SEASONAL AND INTERANNUAL VARIATIONS IN SPATIAL AUTOCORRELATION STATISTICS OF TROPICAL PRECIPITATION

by

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SEASONAL AND INTERANNUAL VARIATIONS IN SPATIAL AUTOCORRELATION STATISTICS OF TROPICAL PRECIPITATION

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Spatial autocorrelation of tropical precipitation is examined by the application of Moran's *I* index to the 17-year CMAP data set. Global *I* indices, which express the overall spatial autocorrelation of precipitation for the entire tropics, have an annual cycle characterized by bimodalism. A higher degree of spatial organization of tropical precipitation occurs during both boreal and austral summers. While the annual cycle of mean precipitation appears to be more unimodal, global *I* indices, therefore, provide an alternative definition of precipitation seasonality in the tropics. The seasonal variations in global *I* indices are small in the equatorial region, but are very large in subtropical latitudes.

Local *I* indices which specify the spatial autocorrelation of precipitation in a small geographical area are also calculated at each individual grid cell using a moving window approach. Generally, high local *I* indices are associated with large precipitation gradients and low local *I* indices are related to areas of precipitation maxima or minima. Due to this unique property, local *I* indices are very useful in the identification of the core locations of large scale convective features such as the ITCZ and SPCZ.

The interannual variations of tropical precipitation and associated spatial autocorrelation are affected by ENSO-related atmospheric/oceanic forcings. Changes in the local spatial autocorrelation of tropical precipitation during an ENSO event are induced by the shifting of convective centers (change of local precipitation) and the corresponding increase or decrease of the precipitation gradient for a location. Regions where precipitation variables are affected by ENSO include most of the tropical Pacific, Indonesia, Amazonia, Northeast Brazil and West Africa. These ENSO-related connections are strongest in DJF, when the SOI leads the precipitation variable and weakest in JJA, when the precipitation variables lead the SOI. Due to this relationship, JJA precipitation statistics may prove to be a useful predictor of future ENSO activities.

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TABLE OF CONTENTS

Chapter **Page**

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Precipitation from tropical convective cloud clusters accounts for over two-thirds of the total precipitation of the world during a given year. While most of this precipitation falls in highly concentrated events, the spatial and temporal distribution of precipitation varies widely (Simpson 1992). Different precipitation regimes in the tropics, from wet equatorial to arid, have been identified and mapped for decades using either a deductive class assignment approach (e.g., Wang 1994) or an inductive grouping approach that clusters similar regimes (e.g., Moron et al. 1995). Despite these attempts to classify and/or regionalize tropical climate, the spatial aspects of tropical precipitation variability are yet to be fully explored. Specifically, the local spatial autocorrelation of tropical precipitation has not been adequately studied.

The concept of spatial autocorrelation is a reflection the "first law of geography" by Tobler (1970, p. 236), which stated that "everything is related to everything else but near things are more related than distant things." Autocorrelation can be loosely defined as how a single variable correlates to itself between pairs of observation. The pairs of observation can be any two consecutive records of the same location over time or any two neighboring records at the same time over space. When the latter case is the concern, it is referred to as spatial autocorrelation. Spatial autocorrelation problems are more sophisticated than temporal autocorrelation (time series) ones in the way that a single observation may have multiple neighboring records instead of only two.

Spatial autocorrelation of precipitation is a quantitative measurement of the degree of clustering or concentration of precipitation over space. It provides additional information about monthly precipitation distribution beyond precipitation rate or amount information alone. An isohyet map is utilized to show the spatial distribution of rainfall over a certain region, within a certain period of time. Closely spaced isohyets are located over transitional areas with a large "rainfall gradient" separating areas of spatially uniform dryness from areas of spatially uniform wetness. While the use of descriptive statistics such as total, range, mean, and variance to summarize the overall spatial distribution of precipitation is widely adopted, the application of spatial autocorrelation statistics to summarize the overall spatial organization of precipitation is rare. Unfortunately, this additional but not secondary information is often neglected.

Positive spatial autocorrelation, which represents a spatial clustering of observations with similar values, is a form of redundancy. Hence, the total information content of positively spatial autocorrelated data is less than that of independent, uncorrelated data. Since traditional distribution theories are all based on the assumption of independent samples (Glass et al. 1972), they are inapplicable to autocorrelated fields. The consequence of this is that positive spatial autocorrelation causes an over-estimation of the significance of statistical inferences (Cliff and Ord 1973).

In the tropics, where surface-based observations are limited and/or unevenly distributed over space, knowledge of the spatial autocorrelation of precipitation can facilitate the estimation of precipitation over vast unpopulated areas. Moreover, as precipitation in the deep tropics is an important forcing mechanism for the large-scale

atmospheric circulation and climate (Rasmusson and Arkin 1993), an understanding of the spatial autocorrelation (organization) of tropical precipitation can also provide insights to the functioning of the global climatic system as a whole. Finally, since precipitation is the primary component in the hydrological cycle that provides fresh water to human society, identification of patterns of spatial autocorrelation of tropical precipitation can also contribute to the planning of water resources in tropical countries, especially those with an agricultural economy.

1.1 Research Objectives and Organization

The goals of this study are: (1) the characterization of the spatial autocorrelation of tropical precipitation, and (2) the examination of its relationships to atmospheric and/or oceanic phenomena. In particular, El Niño/Southern Oscillation (ENSO) events and sea surface temperature (SST) variations, known to be driving forces of low latitude climate and climate variability, will be linked to precipitation spatial autocorrelation.

The spatial distribution and the spatial autocorrelation (organization) of tropical precipitation are two related and parallel concepts. Therefore, an understanding of the mechanisms of tropical precipitation and the factors governing the spatial distribution of tropical precipitation is required for further investigation of the spatial autocorrelation of tropical precipitation. The circulation patterns leading to organized convection will first be outlined. An analysis of the interannual variations in tropical climate reveals the dominant role of the ENSO cycle. The spatial coherence between SST anomalies and tropical precipitation will also be addressed.

In this study, three data sets are utilized: the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) (Xie and Arkin 1997); the Optimum Interpolation (OI) sea surface temperature (SST) analysis (Reynolds and Smith 1994); and the Climate Analysis Center (CAC) operational Southern Oscillation Index (SOI) (Ropelewski and Jones 1987). A mathematical definition and the corresponding theory of statistical hypothesis testing of spatial autocorrelation will be given for the Moran's *I* index (Moran 1948, 1950) utilized in this study. Data analysis procedures used to relate precipitation spatial autocorrelation to ENSO and SST forcings will also be presented.

One of the objectives of this study is to identify the normal patterns of high (and low) precipitation spatial autocorrelation of monthly precipitation in the tropics (both land and ocean areas). Maps and diagrams illustrating the annual cycle of precipitation spatial autocorrelation in the tropics will be included. Comparisons of these patterns to the original precipitation distribution will also be made.

The other key objective of this analysis is to identify the mechanisms related to seasonal and interannual variations in the spatial autocorrelation of tropical precipitation. Possible cause-effect relationships linking these temporal variations to SOI and SST anomalies will be identified and discussed. The question will first be investigated for the tropical region as a whole. Regional case studies for different sub-divisions, such as monsoon India, maritime Indonesia, and the equatorial central Pacific, will follow to provide more detailed geographical syntheses. The findings in this study will be summarized, and some recommendations for further studies will be presented.

CHAPTER 2

TROPICAL PRECIPITATION VARIABILITY

Variability of annual precipitation increases with a decreasing mean, a more equatorial latitude and a greater influence of the El Niño/Southern Oscillation cycle (Nicholls and Wong 1990). The tropical region, therefore, should display the most complex map of precipitation distribution in the world. A hierarchical time/space organization of the structure of tropical precipitation variability in the equatorial belt of the eastern Indian Ocean-western Pacific Ocean sector was proposed by Rasmusson and Arkin (1993; Figure 2.1). The fundamental control represented by the outermost ring is the average annual cycle, which is in turn modified by the 2-6 year ENSO event cycles in the adjacent inner ring. The next element, the Madden-Julian intraseasonal oscillation (Madden and Julian 1971, 1972), affects tropical precipitation patterns by inducing a precipitation anomaly that travels primarily from the western Indian Ocean to the central Pacific Ocean (Weickmann et al. 1985). During the summer, the traveling precipitation wave can be traced all around the tropics, repeating every 40 to 50 days. The final component of tropical precipitation is the synoptic scale cloud clusters that cause day-to-day weather.

In addition to temporal variations, convection tends to cluster spatially in large structures in the tropics. The two most important convection centers are the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ; Trenberth 1976). The variations in locations and intensities of the ITCZ and SPCZ as influenced by atmospheric circulation patterns at different time scales will be addressed below. The

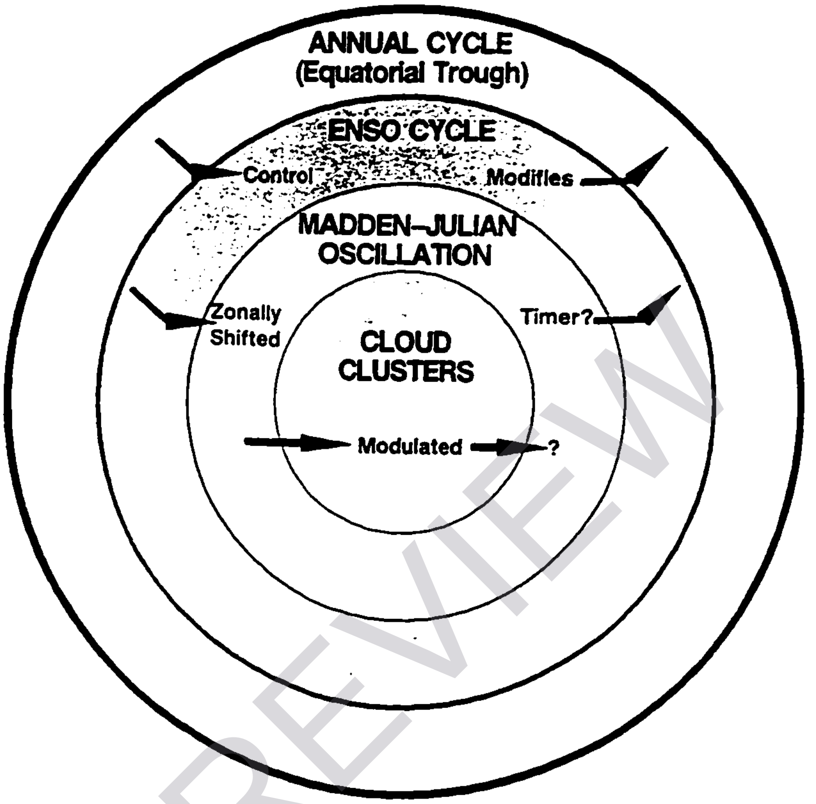

Figure 2.1 Schematic illustration of the modes of variability in the Indian Ocean-Pacific sector of the equatorial trough (from Rasmasson and Arkin 1993, p.1500).

general associations of precipitation with tropical ocean variables such as sea surface temperatures (SSTs) will also be discussed.

2.1 Circulation Features and Seasonal Variations of Tropical Precipitation

According to Oort and Peixoto (1983), the principal tropical precipitation mechanism is moisture convergence into the ITCZ or SPCZ due to the trade winds and monsoon circulations. These atmospheric motions draw moisture from the major water vapor source region of the subtropical oceans, where evaporation significantly exceeds precipitation. Hence, an understanding of the movement of the ITCZ and SPCZ is critical to the explanation of spatial variations in tropical precipitation.

As delineated from various satellite data sets, the ITCZ consists of interrupted segments extending over the continents and oceans of the tropics (Hubert et al. 1969; Sikka and Gadgil 1980; Gadgil and Guruprasad 1990; Waliser and Gautier 1993; Figure 2.2). The ITCZ tends to stay in the Northern Pacific and Atlantic in all seasons because of the interactions between the atmosphere and the oceans and the geometry of the continents (Philander et al. 1996). An examination of highly reflective cloud (HRC) associated with tropical convection (Waliser and Gautier 1993), for instance, showed that departures from the mean annual migrations of the ITCZ can be as large as 6 degrees in latitude on a regional basis. In addition to the position of the ITCZ, Janicot (1992a,b) suggested that the intensity of the convection along the ITCZ is also responsible for precipitation variability in the Sahelian West African region. While Ba et al. (1995) agreed that the intensity of the convection is an influential factor, their findings indicated

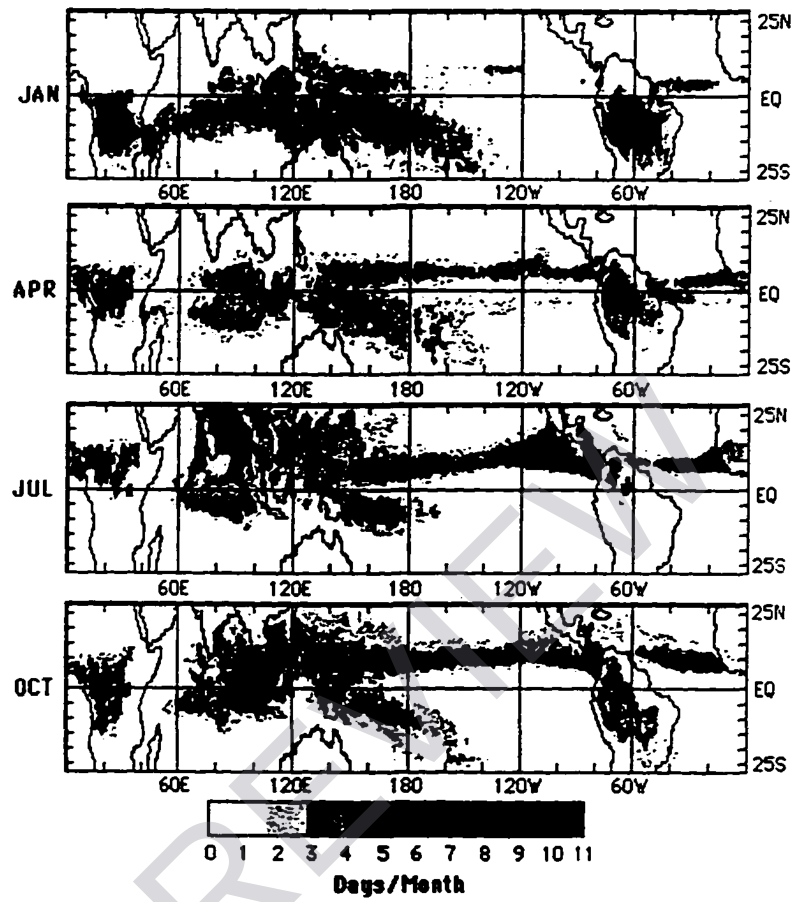

Figure 2.2 Mean monthly ITCZ and SPCZ structures for the months January, April, July, and October (from Waliser and Gautier 1993, p. 2163).

that the latitudinal extent of the ITCZ plays a more important role than merely position in causing drought in the Sahel.

The geographical aspects of the tropical annual cycle were investigated by Horel et al. (1989). Symmetry along the equator, defined as a wet season of comparable duration in both hemispheres, is observed over the tropical Americas, but not in Africa, Southeast Asia, Indonesia, or northern Australia. Srinivasan and Smith (1996) demonstrated that the limited meridional movement of the ITCZ in the West Africa-eastern Atlantic Ocean region is controlled by the negative planetary net radiation balance over the Sahara Desert. Significant meridional movements of the ITCZ in the Indian and western Pacific Oceans are the consequence of great land-sea temperature contrasts (Webster 1983). The reason for the northward movement in the Atlantic Ocean, where there are no land-sea temperature differences, was proposed by Emanuel (1987) to be a wind-evaporation feedback mechanism. The tendency of the ITCZ to stay in the North Pacific was shown in a coupled ocean-atmospheric model to be the result of land heating forcing, subject to modification by the seasonal solar forcing (Xie 1996).

The region of permanent convective activity spanning the equatorial western Pacific to the subtropical South Pacific is generally known as the South Pacific Convergence Zone (Trenberth 1976). The SPCZ mean axis normally extends from New Guinea east-southeastward to about 30°S, 120°W (Ramussson and Carpenter 1982) and its northwest end merges with the ITCZ and extends to the Indian Ocean (Vincent 1994). The location and the magnitude of the SPCZ is controlled by the thermal contrast between the cold and warm pools of the eastern and western South Pacific (Wang 1994).