focus of future research.

References


