Variability of Pacific tropical convergence zones in observations

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Earth System Science

by

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2015
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Figures</td>
<td>iv</td>
</tr>
<tr>
<td>List of Tables</td>
<td>vi</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>vii</td>
</tr>
<tr>
<td>Curriculum Vitae</td>
<td>viii</td>
</tr>
<tr>
<td>Abstract of the Dissertation</td>
<td>ix</td>
</tr>
<tr>
<td>Chapter 1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 The tropical convergence zones</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Identifying the instantaneous ITCZ</td>
<td>3</td>
</tr>
<tr>
<td>1.3 The SPCZ and east Pacific ITCZ</td>
<td>5</td>
</tr>
<tr>
<td>1.4 Outline of the dissertation</td>
<td>6</td>
</tr>
<tr>
<td>Chapter 2 The South Pacific Convergence Zone in three decades of satellite images</td>
<td>8</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>10</td>
</tr>
<tr>
<td>2.2 Data and Methods</td>
<td>13</td>
</tr>
<tr>
<td>2.2.1 Satellite data</td>
<td>13</td>
</tr>
<tr>
<td>2.2.2 SPCZ labels</td>
<td>14</td>
</tr>
<tr>
<td>2.2.3 SPCZ axis lines</td>
<td>16</td>
</tr>
<tr>
<td>2.2.4 Grouping patterns of interannual variability</td>
<td>18</td>
</tr>
<tr>
<td>2.2.5 Additional data used in analysis</td>
<td>19</td>
</tr>
<tr>
<td>2.3 Results and Analysis</td>
<td>20</td>
</tr>
<tr>
<td>2.3.1 Interannual variability of the SPCZ</td>
<td>22</td>
</tr>
<tr>
<td>2.3.2 Seasonal evolution of the SPCZ</td>
<td>29</td>
</tr>
<tr>
<td>2.3.3 Intraseasonal variability of the SPCZ</td>
<td>33</td>
</tr>
<tr>
<td>2.4 Concluding Remarks</td>
<td>37</td>
</tr>
<tr>
<td>Chapter 3 The diurnal cycle of clouds in the South Pacific Convergence Zone</td>
<td>40</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>42</td>
</tr>
<tr>
<td>3.2 Dataset</td>
<td>45</td>
</tr>
<tr>
<td>3.3 Results</td>
<td>48</td>
</tr>
<tr>
<td>3.3.1 Diurnal cycle of SPCZ area, IR, and cloud height</td>
<td>48</td>
</tr>
<tr>
<td>3.3.2 Seasonal changes to the diurnal cycle in SPCZ area, and mean IR</td>
<td>52</td>
</tr>
<tr>
<td>3.3.3 Modulation of the diurnal cycle during MJO events</td>
<td>56</td>
</tr>
<tr>
<td>3.3.4 Impact of ENSO on the amplitude of diurnal cycle</td>
<td>61</td>
</tr>
</tbody>
</table>
3.4 Conclusions..................................................................................................................63

Chapter 4 Observations of the instantaneous double ITCZ: the east Pacific ITCZ in three decades of high-resolution satellite data.................................67

  4.1 Introduction..................................................................................................................69
  4.2 Data and Methods .....................................................................................................72
    4.2.1 Datasets ................................................................................................................72
    4.2.2 Statistical model for classifying ITCZ state .........................................................73
  4.3 Results.........................................................................................................................76
    4.3.1 Distribution of ITCZ states .....................................................................................76
    4.3.2 Composites of ITCZ states in March-April .........................................................80
  4.4 Conditions during ITCZ states....................................................................................86
    4.4.1 SST associated with ITCZ states ...........................................................................86
    4.4.2 Large-scale circulation associated with the ITCZ states .....................................90
  4.5 Connection to the SPCZ .............................................................................................95
  4.6 Concluding Remarks.................................................................................................97

Chapter 5 Conclusions......................................................................................................101

References.........................................................................................................................107
# List of Figures

## Chapter 2

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Mean SPCZ activity and mean SST from Nov-Apr</td>
<td>14</td>
</tr>
<tr>
<td>2.2</td>
<td>Examples of SPCZ labels</td>
<td>21</td>
</tr>
<tr>
<td>2.3</td>
<td>Mean SPCZ activity in each year from 1980-2012</td>
<td>23</td>
</tr>
<tr>
<td>2.4</td>
<td>SPCZ activity anomalies for each year from 1980-2012</td>
<td>24</td>
</tr>
<tr>
<td>2.5</td>
<td>Eight groups describing different configuration so the SPCZ</td>
<td>25</td>
</tr>
<tr>
<td>2.6</td>
<td>Seasonal evolution of SPCZ activity from Nov-Apr</td>
<td>30</td>
</tr>
<tr>
<td>2.7</td>
<td>Mean SPCZ area in the northeast and southwest regions</td>
<td>31</td>
</tr>
<tr>
<td>2.8</td>
<td>Seasonal evolution of SPCZ during different phases of ENSO</td>
<td>32</td>
</tr>
<tr>
<td>2.9</td>
<td>Power spectra for 3-hourly SPCZ area</td>
<td>34</td>
</tr>
<tr>
<td>2.10</td>
<td>Intraseasonal variability of the SPCZ associated with the MJO</td>
<td>36</td>
</tr>
</tbody>
</table>

## Chapter 3

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Domain and sub-regions, mean SPCZ, and example of SPCZ label</td>
<td>47</td>
</tr>
<tr>
<td>3.2</td>
<td>Diurnal cycle of SPCZ area and mean IR</td>
<td>49</td>
</tr>
<tr>
<td>3.3</td>
<td>Diurnal cycle cloud height within SPCZ</td>
<td>51</td>
</tr>
<tr>
<td>3.4</td>
<td>Seasonal evolution of diurnal cycle of SPCZ area and mean IR</td>
<td>53</td>
</tr>
<tr>
<td>3.5</td>
<td>Diurnal cycle of SPCZ area and mean IR during MJO phases</td>
<td>58</td>
</tr>
<tr>
<td>3.6</td>
<td>Diurnal cycle of cloud height with SPCZ during MJO phases</td>
<td>60</td>
</tr>
<tr>
<td>3.7</td>
<td>Seasonal evolution of diurnal cycle of SPCZ mean IR for ENSO phases</td>
<td>62</td>
</tr>
</tbody>
</table>
Chapter 4

Figure 4.1 Daily ITCZ state from 1980-2012 .......................................................... 77
Figure 4.2 ITCZ state distribution by months ............................................................ 79
Figure 4.3 ITCZ state distribution by years .............................................................. 79
Figure 4.4 Composite of IR temperature and GPCP precipitation by ITCZ state...... 81
Figure 4.5 Composites of TRMM rainfall by ITCZ state ......................................... 82
Figure 4.6 Meridional profile of IR temperature, precipitation, and vertical velocity 84
Figure 4.7 Composites of SST anomalies by ITCZ state ......................................... 87
Figure 4.8 Meridional profile and meridional gradient of SST for each ITCZ state .. 89
Figure 4.9 Composites of daily $\chi$ and $\psi$ anomalies by ITCZ at 850 hPa............ 91
Figure 4.10 Composites of daily $\chi$ and $\psi$ anomalies by ITCZ at 200 hPa.......... 92
Figure 4.11 Composites of SPCZ anomalies by ITCZ state in March ....................... 96
Figure 4.12 Composites of ERA-Interim precipitation by ITCZ state ....................... 97
List of Tables

Table 2.1  Mean slope and segmentation point for ENSO states.............................29
Table 4.1  Value and latitude of peak cloudiness, rainfall, SST and w .........................84
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**Conferences and Workshops Attended**

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Geophysical Union Fall Meeting, San Francisco, CA</td>
<td>2014 Dec. 15-19</td>
</tr>
<tr>
<td>Advanced Study Program Summer Colloquium, Boulder, CO</td>
<td>2012 June 4-22</td>
</tr>
<tr>
<td>AMS Hurricanes and Tropical Meteorology, Ponte Vedra Beach, FL</td>
<td>2012 April 15-19</td>
</tr>
<tr>
<td>Weather Research and Forecasting Tutorial, Boulder, CO</td>
<td>2011 July 11-15</td>
</tr>
<tr>
<td>American Geophysical Union Fall Meeting, San Francisco, CA</td>
<td>2010 Dec. 13-17</td>
</tr>
<tr>
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</tr>
</tbody>
</table>
Abstract of the Dissertation

Variability of Pacific tropical convergence zones in observations

By

Colene Michelle Haffke

Doctor of Philosophy in Earth System Science

University of California, Irvine, 2015

Professor Gudrun Magnusdottir, Chair

The instantaneous South Pacific Convergence Zone (SPCZ) and east Pacific Intertropical Convergence Zone (ITCZ) are identified in long-term satellite observations using two automated statistical models. The statistical models are designed to emulate visual identification of convergence zones, balancing the complex definition of a convergence zone as an elongated envelope of convection including clouds of varying heights as well as clear sky, against the need for automatic detection in large amounts of data. Identification occurs in 3-hourly infrared (IR) images from geostationary satellites from 1980-2012. For the SPCZ, the study is limited to November through April but the east Pacific ITCZ is identified year round.

Interannual variability, seasonal evolution, and intraseasonal variability of the SPCZ are quantified using 3-hourly SPCZ labels. The SPCZ is found to have two distinct parts: a tropical segment which is more active, particularly in December through February, having a mostly zonal orientation and a subtropical segment which is less active and has a tilted orientation. The El Niño Southern Oscillation (ENSO) influences the SPCZ on interannual time scales as the SPCZ shifts equatorward during El Niño and poleward during La Niña. On the intraseasonal time scale the SPCZ changes intensity and location according to various phases of the Madden Julian

xi
Oscillation (MJO). The SPCZ also has a distinct diurnal cycle in area, mean IR temperature, and cloud height, which changes throughout the season and is influenced by ENSO and the MJO.

In the east Pacific, the ITCZ can take on several configurations. A statistical model is used to automatically assess the daily state of the east Pacific ITCZ based on the location of cloud bands: north of the equator (nITCZ), south of the equator (sITCZ), simultaneously north and south of the equator (dITCZ), and over the equator (eITCZ). A fifth state describes when no cloud bands exist in the east Pacific (aITCZ). Most of the year is dominated by the nITCZ state but in the boreal spring all states occur and variability is high. In March and April the dITCZ occurs, on average, 34% of the time, indicating that the double ITCZ occurs frequently in instantaneous data.
Chapter 1

Introduction

1.1 The tropical convergence zones

One of the most distinctive features of the global atmospheric circulation is the Intertropical Convergence Zone (ITCZ). Easily identifiable in monthly or annual mean images of clouds and precipitation, the ITCZ circles the Earth in the tropics where the easterly trade winds converge. With a global perspective it is easy to imagine the ITCZ as the rising branch of the Hadley circulation, associated with warm surface temperatures and converging trade winds, which both drive and enhance rising motion, convection, and precipitation. Waliser and Gutier (1993) provided the first long-term global climatology of the ITCZ using two decades of satellite derived cloud measurements. Their study confirmed and expanded on a decade’s worth of work based on more regional
scales. More recently, Berry and Reeder (2014) revisited the global climatology of the ITCZ, identifying the convergence zones using near-surface winds from ERA-Interim reanalysis. Both studies identify the major characteristics and the seasonal to interannual variability of the tropical convergence zones. The ITCZ circle the globe, migrating north and south with changing solar insolation but often having a tendency to be located in the Northern Hemisphere. The migrations tend to be most pronounced over land and over the Indian Ocean and rather subdued in the east Pacific. The ITCZ is narrow and well defined over the Pacific and Atlantic Oceans but tends to spread out over a larger latitudinal range in the western Pacific and Indian Oceans.

A major component of the tropical convergence zones is the South Pacific Convergence Zone, which connects to the ITCZ is in the west Pacific but takes on a tilted orientation in the central Pacific extending to 30°S (Vincent 1994). Studies like Waliser and Gautier (1993) and Berry and Reeder (2014) also note the existence of the double ITCZ, an observable convergence zone existing in both hemispheres in the east Pacific in the boreal spring.

A global view of the tropics has been made possible by satellite observations since the late 1970’s. By studying the global mean convergence zones, we have increased our knowledge of the behavior of the ITCZ and SPCZ, tropical dynamics, and global circulation. However, the mean ITCZ and SPCZ can only provide a limited understanding of the physical processes that control this feature. Until recently, few studies explored how the mean ITCZ relates to the instantaneous ITCZ in long-term data. For example, Wang and Magnusdottir (2006) described the dynamic, day-to-day variations in the central and east Pacific ITCZ structure on synoptic time scales noting
that on one day the ITCZ may form an elongated band of clouds but in following days this structure breaks down into individual disturbances. The identification of the instantaneous structure was key to understanding the mechanisms controlling ITCZ breakdown process and imperative to the identification were the high spatial (less than 1.1° x 1.1°) and temporal (sub-daily) geostationary satellite observations.

While clearly important, the identification of the instantaneous ITCZ can be a cumbersome task. Wang and Magnusdottir (2006) relied on visual identification, which limits the amount of data that can be analyzed. Many other studies employ thresholding techniques to define convective areas by identifying locations where the cloud top temperatures are cold, indicating deep convection. When averaged over a month or more, this technique can provide valuable information about ITCZ behavior. However, the thresholding technique is less useful for instantaneous identification because it only captures clouds above a certain height, limiting the ITCZ to a collection of scattered high cloud tops not necessarily representing the elongated contiguous structure of the ITCZ. A better method would keep the automated nature of thresholding but would identify the ITCZ in a way that emulates visual identification by a human observer and take into account the many nuances of ITCZ structure and behavior.

1.2 Identifying the instantaneous ITCZ

Recently, a global geostationary satellite dataset called GridSat became available, providing over 30 years of inter-calibrated satellite measurements from the infrared (IR) channel (Knapp et al. 2011). The ITCZ and SPCZ are identifiable in IR temperature
satellite images as an elongated envelope of convection that includes a combination of deep clouds, mid-level clouds, low clouds, and clear-sky. However, just because a feature is easily identifiable does not mean it is easy to define a set of characteristics to describe it. For example, you can easily recognize your mother’s voice but could you write down what it sounds like in a way that would make it possible for other people, or a computer, to identify? With a few days, or a month worth of 3-hourly satellite images it is not an unreasonable task to manually identify the ITCZ or SPCZ. However, this is not feasible to do manually with 30-years of data. A simple definition of the ITCZ, say, a threshold in IR temperature, is a fast way to automatically identify deep convection, but this method is not likely to identify the same ITCZ as a human observer would. The abundance of data available from geostationary satellites presents a unique opportunity but also a challenge for studying the ITCZ and SPCZ: How does one balance the desire to identify the convection bands the way a human observer would and the need to do this task automatically?

To address this issue, two machine-learning methods were developed in partnership with the Computer Science and Statistics departments at UCI to automatically identify the ITCZ and SPCZ in satellite images. The first method outlines the location of the SPCZ in 3-hourly IR temperature observations and the second determines the state of the east Pacific ITCZ by assigning it to a northern only state (nITCZ), a southern only state (sITCZ), a double ITCZ state (dITCZ), an equatorial ITCZ state (eITCZ), or an ITCZ absent state (aITCZ). Using datasets created by these techniques I define the variability of SPCZ and east Pacific ITCZ and discuss various mechanisms behind the variability.
1.3 The SPCZ and east Pacific ITCZ

The research presented in this dissertation builds upon the ideas and methods outlined above, with the goal of identifying tropical convection zones in terms of elongated cloud bands in instantaneous data and using this information to advance our understanding of the mean structure and characteristics as well as quantify the variability on multiple time scales. Specifically, I will examine two regions in the Pacific: the SPCZ and the east Pacific ITCZ, both north and south of the equator.

The east Pacific ITCZ and the SPCZ are the two prominent convection bands in the tropical Pacific and many questions remain regarding their formation, maintenance, and variability over time. In particular, the east Pacific ITCZ remains north of the equator for most of the year but in the boreal spring a southern hemisphere ITCZ can also form. At times, a northern hemisphere ITCZ and a southern hemisphere ITCZ can exist simultaneously forming what is known as a double ITCZ. The nature of the variability of the east Pacific ITCZ is not well known, as past studies have looked mostly at monthly means and the mechanisms behind the variation is not well understood on shorter time scales. In the west Pacific, the SPCZ forms in the Southern Hemisphere as a diagonally slanted convergence zone instead of the typical zonal convergence zone. Again, few studies have looked at SPCZ behavior on short time scales and variability has not been well defined. In particular, very little is known about the differences between the tropical and subtropical parts of the SPCZ. Variability within the tropical convergence zones occurs over multiple time scales: ENSO influences the position and activity of convergence zones on an interannual time scale, changing solar insolation over the
annual cycle, the Madden Julian Oscillation (MJO) over the intraseasonal 40-60 day time scale, and local synoptic scale disturbances over daily to weekly time scales.

1.4 Outline of the dissertation

The purpose of this research is to characterize the variability of the SPCZ and east Pacific ITCZ over the past 30 plus years using daily or sub-daily observations, and in doing so, fully utilize the complete observational record of IR temperature by employing machine learning methods. The introduction here has been brief as each chapter contains an extensive introduction specific to each part of the study. The remainder of the dissertation will be organized as follows:

In Chapter 2, I explore the variability of the SPCZ on time scales ranging from the seasonal cycle to interannual variability. I apply a spatio-temporal detection method to define a binary mask specifying SPCZ location at a 3-hourly time step from November 1980 – April 2012. Results indicate the importance of ENSO and the Madden Julian Oscillation (MJO) on the location and overall activity of the SPCZ.

In Chapter 3, I use the same SPCZ labels described in Chapter 2 to characterize the diurnal cycle of SPCZ area, mean IR temperature, and cloud height. The influence of the seasonal cycle, ENSO, and the MJO are highlighted.

In Chapter 4, I examine the east Pacific ITCZ using a new identification method. I define five ITCZ states to describe the configuration of the ITCZ and present the daily variability of those five states from 1980-2012. Each state is described in detail in terms of IR temperature, precipitation, and vertical velocity for March-April when all states
frequently occur. I then discuss the relative importance of the underlying sea surface temperature profile versus the large-scale atmospheric circulation in determining the ITCZ state. This chapter concludes with a discussion of the relationship between the SPCZ and east Pacific ITCZ.

Chapter 5 will present concluding remarks regarding the dissertation work and a discussion of future work. References for all chapters will be given at the end of the dissertation.
Chapter 2

The South Pacific Convergence Zone in three decades of satellite images.

Abstract

Interannual variability, seasonal evolution and intraseasonal variability of the South Pacific Convergence Zone (SPCZ) are quantified using a new data set of 3-hourly SPCZ labels, available from 1980–2012, Nov–Apr. The SPCZ label is a binary field indicating presence (1) or absence (0) of the SPCZ at each grid point ($\frac{1}{2}^\circ$ lon by $\frac{1}{2}^\circ$ lat) as a function of time and is the output of a Bayesian spatiotemporal statistical model that takes in instantaneous data from geostationary satellites. The statistical model is designed to emulate the way human observers identify the SPCZ. Results show two distinct parts to the SPCZ, the western tropical part and the eastern subtropical part. At times, the two parts do not connect. When they do connect they are oriented quite differently, such that the subtropical part has a steeper meridional slope. The SPCZ is present 50-70% of the
time in the tropics from Jan–Mar and is usually anchored to the warm sea surface
temperature (SST) distribution of the equatorial west Pacific. The subtropical part does
not have the same sensitivity to the underlying SST distribution and is present more often
in Nov–Dec and Apr than in Jan-Mar when the SST is highest. Interannual variability in
SPCZ location is strongly associated with El Niño Southern Oscillation (ENSO),
however no change in overall SPCZ area is associated with ENSO. On the intraseasonal
time scale, composite analysis shows the distinct spatial patterns in SPCZ presence
associated with each phase of the Madden Julian Oscillation.
2.1 Introduction

The South Pacific Convergence Zone (SPCZ) is an elongated convection zone that is easily recognizable from space, especially during the austral summer half-year (Nov – Apr). In monthly or seasonal averages, and sometimes instantaneously, it is located on a path stretching from the equatorial region near New Guinea in the west (near 140°E) to the subtropics near 30°S, 120°W in the east (e.g., Vincent 1994). The tilt in latitude makes the SPCZ different from other elongated tropical convergence zones such as the east Pacific Intertropical Convergence Zone (ITCZ), which is active north of the equator, especially during boreal summer (Bain et al. 2011). Part of the SPCZ is located within the deep tropics, part is located in the subtropics, and part occasionally stretches into the extratropics in the east, with dynamical processes in each region playing a role in SPCZ formation and maintenance. The exact location of the SPCZ controls the distribution of precipitation and any severe weather since, true to any tropical convergence zone, cyclogenesis takes place on the poleward side of the tropical portion of the SPCZ (Gray 1979; Jourdain et al. 2011; Vincent et al. 2011; Lorrey et al. 2012).

The orientation and extent of the SPCZ have been attributed to various processes such as: 1) control from a tropical heat source over the maritime continent and a forced equatorial Rossby wave response in the Southern Hemisphere (Matthews et al. 1996), 2) the interaction of subtropical flow, resulting from a tropical heat-source forcing, and the mean extratropical flow southwest of the SPCZ (Kodama 1999 and references therein), and 3) eddy forcing from the extratropics (e.g., Matthews 2012, Widlanski et al. 2011, and references therein). Takahashi and Battisti (2007) present convincing evidence, using
a coupled global climate model, that the Andes play a major role in setting up the dry zone bounding the SPCZ in the equatorial direction, thus providing a complementary viewpoint. While blocking the westerlies, the Andes force a subsiding equatorward flow on the windward side, leading to evaporative cooling, low sea surface temperatures (SST), and stratus clouds in the southeast Pacific. The diagonal shape of the SPCZ is associated with streamlines of the southeasterly trades in this wedge-shaped, precipitation-free area. Lintner and Neelin (2008) confirmed in observations that high-frequency wind variations of the inflow in the dry zone determine the eastern extent of the SPCZ.

Previous observational studies have primarily focused on describing the mean state of the SPCZ in terms of cloud and/or rainfall location, and describing interannual variability, especially variability in SPCZ location associated with the El Niño Southern Oscillation (ENSO). The SPCZ shifts to the north during El Niño years, becoming more zonally oriented like a typical tropical convergence zone such as the east Pacific ITCZ (e.g. Bain et al. 2011). During La Niña years it shifts southwest from its mean location (Folland et al. 2002). Vincent et al. (2011) recently showed that the SPCZ response to ENSO is slightly more complicated. They examined a 24-yr (1979-2002) record in ERA40 reanalysis and in rainfall data from the Global Precipitation Climatology Project (GPCP). Three out of seven El Niño events during their record show a zonally oriented tropical SPCZ, the rest exhibiting a northward shift without the zonal alignment. Three ENSO neutral years in their study also show a northward shift of the SPCZ.

In this study we will quantify interannual and intraseasonal variability in SPCZ location and area using a 3-hourly data set of SPCZ presence. SPCZ presence labels are
generated by adapting and applying the Markov Random Field (MRF) spatiotemporal statistical model originally developed by Bain et al. (2011) to identify the east Pacific ITCZ. The statistical model has a built-in tendency to clump together observations of SPCZ presence in space and time, emulating the way a human would recognize this meteorological feature. By automating the method, more data may be processed and the results are independent of human judgment so that the same results are always obtained given the same raw data, which may not be the case for human analysis (Bain et al. 2011; Henke et al. 2012). The model can accept multiple forms of input data at one time but we will concentrate on showing results based on the atmospheric window infrared channel (IR) from the GridSat database (Knapp et al. 2011) as it gives a 30-yr record of variability in cloudiness. SPCZ presence labels are also created using total precipitable water (TPW) and the visible channel (VS) from the GridSat database in addition to IR input, but this resulted in a much shorter record of only 15 years. The SPCZ labels produced using TPS, VS, and IR input are not significantly different from the IR-only input labels. In past studies, IR-only labels were used to study the diurnal cycle of the east Pacific ITCZ (Bain et al., 2010) as well as its interannual variability (Bain et al. 2011).

This dataset of SPCZ labels is unique in that it gives the location and outline of the instantaneous SPCZ every three hours from which the total area or cloud top height distribution within the SPCZ can be calculated, for example. Likewise, composite analysis based on certain climate indices, such as the MJO, can be performed. To our knowledge this technique has not been used before as previous studies have relied on averages, mostly of precipitation, over a certain time period, such as a month or a season.
However, instantaneous fields of precipitation are noisy and even when thresholding outgoing longwave radiation (OLR) or the IR channel used here, the results are also quite noisy in instantaneous data (see discussion in Bain et al. (2011)).

This paper is organized as follows: Section 2.2 describes data and methods. Section 2.3 contains results on the mean SPCZ and its variability in terms of interannual variability of the SPCZ in 2.3.1, in terms of seasonal evolution in 2.3.2 and in terms of intraseasonal variability associated with the MJO in section 2.3.3. Section 2.4 contains concluding remarks.

2.2 Data and Methods

2.2.1 Satellite data

In this study we take the SPCZ to represent a convection zone as seen in cloud fields or outgoing longwave radiation from the IR atmospheric window channel in the GridSat data set. GridSat is a recently archived collection of geostationary satellite images with global, long-term coverage appropriate for climate studies (Knapp et al. 2011). Measurements originally brought together as part of the ISCCP B1 archive from geostationary satellites (from the US, Europe, Japan, and China) have been intercalibrated and stitched together to form the dataset. IR images are available every three hours from 1980 to 2012 at 8 km spatial resolution. To improve efficiency of the statistical model the IR data was coarsened to 0.5° spatial resolution.
2.2.2 *SPCZ labels*

The 3-hourly data set of SPCZ location consists of binary labels designating the presence/absence of the SPCZ for each grid point in a $0.5^\circ \times 0.5^\circ$ gridded IR satellite image. The domain of study extends from the equator to $30^\circ$S and from $130^\circ$E to $110^\circ$W as shown in Fig. 2.1. The SPCZ labels are available every three hours during the austral summer half-year.

![Figure 2.1](image)

**Figure 2.1.** The domain for this study spans 0-30°S, 130°E-110°W and is outlined by the smaller black box. SPCZ fraction of time present for the 1980–2011 austral summer half-year (Nov-Apr) is shown in black contours starting at 10% in intervals of 10%. 1987 and 1988 are excluded. Shading shows mean SST (°C) from 1982–2011 over the austral summer half-year. Dashed black lines split domain into quadrants and the two bold black lines show the main axis of the 30-year mean SPCZ.

The labels are generated by a Markov random field statistical model, using IR data as input. The model calculates the probability of SPCZ presence at each grid point and classifies points as SPCZ if the probability is greater than 0.5. This ensures that grid points that are more likely to be SPCZ than non-SPCZ are included in the SPCZ label. Results are not sensitive to the threshold of 0.5 because a large majority of grid points have probabilities of being SPCZ that are near to zero or one. The probabilities depend
on the following factors: The likelihood (via Bayes rule) of the observed IR value at the
grid point, the presence/absence of SPCZ at neighboring grid points in space and time,
and the location of the grid point in the domain. The dependence on neighboring grid
points introduces a recursive aspect to the computation, and the location term ensures that
unrelated features are not identified as being part of the SPCZ. The technique of Gibbs
sampling (Geman and Geman 1984; Gilks et al. 1996) is used to stochastically search for
high-probability assignments of each grid point to SPCZ presence/absence, given the
observed IR data. Smooth, continuous regions of SPCZ are identified by this method.
Full details of the model as applied to the east Pacific ITCZ are given by Bain et al.
(2011). The only difference in the statistical model as applied to the SPCZ is that the
spatial prior that was zonally symmetric for the ITCZ with a Gaussian distribution in
latitude is tilted in latitude for the SPCZ with the same Gaussian distribution off the tilted
line (see Fig. 2b in Bain et al. (2011)). To retrain the model, three meteorologists
manually outlined the SPCZ in a one-month subset (January, 2001) of 3-hourly IR
images to obtain the likelihood of the observed IR values for SPCZ versus non-SPCZ
grid points. Bain et al. (2011) found that this statistical method provided systematic
improvement in labeling accuracy over other automated techniques when compared to
human labelers. The statistical method was also more consistent with other automated
techniques than they were with each other. Figure 2.2 shows five different examples of
instantaneous SPCZ labels produced by the statistical model, demonstrating its ability to
handle very different SPCZ configurations. In particular, Fig. 2.2e shows how the model
is able to capture the equatorward shift of the SPCZ in an El Niño year.
As mentioned previously, an additional data set of SPCZ labels was created using VS, TPW, and IR as input to the statistical model. The VS and TPW data are only available since 1995 and this resulted in a shorter time series of SPCZ presence. Climatology based on SPCZ labels using all three inputs were broadly in line with climatology based on the longer time series of IR-only labels. SPCZ labels created using all three inputs were more inclusive than IR-only SPCZ labels north of 25°S and slightly less inclusive south of this latitude, however, there was little difference in the location of the labels. Results in this paper therefore focus on the IR-only labels. We will also note that no attempt was made to separate out tropical cyclone convection from the SPCZ labels although the connection between the location of the SPCZ and tropical cyclone development has been noted (e.g. Diamond et al. 2013; Lorrey et al. 2012; Jourdain et al. 2011).

The 3-hourly SPCZ labels are produced for Nov – Apr from 1980 to 2012 except for the 1987 and 1988 seasons when large gaps exist in the raw satellite data. This study is limited to the austral summer half-year as the SPCZ is less active in austral winter. The following analysis will make use of the absolute spatial extent of the SPCZ label as a proxy for SPCZ area. The frequency of occurrence of SPCZ at a particular grid point refers to relative frequency of the label being equal to 1 at that location.

2.2.3 SPCZ axis lines

Mean SPCZ location and extent can be quantified by compositing the SPCZ labels over different periods of time, giving the fraction of time the SPCZ is present in
any location. The mean location and orientation will be described by the main axis of the mean SPCZ, consisting of two line segments, one representing the tropical SPCZ, and the other representing the subtropical SPCZ. Although the model was designed to identify the SPCZ as one continuous, elongated convective zone, stretching from the tropics to the subtropics, most often the mean SPCZ naturally segments into two linear parts that have different slopes (see contours in Fig 2.6, for example). The tropical portion is usually more zonally oriented and is present more often during the active season, while the subtropical portion has a steeper slope, or steeper angle of incidence into the subtropics, and is more spatially variable.

The following steps are used to create the two lines describing the main axis of the mean SPCZ. First, the SPCZ binary labels (SPCZ or non-SPCZ) are composited over a given time period (one season, for example), which produces a mean SPCZ with units of fraction of time present. Next, the locations of maximum fraction of time present are found. For each longitude in the domain there will be one latitudinal location where the SPCZ fraction of time present is maximum, resulting in 241 lat,lon grid points of maximum SPCZ fraction of time present. One line is fit through the western portion of these points to describe the tropical SPCZ and a second line is fit through the eastern portion to describe the subtropical SPCZ. If the maximum fraction of time present is located at 30°S, all points to the east of this point are not included in the calculation of the eastern line. Two methods were used to determine the longitudinal segmentation between the grid points describing the tropical SPCZ and those describing the subtropical SPCZ, one automatic and one manual. For the automatic method, the error between the grid points of the maximum SPCZ fraction of time present and the two lines representing
the SPCZ is minimized by changing the longitude of the segmentation point. We found
that this method produced useful results most of the time, however, for some years the
fraction of time present pattern was such that this method segmented the SPCZ in a way
that did not support our goal of describing the tropical and subtropical segments. For
example, the automatic method would segment the SPCZ too far west, creating a
‘subtropical SPCZ’ that stretched all the way to the equator and a ‘tropical SPCZ’ that
spanned a short distance to the western boundary. Due to this discrepancy we also
performed a manual method of segmenting the two lines by making a visual inspection of
the SPCZ fraction of time present plot to determine the longitude where the tropical and
subtropical SPCZ naturally segments. The automatic method works well for the 30-year
mean SPCZ (Fig. 2.1) and monthly mean SPCZ (see Fig. 2.6), but the manual method was
necessary for seasonal mean SPCZ (see Fig. 2.3).

2.2.4 Grouping patterns of interannual variability

To characterize SPCZ interannual variability we develop a method that groups
seasons based on the spatial pattern of SPCZ presence anomalies. To create SPCZ
presence anomalies, we first take a 30-year average of SPCZ labels at each 3-hour time
step, forming the mean seasonal cycle, and then we subtract the seasonal cycle from each
time step in all 30 years. The time series of SPCZ presence anomalies is then used to
make a composite for each season. Using the composites, SPCZ anomalies are averaged
over latitudes equatorward of the main axis of the 30-year mean SPCZ (see Fig. 2.1) as a
function of longitude. This specific metric is chosen because it concisely captures the
changes in SPCZ behavior throughout the entire domain. Three variables can describe the shape of our metric as a function of longitude: 1) the mean SPCZ presence anomaly at 130°E (the westernmost point), 2) the longitude at which the mean anomaly reaches an extremum in the central part of the domain, and 3) the value of the mean anomaly at that longitude. Seasons with similar values for these three variables are grouped together, creating a total of eight groups. Although we do not consider ENSO mode in our method, seasons with the same ENSO mode are generally grouped together, with several exceptions.

2.2.5 Additional data used in analysis

SPCZ location will be compared to the underlying SST. Monthly mean SST is obtained from the NOAA Optimum Interpolated SST V2 data set (Reynolds et al. 2002) at a 1.0 x 1.0 degree resolution for the years 1982 through 2012, Nov – Apr. This data set is a combination of in situ and satellite measurements. The SST data is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. The SST data is interpolated onto a 0.5 x 0.5 degree grid for comparison to SPCZ labels.

SPCZ activity is examined with respect to MJO phase in section 2.3.3. MJO phase and amplitude data are described in Wheeler and Hendon (2004) and downloaded from cawcr.gov.au/staff/mwheeler/maproom/RMM/. This data set lists the MJO phase and amplitude for each day since 1974. Only days with an MJO amplitude greater than one are used.

2.3 Results and Analysis

Examples of instantaneous, 3-hourly SPCZ labels, shown in Fig. 2.2, highlight the variable nature of SPCZ extent and location. At times the SPCZ is fragmented, consisting of several unconnected pieces that, together, span the length of the domain (Fig. 2.2a). At other times the SPCZ is active only in the tropics (Fig. 2.2b), or the subtropics (Fig. 2.2c). Sometimes the SPCZ exists as one complete feature, stretching from the tropics to the subtropics without any segmentation (Fig. 2.2d). Individual labels can appear in the tropics and then propagate along the length of the SPCZ axis or they can appear and
Figure 2.2. Examples of instantaneous SPCZ binary labels created by the spatiotemporal statistical model. The five dates are chosen to demonstrate the model’s ability to capture the SPCZs varied location.

disappear in one location, indicating the varied nature of convection within the SPCZ.

The SPCZ mean state is defined by a composite of all SPCZ labels from 1980 to 2012 during the austral summer half-year (Nov – Apr). Black contours in Fig. 2.1 indicate the fraction of time the SPCZ is present in each location in the domain. Throughout the paper we will also use the phrase “SPCZ activity” to refer to SPCZ fraction of time present.
The two bold black lines show the location of the main axis of the 30-year mean SPCZ and are created using the automatic method described in section 2.2.3. The SPCZ is most active in the tropics near Papua New Guinea, where it is present 50% to 70% of the time in the 30-year average. SPCZ activity decreases to the east and south and is present less than 30% of the time in the subtropics. The shading in Fig. 2.1 shows the mean SST for Nov – Apr in the years 1982 to 2012 over a region including and extending beyond the domain used for SPCZ detection. North of the equator, the location of the ITCZ is associated with the band of maximum SST and the strong SST gradient (Xie 2005). Similar to the ITCZ in boreal summer (Bain et al. 2011), the tropical part of the SPCZ in Fig. 2.1 is anchored to the high SST in the west Pacific warm pool. The subtropical SPCZ deviates from the pattern of high SST. Even though there is some tilt in latitude of the high SST pattern going from west to east, this tilt is far less pronounced than the tilt in SPCZ location east of the dateline.

2.3.1 Interannual variability of the SPCZ

From the binary SPCZ labels we obtain 30 years of SPCZ presence from 1980 – 2011, excluding 1987 and 1988. Fig. 2.3 shows the fraction of time the SPCZ is present, as well as two bold lines indicating the main axis of the 30-year mean SPCZ (also shown in Fig. 2.1), for each austral summer half-year. SPCZ fraction of time present anomalies are shown in Fig 2.4. The pattern of SPCZ presence changes from year to year, indicating
Figure 2.3. SPCZ fraction of time present for each austral summer half year (Nov – Apr). Panel titled 1980 represents Nov 1980 through Apr 1981. Panel titles are color coded by ENSO mode: red – El Niño seasons (MEI > 0.5), blue – La Niña seasons (MEI < -0.5), and black – ENSO neutral seasons (-0.5 < MEI < 0.5). Bold black lines are the same for each panel and show the main axis of the 30-year mean SPCZ.

variability in the location of SPCZ labels. Despite the variability from year to year, common spatial patterns emerge when seasons are compared. For example, 1986, 1991, and 1992 all show a northward shift in SPCZ location compared to the 30-year mean, while 2011, 1998, and 1999 all have a southward shift. Past studies describe how interannual variability of SPCZ position is dominated by ENSO (e.g. Folland et al. 2002; Vincent et al. 2011). In El Niño years, the SPCZ shifts equatorward and east, such as in 1982. The opposite occurs in La Niña years when the SPCZ shifts poleward and west, such as in 1999. To better describe interannual variability we use the method described in
Figure 2.4. Composites of SPCZ labels, in units of fraction of time present, during each season after the seasonal cycle has been removed. Red (blue) shading indicates areas where the SPCZ is more (less) frequently present in each season compared to the mean. Bold black lines show the location of the main axis of the mean SPCZ for each season calculated using the manual method described in section 2.3. Panel labels are color coded to indicate ENSO mode: red – El Niño, blue La Niña, and black - ENSO neutral.

Section 2.2.4 to represent the continuum of behavior with respect to the mean location shown in Fig. 2.1. The method, which does not rely on categorization according to ENSO, results in eight groups, each describing a unique spatial pattern of SPCZ presence.

The eight groups are presented in Fig. 2.5. The curves represent the spatial pattern of the SPCZ anomalies north of the main axis of the 30-year mean SPCZ for each season. As group number increases from one to eight, SPCZ anomalies north of the 30-year main axis get more positive. Groups 1, 2, and 3 have mostly negative anomalies north of the main axis line, and as the group number increases the area of the negative anomaly decreases and shifts to the east. Groups 4-8 have mostly positive anomalies north of the
Figure 2.5. Each panel describes one of eight groups used to categorize SPCZ interannual spatial variability. The title for each panel lists the group number and all seasons belonging to that group. Curves show the mean fraction of time present (after seasonal cycle has been removed) north of the main axis of the 30-year mean SPCZ as a function of longitude. Curves for the group being described are shown in bold in each panel. Smaller inset panels show the fraction of time present with the seasonal cycle removed over all seasons belonging to that group. Blue shading represents locations where the SPCZ is less frequently present than the mean, while red shading shows areas where the SPCZ is more frequently present than the mean. Contours start at 3% (-3%) and are at intervals of 6% (-6%). Two bold black lines in the smaller inset panels show the main axis of the 30-year mean SPCZ.
main axis line, and as the group number increases the area of the positive anomaly increases and shifts east.

Although not explicitly accounted for, seasons with the same ENSO mode are typically grouped together. The eight groups provide more detail about variability in SPCZ behavior within years belonging to the same ENSO mode. Group 1 is composed of the first (2010), third (1998), and fourth (1999) strongest La Niña seasons as indicated by average MEI value. Seasons in this group have a strong negative SPCZ anomaly north of the mean axis line and a fairly strong positive anomaly south of the main axis line indicating a shift in SPCZ location to the southwest. Group 2 comprises six La Niña seasons, including the strongest (2007), and one ENSO neutral season (1983). The SPCZ also shifts to the southwest for Group 2, but the shift is not as great as for Group 1.

An inspection of the two ENSO neutral seasons in Group 3 (1981 and 1985) suggests a concentration of SPCZ activity in the west as opposed to a shift in SPCZ location as seen in Groups 1 and 2. A similar, but weaker pattern is evident in Group 4 and Group 5. Group 5 contains only ENSO neutral seasons while Group 4 contains one El Niño season (2004) and one La Niña season (1984), in addition to four ENSO neutral seasons. While 2004 is the weakest El Niño season with an MEI value 0.662, 1984 is not the weakest La Niña season as 2005, 2000, and 1995 all have less negative MEI values (closer to the cutoff of -0.5). On average, seasons in Groups 4 and 5 do not show strong positive or negative anomalies indicating these seasons have a SPCZ fraction of time present pattern that is close to the overall mean.

Group 6 contains the next four weakest El Niño seasons after 2004. The anomaly pattern for seasons in Group 6 is more indicative of a shift to the northeast than that seen
in Group 5. A strong northeastward shift is indicated by the spatial pattern for seasons in Group 7, which contains the first (1982), third (1991), and fourth (1986) strongest El Niño years. Group 8 only consists of one season, 1997, which is the second strongest El Niño season.

Again, the eight groups generally follow ENSO mode, but they also capture subtle differences in the location and strength of the shifting SPCZ. Vincent et al. (2011) categorize interannual SPCZ location into four classes (asymmetric, positive, neural, and negative). When comparing the classes defined in Vincent et al. (2011) to the eight groups we find that they mostly agree. For example all seasons in Groups 1 and 2 are classified as negative, but Groups 4 and 5 are split between neutral and positive classes. Although 1982, 1991, and 1997 are all classified as asymmetric in Vincent et al. (2011), we find that 1982 and 1991, as well as 1986, belong to Group 7 while only 1997 belongs to Group 8.

ENSO mode strongly influences SPCZ location but we find that it does not strongly influence total SPCZ area. The mean area (not shown) during each season is calculated over the entire domain as well as for each of the four regions shown by dashed lines in Fig. 2.1. Area is calculated by summing all grid points included in the SPCZ labels. Mean annual SPCZ area in both the northeast and the southwest regions is highly correlated/anticorrelated with the annual mean MEI (0.84 and -0.90, respectively). This arises because the SPCZ typically shifts into the northeast region during El Niño years and into the southwest region in La Niña years. SPCZ area in the northwest and southeast regions, where the SPCZ is most present, are not correlated with MEI, having correlation coefficients of 0.21 and -0.04, respectively. Thus, mean SPCZ area over the entire
domain is not strongly correlated with MEI on an interannual time scale, having a
correlation coefficient of 0.35. The top five seasons by SPCZ area are: 1985, 1989, 2004,
2009, and 1984. Two ENSO neutral seasons, two El Niño seasons, and one La Niña
season, respectively. All top five seasons by area belong to Groups 3-6, groups that have
the smallest SPCZ anomalies. The five seasons with the smallest SPCZ area are: 2010,
1999, 1980, 1982, and 1988. 1980 is an ENSO neutral year, 1982 is an El Niño year and
the other three are La Niña years. Group 1 and Group 7 have strong SPCZ anomalies and
four out of the five seasons with the smallest SPCZ area are in these groups. Six out of
nine El Niño years fall within the top half of seasons by area while eight out of ten La
Niña seasons fall within the bottom half.

The orientation of the SPCZ also changes depending on ENSO mode. Table 1
summarizes the mean slopes of the main axis of the seasonal mean SPCZ (slopes shown
in Fig. 2.4), as well as the mean longitude of segmentation between the two portions
during ENSO neutral, La Niña, and El Niño years. During El Niño years, the tropical
portion of the SPCZ becomes more zonal as compared to ENSO neutral years. During La
Niña years, the opposite is true; the slope of the tropical SPCZ becomes steeper. The
segmentation of the SPCZ also changes with ENSO mode. In El Niño years the tropical
segment of the SPCZ stretches further to the east and during La Niña years the tropical
segment is shorter, being cut off further to the west. The mean longitude of segmentation
during El Niño years is at 155°W and during La Niña years is at 163°W.
To describe the seasonal evolution, SPCZ labels are used to calculate area and the fraction of time the SPCZ is present. For each month, Fig. 2.6 shows the composite of SPCZ labels over all years (contours) plotted with the mean SST for each month from 1982-2012 (shading). Two bold black lines in each panel indicate the main axis of the mean SPCZ for that month and are created by the method described in section 2.2.3. Fig. 2.6 shows how the SPCZ fraction of time present evolves throughout the season and how this evolution is different in the tropics (north of 15°S and west of 160°W) than in the subtropics (south of 20°S and east of 160°W).

Figure 2.7 shows the mean SPCZ area for each 3-hourly time step. Fractional area covered by the SPCZ is calculated by summing all points within the SPCZ label at every 3-hour time step within each region, and then averaging over all years. The domain is split into four quadrants, each extending over 15° in latitude and 60° in longitude. Dashed lines in Fig. 2.1 outline the quadrant. The northwest quadrant (130°E-170°W, 0-15°S) and the southeast quadrant (170°W-110°W, 15°S-30°S) are used to describe SPCZ area since they capture the majority of SPCZ activity. The thick black curves in Fig. 2.7 show

### Table 2.1. Mean slope values and segmentation points during different states of ENSO

<table>
<thead>
<tr>
<th></th>
<th>Slope of Western SPCZ ('°lat/°lon)</th>
<th>Slope of Eastern SPCZ ('°lat/°lon)</th>
<th>Longitude of Segmentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENSO Neutral</td>
<td>0.18 (0.04)</td>
<td>0.46 (0.08)</td>
<td>160°W (6°)</td>
</tr>
<tr>
<td>La Niña</td>
<td>0.23 (0.04)</td>
<td>0.38 (0.24)</td>
<td>163°W (10°)</td>
</tr>
<tr>
<td>El Niño</td>
<td>0.14 (0.04)</td>
<td>0.45 (0.23)</td>
<td>155°W (8°)</td>
</tr>
</tbody>
</table>

aStandard deviations are shown in parentheses.

### 2.3.2 Seasonal evolution of the SPCZ

To describe the seasonal evolution, SPCZ labels are used to calculate area and the fraction of time the SPCZ is present. For each month, Fig. 2.6 shows the composite of SPCZ labels over all years (contours) plotted with the mean SST for each month from 1982-2012 (shading). Two bold black lines in each panel indicate the main axis of the mean SPCZ for that month and are created by the method described in section 2.2.3. Fig. 2.6 shows how the SPCZ fraction of time present evolves throughout the season and how this evolution is different in the tropics (north of 15°S and west of 160°W) than in the subtropics (south of 20°S and east of 160°W).

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the 7-day running mean of SPCZ area for each region. The highest frequency variability is due to the diurnal cycle, which shows up clearly in both regions in terms of SPCZ area (see section 2.3.3 for a discussion of spectral analysis of the signal).

Focusing first on the subtropics in Fig. 2.6, the fraction of time the SPCZ is present is the highest in November and December (greater than 30%), indicating that the SPCZ is most active in this region early in the season. SPCZ area is also greatest in the subtropics in November and December, reaching a maximum in late December (Fig. 2.7). In November, the axis lines in Fig. 2.6 do not meet, indicating the SPCZ in the two
regions is disconnected. During January, February, and most of March SPCZ area in the subtropics gets smaller, reaching a minimum in late March. This is consistent with a decline in the fraction of time the SPCZ is present in the subtropics in Jan-Mar (Fig. 2.6). In April there is a small region near the southern boarder of the domain where the SPCZ is present more than 30% of the time (Fig. 2.6, bottom panel). SPCZ area in the subtropics also increases in April.

In the tropics, the SPCZ is not as active in November as during the rest of the season. Activity picks up in December and by February the SPCZ is present 78% of the time at maximum. The maximum fraction of time present in each month can be found near 4°S, 139°E, over Papua New Guinea. Although the highest fraction of time present at any one point occurs in February, the SPCZ is most active over the largest area in January. During December, January, and February the axis lines are connected, indicating activity occurring along a continuous path. In March the SPCZ occurs less frequently in the tropics and in April SPCZ presence and area continue to decrease.

Seasonal changes in the location of maximum SST in the east Pacific are accompanied by a similar change in maximum ITCZ fraction of time present (Bain et al. 2011). As the maximum SST shifts north, so does the ITCZ, indicating that high SST and
ITCZ position are closely linked. A similar relationship was not found for the subtropical SPCZ. From November to April the warm pool expands to the east and south so that the coldest SST are located in the sub tropics in November at the same time the SPCZ is most active in the same region. SST is warmest in the sub tropics in February and March, a time when SPCZ activity in the sub tropics is lowest.

The variability in SPCZ fraction of time present described above represents a long-term mean, but the seasonal evolution could vary from year to year, for example, during different phases of ENSO. To examine this possibility, SPCZ monthly composites
similar to those in Fig. 2.6 are created for El Niño seasons only, La Niña season only, and ENSO neutral seasons only (Fig. 2.8). Seasons are categorized based on the method described in section 2.2.5. We do not find a difference in seasonal evolution as described above during different phases of ENSO. The subtropical SPCZ is still most active during November and December and the tropical SPCZ is most active in January and February. The biggest difference during El Niño years is an increase in SPCZ activity near the equator early in the season, starting in the beginning of November. In La Niña years a large positive SPCZ anomaly is located north of Australia early in the season, starting at the end of November.

2.3.3 Intraseasonal variability of the SPCZ

Within any given year there is intraseasonal variability in SPCZ area and location. Figures similar to Fig. 2.7, but for each year individually (not shown), indicate a wide range of variability in SPCZ area. At times, the area of the tropical SPCZ will increase or decrease along with the area of the subtropical SPCZ and at other times the area in two regions will change independently. Figure 2.9a shows a power spectrum of 3-hourly SPCZ area in the northwest region and indicates peaks above the 95% confidence spectra for periods less than 30 days. The most significant peak occurs at 1 day and indicates a strong diurnal cycle in SPCZ area while a second peak occurs at 14 days. Figure 2.9b shows the same plot but for the southeast region. In the subtropics, spectral peaks in SPCZ area occur above the 95% confidence level for periods less than 22 days. Again, the largest peak occurs at 1 day.
Past studies have noted that on the intraseasonal time scale SPCZ location and intensity change during different phases of the MJO (Matthews et al. 1996; Matthews 2012). The MJO is an atmospheric circulation pattern characterized by a region of enhanced convection, followed and preceded by a region of suppressed convection, which propagates eastward along the equator with a period of 30-60 days (Madden and Julian 1993). One way to describe the propagation of the MJO is by categorizing the location of enhanced convection. Wheeler and Hendon (2004) define an index which describes the strength and phase of the MJO daily from 1974 to the present. The index is based on the combined empirical orthogonal functions (EOF) of 850 hPa and 200 hPa zonal wind, along with OLR. Matthews (2012) finds that the MJO can modify the basic state to change the probability of occurrence of two modes of SPCZ variability that they identify: a SPCZ that is shifted southwestward and an enhanced SPCZ located in the typical location. Here we expand this description of the MJO-SPCZ relationship by

**Figure 2.9.** Solid black curve shows the power spectra for 3-hourly SPCZ area from 1980 – 2011, Nov – Apr for the northwest region and southeast region of the domain (see regions in Fig. 2.1). Lower red curve is the red-noise spectra and upper red curve is the 95% confidence spectra. Light gray lines are the power spectra for the individual seasons (30 total).
providing the spatial patterns of SPCZ presence during each phase of the MJO. After removing the seasonal cycle from the 3-hourly SPCZ labels, the spatial pattern is calculated by compositing by MJO phase. Only days with a strong MJO signal are considered (MJO amplitude has to exceed 1, see Wheeler and Hendon (2004)). This selection process results in approximately 63% the SPCZ labels being included (37% of SPCZ labels occur on days when there is not a strong MJO signal). Figure 2.10 shows the result of this composite in units of fraction of time present. Each panel is labeled with the MJO phase number, the location of enhanced MJO convection, and the number of days that were included in the composite.

The propagation of the MJO signal within the SPCZ is quite clear. Both enhanced and suppressed convective signatures associated with the MJO are evident in SPCZ fraction of time present, and a distinct SPCZ spatial pattern is associated with each phase of the MJO. During MJO phases two and three the enhanced convection associated with the MJO is located over the Indian Ocean (outside the domain) and convection is suppressed north of Australia as is reflected in Fig. 2.10. The absence of SPCZ activity north of Australia in MJO phase two becomes less pronounced in phase three. During MJO phases four and five, the MJO associated convection is located over the Maritime Continent, as reflected in increased SPCZ presence north of Australia. This enhanced SPCZ activity is not isolated to the tropics, but stretches southward to 30°S. The enhanced subtropical activity during these phases is confined between 160°E and 160°W. During MJO phases six and seven, the area where the SPCZ is more frequently present than normal expands eastward and poleward. Finally, during phases eight and one, there
Figure 2.10. SPCZ fraction of time present anomalies (with respect to the average seasonal evolution) during each phase of the MJO. Phase based on the *Wheeler and Hendon* (2004) MJO index. Red shading indicates regions where the SPCZ is more frequently present than the mean while blue shading indicates regions where the SPCZ is less frequently present than the mean. Titles indicate MJO phase number, location of enhanced convection associated with the MJO, and the number of days included in the composite.

is again an absence of SPCZ north of Australia while the SPCZ is still more frequently present than normal over the central Pacific.

SPCZ anomalies associated with an active MJO are not confined to the tropics but are seen as far south as 30°S. This is consistent with the analysis of a single case study during a
strong MJO event in Mar-Apr, 1988 by Matthews et al. (1996). They note a poleward and eastward progression of low OLR (deep convection) along the SPCZ. Figure 2.10 shows the eastward progression of the pattern of enhanced convection associated with the propagation of the MJO in terms of 30 years of SPCZ activity.

2.4 Concluding Remarks

A new and unique data set of SPCZ presence based on geostationary satellite observations has been used to quantify interannual and intraseasonal variability as well as the seasonal evolution of SPCZ location and extent over the past 30 years during the austral summer half-year (Nov – Apr). Our results suggest that two main axis lines describe the orientation of the SPCZ, one representing the more subtropical part in the southeast and another representing the tropical part in the northwest. In the subtropics the SPCZ is most active early in the season (Nov – Dec) when the SPCZ is present 30-40% of the time. SPCZ area in the subtropics peaks in late December. Studies that only consider the height of the SPCZ active season, which is typically defined as Dec – Feb, miss this activity in the subtropics in their analysis. We find that during the middle of the austral summer half-year, in Dec-Feb, the two axes of the mean SPCZ align to create one continuous convective region. During this time the SPCZ is frequently present in the tropics, 50-70% of the time, and SPCZ area in the tropics peaks in late January.

The SPCZ is more constant and better defined in the tropics where the position and tilt align with the SST gradient. The warming of underlying SST in the subtropics during Jan – Mar does not directly effect SPCZ presence (as fraction of time present) and SPCZ area reaches a minimum in the subtropics in Jan - Mar. The latitudinal tilt in SPCZ presence is greater in the
subtropics than the tilt of the warm SST pattern (Fig. 2.6). Thus the association of the subtropical SPCZ to seasonal changes in SST is different from that of the ITCZ in the tropical east Pacific, where ITCZ location is directly tied to the warmest SST (Bain et al. 2011). The different behavior is directly tied to the different mechanisms for SPCZ maintenance in the subtropics, such as the role of the orography, the resulting subsidence, and dry air intrusion in organizing the tilt of the SPCZ (Takahashi and Battisti 2007; Lintner and Neelin 2008), and possible forcing from the Southern Hemispheric stormtrack (e.g. Matthews 2012).

We categorize each of the 30 seasons into a continuum of eight groups describing the dominant patterns of spatial variability of the SPCZ with no previous knowledge of ENSO mode. The resulting groups align with ENSO mode with some exceptions and this is broadly in agreement with Vincent et al. (2011), which defines four groups of interannual variability of the SPCZ. To summarize our results, during El Niño years the SPCZ shifts to the north and east and the tropical portion takes on a more zonal orientation. During La Niña years the SPCZ shifts south and west and the slope of the tropical portion becomes steeper. Previous studies did not have the means of examining the interannual variability in SPCZ area accompanying the shift in location. We find that despite the shifts in SPCZ location, there is no change in overall area associated with ENSO.

We find a clear influence of the MJO in SPCZ location and extent on the intraseasonal time scale. We show the detailed spatial pattern of SPCZ presence during each phase of the MJO, indicating the exact locations where SPCZ activity is enhanced and suppressed in each phase. Regions of enhanced SPCZ activity progress eastward with the propagation of MJO and we find that the MJO can influence SPCZ activity throughout the domain, as far as 30°S.
The instantaneous SPCZ presence labels allow the study of SPCZ behavior on shorter time scales than those discussed in this paper. For example, SPCZ area shows a clear diurnal cycle. The diurnal cycle in SPCZ area and cloud top height within the SPCZ will be the topic of a future publication.

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Chapter 3

Diurnal cycle of clouds in the South Pacific Convergence Zone

Abstract

This study examines the diurnal cycle in cloudiness in the South Pacific Convergence Zone (SPCZ) using a dataset of SPCZ labels from 1980-2012, Nov – Apr. Maximum SPCZ area occurs between 1500-1800 LST. Two minima in IR mean temperature occur, one between 1300 – 1600 LST, nearly coinciding with the maximum in area, and the second in the early morning hours between 0500-0700 LST. On average, the morning minimum in IR temperature dominates in the tropical regions of the SPCZ while the afternoon IR minimum dominates in the subtropical regions of the SPCZ. The relative strength of the two IR minima are affected by the seasonal cycle, intraseasonal variability caused by active Madden Julian Oscillation events, and the El Niño Southern Oscillation, with the morning IR minimum becoming more important when the SPCZ is more active or shifted toward the equator. In terms of cloud height, mid-level clouds
dominate at all times in all regions of the SPCZ and peak in abundance between 1500-1800 LST.

Low-level clouds peak near midnight and then transition to high-level clouds, which peak between 0300-0600 LST, just before sunrise.
3.1 Introduction

The South Pacific Convergence Zone (SPCZ) is an elongated convection zone that stretches from the tropics north of Australia poleward and eastward toward 30°S in the central Pacific (e.g. Vincent 1994). In a global context it is a major precipitating region, most active during the austral summer half-year from November-April. The SPCZ has a diagonal tilt and the western part of the cloud band is located in the tropics while the eastern part is located in the subtropics. Haffke and Magnusdottir (2013) describe some of the major differences between the tropical and subtropical SPCZ. In the tropics deeper convection over a larger area is common compared to the subtropics. The seasonality of SPCZ area and overall activity is different between the tropics and subtropics. In the tropics, overall SPCZ activity, in terms of fraction of time present, reaches a maximum over the greatest area in January and SPCZ area peaks in early February. In the subtropics, area and activity peak in December. Coupled climate models often have a difficult time accurately depicting the orientation of the SPCZ and the interannual variability in that orientation (Brown et al. 2011). Despite these deficiencies, studies have begun to look at projections of SPCZ behavior in a future climate (Brown et al. 2012; Widlanski et al. 2012; Cai et al. 2012).

Historically, in situ observations of the SPCZ have been scarce due to its relatively remote location over the central Pacific ocean. Satellites have provided a wealth of information since around 1980 through infrared and visible images from which cloud cover, and precipitation can be inferred. Recently, satellite observations have been used to greatly advance our knowledge of SPCZ behavior on a number of time scales. Our understanding of the interannual variability (Folland et al. 2002; Vincent et al. 2011; Haffke and Magnusdottir 2013) and
intraseasonal variability (Haffke and Magnusdottir 2013) of the SPCZ has improved within the last decade. Hypothesis on SPCZ formation and maintenance have also emerged (Takahashi and Battisti 2007; Widlanski et al. 2011; Matthews et al. 2012). Compared to these longer time scales, little has been discussed recently regarding shorter time scales such as the diurnal cycle.

The diurnal cycle in cloudiness is forced by incoming solar radiation, which reaches a peak intensity at local noon and maximum total heating in late afternoon. On land this often results in a direct response from convective clouds as instability reaches a maximum when the surface reaches maximum heating in late afternoon (Meisner and Arkin 1987; Yang and Slingo 2001; Janowiak et al. 1994). Over the ocean the relationship between solar heating and maximum in cloud cover and deep convection is a bit more complicated. Maximum mid-level cloud cover tends to occur in the afternoon or early evening over the open ocean while maximum deep cloud coverage occurs in the early morning (e.g. Yang and Slingo 2001). One explanation for the morning maximum in deep clouds is due to a direct radiation-convection effect where afternoon convection is suppressed due to more solar radiation being absorbed by cloud tops, stabilizing the air and suppressing convection, while nighttime convection is enhanced as radiative cooling of cloud tops enhances instability and promotes convection (Randall et al. 1991; Yang and Slingo 2001). Other theories highlight the importance of the organization of the cloud systems and suggest that the morning maximum is associated with a day versus night contrast between radiative cooling in the developed cloudy area and the surrounding cloud-free areas. (Gray and Jaconson 1977; Yang and Slingo 2001). Similarly, Nesbitt and Zipser (2003) argue that the morning maximum in precipitation rate is due to an increased number of mesoscale convective systems that are favored to grow and become long lived in the night time
hours. Due to the conflicting theories and limited observations in the past, the behavior of the
diurnal cycle in cloudiness over the ocean is less well understood than that over land.

Many studies have assessed the phase and amplitude of the diurnal cycle over the tropical oceans. Table 1 of Bain et al. (2010) presents an overview of the key results. Many of these studies are limited by the spatial resolution of the data using only surface station data, or by time span of the data set. In terms of deep clouds and rainfall, most studies find an early morning peak and some also note an afternoon maximum in warmer clouds. Two of the longest studies were conducted using 22 years of ship and surface station rainfall observations (Dorman and Bourke 1979; Dai 2001). Satellite observations with higher spatial resolution often cover a shorter time span ranging from one month to 13 years (according to the summary in Table 1, Bain et al. (2010)). Nitta and Sekine (1994) examined the diurnal cycle over the west Pacific using geostationary IR temperature data from 1980-1990 and Yen (2005) also looked in the west Pacific over a similar time span, 1980-1993, but only from 15°S – 45°S, excluding much of the SPCZ. Few studies have focused specifically on the diurnal cycle in the SPCZ.

Using GOES IR satellite data from Jan-Feb, 1979, Albright et al. (1985) found a pronounced diurnal cycle in the fractional coverage of very deep clouds (IR < 218 K) in the SPCZ region that deviated from the daily mean by as much as 60% peaking in the early morning hours, between 0300-0600. In contrast, fractional coverage of deep clouds (IR < 237 K) peaked in the afternoon or evening. Albright et al. (1985) also note differences between the western SPCZ (170°E – 170°W) and eastern SPCZ (170°W – 147°W) in the cloud types, precipitation amounts, and phase of the diurnal cycle noting that the east SPCZ has a peak in the afternoon while the west Pacific peaks in the early evening around 2100 LST. Albright et al. (1985) define the SPCZ as the region where the average fractional cover of deep clouds (IR < 237 K) is greater.
than 20%. A study by Nitta and Sekine (1994) corroborate the double peak in the diurnal cycle of the SPCZ using a longer time series of IR satellite images (1980-1989), finding one in the early morning between 0300-0400 LST and one in the afternoon between 1500-1600 LST. In this study the diurnal cycle of the SPCZ was analyzed at four latitudes (6.5°S, 8.5°S, 10.5°S, and 12.5°S) along 170.5°E, an area where clouds were, on average, colder than 250 K.

We will expand on these findings to fully describe the diurnal cycle of the SPCZ. Using a more sophisticated definition of SPCZ presence and extent, we will describe the diurnal cycle of the entire SPCZ, including the subtropical portion, which has largely been ignored in previous studies due to generally warmer cloud tops. We will also quantify the impact of the seasonal cycle, intraseasonal variability in terms of the Madden Julian Oscillation (MJO), and variability related to the El Niño Southern Oscillation (ENSO) to the diurnal cycle.

The remainder of this chapter will be organized as follows: Section 3.2 will describe the SPCZ labels and IR dataset that will be used to investigate the diurnal cycle in area and cloudiness. Section 3.3 will contain results, first in terms of the basic diurnal cycle in section 3.3.1. Next, the seasonal variations to the diurnal cycle will be outlined in section 3.3.2. Sections 3.3.3 and 3.3.4 will show how the diurnal cycle is affected by ENSO and the MJO, respectively. Concluding remarks will be made in section 3.4.

3.2 Dataset

Haffke and Magnusdottir (2013) created a set of SPCZ ‘labels’, defining the instantaneous location and area extent of the SPCZ every three hours from 1980-2012 during Nov-Apr. The binary labels indicate SPCZ presence or absence at each 0.5° x 0.5° grid point in a
domain extending from the equator to 30°S and from 130°E - 110°W. SPCZ labels are based on IR satellite images from the Gridsat archive (Knapp et al. 2011) which were used as input to a Markov random field statistical model. The statistical model uses a Bayesian method to determine the probability of the SPCZ being present or absent at each grid point and is designed to emulate the way a human observer would identify the SPCZ. A full description of the model is found in Bain et al. (2011) and details of how the model is adapted for the SPCZ is found in Haffke and Magnusdottir (2013). The SPCZ labels provide a uniquely useful dataset for this study because they describe the envelope of convection associated with the SPCZ and allow for quantification of SPCZ area as well as quantities within the labels, such as IR temperature.

Figure 3.1 shows the study domain and designates eight regions that will be used to correct for local standard time (LST). In addition to the study region and sub-regions Fig. 3.1a shows a composite mean of all SPCZ labels to indicate the mean location of the SPCZ over Nov-Apr, 1980-2012 and Fig. 3.1b shows an example of a single SPCZ label from 28 Nov 2006 at 18Z. The regions will also be used to describe how the diurnal cycle is different along the length of the SPCZ. In the far west region (region 1) there are numerous islands resulting in a high proportion of land surface, but the other regions are primarily over the ocean.

In the following sections the diurnal cycle will be described in terms of area, mean IR temperature, and fractional coverage of clouds at different heights. Area will be
Figure 3.1. The domain for this study is outlined above in the inner black box spanning 0 – 30°S, 130°E – 110°W. Eight sub-regions are outlined in the smaller black boxes spanning 0 – 30°S in latitude and longitudinally as follows: 1) 130°E – 145°E, 2) 145°E – 160°E, 3) 160°E – 175°E, 4) 175°E – 170°W, 5) 170 °W – 155°W, 6) 155°W – 140°W, 7) 140°W – 125°W, and 8) 125°W – 110°W. Sub-regions are used to correct for LST and to isolate different parts of the SPCZ to compare behavior. Gray contours in the top panel show a composite of all SPCZ labels, Nov – Apr, 1980-2012 (excluding Nov 1987-Apr 1989). Units are in fraction of time present starting at 10% in intervals of 10%. An example of an SPCZ label is shown in the bottom panel from 28 Nov 2006 at 18Z.

calculated as the spatial extent of the SPCZ label within a given region. Mean IR will be calculated as the mean of all IR temperature within the SPCZ labels. The coverage percentage of different cloud heights will be based on the fraction of the SPCZ label covered by IR temperatures within a certain range. Cloud height is estimated using IR temperatures by assuming warmer temperatures indicate low cloud heights and cooler temperatures indicate high cloud heights. The warmest IR temperatures represent a clear sky. Based on a similar method used in Bain et al. (2010) we have assigned a range of IR temperature values to four categories of clouds: high clouds (IR < 220K), mid-level clouds (220K < IR < 255K), low-level clouds (255K < IR < 280K) and clear sky (IR > 280K).
3.3 Results

3.3.1 Diurnal cycle of SPCZ area, IR, and cloud height

The diurnal cycle of SPCZ area and mean IR brightness temperature are shown in Fig. 3.2 where the top row shows mean values for each region, and the bottom row shows anomalies from the regional mean. Here SPCZ area is averaged over all days from Nov-Apr, 1980-2012 giving a mean value for each 3-hr observational time. The same is done for IR temperature after first averaging the IR temperature spatially within the SPCZ label. Figure 3.2a and 3.2b highlight major differences between the regions while 3.2c and 3.2d emphasize the diurnal cycle characteristics. For example, the clouds that make up the tropical part of the SPCZ in the west tend to be deeper (cooler IR temperatures) and cover more area than the clouds that make up the SPCZ further east and between 15°S-30°S, shown in Fig. 3.2a and 3.2b.

Despite large differences in the overall mean area between regions the anomalies are quite similar. Maximum area occurs between 1500 - 1800 LST in all regions when area is between 10-21% greater than the mean. With the exception of the easternmost and westernmost regions, minimum area occurs between 0500 - 0900 LST, during which time the area is between 7 - 11% below the mean value. In the easternmost region, where the SPCZ is located near 30°S, the minimum in area occurs between 0100-0200 LST. The
The diurnal cycle of the SPCZ in the westernmost region, which is partially over land, reaches a lower minimum area at a later time, between 0900-1200 LST. The amplitude of the diurnal cycle in area is smaller in western, tropical regions and larger for eastern regions where the SPCZ is located in the subtropics. This contradicts previous work such as Fu et al. (1990), which notes that the diurnal cycle is strongest where convection is strongest.

Figure 3.2b demonstrates the difference in mean IR temperature within SPCZ labels in the different regions. The mean IR temperature is an average over all cloud types within the SPCZ label, but, in general, cooler mean IR temperature is associated with a greater number of high clouds while a warmer mean IR temperature is associated with more clear sky and lower
clouds. The phase of the diurnal cycle in terms of mean IR temperature is different for the different regions, which was not the case for SPCZ area. All regions have a double minimum in IR temperature, one occurring in the morning and one occurring in the afternoon. In the western regions (2-4) the primary minimum in IR temperature occurs in the early morning between 0500 - 0700 LST. In the eastern regions (5-8) the primary minimum in IR occurs in the afternoon between 1300 - 1600 LST. The double peak is more obvious in Fig. 3.2d, which shows anomalies from the mean. In the summer east Pacific ITCZ Bain et al. 2010 finds that between 90°W-120°W the minimum in IR temperature occurs in the afternoon while further west, between 150°-180°W it occurs both in the morning and afternoon. Region 1 has a unique diurnal cycle with a minimum IR temperature occurring at 1200 LST and a secondary minimum occurring at 2100 LST (Fig. 3.2b, 3.2d). Similar to area, we find that the amplitude of the diurnal cycle in terms of mean IR temperature is larger in the subtopics than in the tropics when normalized by mean IR temperature for the region (Fig. 3.2d).

A breakdown of the IR temperatures within the SPCZ labels clarifies the regional differences in the phase of the diurnal cycle. The diurnal cycle of each cloud type is shown in Fig. 3.3 for each region. Figure 3.3 also includes a timeline highlighting the timing of relevant events. Mid-level clouds cover the largest percentage of the SPCZ in all regions at all times, on average covering between 40%-60% of the area. The subtropical parts of the SPCZ have a higher percentage of mid-level clouds than the tropical parts of the SPCZ. Low-level clouds are the next most abundant, covering between 28%-48% of the SPCZ area depending on the time of day and region. Again, the subtropical SPCZ has a higher percentage of low-level clouds than the tropical SPCZ. High-level clouds cover between 2%-20% of SPCZ area and, as expected, the tropical SPCZ has a higher percentage of high-level clouds.
Figure 3.3. Diurnal cycle of various cloud types within SPCZ (% of SPCZ area) for each sub-region. Minimum SPCZ area and maximum SPCZ area are also indicated with hash marks. Yellow shading approximates daylight hours within the diurnal cycle.

Each cloud type peaks at a different point in the diurnal cycle indicating a preference for different convection types at different times of the day. At the beginning of the day at 000 LST, low-level clouds are at a maximum and this peak has been building since the 1500 LST the previous day. After midnight the abundance of low-level clouds lessens and the percent of high-level clouds begins to increase. During this time there is little change in mid-level clouds indicating a quick transition from low-level to high-level clouds in the early morning hours. Bain et al. 2010 found the same quick transition from low-level to high-level clouds in the early morning hours in the summer east Pacific ITCZ. Some studies suggest that an early morning peak in deep clouds over the ocean could be due to cloud top radiative cooling causing instability and increased convection (e.g. Yang and Slingo 2001) The quick transition from low to high-
level clouds supports this idea. The abundance of high-level clouds peaks between 0300-0600 LST. This corresponds to a time when the overall SPCZ area is at a minimum. By late afternoon when SPCZ area is at a maximum (1500-1800 LST), mid-level clouds have reached maximum coverage (1500-1800) and low-level clouds are at a minimum (1400-1600 LST). High-level clouds reach a minimum area between 1800-2100.

This analysis clarifies that the morning minimum in mean IR temperature is due to an increase of deep clouds. In subtropical regions the morning minimum is the secondary peak in cloudiness because there are fewer deep clouds away from the equator. The afternoon minimum mean IR occurs just before the peak in mid-level clouds and during maximum SPCZ area and is the time when there is a balance between a shrinking number of deep cold clouds and growing number of mid-level clouds. Again, this is consistent with the east Pacific ITCZ (Bain et al. 2010).

3.3.2 Seasonal changes to the diurnal cycle in SPCZ area, and mean IR

Kikuchi and Wang (2008) show differences in the diurnal cycle of TRMM rainfall between the summer (JJA) and winter seasons (DJF) and Nitta and Sekine (1994) show changes to the diurnal cycle in cold clouds (< 250 K) over the entire year, but only at four locations. To our knowledge there has never been a comprehensive study of if and how the diurnal cycle in the SPCZ changes from November through April and how changes may be different for different parts of the SPCZ.

To address this, three of the eight regions described above have been chosen to represent different segments of the SPCZ. Region 3 is used for the tropical, western portion of the SPCZ,
region 5 is used for the transition, or central portion of the SPCZ, and region 7 is used for the subtropical, eastern portion of the SPCZ. Haffke and Magnusdottir (2013) show that the tropical and subtropical parts of the SPCZ have different seasonal cycles in terms of area and activity (fraction of time present). The subtropical SPCZ is most frequently present in Nov and Dec and present least often in Mar while the tropical SPCZ is frequently active in Jan and Feb and least active in Nov. The same is true of SPCZ area. Due to these differences, one might expect the amplitude or timing of the diurnal cycle to change throughout the SPCZ active season and not necessarily change in the same way for all parts of the SPCZ. Figure 3.4 shows how this seasonal variability in SPCZ activity impacts the diurnal cycle in cloud height and area for three different segments of the SPCZ. In Fig. 3.4 time of year is labeled by months

![Figure 3.4](image)

**Figure 3.4.** The top row (a-c) shows the seasonal change in the diurnal cycle in terms of anomalies in mean area (number of \(\frac{1}{2}\)° pixels, each region is of equal total area) for regions 3, 5, and 7. The bottom row (d-f) shows the same for mean IR temperature (K).

53
from Nov-Apr on the vertical axis and increases toward the top while LST is plotted on the horizontal axis and increases toward the right.

Figure 3.2c shows that, when averaged over the season, the tropical SPCZ (region 3) reaches maximum area around 1700 LST, minimum area around 0800 LST. When the diurnal cycle is examined throughout the SPCZ active season we find that the phase is the same but the amplitude changes over this time period (Fig. 3.4a). The afternoon maximum in area is strongest during two separate times of the season, in late Jan into early Feb and in late Feb into early Mar with a relative minimum in between. The largest amplitude in area during the diurnal cycle occurs in mid-Feb. Figure 3.2b shows that, on average over Nov-Apr, a maximum in IR temperature occurs around 2000 LST. The primary minimum IR temperature occurs around 0500 LST, when the largest percentage of deep cloud coverage is reported (Fig. 3.3). The secondary minimum in IR temperature occurs around 1400 LST as mid-level clouds are increasing. Figure 3.4d indicates how this pattern changes from Nov-Apr. The tropical segment of the SPCZ has a double peak in cloud height (cool IR temperatures), one occurring between 0500 - 0800 LST and the other occurring between 1300-1500 LST. The secondary, early afternoon IR minimum is much weaker in the early and late parts of the season but in Feb they are similar (Fig 3.4d). The timing of the minimum and maximum IR temperature does not change from Nov-Apr.

In the central/transition segment of the SPCZ (region 5, Fig. 3.4b) area peaks near 1600 LST both in the seasonal mean and at all times of the season. The minimum area occurs around 0700 LST on average, but the timing changes throughout the season. From Nov through early Mar the minimum area occurs at 0700 LST but in Mar and Apr it occurs much earlier, around 2200 LST the day before. The afternoon peak in area is strongest in Jan and Feb, which is earlier
In the season compared to the tropical region, and the amplitude of the diurnal cycle in SPCZ area peaks at the end of Jan. In terms of IR temperature (Fig. 3.4e), on average a minimum occurs around 1300 LST and a secondary minimum occurs around 0700 LST. However, we find that the double minimum in IR temperature only begins to occur in Jan, although weakly, and then strengthens throughout the season. Only the afternoon peak is evident before late December.

In this segment of the SPCZ, characteristics of both the tropical and subtropical SPCZ can be identified. The magnitude of the double peak in cold clouds is nearly equal from Jan onwards indicating a mix of the tropical, morning dominated IR minimum and the subtropical, afternoon dominated IR minimum. In the beginning of the season this transition region has diurnal cycle characteristics more similar to the subtropical region, in that the afternoon IR minimum is the only peak in cold clouds.

Over the course of the season the subtropical SPCZ (region 7) has the largest change in IR temperature (Fig. 3.4f) but the smallest change in SPCZ area (Fig. 3.4c) compared to the other two regions. On average the maximum SPCZ area occurs at 1500 LST and the minimum at 0600 LST, according to Fig. 3.1. In Fig 3.4c maximum SPCZ area is indeed seen around this time for most of the season although in Dec, when area is the highest, it peaks slightly later, around 1800 LST. A shift in the timing of minimum area also occurs. From Nov through mid-Jan area minimum occurs around 0600 LST then from mid-Jan to mid-Feb the minimum occurs early, around 0300 LST, then from mid-Feb through the remainder of the season the minimum occurs around midnight LST. This is the largest seasonal change in the phase of the diurnal cycle from all three regions. In terms of IR, a strong peak in deep cloud cover occurs in the afternoon, peaking near 1500 LST during all months and a secondary peak in deeper cloud cover occurs around 0600 LST starting in mid-Jan. The coldest clouds occur around the beginning of Mar,
fairly late in the season compared to the tropical and transition regions. In general, clouds in the subtropical SPCZ are considerably warmer than in the tropical and transition regions.

In summary, we find that the seasonal cycle has a small impact on the timing of the diurnal cycle in area, in most regions. Throughout the season the amplitude of the diurnal cycle in mean IR can change sometime resulting the timing of minimum IR to switch between morning and afternoon. This implies that the months being averaged will impact the phase of the diurnal cycle in IR temperature.

3.3.3 Modulation of the diurnal cycle during MJO events

The MJO is a dominant mode of variability in the tropical Pacific (Madden and Julian 1993). Past studies have indicated that the diurnal cycle is modulated by the MJO by either increasing (Chen and Houze 1997; Tain et al. 2006; Peatman et al. 2013) or decreasing (Sui and Lau 1992) the strength of the diurnal cycle. To further explore this, the diurnal cycle in regions 3, 5, and 7 will be examined in detail during different phases of the MJO. Here we will use the MJO phases described in Wheeler and Hendon (2004).

Haffke and Magnusdottir (2013) indicate how SPCZ activity changes during each phase of the MJO (Fig 2.10 here) by compositing SPCZ labels by MJO phase. When the MJO is initiated in the Indian Ocean, subsidence occurs over the maritime continent and western Pacific (phase 2 and 3), suppressing SPCZ activity. The MJO then passes over the maritime continent (phases 4 and 5) causing enhanced SPCZ activity over New Guinea and suppressed convection directly to the east near the equator, resulting in a poleward shift in SPCZ location. The poleward shift may be enhanced by an increase in easterly winds to the west of the suppressed portion of
the SPCZ, enhancing convergence to the west. During MJO phases 6 and 7 the convectively active part of the MJO moves over the west Pacific and SPCZ activity is enhanced. Finally, in phases 8 and 1 SPCZ activity is enhanced near the equator in the central Pacific and enhanced over New Guinea and further poleward resulting in an equatorward shift in SPCZ location. To summarize, the behavior of the SPCZ can be sorted into 4 categories: 1) suppressed SPCZ during MJO phases 2 and 3, 2) a poleward shifted SPCZ during MJO phases 4 and 5, 3) an enhanced SPCZ during MJO phases 6 and 7, and 4) an equatorward shifted SPCZ during MJO phases 8 and 1.

By composite analysis, we find that the magnitude of the peaks in SPCZ area and mean IR temperature change during an active MJO and in specific ways for each MJO phase. This is shown in Fig. 3.5 indicating the diurnal cycle of area and mean IR for regions 3, 5, and 7 during all MJO phases. In region 3 (Fig 3.5a and 3.5d), the morning and afternoon minimum in IR and the peak in SPCZ area are all largest during MJO phases 6 and 7 when SPCZ activity is enhanced everywhere. In contrast the warmest cloud peaks in this region occur during MJO phases 4 and 5 when the SPCZ tends to shift poleward. The smallest peak in SPCZ area occurs in MJO phase 1, when much of the SPCZ is shifted equatorward but the SPCZ in region 3 is suppressed, and phases 2 and 3 when most of the SPCZ is suppressed. The afternoon peak in SPCZ area is 1.6 times greater in MJO phase 6 than in MJO phase 1.
Figure 3.5. Top row (a-c) show changes to the diurnal cycle of mean SPCZ area (number of ½° pixels) between different phases of the MJO for regions 3, 5, and 7. Bottom row (d-f) shows the same for mean IR temperature (K).

In region 5 (Fig 3.5b and 3.5e) the SPCZ reaction to an MJO event is slightly delayed compared to region 3. In region 5 the SPCZ area peaks are the greatest in MJO phases 7, when the SPCZ is enhanced, and 8, when the SPCZ shifts equatorward. In terms of minimum IR, the greatest minimum is observed during MJO phases 1 and 8 when the SPCZ is shifted equatorward. During phases 1, 8, and 7 the morning and afternoon IR minimums are nearly equal in magnitude and in phase 1 the morning peak dominates. During all other times the afternoon IR minimum is largest. The movement closer to the tropics causes the SPCZ to form over warmer SSTs, which should allow for the development of deeper clouds. In contrast the warmest IR minimums occur in MJO phases 4 and 5 when the SPCZ shifts poleward, away from warm SST.
The smallest peak in area occurs in MJO phase 3 when the SPCZ is suppressed. During phase 7 the peak in area is 1.4 times larger.

Region 7 (Fig. 3.5d and 3.5f) has a much smaller area at all times compared to the other two regions. The morning and afternoon IR minimum are strongest during MJO phase 8 but weakest just a short time later in phase 1. The area of the SPCZ in region 7 is much smaller than in regions 3 and 5, which could impact the significance of the IR results. SPCZ area has the largest peak during MJO phases 7 and 8 when it is 1.4 times larger than in phase 5 when the peak is the smallest.

We also consider the MJO impact on cloud height. The distribution of cloud type in region 3 can be seen in Fig. 3.6a showing that 42% - 57% are mid-level clouds depending on the time of day and MJO phase. For low-level clouds, fractional cover ranges from 27% - 36% and for high-level clouds, from 9% - 22%. We find mid-level clouds are at a maximum during phases 4 and 5 and at a minimum during phases 7, 8, and 1. The opposite is true of high-level clouds when the highest coverage occurs during phase 7 and the lowest coverage occurs during phases 4 and 5. The difference in low-level cloud and clear sky coverage between MJO phases is smaller suggesting a trade off between high-level and mid-level clouds, depending on MJO phase. We noted earlier that during phases 4, and 5 the SPCZ tends to be located further poleward, supporting the idea of more mid-level clouds at the expense of deep convection. Conversely, during phases 8 and 1 the SPCZ is shifted equatorward while during phase 7 the SPCZ is enhanced, all suggesting that the occurrence of high-level clouds may increase as the SPCZ moves toward the equator and is therefore more active. We find that the timing of the diurnal cycle is the same during all MJO phases and the same as when all days are considered (Fig. 3.3).
Figure 3.6. Each panel shows the changes in the distribution of different cloud types during each phase of the MJO for regions 3, 5, and 7. Each group of lines shows a different cloud type: high clouds (T<220K) (dashed), mid-level clouds (220K<T<255K) (dotted), low-level cloud (255K<T<280K) (solid), and clear sky (T>280K) (dash-dot).

Very similar results are found for region 5 (Fig. 3.6b). During phases 8 and 1 more high-level cloud coverage is seen suggesting the SPCZ may shift equatorward and take on more tropical characteristics. The peak in mid-level and low-level cloud coverage occurs 1 hour later in the day while the peak in high-level cloud coverage occurs slightly earlier.

In region 7 (Fig. 3.6c) the SPCZ is located, on average, near 30°S. The difference in cloud cover between the different MJO phases is smaller in this region. The timing of the diurnal cycle is also slightly different in that peak in mid-level high-level, and low level clouds during active MJO events occurs two hours later compared to when all days are considered.

These results agree well with Tain et al. (2006), which found that the diurnal cycle of deep convective clouds was amplified during the active convective phases of the MJO and suppressed during the suppressed phases of the MJO without a change in diurnal cycle phase. Sui and Lau (1992) found an opposite trend showing that the diurnal cycle diminished during the active phase and was enhanced during the suppressed phase. Similar to Chen and Houze (1997), we find a tendency for the morning peak in cloudiness to occur with the active phase of the MJO.
All studies that specifically looked at the modulation of the diurnal cycle by the MJO looked in the tropics, north of 20°S. To the best of our knowledge, ours is the only analysis of changes to the subtropical part of the SPCZ.

3.3.4 Impact of ENSO on the amplitude of diurnal cycle

Figure 3.7. Each panel shows seasonal changes to the diurnal cycle in terms of anomalies of mean IR temperature (K) during El Niño years (a-c), ENSO neutral years (d-f), and La Niña years (g-i) for regions 3, 5, and 7.

Typically during El Niño years the SPCZ average position shifts equatorward and becomes more zonal while during La Niña years it shifts poleward (Folland et al. 2002; Vincent et al. 2011; Haffke and Magnusdottir 2013). The goal of this section is to determine if the diurnal cycle of the SPCZ changes during El Niño and La Niña events, potentially due to shifting SPCZ location. To retain the seasonal information, diagrams are shown indicating the diurnal cycle as a
function of time of season, similar to Fig. 3.4, as a composite of El Niño years (Fig 3.7a-c), ENSO neutral years (Fig 3.7d-f) and La Niña years (Fig 3.7g-i). Again we focus on the three regions discussed previously, region 3, region 5, and region 7.

We find that, depending on the region, the timing of minimum IR is different in El Niño, La Niña, and ENSO neutral years. In region 3 during neutral or El Niño years, the morning minimum IR is either the only IR minimum throughout the day, or it is the stronger minimum indicating that during these years the morning minimum, attributed to the peak in high cloud cover, is the dominant factor in the IR diurnal cycle. However, in La Niña years the afternoon minimum in IR is also strong, particularly from late Jan-early Mar. During these years the diurnal cycle in mean IR in the tropical part of the SPCZ looks more like the pattern typically seen in region 7 as the SPCZ shifts away from the equator.

The behavior of the SPCZ in region 7 also supports this argument. The morning minimum is weak or does not exist during neutral years but is evident in El Niño years. The morning minimum is more characteristic of the tropical regions of the SPCZ and so we see the subtropical SPCZ taking on tropical characteristics during El Niño years, when it shifts equatorward.

3.4 Conclusions

Here we use a unique data set to quantify the diurnal cycle of SPCZ area, mean IR temperature, and cloud height. The data used spans the months of Nov-Apr and includes the years 1980-2012. We split the SPCZ into eight regions to correct for local standard time and to study how the tropical SPCZ and subtropical SPCZ may differ in terms of the diurnal cycle. We
find that the SPCZ reaches a minimum area in the morning, between 0600-0900 LST and a maximum in the late afternoon, between 1500-1800 LST for all regions except the easternmost and westernmost regions. The amplitude of the diurnal cycle in area is stronger for the easternmost regions meaning the more subtropical parts of the SPCZ see a larger change in area throughout the day.

While the diurnal cycle of SPCZ area is consistent for all regions, the same is not true for the diurnal cycle of mean IR temperature. In the tropics, SPCZ area decreases and convection deepens in the early morning. In the subtropics, SPCZ area increases and mid-level clouds dominate in the afternoon. The tropical SPCZ has minimum IR temperatures (peak in deep convection or cloudiness) in the morning between 0500 - 0700 LST while the subtropical SPCZ has minimum IR temperatures in the afternoon between 1300 – 1600 LST. Albright et al. (1985) also noted the eastern, subtropical SPCZ has an afternoon peak in mean IR. However, they find the western SPCZ has a peak in mean IR in the late evening hours, around 2100 LST, much earlier than the morning peak we find in the western, tropical SPCZ. Our results largely agree with those presented in Nitta and Sekine (1994) who indicate a morning peak between 0300 – 0400 LST (our early morning peak occurs slightly later) and a second peak between 1500 - 1600 LST.

We find that the timing of the diurnal cycle is consistent throughout the year in the tropics, especially in terms of SPCZ area. More variability between the beginning of the season, height of the season, and end of the season are seen in the central part of the SPCZ, where it transitions from a more tropical based cloud band to a more subtropical-based cloud band. In these regions the timing of the minimum SPCZ area tends to shift to earlier hours of the morning or to late at night the day before later in the season. In all regions there tends to be a double
minimum in IR temperature, a morning peak associated with a maximum in high clouds and an afternoon peak associated with an increase in mid-level clouds. However, we find that only the afternoon minimum IR occurs in the transition or subtropical regions in the beginning of the SPCZ active season. This seems to indicate that the more subtropical parts of the SPCZ tend to start behaving more like the tropical SPCZ only after Jan even though this is when the subtropical SPCZ tends to be less active compared to the beginning of the season.

Changes to the diurnal cycle of mean IR temperature due to the MJO or ENSO have a similar pattern: when the SPCZ shifts equatorward, either during an El Niño year or during phases 8 and 1 of the MJO, deep clouds tend to cover more area and the morning peak in mean IR dominates. When the SPCZ shifts poleward, either during La Niña or during phases 4 and 5, the afternoon peak in mean IR temperature tends to dominate as the percentage of deep clouds is minimized. This is particularly apparent in region 5 where larger north-south shifts in SPCZ position can occur. This suggests that the proximity of the SPCZ to the equator is an important factor to determine if the morning minimum in IR temperature is dominant. If the SPCZ is closer to the equator, conditions are more favorable for deep convection to occur suggesting there is more instability or more convergence in this location.

Previous studies have noted that the proximity to land is important for the diurnal cycle showing that the afternoon peak dominates closer to land (Bain et al. 2010; Yang and Slingo, 2001). This was not indicated by our results where the western regions were closest to land but had the stronger early morning peak.

We find a quick transition from low-level cloud to high clouds in the early morning hours. The percentage of low-level clouds peaks just before midnight and the peak in deep clouds occurs between 0500 – 0700 LST. The transition from low-level to deep clouds is
relatively fast and between 0000 – 0500 LST the percentage of mid-level clouds is not changing. This supports a theory in which the atmosphere destabilizes during this time causing a quick transition from low-level to deep clouds (Yang and Slingo 2001; Randall et al. 1991) but not necessarily one in which mesoscale cloud systems persist from the afternoon to the early morning hours (Nesbitt and Zipser 2003).
Chapter 4

Observations of the instantaneous double ITCZ: the east Pacific ITCZ in three decades of high-resolution satellite data

Abstract

In the east Pacific, zonally elongated cloud bands associated with the Intertropical Convergence Zone (ITCZ) can take on several configurations. A novel statistical model is used to automatically assess the daily state of the east Pacific ITCZ using infrared satellite images from 1980-2012. Four different ITCZ states are defined based on ITCZ location: north of the equator (nITCZ), south of the equator (sITCZ), simultaneously north and south of the equator (dITCZ), and over the equator (eITCZ). The fifth ITCZ state describes when no cloud band is present (aITCZ).

The most striking variability is observed in March-April and the analysis is focused on the two months. On average, the dITCZ state occurs 34% of the time, second only to the nITCZ state. The interannual variability of the state distribution is large; for example, 2003 had only one dITCZ day in March-April while 2001 had 40. Composites of observed precipitation and infrared
temperature by daily ITCZ state reveal distinct configurations of rain and cloud bands for each. The cloud and precipitation bands are located closer to the equator during the dITCZ state but rain rates and cloud heights tend to be lower compared to nITCZ or sITCZ states. Strong sea surface temperature anomalies are associated with eITCZ and sITCZ states but weak anomalies exist during the other three states. However, distinct atmospheric circulation patterns are associated with each ITCZ state. Consistent with these patterns, activity in the east Pacific ITCZ corresponds to significant anomalies in South Pacific Convergence Zone activity.
4.1 Introduction

The Intertropical Convergence Zone (ITCZ) is a narrow, zonally elongated band of surface convergence located near the equator, which corresponds to rising air, clouds and precipitation. It is often thought about in a global mean sense as the rising branch of the Hadley circulation located where the easterly trade winds converge. The ITCZ can be identified using satellite observations of clouds, precipitation, or surface winds and also using dynamical fields in reanalysis data. Many studies have identified the characteristics and variability of the global mean ITCZ (e.g. Waliser and Gautier 1993; Berry and Reeder 2014), but fewer studies have examined the highly dynamic day-to-day variability of the ITCZ. To do this requires instantaneous identification of the ITCZ, which is a tedious task in long-term data with high-temporal resolution, such as the GridSat database (3-hourly infrared (IR) and visible (VS) images). However, within the last decade several studies have examined the day-to-day variability of the ITCZ in the east Pacific, first using visual identification of ITCZ structure in satellite images to assess the breakdown of the ITCZ on synoptic time scales (Wang and Magnusdottir 2006) and then using an automatic statistical model to quantify the variability on diurnal to decadal timescales (Bain et al. 2010; Bain et al. 2011). Recently a method was developed to identify different states of the east Pacific ITCZ in instantaneous IR and VS satellite images (Henke et al. 2013) with the goal of identifying the instantaneous double ITCZ during the boreal spring.

Many aspects of the observed double ITCZ are not well understood. Past studies have defined the double ITCZ using monthly mean variables such as cloud cover, rainfall, and horizontal wind convergence at the surface (Waliser and Gautier 1993; Zhang 2001; Halpern and
Hung 2001; Lietzke et al. 2001; Liu and Xie 2002; Gu et al. 2005; and Masunaga and L’Ecuyer 2010). A double ITCZ in surface wind convergence occurs year-round in the Atlantic and Pacific, although the southern hemisphere branch is often not accompanied by clouds (Liu and Xie 2002). In the east Pacific a double ITCZ can be seen in monthly mean observations of clouds or precipitation in March and April, when the underlying SST north and south of the equator is sufficiently warm and SST along the equator is cool (Zhang 2001; Halpern and Hung 2001; Gu et al. 2005; and Masunaga and L’Ecuyer 2010). Lietzke et al. (2010) note that the presence of the cool equatorial SST is the key factor regulating double ITCZ formation and when it does not exist, such as in strong El Niño years, a single band of convection occurs on the equator. The role that large-scale atmospheric dynamics plays in the formation of the double ITCZ is still largely unknown.

Although the double ITCZ is usually only seen in the boreal spring in observations, climate models have a tendency to over represent the presence of the double ITCZ (Mechoso et al. 1995). The double ITCZ and the excessively cold equatorial SSTs in the Pacific are the most prominent bias in the current generation global climate models (GCM) (Li and Xie 2014; Hwang and Frierson 2013). Lin et al. (2007) shows that various feedback processes between SST and precipitation are not accurately represented in coupled atmosphere-ocean climate models, causing precipitation to be too closely linked to high SST throughout the tropics. In addition, models may not capture the atmospheric dynamics responsible for suppressing deep convection (Lin et al. 2007).

Because past studies have identified the east Pacific double ITCZ in monthly mean data it is unclear how often an instantaneous double ITCZ (dITCZ) occurs. For the west to central Pacific, Chen et al. (2008) find that the monthly mean double ITCZ in the central-to-western
Pacific is mostly a combination of north only and south only ITCZ, and the instantaneous double ITCZ occurs only 6% of the time over the time period 1996-2006. In their study the ITCZ is identified using the daily percent of area covered by of heavy precipitation within certain latitude bands north, south, and over the equator. The relative frequency of the east Pacific instantaneous double ITCZ is unknown. Furthermore, we do not know whether the instantaneous double ITCZ is a unique feature with a corresponding unique SST distribution and an associated unique atmospheric circulation pattern, or simply a combination of features associated with the Northern Hemisphere ITCZ and the Southern Hemisphere ITCZ.

Recently a new statistical model was developed to automatically detect the position of the east Pacific ITCZ using infrared (IR, in the atmospheric window) and visible (VS) satellite images during Feb-May, 2000-2004 at 3-hourly and daily resolution, respectively (Henke et al. 2012). This method identifies instantaneous states of the east Pacific ITCZ based on the location of elongated cloud bands: north of the equator (nITCZ), south of the equator (sITCZ), and simultaneously north and south of the equator (dITCZ). Another ITCZ state describes when no cloud band is present and is referred to as ‘no ITCZ’ in Henke et al. (2012) but ‘aITCZ’ in our study. When the model was applied to a longer dataset we found that a fifth state of the ITCZ was required, the equatorial ITCZ (eITCZ). This state of the ITCZ is favored when the equatorial cold tongue in the ocean gets replaced with warm SST such as occurs during strong east Pacific El Niño events. We have modified the detection method to include this equatorial ITCZ state.

This paper shows results from applying the statistical model to three-hourly IR satellite images in the tropical east Pacific during 33 years from 1980-2012, focusing in particular on March-April, which show the richest variability of ITCZ states. Output from the method allows for a new look at the double ITCZ in the tropical east Pacific. The paper is organized as follows:
Section 4.2 describes the data and methods, where subsection 4.2.2 summarizes the statistical model that is a slight variation of the model for automatic detection of ITCZ states that was described in Henke et al. (2012). Section 4.3 contains the main results from the study including the distribution of ITCZ states in the east Pacific through the seasonal cycle, over all years. In the remainder of the paper we focus on March-April of each year. In section 4.3.2 we show composite fields according to ITCZ state in terms of cloud top temperature (the variable used to detect the ITCZ state), but also in terms of precipitation rate from another satellite data set. The relationship of ITCZ state to the underlying SST distribution is described in Section 4.4.1, while the large-scale atmospheric circulation patterns associated with each ITCZ state are described in Section 4.4.2. In Section 4.5 we discuss the connection between convective activity in the South Pacific Convergence Zone (SPCZ) and ITCZ state. Conclusions are presented in Section 4.6.

4.2 Data and Methods

4.2.1 Datasets

The ITCZ detection method described below requires high-resolution atmospheric-window IR satellite images. These data are obtained from the GridSat database that provides geostationary satellite data from Europe, Japan, China, and the U.S. that have been intercalibrated and consistently stitched together to provide long-term, global coverage appropriate for climate studies (Knapp et al. 2011). GridSat includes global 3-hourly IR images from 1980 to 2012 at 8 km resolution.

We use other satellite observations and reanalysis data to characterize the regional and
global atmospheric conditions and SST patterns associated with different ITCZ states. Daily SST is obtained from the NOAA Optimum Interpolated SST V2 High Resolution Dataset (Reynolds et al. 2007) at a 0.25 x 0.25 degree resolution for the years 1982 through 2012. Precipitation rate from both the Tropical Rainfall Measurement Mission Project (TRMM) and the Global Precipitation Climatology Project (GPCP) are used. The TRMM product is a daily 0.25 x 0.25 degree resolution precipitation rate, which is available from 1999-2012 (Huffman et al. 2007). The GPCP precipitation 1DD data are of coarser resolution than TRMM precipitation at 1°x1°, but they are available daily from 1997-2012, providing a longer dataset (Huffman et al. 2001). To supplement the satellite data we also use the three dimensional velocity field and precipitation from the European Center for Medium-Range Weather Forecasts ERA-Interim reanalysis (Dee et al. 2011).

4.2.2 Statistical model for classifying ITCZ state

Tracking the ITCZ in three-hourly geostationary satellite images gives a new perspective on ITCZ variability. Manually identifying the ITCZ is tedious at such high temporal resolution and, moreover, there may be inconsistencies due to variability in human perception of an ITCZ. An automated method is ideal as in that case the results are consistent and reproducible given the same input data. A human observer can easily recognize the zonally elongated cloud bands associated with convection in the east Pacific ITCZ using visible (VS) or IR satellite images. However, it is hard to come up with a small set of simple characteristics to describe the ITCZ at all times because the location, orientation, east-west extent, and total area of the cloud bands change over time. While an expert observer can cope with these changes, for example, when the
ITCZ migrates north and south over the course of a year or changes shape and position over the course of a day, these changes prove more challenging for automated methods.

A new well-suited method for the task of automatically identify the east Pacific ITCZ in IR and VS satellite images at high temporal and spatial resolution was developed in Henke et al. (2012). We will briefly summarize the method here and describe necessary modifications that were implemented for the current study.

The method is subdivided in two major parts: (a) spatially identifying and segmenting the convection zones over the east Pacific basin on both sides of the equator (20°S - 20°N and 180°W - 90°W) and (b) tracking the temporal variability of the ITCZ. For (a), the ITCZ is localized in each hemisphere via a backbone path that maximizes the intensity value of the zonally summed pixels along the path. Subsequently, a region-growing algorithm is applied with seed points obtained from the backbone path to determine the spatial extent of the clouds associated with the ITCZ in each hemisphere while simultaneously suppressing other cloud formations. Examples of the backbone path and the segmentation mask based on a VS image can be found in Fig. 2 & 3 of Henke et al. (2012). A set of meaningful ITCZ features can be derived from the backbone path, the segmentation mask and the complete satellite image. A subset of these features (see appendix B, Henke et al. (2012) serves as input to (b). In (b), a (semi-)supervised hidden Markov model / support vector machine hybrid approach enables the classification of a time-series of satellite images in mutually exclusive ITCZ states: first, the model parameters are learned based on a small subset of expert-labeled images with one label per day. This allows for a fully supervised situation for the VS data where only one satellite image is available per day but a semi-supervised situation for the IR, which has eight images available per day, only one of which has been manually labeled. Second, for an unknown image
sequence, the current ITCZ state is estimated based on the previous state of the system (ITCZ state in the previous time step) and the current observations (image features at the current time step) generating a ITCZ classification with similar accuracy as human expert labelers (for details on the algorithm and performance, see Henke et al. 2012).

In Henke et al. (2012), the method was applied to a small set of GridSat data from Feb-May 2000-2004 only and ITCZ states were group in four classes: nITCZ, sITCZ, dITCZ, and aITCZ\(^1\). The current study expands on the methods outlined in Henke et al. (2012) by including all available IR and VS images in the GridSat dataset. The ITCZ state is assigned 3-hourly (IR) / daily (VS) and year-round from 1980 (IR) / 1994 (VS) to 2012. The longer datasets required a major modification to the original algorithm: the inclusion of an additional fifth ITCZ state, the eITCZ state. It is needed to accommodate the cloud pattern seen during strong east Pacific El Niño years (most notable in 1982/1983 and 1997/1998) when convection in the east Pacific is located on the equator and covers a broad north-south band. This type of convection does not fit into one of the four states defined in Henke et al. (2012) and did not occur in the 2000-2004 test period. Adding the eITCZ state (for equatorial) required some additional manual labeling that includes eITCZ days (total learning set: Feb-May of 4 years) and minor modifications to the model; however, no new image features were calculated. Although the VS version of the method was also executed, in this paper we only use results based on IR images because of the longer temporal coverage.

Although only images from Feb-May are used for manual labeling the method produces accurate ITCZ states year round. For analysis, daily ITCZ state labels were often more desirable than the 3-hourly labels. Daily labels were assigned by choosing the state that occurred most often during the eight observational times each day.

\(^1\) note: in Henke et al. 2012, the aITCZ state is referred to as ‘no ITCZ’
4.3 Results

4.3.1 Distribution of ITCZ states

Figure 4.1 summarizes the daily ITCZ state from 1980-2012 showing the time distribution of daily states, where the vertical axis shows the year increasing downward and the horizontal axis shows the month increasing to the right. The figure shows the seasonality and interannual variability of ITCZ states. January through May is characterized by considerable variability when the ITCZ state changes often and the nITCZ, dITCZ, sITCZ, and aITCZ states all occur frequently. The remainder of the year is less variable with the nITCZ state dominating (white in Fig. 4.1) with a few exceptions. Late 1982 and 1997 were characterized as parts of major El Niño events with high incidence of double and equatorial ITCZ states. These two El Niño events continue into early 1983 and 1998, respectively, with overwhelming incidence of the equatorial ITCZ (eITCZ). As discussed in section 4.2.2, the equatorial ITCZ was introduced specifically to account for strong east Pacific El Niño events as it only occurs when the east Pacific equatorial cold tongue is replaced by a warm mixed layer.

The seasonality is further depicted in Fig. 4.2, which shows the average fraction of time spent in each state by month. The eITCZ state has been excluded in this figure because it only occurs frequently during the two east Pacific El Niño events in 1998 and 1983. Figure 4.2 shows that the nITCZ is the most frequently observed state in all months and it is especially dominant in May through January. It is only in March and April that the dITCZ state is a close second. The number of days when the ITCZ is absent peaks in February. In May there is a sharp drop in the number of days classified as states other than nITCZ and the nITCZ state clearly dominates
Figure 4.1. Daily ITCZ state from 1980 – 2012 assigned by the statistical state-labeling algorithm. The vertical axis shows years increasing toward the bottom. The horizontal axis shows time of year, labeled with months, increasing toward the right. Each state is shown as a different color: nITCZ - white, sITCZ - yellow, dITCZ - blue, aITCZ - red, and eITCZ - black. The time variability of ITCZ states is shown indicating both the seasonal distribution of ITCZ states as well as the interannual variability of ITCZ states.
until the following January or February when the aITCZ state picks up again. Of all the months, March and April are perhaps the most interesting in terms of ITCZ state because this is when the occurrence of the dITCZ is comparable to that of the nITCZ. Overall, the distribution between states is the most similar in March-April. In Sections 4.3.2, 4.4 and 4.5 in this paper, our analysis of ITCZ states is focused on March-April only.

In addition to the seasonal changes in ITCZ state, Fig. 4.1 also indicates the interannual variability, which is further highlighted in Fig. 4.3 (for March-April only). While the seasonality described above holds true for most years, there are clear exceptions. From Fig. 4.1, it can be seen that the rarely occurring eITCZ state dominates from January-May in 1983 and 1998. Both were strong east Pacific El Nino years. In some years, such as 1989, 1999, 2000, 2006 and 2009, the sITCZ state is frequently present in March-April while in other years, such as 1980-83, 1993, 2003-05, 2007-08, 2010-12 it does not occur at all. In some years such as 1980, 1991, and 2003 are dominated by nITCZ throughout the year while in 1999, 2000, and 2009 the number of nITCZ cases was below 10 days in March and April, and the dITCZ, sITCZ, and aITCZ states are seen more frequently. Other years, such as 2001, 2004, and 2009 are dominated by dITCZ state in March and April. Some years have very high variability of ITCZ state in March-April, such as 2000, while other years have very little, such as 2003, which is dominated by nITCZ.

In addition to variability in March and April, Fig. 4.1 also shows interannual variability in the summer and fall season. While most summer and fall seasons are dominated by the nITCZ state, several years show slightly more variability. In 1989-1992 there was an increased frequency of sITCZ cases and in 2010-2012 an unusually high number of dITCZ cases occur.

This initial look at the distribution of ITCZ states confirms that the instantaneous double ITCZ is occurring frequently in March-April during most years. During this time, especially in
Figure 4.2. For each month the average fraction of time spent in each ITCZ state is shown. The equatorial (eITCZ) state only occurs frequently in 1997/1998 and 1982/1983 and is not shown, as it does not represent the typical distribution of ITCZ states in most years. The average distribution of ITCZ states throughout the year is quantified indicating more variability in ITCZ state during January-April and the dominance of the nITCZ state in May-Nov.

Figure 4.3. The number of days spent in each state during March-April for each year. The top panel shows years 1980-1995 while the bottom panel shows years 1996-2012. Large differences in the March-April state distribution between years is evident.
March, the sITCZ and aITCZ states are also frequently present. Specifically, the dITCZ is present 34% of the time, the sITCZ is present 8% of the time, the aITCZ state is present 12% of the time and the nITCZ state is present 39% of the time in March and April. While only frequently present in 1983 and 1998, the eITCZ state occurs 76-96% of the time during these years in March and April. The remainder of this paper will focus on these two months and describe conditions in the tropical east Pacific during each ITCZ state.

4.3.2 Composites of ITCZ states in March-April

Precipitation fields are frequently used to depict the time mean ITCZ both in observations and model output. Using our data we can make composites of the time mean of different ITCZ states in terms of IR temperature or cloud top temperature as well as other independent observations such as precipitation. Here we show March-April composites of cloud top temperature and GPCP precipitation rate for different ITCZ states (Fig. 4.4). The GPCP product spans only a subset of the time period for which ITCZ states are available (1997-2012 vs. 1980-2012), however the distribution of states during the shorter time periods is representative of the entire time period (not shown). We also made composites of TRMM precipitation (Fig. 4.5) and found that the spatial distribution of precipitation in the two datasets is similar, although GPCP has coarser spatial resolution and tends to estimate somewhat lower rain rates than TRMM. Here we focus on GPCP precipitation because it includes one of the two east Pacific El Niño events when the eITCZ state dominates.

Composites of IR temperature and precipitation by ITCZ state (Fig. 4.4) show the unique cloud and precipitation pattern associated with each ITCZ state. Although we focus on March-
Figure 4.4. Composites of daily GridSat IR temperature (K) and GPCP precipitation rate (mm/day). The top row shows composites of daily IR temperature during all days in March-April (4.4a) and all days in June-July (4.4b). The remaining rows on the left show composites of IR temperature by ITCZ state during March-April (1980-2012) and on the right show composites of GPCP precipitation rate by ITCZ state during March-April (1997-2012). Panel titles indicate the ITCZ state and the number of days included in each composite.
April here, typically the east Pacific ITCZ is most active in June-July (Bain et al. 2011) when it is almost exclusively located north of the equator (also shown in Fig. 4.2). For context, the June-July climatology in IR temperatures is shown in Fig. 4.4b. The nITCZ dominates during these months as is evident by the clearly defined deep cloud band in the northern hemisphere. This is compared to the March-April IR temperature climatology, shown in Fig. 4.4a. In March-April the time mean cloud band is shallower with a secondary minimum in cloud top temperature south of the equator, indicating a mixture of ITCZ states occurring during these months.

The June-July IR climatology has a similar pattern to the March-April nITCZ composite (Fig. 4.4e) although, the deepest convection is located in the far east Pacific in June-July whereas in March-April it is located further west.

**Figure 4.5.** Composites of daily TRMM precipitation rate (mm/day) by ITCZ state during March-April (1999-2012). The eITCZ state is not shown because few eITCZ days occur from 1999-2012. Panel titles indicate the ITCZ state and the number of days included in each composite.
As discussed above and indicated by the number of days in the figure titles to Fig. 4.4, the nITCZ is the dominant state throughout the year including March-April. Distinct cloud and precipitation bands occur in the northern hemisphere and are absent in the southern hemisphere (Fig. 4.4e-f). Even though there are fewer sITCZ days, the opposite general pattern is clear in the sITCZ composites: well defined cloud bands in the southern hemisphere and little cloud and precipitation in the northern hemisphere (Fig. 4.4g-h).

We averaged the ITCZ-state composite fields in longitude over 90°W-130°W and in Fig. 4.6 we show the meridional profiles for different ITCZ states. This longitudinal range is limited toward the west, but by excluding the far western part of the domain we avoid influence from the SPCZ. In addition to IR temperature (Fig. 4.6a) and precipitation (Fig. 4.6b) we also computed the composite \( \omega \) of the vertical velocity (\( \omega \)) at 850 hPa from ERA Interim reanalysis (Fig. 4.6c). Dynamical fields are not available from satellite observations and the reanalysis fields, while not as reliable as observations, can provide additional valuable insight. In general the three independent fields are consistent and the ITCZ states are clearly displayed in each, although the field of \( \omega \) is representative of only one level (850 hPa) whereas one can argue that both precipitation and cloud top temperature represent more vertically integrated quantities. There is less difference in the value of \( \omega \) between different composites than in value of precipitation and IR temperature. The latitude and value of maximum precipitation, vertical velocity, and minimum IR temperature in the longitudinal averages of the different composites are summarized in Table 4.1.
**Figure 4.6.** Meridional profiles from 15°S – 15°N of a) IR temperature (K), b) GPCP precipitation rate (mm/day), c) ERA-Interim vertical velocity ($\omega$) at 850 hPa (Pa/s), and d) TRMM precipitation rate (mm/day). To calculate the meridional profiles composites of IR temperature, precipitation rate and $\omega$ by ITCZ state are averaged between 90°W - 130°W. The datasets are available during different years, indicated in the panel titles. Table 4.1 compliments this figure, quantifying the latitude and value of the peaks in the fields shown.

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**Table 4.1.** Latitude and value of minimum IR temperature, maximum TRMM and GPCP precipitation rate, SST, and vertical velocity based on meridional profiles of composites by ITCZ state averaged between 90°W – 130°W. Values for both the northern hemisphere and southern hemisphere shown, indicated by column headings N and S respectively.
Figure 4.6 shows that the meridional profile of the sITCZ state has slightly higher rainfall rates, cooler IR temperatures and stronger vertical velocity than the nITCZ and dITCZ states in the longitudinal average. During the dITCZ state horizontally elongated cloud and precipitation bands are present on both sides of the equator at the same time. The dITCZ composite shows warmer cloud top temperatures of the cloud bands and therefore lower clouds when compared to the nITCZ state and sITCZ state (Fig. 4.4c-d). Figure 4.6b shows that peak precipitation is also lower during dITCZ cases compared to nITCZ cases and sITCZ cases. The latitudinal distribution of rainfall, deep clouds and strong vertical velocity during dITCZ days occurs over a narrower latitudinal range and the peak rainfall occurs closer to the equator when compared to rainfall during nITCZ days or sITCZ days (Table 4.1).

During the aITCZ state only isolated convection takes place in the east Pacific (Fig. 4.4k-l). Interestingly, the SPCZ is particularly active during the aITCZ state. This will be discussed further in Section 4.5.

The IR temperature and GPCP composites during the eITCZ state (Fig. 4.4i-j) show a wide cloud band just south of the equator in the central Pacific and directly over the equator in the eastern Pacific. IR temperatures are quite cold in eITCZ composites indicating widespread deep convection. In past studies such as Gu et al. (2005) and Zhang (2001) this signature was noted in monthly means during El Niño years. The central Pacific cloud band south of the equator is associated with the SPCZ, which migrates equatorward and takes on a more horizontal orientation during strong El Niño years (Haffke and Magnusdottir 2013; Vincent et al. 2011; Folland et al. 2002).

To summarize, each ITCZ state has a unique cloud and precipitation pattern associated with it. While it is not surprising that the aITCZ and nITCZ states, for example, have quite
different cloud, precipitation, and vertical velocity profiles, other results are more intriguing. One might expect the northern hemisphere ITCZ in March-April to have the same characteristics whether it is classified as a nITCZ state or as a dITCZ state, but this is not the case. The northern branch of the dITCZ is different from the nITCZ in terms of location and intensity (rain rate and IR temperature) indicating that different conditions are present during the dITCZ state. It is also possible that the simultaneous presence of the ITCZ in the southern hemisphere impacts the northern branch of the dITCZ causing it to be less intense and located closer to the equator.

4.4 Conditions during ITCZ states

4.4.1 SST associated with ITCZ states

Past studies have indicated that the underlying SST distribution is key to controlling the occurrence of the double ITCZ in the east Pacific on monthly time scales (Zhang 2001; Halpern and Hung 2001; Gu et al. 2005; and Masunaga and L’Ecuyer 2010). To see if the same is true for daily ITCZ states, we constructed composites of SST based on the ITCZ state. Composites of daily SST anomalies for the ITCZ states are shown in Fig. 4.7 where the anomalies are deviations from the March-April SST climatology. Fig. 4.7 shows that the SST varies by less than 1°C throughout the east Pacific between ITCZ states, except during the eITCZ state (Fig 4.7d). During the eITCZ state warm SST anomalies are present throughout the equatorial Pacific. During the dITCZ state, much of the equatorial central and east Pacific has cool SST. Cool SST anomalies are even stronger and more extensive in area during sITCZ cases, especially at and north of the equator (Fig. 4.7c). SST during nITCZ cases (Fig. 4.7b) is characterized by warmer
than normal SST in the western tropical Pacific and cooler than normal SST in the equatorial east Pacific and south of the equator. In general the east Pacific cold tongue region has small temperature anomalies associated with the instantaneous ITCZ states.

**Figure 4.7.** Composites of daily SST (°C) anomalies by ITCZ state in March-April (1982-2012). Values are only plotted where statistically significant based on a Student’s t-test with a critical level of 0.05. Panel title indicates ITCZ state and the number of days included in the composite.
Meridional profiles of 90°W – 130°W longitudinal averages of SST in each state, as well as the latitudinal derivative of the SST profiles are shown in Fig. 4.8. Aside from the eITCZ composite, the equatorial cold tongue is quite similar between all ITCZ states, varying by less than 0.5°C on average. Temperatures at the equator are coolest, on average, during sITCZ states (see also Fig. 4.7c). The only statistically significant differences in mean SST between states occur north of 2.6°N. This suggests that while the equatorial cold tongue SST is important for developing the mean double ITCZ on monthly time scales (Zhang 2001; Halpern and Hung 2001; Gu et al. 2005; and Masunaga and L’Ecuyer 2010), the occurrence of an instantaneous double ITCZ is less sensitive to this value. Similarly, aside from the eITCZ composites, the mean SST in the southern hemisphere is quite consistent between different ITCZ states. The largest difference in SST between the different states is in the northern hemisphere where, on average, a spread in average SST is present between 2.5°N and 13°N.

Gu et al. (2005) found in monthly mean data that during the double ITCZ, maximum rainfall is located poleward of the maximum SST while Lietzke et al. (2001) found that maximum rainfall in the monthly mean double ITCZ is located equatorward of the maximum SST. Gu et al (2005) attribute this to differences in the data set used (TRMM versus Microwave Sounding Unit derived precipitation). Results here indicate that the relationship between the latitude of maximum SST, maximum rainfall and minimum IR temperature is slightly more complicated and depends on the hemisphere being described (Table 4.1). Maximum rainfall and deep convection in the dITCZ are located equatorward of the maximum SST in the northern hemisphere and poleward of the maximum SST in the southern hemisphere. Furthermore, maximum SST is located closer to the equator during dITCZ cases compared to nITCZ or sITCZ cases, but the largest difference occurs between the southern and northern hemisphere, regardless
of state. Maximum SST is located around 2° closer to the equator in the southern hemisphere. This difference between hemispheres is minimized or nonexistent when comparing precipitation rate or IR temperature. While the difference in the location of maximum SST and maximum rainfall or IR temperature may be due to the datasets used, it could also indicate a lack of a simple relationship between SST and ITCZ position in the east Pacific on this time scale.

Note that although the highest SST is found in the northern hemisphere, the same is not true for precipitation rate, again pointing to a disconnect between ITCZ activity and SST.
amplitude. Even during the sITCZ state when the highest precipitation rates are found in the southern hemisphere, SST is higher in the northern hemisphere. Gu et al. (2005) also found that as long as the SST was above a certain threshold value, increasing SST did not cause increasing precipitation. The meridional gradient of SST is compared between states and in Fig. 4.8b and is found to be very similar except for the eITCZ.

4.4.2 Large-scale circulation associated with the ITCZ states

Small differences in SST patterns between ITCZ states, especially in the southern hemisphere, suggest that atmospheric dynamics may play a dominant role in determining the states. To assess the large-scale atmospheric circulation associated with each state, composites of daily anomalies of streamfunction ($\psi$) and velocity potential ($\chi$) are computed using the following method. Daily $\psi$ and $\chi$ are calculated at 850 hPa and 200 hPa using the daily averaged horizontal wind field from ERA Interim. The daily values were averaged over all years then we apply a 15-day running average to create a climatology. We use the climatology to compute daily $\psi$ and $\chi$ anomaly fields. Composites of the anomalies are then created based on ITCZ state during March-April, providing a global circulation pattern associated with each state at both levels.

After an initial look at the composites, it was clear that anomalies for the eITCZ state were much larger than for the other states (Fig. 4.9g-h), and the impact of this state on the climatology was overwhelming. We computed the daily $\psi$ and $\chi$ anomalies again, this time from a climatology in which days belonging to the eITCZ state were excluded. Composite anomalies from this second method are shown for the 850 hPa fields in Fig. 4.9 for the dITCZ, nITCZ,
Figure 4.9. Composites of daily $\psi$ and $\chi$ anomalies by ITCZ state at 850 hPa during March-April are shown in solid and dashed contours. Solid contours indicate positive anomalies and dashed contours indicate negative anomalies. Daily $\psi$ and $\chi$ are calculated using ERA-Interim horizontal wind fields. For composites of all states except the eITCZ state, anomalies are calculated from a climatology based on all days excluding eITCZ state days. For composites of the eITCZ state, anomalies are calculated from a climatology including all days. Shading indicates statistically significant values based on a Student’s t-test with a critical value of 0.05. Panel titles indicate ITCZ state and the number of days included in the composite.
Figure 4.10. Composites of daily $\psi$ and $\chi$ anomalies by ITCZ state at 200 hPa are shown in solid and dashed contours. Solid contours indicate positive anomalies and dashed contours indicate negative anomalies. Daily $\psi$ and $\chi$ are calculated using ERA-Interim horizontal wind fields. For composites of all states except the eITCZ state, anomalies are calculated from a climatology based on all days excluding eITCZ state days. For composites of the eITCZ state, anomalies are calculated from a climatology including all days. Shading indicates statistically significant values based on a Student’s t-test with a critical value of 0.05. Panel titles indicate ITCZ state and the number of days included in the composite.
sITCZ, and aITCZ states. The $\psi$ and $\chi$-anomaly composites for the eITCZ state were computed using the original method (all the data). Figure 4.9 only shows anomalies that are statistically significant based on two-sided t-test with a critical significance value of 0.05. We found that the 850 hPa and 200 hPa $\psi$ and $\chi$ generally complimented one another. The 850 hPa level is shown in Fig. 4.9 and the 200 hPa level is shown in Fig 4.10.

Distinct $\psi$ and $\chi$ anomaly patterns emerge for each ITCZ state. The sITCZ and nITCZ states have opposite patterns in terms of $\psi$, particularly at upper levels (Fig. 4.10). During the nITCZ (sITCZ) state, upper level westerlies are weaker (stronger) at the equator and stronger (weaker) in the subtropics. In the case of the sITCZ state the circulation pattern at 850 hPa shows enhanced anticyclonic flow on both sides of the equator in the Pacific indicating enhanced surface easterlies and, in combination with upper level flows, an enhancement of the Walker circulation. For the nITCZ composite, the 850 hPa anomalies are weaker but suggest the opposite, a weakening of the easterly trade winds. The enhancement of the Walker circulation during sITCZ state is further supported by the $\chi$ pattern where convergence at upper levels and divergence at 850 hPa suggests suppressed convection in the east Pacific while conditions for enhanced convection exist over the Maritime Continent. At 850 hPa in the east Pacific the divergence is located north of the equator, which is expected given that there is no northern hemisphere ITCZ during the sITCZ state. During the nITCZ state at 850 hPa the $\chi$ composite indicates divergence south of the equator, also expected since there is no ITCZ in the southern hemisphere during nITCZ state.

While the circulation patterns for the nITCZ and sITCZ state generally indicate opposite circulation anomalies, the dITCZ state has a circulation pattern that is quite different. The $\chi$ anomalies (Fig. 4.9b) indicate a clear pattern of enhanced convection over the east Pacific, both
north and south of the equator, accompanied by suppressed convection over Africa and the Indian Ocean. In fact, this is the only state where the $\chi$ field suggests that convection should be enhanced in the east Pacific, and the maximum $\chi$ anomaly lies quite close to the equator. This is consistent with the equatorward shift of the cloud and precipitation bands associated with the double ITCZ compared to their location for the nITCZ and sITCZ states. The $\psi$ anomalies during the dITCZ (Fig. 4.9a) are rather small, although significant, and do not indicate a clear pattern.

During the aITCZ state at 850 hPa there is divergence north of the equator in the central Pacific and convergence over South America. In the region of the SPCZ the $\psi$ anomalies during the aITCZ state resemble those during the eITCZ state, although considerably weaker in amplitude. During the aITCZ case, SPCZ activity is enhanced and shifted equatorward and eastward, similar to what happens during El Niño. Velocity potential patterns, particularly at 200 hPa, indicate suppressed convection north of the equator in the central to east Pacific, and enhanced convection south of the equator in the central Pacific, near the SPCZ.

The eITCZ state has strong $\psi$ and $\chi$ anomaly patterns at both levels that are quite different from the other states and largely resemble the circulation patterns seen during strong El Niño events. Velocity potential anomalies indicate enhanced strong convection in the east Pacific indicated by strong negative (positive) anomalies at 200 hPa (850 hPa) and a weakening of the Pacific Walker circulation.
4.5 Connection to the SPCZ

Enhanced SPCZ activity was apparent during the aITCZ state in IR and rainfall composites (Fig. 4.4k-l). Streamfunction anomalies in Fig. 4.9j and 4.10j are consistent and suggest that when the east Pacific ITCZ is absent, convergence may be enhanced in the SPCZ. To further explore the potential connection between the southern hemisphere west to central Pacific and eastern Pacific, a data set of binary SPCZ labels outlining the location of the SPCZ every 3 hours from 1980-2011 (Haffke and Magnusdottir 2013) is used to examine SPCZ activity during different east Pacific ITCZ states. Here we focus on March only. Additionally, times identified as eITCZ have been removed from this analysis because they overwhelmed SPCZ anomalies during the other east Pacific ITCZ states. Figure 4.11 shows composites of SPCZ anomalies by ITCZ state for March. SPCZ anomalies are computed by subtracting the composite of SPCZ activity during all days in March from the composite of SPCZ activity during each ITCZ state in March.

The SPCZ is suppressed during the dITCZ state and even more so during the sITCZ state, indicated by negative fraction of time present anomalies along most of the SPCZ (Fig. 4.11a and 4.11c). During nITCZ events (Fig. 4.11b) the SPCZ looks more like climatology (not shown) but small negative anomalies are found equatorward and to the east of the typical SPCZ location. During the aITCZ state, SPCZ activity is enhanced, especially on the northeastern margin and slightly decreased on the southwest margin, indicating that SPCZ activity shifts eastward (Fig. 4.11d). Positive (negative) χ anomalies are co-located with the increased SPCZ activity at 850 hPa (200 hPa) indicating increased surface convergence and convection.
Global maps of ERA Interim precipitation in March-April highlight the changes in SPCZ activity as well as global patterns associated with each ITCZ state (Fig. 4.12). During the dITCZ state convection in the east Pacific takes place on both sides of the equator, although the precipitation rate is higher in the northern hemisphere. In the western Pacific, precipitation is strong in the northern hemisphere but rather weak in the SPCZ region. When the ITCZ is suppressed (aITCZ state), precipitation is enhanced in the SPCZ while suppressed in the northern hemisphere western Pacific. During the sITCZ state the SPCZ seems to disappear all together. Although the circulation during the sITCZ somewhat resembles La Nina years when the Walker circulation is enhanced, the SPCZ does not show changes expected during a La Nina state (a shift poleward and westward).

**Figure 4.11.** Composites of SPCZ anomalies by ITCZ state during March. SPCZ anomalies are calculated using SPCZ labels created by Haffke and Magnusdottir 2013 and are calculated from March climatology excluding eITCZ state days. Anomalies are shown in units of fraction of time present only shown where statistically significant based on a Student’s t-test with a critical value of 0.05. Panel title indicates the ITCZ state and the number of days included in the composite.
4.6 Concluding Remarks

The east Pacific ITCZ has been organized into five different states: nITCZ, sITCZ, dITCZ, aITCZ, and eITCZ based on clouds band configurations. Three-hourly GridSat IR satellite images are examined using an automatic statistical model to determine the east Pacific ITCZ state from 1980-2012. Figure 4.1 presents the distribution of ITCZ through time. We find that the nITCZ occurs most frequently in all months and dominates in the summer and fall when ITCZ state variability is low. Variability is high in the boreal spring when all states occur.
frequently, especially in March and April. Specifically the dITCZ state occurs 34% of the time, the sITCZ occurs 8% of the time, the aITCZ state occurs 12% of the time and the nITCZ state occurs 39% of the time on average, in March and April. To the best of our knowledge, this is the first time the state of the ITCZ has been assessed on daily and sub-daily time scales and the first look at the frequency of the instantaneous double ITCZ in a long-term data set.

Composites of IR temperature, precipitation and $\omega$ based on ITCZ state during March-April highlight the structure of the cloud and precipitation bands associated with each state. The three independent fields are consistent and show that the dITCZ state tends to have shallower convection and lower rain rates compared to the sITCZ and nITCZ states. This is consistent with the idea of competition between hemispheres in monthly mean rainfall presented in Gu et al. 2005. In addition the precipitation and cloud bands tend to be located closer to the equator during the dITCZ state compared to the nITCZ or sITCZ state.

We find that SST anomalies are large during the eITCZ state, and to a lesser degree, the sITCZ state. However, small SST anomalies occur during the dITCZ, nITCZ, and aITCZ states indicating only small differences in the underlying SST pattern. The small difference in SST, particularly between the nITCZ, dITCZ, and aITCZ state suggest that SST is not the dominant factor controlling the ITCZ state on the daily time scale, at least for these three states. In contrast, we find that the large-scale atmospheric circulation pattern for each ITCZ state is quite unique. Composites of daily $\chi$ anomalies by ITCZ state show patterns of suppressed and enhanced convection in the east Pacific that are consistent with cloud band and precipitation activity. During the nITCZ state a region of surface divergence indicating suppressed convection is found in the southern hemisphere while during the sITCZ state surface divergence is found in the northern hemisphere. Interestingly, the dITCZ state is the only state in which the $\chi$ composite
indicates anomalous surface convergence indicating enhanced convection in the eastern Pacific. The convergence at 850 hPa is located directly over the equator, consistent with the cloud and precipitation bands being located closer to the equator during the dITCZ state compared to the nITCZ and sITCZ states.

We note a clear connection between activity in the east Pacific ITCZ, particularly in the southern hemisphere, and the SPCZ in the west-central Pacific. When the east Pacific ITCZ is absent the SPCZ is enhanced, with anomalously high activity equatorward of the typical mean position. When the east Pacific ITCZ is active, particularly during the sITCZ state, the SPCZ is suppressed. This could represent changes in the Walker circulation, which connects the western and eastern parts of the Pacific. The large scale-circulation, shown by $\chi$ and $\psi$ anomalies, also indicate this connection.

The dataset containing the classification of east Pacific ITCZ states contains an abundance of information that was not fully explored here. For example, cases of anomalous sITCZ states during the summers of 1989-1991, or the lack of variability in the boreal spring in 1980, 1991, and 2003 provide interesting case studies of ITCZ behavior that was beyond the scope of this study.

The dataset of east Pacific ITCZ state could be a valuable tool for assessing global climate models. Currently, it is unknown if climate models produce a distribution of states similar to what we find in observations. Furthermore, based on these results it may be that the eITCZ and sITCZ states are more influenced by the underlying SST while the distinction between the aITCZ, dITCZ and nITCZ is determined based on atmospheric dynamics.
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Chapter 5

Conclusions

Most of the current understanding of the SPCZ and the east Pacific double ITCZ comes from monthly mean observations of clouds, precipitation, or surface winds. Previous to this work, these convergence zones have not been identified in instantaneous, long-term data due to the cumbersome nature of visual identification of the ITCZ. Automatic thresholding techniques do not do justice to the dynamic and varied characteristics of the elongated envelopes of convection that describes the ITCZ in cloud cover. Recently, more sophisticated statistical models have been developed using machine learning techniques to automatically identify these features in high temporal resolution data. This work uses these statistical models to automatically determine the presence of the SPCZ and the state of the east Pacific ITCZ in 3-hourly IR images, for the first time. The identification of the SPCZ and ITCZ at this relatively high temporal
resolution allows for a unique look at the variability and mean state of these two prominent tropical convection zones.

Chapters 2 and 3 describe how the instantaneous labels of the SPCZ can be used to better understand SPCZ climatology in terms of location and to quantify the variability of the SPCZ on time scales ranging from diurnal to interannual. The work in Chapter 2 quantifies the interannual, intraseasonal variability as well as the seasonal evolution of SPCZ location and extent from 1980-2012, Nov-Apr. Results suggest that two main axis lines describe the orientation of the SPCZ, one representing the more subtropical section in the southeast and another representing the tropical section in the northwest. The SPCZ is more consistent and well defined in the tropics where the position and tilt align with the SST gradient. In Dec. - Feb. the SPCZ is frequently present in the tropics, 50-70% of the time, and SPCZ area in the tropics peaks in late January. In the subtropics, the SPCZ is most active early in the season (Nov. – Dec.), which suggests that studies that only consider the height of the SPCZ active season, which is typically defined as Dec. – Feb., miss this subtropical activity in their analysis. The latitudinal tilt in SPCZ presence is greater in the subtropics than the tilt of the warm SST pattern (Fig. 2.5).

In terms of interannual variability, the SPCZ shifts equatorward and eastward during El Niño years and poleward and westward during La Niña years, consistent with previous work (Folland et al. 2001; Vincent et al. 2011). However, previous studies did not have the means of examining the interannual variability in SPCZ area accompanying the shift in location. We find that despite the shifts in SPCZ location, there is no change in overall area associated with ENSO.

The MJO is found to influence SPCZ location and extent on the intraseasonal time scale. The SPCZ labels allow for composites of SPCZ location by MJO state to be computed using daily data. The detailed spatial pattern of SPCZ presence during each phase of the MJO
indicates the exact locations where SPCZ activity is enhanced and suppressed in each phase. Regions of enhanced SPCZ activity progress eastward with the propagation of MJO, influencing SPCZ activity as far as 30°S.

In Chapter 3, I quantify the diurnal cycle of SPCZ area, mean IR temperature, and cloud height. This work is unique in that it is the first study to look at SPCZ area without directly thresholding IR temperature. This allows for an analysis of SPCZ area and an analysis of cloud distribution within the SPCZ and therefore offers a unique perspective on the diurnal cycle of the SPCZ. The SPCZ reaches maximum area in the late afternoon between 1500-1800 LST, when it also has the maximum fractional coverage by mid-level clouds. By local midnight, low-level clouds peak in abundance while mid-level clouds are decreasing. In the early morning hours (~0600 LST) deep convection peaks, just before the minimum SPCZ area occurs. The morning peak in deep clouds dominates the diurnal cycle of mean IR temperature in the tropical part of the SPCZ, while the afternoon peak in mid-level clouds dominates the diurnal cycle of mean IR in the subtropical part of the SPCZ. The timing of the diurnal cycle is consistent throughout the year in the tropics, especially in terms of SPCZ area. More variability between the beginning of the SPCZ active season, height of the season, and end of the season are seen in the central part of the SPCZ, where it transitions from a more tropical based cloud band to a more subtropical-based cloud band. ENSO and the MJO have a similar effect on the diurnal cycle. When the MJO or ENSO cause the SPCZ to shift closer to the equator, the diurnal cycle tends to favor the morning minimum in IR temperature associated with high clouds. When the MJO or ENSO cause the SPCZ to shift poleward, the diurnal cycle favors the afternoon minimum in IR temperature associated with mid-level clouds.
Chapter 4 describes a different statistical model that determines the instantaneous state of the east Pacific ITCZ. The model was designed to determine the state of the east Pacific ITCZ based on the location of the ITCZ: northern hemisphere only (nITCZ), southern hemisphere only (sITCZ), both hemispheres simultaneously (dITCZ), or along the equator (eITCZ). A fifth state describes the east Pacific when no convection band is present (aITCZ). The model classifies the ITCZ state year round from 1980-2012.

We find that the nITCZ occurs most frequently in all months and dominates in the summer and fall when ITCZ state variability is low. Variability is high in the boreal spring when all states occur frequently, especially in March and April. Specifically, the dITCZ state occurs 34% of the time, the sITCZ occurs 8% of the time, the aITCZ state occurs 12% of the time and the nITCZ state occurs 39% of the time on average in March and April. This is the first time the state of the ITCZ has been assessed on daily and sub-daily time scales and the first look at the frequency of the instantaneous double ITCZ in a long-term data set.

The dITCZ state tends to be associated with shallower convection and lower rain rates compared to the sITCZ and nITCZ states. In addition, the precipitation and cloud bands tend to be located closer to the equator during the dITCZ state compared to the nITCZ or sITCZ states. By comparing composites of daily SST anomalies against daily atmospheric circulation anomalies (both based on ITCZ state), it is clear that each state has a unique atmospheric circulation associated with it while the SST patterns are quite similar, except during the eITCZ and sITCZ state when SST anomalies are large.

We note a clear connection between activity in the east Pacific ITCZ, particularly in the southern hemisphere, and the SPCZ in the west-central Pacific. When the east Pacific ITCZ is absent the SPCZ is enhanced, with anomalously high activity equatorward of the typical mean
position. When the east Pacific ITCZ is active, particularly during the sITCZ state, the SPCZ is suppressed.

The data sets of SPCZ presence and east Pacific ITCZ state created here contain more information than is presented in this dissertation and many interesting aspects of the datasets are left unexplored. The SPCZ labels could be a useful tool for exploring if there are any trends in SPCZ location, area, and overall activity, in terms of strength of convection over the past 30 years. The statistical model used to create the SPCZ labels is fast to run and new satellite data can be examined to continually update the SPCZ label dataset. In terms of the east Pacific ITCZ state, Fig 4.1 highlights the wealth of information contained in the data set. Many interesting patterns of variability, both interannual and seasonal, remain unexplored and I think several case studies would be interesting. For example, the high frequency of sITCZ states during the summer months of 1989-1991 could be further investigated. Other years of interest are 1980, 1991, 1995, and 2003 when the nITCZ state dominated during the boreal spring.

Additionally, because this study was limited to observations, little can be concluded about cause an effect. A modeling study would provide insight to the relative importance of the SST as opposed to the atmospheric large-scale circulation in determining the east Pacific ITCZ state.

Both datasets provide an excellent source of information for assessing current climate models. The statistical models described here could be run with climate model output (OLR, for example) as input and results could be compared for consistency with observations. It is largely unknown how well climate models produce daily variability of features such as the SPCZ or double ITCZ in the east Pacific. Understanding more about this could lead to better parameterizations and an improvement in our predictions. We know that models tend to have an
overactive double ITCZ in the boreal spring, and year round, but the distribution of ITCZ states in models is unknown on a daily time scale. Many questions remain, including the following: Do models always produce a double ITCZ in the boreal springtime or is it a combination of states, as seen in observations? Do climate models produce the same daily variability in terms of east Pacific ITCZ state in the boreal spring? How often is the instantaneous double ITCZ occurring in climate models? We find that the differences in the atmospheric circulation are larger than differences in SST for the nITCZ, dITCZ, and aITCZ. What does the atmospheric circulation and SST look like in states defined by climate model data? The SPCZ labels can play a similar role in west to central Pacific to assess if models are getting the location and variability of the SPCZ right, and perhaps more importantly, in what ways are they getting it wrong.

The automatic detection of instantaneous features in satellite data has proven to be a valuable venture. In the future similar techniques could be used in many other areas of atmospheric science and automatic detection will become increasingly necessary as data accumulates.
References


