EVALUATION OF PRECIPITATION DIURNAL VARIABILITY BY TRMM: CASE OF PAKISTAN'S 2010 INTENSE MONSOON

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ABSTRACT

This study examines the spatial and temporal distribution of the Asian pre-monsoon (AMJ) and monsoon (JAS) seasons in Pakistan over the intense flood year of 2010. This is completed using Tropical Rainfall Measuring Mission (TRMM) 3-hourly data with a spatial resolution of 0.25° x 0.25° and comparing the rain rates from 2010 with those from 2005-2009. For better examination, the rainfall data was divided into four categories: the pre-monsoon seasons of 2005-2009, the pre-monsoon season of 2010, the monsoon seasons of 2005-2009, and the monsoon season of 2010. Both the pre-monsoon and monsoon seasons of 2010 showed an increase in rain rates associated with anomalous atmospheric conditions. The only spatial difference exhibited in 2010 was an increase in the intensity of rainfall at slightly higher elevations than normal, which can be attributed to the increase of moisture content in the atmosphere. Otherwise, a majority of the precipitation occurred along the Himalayan foothills in the northeastern region of Pakistan. The temporal shift between pre-monsoon and monsoon seasons was enhanced in 2010, showing the shift from the deep convection associated with severe storms to the strong, wide convection associated the Mesoscale Convective Systems.

1. INTRODUCTION

Every summer, the Asian Monsoon brings heavy rainfall to South Asia. These heavy rains often produce severe flooding, which has devastating effects on both the people and economies of the countries affected. Some areas are more accustomed to heavy precipitation, while others, such as Pakistan, can be easily overwhelmed by a season with larger than normal amounts of rainfall. This occurred in the summer of 2010, cutting a path of destruction through the Indus River Valley which stretched from the Himalayas to the Arabian Sea. Anomalously heavy precipitation during late July and early August forced the Indus River from its banks, resulting in heavy casualties and the destruction of homes, bridges, roads, and power stations. By the end of August, 20% of Pakistan was submerged under the flood waters, there were close to 2,000 deaths, and almost 20 million people were in need of medical care, food, and shelter. The more than 40 billion dollars' worth of damage could have been decreased substantially had there been prior knowledge of, and experience with, the types of atmospheric conditions which were present at the time of the excessive rainfall (Webster et al. 2011).

Precipitation in Pakistan predominantly occurs in two seasons and can be heavily influenced by variations within the South Asian trough. Upper-level shortwave troughs provide rainfall in late winter to early spring, and the summer brings heavy monsoon rainfall to the East. The arrival of the monsoon season is triggered by the northwestward progression of the South Asian trough from the Bay of Bengal. The precipitation produced comprises 50-75% of Pakistan's annual total and is due to what Houze et al. (2011) refer to as "deep convective cells." These cells contain strong updrafts and occur over lower terrains on the boundary where moist air from the Arabian Sea encounters dry air from the Afghan Plateau. This region experiences some of the world's strongest, tallest, and most lightning-prone storms. Although powerful, these cells do not produce large quantities of rainfall, nor do they

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cover a wide area, due to a surrounding layer of dry air which forces them to grow vertically in the atmosphere. This prevents them from spreading into shallower storms associated with widespread stratiform precipitation. Storms associated with this second variety of precipitation form along the same convergence boundary and tend to be less intense, but commonly last longer and produce significant amounts of rainfall, similar to what was observed in the summer of 2010.

Houze et al. (2011) listed major differences in atmospheric circulations as the cause for the flooding in Pakistan over July and August of 2010. The trough commonly present over the Bay of Bengal propagated westward to preside over the Arabian Sea and an anomalous center of high pressure was located over the Tibetan Plateau. The close proximity of these synoptic features produced a very large pressure gradient, forcing southeasterly airflow deep into the Himalayas. The moisture content of the air was considerably increased due to warmer ocean temperatures, which served to increase the buoyancy of the air in the region. This moist, warm air was conveyed into higher elevations than is typically observed, creating a humid environment in which moisture-laden storms could grow. Without a surrounding layer of dry air to limit their width, the storms expanded into extensive areas of strong, stratiform precipitation centered in the northern, mountainous regions of Pakistan. The topography of this region is unaccustomed to heavy rainfall and, as a result, there were extensive areas of runoff which caused flooding.

Very important factors to consider when analyzing years of intense flooding events are regularly observed trends found in the temporal characteristics of rainfall. Chen et al (2012) defines the diurnal cycle as a response to solar radiation by the sea, land, and atmosphere which is convection, cloudiness, and rainfall. This cycle depends on the influences of outside factors such as the heating of land surfaces and the areas of convergence for land and sea breezes (Sorooshian et al. 2002). A study by Romatschke et al (2010) looks at diurnal variability over the entire region of South Asia in order to analyze the temporal aspects of various classifications of convection. The three categories defined in this research are deep convective cores, wide convective cores, and broad stratiform convection. Deep convective cores tend to occur between noon and midnight, due to a direct connection with land surface heating by solar radiation, and are produced by vigorous updrafts and strong convection which result in extremely tall convective cells. This is the same variety of convection which Houze et al. (2011) refers to as deep convective cells. Wide convective cores are generally found in strong Mesoscale Convective Systems (MCSs) which are described by Houze (2011) as a sequence of developing and decaying convective updrafts which group together, forming regions of widespread, stratiform precipitation. This type of convection has been occasionally observed to occur during the evening hours in the pre-monsoon season, but it primarily occurs during monsoon seasons and takes place between midnight and the early morning hours. The third type, broad stratiform convection, is found in weaker MCSs and, as a result, has a shorter stature than the other two types. This type of convection tends to occur around midday and is primarily located over oceans, although its width is extensive and can encompass coastal land surfaces as well.

The purpose of this paper is to explore how the diurnal variability of the monsoon season changed over Pakistan as a result of anomalous atmospheric circulations in 2010. To complete this analysis, data from the Tropical Rainfall Measuring Mission (TRMM) satellite is used. In research conducted by Islam et al. (2007), this satellite was found to accurately measure 97.36% of surface rainfall which occurred over Bangladesh. Additionally, they made the conclusion that the 3B42 product can more precisely detect tall, strong convective episodes which occur in the pre-monsoon seasons than the shorter, longer-lasting type of convection which occurs during the monsoon seasons. Similarly, Webster et al. (2011) notes that the TRMM satellite tends to overestimate rates of precipitation in the higher terrain of northern Pakistan, but is found to have far more accurate estimates over the country’s southern plains, displaying errors associated with drastic changes in topography.

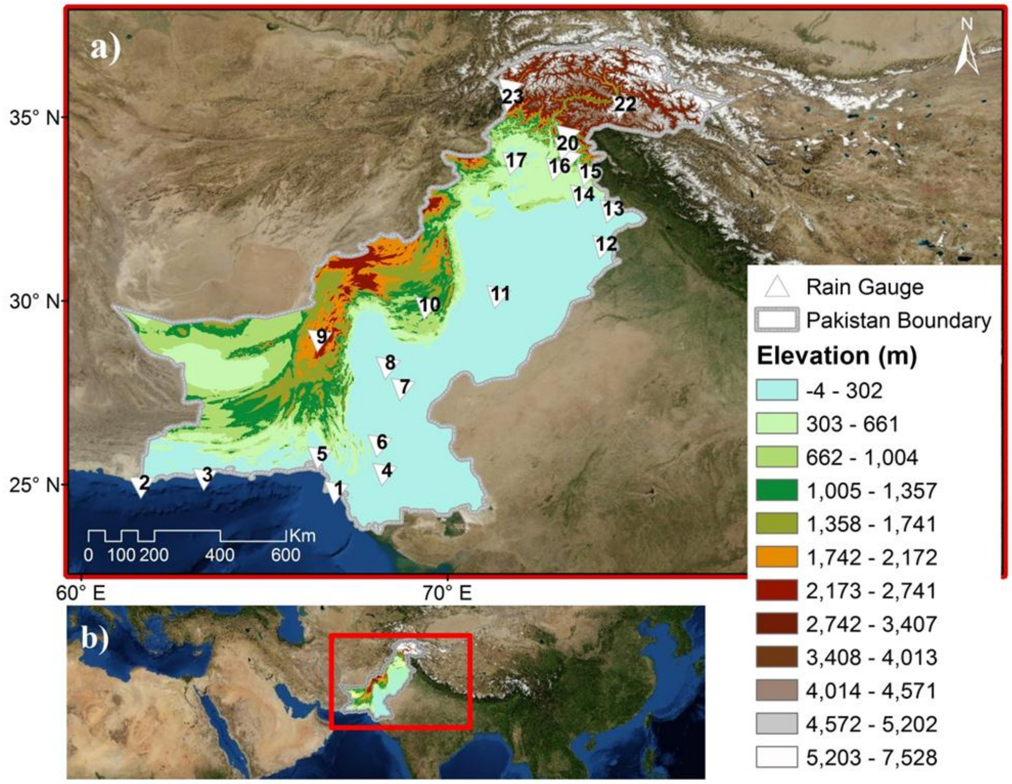

Figure 1. a) Map of Pakistan with topography (m) and the PMD stations (numbered), used to compare the TRMM V7 satellite precipitation product for 2005-2010 summer monsoon and pre monsoon season. b) Intense Monsoon region.

Station Number	Station Name	Elevation (m)	Latitude (°N)	Longitude (°E)
1	Karachi	22	24.89	67.05
2	Jiwani	56	25.04	61.74
3	Pasni	9	25.26	63.46
4	Hyderabad	28	25.38	68.36
5	Lasbella	87	25.83	66.58
6	Nawabshah	37	26.15	68.22
7	Rohri	60	27.69	68.85
8	Jacobabad	55	28.27	68.45
9	Kalat	2015	29.02	66.58
10	Barkhan	1372	29.89	69.52
11	Multan	121	30.19	71.46
12	Lahore	214	31.54	74.34
13	Sialkot	255	32.5	74.53
14	Jhelum	287	32.93	73.72
15	Kotli	614	33.52	73.9
16	Islamabad	508	33.66	73.06
17	Cherat	1250	33.82	71.88
18	Murree	1900	33.91	73.39
19	Garidopatta	813	34.13	73.37
20	Muzaffarabad	838	34.22	73.29
21	Balakot	995	34.55	73.35
22	Astore	2168	35.35	74.86
23	Drosh	1463	35.55	71.79
24	Chitral	1497	35.83	71.78

Table 1. A numbered list of the PMD rain gauge stations with their respective elevations and geographical coordinates.

2. DATA AND METHODS

Four primary studies were conducted to analyze the diurnal cycle of the Asian monsoon over Pakistan. The rain rate data used for these analyses was derived from the TRMM satellite over a 6 year period, from 2005-2010. The spatial resolution of the satellite data is 0.25° x 0.25° with a 3-hourly temporal resolution. The TRMM satellite covers an area of 50°N to 50°S and 180°W to 180°E. For the purpose of this research, the coverage area was restricted to the boundaries of Pakistan, which extends from approximately 23°N to 37°N and 60°E to 78°E. The algorithm for the 3B42 product was designed to produce adjusted, merged-infrared (IR) rain rates. Monthly IR calibration parameters are used to make adjustments to the merged-IR rain rates, which are composed through the use of datasets from multiple satellites. The final results of the algorithm are adjusted, gridded merged-IR rain rate estimates. Version 7 of this product is used for this research because it provides the most accurate precipitation estimates on a spatial scale. The transition from Version 6 to Version 7 occurred on June 30, 2011, implementing many changes, including additional satellites with a scheme for latitude-band calibration, a single, uniformly processed surface rainfall gauge analysis, and the addition of gauge relative weighting(http://pps.gsfc.nasa.gov/tsdis/Documents/3B42_3B43_doc.pdf).

For all of the analyses conducted, the 3-hourly rain rate data is divided into four separate categories: the pre-monsoon seasons from 2005-2009, the monsoon seasons from 2005-2009, the pre-monsoon season of 2010, and the monsoon season of 2010. The pre-monsoon season is defined as April, May, and June of each year and the monsoon season is defined as July, August, and September. The time span from 2005-2009 is representative of the average pre-monsoon and monsoon seasons so as to provide an accurate comparison with, and analysis of, the 2010 pre-monsoon and monsoon seasons.

The first analysis calculates the percent frequency of rainfall occurrence in 3-hour intervals for each grid cell overlaid onto Pakistan. The frequency is calculated for each category by adding up the number of days in which rainfall occurred, in and dividing that amount by the total number of days. The resulting numbers are converted into percentages so as to better represent the spatial aspects of the diurnal variability of the rainfall. For the second analysis, the rainfall rates for each 3-hour time period are added up over each season and then divided by the number of days in the season, producing averaged rainfall estimates. Images are then produced from these estimates in order to evaluate the diurnal variation of rainfall over the entire country, and to highlight any differences which occur over Pakistan in the 2010 season.

The third analysis involves the comparison of the average rain rate estimates with changes in elevation. In order to complete this analysis, several locations throughout Pakistan are chosen from a list of rain gauge stations provided by the Pakistan Meteorological Department (PMD), shown in Table 1. Average rates of rainfall are then assigned to each station by correlating the geographical positions of the stations with the equivalently located grid points on the images from the second analysis. The estimates at each location are then divided into two predetermined categories based on whether the precipitation occurred in the morning hours or the afternoon and evening hours. From there, each set of averages is compared to increasing elevation so as to evaluate topographical effects on the temporal aspects of the diurnal variations within each category.

For the fourth analysis, two stations are chosen from Table 1 in order to examine the diurnal variability of the averaged rain rates on an even smaller spatial scale. Stations 15 and 22 in Fig. 1, listed as Kotli and Astore, respectively are chosen based on the fluctuations exhibited in their daily rainfall patterns as seen in Figures 2, 3, and 4, and also their positions relative to major topographical features known to have strong influences on air flow. The purpose of this analysis is to further investigate the effects of landforms on convection type.

3. RESULTS

(a) Percent Frequency of Rainfall Occurrence

Spatial patterns of the diurnal cycle are vital to the understanding of how different types of convection within an intense season are caused. The first step to understanding the patterns in this research is to examine the images produced by computing the percent frequency of occurrence. Fig. 2 shows a latitude-longitude cross-section of

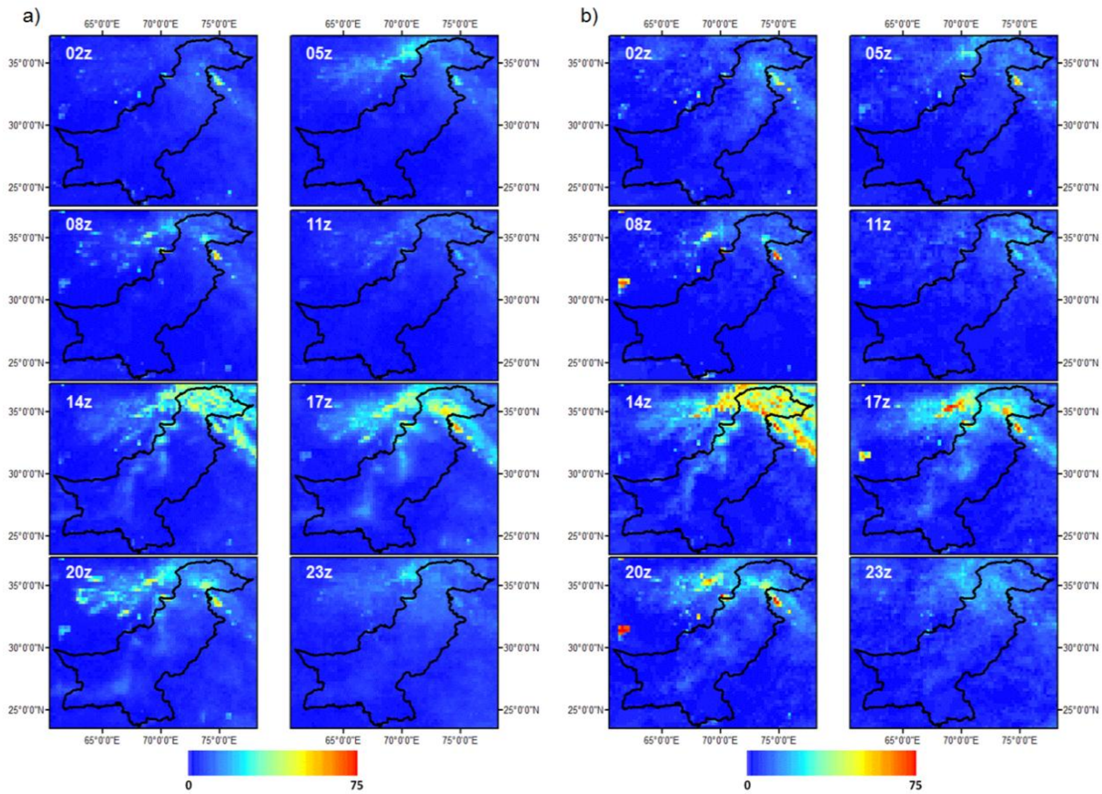

Figure 2. Diurnal variation of the percent frequency of occurrence at each grid point for the pre-Monsoon seasons of (a) 2005-2009 and (b) 2010.

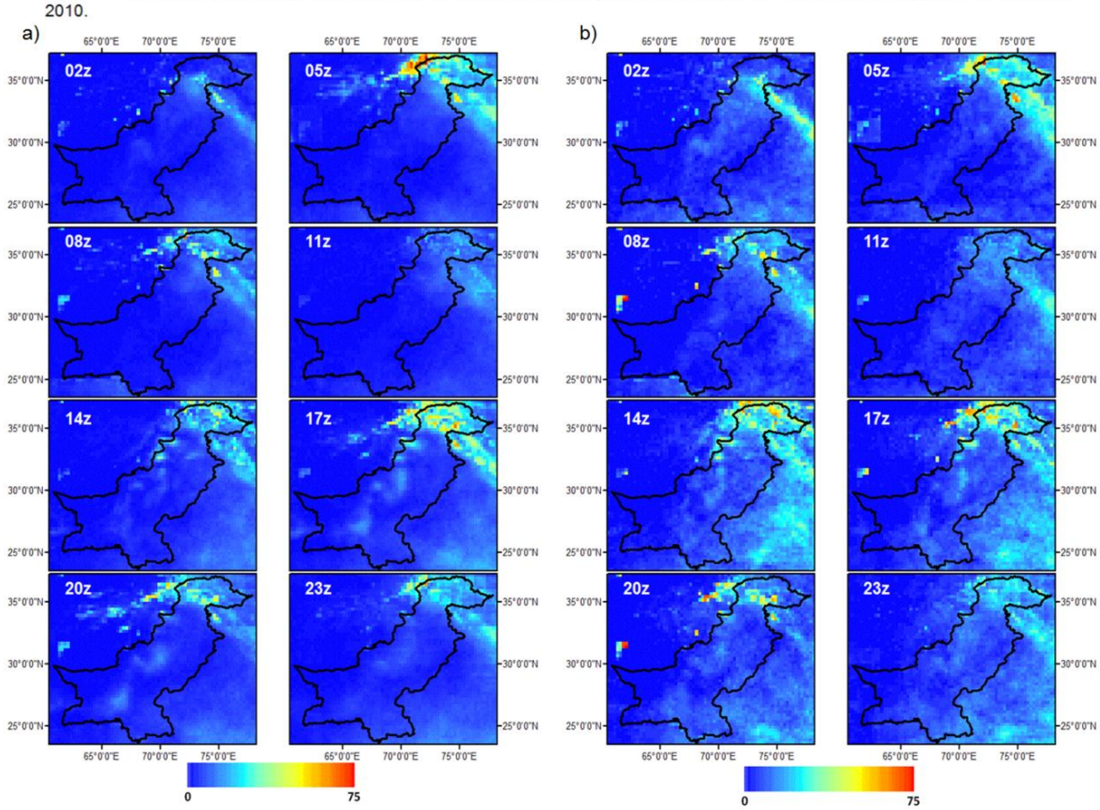

Figure 3. Diurnal variation of the percent frequency of occurrence at each grid point for the Monsoon seasons of (a) 2005-2009 and (b) 2010.

the occurrence of rainfall for the pre-monsoon seasons. Most of the precipitation events occur in the northeastern region of Pakistan, specifically among the foothills of the Himalayas. Additionally, this maximum occurrence of events takes place in the afternoon and evening hours around 14-17z with maximum percentages ranging from 47.5%-53.2% in 2005-2009 and from 60.4%-72.5% in 2010. Referring back to the research completed by Romatscke et al. (2010), a maximum of events later in the day could be closely correlated with deep convective core systems which are powered by the heating of the land surface. An increase of atmospheric moisture content in 2010 can be observed in Fig. 2b, which exhibits an increase in the number of rainfall events.

Fig. 3 shows the number of precipitation events which occurs in the monsoon seasons. Similar to the pre-monsoon images in Fig. 2, there is a peak in the number of rain events in the afternoon hours along the foothills of the Himalayas. The difference is that this peak is considerably smaller, especially around 14z. The 17z peak is noticeably smaller and of a wider spatial coverage in the monsoon seasons than in the pre-monsoon seasons with maximum values ranging from 50.9% t0 66.9% in 2005-2009 and from 61.9%-70.7% in 2010. The dominant peak of occurrences in the monsoon seasons ranges from 67.8 %-79% and takes place in the early morning hours, between 02-05z, which can be associated with the wide convective core systems Romatschke et al. (2010) describe in their research. Also, in Fig. 3b, there are more rainfall events over a majority of Pakistan, again showing an increase in the moisture content of the atmosphere.

(b) 3-Hourly Averaged Rainfall over Pakistan

In addition to evaluating the percentage of events which occur in each of the four categories, another more comprehensive method with which to examine the spatial characteristics of the diurnal cycle is through the analysis of average rates of rainfall. This is a more comprehensive approach because the area in which rain falls, and its intensity, can be identified. Knowledge of the quantity of rain which falls over a certain amount of time is vital to gaining a better understanding of circumstances which lead to severe floods. Fig. 4 shows a latitude-longitude cross-section of the 3-hourly averaged rain rates for the pre-monsoon seasons. As is exhibited in Fig. 2, these images show a peak, along the Himalayan foothills, occurring in the evening hours around 17z. The values for the 2005-2009 time period range from 0.29-0.34 mm/h. The intensity of the 2010 rainfall in this region is higher than that of the 2005-2009 pre-monsoon intensity, with values ranging between 0.26 and 0.32 mm/h. This afternoon peak in rainfall seems to be a result of systems with deep convective cores. Also, there is an additional area in Fig. 4b which shows a peak in rain rates that is not seen in Fig. 4a. This maximum, along with the increase in rain rate intensity closer to the Himalayas, supports the findings in the research by Houze (2010) that the atmosphere over Pakistan was more humid.

The images in Fig. 5 show the 3-hourly average rain rates for the monsoon seasons. Similar to the trend exhibited in Fig. 2 and 3, there is an evident maximum in the morning hours, but unlike the previous images, there is no second peak towards the evening hours. The average rain rates for the morning hours range from 0.48-0.55 mm/h in 2005-2009 and from 0.76-1.22 mm/h in 2010. This shows that the highest intensity of rainfall occurs in the morning hours of the monsoon seasons, around 05z, even though precipitation may occur throughout the day in various locations. The temporal shift exhibited by the precipitation patterns from the evening hours to the morning hours is representative of a change in the type of convection from deep convective cores to wide convective cores.

(c) Averaged Rainfall Estimates compared with Elevation

The position of a location relative to predominant topographical features determines what type of convection, and therefore precipitation, occurs. If a region is near to an ocean, it will be strongly affected by the shifts between sea breezes and land breezes. Similarly, a region near to mountainous terrain will be affected by various meteorological processes resulting from rapid changes in elevation. Pakistan is in a geographic region which experiences both types of phenomena. Figures 6 and 7 compare the temporal aspects of the average rain rates for the locations of the rain gauge sites in Table 1 with changes in elevation. Fig. 6 shows how the pre-monsoon rain rate averages change with elevation and time.

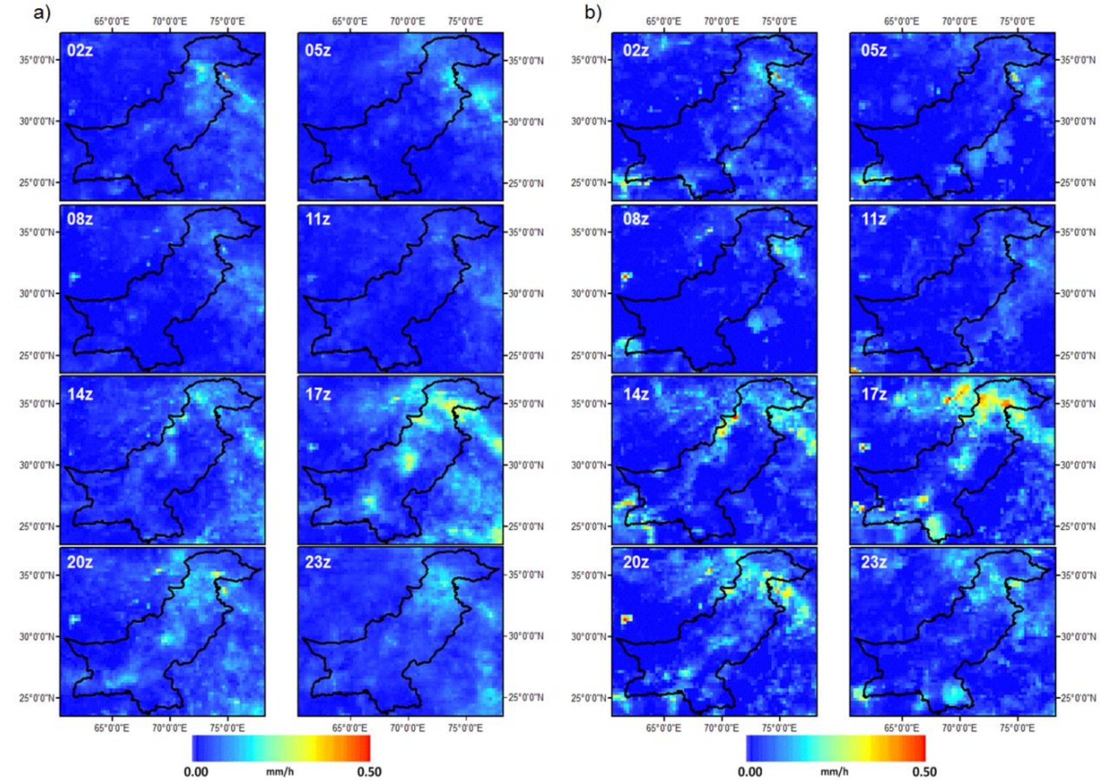

Figure 4. Averaged 3-hourly rain rate estimates (mm/h) calculated over the pre-Monsoon seasons (a) of 2005-2009 and (b) 2010.

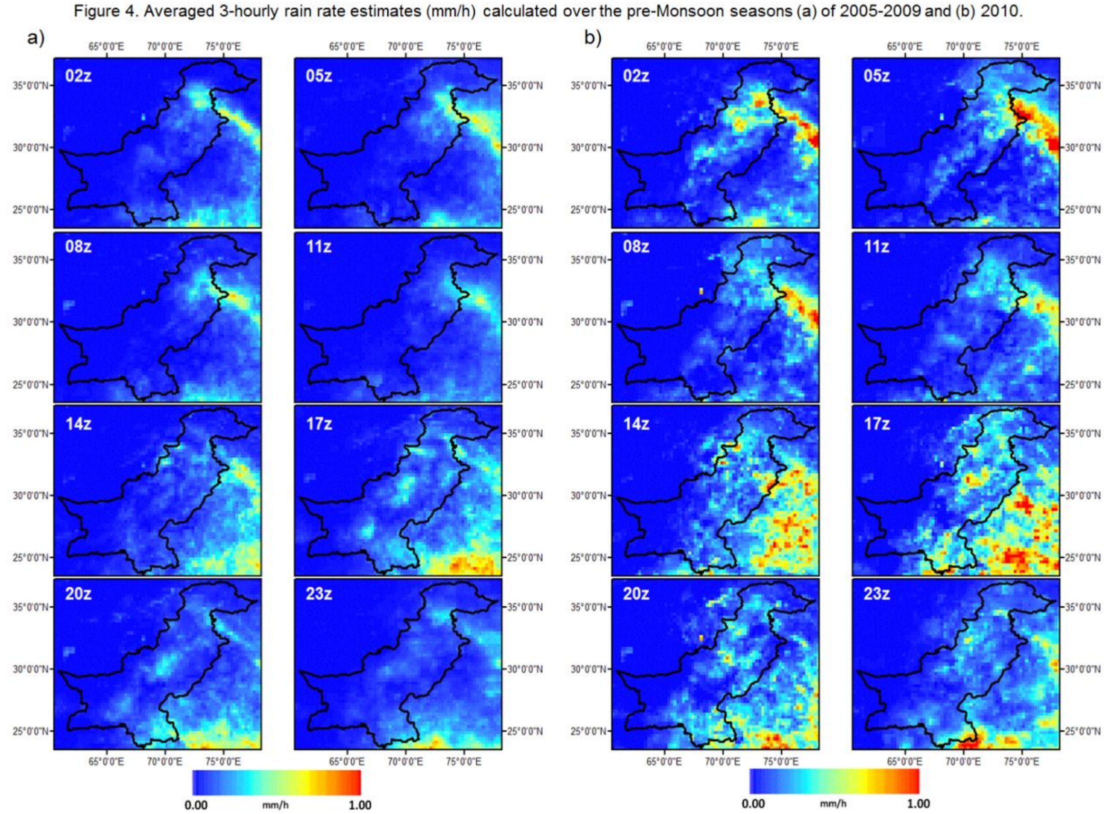

Figure 5. Averaged 3-hourly rain rate estimates (mm/h) calculated over the Monsoon seasons (a) of 2005-2009 and (b) 2010.

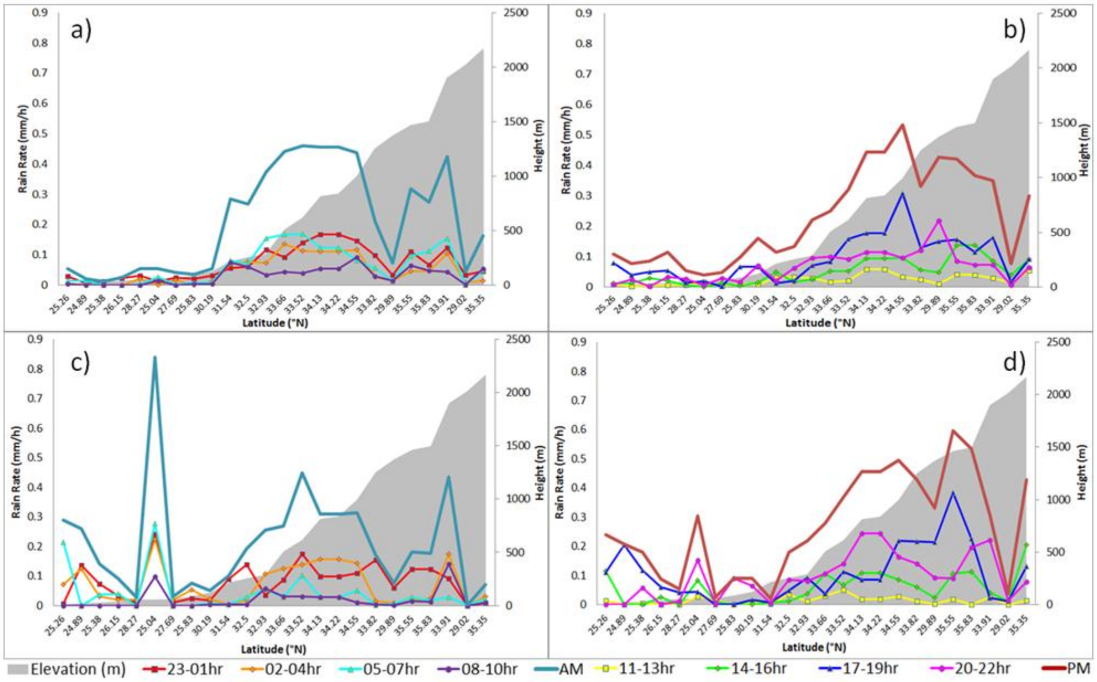

Figure. 6: Averaged 3-hourly rain rate estimates (mm/h) for the 2005-2009 pre-Monsoon seasons at the latitude (°N) of each station compared elevation (m) for both the (a) morning hours and (b) the afternoon and evening hours and for the 2010 pre-Monsoon season in both the (c) morning hours and (d) the afternoon and evening hours.

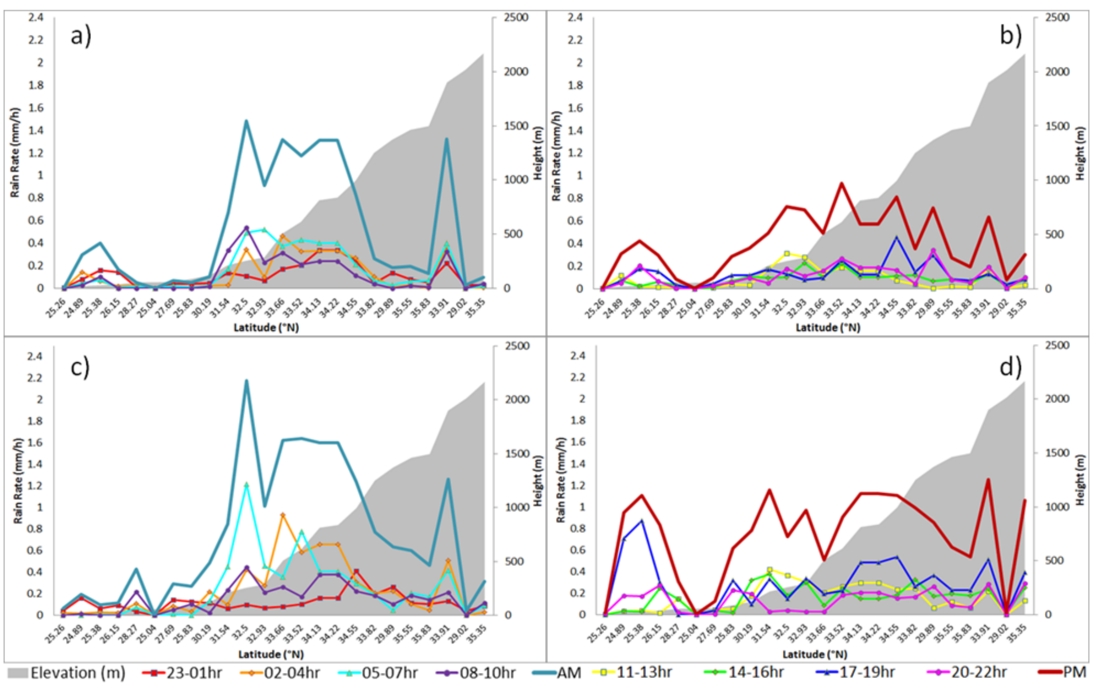

Figure. 7: Averaged 3-hourly rain rate estimates (mm/h) for the 2005-2009 Monsoon seasons at the latitude (°N) of each station compared elevation (m) for both the (a) morning hours and (b) the afternoon and evening hours and for the 2010 Monsoon season both the (c) morning hours and (d) the afternoon and evening hours.

The thicker lines in each graph represent the sum of the four average rates in order to show any peaks in intensity that occur. As shown in previous pre-monsoon figures, most of the precipitation in this time period tends to occur in the afternoon and evening hours. This is with the exception of the location in the southwestern, coastal region of Pakistan. Fig. 7 temporally compares the average rain rates of the monsoon seasons with elevation. As previously evidenced, the largest rainfall intensities occur in the morning hours of the monsoon seasons.

(d) Diurnal Evaluation at Multiple Stations

Examining diurnal patterns on a small scale is important when completing topographical and rain rate comparisons, especially when there are explanations required pertaining to the dynamic processes involved. For this research, two stations are chosen from Table 1 so as to take a closer look at the mechanisms involved in the convection processes which lead to rainfall. The first station, Kotli, is located in the lower foothills of the Himalayas in an area Romatschke et al. (2010) refers to as a location of convergence for different air masses. Downslope air flow, created by the cooling of high terrain, converges with moist, warm air from the monsoon which is flowing toward the Himalayas. The convection which results from this convergence is widespread, but also relatively strong due to some orographic lifting which occurs along the edge of the terrain, and results in the formation of a strong MCS. As seen in Fig. 8a, the convergence pattern is present during the pre-monsoon seasons, but it is less noticeable than in the monsoon seasons, shown in Fig. 8b, due to a lack of moisture before the monsoon progresses into Pakistan. Fig. 8a shows two peaks in rainfall intensity during the pre-monsoon seasons of 2005-2009, consistent with the findings by Romatschke et al. (2010). The evening peak is associated with processes similar to a deep convective system, but not of the same intensity. Note how the rain rates have a much smoother transition between the maximum and minimum values in 2010 than in 2005-2009. This, combined with the fact that the primary early morning maximum in the 2010 pre-monsoon season, provides evidence for the occurrence of wide core convection rather than deep core convection. The early morning peaks displayed in the 05-07hr time periods in Figures 8a and 8b are characteristic of wide core convective systems, which are more prominent in this region due to its location near the convergence zone.

Fig. 9 displays the temporal aspects of the diurnal cycle for Astore, which is located at a much higher elevation of 2168 meters than Kotli, which is resides at a height of 614 meters and is not as near to the boundary of downslope and monsoon convergence. As is shown by the prominent afternoon peaks in the diurnal graphs, changes in elevation play a major role in the type of convection that occurs at this station. In the pre-monsoon and monsoon seasons of 2010, the intense rain rates can be attributed to deep core convection produced by the heating of the land surface. A diurnal cycle is not as evident in the 2005-2009 seasons due to a lack of moisture at higher elevations. The anomalous atmospheric circulations present in 2010 created a layer of moist air which extended far into the Himalayas.

4. CONCLUSIONS

This research has shown the temporal and spatial characteristics of diurnal variability for the 2010 intense flood year of Pakistan and the 5 years preceding this event. Through the evaluation of TRMM 3B42 V7 rain rate data, a few key features stood out. The first was the temporal pattern exhibited by the arrival of the monsoon seasons. Preceding the monsoon, the highest number of rainfall events, and the largest average rain rate intensities, occur in the afternoon and evening hours, generally around 17z. As a result of this finding, it can be concluded that most of the precipitation which occurs during a pre-monsoon season is a result of severe storms with deep convective cores. Upon the arrival of the monsoon, the highest number of events and the most intense rainfall occurs in the early morning hours, generally around 05z. This is indicative of a shift in convection type from deep and severe to shallower storms with wide convective cores. These findings are congruent with those of Romatschke et al. (2010) who found most of the precipitation during a monsoon to be a result of MCSs.

The other finding relates to additional evidence as to why Pakistan experienced heavy flooding in 2010. The warmer ocean temperatures increased the humidity of the air, which was then carried over the Pakistan region by an anomalous cyclonic circulation pattern located over northern Pakistan. These processes created an environment which produced increased rainfall

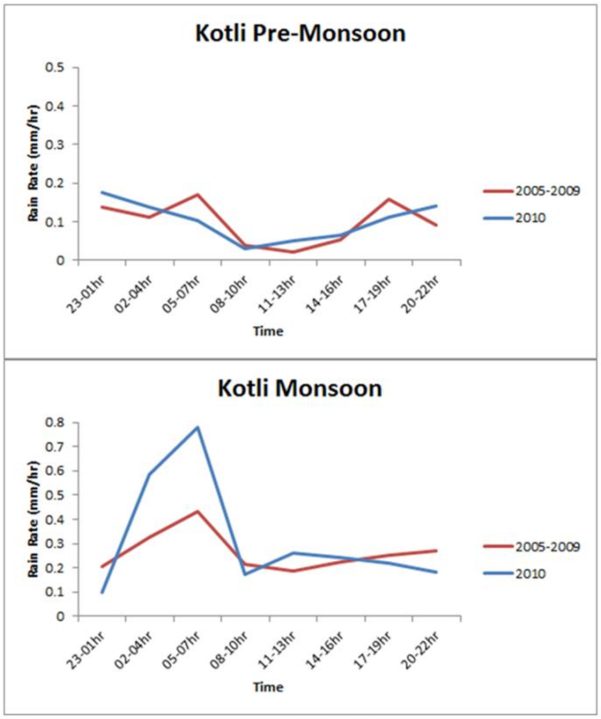

Figure 8. The average rain rates (mm/h) in 2005-2009 and 2010 for Kotli (latitude 33.52°) compared with time.

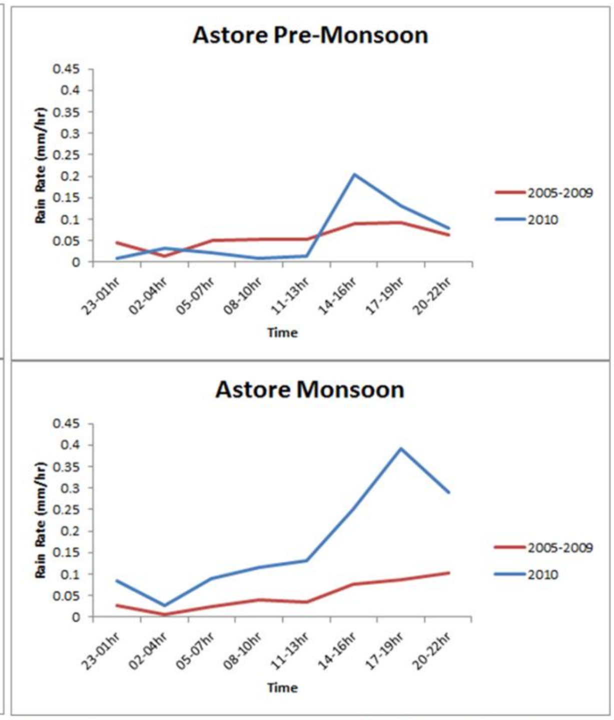

Figure 9. The average rain rates (mm/h) in 2005-2009 and 2010 for Astore (latitude 35.35°) compared with time.

not only in the monsoon season, but also in the pre-monsoon season. This increase in rainfall during the pre-monsoon season resulted in increased saturation of the soil before the heavy monsoon rains even began. The rainfall during the monsoon season was more intense than average and the soil quickly became supersaturated, resulting in extreme run-off into rivers throughout Pakistan. The river most affected by the influx of water was the Indus River, which flooded and caused widespread devastation to the entire Indus River Valley.

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