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On the influence of cloud fraction diurnal cycle and sub-grid cloud optical thickness variability on all-sky direct aerosol radiative forcing

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ABSTRACT

The objective of this study is to understand how cloud fraction diurnal cycle and sub-grid cloud optical thickness variability influence the all-sky direct aerosol radiative forcing (DARF). We focus on the southeast Atlantic region where transported smoke is often observed above low-level water clouds during burning seasons. We use the CALIOP observations to derive the optical properties of aerosols. We developed two diurnal cloud fraction variation models. One is based on sinusoidal fitting of MODIS observations from Terra and Aqua satellites. The other is based on high-temporal frequency diurnal cloud fraction observations from SEVIRI on board of geostationary satellite. Both models indicate a strong cloud fraction diurnal cycle over the southeast Atlantic region. Sensitivity studies indicate that using a constant cloud fraction corresponding to Aqua local equatorial crossing time (1:30 PM) generally leads to an underestimated (less positive) diurnal mean DARF even if solar diurnal variation is considered. Using cloud fraction corresponding to Terra local equatorial crossing time (10:30 AM) generally leads overestimation. The biases are a typically around 10–20%, but up to more than 50%.

The influence of sub-grid cloud optical thickness variability on DARF is studied utilizing the cloud optical thickness histogram available in MODIS Level-3 daily data. Similar to previous studies, we found the above-cloud smoke in the southeast Atlantic region has a strong warming effect at the top of the atmosphere. However, because of the plane-parallel albedo bias the warming effect of above-cloud smoke could be significantly overestimated if the grid-mean, instead of the full histogram, of cloud optical thickness is used in the computation. This bias generally increases with increasing above-cloud aerosol optical thickness and sub-grid cloud optical thickness inhomogeneity. Our results suggest that the cloud diurnal cycle and sub-grid cloud variability are important factors to be accounted for in the studies of all-sky DARF.

1. Introduction

Over the last decade, significant advances have been made in quantifying the direct aerosol radiative forcing (DARF) under clear-sky (i.e., cloud-free) conditions based on satellite remote sensing observations [1] and model simulations [2]. In contrast, DARF under cloudy conditions remain poorly understood [2]. One of the important reasons for this is because conventional satellite-based remote sensing methods, in particular those based on passive sensors, can provide aerosol property retrievals only under cloud-free conditions. As a result, there has been a lack of observational constraints on model simulations of cloudy-sky DARF. Recently, the global observations

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from the space-born lidar Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission have greatly improved our knowledge of the vertical distribution of aerosols and clouds, in particular the occurrence of above-cloud aerosols (ACA), and thus has opened a new avenue for studying the cloudy-sky DARF [3–5]. In addition to CALIOP observation, attempts have also been made recently to detect ACAs and retrieve their properties using passive imagers. Waquet et al. [6] developed a method based on multi-angular, polarization measurements from Polarization and Directionality of the Earth Reflectances (POLDER) to retrieve the aerosol optical thickness (AOT) of above-cloud smoke. This method has recently been extended to include both smoke and dust aerosols [7]. Most recently, Torres et al. [8] developed an algorithm to retrieve the AOT of ACA using Ozone Monitoring Instrument (OMI) on board of Aura satellite. Jethva et al. [9] demonstrated a color ratio method to retrieve the above-cloud AOT based on MODIS multiple spectral cloud reflectance measurements. A review of the emerging satellite-based observations of ACA can be found in Yu and Zhang [10]. These novel techniques based on passive sensors will provide a revealing perspective on ACA complementary to CALIOP. In particular, the global above-cloud aerosol retrievals from POLDER [11] will soon become publically available (Waquet 2013, personal communication). These new datasets will provide us more opportunities for comparison and evaluation studies like [12] to understand the accuracy and limitations of each method.

Using multiple years of CALIOP observations, Devasthale and Thomas [4] located several geographical regions where elevated aerosols are often found above low-level liquid phase clouds. For example, during the austral winter and spring light-absorbing smoke aerosols originating from seasonal burning of the southwestern African Savannah are often observed over the bright stratocumulus decks over southeast Atlantic. In contrast to cloud-free DARF that generally has a cooling effect at the top of the atmosphere (TOA), above-cloud smoke can have a strong warming effect at TOA because the bright cloud layer beneath significantly enhances smoke absorption [13–15]. In addition to DARF, above-cloud aerosols can also have semi-direct effects on the clouds beneath [16,17]. For these reasons, above-cloud smoke in the southeast Atlantic has attracted increasing attention recently.

The CALIOP ACA property retrievals have been used in several recent studies in combination with cloud products from Moderate Resolution Imaging Spectroradiometer (MODIS) to derive the DARF of above-cloud light-absorbing aerosols in southeast Atlantic region with radiative transfer simulations [15,18,19]. In Chand et al. [15], the CALIOP level-2 above-cloud AOT retrievals [20] and the MODIS monthly mean cloud optical thickness (COT) from the MODIS monthly level-3 product ($1^{\circ}\times 1^{\circ}$ resolution) were both aggregated to $5^{\circ}\times 5^{\circ}$ resolution and then used to compute the DARF of above-cloud smoke. A major point made in this study is that the all-sky TOA DARF is strongly modulated by the underlying cloud fraction as a result of the dramatic difference between the clear-sky DARF (generally negative) and the DARF of ACA (strongly positive). Based on a similar methodology as in Chand et al. [15], Oikawa et al. [18] used the MODIS level-3 monthly mean COT and aggregated CALIOP ACA retrievals to derive the all-sky DARF and compared the results with model simulations from a GCM. These recent studies have shed light on the important and unique role of ACA in the climate system and clearly demonstrated the usefulness of satellite remote sensing data; in particular, CALIOP data, for estimating ACA DARF. However, these studies have a common limitation in that they use coarse resolution monthly mean data in their computation, which obscures the influence of cloud diurnal cycle and sub-grid spatial variability on all-sky DARF.

It is well known that marine boundary layer (MBL) clouds, such as those over southeast Atlantic, have a strong diurnal cycle driven largely by cloud solar absorption [21–23]. Wood et al. [22] found that the diurnal amplitudes of the liquid water path (LWP) in low cloud regions to the west of continents (e.g., southeast Atlantic and southeast Pacific stratocumulus decks) are typically 15–35% fraction of the diurnal mean. In this study, we developed two diurnal cloud fraction variation models (see Section 3 for details). One is based on sinusoidal fitting of MODIS observations from Terra (10:30 AM local equatorial crossing time) and Aqua (1:30 PM local equatorial crossing time) satellites. The other is based on high-temporal frequency diurnal cloud fraction observations from SEVIRI (Spinning Enhanced Visible and Infrared Imager) on board of geostationary satellite. Both models indicate a strong cloud fraction diurnal cycle over the southeast Atlantic region. In both Chand et al. [15] and Oikawa et al. [18], as well as most previous studies [5,19,24], the cloud property used in ACA DARF computations were from retrievals based on polar-orbiting satellites (e.g., Terra or Aqua MODIS), which provide only an instantaneous snapshot of the cloud field at the local crossing time. As a result, the strong diurnal cycle of MBL clouds is not accounted for in these studies, which as shown later in this study could cause significant bias in diurnal mean DARF computation. MBL clouds are also known to have significant small-scale heterogeneity [25–27]. It is well known that using the grid mean COT to estimate the shortwave radiative effects of clouds with horizontal heterogeneity can lead to significant bias, an effect known as the “plane-parallel albedo bias” [27–29]. Note that several of the above-motioned studies have used the coarse resolution grid-mean COT in ACA DARF computation (e.g., $5^{\circ}\times 5^{\circ}$ resolution as in Chand et al. [15]). The potential impact of plane-parallel albedo bias on these studies remains unknown.

The objective of the present investigation is to study the influence of the temporal (i.e., diurnal cycle) and spatial variability (i.e., sub-grid heterogeneity) of clouds on the estimate of all-sky ACA DARF. Here we will focus on the southeast Atlantic region where light-absorbing aerosols are often found above low-level MBL clouds. We will first briefly introduce the CALIOP, MODIS and SEVIRI products used in this study in Section 2. In Section 3, we present a study of how cloud fraction diurnal cycle influences the all-sky ACA DARF computation. In Section 4, we present a study of how sub-grid heterogeneity