学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

A Study on Global Land-Atmosphere Interactions with Focus on the Bimodality of Soil Wetness
(土壌湿潤度の二峰性に着目した全球スケールの大気陸面相互作用に関する研究)

Rainfall impacts land surfaces, but how do land surfaces influence atmospheric circulation and rainfall? The Global land surface coupled atmospheric general circulation models have identified Land-Atmosphere hotspots where summer rainfall is sensitive to soil moisture: the central Great Plains of the United States, the western Sahel of Africa, and mid-north India, which is also corroborated in observations. The regions are covered with croplands and have intense irrigation, particularly in mid-north India and the central Great Plains. Additionally, satellite observations over hotspots have detected a unique summer characteristic: soil moisture bimodality, indicated by two peaks at different wetness states in the probability distribution. This thesis reveals the mechanisms behind the interplay of land-atmosphere interaction, soil moisture bimodality, and intense irrigation by investigating modes of land surface interaction with atmosphere and the impact of irrigation over three hotspots using an analytical land-atmosphere coupled model, observations and a land surface model.

In Chapter 2, A zero-dimensional analytical land-vegetation-atmosphere coupled model is developed to determine the land surface vegetation that led to summer season soil moisture bimodality and how this bimodality impact on rainfall and near-surface temperature. The model incorporates three vegetation schemes: barren land, forest, and cropland. Bimodality is found to occur only over cropland. There are two equilibrium states—a dry equilibrium state and a wet equilibrium state—arising from dry and wet soil moisture initializations, respectively. A dry initialization limits evapotranspiration, which reduces rainfall and further dries the soil. This, in turn, increases sensible heat flux, raises near-surface temperatures, and reduces latent heat, ultimately creating a hot, dry summer. Conversely, a wet initialization results in a cool, wet summer. Forests, with potential evapotranspiration, lead to cool, wet summers, while barren land, with its limited evapotranspiration, results in hot, dry summers regardless of soil moisture initialization. This chapter establishes that cropland is a potential region for summer season bimodality, where rainfall and temperature can alternate between dry and wet states and are sensitive to soil wetness. Importantly, forests, with characteristics similar to irrigated regions, diminish bimodality.

In Chapter 3, A bimodality detection algorithm using a Gaussian Mixture Model, with parameter estimation through the Expectation-Maximization algorithm is developed to detect global bimodality hotspots using satellite summer season soil moisture observation datasets. Bimodal hotspots were detected in mid-north India, the western Sahel, and the central United States—regions also recognized as key land-atmosphere interaction hotspots and covered with croplands, aligning with the results obtained in Chapter 2 and in series global land surface coupled atmospheric general circulation models studies. Subsequently, natural climate variability for bimodality was investigated. The transition from dry to wet conditions during the summer emerged as the principal driver for bimodality in mid-north India and the western Sahel. In contrast, interannual variations, combining dry and wet summers, were dominant in inducing bimodality in the central Great Plains. Additionally, the impact of irrigation over Northern Hemisphere croplands is examined using irrigation intensity and bimodal strength; as irrigation

intensity increases, bimodality diminishes, consistent with the findings in Chapter 2.

In Chapter 4, the MIROC Integrated LAND surface model version 1 is used for its capability to represent complex hydrological and ecological dynamics and to conduct experiments with and without irrigation. The aim is to understand the physical mechanisms behind bimodality and quantify the impact of irrigation on bimodality and water and energy exchanges. Two distinct experiments of MIROC-INTEG-LAND were conducted: one including irrigation and another without. For the central Great Plains, higher irrigation intensity decreased the bimodal region and diminished their strength. These effects were more pronounced in the irrigation experiment, consistent with the observations in Chapter 2 and Chapter 3. The climatic characteristics for bimodality were studied using the Global Aridity Index, indicating that semi-arid regions tend to exhibit higher bimodality compared to hyper-arid, arid, and dry sub-humid regions. This aligns with a series of past studies suggesting that surface fluxes in semi-arid regions are sensitive to soil moisture.

Chapter 5 presents a case study of Pakistan, a semi-arid region with intense irrigation around the Indus River, which experienced major flood events in summer of 2010 and 2022. Bimodality is analyzed in the context of heavy rainfall impacts. Pakistan's bimodality was twice as high in 2010 and 2022 compared to climatology. A time series changepoint analysis on rainfall data reveals that the rapid transition, i.e., high amplitude and large differences in the mean before and after the changepoint due to heavy rainfall, is statistically significant in causing bimodality. This study attributes the heavy rainfall in 2010 and 2022 to European atmospheric blocking and heatwaves, which played crucial roles. On the days of heavy rainfall, Rossby wave breaking events facilitated the penetration of extratropical disturbances into Pakistan, leading to the ascent of moist air and subsequent rainfall. Specifically for 2022, the presence of a low-pressure system over southern Pakistan further intensified the rainfall in that region. Southern Pakistan, primarily a desert and located at the boundary of a climate transition zone, is particularly sensitive to future increases in heavy rainfall. In this region, the bimodal distribution of rainfall may exhibit a significant separation between dry and wet peaks, creating major challenges for water management.

In conclusion, this thesis explores the intricate relationship between summer season soil moisture bimodality, land-atmosphere interaction and irrigation, their impact on rainfall and temperature. Developed a zero-dimensional coupled land-atmosphere analytical model in Chapter 2 that identifies croplands as potential regions for summer season bimodality. Chapter 3 develops a bimodality detection algorithm to identify global bimodality hotspots overlapping with land-atmosphere and irrigation hotspots. Chapter 4 employs the land surface model to further bimodality's physical mechanisms and the effects of irrigation. Finally, Chapter 5 presents a case study of Pakistan, demonstrating the impact of heavy rainfall on soil moisture bimodality and its implications for flood events. These findings underscore the importance of incorporating irrigation activities and accurately simulating soil moisture bimodality in climate models to enhance water management practices.