Final Report DE-SC0014641

Final Progress Report
(DOE Award Number, **DE-SC0014641**)

**Project Title: Evaluation of NCAR CAM5 Simulated Marine Boundary Layer Cloud Properties Using A Combination of Satellite And Surface Observations**

**Principle Investigator**: Dr. Zhibo Zhang
Department of Physics
University of Maryland, Baltimore County (UMBC)
Baltimore, Maryland, 21250
Tel: (410) 455-6315; Fax: 410-455-1072
Email: zhibo.zhang@umbc.edu

**Co-Investigator**: Dr. Xiquan Dong
Department of Hydrology and Atmospheric Sciences
University of Arizona

**Co-Investigator**: Dr. Po-Lun Ma
Pacific Northwest National Laboratory
Department of Energy

## 1. Highlight of Key Achievements

The main objective of the project is to systematically evaluate the marine boundary layer (MBL) cloud properties simulated in three versions of Community Atmosphere Model (CAM5) models, including the CAM5-Base, CAM5-CLUBB and SP-CAM5, using a combination of satellite-based CloudSat/MODIS observations and ground-based observations from the ARM Azores site, with a special focus on MBL cloud microphysics and warm rain process. I am pleased to report that we have successfully finished the project and achieved all the proposed research and educational objectives. During the funding period, we published **six (6)** peer-reviewed articles in highly-quality journals, including one in PNAS (Proceedings of the National Academy of Sciences of the United States of America). Our research has been reported in several popular publications, newsletters and blogs. The funding has helped PI supported 1 graduate student and one postdoctoral researcher at UMBC. The PI of the project, Zhibo Zhang, has been invited to talk about the research funded by this grant in numerous national and inter-national conferences.

**Publications supported by this project:**

1. ***Zhang, Z.,*** *H. Song, P.-L. Ma, V. E. Larson, M. Wang, X. Dong, and J. Wang (2019), Subgrid variations of the cloud water and droplet number concentration over the tropical ocean: satellite observations and implications for warm rain simulations in climate models, Atmospheric Chemistry and Physics, 19(2), 1077–1096, doi:10.5194/acp-19-1077-2019.*

2. *Wu, P., B. Xi, X. Dong, and* ***Z. Zhang*** *(2018), Evaluation of autoconversion and accretion enhancement factors in general circulation model warm-rain parameterizations using ground-based measurements over the Azores, Atmospheric Chemistry and Physics, 18(23), 17405–17420, doi:10.5194/acp-18-17405-2018.*

3. *Song, H.,* ***Zhang, Z.,*** *Ma, P.-L., Ghan, S., and Wang, M. (2018): The Importance of Considering Sub-grid Cloud Variability When Using Satellite Observations to Evaluate the Cloud and Precipitation Simulations in Climate Models, Geosci. Model Dev., https://doi.org/10.5194/gmd-2018-13*

4. *Song, H.,* ***Z. Zhang****, P.-L. Ma, S. J. Ghan, M. Wang, and H. Song (2018), An Evaluation of Marine Boundary Layer Cloud Property Simulations in the Community Atmosphere Model Using Satellite Observations: Conventional Subgrid Parameterization versus CLUBB, Journal of Climate, 31(6), 2299–2320, doi:10.1175/JCLI-D-17-0277.1.*

5. *Lu, Z., X. Liu,* ***Z. Zhang****, C. Zhao, K. Meyer, C. Rajapakshe, C. Wu, Z. Yang, and J. E. Penner (2018), Biomass smoke from southern Africa can significantly enhance the brightness of stratocumulus over the southeastern Atlantic Ocean, PNAS, 115(12), 201713703–2929, doi:10.1073/pnas.1713703115.*

6. ***Zhang, Z****., X. Dong, B. Xi, H. Song, P.-L. Ma, S. J. Ghan, S. Platnick, and P. Minnis (2017), Intercomparisons of marine boundary layer cloud properties from the ARM CAP-MBL campaign and two MODIS cloud products, J. Geophys. Res. Atmos., 122, 2351–2365, doi:10.1002/2016JD025763.*

**Press release and media report**

- **Phys.org reports on our publication Zhang et al. 2016**
  - **https://phys.org/news/2017-04-satellites-ground-based-instruments-cloud-characteristics.html**
- **PNNL reports on Zhang et al. 2016**
  - **https://www.pnnl.gov/science/highlights/highlight.asp?id=4580**
- **Phys.org reports on our publication Lu et al. 2018**
  - **https://phys.org/news/2018-03-physicists-interactions-clouds-unexpected-cooling.html**
- **UMBC reports on our publication Lu et al. 2018**
  - **https://news.umbc.edu/umbc-physicists-discover-unexpected-effect-of-african-wildfires-on-climate/**

## 2. Background

Marine boundary layer (MBL) clouds are a strong modulator of Earth's radiative energy budget. The feedback of MBL clouds in a changing climate remains one of the largest uncertainties in our understanding of climate sensitivity, and recent studies have also suggested that radiative feedbacks related to MBL clouds may play an important role in low-frequency climate variabilities such as the Atlantic multidecadal oscillation. Despite their importance in the climate system, simulating MBL clouds in Earth system models (ESMs) has proved to be extremely challenging. The overarching objective of this proposal is to evaluate the MBL cloud simulation skills of the CAM5 with different cloud parameterization schemes through systematic comparison with both ground- and satellite based cloud observations. In particular, we seek to understand the advantages and limitations of the newly developed subgrid cloud parameterization scheme CLUBB (Cloud Layers Unified By Binormals) for simulation MBL clouds through comparisons of CAM5-CLUBB simulations with ARM (CAP-MBL campaign data) and satellite observations, as well as the "conventional" CAM5 and a CAM5 with the so-called super-parameterization (i.e., CAM5-MMF). In the rest of this report, we will briefly highlight our major research achievements.

## 3. Research Achievements

### 3.1. A systematic comparison of ground- and satellite-based MBL cloud property retrievals at DOE ENA site

A major goal of this proposal is to use both ground-based and satellite-based cloud measurement to assess cloud simulations in GCMs. To achieve this goal, a necessary and important step is to identify and understand the differences between ground- and satellite-based measurements. The differences can be considered as observation uncertainties that are important for model evaluations. Therefore, we carried out an inter-comparison of two satellite-based (i.e., MODIS) cloud products and ground-based cloud optical and microphysical property retrievals over DOE ARM Azores site. The first MODIS product is the "MOD06" product developed and maintained by a science team at NASA's Goddard Space Flight Center (GSFC). The other one is developed by a science team at

NASA's Langley Research Center, as part of the Clouds and Earth's Radiant Energy System (CERES) project. Both products are widely used for climate and aerosol-cloud interaction studies. We have identified 63 daytime cases when MODIS overpassed the ARM Azores site during Sept. 2009 ~ December 2010 period. We compared a variety of cloud property retrievals, namely, cloud liquid water path (LWP), cloud optical thickness (COT), and cloud-droplet effective radius (CER).

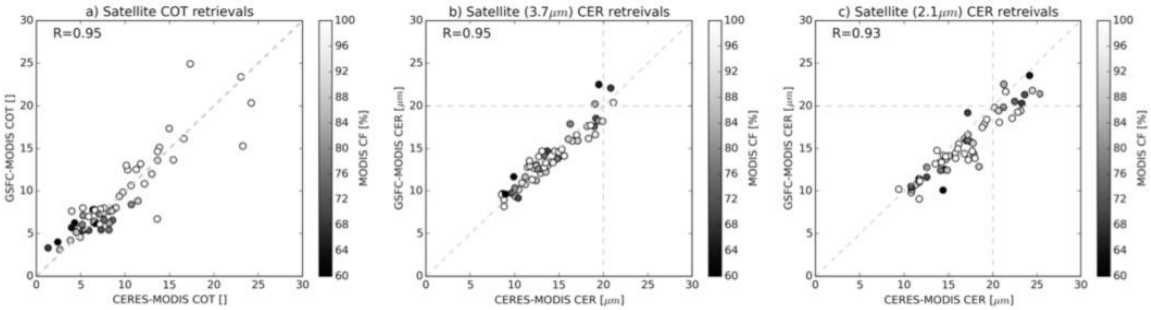


*Figure 1 Comparison of (a) COT, (b) CER2.1, and (c) CER3.7 of MBL clouds between collocated the CERES-MODIS and GSFC-MODIS products for the 63 selected cases.*

As shown in the Figure 1, comparison of collocated retrievals indicates that the two MODIS cloud products agree well on both COT and CER retrievals, with the correlation coefficient R > 0.95, despite their significant difference in spatial sampling. In both MODIS products, the CER retrievals based on the 2.1 μm band (CER2.1) are significantly larger than those based on the 3.7 μm band (CER3.7). The GSFC-MODIS cloud product is collocated and compared with ground-based ARM observations at several temporal-spatial scales. As shown in Figure 2, In general, the correlation increases with more precise collocation., for the 63 selected MBL cloud cases, the GSFC-MODIS LWP and COT retrievals agree reasonably well with the ground-based observations with no apparent bias and correlation coefficient R around 0.85 and 0.70, respectively. However, GSFC-MODIS CER3.7 and CER2.1 retrievals have a lower correlation (R ~ 0.5) with the ground-based retrievals. For the 63 selected cases, they are on average larger than ground observations by about 1.5 μm and 3.0 μm, respectively. Taking into account that the MODIS CER retrievals are only sensitive to cloud top reduces the bias only by 0.5 μm.

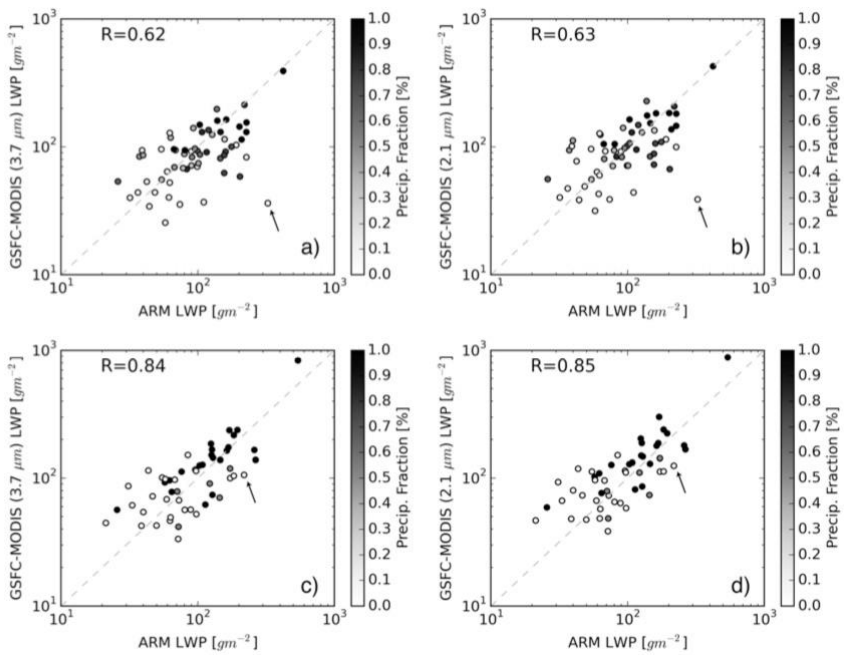


*Figure 2Comparisons of ground-based LWP retrievals from MWR with the GSFC-MODIS (a) LWP2.1 and (b) LWP3.7 products using the dL30km-dt60min averaging scheme. (c and d) Same as Figures 5a and 5b except for the averages from the dL10km-dt10min scheme. Gray scale of the dots corresponds to the fraction of precipitating MBL clouds during the temporal averaging window according to the ARM ground-based MMCR observations.*

### 3.2. An Evaluation of Marine Boundary Layer Cloud Property Simulations in the Community Atmosphere Model Using Satellite Observations: Conventional Subgrid Parameterization versus CLUBB

As a major part of this research project, we performed a two-step evaluation of the marine boundary layer (MBL) cloud properties from two Community Atmospheric Model (version 5.3, CAM5) simulations, one based on the CAM5 standard parameterization schemes (CAM5-Base), and the other on the Cloud Layers Unified By Binormals (CLUBB) scheme (CAM5-CLUBB). In the first step, we compare the cloud properties directly from model outputs between the two simulations. As shown in Figure 3, we find that the CAM5-CLUBB run produces more MBL clouds in the tropical and subtropical large-scale descending regions. Moreover, the stratocumulus (Sc) to cumulus (Cu) cloud regime transition is much smoother in CAM5-CLUBB than in CAM5-Base. In addition, in CAM5-Base we find some grid cells with very small low cloud fraction (<20%) to have very high in-cloud water content (mixing ratio up to 400mg/kg). We find no such grid cells in the CAM5-CLUBB run. However, we also note that both

simulations, especially CAM5-CLUBB, produce a significant amount of “empty” low cloud cells with significant cloud fraction (up to 70%) and near-zero in-cloud water content.

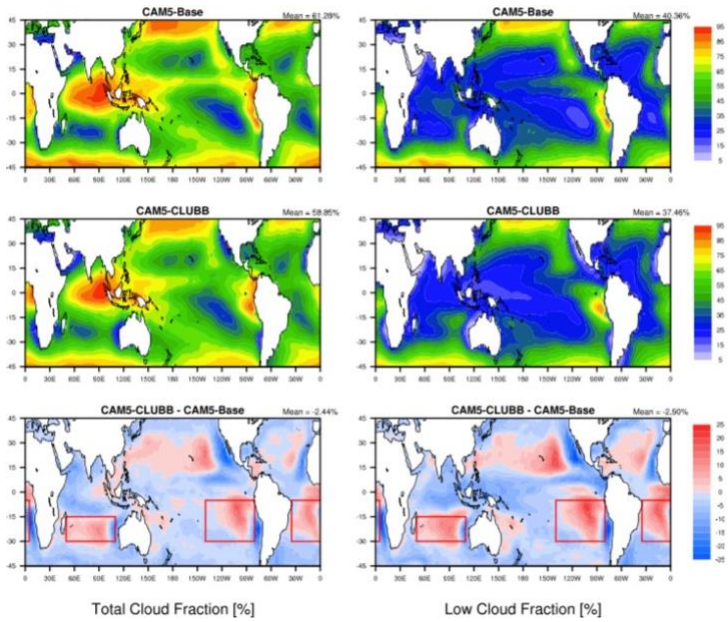


*Figure 3 (left) Total cloud fraction (%) and (right) low cloud fraction (%) averaged over the 2-yr simulation of (top) CAM5–Base, (middle) CAM5–CLUBB, and (bottom) the difference between the two.*

In the second step, we use satellite observations from CERES, MODIS and CloudSat to evaluate the simulated MBL cloud properties by employing the COSP satellite simulators. We note that a feature of the COSP-MODIS simulator to mimic the minimum detection threshold of MODIS cloud masking removes much more low clouds from CAM5-CLUBB than it does from CAM5-Base (see Figure 4 below). This leads to a surprising result — in the large-scale descending regions CAM5-CLUBB has a smaller COSP-MODIS cloud fraction and weaker shortwave cloud radiative forcing than CAM5-Base. A sensitivity study suggests that this is because CAM5-CLUBB suffer more from the above-mentioned “empty” clouds issue than CAM5-Base.

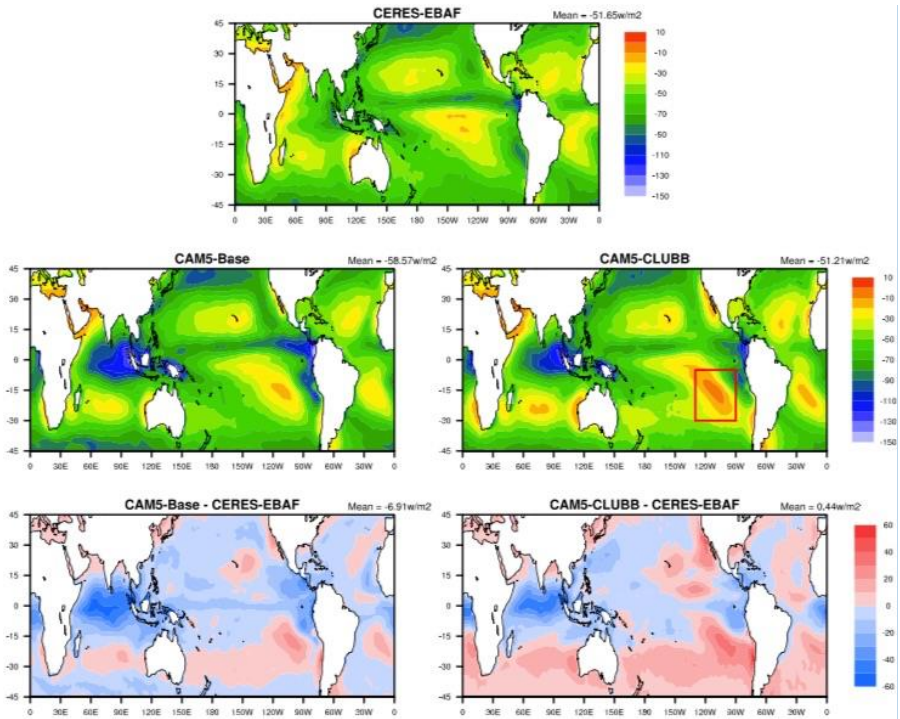


*Figure 4 Annual mean SWCF (W m22) in the (top) CERES–EBAF observation, (middle left) CAM5–Base, and (middle right) CAM5– CLUBB. Difference in SWCF (W m22) between the two simulations and observation: (bottom left) CAM5–Base 2 CERES and (bottom right) CAM5–CLUBB 2 CERES.*

The COSP-MODIS cloud droplet effective radius in CAM5-CLUBB shows a spatial increase from coastal St toward Cu, which is in qualitative agreement with MODIS observations. In contrast, COSP-MODIS cloud droplet effective radius in CAM5-Base almost remains a constant. In comparison with CloudSat observations, the histogram of the radar reflectivity from modeled MBL clouds is too narrow without a distinct separation between cloud and drizzle modes. Moreover, the probability of drizzle in both simulations is almost twice as high as the observation. Future studies are needed to understand the causes of these differences and their potential connection with the "empty" cloud issues in the model.

### 3.3. The importance of considering sub-grid cloud variability when using satellite observations to evaluate the cloud and precipitation simulations in climate models

Satellite cloud observations are an important source of data for evaluating general circulation models (GCMs). To facilitate the satellite and GCM comparisons, the CFMIP (Cloud Feedback Model Inter-comparison Project) Observation Simulator Package (COSP) has been developed and is now increasingly used in GCM evaluations. Real-

world clouds and precipitation can have significant sub-grid variations, which, however, are often ignored or oversimplified in the COSP simulation. In this study, we use COSP cloud simulations from the Super-Parameterized Community Atmosphere Model (SPCAM5) and satellite observations from the Moderate Resolution Imaging Spectro-radiometer (MODIS) and CloudSat to demonstrate the importance of considering the sub-grid variability of cloud and precipitation when using the COSP to evaluate GCM simulations. We carry out two sensitivity tests: SPCAM5 COSP and SPCAM5-Homogeneous COSP. In the SPCAM5 COSP run, the sub-grid cloud and precipitation properties from the embedded cloud-resolving model (CRM) of SPCAM5 are used to drive the COSP simulation, while in the SPCAM5- Homogeneous COSP run only grid-mean cloud and precipitation properties (i.e., no sub-grid variations) are given to the COSP. We find that the warm rain signatures in the SPCAM5 COSP run agree with the MODIS and CloudSat observations quite well. In contrast, the SPCAM5-Homogeneous COSP run which ignores the sub-grid cloud variations substantially overestimates the radar reflectivity and probability of precipitation compared to the satellite observations, as well as the results from the SPCAM5 COSP run. The significant differences between the two COSP runs demonstrate that it is important to take into account the sub-grid variations of cloud and precipitation when using COSP to evaluate the GCM to avoid confusing and misleading results.

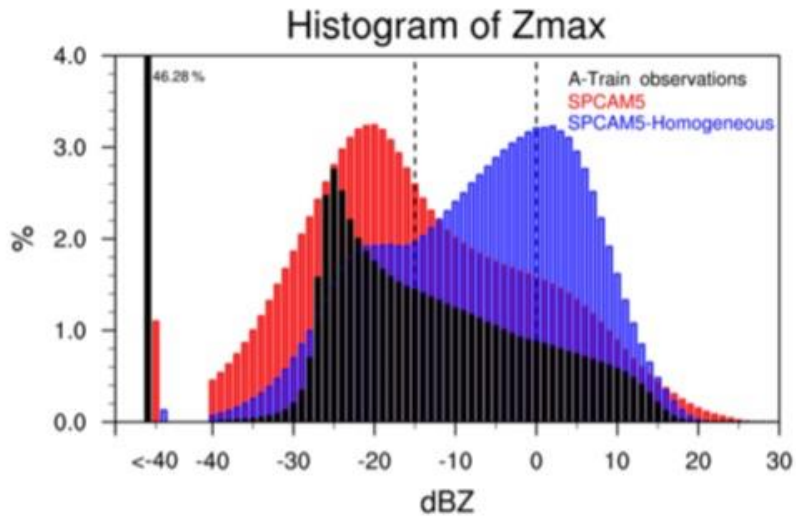


*Figure 5 The histograms of column maximum radar reflectiv- ity for liquid clouds over oceanic regions from 45◦ S to 45◦ N in A-Train satellite observations, SPCAM5 COSP, and SPCAM5- Homogeneous COSP simulations.*

### 3.4. Evaluation of autoconversion and accretion enhancement factors in general circulation model warm-rain parameterizations using ground-based measurements over the Azores

A great challenge in climate modeling is how to parameterize subgrid cloud processes, such as autoconversion and accretion in warm-rain formation. In this study, we use ground-based observations and retrievals over the Azores to investigate the so-called enhancement factors, $E_{auto}$ and $E_{accr}$, which are often used in climate models to account for the influence of subgrid variance of cloud and precipitation water on the autoconversion and accretion processes. $E_{auto}$ and $E_{accr}$ are computed for different equivalent model grid sizes. The calculated $E_{auto}$ values increase from 1.96 (30 km) to 3.2 (180 km), and the calculated $E_{accr}$ values in- crease from 1.53 (30 km) to 1.76 (180 km). Comparing the prescribed enhancement factors in Morrison and Gettleman (2008, MG08) to the observed ones, we found that a higher $E_{auto}$ (3.2) at small grids and lower $E_{accr}$ (1.07) are used in MG08, which might explain why most of the general circulation models (GCMs) produce too-frequent precipitation events but with too-light precipitation intensity. The ratios of the rain to cloud water mixing ratio (qr/qc) at $E_{accr}$ = 1.07 and $E_{accr}$ = 2.0 are 0.063 and 0.142, respectively, from observations, further suggesting that the prescribed value of $E_{accr}$ = 1.07 used in MG08 is too small to simulate precipitation intensity correctly. Both $E_{auto}$ and $E_{accr}$ increase when the boundary layer becomes less

stable, and the values are larger in precipitating clouds (CLWP > 75 gm−2) than those in non-precipitating clouds (CLWP < 75 gm−2). Therefore, the selection of $E_{auto}$ and $E_{accr}$ values in GCMs should be regime- and resolution-dependent.

### 3.5. Subgrid variations of the cloud water and droplet number concentration over the tropical ocean: satellite observations and implications for warm rain simulations in climate models

One of the challenges in representing warm rain processes in global climate models (GCMs) is related to the representation of the subgrid variability of cloud properties, such as cloud water and cloud droplet number concentration (CDNC), and the effect thereof on individual precipitation processes such as autoconversion. This effect is convention- ally treated by multiplying the resolved-scale warm rain process rates by an enhancement factor (Eq) which is derived from integrating over an assumed subgrid cloud water distribution. The assumed subgrid cloud distribution remains highly uncertain. In this study, we derive the subgrid variations of liquid-phase cloud properties over the tropical ocean using the satellite remote sensing products from Moderate Resolution Imaging Spectroradiometer (MODIS) and investigate the corresponding enhancement factors for the GCM parameterization of autoconversion rate. We find that the conventional approach of using only subgrid variability of cloud water is insufficient and that the subgrid variability of CDNC, as well as the correlation between the two, is also important for correctly simulating the autoconversion process in GCMs. Using the MODIS data which have near-global data coverage, as shown in Figure 6 we find that Eq shows a strong dependence on cloud regimes due to the fact that the subgrid variability of cloud water and CDNC is regime dependent. Our analysis shows a significant increase of Eq from the stratocumulus

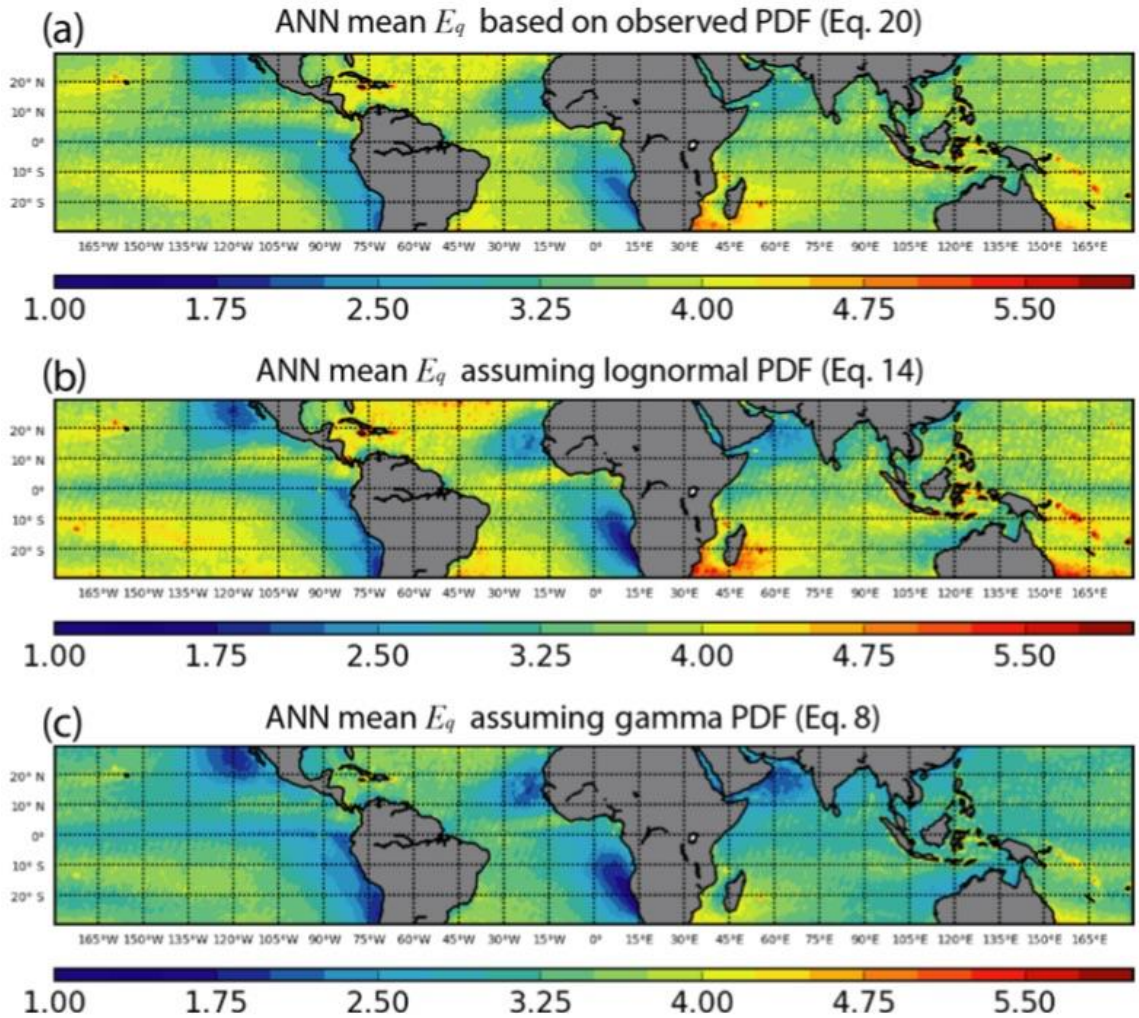


*Figure 6 The annual mean factor for the KK2000 scheme due to subgrid variation of LWP computed (a) directly from observation, i.e., Eq in Eq. (20), (b) from relative variance assuming lognormal PDF of LWP, i.e., Eq in Eq. (14), and (c) from relative variance assuming the gamma PDF of LWP, i.e., Eq in Eq. (8). (See Zhang et al. 2019 for equations and other details)*

(Sc) to cumulus (Cu) regions. Furthermore, the enhancement factor EN due to the subgrid variation of CDNC is derived from satellite observation for the first time (see Figure 7 below), and results re- veal several regions downwind of biomass burning aerosols (e.g., Gulf of Guinea, east coast of South Africa), air pollution (i.e., East China Sea), and active volcanos (e.g., Kilauea, Hawaii, and Ambae, Vanuatu), where the EN is com- parable to or even larger than Eq, suggesting an important role of aerosol in influencing the EN . MODIS observations suggest that the subgrid variations of cloud liquid water path (LWP) and CDNC are generally positively correlated. As a result, the combined enhancement factor, including the effect of LWP and CDNC correlation, is significantly

smaller than the simple product of Eq · EN. Given the importance of warm rain processes in understanding the Earth's system dynamics and water cycle, we conclude that more observational studies are needed to provide a better constraint on the warm rain processes in GCMs.

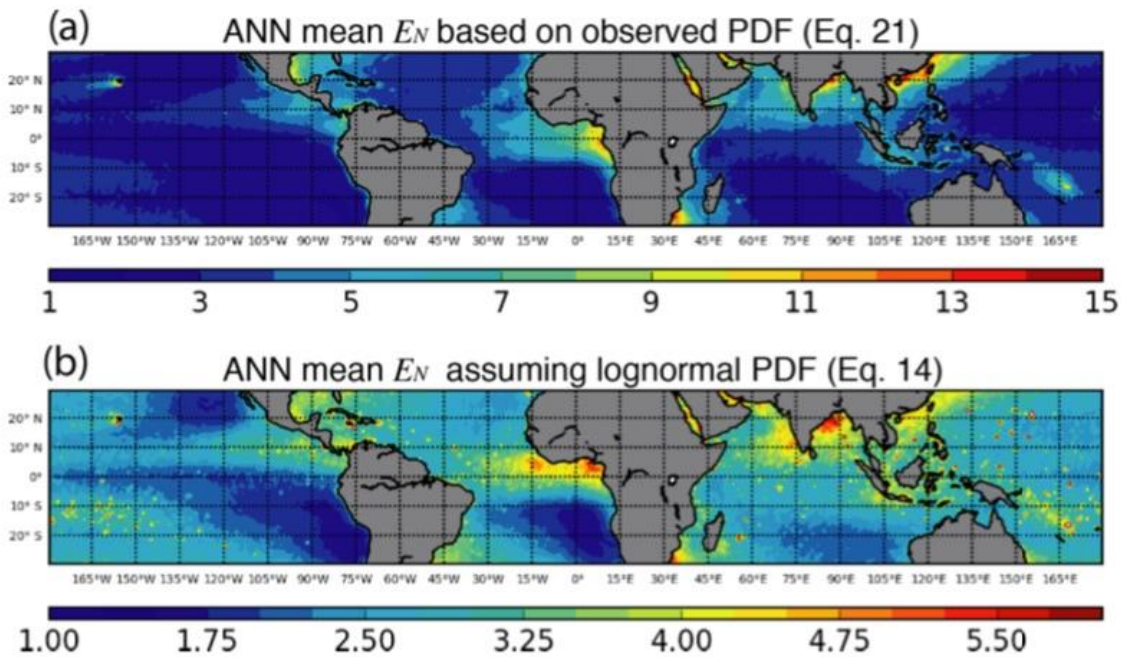


*Figure 7 Annual mean value of the enhancement factor EN computed based on the (a) observed CDNC and (b) a polynomial parameterization scheme in Eq. (31) of Zhang et al. (2019)*

### 3.6. Biomass smoke from southern Africa can significantly enhance the brightness of stratocumulus over the southeastern Atlantic Ocean

Marine stratocumulus clouds cover nearly one-quarter of the ocean surface and thus play an extremely important role in determining the global radiative balance. The semi-permanent marine stratocumulus deck over the southeastern Atlantic Ocean is of particular interest, because of its interactions with seasonal biomass burning aerosols that are emitted in southern Africa. Understanding the impacts of biomass burning aerosols on stratocumulus clouds and the implications for regional and global radiative balance is still very limited. Previous studies have focused on assessing the magnitude of the warming caused by solar scattering and absorption by biomass burning aerosols over stratocumulus (the direct radiative effect) or cloud adjustments to the direct radiative effect (the semidirect effect). Here, using a nested modeling approach in con- junction

with observations from multiple satellites, we demonstrate that cloud condensation nuclei activated from biomass burning aerosols entrained into the stratocumulus (the microphysical effect) can play a dominant role in determining the total radiative forcing at the top of the atmosphere, compared with their direct and semi- direct radiative effects. Biomass burning aerosols over the region and period with heavy loadings can cause a substantial cooling (daily mean −8.05 W m−2), primarily as a result of clouds brightening by reducing the cloud droplet size (the Twomey effect) and secondarily through modulating the diurnal cycle of cloud liquid water path and coverage (the cloud lifetime effect). Our results highlight the importance of realistically representing the interactions of stratocumulus with biomass burning aerosols in global climate models in this region.