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Shallow stratocumulus clouds created below the base of the Saharan Air Layer by the action of Saharan dust

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Abstract

Previous studies showed that, over the global ocean, there is no noticeable hemispheric asymmetry in cloud fraction (CF). This cloud symmetry contributes to the balance in solar radiation reaching the sea surface in the Northern and Southern hemispheres. By contrast, over the tropical Atlantic, the CF hemispheric asymmetry takes place. The tropical Atlantic (30N – 30S) is frequently affected by Saharan dust intrusions. Based on MODIS cloud fraction data during a ten-year study period, we found that these dust intrusions contribute to significant cloud cover up to 0.8 – 0.9 along the Saharan Air Layer (SAL). The area of SAL with significant CF is characterized by limited precipitation, indicating that clouds along the SAL are not developed enough. Meteorological conditions below the temperature inversion at the SAL base include high atmospheric humidity and the presence of large amounts of settling dust particles together with marine aerosols. Being below the temperature inversion and acting as efficient CCN, Saharan dust particles coated with sea-salt contribute to the formation of shallow stratocumulus clouds. Significant cloud fraction under the base of SAL, together with clouds over the Atlantic Inter-tropical Convergence Zone, contributes to the 20% hemispheric CF asymmetry between the tropical North and South Atlantic. Saharan dust is also the major contributor to the pronounced hemispheric aerosol asymmetry over the tropical Atlantic, based on MERRAero aerosol reanalysis data. These two factors could lead to an imbalance in strong solar radiation (which reaches the sea surface between the tropical North and South Atlantic), affecting climate formation in the tropical Atlantic.

Keywords: Shallow stratocumulus clouds; Desert dust; Saharan air layer; Sahara; Atlantic Ocean

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1. Introduction

Tropical oceanic regions accumulate the largest part of incoming solar radiation. Subsequently, oceanic currents redistribute this energy among other parts of the global ocean. Therefore, in the tropical oceanic regions, any factor causing the modulation of solar radiation could affect climate formation not only in these regions, but also in remote parts of the global ocean. Clouds and aerosols are two main factors which are capable of modulating solar energy reaching the sea surface. We chose the tropical Atlantic for our study because this region is characterized by significant Saharan dust intrusions. Our main point is that not only is Saharan dust responsible for the pronounced hemispheric aerosol asymmetry, but it also contributes to significant cloud cover along the Saharan Air Layer (Kishcha et al., 2015). Over the tropical Atlantic in July, along the Saharan Air Layer, MODIS cloud fraction (CF) data showed cloud cover up to 0.8 – 0.9. This cloud fraction along the SAL together with clouds over the Atlantic Inter-tropical Convergence Zone (ITCZ) contributes to the hemispheric CF asymmetry between the tropical North and South Atlantic. This leads to the imbalance in strong solar radiation, which reaches the sea surface between the tropical North and South Atlantic, and, consequently, affects climate formation in the tropical Atlantic.

2. Method

The 10-year NASA GEOS-5 modeled aerosol data set (aka MERRAero) was used in the current study (from July 2002 to June 2012). We used these data in order to estimate the contribution of different aerosol species to hemispheric aerosol asymmetry over the tropical Atlantic Ocean. GEOS-5 includes a module representing atmospheric aerosols such as desert dust; sulfate; sea salt; black carbon and organic carbon aerosols. An important feature of GEOS-5 is including aerosol data assimilation using aerosol optical thickness (AOT) retrieved from MODIS instruments on board the NASA Terra and Aqua satellites. As discussed by Kishcha et al. (2014, 2015), meridional distribution of modeled total AOT and AOT of various aerosol species, zonal averaged over the tropical Atlantic (30^{o}N – 30^{o}S), was used to estimate the contribution of various aerosol species to hemispheric aerosol asymmetry over the tropical Atlantic.

For the purpose of comparing meridional distribution of cloud fraction with that of AOT during the same 10-year period (July 2002 – June 2012), Collection 5.1 of MODIS-Terra L3 monthly daytime cloud fraction (CF) data, with horizontal resolution 1^{o} x 1^{o} was used. Furthermore, to analyse meridional rainfall distribution, the Tropical Rainfall Measuring Mission (TRMM) monthly 0.25° x 0.25° Rainfall Data Product (3B43 Version 7) was used.

3. Results and discussions

The obtained results are described in detail by Kishcha et al. (2014, 2015). Based on MERRAero data, we found that there are strong seasonal variations of hemispheric aerosol asymmetry. Hemispheric aerosol asymmetry is most pronounced during the season from March to July, when large amounts of Saharan dust are transported across the Atlantic. Saharan dust dominates other aerosol species over the tropical North Atlantic (Kishcha et al., 2015, their Fig. 5). Dust AOT, averaged separately over the tropical North Atlantic, is one order of magnitude higher than dust AOT averaged over the tropical South Atlantic (Kishcha et al., 2015). The tropical Atlantic is the only oceanic region, where we have such a pronounced hemispheric asymmetry in desert dust, in accordance with MERRAero aerosol reanalysis data.

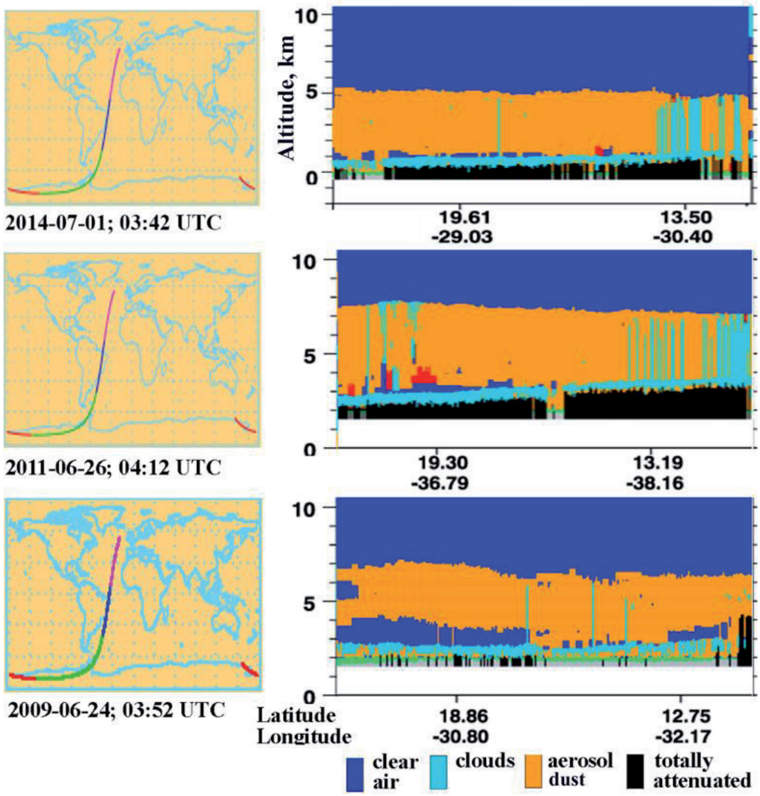

Fig. 1. CALIPSO backscatter measurements of aerosols and clouds in the area of SAL on the following days: (top) July 1, 2014; (centre) June 26, 2011; and (bottom) June 26, 2009

Based on MODIS cloud fraction (CF) data during the ten-year study period, we found that when we have pronounced aerosol asymmetry over the tropical Atlantic, there is hemispheric asymmetry in cloud fraction as well. In the summer months (when pronounced hemispheric dust asymmetry was observed), MODIS CF data showed significant CF (up to 0.8) to the north from the main CF maximum, over the latitudes of transatlantic dust transport within the Saharan Air Layer (SAL). This significant CF to the north of the Atlantic ITCZ is associated with the maximum in dust AOT over the latitudes of the Saharan Air Layer (SAL), between approximately 12^{o}N and 24^{o}N in the North Atlantic (Kishcha et al., 2015, their Fig. 7). In July, CF averaged separately over the tropical North Atlantic is 20% larger than CF averaged over the tropical South Atlantic. Therefore, over the tropical Atlantic, hemispheric asymmetry in aerosols is accompanied by hemispheric asymmetry in cloud cover, in contrast to the situation over the global ocean (Kishcha et al., 2009). The significant cloud fraction along SAL, together with clouds over the Atlantic ITCZ, contributes to hemispheric asymmetry in CF over the tropical Atlantic.

We showed that the area of SAL with significant CF is characterized by limited precipitation, indicating that clouds along the SAL are not developed enough (Kishcha et al., 2015, their Fig. 8). The temperature inversion below the SAL base prevents deep cloud formation; this explains limited precipitation in these zones. On the other hand, meteorological conditions below the temperature inversion at the SAL base include significant atmospheric humidity and the presence of large amounts of settling dust particles together with marine aerosols. As known, aerosol species often combine to form mixed particles, with properties different from those of their components (Andreae et al., 2009). Mineral dust particles are known to be not very efficient cloud condensation nuclei (CCN), unless they are coated with soluble materials (Andreae et al., 2009). Using airplane measurements, Levin et al. (2005) showed that dust transport over the sea could lead to sea-salt coating on dust particles. Coating settling dust particles with sea-salt could modify them into efficient CCN. Being below the temperature inversion and acting as efficient CCN, Saharan dust particles coated with sea-salt contribute to the formation of shallow stratocumulus clouds. This physical mechanism, based on the influence of Saharan dust on stratocumulus clouds below the temperature inversion, could explain the observed significant cloud cover (CF up to 0.8 – 0.9) along the Saharan Air Layer (Kishcha et al., 2015).

Using CALIPSO satellite measurements, Fig. 1 represents examples of the above-mentioned shallow stratocumulus clouds below the SAL base. One can see dust within the SAL layer between 1 km and 5 km altitude (in light brown), and the presence of stratocumulus clouds (in light blue) below the dust layer. The depth of the cloud layer is approximately several hundred meters, indicating that the clouds are very shallow and incapable of producing significant precipitation.

We analyzed possible relationships between properties of clouds in the area of SAL and those of Saharan dust, using MODIS L3 gridded monthly data (1^{o} x 1^{o}) of the effective radius of cloud droplets for liquid water clouds. We found that the effective radius of cloud droplets increases with distance from the Sahara (Kishcha et al., 2015, their Fig. 11). This can be explained by the decrease in CCN numbers associated with the decreasing numbers of settling Saharan dust particles with distance from the Sahara, in accordance with the observed decrease in dust AOT. This relationship supports the above-mentioned physical mechanism of cloud formation below the SAL's base.

4. Conclusions

- The tropical Atlantic is the oceanic region with the most pronounced hemispheric dust asymmetry, in accordance with MERRAero aerosol reanalysis data;
- Over the Atlantic Ocean, Saharan dust intrusions contribute to significant cloud fraction under the base of the Saharan Air Layer;
- Below the temperature inversion at the SAL's base, the presence of large amounts of settling dust particles, covered with sea-salt, produces meteorological conditions favourable for the formation of shallow stratocumulus clouds;
- The significant cloudiness in the area of SAL, together with clouds over the Atlantic intertropical convergence zone, contributes to hemispheric asymmetry in cloud cover over the tropical Atlantic. This could lead to the imbalance in surface solar radiation between the tropical North and South Atlantic.

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