The Role of Orography and Soil Moisture in Hydrological Transitions Associated with Monsoon Onset in Southeast Asia

***Koji Dairaku[1]**
(1: Disaster Prevention Research Group, National Research Institute for Earth Science and Disaster Prevention)
*** National Research Institute for Earth Science and Disaster Prevention, Japan, 3-1, Tennodai, Tsukuba Ibaraki, Japan. e-mail: dairaku@bosai.go.jp**

Abstract

The first transitions into the Asian Summer Monsoon (ASM) occur between late April and early May over inland Indochina, before any transitions occur along the coast. This study used a regional climate model to elucidate the influence of orography and ground wetness on subcontinental-scale hydrological processes. The model reproduced many elements of the onset of the Southeast Asia Monsoon (SEAM) associated with land surface conditions, including the early and abrupt onset observed when mountain effects and relatively dry soil conditions were combined in the model simulations. The nonlinear effects of mountains and ground wetness, combined with realistic increases in precipitation, can modify the hydrological cycle through changes in the surface energy budget. A positive feedback between soil moisture and precipitation increases the moisture source for further precipitation in the first transition period.

Keyword: Monsoon onset, Southeast Asia, Hydrological Processes, Regional Climate Model.

1. Introduction

The Asian monsoon is associated with droughts and floods, which affect billions of people and the economies of dozens of countries in Southeast Asia. Monsoon predictability is therefore a fundamental concern for the region (Charney and Shukla, 1981). The first transition of the Asian Summer Monsoon (ASM) is of great importance for agricultural practices and may foreshadow subsequent monsoon evolution. A more thorough understanding of ASM dynamics is a matter of extreme significance.

ASM onset begins between late April and early May over inland Indochina (Thailand, for example). This is earlier than ASM onset over coastal regions. By the middle of May, a mature ASM circulation establishes itself. Subsequently, land-locked convection over southern Thailand and northern Borneo abruptly advances northward, expanding over the South China Sea (SCS) (Matsumoto, 1997; Lau et al., 1998; Zhang et al., 2002).

Previous studies have shown a lack of precise knowledge of how land surface conditions affect the onset of the Southeast Asia Monsoon (SEAM). This study used a regional climate model to produce a better understanding of the influence of orography and ground wetness on the sub-continental scale hydrological processes during the early onset of the SEAM.

2. Model and Experiments

This study uses a regional climate model to analyze the influence of land surface conditions on sub-continental scale hydrological processes. Special attention was given to the early transition of the ASM. The model used was a three-dimensional, non-hydrostatic compressible dynamic-equations model (RAMS: Regional Atmospheric Modeling System) (Pielke et al., 1992). Cloud activity was parameterized with a simplified Kuo convective scheme (Molinari, 1985) and a cloud microphysics scheme. A two-stream radiation scheme (Harrington et al., 1999) parameterized radiation. The soil and vegetation model used was LEAF-2 (Walko et al., 2000). The model used topography with 30” longitude-latitude resolution (GTOPO30) and land-use data that were estimated from satellite data (AVHRR) by USGS. Sea surface temperatures were derived from OISST Ver.2 (Reynolds et al., 2002), with weekly updates, and were temporally interpolated from weekly data during the experiments. The GAME-reanalysis data with 0.5°×0.5° horizontal resolution and four times daily temporal resolution (Yamazaki et al., 2001), which is objective analysis data and includes observations from the Global Energy and Water Cycle Experiment (GEWEX), Asian Monsoon Experiment Intensive Observing Period (GAME-IOP) from April to October in 1998, provided initial and boundary conditions. The model fields were nudged to the objective analysis data at the 5 outermost lateral boundary grids and above the tropopause. Horizontal model grid spacing was 20 km. The model domain was 200 by 160 grid points (4000 by 3200 km) and there were 35 vertical levels up to 23.4 km (Figure 1). Level thickness in the vertical ranges was from 100 m at the bottom to 1000 m at the top of the domain.

The present study consisted of three different model runs. In each run, the model was integrated for about 2 months, from 1 April to 25 May 1998, a period that included the initiation of the summer monsoon over Southeast Asia. The control run (hereafter CTL) included realistic mountains and horizontally uniform initial soil moisture that was relatively dry (the degree of saturation was 0.35). A second run (NOMNT) included no mountains but was otherwise similar to CTL. The third run (WET) included mountains and extremely wet soil (the degree of saturation was 1.0). The results from the three runs clarify the roles of orography and ground wetness on ASM onset.

3. Role of mountains and soil moisture in SEAM onset

3.1. Hydrological Transition

Simulated precipitation was compared to daily Global Precipitation Climatology Project (GPCP) data (Huffman et al., 2001). Simulated results and observation were averaged over land in the region from 10°N-20ºN and from

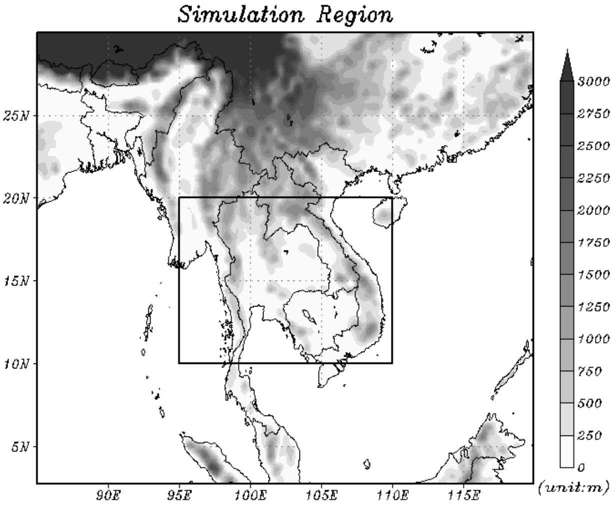

Fig. 1: Simulated region. Solid rectangle indicates the region used for averaging simulated results and observation from 10° N-20º N and 95º E-100º E.

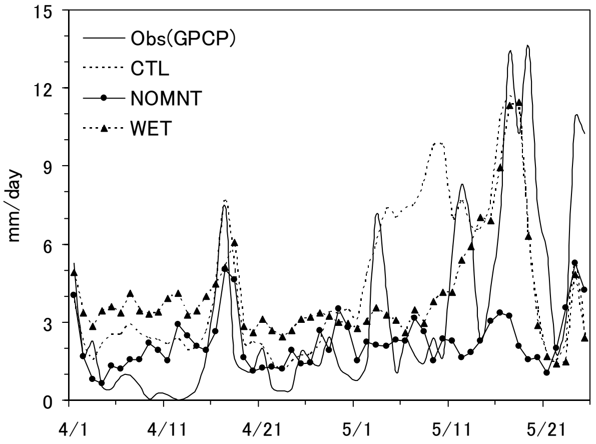

Fig. 2: Evolution of observed and simulated precipitation averaged over land, between 10° N-20º N and 95º E-100º E, from 1 Apr to 25 May 1998. The solid line represents daily precipitation from the GPCP. Simulated precipitation from CTL, NOMNT, and WET runs are represented by the dotted line, solid line with circle, and dotted line with triangle, respectively.

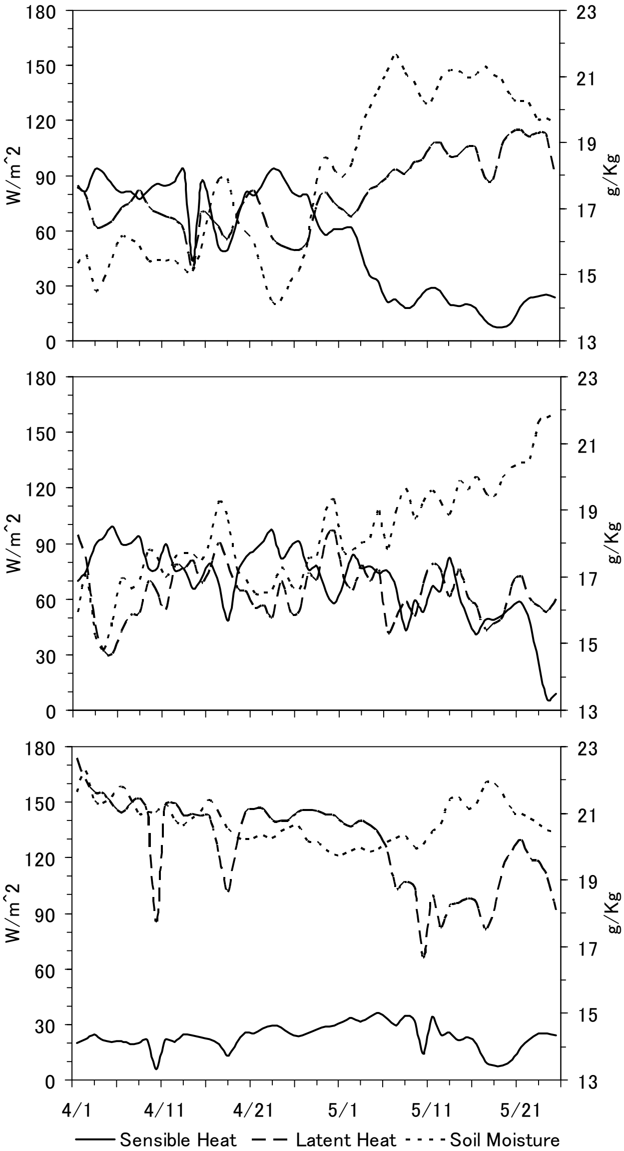

Fig. 3: Evolution of sensible heat flux, latent heat flux, and soil moisture averaged over land, between 10° N-20º N and 95º E-100º E, from 1 Apr to 25 May 1998 for CTL (top), NOMNT(middle), and WET(bottom) experiments.

95ºE-100ºE (Fig. 1). Figure 2 shows that a relatively large rainfall event (7.5 mm/day) occurred in mid-April, and that precipitation increased abruptly in mid-May. The CTL experiment captured these events, although CTL overestimated precipitation between 5-10 May. The NOMNT experiment did not reproduce the abrupt increase in precipitation during mid-May, although NOMNT did reproduce the event in April. Precipitation in the WET experiment was excessive before monsoon onset. However, the WET experiment did reproduce the heavy precipitation during mid-May. Some discrepancies between the experiments and observation can be attributed to the errors during mid-May. Some discrepancies between the experiments and observation can be attributed to the errors produced by the internal circulations developed in the model physics and by the uncertainties present in observational data sets, which can be high especially over mountainous regions (Xie and Arkin, 1997; Dairaku et al., 2004).

Figures 3 shows the evolution of area-averaged sensible heat, latent heat, and the vapor mixing ratio, which is in equilibrium with the soil and directly affects the surface energy budget (hereafter referred to as soil moisture) for each experiment.

The top panel in Figures 3 shows an abrupt decrease of sensible heat and an increase in latent heat flux and soil moisture for the CTL case. These changes coincide with increased precipitation and decreased surface temperature in the first transition period. These changes of sensible heat flux, latent heat flux, soil moisture and surface temperature in the CTL experiment are consistent with the observations reported by Toda et al. (2002). Although pre-onset precipitation slightly exceeds observed precipitation, an abrupt onset and large variation are present in the CTL case.

The middle panel in Figures 3 shows slight decreases in sensible and latent heat and a moderate increase in soil moisture, associated with weak precipitation and a slight decrease in surface temperature during onset.

The bottom panel in Figures 3 shows nearly constant small sensible heat values, considerable soil moisture, and slight decreases in latent heat flux. Because precipitation during pre-onset for the WET case was plentiful, relative variations in the period were smaller, as compared to the CTL case. However, the averaged amount of precipitation during the onset period was closest to observations in the WET case. Surface temperature was much lower than that of CTL in the pre-onset period and was higher in the onset period than in the pre-onset period.

3.2. Precipitation and soil moisture feedback in the first transition period of SEAM

Soil moisture is a source of water vapor that can greatly modify the strength of monsoon onset and influence the induced land-ocean thermal contrasts. Figures 4 depict, for each model run, relationships between soil moisture, evapotranspiration, and precipitation over land from 1 April to 25 May. The top panel in Figures 4 shows that in CTL, soil moisture and precipitation have a strong positive correlation (increment of 0.91; coefficient of determination is 0.61). NOMNT and WET also show statistically significant positive correlations (1% significance level) but show relatively vague relationships, as compared to the relationships in CTL. In addition, evapotranspiration and soil moisture have strong positive correlations in CTL (The bottom panel of Figures 4), but no correlation in NOMNT or WET.

The evolution of equivalent potential temperature indicates that strong convective instability is present during pre-onset for CTL, which coincides with the precipitation in mid-April and with an abrupt increase in precipitation in early May. Comparable strong convective instability occurs in NOMNT. Convective instability is relatively weak, particularly during pre-onset, in WET (not shown).

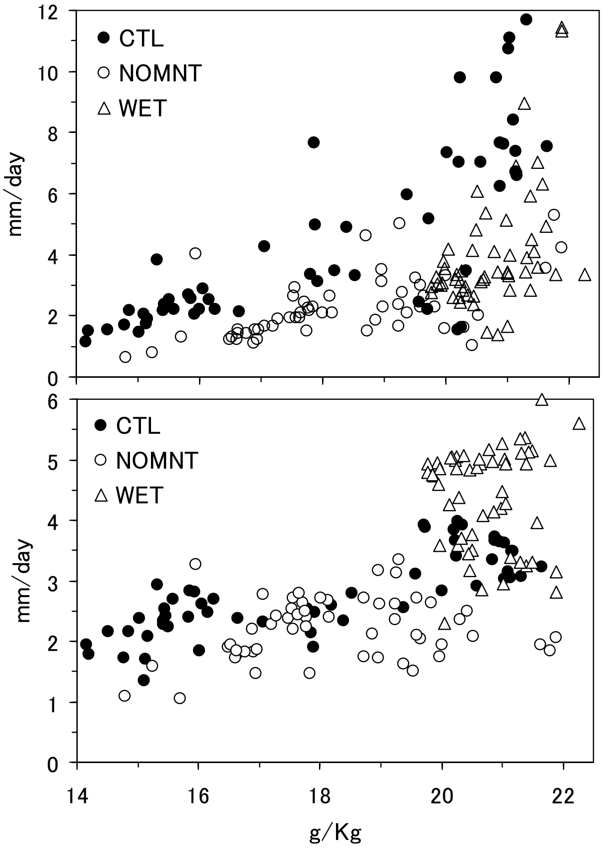

Fig. 4: The area averaged precipitation as a function of soil moisture (top) and the area averaged evapotranspiration as a function of soil moisture (bottom) for the CTL, NOMNT, and WET experiments (filled circle, circle, triangle, respectively). Data averaged over land, between 10° N-20° N and 95° E-100° E, from 1 Apr to 25 May 1998.

4. Conclusions and discussions

Even though the experiments were forced by realistic lateral boundary conditions, the model used in this study reproduced the early evolution of the SEAM when the model was subject only to imposed land surface conditions, and explained the influence on abrupt monsoon onset of mountains and relatively dry soils. That is, the three experiments showed that mountains and antecedent land surface processes strongly influence the first, abrupt transition into the SEAM. Figure 5 shows schematic diagram of the mechanism of SEAM onset.

Relatively dry soil moisture facilitates greater sensible heating over land and intensifies the land-ocean thermal contrast (e.g., *Meehl*, 1994; *Kawamura et al.*, 2002). During pre-onset, wet soil moisture causes pre-onset precipitation that weakens monsoon circulations by reducing the land-ocean thermal contrast. In addition, evaporative cooling chills the land surface and reduces convective instability.

Mountains maintain and intensify a thermal low in one preferred region mechanically and thermodynamically (Hahn and Manabe, 1975). Upward motion, which is associated with the thermal low and the monsoon circulation in the lower troposphere, is weak if mountains are not present (not shown). Orographically induced moist convection enhances monsoon circulations and convergence induced by the thermal low. There is a positive feedback between soil moisture and precipitation:

precipitation in the transition period from dry season to wet season increases surface moisture, which acts as a source for more precipitation.

During 1998, the global climate system evolved from a state in which the warmest sea surface temperature anomalies were over the eastern equatorial Pacific Ocean in 1997/98. Global circulations were influenced by a warm (El Niño) phase of the ENSO cycle (Anyamba et al., 2002). Global precipitation data (GPCP) suggest that 1998 was relatively dry in the region. How the global circulation associated with ENSO influenced the early transition into the SEAM, however, was not clearly identified. The fuller study of the influence of the annual and decadal global climate variability associated with ENSO on the SEAM onset lies outside the scope of this paper. Future investigations will explore the robustness of the present results, which provide evidence of the importance of mountains and internal feedbacks (involving soil moisture) in the initiation of the Asian summer monsoon.

This study suggests that nonlinear effects, including mountains and ground wetness, combine with increases in precipitation to modify the hydrological cycle. Such modifications are achieved through changes in the surface energy budget, and the modifications allow a positive feedback between soil moisture and precipitation by increasing the moisture source for further precipitation.

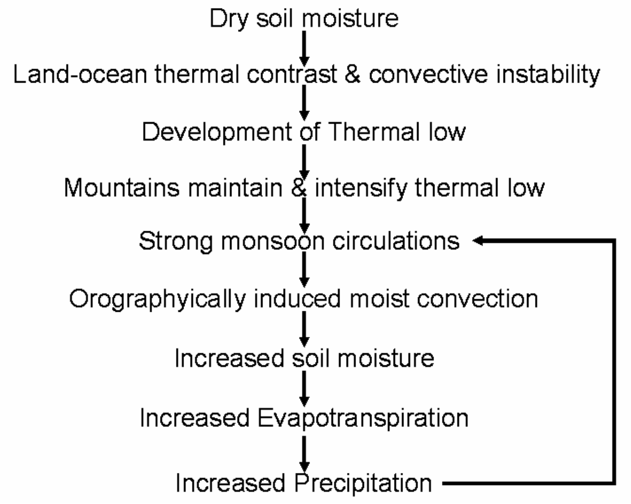

Fig. 5: Schematic diagram indicates dynamical, thermo-dynamical and hydrological processes induce abrupt SEAM onset.

References

Anyamba, A., C. J. Tucker, and R. Mahoney, From El Niño to La Niña, Vegetation response patterns over east and southern Africa during the 1997-2000 period, *J. Climate*, **15**, 3096-3103, 2002.

Charney, J. G. and J. Shukla, Predictability of monsoons. *Monsoon Dynamics*, J. Lighthill, and R. P. Pearce, Eds., Cambridge University Press, Cambridge, UK, 99-109, 1981.

Dairaku, K., S. Emori, and T. Oki, Rainfall amount, intensity, duration, and frequency relationships in the Mae Chaem watershed in southeast Asia, *J. Hydrometeor.*, **5**, 458-470, 2004.

Hahn, D. G., and S. Manabe, The role of mountains in the south Asian monsoon circulation. *J. Atmos. Sci.*, **32**, 1515-1541, 1975.

Harrington, J. Y., T. Reisin, W. R. Cotton, and S. M. Kreidenweis, Cloud resolving simulations of Arctic stratus. part II: Transition-season clouds, *Atmospheric Research*, **51**, 45-75, 1999.

Huffman, G. J., R. F. Adler, M. M. Morrissey, D. T. Bolvin, S. Curtis, R. Joyce, B. McGavock, and J. Susskind, Global Precipitation at One-Degree Daily Resolution from Multisatellite Observations, *J. Hydrometeor.*, **2**, 36-50, 2001.

Kawamura, R., Y. Fukuta, H. Ueda, T. Matsuura, and S. Iizuka, A mechanism of the onset of the Australian summer monsoon, *J. Geophys. Res.*, **107**, 101029/2001JD001, 2002.

Lau, K. -M., H. -T. Wu, and S. Yang, Hydrologic processes associated with the first transition of the Asian summer monsoon: A pilot satellite study, *Bull. Amer. Meteor. Soc.*, **79,** 1871-1882, 1998.

Matsumoto, J., Seasonal transition of summer rainy season over Indochina and adjacent monsoon region, *Adv. Atmos. Sci.*, **14**, 231-245, 1997.

Meehl, G. A., Influence of the land surface in the Asian summer monsoon: external conditions versus internal feedbacks, *J. Climate*, **7**, 1033-1049, 1994.

Molinari, J., A general form of Kuo's cumulus parameterization, *Mon. Weath. Rev.*, **113**, 1411-1416, 1985.

Pielke, R. A., W. R. Cotton, R. L. Walko, C. J. Tremback, W. A. Lyons, L. D. Grasso, M. E. Nicholls, M. D. Moran, D. A. Wesley, T. J. Lee, and J. H. Copeland, A comprehensive meteorological modeling - RAMS, *Meteorology and Atmospheric Physics*, **49**, 69-91, 1992.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, An improved in situ and satellite SST analysis for climate, *J. Climate*, **15**, 1609-1625, 2002.

Toda, M., K. Nishida, N. Ohte, M. Tani, and K. Musiake, Observations of Energy Fluxes and Evapotranspiration over Terrestrial Complex Land Covers in the Tropical Monsoon Environment, *J. Met. Soc. Japan*, **80**, 465-484, 2002.

Walko, R. L., L. E. Band, J. Baron, T. G. F. Kittel, R. Lammers, T. J. Lee, D. Ojima, R. A. Pielke, C. Taylor, C. Tague, C. J. Tremback, and P. L. Vidale, Coupled atmosphere-biophysics-hydrology models for environmental modeling, *J. Appl. Meteorol.*, **39**, 931-944, 2000.

Xie, P., and P. A. Arkin, Global Precipitation: A 17-Year Monthly Analysis Based on Gauge Observations, Satellite Estimates, and Numerical Model Outputs. *Bull. Amer. Meteor. Soc.,* **78**, 2539-2558, 1997.

Yamazaki, N., H. Kamahori, K. Takahashi, and A. Yatagai, On the GAME reanalysis, *UCLA Trop. Meteorol. Newsl.* **44***,* Univ. of Calif., Los Angeles, 2001.

Zhang, Y., T. Li, B. Wang, and G. Wu, Onset of the summer monsoon over the Indochina peninsula: Climatology and interannual variations, *J. Climate*, **15**, 3206-3221, 2002.