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Observational evidence of changes in water vapor, clouds, and radiation at the ARM SGP site

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[1] Characterizing water vapor and cloud effects on the surface radiation budget is critical for understanding the current climate because water vapor is the most important greenhouse gas in the atmosphere and clouds are one of the largest sources of uncertainty in predicting potential future climate change. Several studies have shown that insolation over land declined until 1990 then increased until the present. Using 8 years of data collected at the ARM Southern Great Plains (SGP) surface site, we found that the insolation increased from 1997 to 2000, but significantly decreased from 2001 to 2004, changes that exactly mirror the variation in the second-order fit of cloud fraction. Under clear-sky conditions, the rates of change of water vapor, insolation and downwelling longwave (LW) flux are −0.0166 cm/yr, 0.48 Wm^{-2}/yr, and −1.16 Wm^{-2}/yr, respectively, indicating that water vapor changes are more important for LW flux than for insolation. **Citation:** Dong, X., B. Xi, and P. Minnis (2006), Observational evidence of changes in water vapor, clouds, and radiation at the ARM SGP site, *Geophys. Res. Lett.*, *33*, L19818, doi:10.1029/2006GL027132.

1. Introduction

[2] Characterizing cloud effects on the surface radiation budget is critical for understanding the current climate and an important step toward simulating potential climate change. Therefore, clouds have been classified as the highest priority in climate change by the U.S. Climate Change Research Initiative (USCCRI, 2001; See online at www.climatescience.gov/about/ccri.htm). Solar radiation absorption is modulated by clouds, mainly cloud fraction, height, and microphysical/optical properties [*Wielicki et al.*, 1998]. Although most emphasis in the climate community has been on shortwave (SW) radiation, it accounts for only half of the radiation budget. The variability of longwave (LW) radiation with respect to cloud properties should also be understood. The downwelling LW flux is also strongly correlated with atmospheric water vapor, the atmosphere's dominant greenhouse gas, which has a positive feedback on surface warming.

[3] Several studies [*Wild et al.*, 2005; *Pinker et al.*, 2005; *Wielicki et al.*, 2005] have shown that the decline of insolation (global dimming) on land surfaces ended around 1990, followed by an increase since then. In the mean time, the globally averaged monthly mean cloud fraction (CF) from the International Satellite Cloud Climatology Project (ISCCP) data increased 2–3% from 1983 to 1987, then decreased 3–4% from 1987 to 2000 [http://isccp.giss.nasa.gov/climanal1.html], indicating that CF has a major responsibility to the global dimming. This study, motivated by these studies and ISCCP CF results, presents the monthly anomalies of water vapor, clouds, and surface radiative fluxes using data collected from January 1997 to December 2004 at the Atmospheric Radiation Measurement (ARM) Program Southern Great Plains (SGP) Central Facility (SCF). This comprehensive dataset allows us to investigate the following scientific questions:

[4] 1) What are the long-term variations of atmospheric water vapor, downwelling SW and LW fluxes under clear-sky conditions at the ARM SCF during the 8-yr period?

[5] 2) Can we quantitatively estimate the impact of clouds on the surface radiation budget?

[6] 3) How does the NET flux impact climate change at the ARM SCF?

[7] No attempt is made here to characterize climate change over the SGP because an 8-yr period is too short and some linear relationships reported in this study may be changed if we add or subtract a couple of years. This study, which uses the first nearly continuous set of long-term ground-based cloud and radiation observations, should provide the most reliable estimates, to date, of monthly variations of water vapor, clouds, and surface radiative fluxes at the SGP site. The results should be valuable for advancing our understanding of the cloud-radiation interactions and for enabling climate/forecast modelers to more fully evaluate their simulations over the SCF.

2. Data

[8] An 8-yr record of atmospheric water vapor, clouds, and radiation has been generated using surface observations at the ARM SCF. The centerpiece of the cloud-radiation instrument array is the Millimeter Wavelength Cloud Radar (MMCR) [*Moran et al.*, 1998]. The MMCR operates at a wavelength of 8 mm in a vertically pointing mode and provides continuous profiles of radar reflectivity from hydrometeors moving through the radar field of view, allowing the identification of clear-sky and cloudy conditions. Cloud-base height (Z_{base}) is derived from a composite of Belfort laser ceilometer, Micropulse Lidar (MPL), and MMCR data [*Clothiaux et al.*, 2000]. The precipitable water vapor (PWV) and cloud liquid water path (LWP) are derived from the microwave radiometer brightness temperatures measured at 23.8 and 31.4 GHz using a statistical retrieval method [*Liljegren et al.*, 2001]. The SCF up- and down-looking standard Eppley Precision Spectral Pyranometers (PSPs) and Precision Infrared Pyrgeometers (PIRs) provide measurements of downwelling and upwelling

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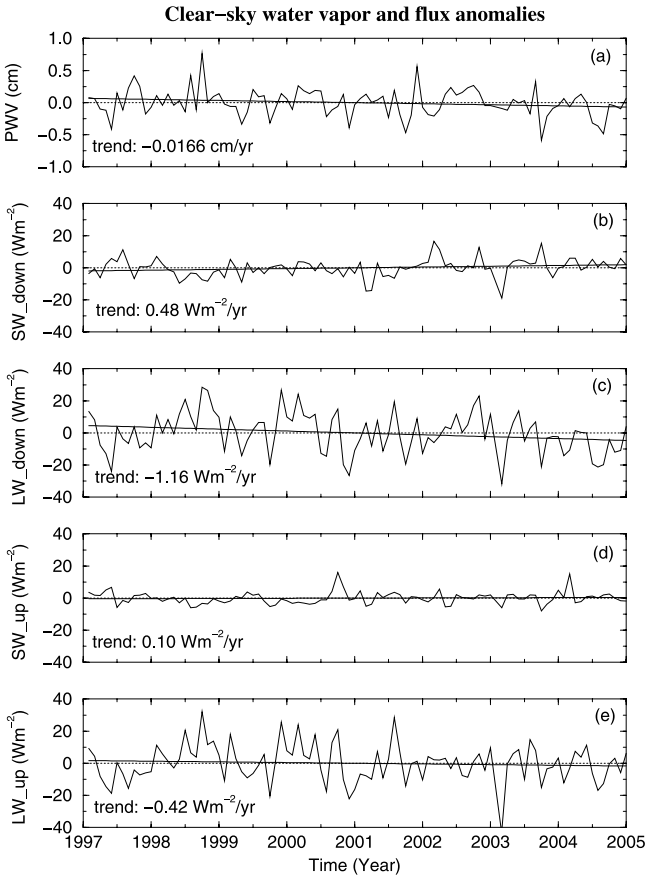

Figure 1. Time series of monthly mean anomalies, after removal of mean annual cycle of clear-sky PWV and downwelling and upwelling SW and LW fluxes at the ARM SCF, 1997–2004.

broadband SW (0.3–3 μm) and LW (4–50 μm) fluxes at the surface, respectively. Here, the SW and LW fluxes are the Best Estimate Flux Value Added Products (VAP) from three different SCF radiometer systems: SIRS (Solar Infrared Station) E13, C1, and BSRN (Baseline Surface Radiation Network)/BRS (Broadband Radiometer Station), and their uncertainties are ~10 Wm^{-2} [*Shi and Long*, 2002].

[9] The monthly mean cloud fraction *CF* is simply the percentage of returns that are cloudy within a month, that is, the ratio of the number of hours when the radar-lidar detected clouds to the total number of hours when all measurements were available. To avoid temporal sampling biases in calculating monthly means, the downwelling and upwelling SW and LW fluxes under both clear-sky and all-sky conditions were binned and averaged in 1-hour intervals first, and then the monthly means were calculated from the average of the 24-hour means. Therefore, each 24-hr mean has been equally weighted in calculating the monthly means regardless of the number of 5-min samples per hour.

3. Water Vapor Effects on Surface Radiation Budget

[10] Figure 1 shows the time series of monthly mean anomalies of clear-sky PWV and downwelling and upwelling SW and LW fluxes at the ARM SCF from January 1997 to December 2004. To eliminate the large seasonal cycle in the data, we removed the mean annual cycle by differencing each January from the average of all eight January months during the 8-yr period (e.g., $\Delta S_{9701} = S_{9701} - S_{Jan}$). A linear regression analysis was performed on all parameters to estimate their variations during the 8-yr period. The trends in PWV, insolation and downwelling LW flux are −0.0166 cm/yr, 0.48 Wm^{-2}/yr, and −1.16 Wm^{-2}/yr, respectively. These results indicate that water vapor has a greater impact on LW flux than on SW flux. Aerosols and water vapor are the main factors affecting clear-sky downwelling fluxes, with the latter dominating in the LW. In the SW, the variations and temporal changes in aerosol however might be of equal importance than water vapor [*Li and Trishchenko*, 2001]. During the 8-yr period, the PWV decreased by 0.133 cm, the insolation increased by 3.84 Wm^{-2}, and the downwelling LW flux decreased by 9.25 Wm^{-2}, suggesting that the net downwelling flux decreases 5.41 Wm^{-2} with a decrease of 0.133 cm in PWV (40.68 Wm^{-2}/cm). These results indicate that the cloud-free atmosphere has become more transparent with more insolation from 1997 to 2004. The increased insolation, however, has been counterbalanced by the change in LW flux, that is, the decreased downwelling LW flux outweighed the increased insolation, resulting in a net decrease of downwelling flux. The correlations between downwelling SW and LW fluxes with PWV are −0.18 and 0.62, respectively.

[11] To provide complete clear-sky information for studying surface radiation budget, we also plot the upwelling SW and LW fluxes in Figure 1. The slopes of upwelling SW and LW fluxes are 0.1 Wm^{-2}/yr and −0.42 Wm^{-2}/yr, respectively. The net SW flux (down-up) rose by 0.38 Wm^{-2} per year and the net LW flux dropped by 0.74 Wm^{-2} per year, resulting in a net loss of 0.36 Wm^{-2} per year at the SCF. Overall, the magnitude of the LW variations is about 2–3 times greater than those of SW. The LW variations correlate better with the PWV variations than those for SW. These cloud-free relationships between PWV and SW and LW variations serve as a baseline for studying the impact of clouds on the surface radiation budget. Although the clear-sky fluxes can also be affected by changes in aerosols and air temperature, those effects should be reduced in cloudy skies and their influence on the clear-sky radiation will be examined in a future study.

4. Cloud Effects on Surface Radiation Budget

[12] Figure 2 illustrates the monthly mean anomalies of *CF* and all-sky downwelling and upwelling SW and LW fluxes at the SCF. Based on linear regressions, both *CF* and insolation increase at the rates of 1%/yr and 0.13 Wm^{-2}/yr, respectively, and all-sky insolation varies more than in clear-sky conditions (standard deviation = 18 Wm^{-2} vs. clear-sky 5.6 Wm^{-2}). This result does not make physical sense because all-sky insolation normally has a negative correlation with *CF*, that is, insolation decreases with increased *CF* [*Dong et al.*, 2006]. Therefore, we use another approach, a second-order least-squares fit, to determine the tendencies of monthly mean anomalies. As demonstrated in Figure 2, there is a nearly perfect negative correlation between *CF* and insolation from the second-order fit,

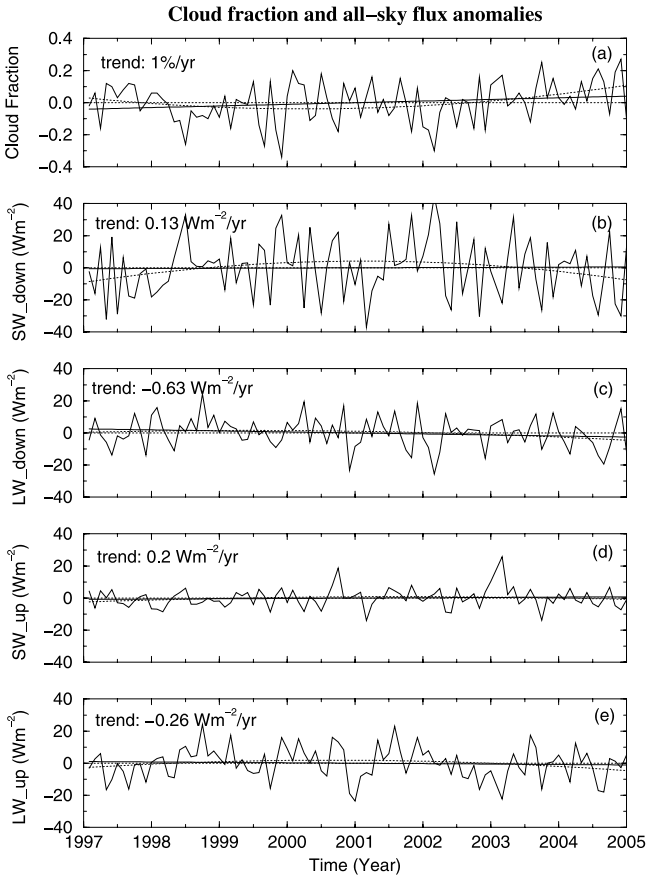

Figure 2. Monthly mean anomalies of cloud fraction and all-sky downwelling and upwelling SW and LW fluxes at the ARM SCF, 1997–2004.

indicating that the second-order fits are more appropriate for mimicking the 8-yr trends in both *CF* and insolation.

[13] If we divide the 8 years into two even time periods, the *CF* decreases 5.5% and insolation increases 12.77 Wm^{-2} (−2.32 Wm^{-2}/%) during the first period (January 1997–December 2000). The situation reverses in the second period when the *CF* increases by 17.3% and insolation decreases by 11.6 Wm^{-2} (−0.67 Wm^{-2}/%). The clouds may be slightly optically thicker in the first period than in the second period, which could cause the different trends. The all-sky PWV values (Figure 3d) are almost the same for these 2 periods, but the cloud-base heights (Figure 3c) during the first period are lower, indicating more liquid clouds, than those in the second period. This change in cloud properties is supported by an earlier study [*Dong et al.*, 2005] of single-layered low-level stratus cloud properties at the SCF, where the averaged cloud optical depth and LWP are 26.1 and 145 gm^{-2} during the first period, and 22.9 and 125.3 gm^{-2} from January 2001 to December 2002. Although the *Dong et al.* [2005] study only considered single-layered clouds up to December 2002, it shows a change in the type of cloud that strongly affects surface SW radiation.

[14] The globally averaged monthly mean *CF* from the International Satellite Cloud Climatology Project (ISCCP) data decreased 3–4% from 1987 to 2000 and increased 1–2% from 2000 to 2004 [http://isccp.giss.nasa.gov/climanal1.html]. This trend is very similar to the second-order fit of ARM SCF *CF* but with different slopes. Several studies [e.g., *Wild et al.*, 2005; *Pinker et al.*, 2005] have shown that the decline of insolation on land surfaces ended around 1990, followed by an increase since then. In this study, we observed the increased insolation from 1997 to 2000, but detected a significant decrease from 2001 to 2004, which exactly mirrors the variation in the second-order fit of *CF*. The strong negative correlation between *CF* and insolation in this study, generated at a single point over the period 1997–2004, is similar to those derived in past field programs although these comparisons are based on data collected at different locations and years.

[15] The downwelling LW flux normally increases with increased *CF*. However, both the first- and second-order fits of the downwelling LW flux in this study decrease with increased *CF* at −0.63 Wm^{-2} per year. The nearly flat trend in all-sky PWV (Figure 3d) cannot explain this downward trend, suggesting that the relationship between the downwelling LW flux and PWV during all-sky conditions does not have the same behavior as that during clear-sky conditions. The linear increase of cloud-base height in Figure 3c helps explain the decline in downwelling LW flux during the 8-yr period. Assuming a constant cloud-base emissivity during entire 8-yr period, the downwelling LW flux should be greater in the first than in the second period because cloud-

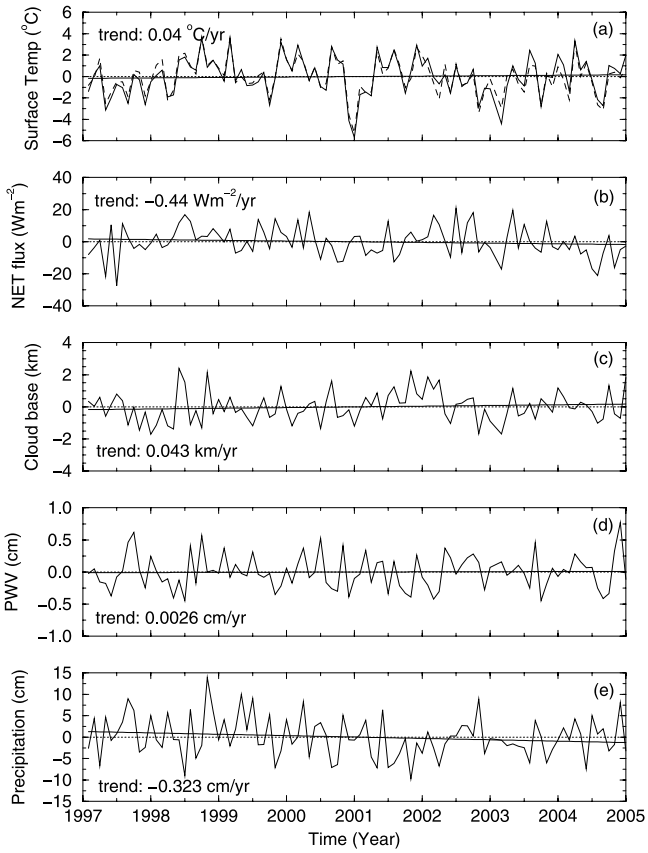

Figure 3. Monthly mean anomalies of all-sky surface temperatures (solid line-ARM data, dotted line-North Central climate division of Oklahoma, provided by the Oklahoma Climatological Survey), NET flux, PWV, and precipitation, as well as cloud base height at the ARM SCF, 1997–2004.

base height changes are inversely related to cloud-base temperature.

[16] Similar to the clear-sky study, we also provide the all-sky upwelling SW and LW fluxes to study the surface radiation budget under all-sky conditions. The rates of net SW and LW fluxes are -0.07 Wm^{-2}/yr and -0.37 Wm^{-2}/yr, respectively, resulting in a decrease of 0.44 Wm^{-2} per year in NET flux at the surface (Figure 3b). The decline of NET flux, however, does not correlate with the increased surface air temperature as illustrated in Figure 3a. The surface air temperature is determined by the sum of NET radiation fluxes (downwelling and upwelling SW and LW fluxes) and nonradiative fluxes (sensible and latent heat fluxes, ground heat flux and energy flux used for melt), as well as the large-scale advection [*Wild et al.*, 2004]. *Wild et al.* [2004] investigated this counterintuitive result and concluded that it may be due to a decrease of surface evaporation and associated reduced evaporative surface cooling. The trend in precipitation over northern Oklahoma (-0.323 cm/yr, Figure 3e) during the period 1997–2004 supports Wild's argument.

[17] Although the linear trends reported in this study can explain most of variations and interactions, there are apparent inconsistencies, suggesting that the 8-yr period may be too short to represent their long-term variations. For example, using the Stefan-Boltzmann equation indicates that an annual increase of 0.04°C air temperature each year corresponds to an increase of 0.4 Wm^{-2} per year in upward LW upward surface emission. However, the measured change is a decrease of 0.26 Wm^{-2} per year as shown in Figure 2e. Therefore, these linear trends should be used with caution.

5. Summary and Concluding Remarks

[18] An 8-yr record of atmospheric water vapor, clouds, and radiation has been generated using data collected from January 1997 to December 2004 at the ARM SCF. This comprehensive dataset was used to examine the monthly anomalies of water vapor, clouds, and radiation, as well as their interactions. The insolation increased and downwelling LW flux decreased with decreasing PWV under clear-sky conditions at the ARM SCF, 1997–2004. These results reveal that the cloud-free atmosphere became more transparent with enhanced insolation that is outweighed by the diminished downwelling LW flux, indicating that PWV changes have a much greater impact on the LW flux than on the SW flux. Cloud fraction is the dominant modulator for determining insolation on the surface, nevertheless cloud-base height (temperature) is more important for downwelling LW flux. This study has shown that the all-sky insolation increases from January 1997 to December 2000 and decreases from January 2001 to December 2004, which mirrors the variation of *CF*. This negative correlation is similar to those derived in past field programs although these comparisons are based on data collected at different locations and years. These results should be valuable for advancing our understanding of the cloud-radiation interactions and for enabling climate/forecast modelers to more fully evaluate their simulations over the SCF. More studies, such as a longer time period at the ARM SCF and other ARM sites in the Tropical Western Pacific and in Barrow, Alaska, are warranted.

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References

Clothiaux, E. E., T. P. Ackerman, G. G. Mace, K. P. Moran, R. T. Marchand, M. A. Miller, and B. E. Martner (2000), Objective determination of cloud heights and radar reflectivities using a combination of active remote sensors at the Atmospheric Radiation Measurement Program Cloud and Radiation Test Bed (ARM CART) sites, *J. Appl. Meteorol.*, *39*, 645–665.

Dong, X., P. Minnis, and B. Xi (2005), A climatology of midlatitude continental clouds from the ARM SGP Central Facility: Part I: Low-level cloud macrophysical, microphysical and radiative properties, *J. Clim.*, *18*, 1391–1410.

Dong, X., B. Xi, and P. Minnis (2006), A climatology of midlatitude continental clouds from the ARM SGP Central Facility: Part II: Cloud fraction and surface radiative forcing, *J. Clim.*, *19*, 1765–1783.

Li, Z., and A. P. Trishchenko (2001), Quantifying uncertainties in determining SW cloud radiative forcing and cloud absorption due to variability in atmospheric conditions, *J. Atmos. Sci.*, *58*, 376–389.

Liljegren, J. C., E. E. Clothiaux, G. G. Mace, S. Kato, and X. Dong (2001), A new retrieval for cloud liquid water path using a ground-based microwave radiometer and measurements of cloud temperature, *J. Geophys. Res.*, *106*, 14,485–14,500.

Moran, K. P., B. E. Martner, M. J. Post, R. A. Kropfli, D. C. Welsh, and K. B. Widener (1998), An unattended cloud-profiling radar for use in climate research, *Bull. Amer. Meteorol. Soc.*, *79*, 443–455.

Pinker, R. T., B. Zhang, and E. G. Dutton (2005), Do satellites detect trends in surface solar radiation?, *Science*, *308*, 850–854.

Shi, Y., and C. N. Long (2002), Best estimate radiation flux value-added procedure: Algorithm operational details and explanations, *ARM Tech. Rep. TR-008*, U.S. Dep. of Energy, Washington, D. C. (Available at http://www.arm.gov/publications/tech_reports/arm-tr-008.pdf).

Wielicki, B. A., et al. (1998), Clouds and the Earth's Radiant Energy System (CERES): Algorithm overview, *IEEE Trans. Geosci. Remote Sens.*, *36*, 1127–1141.

Wielicki, B. A., T. Wong, N. Loeb, P. Minnis, K. Priestley, and R. Kandel (2005), Changes in Earth's albedo measured by satellite, *Science*, *308*, 825.

Wild, M., A. Ohmura, H. Gilgen, and D. Rosenfeld (2004), On the consistency of trends in radiation and temperature records and implications for the global hydrological cycle, *Geophys. Res. Lett.*, *31*, L11201, doi:10.1029/2003GL019188.

Wild, M., et al. (2005), From dimming to brightening: Decadal changes in solar radiation at Earth's surface, *Science*, *308*, 847–850.

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