論文の内容の要旨

Predictability of Precipitation Variability and the Role of Land-Atmosphere Interactions in Atmospheric General Circulation Models

（大気大循環モデルを用いた降水変動の予測可能性と
大気陸面相互作用の解明に関する研究）

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This thesis examines the predictability of precipitation variability and the role of land-atmosphere interactions in atmospheric general circulation models (AGCMs). In particular, it considers how and to what degree the contribution of land surface conditions to weather evolution and seasonal prediction can be improved by the prescription of land surface conditions.

In the first chapter, the author described the background and purpose of this study. The inherent behavior of the atmosphere and its internal variability from its nonlinear and unstable characteristics are chaotic. Therefore, prediction accuracy is limited even under perfect initial conditions. The first person to estimate the limitations of prediction was *Thompson* [1957]. *Lorenz* [1963] suggested that a non-periodic evolution occurs in three types of simultaneous, and ordinary differential equations, even if initial conditions have subtle differences. Because of the chaotic behavior of the atmosphere, the use of individual forecasts of instantaneous weather patterns is constrained to about 10 days or less [*Lorenz* 1982]. Thus, a deterministic numerical forecast with a single atmospheric initial condition may have limited value for prediction. An ensemble forecast consisting of a number of individual forecasts based on a set of simulations, in which each simulation is slightly different, includes several initial conditions, and uses values that have been slightly perturbed, can gauge and reduce the numerical prediction errors that arise from chaotic behavior.　Lorenz's famous statement, ``Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?", made at a conference of the Global Atmospheric Research Program (GARP), reflects the problem of atmospheric chaotic behavior. Predictability has been estimated by some distinguished researchers, e.g., *Charney* [1966], *Smagorinsky* [1969], and　*Epstein* [1969] in different ways. All of their estimations suggested that predictability is only reliable within one to two weeks. Contrary to these pessimistic results concerning predictability (predictability in the first kind), *Lorenz* [1982] showed the existence of another aspect of predictability and demonstrated that　seasonal-scale predictability could be improved if atmospheric boundary conditions (e.g., sea surface temperature, snow cover, and soil moisture) are predicted. The potential predictability (or theoretical limit of predictability) was investigated at the seasonal scale using statistical approaches based on the assumption that the model is perfect and the lower boundary conditions are predicted correctly [e.g., *Charney and Shukla*, 1981].

In the second chapter, the author derived the mathematical structure of a similarity index known as Ω diagnostics, which can be calculated by a simple expression. The author also revealed its statistical characteristics; the Ω diagnostics quantify the similarity among several time series of ensemble members from two aspects of ``phase (correlation)``and ``shape (mean value and amplitude)``. Furthermore, the author introduced two new statistical indices, which quantity the similarity in phase and shape, as singular solutions of Ω diagnostics. One is the average value of the anomaly cross correlation coefficient (ACCC) and the other is the average value of the variance ratio (AVR) against ensemble members. Present medium-range and seasonal weather forecasting are performed by ensemble simulations, which have subtle differences in initial conditions. Skill in ensemble weather forecasts is typically estimated with anomaly correlations or root mean square (RMS) differences. Even if high predictability of shape is estimated with the RMS difference, such accuracy may not be practical or reliable in spite of small predictability for phase similarity. The converse is also true. In the predictability studies originated by *Charney and Shukla* [1982], ensemble simulation results considered the influence of lower boundary conditions (e.g., sea surface temperature, soil moisture) on atmospheric variability by statistical approaches. When all three types of similarity indices are used, we can categorize the predictability of phase and shape taken individually or in combination.

In the third chapter, the author considered the global distribution of land-atmosphere coupling strength (CS) for precipitation variability in the boreal summer. Many sections of this chapter are related to the Global Energy and Water Cycle Experiment (GEWEX) Global Land-Atmosphere Coupling Experiment (GLACE). GLACE involves highly controlled numerical simulations of the boreal summer using 12 climate models to show the global distribution of land-atmosphere CS. The author participated in GLACE using AGCM version 5.6 of the Center for Climate System Research/National Institute for Environmental Studies (CCSR/NIES). GLACE results showed that large land areas of subsurface soil moisture (called "hot spots") impact precipitation variability; the large Ω similarity index was found in the Great Plains of North America, the Sahel, equatorial Africa, and India. The CCSR/NIES AGCM also revealed strong CS over the Great Plains of North America, central Eurasia, and eastern India. CS exhibited large model dependency. However, each model revealed hot spots in semiarid land areas. Including such hot spots in global initializations of soil moisture may enhance precipitation prediction over semiarid regions in boreal summer. The CS, however, cannot reveal locations with long soil moisture memory. The author investigated the global field of soil moisture memory in the boreal summer using three types of similarity indices; Ω, ACCC, and AVR. Analyses with Ω diagnostics revealed long soil moisture memory in some tropical regions, deserts, and semiarid regions, including the Great Plains of North America and parts of central Eurasia. Both of these semiarid regions have strong land-atmosphere CS and long soil moisture memory; thus, precipitation variability could be improved over these regions in the boreal summer by monitoring subsurface soil moisture.

In the fourth chapter, the land-atmosphere CS for precipitation variability was associated with the prescription of all land surface prognostic variables. In this chapter, CS shows a potential limit of predictability associated with land surface boundary conditions. Strong CS for precipitation variability appeared in many regions of North America, especially in the central area, the central region of Eurasia, and Southeast Asia. This chapter discusses constraint factors to define the geographical distribution of the land-atmosphere CS for precipitation variability. In addition, hot spots are found in semiarid regions, where the 6-day variability in latent heat (LH) flux is large. The diagnostic, CS, shows land surface impacts from the viewpoint of sensitivity. LH flux variability, in contrast, indicates land surface impact as the signal. Thus, both large CS for LH flux and large LH flux variability are required for hot spots to occur. Furthermore, large sensible heat (SH) flux is found over the hot spots. The vertical structure of land-atmosphere CS was also focused in this chapter. CS largely decreases within the atmospheric boundary layer (ABL). Large SH flux induces atmospheric instability and creates conditions suitable for conveying evaporated water vapor into the upper level of the ABL. Thus, the author suggests that both large SH flux and large variability in LH flux are necessary for high CS for precipitation. This could be the mechanism determining the locality of land-atmosphere CS. Finally, the locality of land-atmosphere CS (local CS) for precipitation was quantified using another type of land surface prescription experiment. In this experiment, all land surface prognostic variables were prescribed in the hot spots. The results showed that the spatial correlation coefficient between the CS for precipitation and the local CS was about 0.7. In the hot spots, about 60% of the land surface impact was determined locally.

In the fifth chapter, the author discussed the seasonal variation in land-atmosphere CS for precipitation variability associated with land surface conditions. In this chapter, the author estimated the seasonal variation in CS throughout the year and discussed the relationship between local evaporation characteristics and CS. Large seasonal variation in CS decreased from fall to winter, despite strong CS in summer. However, land-atmosphere CS for precipitation was correlated with local evaporation characteristics throughout the year over central North America (CNA). For Indochina, large CS was estimated for the transition periods between the rainy and dry seasons. Over Indochina and southeastern China (SEC), seasonal variation in CS was not correlated with local evaporation characteristics, but it was relatively well correlated with the CS for 850 hPa geopotential height at the annual scale. Thus, land-atmosphere CS for precipitation is affected not only by direct evaporation characteristics, but also by the atmospheric field, which was already impacted by the land surface and could indirectly create high CS from remote impacts to the land surface.

The sixth chapter examined the predictability of the Asian summer monsoon using several sets of 16 simulations with prescribed sea surface temperatures (SSTs) and land surface prognostic variables. Predictability was estimated with the Ω statistical index, which quantified similarity among ensemble members. The model simulations show that the predictabilities of precipitation and low-level moisture flux during May and June are much larger than those in July and August. The role of land-atmosphere interactions was also examined. During May and June, the predictabilities of soil moisture and near surface temperature increased with higher predictability of precipitation. At the same time, the predictability of cumulus-cloud-type precipitation could be improved or maintained by positive feedback from the high predictability of soil moisture and near surface temperature, which was associated with atmospheric instability in the ABL. The land-atmosphere CS and the role of the Tibetan Plateau were also investigated. The results suggest that land surface conditions of the Tibetan Plateau may contribute to the predictability of air temperature at the 850 hPa height in June from the Tibetan Plateau to Japan, a region of East Asia including large areas of China and Korea. Increased predictability of air temperature at this height relates to the accuracy of atmospheric condensation temperature predictability and leads indirectly to enhanced precipitation predictability. This result suggests the possibility of well-connected predictability associated with the prescription of land surface conditions.

In seventh chapter, three sets of ensemble experiments were carried out to investigate the predictability and the reproducibility of precipitation and near surface variables variability associated with the semi-observed subsurface soil moisture. One of the target regions is East Asia where the Meiyu (Baiu) frontal activity produces much rainfall in the boreal summer. The author conducted three sets of ensemble experiments with both T239 (50km grid cell) and T39 (300km grid cell) horizontal scales, and discussed the horizontal resolution dependency concerning the predictability associated with the subsurface soil moisture. The author also examined the relationship between the predictability and the reproducibility of near surface variables. As the results of analyses, a model simulation using the semi-observed subsurface soil moisture improved the reproducibility of the surface soil wetness, 2m height air temperature, and the sea level pressure field. In particular, large predictability and reproducibility were shown over China, and these results suggest that the initialization of subsurface soil moisture could be one of the contributors to improve the seasonal prediction of at least near surface variables.