

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

PREVIEW

**SEASONAL AND INTERANNUAL VARIATIONS IN SPATIAL
AUTOCORRELATION STATISTICS OF TROPICAL PRECIPITATION**

by

Wai-Lok Siu

A Dissertation

**Presented to the Faculty of
The Graduate College in the University of Nebraska
In Partial Fulfillment of Requirements
For the Degree of Doctor of Philosophy**

Major : Geography

Under the Supervision of Professors Mark R. Anderson and Michael A. Palecki

Lincoln, Nebraska

June, 1997

UMI Number: 9734642

UMI Microform 9734642
Copyright 1997, by UMI Company. All rights reserved.

**This microform edition is protected against unauthorized
copying under Title 17, United States Code.**

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

DISSERTATION TITLE

SEASONAL AND INTERANNUAL VARIATIONS IN SPATIAL AUTOCORRELATION

STATISTICS OF TROPICAL PRECIPITATION

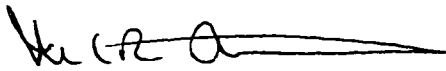
BY

Wai-lok Siu

SUPERVISORY COMMITTEE:

APPROVED

DATE



Signature

Dr. Mark Anderson

Typed Name

6-11-97



Signature

Dr. Michael Palecki

Typed Name

6-11-97

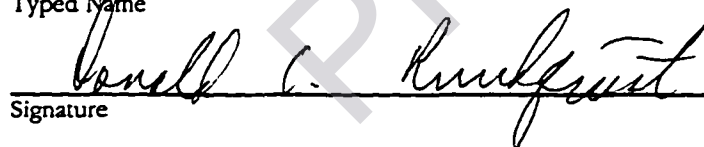


Signature

Dr. Clinton Rowe

Typed Name

6-11-97



Signature

Dr. Donald Rundquist

Typed Name

6-11-97



Signature

Dr. Kenneth Hubbard

Typed Name

6-11-97

Signature

Typed Name



SEASONAL AND INTERANNUAL VARIATIONS IN SPATIAL AUTOCORRELATION STATISTICS OF TROPICAL PRECIPITATION

Wai-lok Siu, Ph. D.

University of Nebraska, 1997

Advisor: Mark R. Anderson

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.

PREVIEW

ACKNOWLEDGEMENTS

The author would like to extend his deepest gratitude and tribute to his advisors, Dr. Michael Palecki and Dr. Mark Anderson, and all other supervisory committee members, Dr. Clinton Rowe, Dr. Donald Rundquist, and Dr. Kenneth Hubbard, for their guidance and direction.

The kind provision of information related to the CMAP data set by Dr. Ping-Ping Xie of NCEP NOAA is also acknowledged.

PREVIEW

TABLE OF CONTENTS

Acknowledgements	i
Table of Contents	ii
List of Figures	iv
List of Tables.	vii

Chapter	Page
1 Introduction	1
1.1 Research Objectives and Organization	3
2 Tropical Precipitation Variability.	5
2.1 Circulation Features and Seasonal Variations of Tropical Precipitation.	7
2.2 Interannual Variations of Tropical Precipitation	13
2.3 Sea surface Temperature and Tropical Precipitation	21
3 Data and Methodology.	27
3.1 Precipitation, SST and SOI Data Sets	27
3.2 Spatial Autocorrelation Statistics	34
3.3 Preparation of Precipitation Spatial Autocorrelation Statistics	38
3.4 Relationships of Precipitation and <i>I</i> Indices to SOI and SST Anomalies	42
4 Seasonal Variations in Spatial Autocorrelation of Tropical Precipitation	45
4.1 Spatial Distribution of Tropical Precipitation	45
4.2 Spatial Autocorrelation of Tropical Precipitation	49
4.2.1 Global Spatial Autocorrelation of Tropical Precipitation	49
4.2.2 Local Spatial Autocorrelation of Tropical Precipitation	57

Chapter	Page
4.3	RPCs of Local Spatial Autocorrelation of Tropical Precipitation 63
4.3.1	DJF RPCs 66
4.3.2	MAM RPCs 69
4.3.3	JJA RPCs 73
4.3.4	SON RPCs 76
4.4	RPCA of Sea Surface Temperature (SST) 80
4.5	Summary 83
5	Spatial Autocorrelation of Tropical Precipitation, the Southern Oscillation and SST Anomalies 85
5.1	Correlations of Local <i>I</i> Indices to the SOI and SST Anomalies 85
5.1.1	The DJF Season 85
5.1.2	The MAM Season 92
5.1.3	The JJA Season 98
5.1.4	The SON Season 102
5.2	The Relationship of the RPCs of Precipitation and Local <i>I</i> Indices of Precipitation to the SOI and SST RPCs 109
5.2.1	The DJF Season 108
5.2.2	The MAM Season 112
5.2.3	The JJA Season 117
5.2.4	The SON Season 120
5.3	Regional Case Studies 122
5.3.1	The Latitudinal Sub-divisions 124
5.3.2	India, Indonesia and Central Pacific 130
5.4	Summary 137
6	Conclusions 138
	References 143
	Appendix A 151

LIST OF FIGURES

Figure	Page
2.1 Schematic illustration of the modes of variability in the Indian Ocean-Pacific sector of the equatorial trough.	6
2.2 Mean monthly ITCZ and SPCZ structures for the months January, April, July, and October.	8
2.3 Climatic regime diagram for tropical convection/precipitation.	11
2.4 Schematic diagram illustrating the evolution of convection during a strong composite annual cycle and a weak composite annual cycle.	15
2.5 Schematic representation of the principal lag relationships of ENSO-related precipitation variations.	16
2.6 Synthesis of circulation along the equator during the March-April rainy season in northern Amazonia.. . . .	18
2.7 Precipitation anomaly patterns for DJFM formed by compositing all years classified as warm and cold event years.	20
2.8 Cold minus warm event composite SST during DJF and MAM.	24
2.9 Sea surface temperature anomalies in the tropical Atlantic: during dry and wet years in the Sahel region.	25
3.1 Data sources of the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data set.	28
3.2 The study area and three sub-regions.	32
3.3 The Southern Oscillation Index for 1979-19995	35
3.4 Interpretation of Moran's <i>I</i> index.	38
3.5 Schematic representation of the contiguity function for a single grid cell used for this data analysis.	40

Figure	Page
4.1 Average seasonal precipitation.. . . . .	.46
4.2 Seasonal variations in precipitation and global <i>I</i> indices for the tropics. . . . .	.51
4.3 Seasonal variations in precipitation and global <i>I</i> indices for the equatorial region. . . . .	.53
4.4 Seasonal variations in precipitation and global <i>I</i> indices for the northern subtropics . . . . .	.54
4.5 Seasonal variations in precipitation and global <i>I</i> indices for the southern subtropics . . . . .	.56
4.6 Average seasonal local <i>I</i> indices. . . . .	.58
4.7 Seasonal variations in mean monthly local <i>I</i> indices.	60-61
4.8 Spatial loading patterns of the RPCs in DJF.	67
4.9 Score time series of the RPCs in DJF. . . . .	.68
4.10 Spatial loading patterns of the RPCs in MAM.. . . .	.70
4.11 Score time series of the RPCs in MAM. . . . .	.71
4.12 Spatial loading patterns of the RPCs in JJA. . . . .	.74
4.13 Score time series of the RPCs in JJA. . . . .	.75
4.14 Spatial loading patterns of the RPCs in SON. . . . .	.77
4.15 Score time series of the RPCs in SON. . . . .	.78
4.16 Spatial loading patterns of the RPCs of SST. . . . .	.81
4.17 Score time series of the third RPCs of SST . . . . .	.82
5.1 Correlation fields of DJF precipitation and the SOI . . . . .	.86
5.2 Correlation fields of DJF precipitation and the SST RPCs.. . . .	.88

Figure	Page
5.3 Correlation fields of DJF local <i>I</i> indices and the SOI. . . . .	.90
5.4 Correlation fields of DJF local <i>I</i> indices and the SST RPCs. . . . .	.91
5.5 Correlation fields of MAM precipitation and the SOI. . . . .	.93
5.6 Correlation fields of MAM precipitation and the SST RPCs.. . . .	.94
5.7 Correlation fields of MAM local <i>I</i> indices and the SOI.	96
5.8 Correlation fields of MAM local <i>I</i> indices and the SST RPCs. . . . .	.97
5.9 Correlation fields of JJA precipitation and the SOI. . . . .	.99
5.10 Correlation fields of JJA precipitation and the SST RPCs.	100
5.11 Correlation fields of JJA local <i>I</i> indices and the SOI.	101
5.12 Correlation fields of JJA local <i>I</i> indices and the SST RPCs.	103
5.13 Correlation fields of SON precipitation and the SOI.	104
5.14 Correlation fields of SON precipitation and the SST RPCs.	105
5.15 Correlation fields of SON local <i>I</i> indices and the SOI.	107
5.16 Correlation fields of SON local <i>I</i> indices and the SST PPCs.	108
5.17 Scatter diagram of DJF SOI against the scores of RPC2 of MAM precipitation.	115
5.18 Scatter diagram of DJF SOI against the scores of RPC2 of JJA local <i>I</i> indices.	119
5.19 Scatter diagram of the scores of SON SST RPC3 against the scores of RPC2 of SON precipitation.	123

LIST OF TABLES

Table	Page
4.1 Percentages of total variance explained by the first two RPCs of precipitation and local <i>I</i> index.	64
4.2 Bivariate correlations among the score time series of RPCs.	65
5.1 Pearson correlation coefficients of the first and second rotated principal components of precipitation (RPC(P)1, RPC(P)2), the first and second rotated principal components of local <i>I</i> indices (RPC(<i>I</i>)1, RPC(<i>I</i>)2) to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal components of SST (SST RPC1-RPC3) in DJF.	110
5.2 Pearson correlation coefficients of the first and second rotated principal components of precipitation (RPC(P)1, RPC(P)2), the first and second rotated principal components of local <i>I</i> indices (RPC(<i>I</i>)1, RPC(<i>I</i>)2) to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal components of SST (SST RPC1-RPC3) in MAM.	113
5.3 Pearson correlation coefficients of the first and second rotated principal components of precipitation (RPC(P)1, RPC(P)2), the first and second rotated principal components of local <i>I</i> indices (RPC(<i>I</i>)1, RPC(<i>I</i>)2) to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal components of SST (SST RPC1-RPC3) in JJA.	117
5.4 Pearson correlation coefficients of the first and second rotated principal components of precipitation (RPC(P)1, RPC(P)2), the first and second rotated principal components of local <i>I</i> indices (RPC(<i>I</i>)1, RPC(<i>I</i>)2) to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal components of SST (SST RPC1-RPC3) in SON.	121
5.5 Pearson correlation coefficients of precipitation, global <i>I</i> indices and local <i>I</i> indices to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal components of SST in the tropics.	125
5.6 Pearson correlation coefficients of precipitation, global <i>I</i> indices and local <i>I</i> indices to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal components of SST in the equatorial region.	127

Table	Page
5.7 Pearson correlation coefficients of precipitation, global <i>I</i> indices and local <i>I</i> indices to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal omponents of SST in the northern subtropics.	129
5.8 Pearson correlation coefficients of precipitation, global <i>I</i> indices and local <i>I</i> indices to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal omponents of SST in the southern subtropics.	131
5.9 Pearson correlation coefficients of precipitation, global <i>I</i> indices and local <i>I</i> indices to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal omponents of SST in India.	132
5.10 Pearson correlation coefficients of precipitation, global <i>I</i> indices and local <i>I</i> indices to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal omponents of SST in Indonesia.	134
5.11 Pearson correlation coefficients of precipitation, global <i>I</i> indices and local <i>I</i> indices to the SOI at lag intervals of -2, -1, 0, +1, and +2 seasons and the rotated principal omponents of SST in the central Pacific.	136

PREVIEW

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

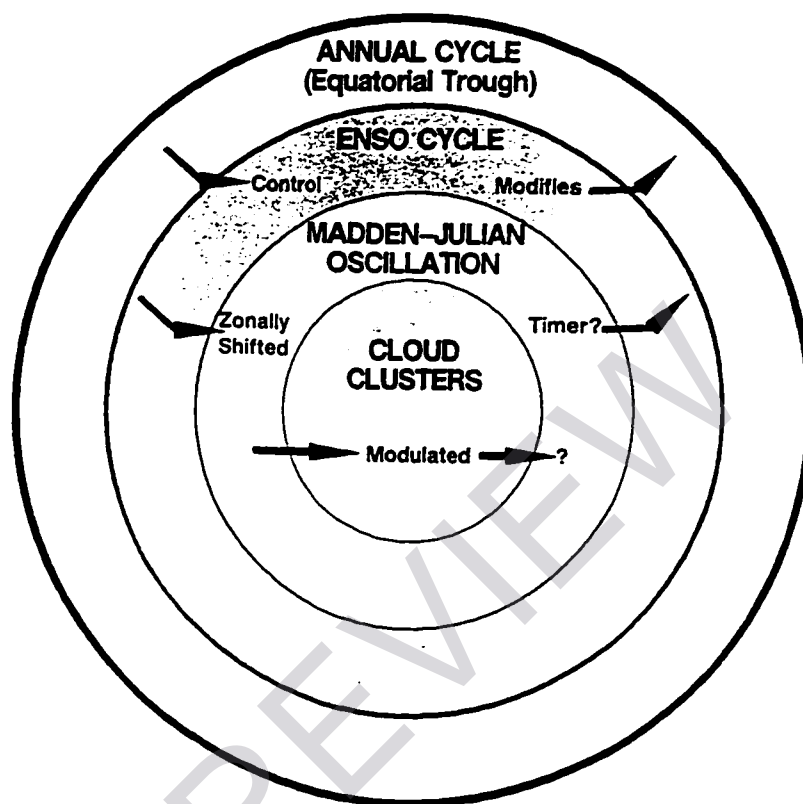


Figure 2.1 Schematic illustration of the modes of variability in the Indian Ocean-Pacific sector of the equatorial trough (from Rasmusson and Arkin 1993, p.1500).

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

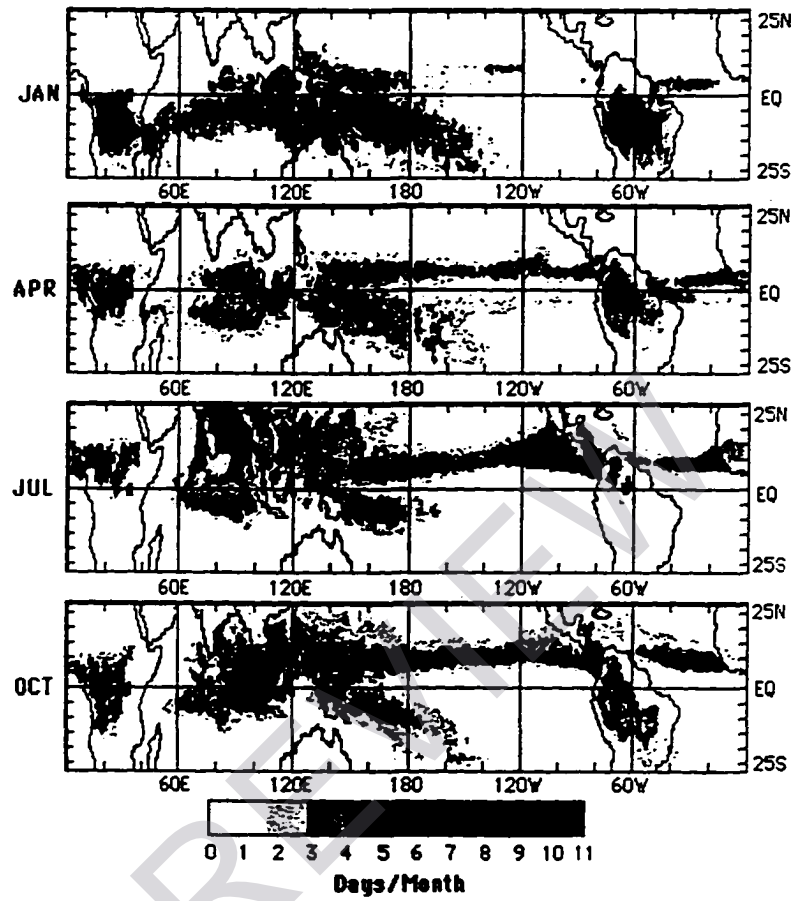


Figure 2.2 Mean monthly ITCZ and SPCZ structures for the months January, April, July, and October (from Waliser and Gautier 1993, p. 2163).

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 (Ramusson 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).