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MODIS observed seasonal and interannual variations of atmospheric conditions associated with hydrological cycle over Tibetan Plateau

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[1] This paper aims to provide a prototype research of how MODIS observations can help to better understand surface and atmosphere conditions over the Tibetan Plateau. Snow melt and summer rainfall over the Tibetan Plateau provide the origin for most of the rivers in South Asia. Therefore, adequately monitoring as many components of the hydrological cycle as possible over the Tibetan Plateau can make major contributions to predictions of drought/flood in the surrounding countries. Observing large, inaccessible high plateau regions is one unique advantage of satellite remote sensing. In this paper, five years (2000–2005) of aerosols, clouds, water vapor and cirrus observations measured by the National Aeronautics and Space Administration (NASA) Terra Moderate Resolution Imaging Spectroradiometer (MODIS) reveal distinct seasonality and inter-annual variations over the Tibetan Plateau. Quantitative understanding of these atmospheric conditions is the first step for simulating land-atmosphere water budget and predicting snow coverage. **Citation:** Jin, M. (2006), MODIS observed seasonal and interannual variations of atmospheric conditions associated with hydrological cycle over Tibetan Plateau, *Geophys. Res. Lett.*, *33*, L19707, doi:10.1029/2006GL026713.

1. Introduction

[2] The Tibetan Plateau locates at the south west of China and covers over 1.2 million square kilometers with the averaged elevation more than 4000 meters above sea level. Therefore, it is often called ‘‘the roof of the world’’. Although significantly affecting the general circulation [*Wu and Chen*, 1985] and regional monsoon system by causing the earliest monsoon onset occurring over the eastern Bay of Bengal [*Fu and Fletcher*, 1985; *Li and Yanai*, 1996; *Wu and Zhang*, 1998; *Liu and Yanai*, 2001], it is hard to make conventional, in-situ measurements over the Tibetan Plateau because this large plateau has rugged and highly varying topography with the heights of mountain rarely found in other regions of the world. The Himalayan mountains block water vapor transported by Indian Monsoon from southwest, but suck air and moisture from southeast due to sensible-heating–induced air pump phenomena described by *Wu et al.* [2004].

[3] Large regions over the Tibetan Plateau have diverse land cover (Figure 1), determined not only by surface height but also by temperature and precipitation. Using 5km by 5 km resolution land cover product observed from the National Aeronautics and Space Administration (NASA) Terra Moderate Resolution Imaging Spectroradiometer (MODIS) [*Friedl et al.*, 2002], for the Tibetan Plateau (27.5–37.5°N, 80–100°E, following *Wu and Chen* [1985]), 35.8% of the regions is open shrubland (Figure 1, land cover type 7), 24.9% is deserts (land cover type 16), 26.3% is grasslands (land cover type 10). The remaining regions are covered by snow and ice (~0.5%, land cover type 15), urbanization (~1.7%, land cover 13), mixed forest (4.6%, landcover 5), and woody savannas (0.9%, land cover 8) together with other land types. Such high diversity in land cover and heterogeneity in surface elevation most likely induces complex impacts on overlying atmosphere through convection, conduction, and radiation transfer.

[4] NASA launched the Terra and Aqua satellites in 1999 and 2002 respectively [*King et al.*, 2003]. The MODIS instrument on these two missions was designed to make daily observations of several properties of the land and the atmosphere at several nominal spatial resolutions ranging from 250 meter to 1000 kilometer. MODIS provides, for example, land surface skin temperature, surface albedo, snow coverage, leaf area index, clouds properties, aerosol, and water vapor information [*Jin and Shepherd*, 2005; *Platnick et al.*, 2003; *King et al.*, 2003; *Gao et al.*, 2002; *Kaufman et al.*, 1997]. Such rich, high quality observations meet the urgent desire in climate community for studying remote, rarely-accessible regions like the Tibetan Plateau. For example, *Gao et al.* [2003] reveals the first look on water vapor and cirrus over the Tibetan Plateau by using MODIS observations. Disclosing what MODIS observations contain provides quantitative, unique, new understanding on the Tibetan Plateau meteorology and hydrometeorology from surface to atmosphere, spatially and temporally. Because MODIS products are more reliable at monthly resolution (i.e., Level 3 data) than daily resolution (Level 2 data), we analyze monthly data in this work.

2. Results

[5] This paper focuses on the geographical distribution as well as the seasonal and inter-annual variations of aerosol, water vapor, cirrus fraction and the total cloud fraction (i.e., all clouds) over the Tibetan Plateau. These variables are selected here to represent MODIS information partly because of their critical role to atmosphere energy and water budgets, and partly because such information has rarely been studied in an integrated fashion for atmosphere conditions over the Tibetan plateau regions.

[6] The spatial distribution of aerosol optical thickness (AOT) varies significantly, as shown in Julys of 2004 (Figure 2a). AOT represents the attenuation of aerosol to

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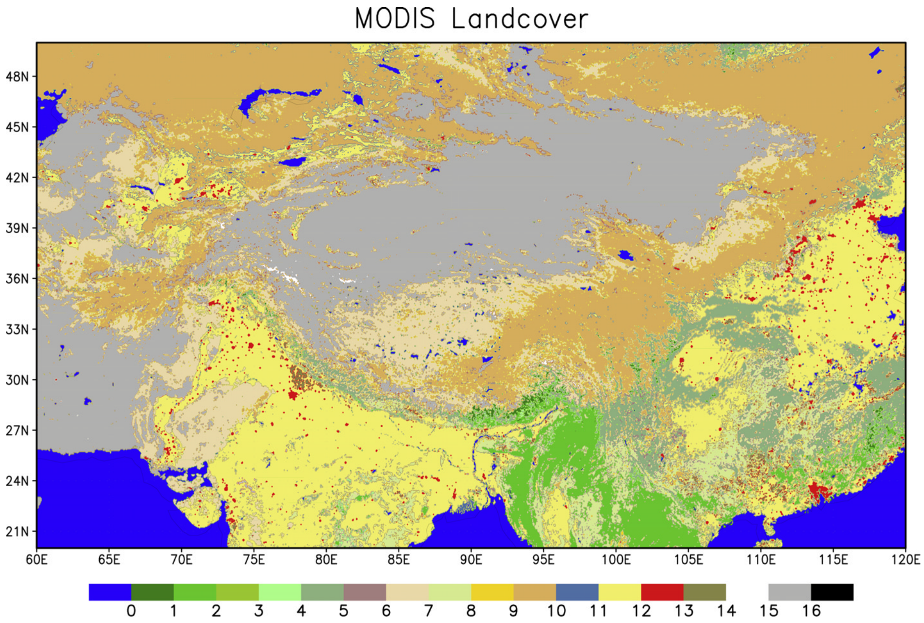

Figure 1. MODIS observed land cover information for Tibetan Plateau and surrounding regions. Land cover is defines as: 0, water; 1, evergreen needleleaf forest; 2, evergreen broadleaf forest; 3, deciduous needleleaf forest; 4, deciduous broadleaf forest; 5, mixed forests; 6, closed shrublands; 7, open shrublands; 8, woody savannas; 9, savannas; 10, grasslands; 11, permanent wetlands; 12, croplands; 13, urban and build-ups; 14, cropland/Natural Vegetation Mosaic; 15, Snow and Ice; 16, Barren or Sparsely Vegetated.

solar radiation at specific wavelength [*King et al.*, 2003]. Note that value of aerosol thickness over large desert regions are missing because aerosol retrieval algorithm used to produce products shown here has limit on bright surfaces (Y. J. Kaufman, personal communication, 2005). Nevertheless, the available pixels still provide insights for the spatial and temporal variations of surface aerosols. For example, in July 2004, the AOT over the Tibetan Plateau changes from 0.1 at the 27°N, 100°E up to 0.8 at 39°N, 75°E. Interannual variations of AOT are evident over the Tibetan Plateau, probably partly due to the winds that arises local dust or transports dust from surrounding regions. Figure 2b presents that the maximum AOT during each year occurs in May/June and remains high over summer, and the minimum AOT occurs in the November/December timeframe. In year 2005, the seasonality of AOT is much smaller than that in other years (2001–2004), with a decrease of summer 2005 and an increase in winter 2004. Nevertheless, note that in winter, MODIS retrieval of aerosol is largely missing (not shown) therefore the absolute values of AOT is highly questionable. However, the relative values between July and wintertime still imply the possible seasonal variations over the Tibetan Plateau.

[7] In general, total column water vapor highly depends on surface temperature. Nevertheless, the Tibetan Plateau has the minimum water vapor in Asia (Figure 3b) mainly due to its high altitude. Over the Plateau, the water vapor is less than 1.0cm, with the lowest values less than 0.5cm over the mountain regions in west and northeast of the Tibetan Plateau. Abundant water vapor over India and its surrounding regions is due to Indian monsoon. The high Himalayas at the south blocks the transport of water vapor from monsoon regions to the inner China. In addition, seasonal

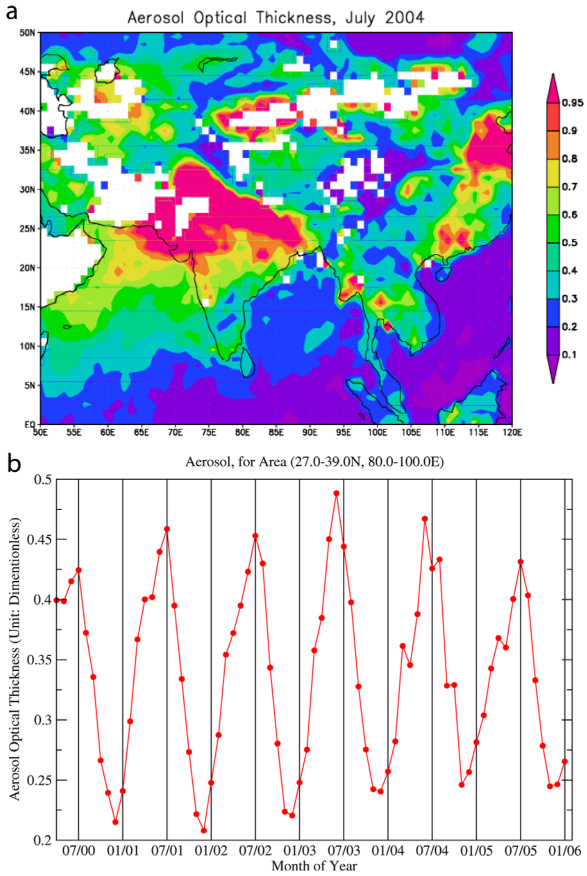

Figure 2. MODIS observed aerosol optical thickness at 0.55μm. (a) Spatial distribution for July 2004. (b) Tibetan Plateau area-averaged aerosol optical thickness (averaged for aerosol observation available pixels over 27–39N, 80–100E).

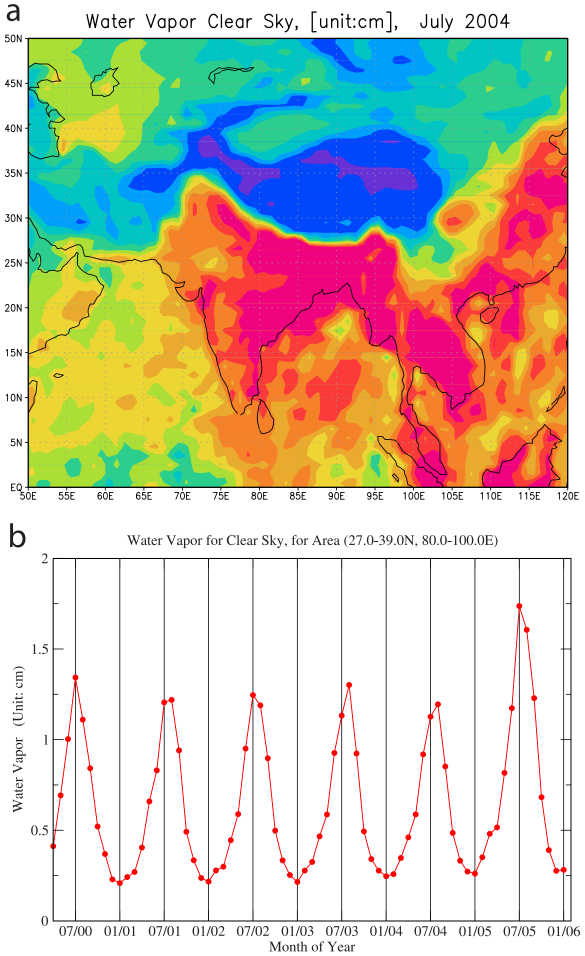

Figure 3. Atmosphere-column water vapor: (a) spatial distribution over the Tibetan Plateau and (b) seasonal variation of water vapor averaged over Tibetan Plateau (27–39°N, 80–100°E).

variations are evident (Figure 3a). The peaks of plateat-averaged (27–39°N, 80–100°E) water vapor occur in Julys (in year 2000, 2001, and 2005) and Augusts (Year 2002–2004), and the minima occur in Januarys. Besides, the month to month difference in winter is much less than that in other seasons. For example, in October water vapor is 0.4cm, about 40% reduction from September (0.65cm). Furthermore, the overall interannual variation over the region may not be significant, and summers have larger interannual changes than winters. For example, all the Januarys during 2001–2005 have water vapor around 0.02cm, while all the Julys have water vapor from 0.8 in 2000–2003 to 0.9 in 2004 and 2005, a 12.5% change in different Julys.

[8] Convection induced by surface heating contributes to the formation of cirrus [*Yeh et al.*, 1957; *Yanai et al.*, 1992; *Chen and Liu*, 2005]. MODIS observed cirrus fraction and cirrus reflectance help identify the extent of the cirrus and, subsequently, allow better calculations of cirrus attenuation on surface insolation and increases on the planetary albedo, both which are critical in determining surface and atmosphere energy budget. Figure 4a shows that, in July 2004, cirrus fraction is as high as 0.8–0.9 over the most regions of the Plateau. The minimum is 0.7 in the central part of the Plateau (around 34°N, 85°E). The seasonality (Figure 4b) shows that the largest cirrus fraction occurs in the early Spring, namely, March to May. Summers have the lowest cirrus fraction in the whole year. Specifically, the cirrus fraction is 0.93 in March 2001, while it reduces to only 0.73 in July 2001. *Chen and Liu* [2005] attribute cirrus presence to "relatively warm and moist air being slowly lifted over a large area by an approaching cold front and topographic lifting". Such a synoptic mechanism is more evident in spring time.

[9] Unlike water vapor or cirrus fraction which has unique spatial pattern determined by underlying Plateau surface, clouds fraction and cloud top temperature over the Tibetan Plateau are not distinguish from the surrounding regions, implying that these fields may be largely determined by large-scale advection instead of by surface-atmosphere interaction. Specifically, cloud fraction in July (Figure 5a) is high over south Asia associated with the Indian monsoon system, and decreases toward plateau. Similarly, cloud top temperature is low over south of Himalayas implying deeper convection there, and gradually increases over the Tibetan Plateau. Cloud optical thickness (not shown) does not show distinguish footprint of Tibetan

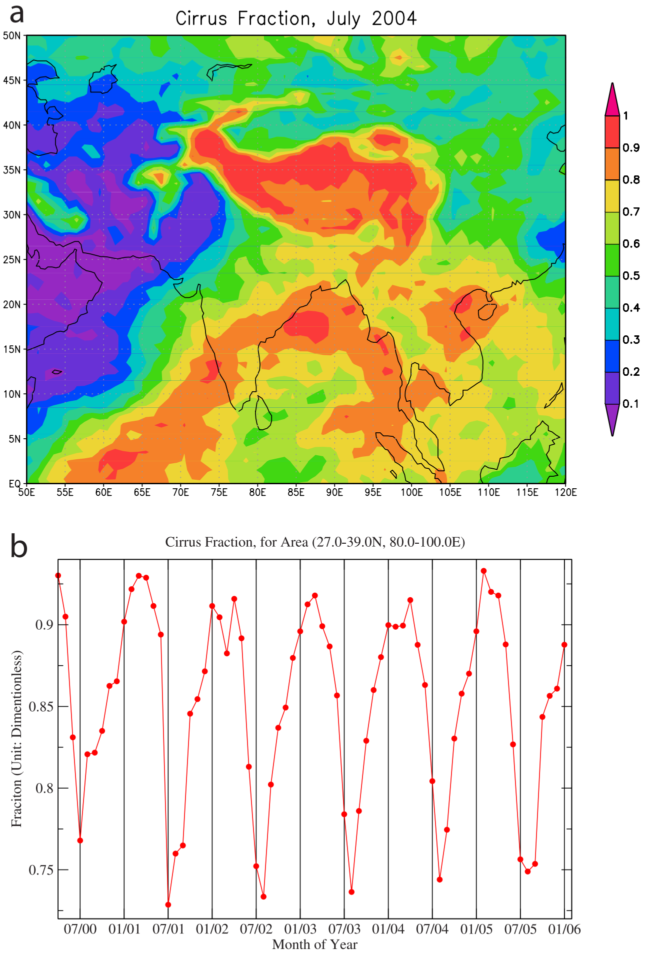

Figure 4. Same as Figure 3, except for cirrus (a) spatial distribution over the Tibetan Plateau and (b) seasonal variation of cirrus fraction, averaged over Tibetan Plateau (27–39°N, 80–100°E).

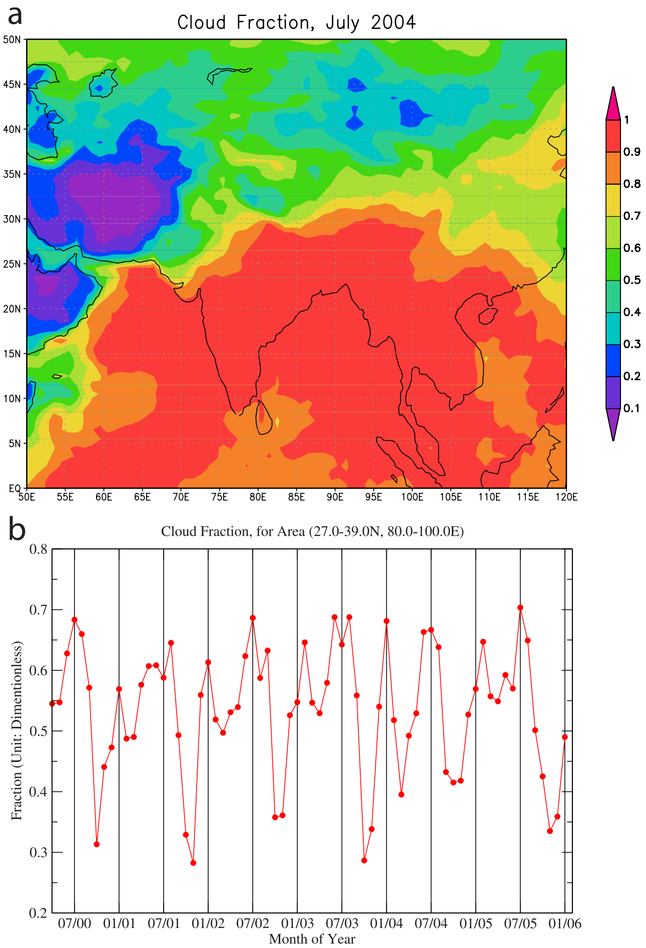

Figure 5. MODIS observed cloud properties: (a) cloud fraction in daytime for July 2004 and (b) monthly variation of cloud optical thickness averaged over 27–30°N, 80–100°E.

Plateau. This might be because the MODIS' view is blocked by high clouds, resulting in few low and middle clouds being reported, and because the MODIS retrieval algorithm assumes single-layer clouds. Nevertheless, cloud optical thickness still has evident seasonal variations, with high values in summers and low values in winters.

3. Discussion

[10] Cloud and water vapor are directly related to rainfall and snowfall. Combined with rainfall observations [*Simpson et al.*, 1988], MODIS observations make it possible to study clouds, water vapor, and rainfall as linked physical processes. For example, corresponding to the seasonality of water vapor and clouds, rainfall is high in summer and low in winter, which is consistent with cloud properties and water vapor (Figure 5b).

[11] Another importance of MODIS atmosphere measurements is its validation value for climate model simulations. Because of the lack of observations as well as lack of understanding for physical processes over the Tibetan Plateau, climate models cannot accurately represent Tibetan Plateau currently. For example, in the most advanced climate model of NASA, cloud parameterization scheme over the Tibetan Plateau is the same as those over short grass. Therefore, unique features for cirrus over the Tibetan Plateau may not be captured (B. Chen, personal communication, 2005).

[12] Uncertainty of observations must be kept in mind when we try to interpret our results. Standard deviations for every variable of MODIS atmosphere data are given in original MODIS data sets, which are essential to show the reliability of observations [*King et al.*, 2003]. At this moment, over the Tibetan Plateau, MODIS atmosphere data is more reliable at monthly and 1 degree resolution than at instantaneous pixel level.

[13] Although MODIS aerosol measurements are missing over most snow or desert pixels, the available information can still serve as an index to examine seasonal and interannual variations. Aerosols affect cloud formation and consequently affect clouds albedo and rainfall, therefore, studying the Tibetan Plateau hydrological cycle should consider aerosol properties. This area of research has not received much attention yet. Furthermore, aerosols also modify surface energy balance [*Jin et al.*, 2005], which then may affect surface snowmelt.

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