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The role of land-sea distribution in the formation of the Asian summer monsoon

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[1] The role of land-sea distribution in the formation of the Asian summer monsoon is examined through a series of idealized numerical experiments. Results show that the existence and geometric shape of land-sea distribution crucially affect the Asian summer monsoon. In an aqua-planet case, no monsoon is observed. In an experiment in which only the subtropical Eurasian landmass exists, there is a weak summer monsoon over its southeastern corner, but there is no tropical summer monsoon. The existence of tropical lands induces cross-equatorial flows and strong low-level southwesterlies over the tropical regions, leading to the formation of the Asian summer monsoon over India, the Bay of Bengal (BOB), and the South China Sea (SCS). The extension of the subtropical continent into the tropics greatly enhances the "East Asian monsoon". **Citation:** Liang, X., Y. Liu, and G. Wu (2005), The role of land-sea distribution in the formation of the Asian summer monsoon, *Geophys. Res. Lett.*, *32*, L03708, doi:10.1029/2004GL021587.

1. Introduction

[2] The monsoon circulations exist primarily owing to the seasonal movement of the sun, the land-sea contrast, and orography. The importance of the land-sea distribution (LSD) with regard to the existence of the monsoon circulation has long been recognized [*Webster*, 1987]. Despite great efforts on this topic [*Fennessy et al.*, 1994; *Meehl*, 1994; *Li and Yanai*, 1996; *Liu and Yanai*, 2001; *Chen and Chen*, 1991; *Ren and Qian*, 2002; *Xu et al.*, 2001, 2002], the dynamic details related to the onset of the monsoon are still not clear, and the complexity of the effect of LSD has not been deeply explored. Much of the land area in low latitudes lies in the domain of monsoons, particularly in the eastern hemisphere. The monsoon system in this area involves complex multi-scale processes and their interactions. Only when these are systematically and fully explored can the mechanism for the onset of the Asian summer monsoon be reliably revealed. The effects of LSD in different latitudes on the formation of the Asian summer monsoon are investigated in this study by using the atmospheric component of a coupled climate model with idealized LSD.

2. Model and Experimental Design

[3] The model used is the atmospheric component of the global ocean- atmosphere- land coupled GCM developed at the Institute of Atmospheric Physics (IAP). The AGCM(R42L9) is spectral with rhomboidal truncation at wavenumber 42. It has 9 vertical layers with the top at 9 hPa [*Wu et al.*, 2003].

[4] In order to take into account the regional features of the Asian summer monsoon and the geometric shape of the European, Asian and African continents, a series of idealized experiments are designed (Table 1). These continents are presented with ground cover but without orography in all experiments. The prescribed monthly means of sea surface temperature (SST) and sea ice are computed from the zonal average of the Atmospheric Model Intercomparison Project II (AMIP II) data. The monthly mean zonal averaged external forcing such as solar radiative heating and longwave radiative cooling of AMIP II are used in all experiments. Each integration period is ten years. The results from the last eight years are analyzed for this study.

3. Results

3.1. Aqua Planet Experiment

[5] In the AQ experiment without land in July, there are three mean meridional cells in each hemisphere (Figure 1a). The strongest ascending motion occurs just to the north of the equator, in correspondence with the inter-tropical convergence zone (ITCZ) and the belt of heavy rainfall of more than 10 mm day^{-1} (Figure 1b), where the maximum zonal mean SST appears. In the Northern Hemisphere in summer, the northeast trades prevail in the lower troposphere between 30°N and the ITCZ, southwesterlies between 30°N and 60°N, and northeasterlies north of 60°N (Figure 1b). There is no southwesterly flow between 30°N and the ITCZ. The seasonal migration of the planetary wind system only takes place in two narrow belts near 30°N and 60°N where the directions of the prevailing wind in winter and summer are almost opposite. The belt near 30°N corresponds to the region where the ridge line of the subtropical anticyclone migrates north and south between winter and summer, and the wind speed is very small. Furthermore, the differences between winter and summer precipitation in the two belts are also very small (Figure 1c). Therefore it can be concluded that there is no summer monsoon in this circumstance.

3.2. Effect of a Subtropical Continent

[6] In the HL experiment, only a simplified subtropical continent exists in the boreal hemisphere, and both the initial fields and external forcing fields (such as albedo and solar radiation) are zonally symmetric. Any zonally asymmetric fields should result only from the zonally asymmetric LSD, according to *Liu* [2003].

[7] In boreal summer, a southwesterly flow occurs in the lower troposphere over the south and southeast of the

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Table 1. Experimental Schemes

Experiment	Extent of the land
Aqua-planet (AQ)	no land.
Half land (HL)	0–120°E, 20–90°N.
Indochina Pen. (T-IC)	0–120°E, 20–90°N; 95–105°E, 10°S–20°N.
Indian Pen. (T-IN)	0–120°E, 20–90°N; 75–85°E, 5–20°N.
African Contin. (T-AC)	0–120°E, 20–90°N; 0–50°E, 35°S–20°N.
E land (EL)	0–120°E, 20–90°N; 95–105°E, 10°S–20°N; 75–85°E, 5–20°N; 0–50°E, 35°S–20°N. Land areas = summation of those in T land Exps. (T-IC + T-IN + T-AC).

continent between 15°N and 30°N where a northeasterly flow occurs in winter (Figure 2a). Furthermore, there is a detectable difference between winter and summer precipitation over southeastern corner of the Eurasian continent (SEEu) (Figure 2b), where the winter precipitation is ignorable but the summer precipitation is about 3 mm day^{-1} owing to the atmospheric thermal adaptation to the continental scale heating in the summer subtropics [*Wu and Liu*, 2003; *Liu et al.*, 2004]. Following the *PV*-θ view of *Hoskins* [1991], such an adaptation generates large-scale cyclonic circulation in the lower troposphere over the continental heating, bringing warm and moist southwesterlies over SEEu. Therefore SEEu experiences a weak monsoon. However, in this case there is no distinct cross-equatorial flow, nor the Indian, BOB (85°–95°E, 10°–20°N), or SCS (105°–120°E, 5°–20°N) summer monsoons.

3.3. Effects of Tropical LSD

[8] In spring, the strongest heating in Northern Hemisphere lies over the tropical subcontinent, dominated by the surface sensible heating. It can generate cyclonic vorticity and southerlies above the heating center in the lower Troposphere in terms of linear theory [*Gill*, 1980; *Hoskins and Karoly*, 1981]. The southerlies carrying warm/wet air from lower latitudes bring in moisture to the tropical subcontinent and a large amount of latent heat is released over there. In the light of the study on thermal adaptation [*Wu et al.*, 1999; *Wu and Liu*, 2000; *Liu et al.*, 2001], there is further development of the southerlies below the maximum latent heating level. When such a positive feedback process develops to some extend, the southwesterly summer monsoon then occurs over the tropical subcontinents (Figures 3a, 3c, and 3e).

[9] In T-IC, the tropical subcontinent mimics the existence of the Indochina Peninsula, Malaysia, or the Indonesian islands. The strengthened low-level southerlies over the Indochina Peninsula lead the southeast trades in the Southern Hemisphere to cross the equator over the peninsula. Due to the Coriolis force, they become southwesterlies in the boreal hemisphere, prevailing over the east of the BOB and the Indochina Peninsula (Figures 3a and 3b). The BOB summer monsoon is then formed, and the weak monsoon over SEEu is enhanced. The existence of the Indian Peninsula induces the cross-equatorial flows near 80°E in summer, leading to the formation of the South Asian summer monsoon over the North Arabian Sea, the Indian Peninsula, and the western BOB. However its influence on the subtropical summer monsoon over the southeastern region of the Eurasian Continent is not evident (Figures 3c and 3d). In T-AC, the African continent generates the cross-equatorial flow near 40°E and the pronounced southwesterlies over the northern Indian Ocean. Therefore, not only does the monsoon precipitation in Africa appear, but also the summer monsoon precipitation over the southern edge of the Asian Continent is increased considerably. Furthermore, the summer southwesterlies and monsoon precipitation over SEEu are also strengthened and advance further northwards (Figures 3e and 3f). The tropical land masses play a role of a bridge through which air masses from the southern hemisphere is transported to the northern hemisphere.

[10] In the E land experiment (EL) when the three tropical subcontinents coexist and form an alternating LSD, the western side of each subcontinent provides a southwesterly background flow over the adjacent land on its eastern side, intensifying the downstream southwesterlies (Figure 4). As a result, the summer monsoon precipitation over the Indian Subcontinent and the Indochina Peninsula in EL (Figure 4a) is stronger than that in the corresponding T land experiments (Figures 3a, 3c, and 3e). Besides, the three enhanced cross-equatorial flows merge together to form a much stronger and wider band of southwesterly flow ranging from East Africa to Western Pacific. Figure 4b gives the differences in July rainfall and surface wind between the EL and HL experiments. The coexistence of the three tropical subcontinents greatly reduces the rainfall along the equator, but enhances the monsoon rainfall over Africa, South Asia, BOB and SCS. Furthermore, it also greatly strengthens the East Asian summer monsoon precipitation over SEEu and the Western Pacific (Figure 4b). Therefore, the spatial pattern of the Asian tropical and subtropical monsoon as presented in Figure 4a captures the main features of the real rainfall distribution reasonably

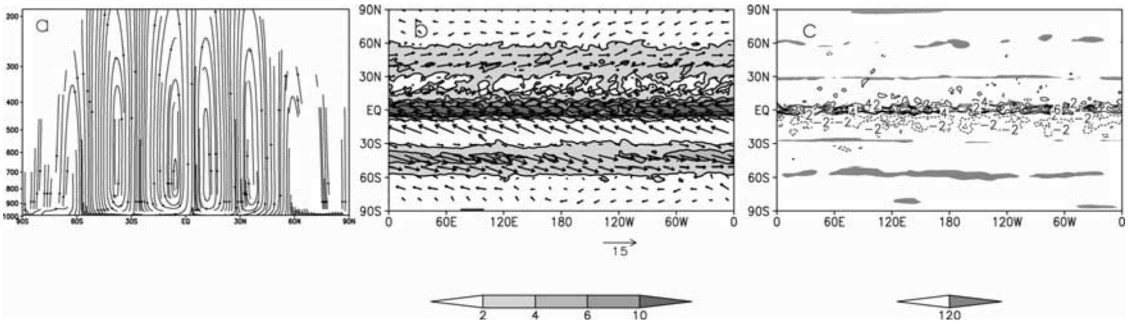

Figure 1. (a) July zonal mean meridional circulation, (b) July surface wind (in m s^{-1}) and precipitation (in mm day^{-1}), and (c) difference of surface wind direction (shading denotes areas where the difference >120°) and precipitation (contour interval is 2 mm day^{-1}) between July and January in the AQ experiment.

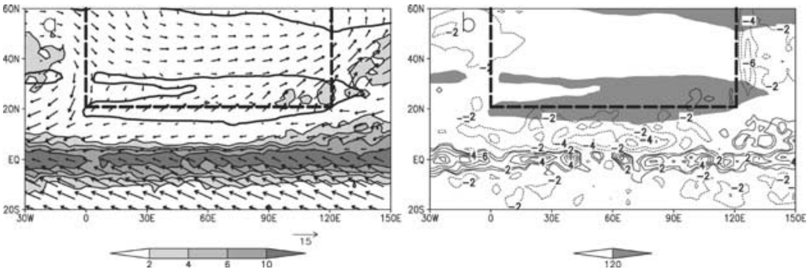

Figure 2. The same as in Figures 1b and 1c, but for the HL experiment. The area encircled by thick curves in (a) and shading in (b) denote where the difference of wind direction between January and July is larger than 120°; and the heavy dashed lines indicate the land areas in (a) and (b).

well, indicating the fundamental importance of LSD in the formation of the Asian monsoon. The present result is in agreement to a resent study by *Chakraborty et al.* [2002] where they show that monsoon onset over the south Asia can occur even in the absence of global orography.

[11] In such a no-orography EL experiment, the simulated cross-equator flows are spread over Africa, rather than concentrated as the "Somali jet" over the region off its eastern coast as observed. Furthermore, the precipitation over the Indian Peninsula is more than 10 mm day^{-1} during July (Figure 4a), which is stronger than observed. All this clearly demonstrates the importance of orography in modulating the detailed monsoon structure.

4. Conclusions

[12] Results from our experiments show that the existence and geometric shape of the LSD crucially affect the formation of the Asian summer monsoon. The main findings are as follows:

[13] 1. If the earth's surface were covered with ocean only, there would be no monsoon.

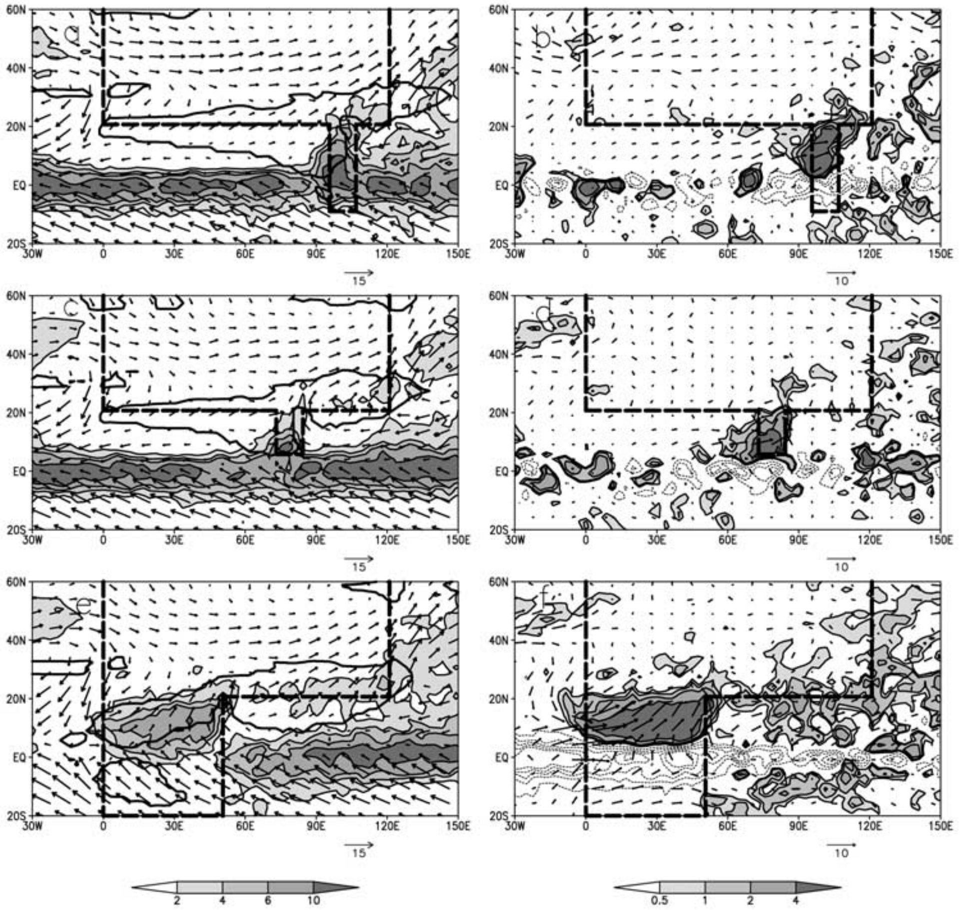

Figure 3. The simulated July surface wind vector (m s^{-1}) and precipitation (shading, in mm day^{-1}) in experiments (a) T-IC, (c) T-IN, (e) T-AC and their differences between (b) T-IC and HL, (d) T-IN and HL, (f) T-AC and HL. The areas encircled by thick curves in (a), (c) and (e) denote where the difference of wind direction between January and July is larger than 120°; and the shading and dotted curves in (b), (d) and (f) denote positive and negative precipitation differences, respectively; and the heavy dashed lines indicate the land areas in (a), (b), (c) and (d).

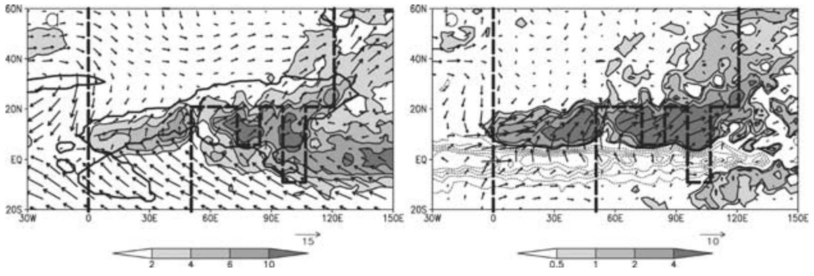

Figure 4. The same as in Figures 3a and 3b, but for the EL experiment.

[14] 2. If only a subtropical large-scale continent existed and the tropical subcontinents were missing, there would be no summer monsoon over the tropical areas. A weak summer monsoon exists only over SEEu.

[15] 3. When a tropical peninsula is merged with the subtropical continent, cross-equatorial flows are generated over the tropical continent in late spring and early summer, and the tropical summer monsoon occurs over the east of the continent and the adjacent ocean. In addition, the existence of the Indochina Peninsula and the African Continent enables the enhancement and northward advance of the summer monsoon over SEEu.

[16] 4. The coexistence of the African continent, Indian Subcontinent and Indochina Peninsula with the Eurasian subtropical continent merges those tropical sub-monsoon systems to form a strong and wide- spread Asian southwesterly summer monsoon system and greatly intensifies the East Asian subtropical summer monsoon over SEEu.

[17] This study clarifies the contributions of different land-sea distributions to the formation of the Asian monsoon. The findings listed above could enhance the dynamical understanding of the monsoon circulation. In addition, the complexity of the effects of LSD and the significance of the spring time land- surface sensible heating and the associated condensation latent heating in the formation of the Asian summer monsoon revealed in this study imply the requirement of elaborate and well-connected designs of land- surface processes as well as convection parameterization for this monsoon area in a numerical model. Therefore, our findings may also feedback on the development of general circulation models and the efforts to better simulate the Asian monsoon and the associated circulation systems. On the other hand, the decoupling of the ocean from the AGCM and the usage of the prescribed zonal mean SST may limit our understanding of the monsoon issue. Moreover, the orography especially the Tibetan Plateau also plays a very important role in many aspects of the Asian monsoon [e.g., *Wu and Zhang*, 1998; *Hahn and Manabe*, 1975; *Kitoh*, 2004]. All these need to be studied further in future.

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