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Asian and trans-Pacific Dust: A multi-model and multi-remote sensing observation analysis

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Key points:

- Dust and total aerosol over Asia and the North Pacific Ocean are evaluated using observations and models.

- Satellites estimate that a 35-70 % decrease of DOD from the west Pacific to the east Pacific.

- Diversity of DOD is mostly driven by the diversity of the dust source followed by residence time and mass extinction efficiency.

Abstract

Dust is one of the dominant aerosol types over Asia and the North Pacific Ocean, but quantitative estimation of dust distribution and its contribution to the total regional aerosol load from observations is challenging due to the presence of significant anthropogenic and natural aerosols and the frequent influence of clouds over the region. This study presents the dust aerosol distributions over Asia and the North Pacific using simulations from five global models that participated in the AeroCom phase II model experiments, and from multiple satellite remote-sensing and ground-based measurements of total aerosol optical depth (AOD) and dust optical depth (DOD). We examine various aspects of aerosol and dust presence in our study domain: (1) the horizontal distribution, (2) the longitudinal gradient during trans-Pacific transport, (3) seasonal variations, (4) vertical profiles, and (5) model-simulated dust life cycles. This study reveals that the diversity of DOD is mostly driven by the diversity of the dust source followed by residence time and mass extinction efficiency.

1. Introduction

Dust aerosol can impact the Earth's weather, climate, and eco-systems by interacting with solar and terrestrial radiation, altering cloud amount and radiative properties, fertilizing land and ocean, and modulating carbon uptake (Haywood et al., 2003; Jickells et al., 2005; Forster et al., 2007; Evan et al., 2008; Kim et al., 2010; Maher et al., 2010; Creamean et al., 2013; Yu et al., 2015a; Song et al., 2018). The majority of global dust sources are from arid surfaces such as North Africa, the Middle East, and parts of Asia, and to a lesser extent Australia and Patagonia (e.g., Tegan et al., 2002; Prospero et al., 2002; Huneeus et al., 2011; Ginoux et al., 2012).

Although dust emission from Asia is estimated as only 25~35% of that from North Africa (Chin et al., 2007; Su and Toon, 2011; Ginoux et al., 2012), it is a dominant source of dust not only over the land areas of Asia. Asian dust is also significant over the North Pacific Ocean, western North America, and the Arctic (e.g., Chin et al., 2007) via long-range transport, playing a key role in the climate and eco-system in these regions (Uno et al., 2009; Shao et al., 2011; Yu et al., 2012). Observation-based estimates of dust amount based on multiple years of satellite AOD data from the Moderate Resolution Imaging Spectro-radiometer (MODIS) suggest that about 140 Tg (1 Tg = 10^6 tons) of dust are exported from East Asia; among which 56 Tg (40%) reach the west coast of North America, and the remaining 84 Tg are deposited in the North Pacific and/or are transported to the Arctic (Yu et al., 2012). Dust is more efficiently transported across the North Pacific Ocean (40%) than other continental aerosols (25%) (Yu et al., 2008) due to the higher elevation of dust layers (Yu et al., 2010, 2012). The satellite-based estimate of trans-Pacific dust transport and deposition differs significantly from those estimated from in-situ measurements and simulated by models, as summarized in Yu et al. (2013).

On the other hand, previous modeling studies of dust outflow from Asia and deposition to the North Pacific have shown different results. A study with the Northern Aerosol Regional Climate Model estimated that out of 120 Tg of dust (< 41 μm in diameter) emitted from Asia in Springtime, 31 Tg (26%) is exported from Asia to the Pacific Ocean and only 4 Tg (13%) of the exported dust reaches North America (Zhao et al., 2006). An inter-model comparison study with eight regional dust emission/transport models demonstrated that participating dust models differ by a wide range over Asia, from emission to surface concentration, horizontal distribution, and vertical profiles during long-range transport (Uno et al., 2006). They suggested that measurements of dust fluxes and accurate, up-to-date land-use information are crucial to achieve more realistic simulations over these regions. Dust simulated from global models have also been extensively compared in the past AeroCom studies (Kinne et al., 2006; Huneeus et al., 2011; Koffi et al., 2012, 2016; Kim et al., 2014), but none of them specifically devoted to assessing model performance in the Asian-Pacific region, partially due to the lack of reliable data over this region. For example, Huneeus et al. (2011) pointed out that a specific Asian dust data set is needed to evaluate the global dust models, and suggested that one way to assess the performance of global dust models over Asia would be to compare measurements of coarse-mode AOD against modeled ones. However, extracting dust data from satellite observations in the Asian-Pacific region is challenging because of the frequent cloud occurrence in the North Pacific and the large amount of pollution aerosol over the Asian continent. Wu et al. (2019) showed that different dust retrieval algorithms based on the CALIOP observations yield significant differences in the dust vertical distribution, which complicates the evaluation of model simulations.

With the recent development of methods to derive satellite-based dust vertical profiles and transport flux estimates based on the CALIOP and MODIS data (Ginoux et al., 2012; Yu et al., 2015a, b; Yu et al., 2019a, 2019b), we present in this paper an evaluation of multiple, global model dust simulations in the Asian-Pacific region from the AeroCom Phase II (AeroCom II) Hindcast model experiment with multiple satellite observations. We also examine several key physical and optical model parameters in order to explain discrepancies between observations and models, and among the models. We use an approach similar to our previous study (Kim et al., 2014), that evaluated AeroCom II model-simulated dust with updated satellite observations in the African-North Atlantic region, and addressed the key processes causing model diversity and deficiency.

In section 2, we briefly describe the AeroCom II Hindcast model simulations and the satellite- and ground-based remote-sensing data. In section 3, we compare the observed and modeled total aerosol and dust aerosol optical depths, including their longitudinal gradients and vertical distributions. In section 4, we investigate details of the dust life cycle in the models, and we compare results from the present study with those of North Africa. Discussion is presented in section 5, followed by a summary in section 6.

2. Models and data

2.1 AeroCom models

AeroCom is an internationally coordinated effort to advance the understanding of atmospheric aerosols and to document and diagnose differences between models and between models and observations (http://aerocom.met.no). The AeroCom II Hindcast experiments produced multi-year simulations from 1980 to 2007, but models cover different simulation lengths. Following Kim et al. (2014), we use the five AeroCom models that provided dust simulations and diagnostics over the time period 2000-2005. The model setup and configurations are highly model-dependent, for example, with horizontal resolution from 1.1° in SPRINTARS to 2.8° in ECHAM5 (Table 1). Vertical coordinates range from 30 layers in GOCARTv4 (hereafter GOCART) to 56 in

SPRINTARS. The meteorology fields that drive dust emissions and transport are taken from three reanalysis products, namely NCEP (used by SPRINTARS and GISS-E2-OMA, formerly known as GISS-modelE and hereafter as GISS), ECMWF (used by HadGEM2 and ECHAM5-HAMMOZ, hereafter ECHAM5), and GEOS4 (used by GOCART). Some models use 10-m wind for dust mobilization parameterization (GOCART, GISS, and SPRINTARS), whereas others use friction velocity (u^*) (ECHAM5 and HadGEM2). Dust density values are similar among the models, ranging from 2.5 to 2.65 g cm^{-3}. The range of dust size and the number of size groups are different among models (Table 1). GOCART and SPRINTARS has the same size range (0.1-10 μm in radius) but different size bins (5 and 6, respectively), GISS includes more extended particle sizes (0.1-16 μm) with 5 size bins, and HadGEM2 covers a wider range of dust particle sizes (0.03-31.6 μm) in 6 size bins. By contrast, ECHAM5 includes only sub-micron particles, in 2 modes ranging from 0.05 to 0.5 μm. The differences in size distribution affect total dust mass amount included in emission, transport, deposition fluxes, mass loading, and overall lifetime, as well as the average mass extinction efficiency that converts mass to light-extinction in different models.

Participating models commonly have two dry removal processes of 1) gravitational settling as a function of aerosol particle size and air viscosity (Fuchs, 1964) and 2) surface deposition as a function of surface type and meteorological conditions (Wesely 1989). Wet scavenging removal in each model is empirically parameterized with the precipitation rate and the scavenging coefficient; thus, a wide range of scavenging coefficients are found among the models. Both GOCART and GISS have similar wet scavenging parameterizations based on the previous work (Giorgi and Chameides 1986;

Balkanski et al., 1993), where Balkanski et al. (1993) adopted a 50% aerosol scavenging efficiency in shallow convection and a 100% scavenging efficiency in deep convection. SPRINTARS uses a size dependent collision efficiency with raindrops (Equation A6 in Takemura et al., 2000); HadGEM2 uses a particle-size-dependent scavenging coefficient (2×10^{-5} for <0.3 μm ~ 4×10^{-4} for >3.16 μm) (Table 1 in Woodward, 2001); ECHAM5 has a scavenging parameter in the range of 0.1~0.9, depending on cloud type (stratiform or convective cloud), or cloud status (liquid, mixed, or ice cloud), and mixing status (Table 3 in Stier et al., 2005).

Overall, dry and wet deposition efficiencies are highly empirical, and depend on the vegetation type, surface conditions, atmospheric stability, particle sizes, and meteorological fields. The model diversity in deposition processes is found from the differences in the spatial distributions of LF and f_{WET} (Figure 10) between models. The differences in size range also affect model diversity in many dust-associated fields, including net emission amount, dry deposition, and DOD.

We compare several monthly mean fields from the model output with remote sensing data or observation-derived quantities, namely the total aerosol optical depth (AOD), dust aerosol optical depth (DOD), and the vertical extinction profiles of total and dust aerosols (σ_{aer} and σ_{du}, respectively, in km^{-1}). Since the dust vertical extinction profiles from the models were not available in the AeroCom archive, they are constructed from the model-calculated dust mass concentrations and the mass extinction coefficient, assuming dust does not take up water vapor, such that DOD does not depend on the ambient relative humidity. The dust mass extinction coefficient is obtained by dividing model calculated DOD with dust mass loading. In addition, model-calculated dust mass loading (LOAD), emission (EMI), dry deposition (DRY), wet deposition (WET), and total precipitation are used to assess possible causes of the inter-model diversity.

When comparing with satellite retrievals and AERONET observations that are available only under clear-sky conditions, it is desirable to use the modeled AOD for clear-sky as well. However, only the GISS model provides such output (other models just provide all-sky results). A previous study showed that clear-sky AOD from the GISS model is 30% lower than all-sky AOD over the North Africa-Northern Atlantic region (Kim et al., 2014). In another estimate based on the GEOS-Chem model, clear-sky AOD is 20% lower than all-sky AOD on global average (Yu et al., 2012). DOD is not sensitive to differences between clear-sky and all-sky conditions due to the hydrophobic nature of dust (Kim et al., 2014), although the different averaging times between all-sky and clear-sky conditions are also expected to produce different AOD values. DOD in ECHAM5 is approximated from the dust volume-weighted AOD of two internally mixed modes where dust is present (Stier et al., 2005). The internal mixing of dust has the potential to cause additional differences between ECHAM5 and other models in the inter-model comparison. Although some models do not consider the chemistry on dust surfaces, previous studies have estimated that the enhanced hygroscopicity of dust by heterogeneous mixing can reduce the global dust burden on 17%~28% in GISS (Bauer and Koch, 2005) and 5% in ECHAM5 (Pozzoli et al., 2008).

2.2 Remote sensing data

2.2.1. Vertical profiles

To evaluate the vertical distribution of dust, we use the aerosol and dust extinction profiles from CALIOP at 532 nm, following the method developed by Yu et al. (2015b). As CALIOP data are only available after June 2006, we use the monthly CALIOP data averaged from 2007 to 2011. The difference of time periods between CALIOP and model simulations may cause some vertical profile differences; however, its effect is not expected to be significant, as the climatological data is averaged over a large domain for a long time. Mean extinction profiles of total and dust aerosol are derived from version 4.10 CALIOP Level 2 aerosol profile data with a nominal along-track resolution of 5 km and vertical resolution of 30 m.

The first step is to collect quality-assured aerosol extinction profile data. Here, we use cloud-free nighttime CALIOP data to minimize interference from clouds and sun, and select extinction profiles with good retrieval quality, i.e., QC flag of 0, 1, 16, or 18, following recommendations by Winker et al. (2013). We then separate aerosol from clouds according to the cloud-aerosol-discrimination (CAD) scores, for which the aerosol scores are typically in the range of -100 to -20 (Winker et al., 2013; Tackett et al., 2018). However, in this study we choose a more stringent CAD-score range of -100 to -70 when selecting aerosol data (Yu et al., 2019a), which provides greater confidence in excluding possible cloud contamination. Compared to the relatively relaxed criteria of CAD between -100 and -20, the total aerosol sampling is reduced by up to 15% with our stricter criteria (Figure S1).

The dust fraction for backscatter in each profile is calculated using the CALIOP observed particulate depolarization ratio (dp), as coarse, non-spherical dust particles produce a depolarization signal. The maximum threshold value ($dp > 0.2$) and the dp of non-dust particles is assumed to be 0.02 (Hayasaka et al., 2007, Tesche et al., 2009, and Yu et al., 2012, 2015b, 2019a). A constant lidar ratio value of 44 sr^{-1} (Omar et al., 2010; Young et al., 2018) is used to convert dust backscatter to dust extinction at 532 nm. We calculate the average vertical extinction profile using all the individual profiles during a month within the 2° in latitude × 5° in longitude grid. All averaged total and dust aerosol profiles are at 60-m vertical resolution.

Aerosol extinction is retrieved only where aerosol is detected by the CALIOP feature finder. However, in reality aerosol is present virtually everywhere throughout the troposphere, although aerosol concentration can be very low in pristine oceanic regions. When the aerosol signal is weak, below CALIOP detection limit, no feature is detected in the level 2 atmospheric sounding, and the sample is classified as "clear-air." Aerosol extinction is set to zero (km^{-1}) in the level 3 algorithm, whereas several studies have sought to characterize the optical depth of aerosol layers undetected by CALIOP (Tackett et al. (2018) and references therein). For data identified as "clear-air" in the present comparison, we adopt the approach used in generating the standard level-3 product (Tackett et al., 2018). However, this could cause a low bias in the averaged data because aerosols at low concentrations are missing, especially over the Pacific Ocean. This may also introduce a difference in the shape of aerosol profile because CALIOP tends to detect "clear-air" more often in free troposphere than in the atmospheric boundary layer. In addition to the level 3 algorithm method, we further average the vertical profiles, but excluding "clear-air" data from the averages, which we could expect to represent an upper bound on the profile data. The results are discussed in section 5.

2.2.2. AOD and DOD

The observational datasets used to evaluate the model simulations are listed in Table 2. Seasonal and spatial distributions of AOD are taken from the Moderate Resolution Imaging Spectroradiometer (MODIS) at 550 nm and the Multiangle Imaging SpectroRadiometer (MISR, version V22) at 555 nm on board the EOS-Terra satellite. The merged MODIS dataset used here is the Collection 6 version with combined retrieval results from the Dark Target and Deep Blue algorithms (Levy et al., 2013). Whereas the Dark Target algorithm provides observations over ocean, the Deep Blue algorithm provides observations over bright land and desert scenes using the deep-blue wavelengths (i.e., 0.41 and 0.47 μm).

MODIS AOD over ocean and fine-mode fraction (f) measurements have been used to empirically separate dust (du) AOD from that of combustion aerosol (co) and marine aerosol (ma) in a self-consistent way (Kaufman et al., 2005; Yu et al., 2009, 2019b). Given that $\tau = \tau_{ma} + \tau_{du} + \tau_{co}$ and $f = [f_{ma}\tau_{ma} + f_{du}\tau_{du} + f_{co}\tau_{co}]/\tau$, dust optical depth ($\tau_{du}$ or DOD) is derived from the MODIS Collection 6 data using representative values for f_{ma}, f_{du}, f_{co}, and τ_{ma} (Yu et al., 2019b). Although large spatial and temporal variability of f_{ma} is accounted for following a method in Yu et al. (2009), we assume constant values for f_{du} and f_{co} because of lack of observational constraints. In this study, marine AOD is parameterized as a function of surface wind speed derived from previous studies (Yu et al., 2019b). A detailed description of the method, including uncertainty estimates and assumptions, can be found in the literature (Yu et al., 2009 and 2019b). DOD over land is also derived from MODIS Collection 6 data but with an approach different than ocean, because MODIS fine-mode fraction retrieval over land is less reliable. Over land, DOD is extracted from the MODIS Deep Blue (MDB) datasets, based on 1) the co-function of the continuous angstrom exponent values derived by Anderson et al. (2005), 2) single scattering albedo ω at 412 nm less than 1, and 3) a positive difference of ω between 412 and 670 nm ($\omega_{670} - \omega_{412} > 0$) (Ginoux et al., 2012; Pu and Ginoux, 2016).

Similar to our previous study of transatlantic dust (Kim et al., 2014; Guo et al., 2013), we use MISR AOD over land and ocean, and the non-spherical AOD over ocean, as a proxy for DOD (Kalashnikova and Kahn, 2006; Kahn et al., 2010). Non-spherical AOD is generally of higher quality over ocean for MISR, due to uncertainties in accounting for the brighter and more varying land surface (Kahn and Gaitley, 2015). However, the frequent interference by clouds, especially thin cirrus, contributes to the AOD and the non-spherical AOD uncertainties over the study region (Pierce et al., 2010). Note also that for both MODIS and MISR, sensitivity to the particle-property proxies used to identify the dust component diminishes when the total mid-visible AOD falls below about 0.15 or 0.2. The resulting uncertainty probably contributes significantly to the differences in MODIS and MISR DOD presented in the section 3 below, especially in the low-AOD areas over ocean.

CALIOP monthly AOD and DOD is calculated by vertically integrating the total and dust aerosol extinction coefficient profile at 532 nm, respectively, as described in the previous section.

We also use total AOD and coarse-mode AOD at 550 nm (Version 2, Level 1.5 and 2) from ground-based AErosol RObotic NETwork (AERONET) (Holben et al., 1998) sites located within the study domain to evaluate both satellite measurements and model simulations, although not all coarse-mode aerosols are dust, and some dust is in the fine-mode. Twenty-nine AERONET sites were chosen, to allow enough geographical coverage across the study region (see Table S1 for the latitude and longitude coordinates of these sites). However, AERONET data are rather limited over the ocean in our study domain and time period, as only two remote AERONET sites, in Midway and Hawaii, are available in the northern Pacific, and the AERONET-coordinated Maritime Aerosol Network (MAN, http://aeronet.gsfc.nasa.gov/new_web/man_data.html) data are not available in the Pacific during the study period.

All the model-data comparisons are performed on a monthly, seasonal, or multi-year average basis. This approach may introduce some differences between satellite data and model results because of location and time mis-matches; however, given the large amount of data in our expansive domain over a six-year time span, it should not affect our statistics and conclusions, as shown in several previous evaluation studies (e.g., Chin et al., 2007, 2014; Colarco et al., 2010; Randles et al., 2017). Also, additional caution is needed when comparing remote-sensing-derived and modeled DOD and dust extinction profiles, as the dust data from remote sensing are either dust proxies, or are obtained with several assumptions, and are thus subject to large uncertainties.

3. Evaluation and comparisons of model simulations with observations

In this section, we evaluate the model results with satellite and ground-based remote sensing data by comparing (i) the mean AOD and DOD in the study domain; (ii) the longitudinal gradient of AOD and DOD from the dust source region in East Asia to the downwind areas in the Pacific; (iii) the seasonal variations of AOD and DOD; and (iv) the vertical profiles of aerosol and dust over land and ocean. The results are summarized in Tables 3 and 4. A study domain (60°E~120°W; 10°N~70°N) was chosen to cover dust source regions in Asia and the trans-Pacific transport route. We divide the study area into land (60°E-140°E; 20°N-60°N) and ocean (140°E-140°W; 20°N-60°N) regions and define six sub-domains for vertical profile analysis. Detailed domain information is provided in Figure 1.

3.1 Mean AOD and DOD

Figure 2 shows a comparison between satellite observations and model simulations of the 6-year mean total AOD averaged from 2000 to 2005, with AERONET AODs at 29 sites superimposed using the same color scale. MODIS and MISR agree within 15 % over the study domain (average AOD = 0.226 and 0.194, respectively), with larger difference over land (0.274 and 0.209) than over ocean (0.177 and 0.179) (Table 3). These results reflect the known behavior of the MISR and MODIS products (e.g., Kahn et al., 2009). On the other hand, the CALIOP AOD is significantly lower than MODIS (47 % lower over ocean and 21 % lower over land compared to MODIS), which is also shown in previous studies (Redemann et al., 2012; Kim et al., 2013). There are a few known factors that contribute to the uncertainty of CALIOP AOD over the study domain, including the underestimation of aerosol extinction in the upper troposphere due to the detection limit (Winker et al., 2013), and the narrow lidar swath that may miss some episodic aerosol plumes (Yu et al., 2013).

The satellites and AERONET show high annual mean AOD (>0.4) over East China and the Indo-Gangetic Plain, which are known to be highly polluted regions. Models capture the geographical pattern of the AOD distribution from the satellites, i.e., the higher AOD over polluted regions, the decreasing gradient over ocean from west to east, and northward shifting of the AOD plume center toward the eastern Pacific. Satellite AOD better agrees with AERONET and gives better statistics, showing higher correlation and lower bias than the models (Figure S2). The multi-year domain-averaged AOD from the models differs within 50%, ranging from 0.16 (SPRINTARS) to 0.20 (GOCART) (20%) over the entire domain, 0.18 (ECHAM5) to 0.25 (GOCART) (24%) over land, and 0.11 (SPRINTARS) to 0.19 (GISS) (42%) over ocean.

For dust, satellite-derived DOD is available from MODIS and CALIOP over both land and ocean and MISR only over ocean (Figure 3). Both MODIS and CALIOP products show substantial dust presence (DOD>0.2) over the land source regions of Taklimakan desert, Thar desert, Gobi desert, and Loess Plateau, and the areas immediately downwind. The MODIS and CALIOP DOD values (0.11 and 0.09, respectively) over land are supported by the coarse-mode AOD (proxy for DOD) from AERONET. Over ocean, all satellite data show transported DOD plumes over the northwestern Pacific (i.e., east of 150°W; 30°N-50°N), but the magnitude from CALIOP is much lower than MODIS and MISR. On average, DOD over ocean from CALIOP (0.027) is 54% and 50% lower than that from MODIS (0.059) and MISR (0.054), respectively. The average dust fractions of mid-visible AOD from MODIS and CALIOP are about 36 and 42 % over land and 30 and 29 % over ocean, respectively.

Compared to the relatively small difference (~20%) of average AOD among models (AOD = 0.16-0.20), the difference in average DOD is much larger – a factor of 10 in the domain-average (0.008-0.08). Over land, DOD from ECHAM5 (0.01) and HadGEM2 (0.02) are significantly lower than satellites (0.09-0.11) and other models

(0.05-0.11). The underestimation of DOD in ECHAM5 and HadGEM2 is attributed to lower emissions and more efficient loss frequency of dust, respectively, which is discussed in detail in the later sections. Over the ocean domain, the magnitude of GOCART DOD (0.05) is in between the MODIS-derived DOD (0.06) and CALIOP-derived DOD (0.03), whereas the other models obtain much smaller values (0.001-0.009). Compared with the coarse-mode AOD (proxy of DOD) from AERONET, most models (except GOCART) seem to significantly underestimate the dust transport from source regions across the North Pacific.

Satellites indicate that f_{DOD} values vary depending on sensor type and region ranging 0.27-0.36. The satellite mean f_{DOD} over land (0.39) is 0.11 greater than over ocean (0.28). Models show large range of f_{DOD} both over land (0.11-0.42) and ocean (0.007-0.29). The ensemble means of model AOD, DOD and f_{DOD} are 0.21, 0.05, 0.25 over land and 0.16, 0.02, and 0.1 over ocean, respectively (Table 4). The comparison between satellite and model ensemble means again shows within 10 % differences in AOD over land and ocean, but a factor of two low bias in model is shown for DOD and f_{DOD} over ocean.

3.2 Longitudinal gradient

We examine the longitudinal gradient with the mean AOD and DOD from satellites and models between 20°N and 60°N in 5° longitude intervals between 60°E-120°W (Figure 4a). MODIS shows the highest AOD (0.47) at 115°E-120°E, whereas MISR and CALIOP have the peaks in the same location but with lower values (0.29 and 0.35, respectively). All satellite data show a gradually decreasing pattern eastward across the Pacific Ocean (i.e., east of 140°E). The range of west-to-east AOD gradient between 140°E-120°W in MODIS (from 0.23 to 0.11, a factor of 2.1) is larger than that in MISR (from 0.21 to 0.13, a factor of 1.6). The pattern of the CALIOP AOD gradient over ocean (from 0.11 to 0.06, a factor of 1.8) is similar to that of MODIS and MISR, but the magnitude of AOD is about half of other satellites. Differences in sampling and cloud-masking account for much of the diversity in the satellite-derived AOD gradients. All models capture the location of the maximum AOD over Eastern China, but some of them miss the peak over the Indo-Gangetic Plain and Taklimakan. Although the magnitudes of the decreasing longitudinal AOD gradients vary by model, all models show a decreasing longitudinal gradient of AOD.

Over land, MODIS and CALIOP DOD over the Taklimakan and Thar deserts (i.e., west of 85°E) are larger (0.19 and 0.14, respectively) than over the Gobi Desert and Loess Plateau (0.14 and 0.1, respectively). All the models except GOCART show lower DOD than CALIOP, especially ECHAM5 and HadGEM2, as the average DOD from these two models is only 0.01-0.05 over land. Over ocean, MODIS and MISR show similar decreasing DOD gradient from the west (0.10 and 0.07) to the eastern Pacific (0.03 and 0.04), respectively. The decreasing gradient of CALIOP DOD from west (0.05) to east Pacific (0.01) is only half the MODIS and MISR values. Overall, the satellites show a 40-60 % decrease of AOD and 35-70% decrease of DOD during the long-range transport from the Asian coast to the eastern North Pacific Ocean (i.e., 130°E-125°W). Although most models except GOCART have lower DOD than MODIS by a factor of 3-10 in the coastal region (i.e., 130°E), all models also show the decreasing DOD gradient, which is clear when the data are normalized to their respective values at the Asian coast (130˚E).

The CALIOP DOD fraction over land ($f_{DOD,}$ bottom panel in Figure 4a) is highest (0.55) near 60°E; then it gradually decreases across the Pacific towards the east to 0.32 at 125°W. MODIS also show similar f_{DOD} gradient between west and east (i.e., 0.65 to 0.30). The satellite f_{DOD} values over ocean are close to each other, in the range of 0.24~0.34, across the Pacific. The maximum f_{DOD} values from the models near 60°E are spread by a factor of two (0.28~0.57), and most models seem to show much faster f_{DOD} decrease from west to east over land (a factor of 3-4 decrease) than the satellites and the GOCART model. Over ocean, the mean f_{DOD} values from the models show a large (factor of 30) difference, from 0.01 (ECHAM5) to 0.29 (GOCART), and the latter is the closest to the satellite data.

When normalized to the value at 130°E, satellites estimate a 38-59 % AOD decrease, and a decrease of 34-69 % for DOD, during trans-Pacific transport (Figure 4b). The increasing gradient of MISR f_{DOD} is due to the steeper gradient in DOD than AOD, although its physical explanation needs more investigation. In contrast, models show a wider range of decreasing longitudinal gradients: 42-69 % for AOD and 44-88 % for DOD. The normalized AOD gradient from the models is generally similar to that from satellites, although GISS and ECHAM5 show an increase of AOD in the middle of the Pacific Ocean (160°E-150°W). By contrast, the longitudinal gradients of normalized DOD and f_{DOD} are much more spread out in the satellite data and models, revealing large discrepancies (a fact or of 4) not only between the satellites over the North Pacific, where

AOD and DOD are relatively low, but also among models in dust transport and removal processes.

Overall, all satellites show a gradual decrease of AOD and DOD eastward during trans-Pacific transport. They show that 40-60% of AOD and 30-65% of DOD reach the eastern Pacific from the Asian coast. Models capture the decreasing gradient of the satellite AOD and DOD; however, most models except GOCART largely underestimate DOD and f_{DOD} over ocean.

3.3 Seasonal cycle and inter-annual variability

The seasonal variation of multiyear mean AOD and DOD for land and ocean are shown in Figures 5 and 6, respectively. The seasonal variability of the three satellite AODs agree with each other over land (Figure 5), showing high AOD during April-July and low AOD between October and January. MODIS AOD (0.17-0.37) is higher than MISR and CALIOP by 0.06 to 0.07. The seasonal variation of MODIS and CALIOP DOD is similar to that of AOD with the peak in April (0.21 and 0.14, respectively). The f_{DOD} is highest in March-April (0.46-0.50) for MODIS and CALIOP, and lowest in December-January (0.27-0.28) in MODIS and July-August (0.33) in CALIOP.

Models also show strong seasonal variability over land; however, only GOCART shows the AOD and DOD maxima in April, reproducing the seasonal cycles in the satellite data. The other models shift the seasonal maximum to the boreal summer months. The differences between the modeled AODs range from 0.06~0.07 in winter to 0.18 in April. GOCART resembles closely the magnitude of MODIS, whereas the other models simulate AOD values similar to MISR and CALIOP. The maximum DOD in

GOCART, GISS and SPRINTARS ranges from 0.12-0.22, which is comparable to satellites (0.14-0.21). Interestingly, despite the large differences in seasonal variation among the models, they all consistently show a maximum f_{DOD} in April, even though the values differ by a factor of 2, from 0.3 in ECHAM5 to 0.6 in GOCART, which can be compared to the CALIOP f_{DOD} maximum of 0.5 in spring. Overall, the models capture the magnitude of the satellite AOD over land, but the seasonality differs; apparently, reproducing the magnitude of the observed DOD is more difficult.

Over ocean, there are clear discrepancies among the satellite data. Although the seasonal variability and magnitude of AOD from MODIS and MISR agree with each other (Figure 6) as both showing the highest AOD (0.28 and 0.26, respectively) in April-May, the CALIOP AOD is quite different not only in seasonal variation (maximum AOD from January through April and a minimum in August), but also in magnitude (about a factor of 2 lower). Discrepancies of similar magnitudes are found for satellite-derived DOD and f_{DOD} as well, with the largest difference appearing in the summer. Both MISR and CALIOP display DOD and f_{DOD} minima in July, a feature that is lacking in the MODIS data. As noted in Section 2, sensitivity to the proxies used to identify the DOD component in the satellite retrievals diminishes when the AOD is low.

Model simulations over the ocean also show large discrepancies. Although the AOD seasonal variation from GOCART (0.27) closely follows that from MODIS and MISR with a maximum AOD (0.26-0.28) in April-May, GISS and ECHAM5 indicate a maximum AOD in winter (0.21-0.25) and a minimum AOD (0.12) in summer, which is also out of phase with the seasonal cycle simulated by SPRINTARS and HadGEM2. The largest DOD and f_{DOD} differences over ocean among the models appear between

GOCART and ECHAM5: GOCART-simulated DOD (f_{DOD}) over the North Pacific varies from 0.02 (0.2) in winter to 0.14 (0.48) in April, similar to the corresponding values from MODIS, whereas these fields from ECHAM5 are below 0.03 (Figure 6, right-bottom panel). Overall, the DOD and f_{DOD} diversity among the models is huge, with differences up to a factor of twenty. The same result is obtained when the analysis is conducted over the smaller domains (Figures S3-S5).

Overall, most models, except for GOCART, strongly underestimate the magnitude of DOD over ocean, relative to the satellite results. The absence of dust over ocean in these models produces large differences in ocean-AOD seasonality, with peaks in summer or winter that disagree with the MODIS and MISR AOD. In addition, the AOD and DOD differences between MODIS, MISR, and CALIOP over ocean highlight the challenge of DOD observation in the Northern Pacific region. We will discuss the differences presented by the CALIOP DOD further in later sections.

3.4 Vertical distribution of aerosol and dust

The vertical profiles of modeled aerosol and dust are compared with CALIOP profiles averaged over 2007-2011. Considering the spatial variability within the large domain, we chose six sub-domains (Figure 1); three domains include major dust source regions over the Thar desert (THAR, 70°E-75°E; 25°N-30°N), the Taklimakan desert (TAKL, 75°E-90°E; 35°N-45°N), and the Gobi desert (GOBI, 95°E-115°E; 40°N-45°N), and three sub-domains across the Pacific capture the trans-Pacific transport of aerosol and dust [NWP (135°E-140°E; 25°N-50°N), NCP (175°E-180°E; 30°N-55°N), and NEP (130°W-125°W; 35°N-60°N)].

The comparison includes the area-averaged vertical profiles of extinction coefficients for total aerosol (σ_{aer} in km^{-1}) and dust (σ_{du} in km^{-1}), and the ratio of dust extinction to total aerosol extinction from the surface up to 12 km (Figure 7-8). We also compare the height representing the center of aerosol extinction (Z_α) in each vertical column, following Koffi et al. (2012), such that $Z_\alpha = \frac{\sum_{i=1}^{k}(b_{ext,i} \cdot z_i)}{\sum_{i=1}^{k} b_{ext,i}}$, where k is the total number of layers in each column and $b_{ext,i}$ is extinction coefficient for layer i within the column.

The sub-domain-averaged CALIOP vertical profiles calculated with both "including clear-air" (solid black line) and "excluding clear-air" (dashed black line) are plotted in Figures 7-8 together with the corresponding profiles from the models. The column-integrated AOD and DOD, and the extinction-weighted height, are listed on each panel. In the present section, we focus on the "including clear-air" case of the CALIOP averaged data (described in section 2.2.1); the results for the "excluding clear-air" case are covered subsequently, in the discussion section. We present the result for the spring season between March and May, as CALIOP and the models have stronger aerosol and dust signals during spring in five out of six sub-regions over the sources and the ocean, except for THAR, which has its peak during summer.

Over the dust source regions of THAR, TAKL, and GOBI, the CALIOP observations show a layer of total aerosol and dust extending from the surface to the middle troposphere (~6 km) during the spring season (Figure 7). The CALIOP profiles show different maximum extinction values among these regions, ranging 0.09-0.11 km^{-1} for total aerosol and 0.04-0.06 km^{-1} for dust. The peak aerosol extinction appears near the surface in THAR, but is more elevated in TAKL and GOBI (i.e., 1.0-2.0 km). The extinction-weighted average height of total aerosol ($Z_{\alpha,aer}$) from CALIOP (2.06-2.59 km) is about 0.1-0.4 km lower than that of dust aerosol ($Z_{\alpha,du}$) (2.17-2.97 km), suggesting that even near these source regions, dust tends to reside higher in the atmosphere than other aerosols. The column-integrated AOD and DOD vary with location, between 0.27-0.30 and 0.13-0.18, respectively. In contrast, a clear and significant contribution of dust to total aerosol extinction (f_{DOD}>0.5) appears at most altitudes over all sub-regions. The strong negative bias near the surface is due to a signal artifact that occurs when the level 1B attenuated backscatter becomes strongly negative, preceding a strongly scattering target such as the surface (Winker et al. 2009, 2013; Tackett et al., 2018).

There is a large spread in model-simulated aerosol and dust extinction vertical distributions over the dust source regions in spring (Figures 7). Most models show a maximum value of total aerosol and dust extinction at or near the surface. The average aerosol height ($0.86<Z_{\alpha,aer}<2.01$) and the average dust height ($0.75<Z_{\alpha,du}<2.07$) from the models are about 1-2 km lower than CALIOP. Differences in AOD and DOD in the three dust source regions also appear among the models. GOCART has the highest AOD over TAKL (0.36), whereas other models have the highest AOD over THAR (0.21-0.35), and CALIOP reports highest AOD over GOBI (0.30). For DOD, the highest values appear over TAKL in GOCART (0.30), THAR in GISS (0.17), and GOBI in SPRINTARS (0.30) and HadGEM2 (0.07); CALIOP finds essentially equal springtime DOD peak values over TAKL and THAR (0.18). Figure 7 shows that HadGEM2 severely underestimates the dust amount in THAR and TAKL. The shape of f_{DOD} between CALIOP and models are very different, as CALIOP is consistent throughout the atmosphere whereas the models show f_{DOD} decreasing with elevation. The magnitudes of the modeled f_{DOD} values are spread widely, showing large differences with CALIOP.

Over ocean (Figures 8), CALIOP displays a shallower aerosol and dust layer and lower extinction magnitudes compared to the features in the source regions. According to CALIOP, aerosol and dust are confined below 1 km in all ocean domains. Although the average aerosol height decreases by 0.5 km during long-range transport from NWP ($Z_{\alpha,aer}$ =2.27 km) to NEP ($Z_{\alpha,aer}$ =1.77 km), that of dust maintains at about the same level ($Z_{\alpha,du}$ = 2.49 km in NWP and 2.57 km in NEP). The CALIOP total-column AOD and DOD show strongly decreasing gradients from west to east (from 0.18 over NWP to 0.08 over NEP for AOD, from 0.07 over NWP to 0.03 over NEP for DOD). The f_{DOD} values (~0.5) over ocean are lower than over the land regions.

Large model diversity in aerosol and dust vertical profiles also appears over ocean (Figure 8). In general, total aerosol extinction peaks are located near the surface and decrease with altitude, except for GISS, which places a second aerosol layer around 2 km. However, the models show that dust extinction reaches maximum values in layers aloft, centered around 3 km, and then decreases with altitude. Consequently the averaged dust height $Z_{\alpha,du}$ (2.56-4.22 km) is significantly higher than the average aerosol height $Z_{\alpha,aer}$ (0.69-2.58 km). It is worth noting that $Z_{\alpha,du}$ of all models increases (from 2.56-3.38 km to 3.57-4.22 km) between NWP and NEP, in contrast with the nearly constant height reported by CALIOP, and the modeled $Z_{\alpha,du}$ values are up to 1.5 km higher than CALIOP in the ocean domains.

The comparison of vertical profiles showed that (1) CALIOP derives thick dust layers reaching up to 6 km over that dust source regions, and a shallower, weaker aerosol and dust layer over ocean, whereas the models show a large spread in the vertical distribution of dust over both land and ocean; (2) the average height of dust in the models underestimates CALIOP over land, but they overestimate CALIOP over ocean; (3) $Z_{\alpha,du}$ of all models increases during long-range transport over ocean, whereas $Z_{\alpha,du}$ barely changes according to CALIOP; and (4) CALIOP shows large dust fraction throughout the domains, whereas there are wide differences (factors of a few or more) in dust fraction among models.

4. Diversity of dust emission, removal, and optical parameters among models

4.1 Model emissions and physical/optical parameters

In this section, we examine the model simulations of the dust budget and several internal parameters in the study domain to help diagnose the large diversity among models, including emission, dry and wet depositions, dust mass loading, loss frequency (LF, which is the removal rate divided by the dust mass loading), optical depth, and the mass extinction efficiency (MEE, which converts dust mass to extinction at 550 nm). The results are summarized in Table 4 and some are shown in Figures 9 and 10. For dust emissions, Figure 9 indicates that all models produce similar “hot spots”, such as the Taklimakan desert, Gobi desert, Inner Mongolia, Thar desert, and the deserts in Central Asia. However, there are clear differences in locations and amounts of emission fluxes. GOCART and SPRINTARS show similar areas and emission rates in confined source locations in China, but they differ considerably for locations in India and central Asia. Dust emissions in other models are more spatially spread out but the emission rates are much lower than GOCART and SPRINTARS. Note that differences in dust emission between models are determined not only by the emission parameterization scheme and meteorology, but also by the particle size distribution and the size range. However, the AeroCom database only contains total dust emissions without size-segregated information. The lowest mass emission is in ECHAM5 (77.4 Tg yr^{-1}), which considers smaller size particles in its modal approach (0.05-0.5 µm in radius). SPRINTARS and GOCART have the same maximum size of 10 µm (radius), but SPRINTARS emission (825.9 Tg yr^{-1}) is 21% larger than GOCART (680.5 Tg yr^{-1}). GISS (200.4 Tg yr^{-1}) and HadGEM2 (488.8 Tg yr^{-1}) have maximum size larger than 10 µm (radius), but their emissions are lower than GOCART and SPRINTARS (see Table 4). Overall, the domain dust emission among models differs by more than a factor of 10, from 77.4 Tg yr^{-1} in ECHAM5 to 825.9 Tg yr^{-1} in SPRINTARS. The comparison here suggests that the differences in dust size-range alone cannot explain the diversity in dust emissions between the models. Rather, the dust uplifting mechanisms and/or meteorological conditions (e.g., winds, soil wetness) might also play a role in the dust emission differences among the models.

We compare three physical and optical parameters from the models in our study domain: loss frequency (LF in day^{-1}), which is the total dust deposition rate (sum of wet and dry deposition rates) divided by the dust mass loading; f_{wet}, which is the dust wet deposition fraction of total deposition, and the dust mass extinction efficiency (MEE in m^2g^{-1}), which is the ratio of DOD to dust mass loading (Figure 10). The mean values of these parameters for each region per model are summarized in Table 4.

During long-range transport, aerosol loading and consequently LF are affected by advection and deposition as well as by particle size distribution. The range of the annual mean LF values over the land and ocean domains among the models range between 0.20-0.53 and 0.09-0.21 day^{-1}, respectively (Table 4 and Figure 10a). SPRINTARS and HadGEM2 show higher LF (> 0.9 day^{-1}) in and around their respective source locations, indicating that dust aerosols are quickly removed before transport far from the source region occurs, due to the effective settling of large particles. GOCART and GISS show relatively lower LF (< 0.7 day^{-1}) over source regions. ECHAM5, which allows dust to mix with other aerosols internally, shows low LF (< 0.5 day^{-1}) in and near source regions, but it has high LF (> 0.9 day^{-1}) outside the deserts over land. The highest LF (>0.9 day^{-1}) in the Tibetan Plateau in ECHAM5 is explained by stronger wet-removal than other models. ECHAM5 has the highest LF, which explains why the steepest decreasing DOD gradient shown in Figure 4b corresponds to that model. All models show lower LF (<0.4 day^{-1}) in 20°N-60°N over ocean than near-source (over land).

Dust from the Taklimakan and Gobi Deserts is frequently to be transported toward the North Pacific. The highest emission from these regions is in GOCART (462.3 Tg year^{-1}), followed by SPRINTARS (374.6 Tg year^{-1}), HadGEM2 (134.7 Tg year^{-1}), GISS (81.6 Tg year^{-1}), and ECHAM5 (26.1 Tg year^{-1}) (Table S2). The contribution from these regions to the total domain emission is higher in GOCART (68 %) than other models (28 % in HadGEM2 ~ 45 % in SPRINTARS). Dust emission from the Taklimakan is factor of a few higher in GOCART (252.9 Tg year^{-1}) and SPRINTARS (208.6 Tg year^{-1}) than other models (0.1~31.2 Tg year^{-1}). Similarly, GOCART and SPRINTARS DOD better agrees with MDB DOD over the Taklimakan Desert, whereas other models are understated (Figure S6). The result indicates that the higher DOD (0.08) in GOCART over the Northern Pacific is attributed by the combined effects of lower loss frequency (0.15 day^{-1}) and higher emission. In contrast, dust emission in SPRINTARS is higher than GOCART but its mean DOD (0.05) is 33.5 % lower than GOCART, mainly due to the high loss frequency (0.26 day^{-1}) in SPRINTARS. Other models have much lower emissions than GOCART and SPRINTARS.

The models in the present study include two major deposition processes to remove dust aerosols from the atmosphere: dry (including gravitational settling and aerodynamic deposition) and wet (including convective scavenging and large-scale rainout/washout), and their efficiencies are highly model-dependent. The distributions of wet deposition fraction over total deposition, f_{wet} between models are compared in Figure 10b. For major dust source regions over land, all models give consistently low f_{wet} values of less than 0.1, since total dust removal is dominated by gravitational settling of larger particles near the source. The f_{wet} increases away from the source over land (>0.9 in GISS, ECHAM5, and HadGEM2, and 0.5~0.6 in the other models). Over the Pacific Ocean, the models show substantially higher f_{wet}, with the highest f_{wet} (0.92) in HadGEM2 and the lowest in GOCART (0.62), resulting in a 48 % relative difference between the two. The annual mean precipitation over the North Pacific Ocean ranges from 2.86 (mm day^{-1}) in SPRINTARS to 3.49 (mm day^{-1}) in GISS, and the precipitation field has a peak in summer in all models (Figure S7). The order of f_{wet} between models is not consistent with the order of precipitation, due to differences in the modeled wet and dry removal processes. Overall, GOCART LF along the dust transport route over ocean is also the lowest, resulting in the highest DOD among models, and it actually agrees best with the satellite data.

Although MEE is the extinction efficiency per unit mass, it is also affected by both particle size distribution and the optical properties adopted by the models (e.g., mass extinction coefficient is higher for fine-mode particles than coarse-mode particles). All models show that dust MEE is lower over source regions (0.3-0.8) than downwind towards the eastern Pacific Ocean, consistent with the notion that dust particle size is larger near the source, and that large particles are more efficiently removed than the fine particles. The mean MEE (m^2g^{-1}) among models ranges from 0.57 (GOCART) to 1.01 (SPRINTARS) over land, and from 0.61 (GOCART) to 1.12 (SPRINTARS) over ocean (Table 4). Overall, the spatial distribution of dust MEE is particle-size dependent, ranging from 0.3-0.7 in GOCART to 0.7-1.3 in SPRINTARS, with SRINTARS' dust MEE overall about 80% larger than GOCART.

We estimate the model diversity (Table 4), which is defined as the ratio of the standard deviation of the model results to the multi-model mean (Textor et al., 2006). Over the full domain, diversity for the mass-related parameters (*i.e*., emission, mass loading, dry deposition, and wet deposition) is in the range of 39-100 %. Diversity for the optical parameters of AOD and DOD is 10 and 84 %, respectively, indicating models experience more uncertainty in representing dust mass and DOD than AOD.

Inter-model comparison in this section allows us to explain the large diversity of DOD (i.e., 84%); dust mass loading and mass extinction efficiency are the determining factors for DOD estimation. The diversity of LOAD (100%) is among the largest in the analyzed parameters, mainly due to the combined effects of EMI (69%), DRY (72%), and WET (39%). In comparison, the diversity of MEE is much smaller (23%), suggesting that the diversity of DOD is determined mainly by the diversity of LOAD. For EMI, each model uses its own parameterization scheme, input surface condition, and surface wind speed, generating large differences among models. Each model uses a different parameterization scheme for DRY and WET processes, resulting in 31% diversity in LF. Differences in meteorological fields between models such as wind, precipitation, and circulation also contribute to the diversity of dust lifetime. Further, different optical tables and size distributions among models is an important factor for dust removal process and optical property calculation.

A critical question in this study is which factor among emission, removal, and optical property is more responsible for contributing to the diversity of the AeroCom model simulated DOD? To answer the question, we have calculated a partial sensitivity of DOD to the above model parameters, based on the method in Schulz et al. (2006). Since DOD is determined by the dust load (LOAD) and mass extinction efficiency (MEE), and the LOAD is determined by the source (SRC) and the deposition removal rate (expressed as residence time RES, which is reciprocal of LF), the domain averaged DOD can be expressed as: DOD = SRC (g m^{-2} s^{-1}) × RES (s) × MEE (m^2 g^{-1}). Because of the study domain is not global such that the dust emission is not necessarily balanced by the deposition term averaged over the study time period (several years) and domain, the net SRC is thus expressed as SRC = EMI + (EMI-DEP). For each model n, the DOD sensitivity with respect to factor x is defined as: $\mathrm{DOD}_{x,n} = x_n/\langle x \rangle \times \langle \mathrm{DOD} \rangle$, where $\langle x \rangle$ is the multi-model mean of x and $\langle \mathrm{DOD} \rangle$ is the multi-model mean DOD. Figure 11 shows the partial sensitivity of DOD to the net SRC, RES, and MEE for the five AeroCom models, with the last two points showing the DOD from each model and satellite. For reference, the partial sensitivity of DOD to EMI within the domain is shown as “x” symbol for each model; the difference between the SRC and EMI is the net dust imported to the domain if SRC>EMI or export from the domain if SRC<EMI.

Comparing GOCART and SPRINTARS, the shorter residence time (i.e. the higher loss frequency) in SPRINTARS is likely to be responsible for the lower simulated DOD in SPRINTARS, despite higher dust source and higher MEE in SPRINTARS. The low DOD in GISS and ECHEM is most likely driven by the low dust source (low emission rates and net export). It is interesting that HadGEM2 shows much higher dust source (EMI + net import) than GISS but comparable residence time (or loss frequency) and MEE with GISS, but its simulated DOD is significantly lower than GISS, which is difficult to explain without more detailed information, such as size-segregated emission and optical properties. Overall, the result in Figure 11 shows that the diversity of DOD is mostly driven by the diversity of the dust source followed by that of the residence time, and to a less extent by the differences in MEE.

Among the five models, GOCART agrees with the satellite data the best in terms of DOD over land and ocean, transpacific DOD gradient, and seasonal cycle. However, there is still a lack of observational data to validate or constrain the emission, dry and wet removal (the slowest among models), and MEE (the lowest among models) in GOCART. We can only say that the combination of these factors allows GOCART to simulate the DOD magnitude, horizontal distributions, and seasonal variations that are the closest to the satellite observations.

4.2 Comparison with North African dust

To address how model-simulated dust over the Asia-Pacific Ocean compares with North Africa-Atlantic Ocean, we compare AOD and five dust physical and optical parameters (DOD, f_{DOD}, f_{wet}, LF, and MEE) from the current study with our previous study over North Africa and the Atlantic Ocean (i.e., Kim et al., 2014) (Figure 12 and Table 5). In the comparison, each parameter from the models is averaged over land and ocean to simplify the discussion.

Due to the differences in dust size and meteorology in the source regions, dust emission and DOD over North Africa (1048 Tg yr^{-1} and 0.18, respectively) is 2~3 times larger than over Asia (454 Tg yr^{-1} and 0.05). The models show a factor of two difference in f_{DOD} between North Africa (0.52) and Asia (0.25), indicating that other pollutants play a more important role over Asia. Dust LF is comparable between the two continents (about 10%), with that over North Africa (0.39 day^{-1}) slightly larger than over Asia (0.36 day^{-1}). Considering the spectral dependency of dust particle size, the lower dust MEE between North Africa (0.65 m^2g^{-1}) and Asia (0.73 m^2g^{-1}) suggests larger dust particle size over North Africa than Asia. The higher f_{wet} over Asia (0.55) than over North Africa (0.32) reflects more frequent and abundant precipitation over Asia than North Africa. The comparison between the Atlantic and Pacific Oceans shows a similar pattern as in North Africa and Asia (Figure 12b). Furthermore, the longitudinal gradient of the trans-Pacific dust is about one-half of the trans-Atlantic dust, due to higher dust elevation and differences in precipitation.

AeroCom models use the same anthropogenic emissions, but dust emission is calculated by each model. As a result, the diversity of model AOD over the more polluted Asia region (13%) is much smaller than that for North Africa (50%). However, the diversity of DOD (66-75%) is larger for Asia and North Africa than diversity of AOD. Over ocean, the AOD diversity for the Pacific Ocean (21%) is smaller than for the Atlantic Ocean (34%), but the diversity of DOD for the Pacific Ocean (121%) is three times as large as for the Atlantic Ocean (45%), due to the differences in meteorological fields and removal processes. Diversities of other physical and optical parameters between North Africa and Asia are low and comparable, with differences generally less than 10%.

5. Discussion

The present inter-model dust comparison has shown that there are large differences among models, among the satellite observations, and between models and satellite observations. Among the five participating AeroCom models, most of them except GOCART significantly underestimate DOD relative to the satellite-derived values over Asia and the Pacific Ocean, whereas GOCART emits more dust (i.e., 2nd most dust emission after SPRINTARS) and shows longer dust lifetime during transit. The participating models have different size range and thus they have different size distributions as reflected in Table 1. Recent studies have shown that the wide spread in size-distribution between models, and in addition models generally simulate too much fine dust compared to observations (Kok et al., 2017). The differences in emission, size distribution and dry deposition efficiency (i.e., the ratio of DRY to EMI in Table 4) between models contribute to the large diversity in DRY between models. The aerosol size distribution is a subject of future inter-model comparison studies.

In summary, the analysis of model diversity for various physical/optical parameters raises the following points: (1) Among the mass-related parameters (emission, load, dry and wet deposition), the greatest diversity appears in the dust mass loading, especially over ocean. (2) The diversity of dry deposition is about twice larger than that of wet deposition. (3) There is a sharp contrast between the diversity of AOD and that of DOD, i.e., the diversity of AOD is only 12-17% of the diversity of DOD. (4) The diversity of almost all parameters over ocean is larger than the corresponding quantities over land. (5) The diversity of DOD is mostly driven by the diversity of the dust source followed by that of the residence time, and to a less extent by the differences in MEE.

As presented in section 3, we assigned CALIOP aerosol extinction in "clear-air" a value of 0 km^{-1} following the method described in section 2.2.1. CALIOP data using this method agrees with MODIS and MISR for AOD, and MODIS for DOD over land. However, this causes a low bias in averaged aerosol vertical profiles and thus underestimates AOD and DOD relative to MODIS and MISR, especially over ocean. As constraining aerosol extinction below the detection limit is highly uncertain, we also provide an upper bound on the extinction profiles by excluding the "clear-air" data in the average. If we exclude the clear-air data in the average, it removes much of the sampling, approximately 70 % over dust source regions and 90 % over remote ocean (Figure S1f). The "excluding clear-air" case does not alter the AOD and DOD horizontal patterns and their longitudinal gradients much. However, the AOD and DOD magnitudes are 70-80 % larger than the "including clear-air" case over land and ocean (Figure 13, left panel and Table 6). Actually, in the "excluding clear-air" case, the CALIOP longitudinal gradients agree better with the other satellites over ocean, but the resulting CALIOP AOD and

DOD over land is larger than the other satellites (Figure 13, right panel). Overall, the effects of how "clear-air" is represented produces large differences in AOD and DOD over land and ocean, yet the change to f_{DOD} is less than 10%.

The impact of how "clear-air" is represented on the shape and magnitude of the CALIOP vertical profiles is large (solid and dashed lines in black in Figures 7-8). Over the land domains, the aerosol and dust extinctions of the "excluding clear-air" case are about twice as large as the "including clear-air" case at all altitudes. Also, the average heights (Z_{α}) increase by 0.4-0.9 km for total aerosol and 0.6-1.0 km for dust. Over the ocean domains, aerosol extinctions for the "excluding clear-air" case are about 3-5 times larger and $Z_{\alpha,aer}$ is about 1.2-1.8 km higher than the "including clear-air" case. Dust extinction for the "excluding clear-air" case is 2-5 times larger, and $Z_{\alpha,du}$ is about 1.4-1.8 km higher, than the "including clear-air" case. These results suggest that the low detection limit of CALIOP may miss large amount of background aerosol and dust signal, which is consistent with a previous study (Watson-Parris et al., 2018). Given the limitations and uncertainties in the CALIOP vertical profiles over ocean, where the aerosol amount is low, it is difficult to use the CALIOP data to meaningfully evaluate the model-simulated vertical profiles.

Finally, our study shows that satellite remote sensing is crucial to better understand the large-scale distribution and variation of dust. Although the three satellite data sets considered show general agreement of AOD and DOD patterns, they also leave large uncertainties in estimating aerosol and dust over Asia and especially over Pacific Ocean due to 1) the presence of sea-spay aerosol and clouds, 2) mixing of dust with other continental aerosol, and 3) data sampling biases and instrument sensitivity limitations.

Our study emphasizes that better aerosol and dust detection over the Pacific Ocean is essential to reduce the uncertainty inherent in the present study.

6. Summary

We evaluated dust and total aerosol over Asia and the North Pacific Ocean for five AeroCom II global models by comparing the model-simulated spatial and temporal distributions with a suite of satellite remote-sensing data and with AERONET sun photometer measurements. Our evaluation targeted four areas: (1) spatial distributions of AOD and DOD over Asia and the North Pacific Ocean, (2) longitudinal gradient of AOD and DOD during trans-Pacific transport, (3) seasonal variations of AOD and DOD, and (4) vertical extinction profiles of total aerosol and dust. To understand the inter-model differences in the dust simulations, we also compared several key model parameters, including dust emission, dry and wet deposition, loss frequency, and dust mass extinction efficiency.

The satellites agree that high AOD exists over major pollution regions, and gradually decreases downwind from the source regions. They show a peak in spring and a minimum in winter. Over land, satellite observations of DOD are derived from MODIS (0.11) and CALIOP (0.09), which shows a large dust contribution over land, accounting for 36% and 42% of the total AOD, respectively. Over ocean, satellite observations show that the average AOD is more than half (62%) the value over land, and DOD derived from MODIS, MISR, and CALIOP accounts for 27-30% of AOD. It is worth noting that AOD and DOD of MODIS and MISR are close each other, but CALIOP is much lower than the other satellites over the ocean domain. Overall, satellites show a 35-70 % decrease of DOD from the west Pacific to the east Pacific.

Large differences among models and between models and observations were found in all categories (column AOD/DOD, longitudinal gradient, seasonal variations, and vertical profiles) in this analysis. The mean AODs from models are within 20 % of the satellites; however, the inter-model differences over both land and ocean are comparable to the inter-satellite instrument differences. On the other hand, most models except GOCART underestimate DOD (0.00-0.05) compared to the satellite-derived products (0.03-0.06). The models show a wide range of decreasing longitudinal gradients for AOD (42-69 %) and DOD (45-88 %) across the Pacific Ocean, although the range is comparable to the differences between satellite products (35-70%). The models show large seasonal variations of AOD over land and ocean with a peak in spring or summer (0.2-0.35) and a minimum in winter (0.1-0.2) over land and ocean. The DOD and f_{DOD} differences among the models are very large, as high as a factor of 20. The models also show peak DOD in spring and summer (0.05-0.24) and winter minima (<0.07).

The vertical profiles of CALIOP show thick dust layers up to 6 km over dust source regions, and a shallower and weaker aerosol and dust layer over ocean. The models display a large spread in dust vertical distributions over land and ocean; they underestimate average height of CALIOP over land, but they overestimate over ocean. $Z_{\alpha,du}$ according to CALIOP barely changes during long-range transport; in contrast, the modeled $Z_{\alpha,du}$ increases during transport. Large dust fraction is detected from CALIOP throughout the domain, whereas dust fraction between models vary widely, showing factors of a few differences.

The differences in dust emissions among models are larger than a factor of 10 (77.4-825.9 Tg yr^{-1}) due to differences in source area size, dust size range, and meteorology, with a diversity value of 69%. The inter-model comparison also shows large diversity for mass-related parameters (*i.e.*, LOAD, DRY, and WET; 39-100 %), which explains the large diversity of DOD (84%). The diversity for dry deposition is about twice larger than that for wet deposition. The comparisons show that the AOD diversity is only 12-17% of the DOD diversity. Overall, for most parameters, the diversity over ocean is larger than over land.

While GOCART agrees with the satellite data the best in terms of DOD, there is still a lack of observational data to validate the emission, dry and wet removal rates (the slowest among models), and MEE (the lowest among models) in GOCART. For the same reason, it is difficult to point out specific causes for other models' underestimate the DOD in our study domain. Observation-based estimates on these quantities are needed for future progress in modeling dust aerosols in the atmosphere.

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Table 1. Description of the participating models and their physical characteristics of dust. Adopted from Kim et al. (2014).

	GOCART (GO)	GISS-E2-OMA (GI)	SPRINTARS (SP)	ECHAM5-HAMMOZ* (EC)	HadGEM2 (HG)
Resolution	2.5°×2°	2.5°×2°	1.125°×1.125°	2.8°×2.8°	1.875°×1.25°
Vertical Layers	30	40	56	31	38
Meteorology	GEOS-4 DAS	Horizontal winds nudged to NCEP Reanalysis	NCEP Reanalysis	ECMWF Reanalysis	ECMWF Reanalysis
Winds for emissions	U_{10m}^3	U_{10m}^3	U_{10m}^3	U_*^3	U_*^3
Size distribution (μm)	5 bins 0.1-1.0-1.8-3.0-6.0-10.0	5 bins 0.1-1-2-4-8-16	6 bins 0.1-0.22-0.46-1.0-2.15-4.64-10.0	2 modes (acc. And coarse) $0.05<r_m<0.5$ $0.5<r_m$	6 bins 0.0316-0.1-0.316-1.0-3.16-10-31.6
Density (g cm^{-3})	2.5	2.5 for clay 2.65 for silt	2.6	2.5-2.6	2.65
Dust-related key references	Chin et al. (2002,2009) Ginoux et al. (2001)	Miller et al., (2006); Bauer and Koch (2005)	Takemura et al. (2000, 2005)	Pozzoli et al. (2008, 2011)	Bellouin et al. (2011) (Appendix A)

* Dust particles are emitted in the insoluble accumulation and coarse modes with mass median radii of 0.37 μm and 1.75 μm, respectively. Once emitted dust particles can be mixed with other aerosols, and dust is distributed in two additional modes, internally mixed soluble accumulation and coarse modes.

Table 2: Remote sensing data used in this study. Adopted from Kim et al. (2014).

Sensor/platform	Data products	Major references
MODIS	AOD (combined dark target and deep blue)	Levy et al. (2013); Hsu et al. (2004)
	DOD derived from AOD and aerosol fine-mode fraction over ocean	Kaufman et al. (2005); Yu et al. (2009, 2019b)
	DOD derived from deep blue retrievals over land	Ginoux et al. (2012); Pu and Ginoux (2016)
CALIOP	Aerosol and dust extinction profiles	Winker et al. (2009); Young et al. (2018); Yu et al. (2012, 2015b, 2019a)
MISR	AOD, non-spherical AOD	Kalashnikova and Kahn (2006); Kahn et al. (2010)
AERONET	AOD, coarse-mode AOD	Holben et al. (1998); Dubovik et al. (2000)

Table 3. Mean of optical properties of satellite over land and ocean domains. f_{DOD} is the ratio of DOD to AOD. Data is not available over land for some sensors. [1]Mean of satellites.

	Name	Unit	MODIS	MISR	CALIOP	Mean[1]
Domain	AOD	Unitless	0.226	0.194	0.152	0.191
(60°E-140°W,	DOD	Unitless	0.085	-	0.061	0.073
20°N-60°N)	f_{DOD}	Fraction	0.329	-	0.352	0.341
Land	AOD	Unitless	0.274	0.209	0.217	0.233
(60°E-140°E,	DOD	Unitless	0.111	-	0.094	0.103
20°N-60°N)	f_{DOD}	Fraction	0.362	-	0.416	0.389
Ocean	AOD	Unitless	0.177	0.179	0.084	0.147
(140°E-140°W,	DOD	Unitless	0.059	0.054	0.027	0.047
20°N-60°N)	f_{DOD}	Fraction	0.296	0.268	0.285	0.283

Table 4. Budget analysis and optical properties of dust over different domains. Listed parameters are emission (EMI), dry deposition (DRY), wet deposition (WET), column mass loading (LOAD), aerosol optical depth (AOD), dust optical depth (DOD), DOD fraction to AOD (f_{DOD}), WET fraction to total deposition (f_{WET}), loss frequency (LF), mass extinction efficiency (MEE). Diversity of model parameters (%) is defined as the ratio of standard deviation to the mean of a parameter following Textor et al. (2006). Clear-sky AOD is listed for GISS.

	Name	Unit	GOCART	GISS	SPRINTARS	ECHAM5	HadGEM2	Model mean	Diversity (%)
Domain (60°E-140°W, 20°N-60°N)	EMI	Tg yr^{-1}	680.5	200.4	825.9	77.4	488.8	454.6	69.3
	DRY	Tg yr^{-1}	518.8	123.4	468.0	35.1	323.5	293.8	71.8
	WET	Tg yr^{-1}	164.4	105.8	150.8	70.0	73.2	112.8	38.5
	LOAD	Tg	9.12	2.35	3.06	0.75	1.45	3.34	100.0
	AOD	Unitless	0.202	0.191	0.157	0.182	0.166	0.180	10.2
	DOD	Unitless	0.080	0.028	0.045	0.008	0.013	0.035	83.6
	f_{DOD}	Fraction	0.352	0.138	0.234	0.058	0.101	0.177	66.6
	f_{WET}	Fraction	0.50	0.76	0.62	0.66	0.79	0.66	17.4
	LF	day^{-1}	0.15	0.23	0.26	0.37	0.25	0.25	31.0
	MEE	m^{2}g^{-1}	0.59	0.79	1.06	0.67	0.77	0.78	23.0
Land (60°E-140°E, 20°N-60°N)	DRY	Tg yr^{-1}	495.1	121.5	464.6	33.8	323.0	287.60	71.2
	WET	Tg yr^{-1}	123.2	89.1	134.9	64.3	66.0	95.50	33.9
	LOAD	Tg	6.60	2.05	2.67	0.69	1.22	2.64	88.4
	AOD	Unitless	0.249	0.193	0.202	0.182	0.197	0.205	12.7
	DOD	Unitless	0.111	0.048	0.075	0.014	0.020	0.054	75.1
	f_{DOD}	Fraction	0.416	0.226	0.345	0.110	0.153	0.250	51.4
	f_{WET}	Fraction	0.38	0.62	0.51	0.57	0.67	0.55	20.0
	LF	day^{-1}	0.20	0.28	0.39	0.53	0.41	0.36	35.3
	MEE	m^{2}g^{-1}	0.57	0.71	1.01	0.66	0.68	0.73	23.0
Ocean (140°E-140°W, 20°N-60°N)	DRY	Tg yr^{-1}	25.0	1.9	3.4	1.3	0.5	6.4	162.6
	WET	Tg yr^{-1}	43.3	16.7	15.9	5.7	7.2	17.8	85.1
	LOAD	Tg	2.62	0.30	0.39	0.06	0.23	0.72	148.4
	AOD	Unitless	0.155	0.189	0.111	0.182	0.136	0.155	20.9
	DOD	Unitless	0.049	0.009	0.014	0.001	0.006	0.016	121.2
	f_{DOD}	Fraction	0.286	0.049	0.122	0.007	0.048	0.102	108.1
	f_{WET}	Fraction	0.62	0.89	0.73	0.74	0.92	0.78	15.8
	LF	day^{-1}	0.10	0.18	0.13	0.21	0.09	0.14	34.5
	MEE	m^{2}g^{-1}	0.61	0.86	1.12	0.68	0.86	0.83	23.8

Table 5. Multi-model mean and diversity over land and ocean domains for North Africa and Asia. The values of North Africa are adopted from Kim et al. (2014). Numbers in parenthesis are the diversity of model parameters (%), which is defined as the ratio of standard deviation to the mean of a parameter following Textor et al. (2006).

Name	Unit	Land		Ocean	
		North Africa (17°W-30°E, 0°N-35°N)	Asia (60°E-140°E, 20°N-60°N)	North Africa (90°W-17°W, 0°N-35°N)	Asia (140°E-140°W, 20°N-60°N)
EMI	Tg yr^{-1}	1047.8 (57.1)	454.6 (69.3)	-	-
LOAD	Tg yr^{-1}	5.78 (74.8)	2.64 (88.4)	2.46 (56.5)	0.72 (148.4)
AOD	Unitless	0.29 (50.3)	0.21 (12.7)	0.17 (33.6)	0.16 (20.9)
DOD	Unitless	0.18 (65.8)	0.05 (75.1)	0.06 (44.8)	0.02 (121.2)
f_{DOD}	Fraction	0.52 (31.1)	0.25 (51.4)	0.23 (50.2)	0.10 (108.1)
f_{WET}	Fraction	0.32 (15.3)	0.55 (20.0)	0.62 (23.4)	0.78 (15.8)
LF	day^{-1}	0.39 (44.0)	0.36 (35.3)	0.29 (37.1)	0.14 (34.5)
MEE	m^2g^{-1}	0.65 (26.9)	0.73 (23.0)	0.76 (29.3)	0.83 (23.8)

Table 6. Mean of AOD, DOD and f_{DOD} of CALIOP satellite over land and ocean domains with different integration options of CAD score and clear-sky.

Cases	Land			Ocean		
	AOD	DOD	f_{DOD}	AOD	DOD	f_{DOD}
-100<CAD<-20, exclude clear-air	0.416	0.197	0.429	0.205	0.079	0.305
-100<CAD<-20, include clear-air	0.223	0.109	0.425	0.117	0.040	0.291
-100<CAD<-70, exclude clear-air	0.388	0.169	0.410	0.178	0.058	0.286
-100<CAD<-70, include clear-air	0.211	0.095	0.409	0.104	0.032	0.274

Figure Captions

Figure 1. Name and location of the sub-domains for (1) climatology (black dash-boxes) and (2) CALIOP (red boxes) analysis. Color map is the annual mean of CALIOP DOD. Color circles superimposed on the map are the AERONET retrieved coarse mode AOD. The domains for climatological analysis are LAND [60°E-140°E; 20°N-60°N] and OCEAN [140°E-140°W; 20°N-60°N]. The domain for CALIOP analysis are THAR [70°E-75°E; 25°N-30°N], TAKL [75°E-90°E; 35°N-45°N], GOBI [95°E-115°E; 40°N-45°N], NWP [135°E-140°E; 25°N-50°N], NCP [175°E-180°E; 30°N-55°N], and NEP [130°W-125°W; 35°N-60°N].

Figure 2. Spatial distribution of mean AOD from satellites (MODIS, MISR, and CALIOP) and models (GOCART, GISS, SPRINTARS, ECHAM5, and HadGEM2) averaged over 2000-2005. CALIOP including clear-air samples is averaged for 2007-2011. Color circles superimposed on the map represent AERONET observed AOD.

Figure 3. Spatial distribution of mean dust optical depth (DOD) from satellites (MODIS, MISR, and CALIOP) and models (GOCART, GISS, SPRINTARS, ECHAM5, and HadGEM2) averaged over 2000-2005. CALIOP including clear-air samples and is averaged for 2007-2011. Color circles superimposed on the map are the AERONET retrieved coarse mode AOD.

Figure 4. (a) Meridional mean of AOD, DOD, and f_{DOD} averaged from 20°N to 60°N. Thick lines are satellite retrievals from MODIS (MD), MISR (MI), and CALIOP (CA), and thin lines are model simulations. No DOD is available over land in MISR products. Asia and North America is shaded in gray. (b) Same as (a), except for normalized to values of each variable at the Asian coast of 130°E.

Figure 5. Monthly mean of (top) AOD, (middle) DOD, (bottom) f_{DOD} for land [60°E-140°E; 20°N-60°N]. Left- and right-columns are from satellites and model, respectively. All model plots are averaged from 2000 to 2005. Vertical bars are the standard deviation of monthly mean values.

Figure 6. Monthly mean of (top) AOD, (middle) DOD, (bottom) f_{DOD} for ocean [140°E-140°W; 20°N-60°N]. Left- and right-columns are from satellites and model, respectively. All model plots are averaged from 2000 to 2005. Vertical bars are the standard deviation of monthly mean values.

Figure 7. Mean spring season vertical profile of extinction coefficient of total aerosol (σ_{aer} in km^{-1}), extinction coefficient of dust (σ_{du} in km^{-1}), and $f\sigma_{du}$, the ratio of σ_{du} to σ_{aer} for THAR (Thar desert), TAKL (Taklimakan desert), and GOBI (Gobi desert) domains. Model simulations are for 2006. CALIOP data is averaged from 2007 to 2011. Black solid and dashed-lines are the means of CALIOP data including clear-air samples and excluding clear-air samples, respectively, representing the lower and upper limits for the CALIOP data (range shaded in grey). Numbers in parenthesis are CALIOP data excluding clear-air samples.

Figure 8. Same as Figure 7 except for (left) north-west Pacific domain, (middle) north-center Pacific, (right) north-east Pacific domains.

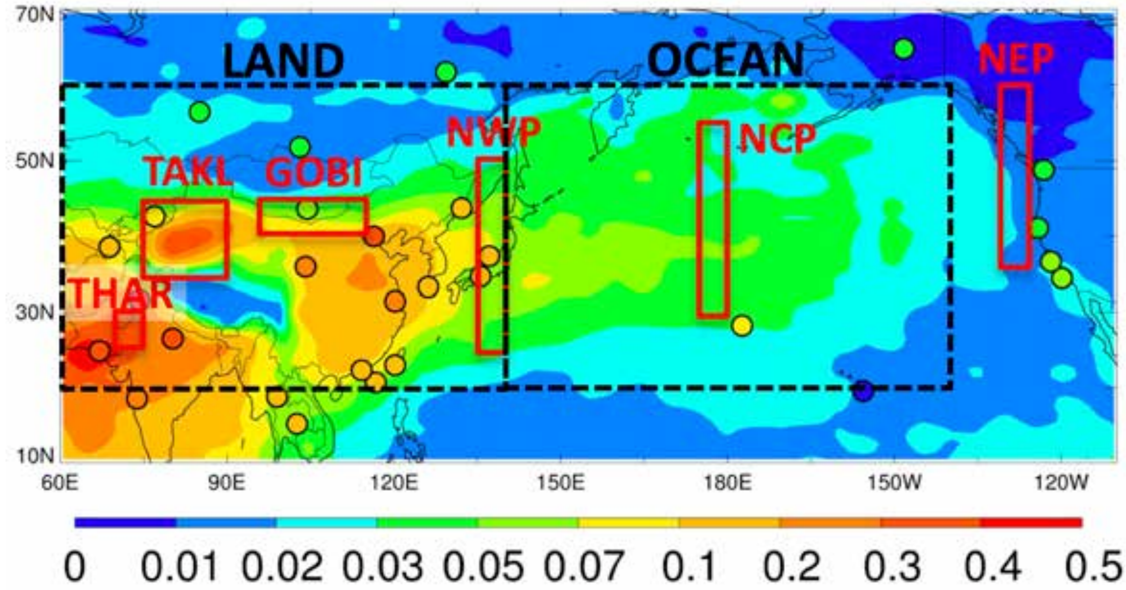
Figure 9. Mean dust emissions from models averaged from 2000 to 2005. Color contour unit is in $gkm^{-2}s^{-1}$.

Figure 10. Map of loss frequency, f_{WET}, and MEE for dust from models averaged from 2000 to 2005. (a) Loss frequency is the ratio of total removal rate to LOAD (day^{-1}), (b) f_{WET} is the fraction of wet removal to the total removal, and (c) MEE is dust mass extinction efficiency at 550 nm (m^2g^{-1}).

Figure 11. The partial sensitivity of DOD to various determining factors of Source (SRC = EMI + mass imbalance), residence time (RES), and mass extinction efficiency (MEE). Model values (GOCART, SPRINTARS, ECHAM5, HadGEM2, and GISS) are averaged for 2000-2005 over the domain (60°E-140°W, 20°N-60°N). "x" symbol of each model is the partial sensitivity of DOD to EMI within the domain. MO and CA are the mean DOD from MODIS and CALIOP averaged over the same time and domain, respectively.

Figure 12. Multi-model mean of optical and physical parameters over (a) Asia and North Africa and (b) Pacific ocean and Atlantic ocean. Models (GOCART, SPRINTARS, ECHAM5, HadGEM2, and GISS) are averaged from 2000 to 2005. Error bars are the standard deviation of model values.

Figure 13. (left) Spatial distribution of mean AOD, DOD, and f_{DOD} from CALIOP averaged for 2007-2011, where, CALIOP excludes clear-air samples. Color circles superimposed on the map represent AERONET data. (right) same as Figure 4a except for CALIOP excludes clear-air samples.



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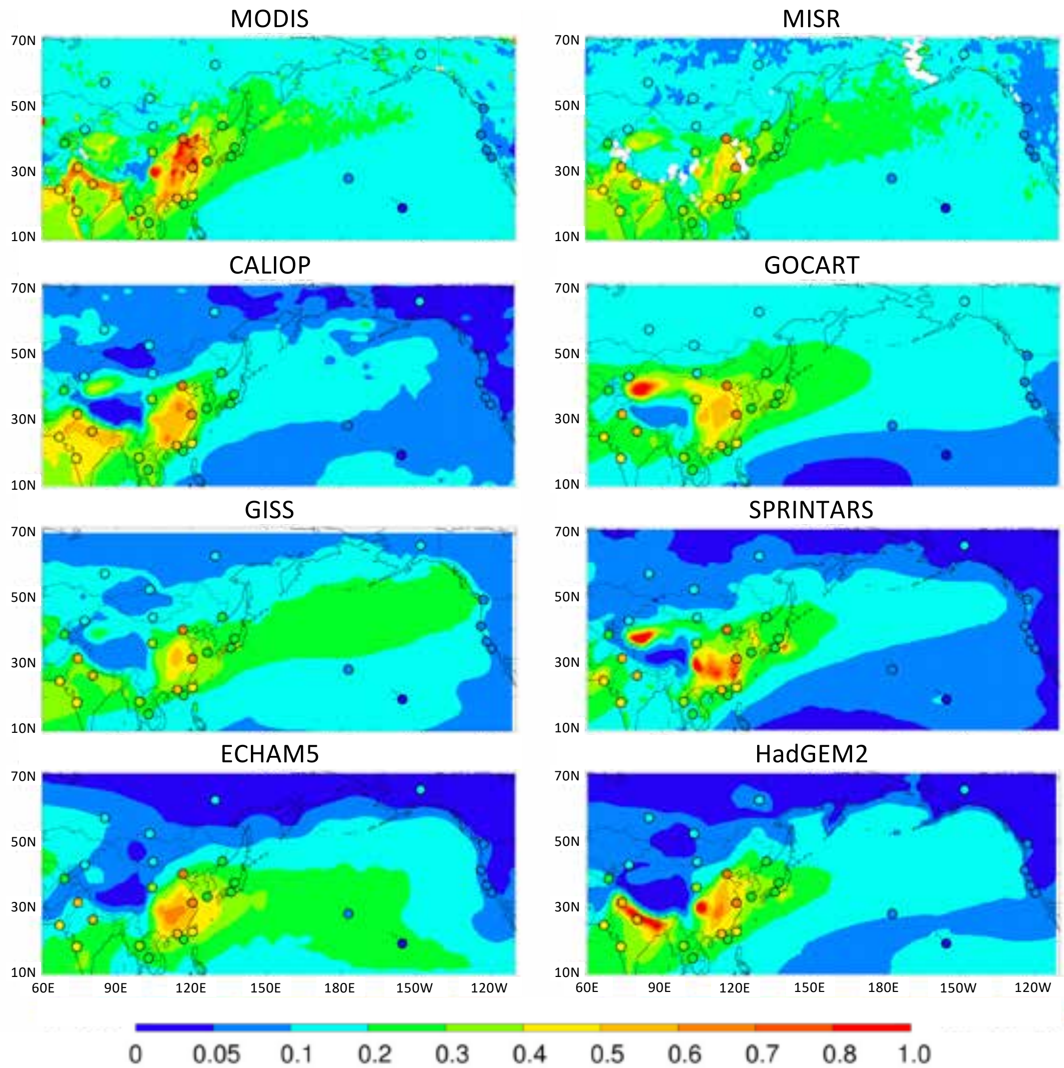

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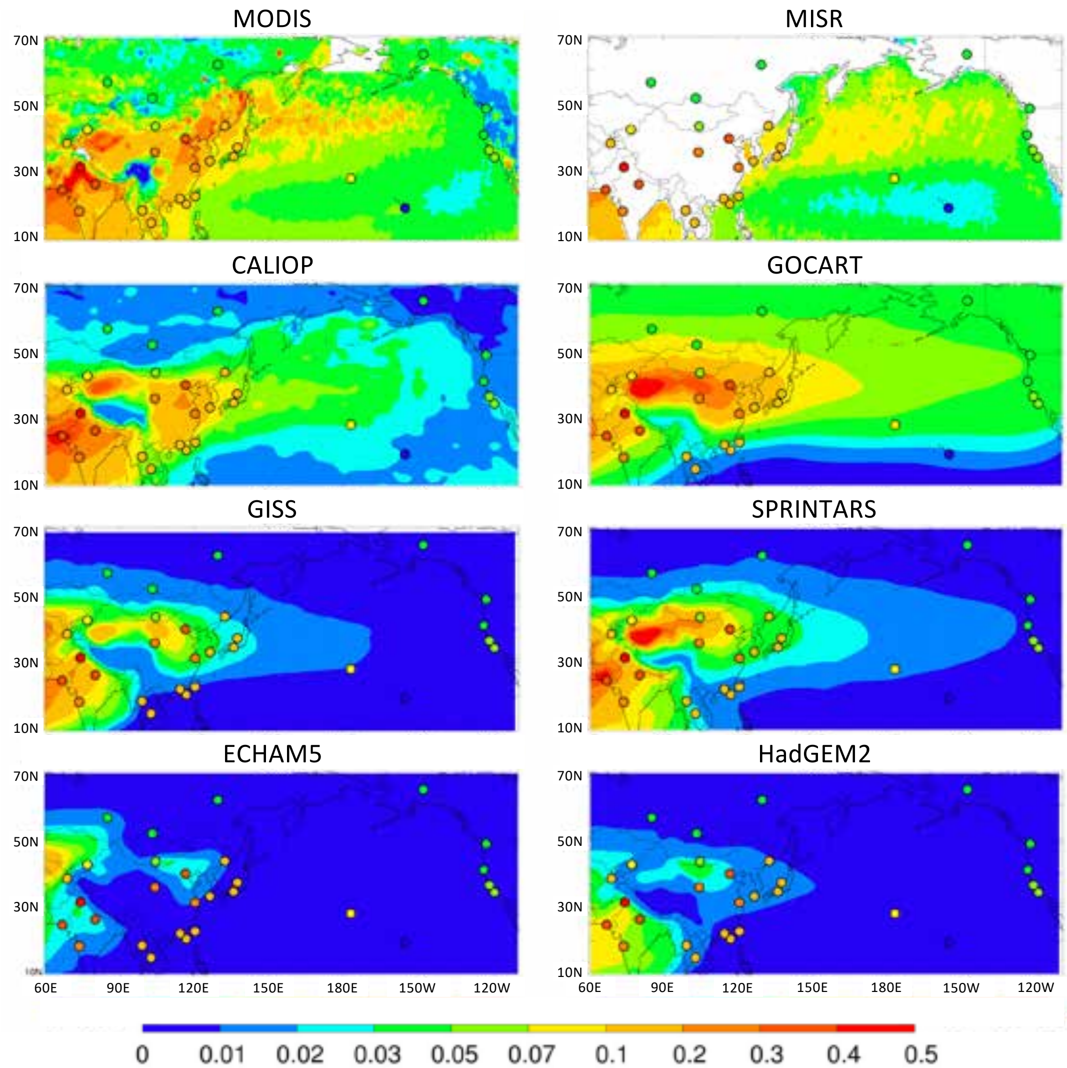

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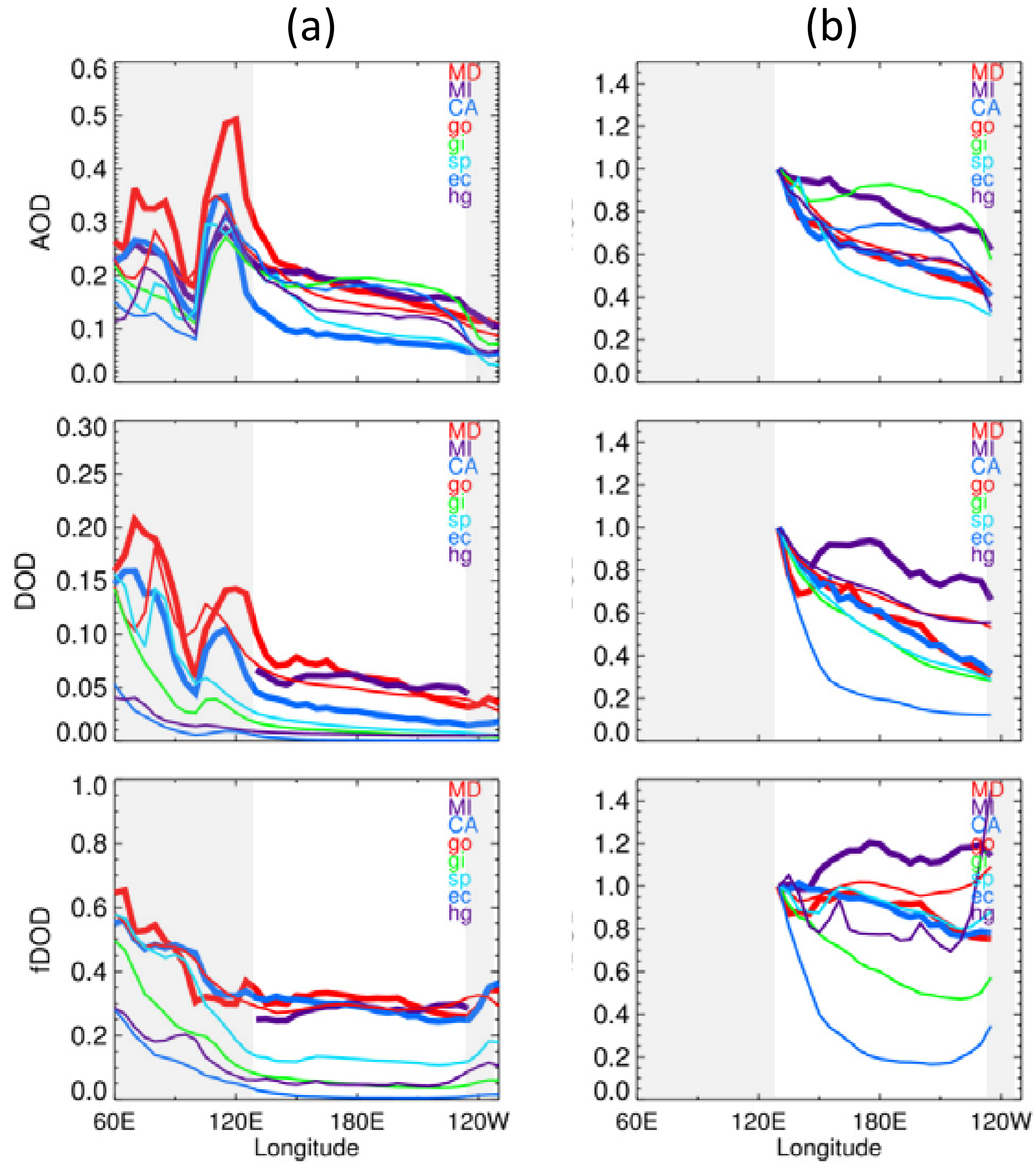

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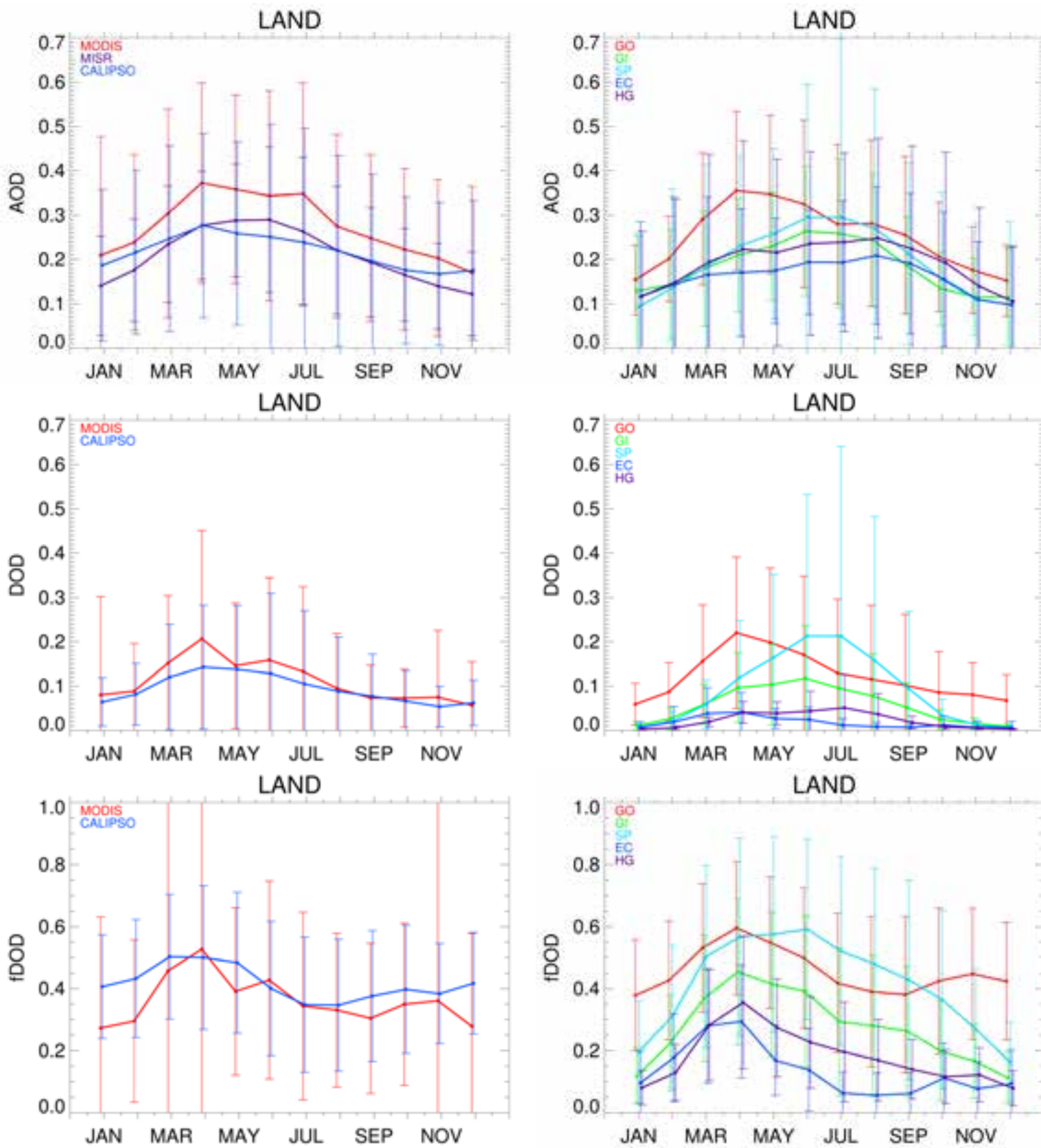

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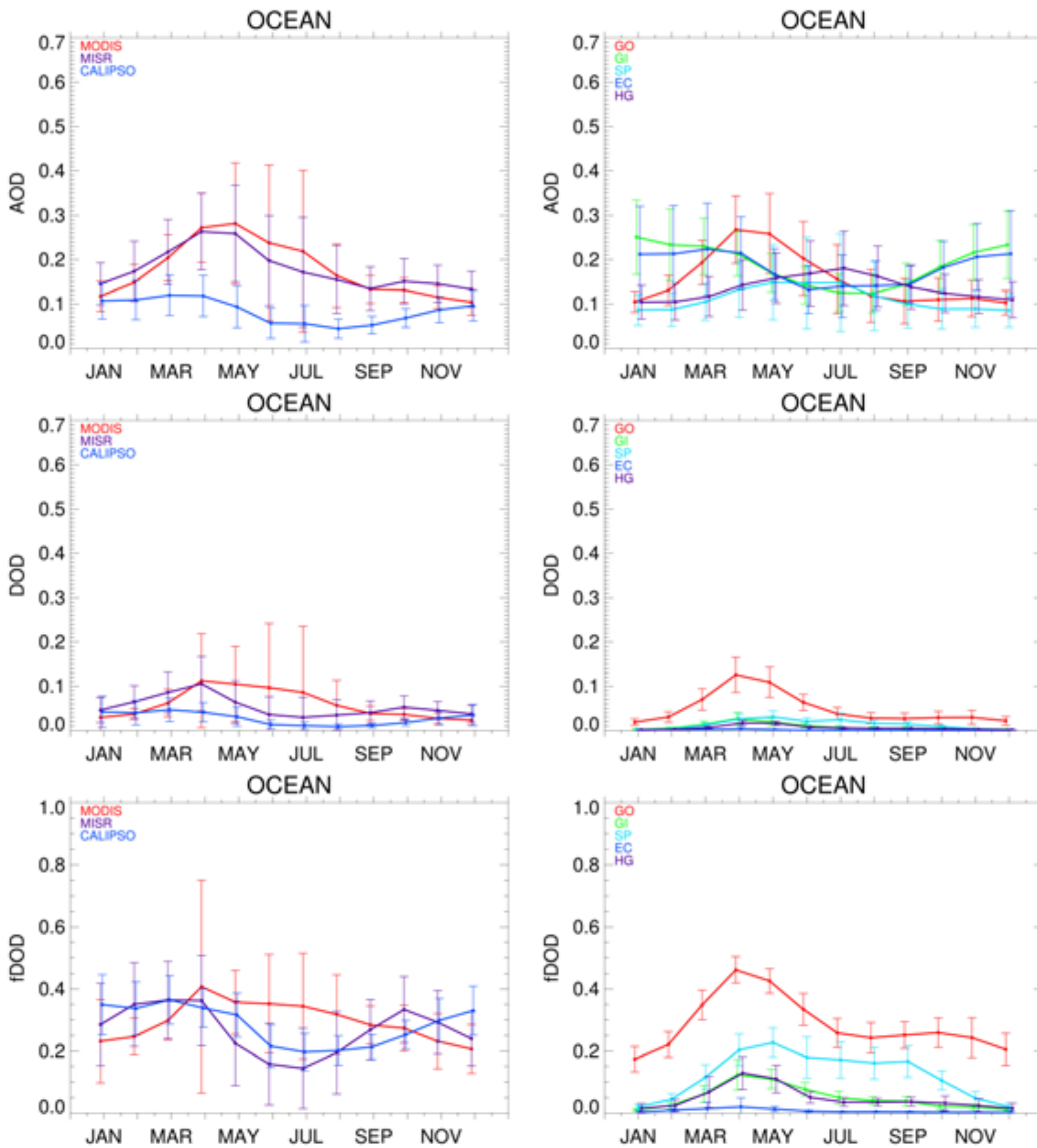

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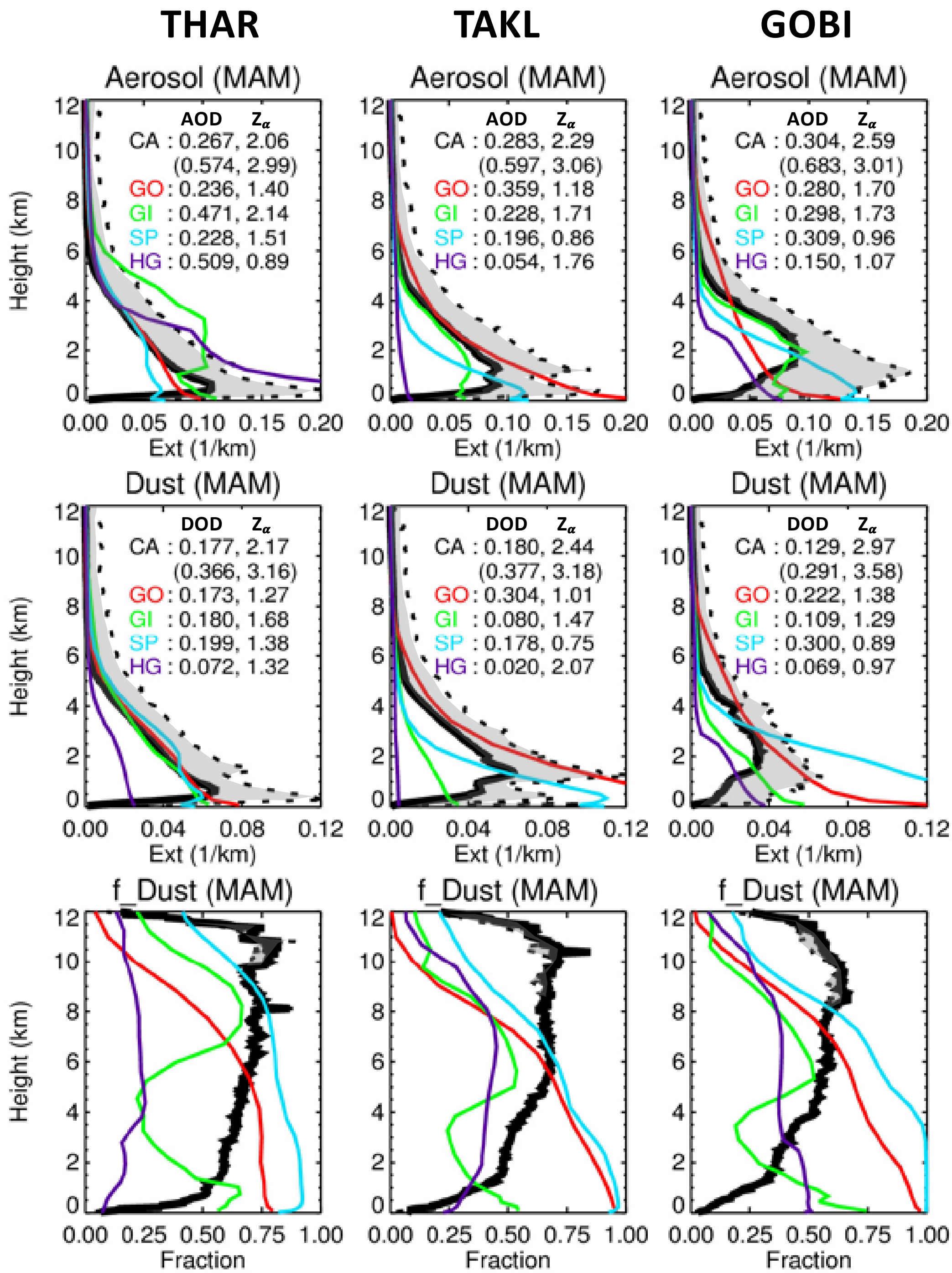

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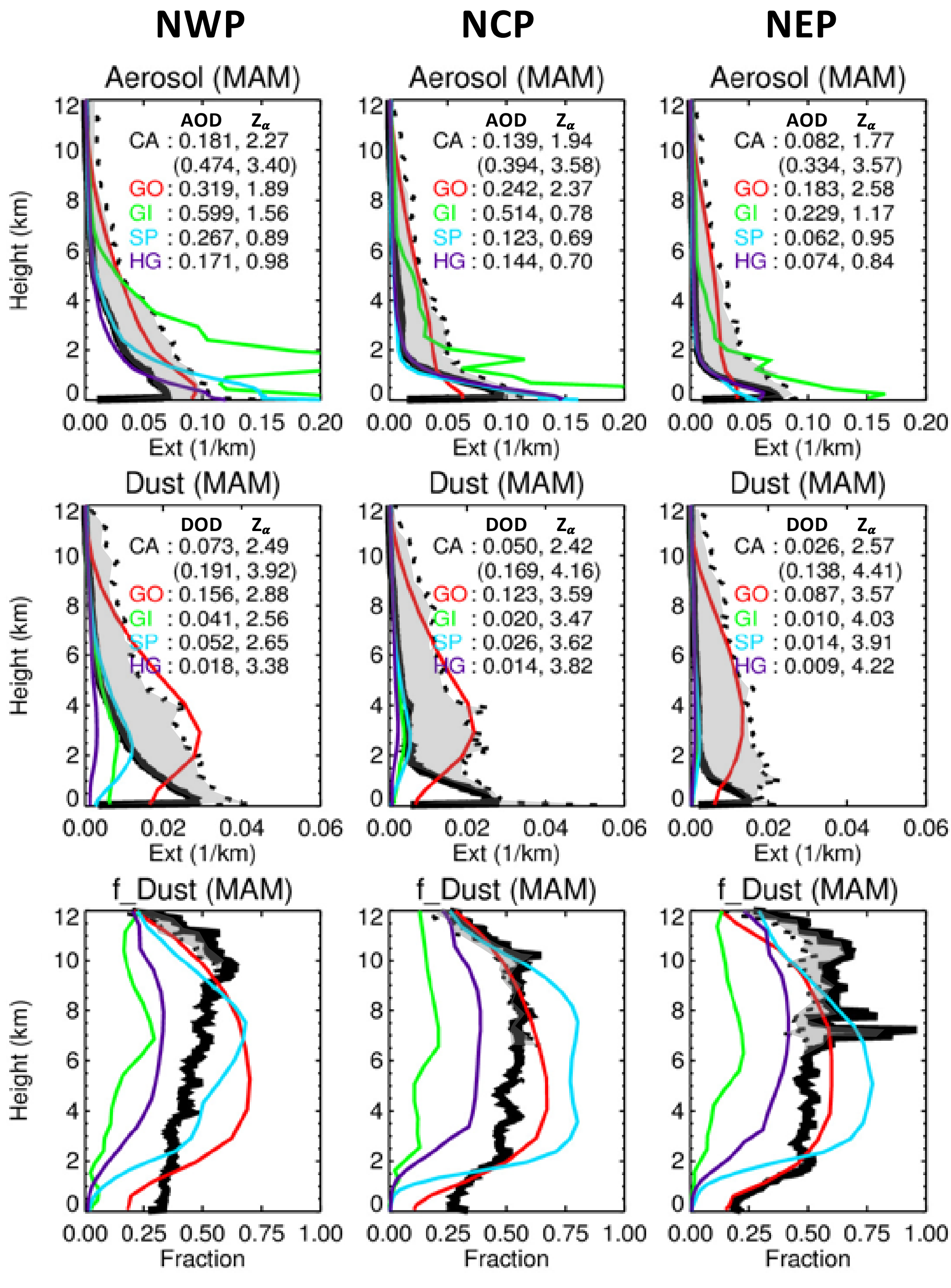

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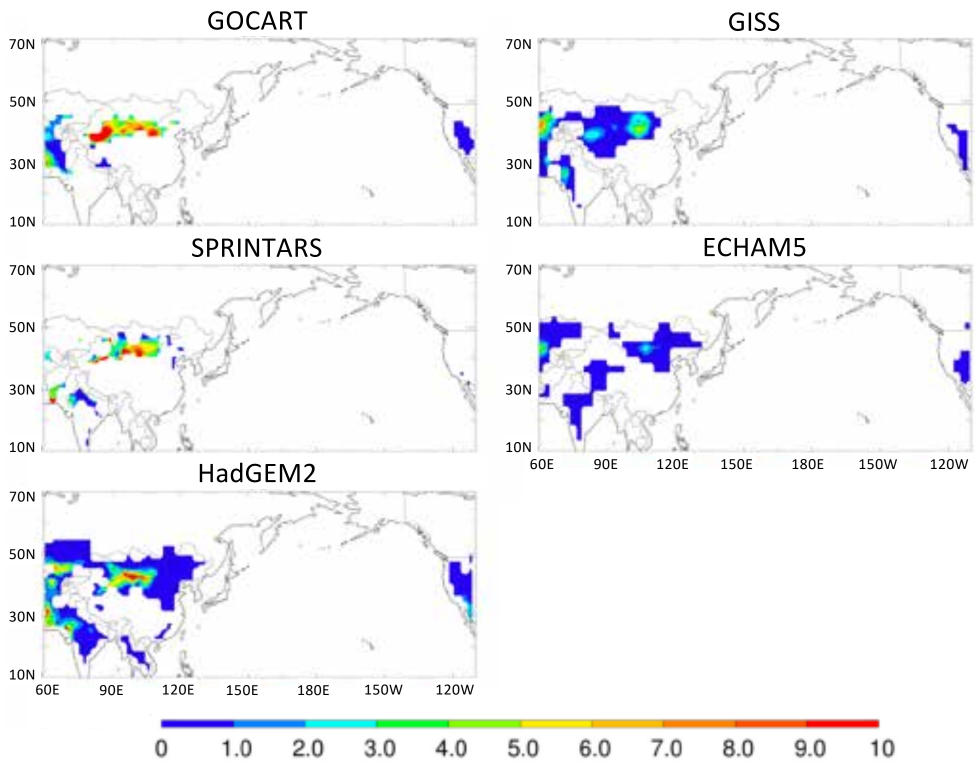

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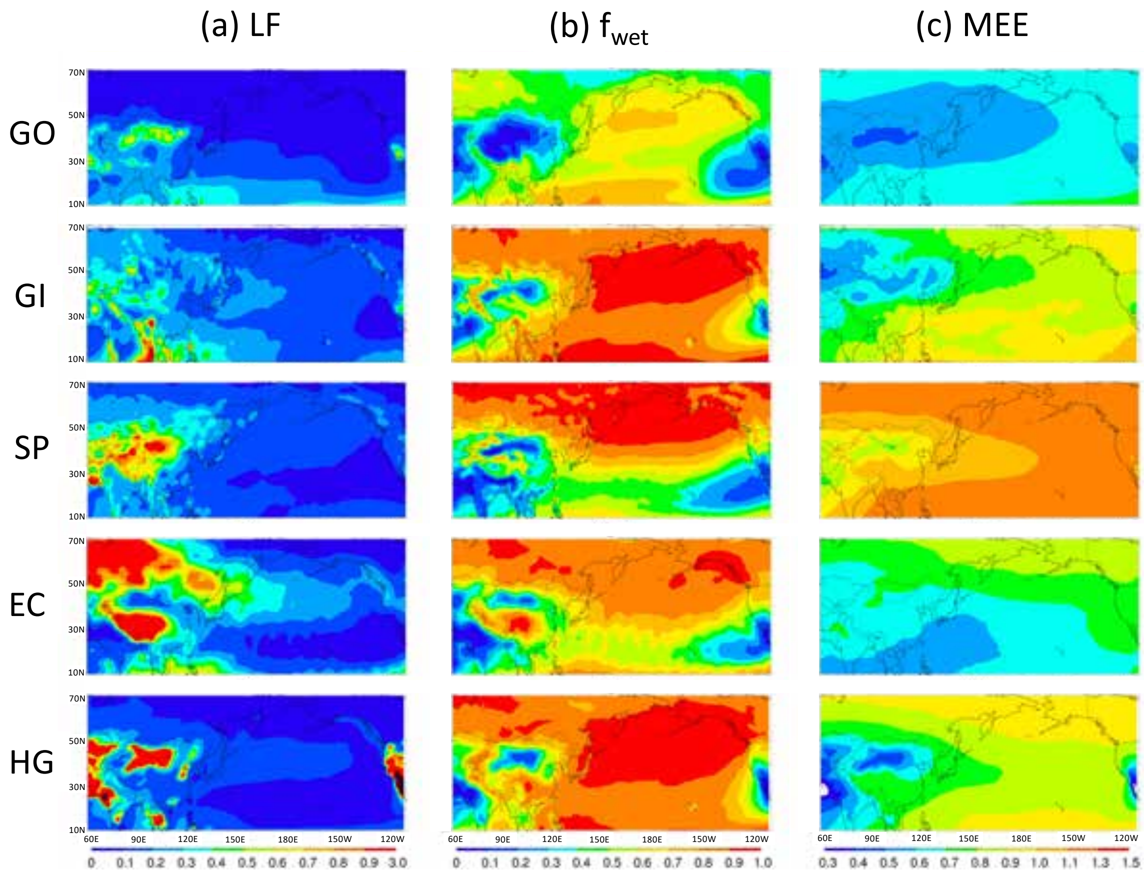

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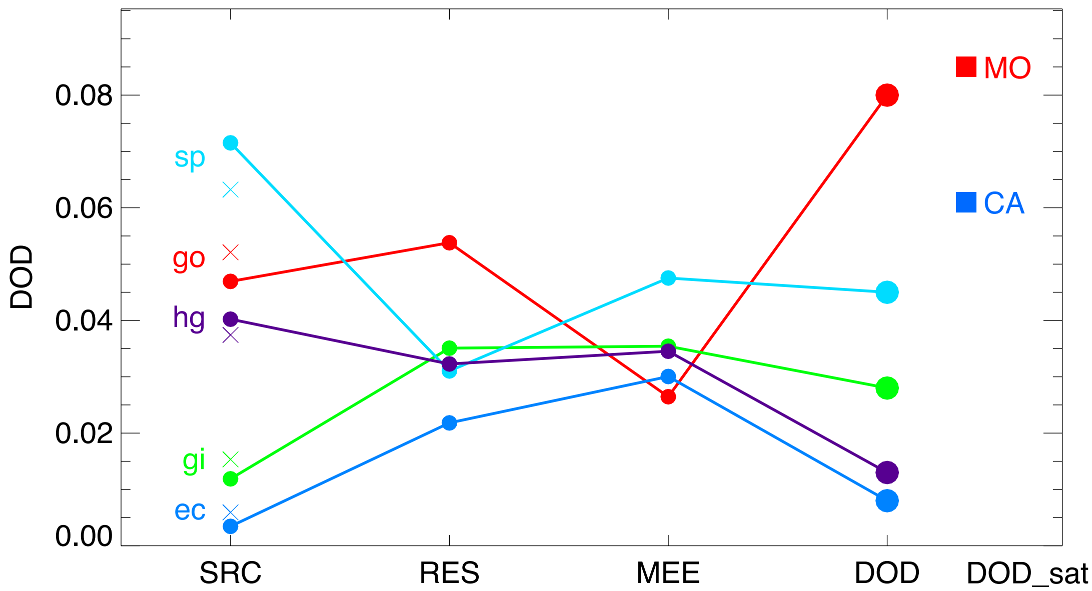

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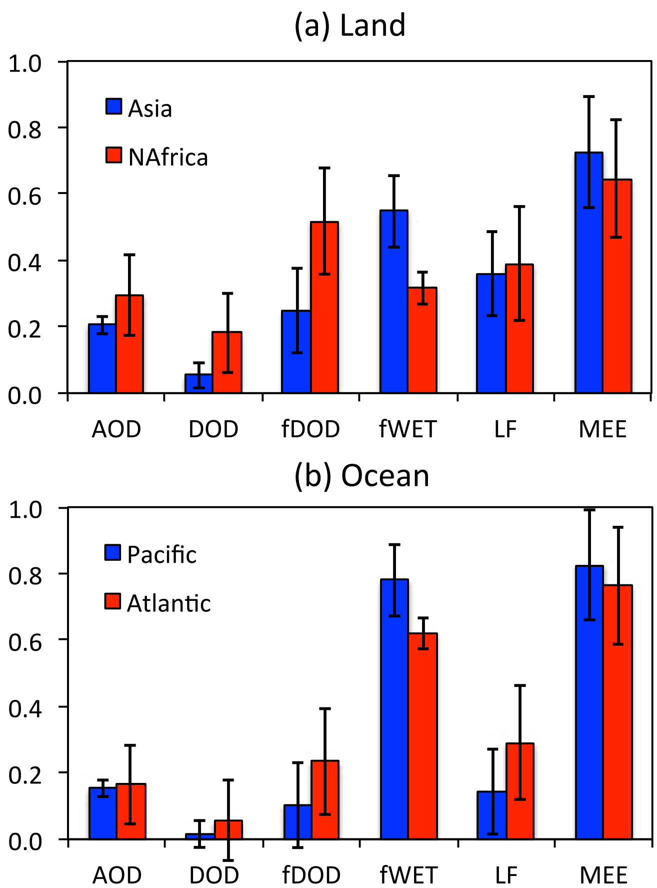

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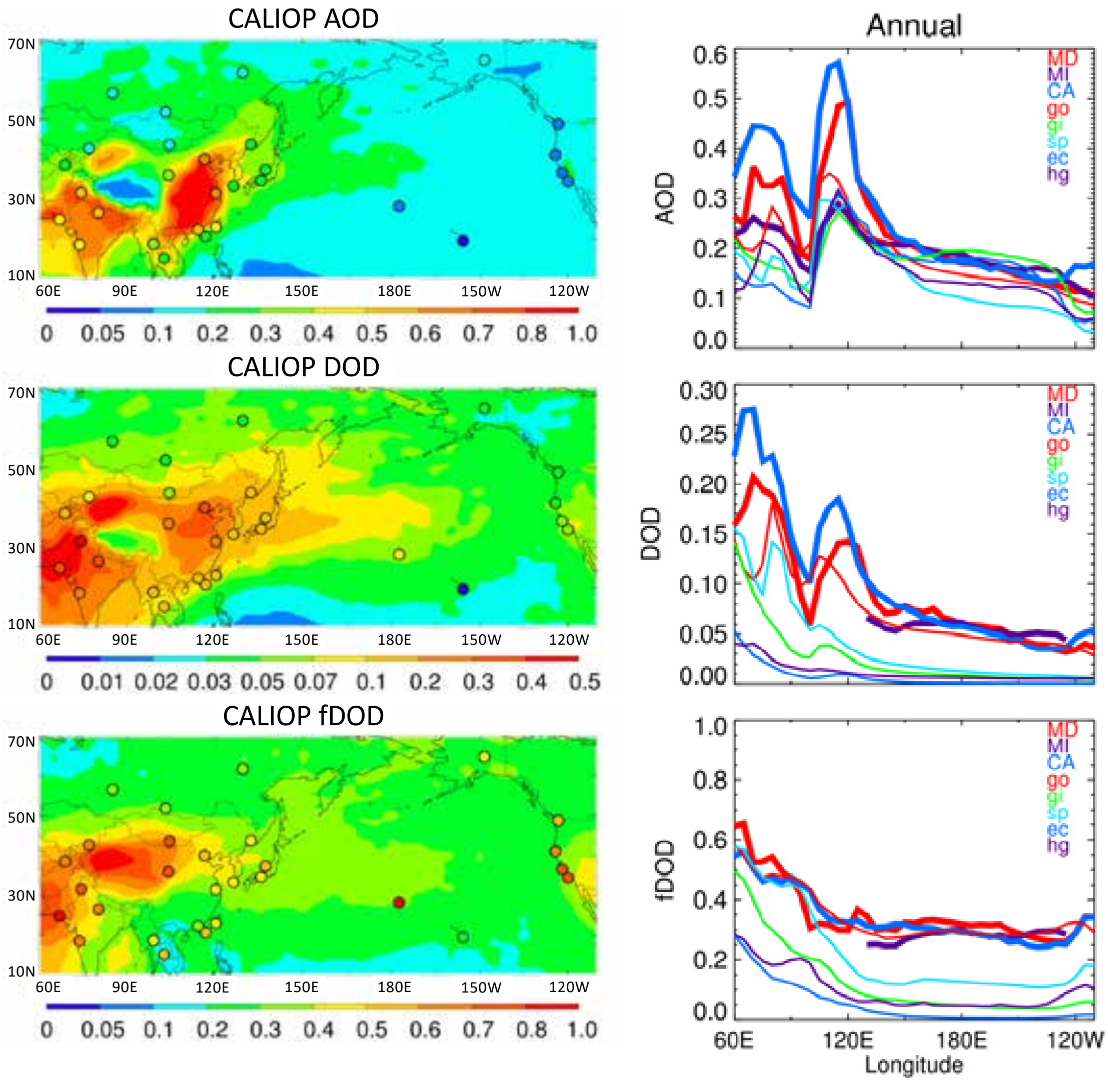

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Auxiliary Material for

Asian and trans-Pacific Dust: A multi-model and multi-remote sensing observation analysis

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[12]Norwegian Meteorological Institute, Oslo, Norway

Introduction

There are a supplement table and six supplement figures. File names and figure captions are presented.

1. Table_S1.docx: AERONET site name, longitude, and latitude.

2. Table_S2.docx: Mean emissions from the Taklimakan desert (75°E-90°E, 35°N-45°N), Gobi Desert (95°E-115°E, 40°N-50°N), and Thar desert (60°E-80°E, 20°N-40°N). SRC_{all} is the sum of TAKL, GOBI and THAR deserts; SRC_{TAGO} is the sum of TAKL, GOBI; Total is the entire domain (60°E-140°W, 20°N-60°N) and the values are taken from Figure 4.

3. Suppliment_Figirures.docx

Supplement Figure Captions

Figure S1. Number of data samples (ncount) in million for January 2007 - December 2011: (a) -100<CAD<-20 and include clear-air; (b) -100<CAD<-70 and include clear-air; (c) -100<CAD<-20 and exclude clear-air; (d) -100<CAD<-70 and exclude clear-air. (e) ncount (-100<CAD<-20, include clear-air) minus ncount (-100<CAD<-70, include clear-air), (f) ratio of exclude clear-air to include clear-air (-100<CAD<-70), (g) percent ratio of CAD<-20 to CAD<-70 (exclude clear-air).

Figure S2. Comparison of monthly mean AOD between AEROENT and other satellite data and model values over the study domain. Number of total data point is 474 between 2000 and 2005. R, B, and E are the correlation coefficient, mean bias, and root-mean-square-error, respectively. Mean bias is defined as the sum of the ratio of the modeled or satellite AOD to AERONET AOD.

Figure S3. Monthly mean AOD over Land-West (60°E-100°E), Land-East (100°E-140°E), Ocean-West (140°E-180°E), Ocean-East (180E°-140°W) domains from top to bottom. Latitudinal ranges are 20°N to 60°N. Left- and right-columns are from satellites and models, respectively. All model plots are averaged from 2000 to 2005. Vertical bars are the standard deviation of monthly mean values.

Figure S4. Same as Figure S3 except for DOD.

Figure S5. Same as Figure S3 except for f_{DOD}.

Figure S6. Monthly mean DOD for 2000-2005 over the Taklimakan desert.

Figure S7. Map of precipitation (mm day^{-1}) of each season from models averaged from 2000 to 2005.

Table S1. AERONET site name, longitude, and latitude.

Site Name	Longitude (°E)	Latitude (°N)
Issyk-Kul	76.98	42.62
Dushanbe	68.86	38.55
SACOL	104.14	35.95
Kanpur	80.23	26.51
Pimai	102.56	15.18
Dalanzadgad	104.42	43.58
Tomsk	85.05	56.48
Karachi	67.03	24.87
Lahore	74.33	31.54
Pune	73.81	18.54
Chiang_Mai_Met_Sta	98.97	18.77
Dongsha_Island	116.73	20.70
Hong_Kong_PolyU	114.18	22.30
Chen-Kung_Univ	120.22	23.00
Irkutsk	103.09	51.80
Yakutsk	129.37	61.66
Midway_Island	-177.38	28.21
Mauna_Loa	-155.58	19.54
Bonanza_Creek	-148.32	64.74
Trinidad_Head	-124.15	41.05
Saturn_Island	-123.13	48.78
UCSB	-119.85	34.42
Monterey	-121.86	36.59
Taihu	120.22	31.42
Beijing	116.38	39.98
Gosan_SNU	126.16	33.29
Osaka	135.59	34.65
Noto	137.14	37.33
Ussuriysk	132.16	43.70

Table S2. Mean emissions from the Taklimakan desert (75°E-90°E, 35°N-45°N), Gobi Desert (95°E-115°E, 40°N-50°N), and Thar desert (60°E-80°E, 20°N-40°N). SRC_{all} is the sum of TAKL, GOBI and THAR deserts; SRC_{TAGO} is the sum of TAKL, GOBI; Total is the entire domain (60°E-140°W, 20°N-60°N) and the values are taken from Figure 4.

Model	Emission (Tg yr^{-1})			Ratio		
	TAKL (TA)	GOBI (GO)	THAR (TH)	SRC_{all} / Total	SRC_{TAGO} / Total	TAKL / GOBI
GO	252.9	209.4	134.4	0.88	0.68	1.21
GI	30.6	51.0	49.5	0.66	0.41	0.60
SP	208.6	166.0	273.2	0.78	0.45	1.26
EC	1.4	24.7	7.1	0.43	0.34	0.06
HG	31.2	103.5	200.9	0.69	0.28	0.30
Mean	104.9	110.9	133.0	0.7	0.4	0.68
STD	116.5	77.2	108.5	0.2	0.2	0.54
DIV	111.0	69.6	81.6	24.4	35.9	78.30

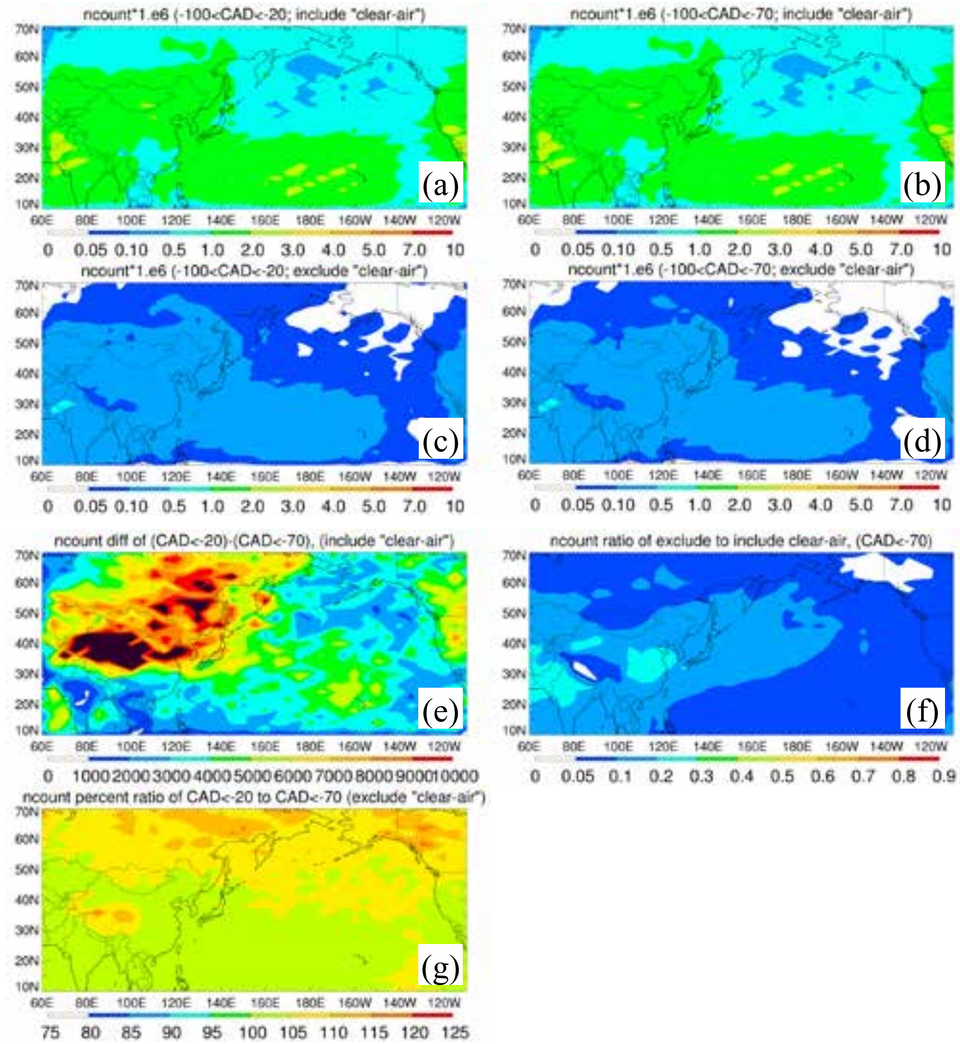

Figure S1. Number of data samples (ncount) in million for January 2007 - December 2011: (a) -100<CAD<-20 and include clear-air; (b) -100<CAD<-70 and include clear-air; (c) -100<CAD<-20 and exclude clear-air; (d) -100<CAD<-70 and exclude clear-air. (e) ncount (-100<CAD<-20, include clear-air) minus ncount (-100<CAD<-70, include clear-air), (f) ratio of exclude clear-air to include clear-air (-100<CAD<-70), (g) percent ratio of CAD<-20 to CAD<-70 (exclude clear-air).

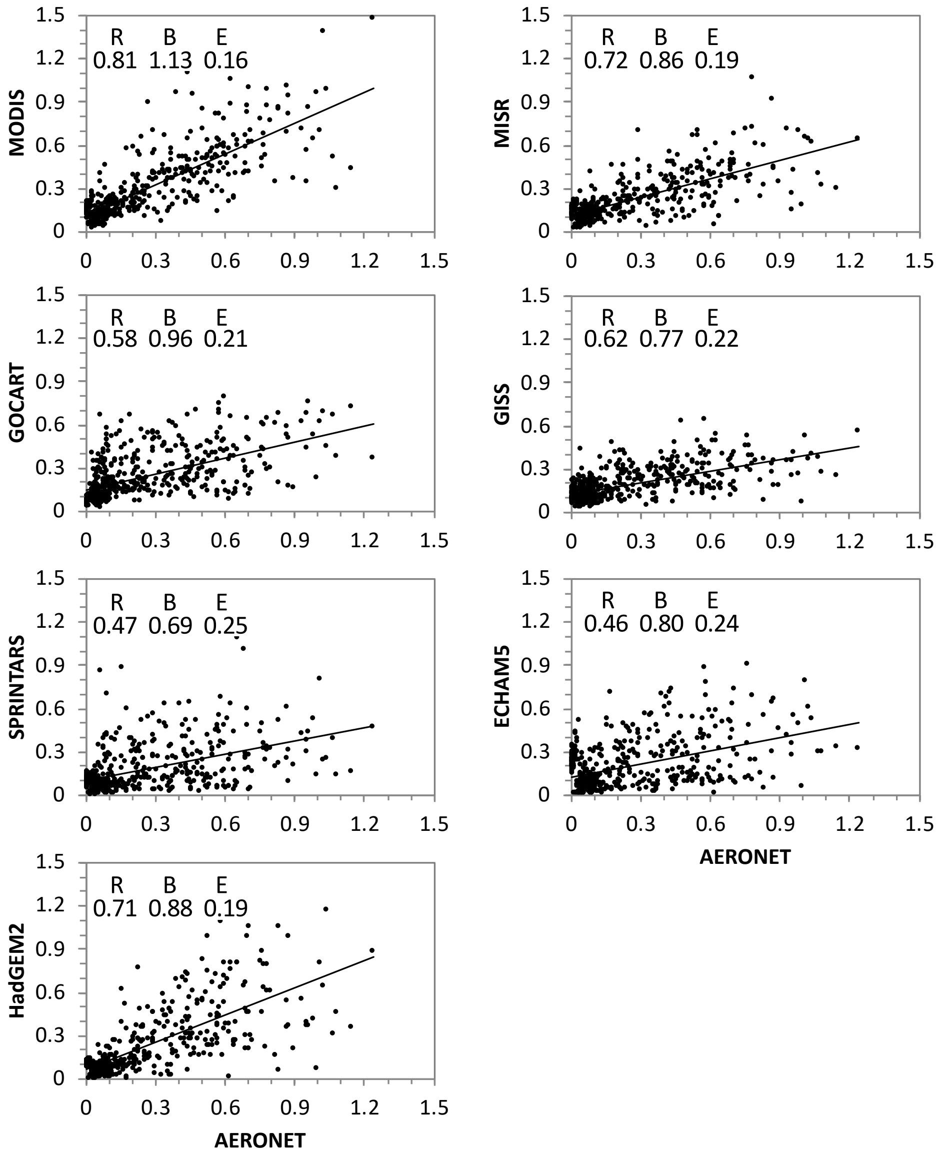

Figure S2. Comparison of monthly mean AOD between AEROENT and other satellite data and model values over the study domain. Number of total data point is 474 between 2000 and 2005. R, B, and E are the correlation coefficient, mean bias, and root-mean-square-error, respectively. Mean bias is defined as the sum of the ratio of the modeled or satellite AOD to AERONET AOD.

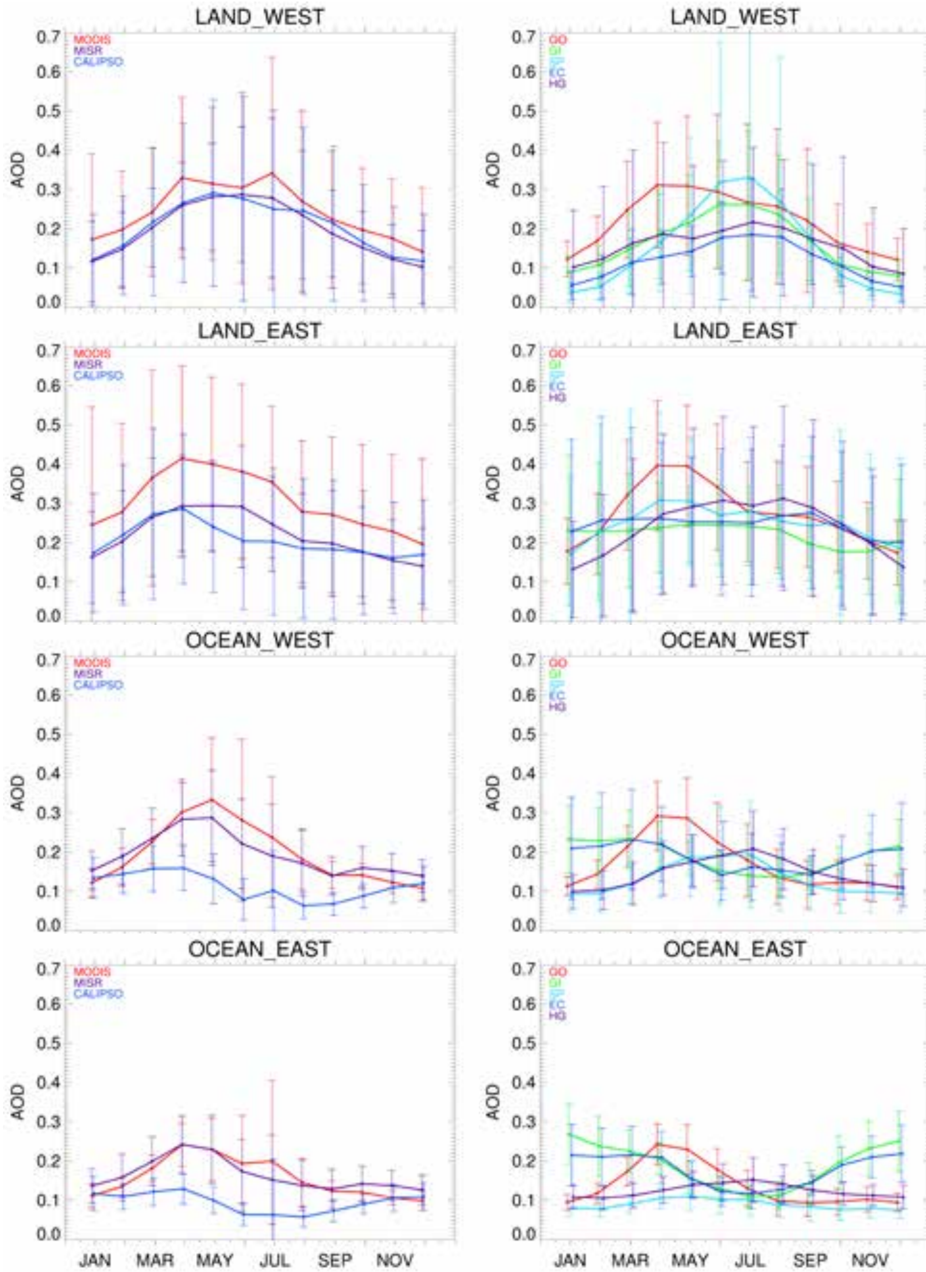

Figure S3. Monthly mean AOD over Land-West (60°E-100°E), Land-East (100°E-140°E), Ocean-West (140°E-180°E), Ocean-East (180E°-140°W) domains from top to bottom. Latitudinal ranges are 20°N to 60°N. Left- and right-columns are from satellites and models, respectively. All model plots are averaged from 2000 to 2005. Vertical bars are the standard deviation of monthly mean values.

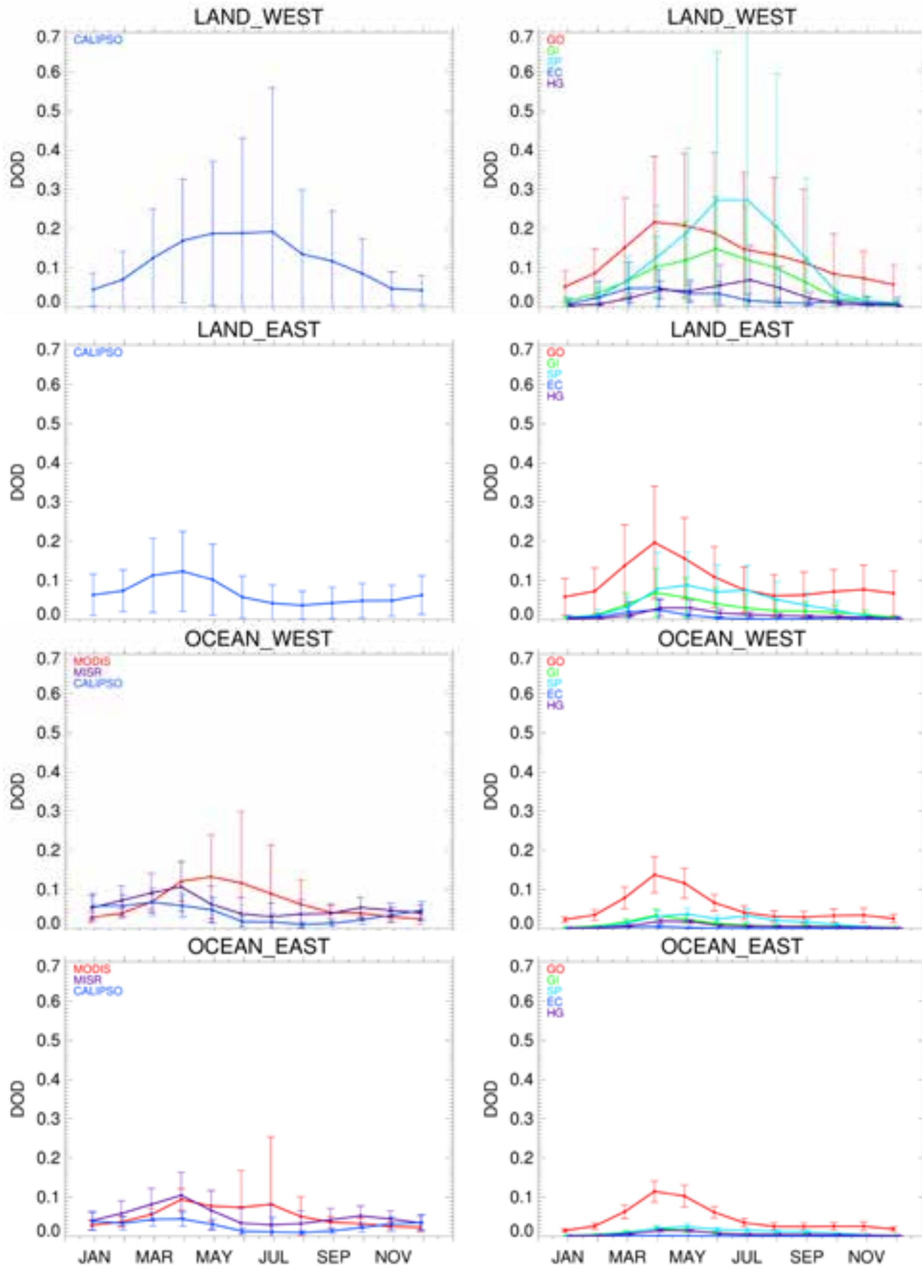

Figure S4. Same as Figure S3 except for DOD.

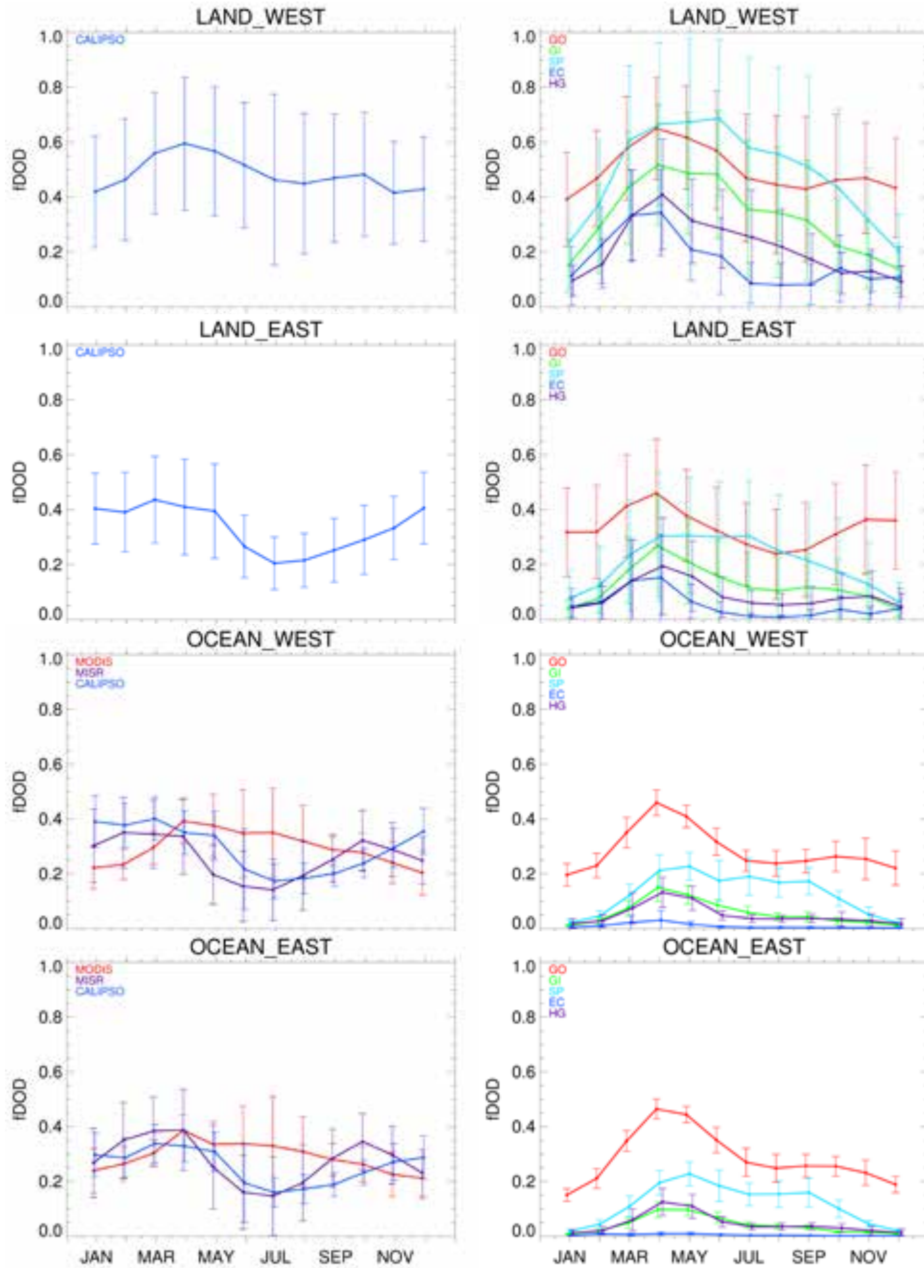

Figure S5. Same as Figure S3 except for f_{DOD}.

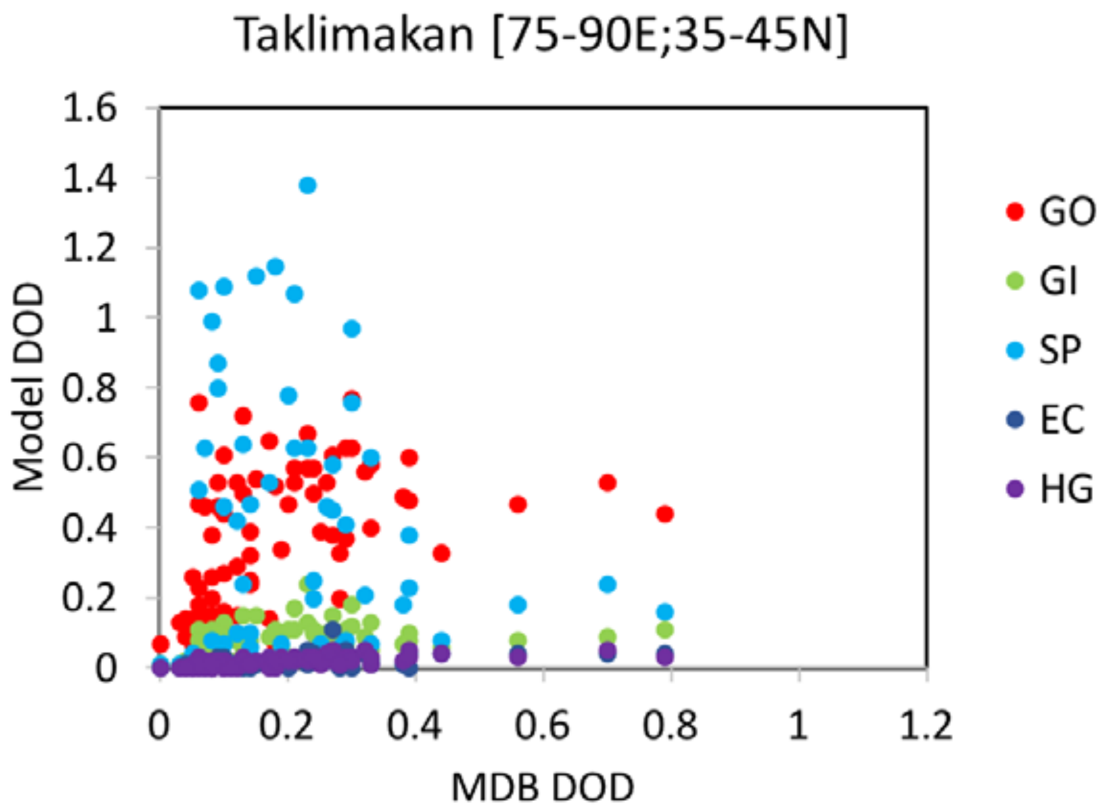

Figure S6. Monthly mean DOD for 2000-2005 over the Taklimakan desert.

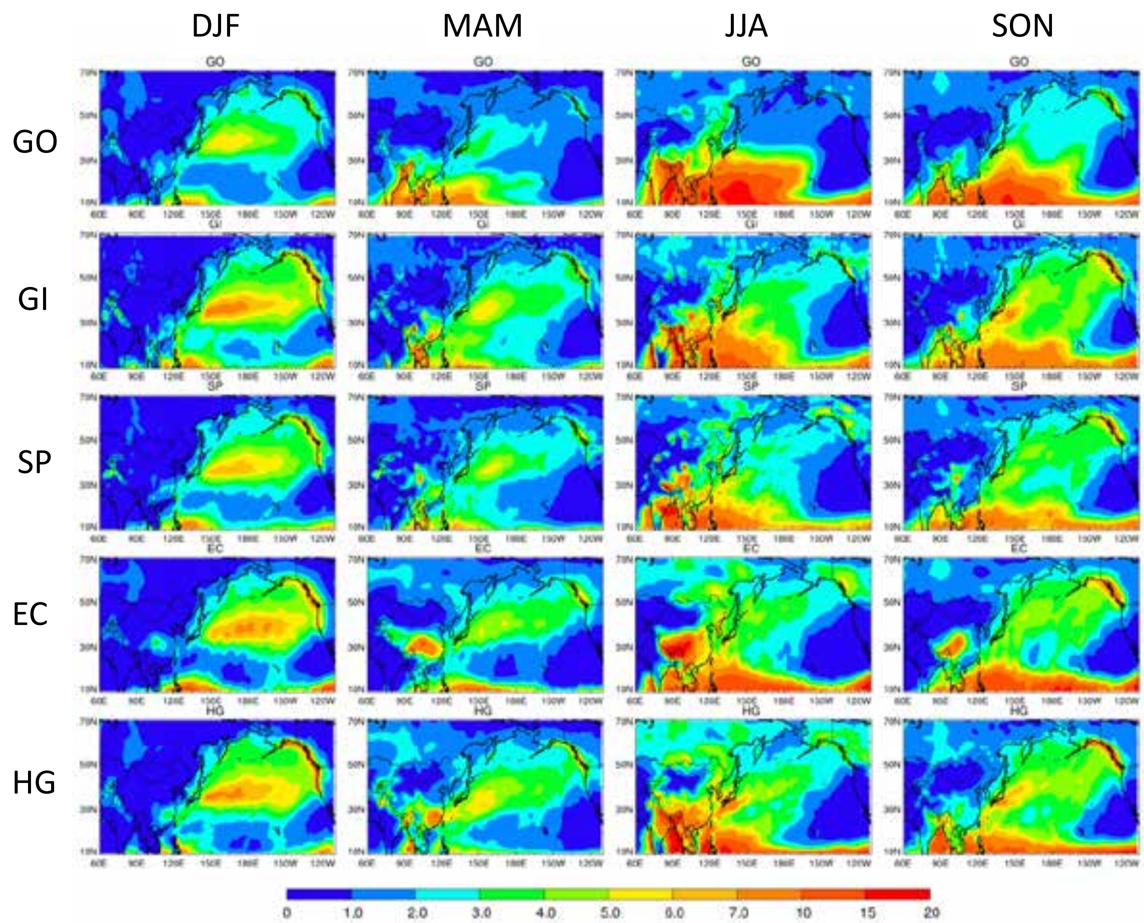

Figure S7. Map of precipitation (mm day^{-1}) of each season from models averaged from 2000 to 2005.