The aerosol- and water vapor-related variability of precipitation in the West Africa Monsoon

Jingfeng Huang*, C. Zhang and J. M. Prospero

Rosenstiel School of Marine and Atmospheric Science, University of Miami
4600 Rickenbacker Causeway, Miami, FL 33149

*Corresponding author address: Dr. Jingfeng Huang, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149.
E-mail: jhuang@rsmas.miami.edu

ABSTRACT

The precipitation variability in the West Africa Monsoon (WAM) is affected by many factors. Close to the largest aerosol emission sources (mineral dust from Sahara and Sahel, and biomass burning smokes from Sahel and southern Africa), the WAM provides a natural laboratory to study the possible connections between aerosol, water vapor and precipitation. Possible aerosol and water vapor effects have, however, not been thoroughly investigated. Additionally how aerosol effect is distinguished from environmental water vapor effect is hardly visited. Using long term multi-satellite observations of aerosol, water vapor and precipitation, this study elucidates possible large-scale effects from the absorbing aerosol (primarily mineral dust and carbonaceous aerosol) and atmospheric water vapor on precipitation over the WAM region. After removing seasonal cycle, ENSO, tropical Atlantic SST and North Atlantic Oscillation (NAO) effects, precipitation difference composite between anomalously high and low aerosol (or water vapor) was made. It is found that in the WAM region both aerosol and water vapor effects on precipitation feature strong seasonality and spatial variability. However, aerosol and water vapor may explain precipitation variability independently to each other: when aerosol is anomalously high, the precipitation is generally suppressed in boreal cold season. This occurs significantly over central WAM; In contrast, when water vapor is anomalously high, precipitation tends to be enhanced at the same region. The Kolmogorov-Smirnov test proved that the precipitation changes related to aerosol are significantly different from those due to random sampling and interannual variability at the 99% confidence level. The aerosol and water vapor related precipitation variability are comparable and both explain ~5-20% of the residual variance of precipitation after known climatic effects (e.g., ENSO, tropical Atlantic SST modes, and NAO) are removed. Aerosol therefore might play an important role in affecting precipitation in the WAM in addition to these known climatic factors and this role is not strongly associated with the precipitation change attributed to environmental dry air.

1. INTRODUCTION

Aerosol plays an important role in the climate system through its direct and indirect effects (Ramanathan et al. 2001; Lohmann and Feichter 2005). To date the aerosol-induced global precipitation is still unknown (IPCC 2007) and large uncertainties are not adequately quantified due to the natural variability and complexity of aerosol effect mechanisms (Menon 2004). The precipitation variability in the West Africa Monsoon (WAM) is affected by many factors. Close to the largest aerosol emission sources (mineral dust from Sahara and Sahel, and biomass burning smokes from Sahel and southern Africa), the WAM provides a natural laboratory to study the possible connections between aerosol, water vapor and precipitation. The competitive roles of aerosol and water vapor effects on the large-scale hydrological cycle have, however, not been thoroughly investigated. Additionally how aerosol effect is distinguished from environmental water vapor effect is hardly visited. Some short-term observational evidence indicated that precipitation variability might be partially associated with aerosol (Kauffman et al. 2005; Rosenfeld 1999; Rosenfeld et al. 2001). But long term statistics are not yet established.

In addition to our previous studies (Huang et al. 2008a, 2008b), we used long term multi-satellite observations of aerosol, water vapor and precipitation, to elucidate possible large-scale effects from the absorbing aerosol (primarily mineral dust and carbonaceous aerosol) and atmospheric water vapor on precipitation in the WAM.

2. DATA AND METHOD

.

The major datasets we used are: 1) the monthly precipitation data from the Global Precipitation Climatology Project (GPCP); 2) the monthly aerosol index (AI) data from the Total Ozone Mapping Spectrometer (TOMS); and 3) the monthly atmospheric water vapor data from the Special Sensor Microwave Imager (SSM/I).

Due to the data availability and quality issues, we conducted data analysis for two periods: 1) 1979-2000 when both TOMS aerosol and GPCP precipitation are available; 2) 1988-2000 when SSM/I water vapor data are also available. The former analysis investigates the link between aerosol and large-scale precipitation variability; and the latter explore the water vapor effect on precipitation and how that might influence the aerosol-related precipitation change.

Fig.1 shows the climatological mean and total variance of aerosol and precipitation over the WAM domain. From Fig.1 we can observe that the large annual mean of absorbing aerosols (~1.2 AI) is in the central WAM where the largest variance of aerosol in the WAM domain is also found. Considering the synoptic nature of aerosol existence, we assume that aerosol variability in the WAM domain can be represented by the aerosol variability in a larger area and the influence from wet deposition can then be minimized by selecting a larger aerosol domain than the precipitation domain.

Precipitation, aerosol and water vapor data were processed equally with the following procedures. We first remove the seasonal cycle of data to obtain the anomalies. We identified the El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and the Atlantic zonal and meridional SST modes as major climate factors and use the

monthly Nino 3.0, NAO index, Atl.3.0, and TNA-TSA indices to represent their variability. These climate effects were linearly removed from precipitation, aerosol and water vapor anomalies through multivariate regression. The residual seasonal signal is further minimized by normalizing the residual anomalies by the domain averaged standard deviation at each calendar month. The normalized anomalies of precipitation, aerosol and water vapor are linearly independent on climate factors, and can be treated equally from month to month.

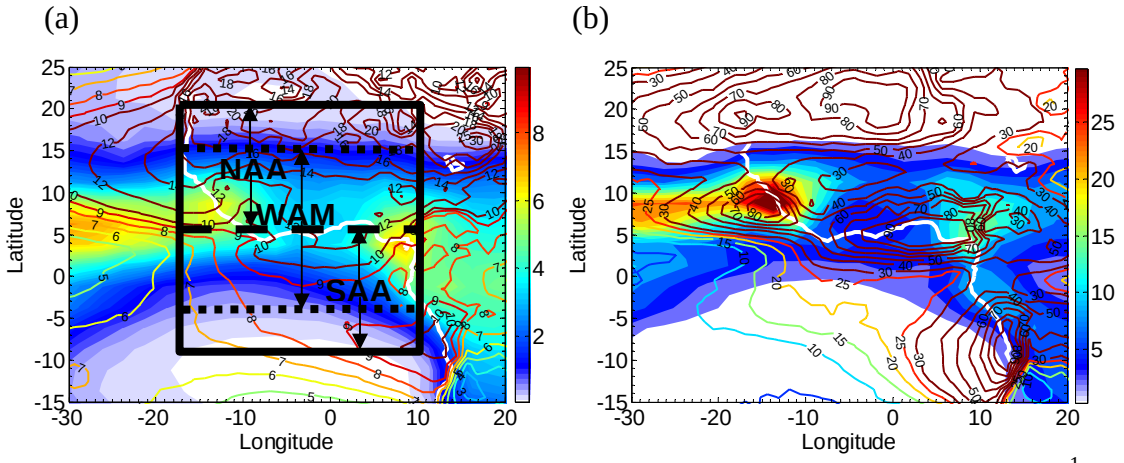

FIG. 1 (a) Analysis domains and climatological means of precipitation (mm day^{-1}, colors) and aerosols (10×AI, no unit, contours,), and (b) total variance of precipitation ((mm^2 day^{-2}, colors) and aerosols ((10×AI)^2, no unit, contours). The African aerosol domain (AA, solid boundaries) is used for domain-averaged aerosol. It is divided into two subdomains, separated at 5˚N (dashed line): NAA to the north and SAA to the south. The West African Monsoon domain (WAM, centered at the dashed line at 5˚N and bounded to the north and south by dotted lines at 15˚N and 5˚S) is used for domain-averaged precipitation (Huang et al. 2008b).

3. AEROSOL RELATED PRECIPITATION VARIABILITY

In a correlation analysis, the AA-domain averaged normalized aerosol and precipitation anomalies are significantly anti-correlated at the 99% confidence level (R = -0.406, n=223). The correlation is highest in boreal winter, followed by autumn, spring and summer. The negative correlation implies the possible precipitation reduction in months with anomalously high aerosol concentrations. On the spatial pattern perspective, a further correlation analysis between the AA-domain averaged normalized aerosol anomalies and the normalized precipitation anomalies at each grid shows that the highest correlation significant at the 99% confidence level was found along the Guinea coast center of the WAM domain.

In addition to the correlation analysis, difference composites of normalized precipitation anomalies were made between the top and bottom terciles of normalized aerosol anomalies. In this way we demonstrate the spatial pattern (Fig.2a) and seasonal cycle (Fig.2b) of precipitation change attributable to aerosol when aerosol concentration

is changing from low to high. A large-scale coherent pattern was observed center of WAM domain indicating a significant reduction of precipitation when aerosol is anomalously high. And it is particularly significant during boreal cold season (from late autumn to winter). Results are consistent with those from correlation analysis. Two-sample Kolmogorov-Smirnov (K-S) tests further proved that the observed precipitation suppression in Fig.2a cannot be reproduced by random sampling and is significantly different from the interannual variability of precipitation at the 99% confidence level. Furthermore, we used the GPCP pentad rain rate data to demonstrate that the precipitation reduction seems more significant at a rain rate range of 2-17 mm/day off the Guinea coast. A back trajectory analysis using HYSPLIT4 model further illustrate that the aerosol in the region where most significant aerosol-related precipitation reduction were found can be traced back to African dust and smoke sources (Huang et al. 2008b).

4. WATER VAPOR RELATED PRECIPITATION VARIABILITY

For a data period of 1988-2005, the AA-domain averaged normalized water vapor anomalies and the WAM-domain averaged precipitation anomalies are positively correlated significant at the 99% confidence level (R=0.23, n=216). The highest correlation is also found in boreal winter.

For the precipitation difference composites, we conducted parallel analysis to precipitation and water vapor for the second data period (1988-2000). The difference composites of normalized precipitation anomalies between top and bottom water vapor terciles are shown in Fig.2c-d. Water vapor and precipitation is more positively correlated in the WAM domain which indicates that precipitation suppression could also occur during dry air outbreaks. Boreal winter has the strongest signal.

It raised the suspicion that the observed aerosol-related precipitation suppression in Fig.2a might be attributed to water vapor but not to aerosol. To answer this question, we made two similar sets of difference composites of precipitation between top and bottom aerosol terciles for this second data period (1988 – 2000): one with the known climate factors removed through a multi-variable linear regression (similar to Fig.2a); the other with water vapor influence also removed along with the climate factors (Fig.3). It has a spatial pattern similar to Fig. 2a. The difference between these two sets of difference composites are the precipitation change linearly attributable to water vapor effect. A quantitative evaluation indicated that the linear contribution of water vapor to the precipitation reduction is no more than 20% of the aerosol contribution. Thus we are confident that the observed precipitation reduction in Fig.2a cannot be fully explained by water vapor effect. In other words, aerosol effect on large-scale precipitation variability is more significant than the influence from ambient water vapor, and they are not strongly associated to each other.

Moreover we conducted variance analysis on the precipitation, aerosol and water vapor anomalies with climate effects removed. After known climatic effects (e.g., ENSO, tropical Atlantic SST modes, and NAO) are removed, both aerosol and water vapor explain ~5-20% of the residual variance of precipitation. These are in value comparable to the precipitation variability explained by climate factors.

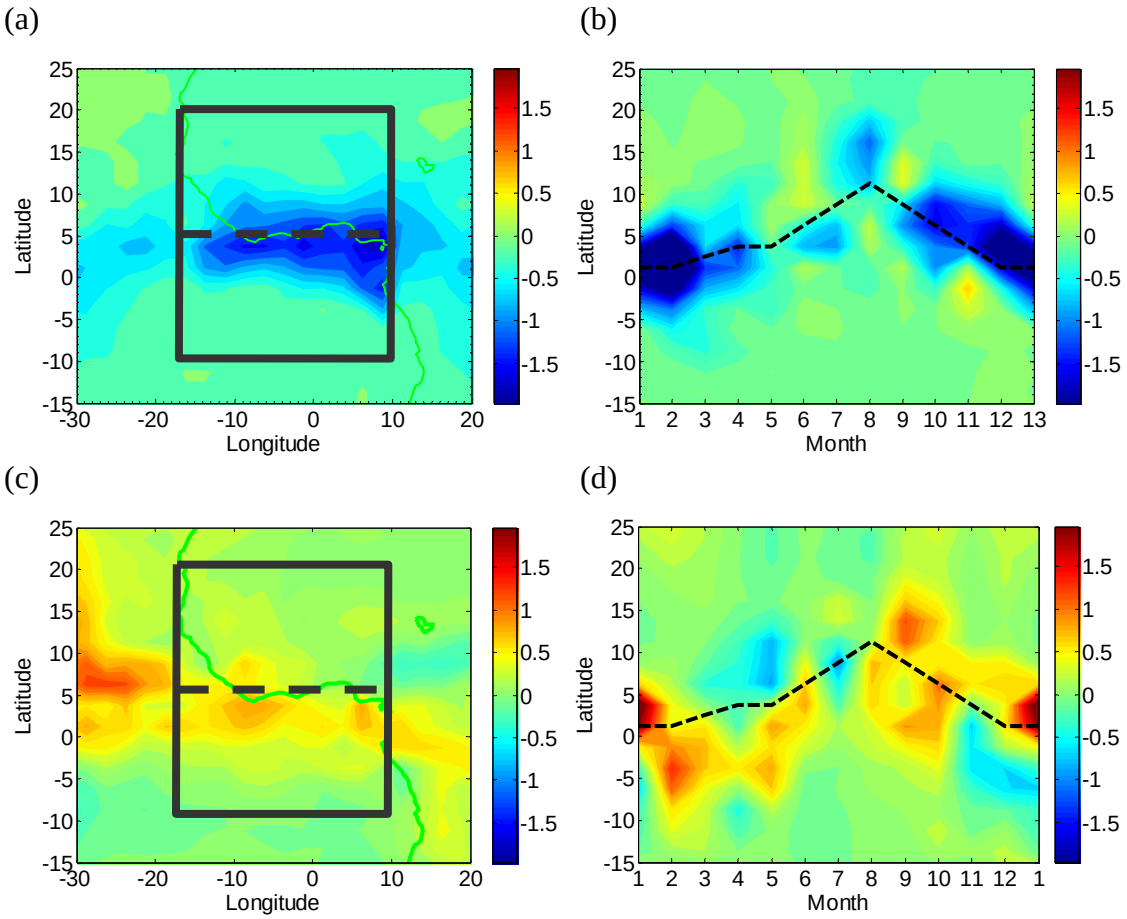

Fig. 2 Difference composite of normalized precipitation anomalies between top and bottom aerosol terciles: (a) spatial pattern, (b) seasonal cycle (Huang et al. 2008b); Difference composite of normalized precipitation anomalies water vapor terciles: (c) spatial pattern, (d) seasonal cycle.

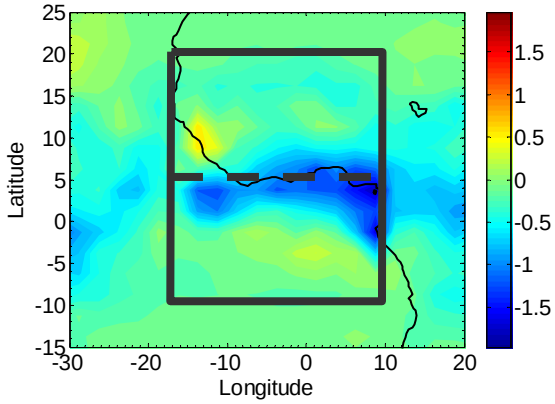

Fig. 3 Difference composite of normalized precipitation anomalies between top and bottom aerosol terciles with water vapor effect linearly removed along with climate factors (Huang et al. 2008b)

5. SUMMARY AND DISCUSSIONS

The study elucidates both the aerosol and water vapor related large-scale variability of precipitation over the WAM domain. With major climate factors, such as ENSO, NAO, and Atlantic zonal and meridional SST modes removed, precipitation is significantly suppressed central of the WAM domain when aerosol is anomalously high during boreal cold season; when water vapor is anomalously high however, precipitation tends to be enhanced along the guinea coast. But the aerosol-related precipitation change is hardly explained by water vapor effect. The aerosol-induced precipitation change observed in this study has similar spatial pattern as that from cloud-resolving model simulation of black carbon effect (Wang 2007). Therefore the fractional contributions from effects of dust and smoke on the precipitation change in the WAM should be further investigated.

The long term observational evidence is useful for model diagnosis, evaluation and further investigation on modulation mechanisms. More investigation is on the way to find the coherence of African aerosol and dry air outbreaks (Zhang and Pennington 2004) and the association of their climate effects.

ACKNOWLEDGEMENT

Authors acknowledge NCDC of NOAA (http://lwf.ncdc.noaa.gov/oa/wmo/wdcamet-ncdc.html) for provision of GPCP precipitation data, GSFC of NASA (http://toms.gsfc.nasa.gov/aerosols/aerosols_v8.html) for provision of TOMS AI, the Data and Information Services Center (DSIC) of NASA (http://disc.sci.gsfc.nasa.gov/) for provision of TRMM and MODIS data, and Remote Sensing Systems (http://www.remss.com/) for provision of SSM/I data. This study is funded by the NOAA office of Global Programs through the Cooperative Institute for Marine and Atmospheric Studies (CIMAS).

REFERENCE

Huang, J., C. Zhang, J. M. Prospero. 2008a: Aerosol-induced large scale variability in precipitation over the tropical Atlantic, *Journal of Climate*, submitted.

Huang, J., C. Zhang, J. M. Prospero. 2008b: Large scale effects of aerosol on rainfall over West Africa, *Quarterly Journal of the Royal Meteorological Society*, submitted.

Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007: The Physical Sciences Basis*, Cambridge University Press, New York, 2007.

Kaufman, Y. J., I. Koren, L. A. Remer, D. Rosenfeld, and Y. Rudich, 2005b: The Effect of smoke, dust and pollution aerosol on shallow cloud development over the Atlantic ocean. *Proceedings of the National Academy of Sciences*, **102**, 11 207-11 212.

Lohmann, U. and J. Feichter, 2005: Global indirect aerosol effects: a review. *Atmos. Chem. Phys.*, **5,** 715–737.

Menon, S., 2004: Current uncertainties in assessing aerosol effects on climate. *Ann. Rev. Environ. Resources*, **29,** 1-30, doi:10.1146/annurev.energy.29.063003.132549.

Ramanathan, V., Crutzen, P. J., Kiehl, J. T., and Rosenfeld, D., 2001: Aerosols, climate, and the hydrological cycle, *Science*, **294**, 2119-2124.

Rosenfeld, D., 1999: TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophys. Res. Lett.*, **26**, 3105-3108.

Rosenfeld, D., Y. Rudich, and R. Lahav, 2001: Desert dust suppressing precipitation -- a possible desertification feedback loop. *Proceedings of the National Academy of Sciences*, **98**, 5975-5980.
Wang, C., 2007: Impact of direct radiative forcing of black carbon aerosols on tropical convective precipitation, *Geophys. Res. Lett.*, **34,** L05709, doi:10.1029/2006GL028416.
Zhang, C. and J. Pennington, 2004: African dry-air outbreaks. *J. Geophys. Res.*, **109**, D20108, doi:10.1029/2003JD003978.