Vertical moisture transport above the mixed layer around the mountains in western Sumatra

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[1] A remarkable increase in moisture frequently occurred in August afternoon radio soundings in 2001 in the layer up to 1000 m above the mixed layer (ML) near the mountains of western Sumatra, Indonesia. This moisture enhancement was also apparent in the monthly mean diurnal cycle. The mixing ratio is not vertically uniform in this layer, suggesting that turbulent mixing cannot be a major mechanism of the vertical moisture transport. A climatological numerical study using a cloud-resolving model suggests that thermally-induced upslope winds converge over the mountain summits during daytime, forming a moist air band along the mountain range. Ambient winds above the mountain range then advect the moist air into the surroundings, moisturizing the air above the ML over the leeward terrain. This mechanism is important for producing diurnal mesoscale precipitation systems over a wide area of the Indian Ocean, as documented by previous studies analyzing TRMM and GMS observational data. *INDEX TERMS:* 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Sasaki, T., P. Wu, S. Mori, J.-I. Hamada, Y. I. Tauhid, M. D. Yamanaka, T. Sribimawati, T. Yoshikane, and F. Kimura (2004), Vertical moisture transport above the mixed layer around the mountains in western Sumatra, *Geophys. Res. Lett.*, *31*, L08106, doi:10.1029/2004GL019730.

1. Introduction

[2] The mechanism of moisture transport becomes more complicated over complex terrain because the evolution of the boundary layer depends strongly on the topographical scale [*Kalthoff et al.*, 1998]. Boundary layer evolution is also affected by terrain-induced circulations [*Whiteman et al.*, 2000], which sometimes exchange moisture between the boundary layer and the free atmosphere [*Kossmann et al.*, 2000].

[3] Moisture transport is an important topic in the tropical western Pacific, especially around Sumatra, Indonesia, where a clear diurnal cycle of convective activity has been noted from cloud data analyses obtained from the Geostationary Meteorological Satellite (GMS). The convection reveals a daily peak in the evening over Sumatra and a peak at night over the ocean near Sumatra [*Nitta and Sekine*, 1994]. Data analyses of the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) have documented the diurnal migration of a rainfall area offshore from the Sumatran mountain range [*Mori et al.*, 2004]. The important fact is that a rain band forms along the whole mountain range and then migrates mainly toward the Indian Ocean. The present study investigates the diurnal cycle of moisture transport around Sumatra using sounding data and numerical simulations.

2. Observed Moisture Profile

[4] A large mountain range extends parallel to the coastline of western Sumatra. Kototabang (100.32°E, 0.20°S, 865 m above sea level; ASL) is located in the mountain range and is locally surrounded by mountains higher than 2000 m ASL (see Figure 1). The research group of the Frontier Observational Research System for Global Change (FORSGC) has conducted radio soundings at Kototabang during intensive observational periods since May 2001. By analyzing the sounding data during a dry season, *Wu et al.* [2003] showed that moisture increases above the mixed layer (ML) in the evening. In this section, the Kototabang sounding data for August 2001 were examined for days when 6-hourly observations were available. During these days, precipitation was seldom observed by the Kototabang rain gauge.

[5] Figure 2a shows the vertical profiles of potential temperature (right side) and mixing ratio (left side) obtained at Kototabang on 20 August 2001 when a typical diurnal cycle was observed without any precipitation. The ML grew

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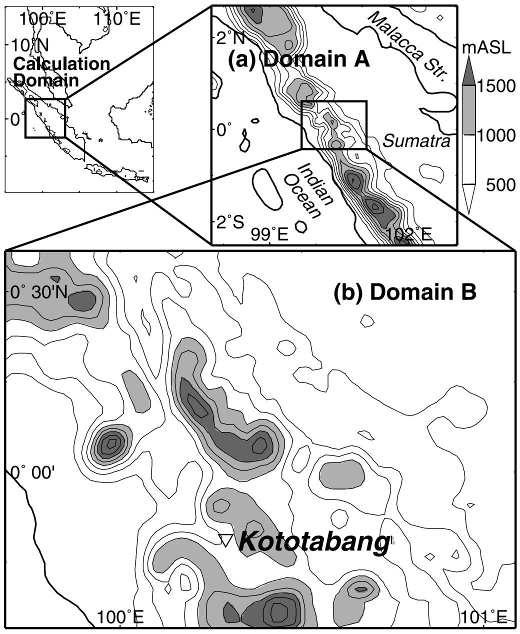

Figure 1. Model domains for (a) a coarse grid system (Domain A; grid interval, 10 km) and (b) a fine grid system (Domain B; grid interval, 2 km). The contour interval is 250 m. The location of Kototabang is shown by a triangle.

up to 2000 m ASL by 1300 LST (local solar time). The mixing ratio was vertically uniform within the ML (layer A in the figure). At 1600 LST, the amount of moisture was still uniform inside the ML. Moisture increased conspicuously in layer B up to 1000 m above the ML, i.e., between 2000 and 3000 m ASL.

[6] Figure 2b is the same as Figure 2a, except it is for mean profiles in August 2001, where the profiles at 1600 LST were replaced by those at 1900 LST. Although the ML typically develops only up to about 2000 m ASL (height C), moisture increases significantly, even in the higher layer below 3000 m ASL (height D) from 1300 to 1900 LST. Since the monthly mean profiles, like the typical day profile of 20 August, indicate a moisture increase above the ML, the diurnal cycle seems to be a part of a predominant regional climate system in this area.

3. Numerical Simulation

[7] A modified version of the Regional Atmospheric Modeling System (RAMS) mesoscale meteorological model (TERC-RAMS) [*Yoshikane et al.*, 2001] was applied to study this moisturizing mechanism. The original RAMS model was developed at Colorado State University [*Pielke et al.*, 1992]. The full-physics numerical simulations were performed for each day of August 2001 beginning every morning at 0700 LST and integrating for 48 hours. The final 24 hours of each of the 31 runs were analyzed.

[8] Figure 1 shows the simulated domains of the two-way nested model: (a) a coarse grid system (Domain A; grid interval, 10 km) and (b) a fine grid system (Domain B; grid interval, 2 km). The model has 30 vertical layers up to about 15 km ASL, and the thickness of the lowest atmospheric layer is 30 m. Six-hourly global reanalysis data provided by the National Centers for Environmental Prediction were applied to the initial and lateral boundary conditions of Domain A. The monthly mean sea surface temperature for August 2001 was specified using data from *Reynolds and Smith* [1994], and homogeneous vegetation and soil types were assumed as the surface boundary.

[9] Figure 3 is the same as Figure 2b, except it shows ensemble mean profiles for August 2001 as simulated by the model. The ML develops up to approximately 2000 m ASL, and moisture increases within the ML by 1300 LST. A remarkable increase in moisture then occurs not only inside the ML but also above the ML below 3000 m ASL from 1300 to 1900 LST.

[10] The simulated monthly ensemble mean mixing ratio is shown in Figure 4 as deviations from that at 0700 LST (gray shaded area) at the 750hPa level (about 2500 m ASL) in Domain B. The figure also shows wind speed by arrows. The 750hPa level is just above the mean height of the mountain crests. Moisture begins to increase over the mountains at around noon, and then a moist air band forms along the entire mountain range. The ambient westerly or northwesterly winds cause the moist air band to migrate eastward or southeastward in the afternoon.

4. Discussion

[11] In general, the daytime increase in moisture within the ML can be explained by evaporation from the ground surface and turbulent mixing. The moisture increase inside the ML is clearer on 20 August (Figure 2a, layer A) than in the monthly mean profiles because the height of the ML fluctuates from day to day. The moisture increase in the afternoon on 20 August (Figure 2a, layer B) cannot be explained by evaporation and subsequent turbulent mixing because part of the moisturized layer extends above the ML and the moisture is not vertically uniform. The monthly mean profiles of moisture also show enrichment in the lower atmosphere both within and above the ML (arrow D in Figure 2b), undertaking that the vertical moisture transport occurs repeatedly from day to day.

[12] The present numerical study suggests that thermally-induced upslope winds transport moisture toward the summit of the mountains around Kototabang. The moist

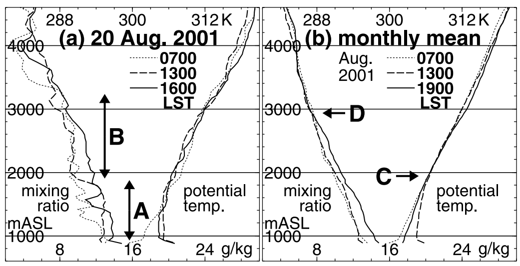

Figure 2. a) Vertical profiles of potential temperature (right side, upper scale) and mixing ratio (left side, lower scale) obtained from the Kototabang sounding data at 0700 LST (dotted lines), 1300 LST (broken lines), and 1600 LST (solid lines) on 20 August 2001. The vertical axis indicates the height ASL. b) The same as Figure 2a, except that it shows the mean profiles in August 2001 and the profiles at 1900 LST instead of those at 1600 LST.

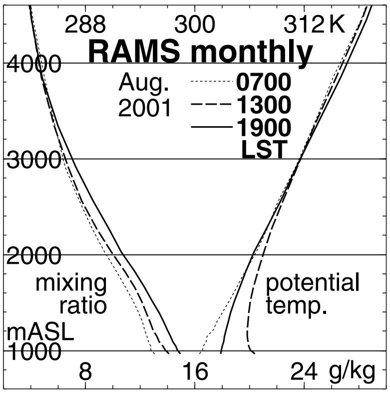

Figure 3. The same as Figure 2b, except for the ensemble mean profiles in August 2001 simulated by the model.

air is then advected away from the mountain crests toward the lee areas by ambient winds at the level of the mountaintop. The advection increases the moisture above the ML at Kototabang, which is located to the lee of the mountains, where the ML develops up to approximately the summit altitude.

[13] In an additional experiment, in which condensation processes were deactivated, the vertical transport of the moisture was almost the same as the control run, although the convergence of the thermally-induced upslope winds becomes stronger over the mountains (figure not shown). In the control run, the vertical moisture transport was intensified by the effect of shallow cloud convection which adds to the effect of weakened thermally-induced local circulations caused by weaker solar radiation under clouds.

[14] Our findings on the moisture transport essentially agree with the findings by *Kossmann et al.* [2000], who carried out some case studies and suggested that moisture flows into the free atmosphere from the boundary layer near ridge tops as a result of ambient winds and slope winds and by updrafts in terrain-induced convective cells. At Kototabang, the vertical moisture transport above the ML can be seen clearly even in the monthly mean profiles.

[15] A moist air band is frequently formed along the entire mountain range around Kototabang by the vertical moisture transport and subsequently advected by the ambient winds. *Sato and Kimura* [2003] investigated the moist air band formed along the mountain range using a two-dimensional numerical model. As the enhanced moisture region is transported to the lee of the mountain by ambient winds, the distribution of static stability and the probability of deep convection also move with the moist region to the lee of the mountain range.

[16] These processes are very important for the mesoscale diurnal precipitation systems observed in a wide area around Sumatra. *Kimura et al.*'s [2003] TRMM PR data analyses from 1998 to 2002 found that a rain band along the Sumatran mountain range migrates toward the Indian Ocean and is synchronized with a diurnal cycle at a velocity almost identical to the ambient easterly winds observed during boreal winters. This suggests that the convergence of upslope winds over the Sumatran mountain range is a climatologically decisive factor for inducing precipitation in this area.

[17] When deep convection grows in the numerical experiment, water vapor is lifted to higher levels, and moisture increases in the layer between 3000 and 6000 m ASL (figure not shown). However, significant rainfall was observed on only a few days in August 2001 at Kototabang so the moisture increase was not confirmed above 3000 m ASL in the monthly mean diurnal cycle of moisture profiles at this site. Most regional atmospheric models may not adequately simulate the presented mechanism because of insufficient horizontal grid resolution.

5. Conclusion

[18] Radio soundings in August 2001 frequently showed a remarkable moisture increase above the ML near the mountains in western Sumatra. This moisture increase cannot be explained by turbulent mixing since the moisture amount is not vertically uniform and it occurs above the ML. A numerical study suggests that thermally-induced upslope winds are a climatologically decisive factor for vertical moisture transport above the ML, involving the following processes:

[19] (1) Thermally-induced upslope winds transport moisture toward the mountain summits.

[20] (2) The upslope winds converge over the mountain summits and develop shallow convection there, which intensifies the vertical moisture transport.

[21] (3) Moisture increases over the mountain summits, forming a moist air band along the entire mountain range.

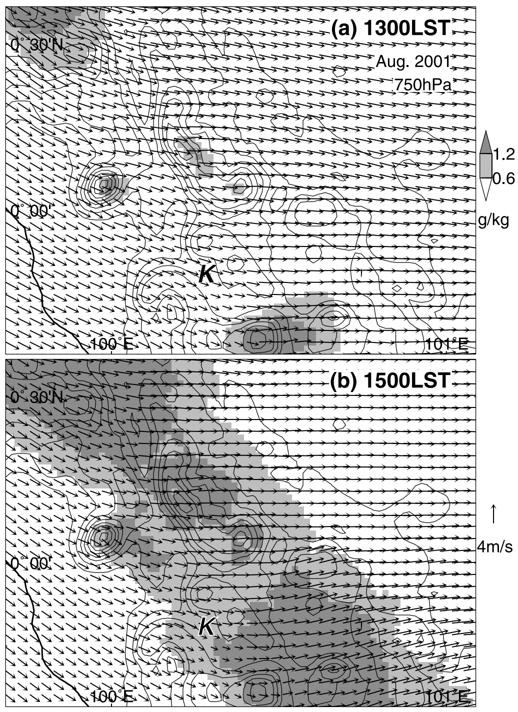

Figure 4. Monthly ensemble mean mixing ratio (gray shaded area) and wind speed (arrows) simulated by the model at the 750hPa level in Domain B at (a) 1300 LST and (b) 1500 LST for August 2001. The mixing ratio (g kg^{-1}) is shown by gray shades as deviations from the mixing ratio at 0700 LST (see legend). The lines are topographical height contours with the contour interval the same as in Figure 1b. Character K in the figure indicates the location of Kototabang.

[22] (4) Ambient winds above the mountains advect the moist air band horizontally into lee areas, increasing the moisture above the ML there, where the ML develops up to approximately the summit.

[23] (5) This mechanism affects the mesoscale diurnal precipitation systems observed over a wide area of the Indian Ocean by previous investigators, although most regional atmospheric models with low resolution cannot adequately simulate them.

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