Were the 2010 Pakistan floods predictable?

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Abstract

During July 2010, a series of monsoonal deluges over northern Pakistan resulted in catastrophic flooding, loss of life and property and an agricultural crisis that may last for years. Was the rainfall abnormal compared to previous years? Furthermore, could a high probability of flooding have been predicted? To address these questions, regional precipitation is analyzed using three dataset sets covering the 1981-2010 time period. It is concluded that the 2010 average May to August (MJJA) rainfall for year 2010 is somewhat greater than in magnitude to previous years. However, the rainfall rate of the July deluges, especially in North Pakistan was exceptionally rare as deduced from limited data. The location of the deluges over the mountainous northern part of the country lead to the devastating floods. The European Centre for Medium Range Weather Forecasts (ECMWF) 15-day Ensemble Prediction System (EPS) is used to assess whether the rainfall over the flood affected region was predictable. A multi-year analysis shows that Pakistan rainfall is highly predictable out to 6-8 days including rainfall in the summer of 2010. We conclude that if these extended quantitative precipitation forecasts had been available in Pakistan, the high risk of flooding could have been foreseen. If these rainfall forecasts had been coupled to a hydrological model then the high risk of extensive and prolonged flooding could have anticipated and actions taken to mitigate their impact.

1. Introduction

Two main factors control South Asian rainfall. On 2-5 year time scales, the El Niño–Southern Oscillation (ENSO) phenomena is associated with above average summer precipitation during a La Niña and deficits during an El Niño [Paolina and Shukla 1983, Kumar et al. 2006]. Far more dramatic and higher amplitude modulations occur on subseasonal time scales. Over much of Asia the summer monsoon is divided into a series of "active" (rainy) and "break" (dry) periods following a roughly 20-40 days cycle [Lawrence and Webster 2001, Webster and Hoyos 2004, Hoyos and Webster 2007] associated with the boreal summer Madden-Julian Oscillation [Madden and Julian 1972] that produce a northeasterly excursion of large-scale convective anomalies under the action of a strong cross-equatorial pressure gradient [Stephens et al. 2004, Wang et al. 2005, 2006]. The arrival of convection over the Indian subcontinent heralds an active pluvial period. Summer rainfall in Pakistan is also monsoonal and, as such, has active and break periods. However, the total summer rainfall is far less than in the east (Fig. 1a) decreasing from the Bay of Bengal (16 mm/day) across the plains of northern India (8-10 mm/day) to values of about 6-8 mm/day in northern Pakistan. Pakistan is at the western edge of the pluvial region of the monsoon.

During the late boreal spring of 2010, the tropical Pacific Ocean entered a La Niña phase and during July 2010 the monsoon over the northern part of the Indian subcontinent was "active" with rainfall extending across the Gangetic Plains between the Bay of Bengal in the east to northern Pakistan in the west (Fig. S1). Embedded in this active period were the deluges that caused the devastating floods in Pakistan. In late July, some Pakistan stations recorded rainfall amounts exceeding 300mm over a four-day period http://www.pakmet.com.pk/FFD/index_files/rainfalljuly10.htm)]. During the following days and weeks, flooding extended through the entire Indus Valley eventually reaching the Arabian Sea leaving behind a wake of devastation and destruction. In the end, the death toll was close to 2000 and over 20 million people were affected. An estimated 20,000 cattle were drowned. Power stations and transmission towers were destroyed along with other major infrastructure such as barrages, bridges and roads. Irrigation systems were destroyed and planting of subsequent crops delayed or abandoned with agricultural costs exceeding $US500M. Overall, estimates of damage exceed $US40B[1]. In general, it was the poor that suffered the most and many of these will face the prospect of intergenerational poverty as a result of the floods (Webster and Jian 2010). Most assessments of the 2010 Pakistan floods have appeared on the internet and in relief organization reports[1]. Eventually, scholarly articles on the flooding will be forthcoming discussing, in more detail, the climate and meteorological conditions that produced the flooding. [e.g., Houze et al. 2010]. However, to date there has been an absence of any comment about the predictability of the deluges or the associated risk of floods. Eventually, skill in predicting floods reduces to the predictability of precipitation and the use of an adequately sophisticated hydrological model. Thus, an immediate and critical question is the degree to which rainfall at the western edge of the South Asian monsoon system is predictable on time scales of 1-2 weeks. Is the predictability of precipitation in the western edge of the monsoon comparable to that seen over the Ganges and Brahmaputra basins [Hopson and Webster, 2010; Webster et al. 2010]?

In this study we focus on the predictability of 1-15-day ECMWF EPS forecasts

[1] http://www.pakistanfloods.pk/, http://en.wikipedia.org/wiki/2010_Pakistan_floods

(Buizza et al. 2007) over Pakistan. In the next section details of the observation and numerical model data are introduced. Section 3 discusses the uniqueness of the July-August flooding events and examines the prediction skill of 15-days rainfall forecast followed by conclusions related to the predictability of floods in Pakistan.

2. Data and analysis

Three precipitation data sets are used to assess the variability of the precipitation over the Pakistan region: the Global Precipitation Climatology Project (GPCP) data [Adler et al., 2003] for the 1981-2009 period, the Tropical Rainfall Measuring Mission (TRMM) [Huffman et al. 2005, 2007] TRMM_3B42 product for1998-2010, and the NOAA CPC Morphing Technique (CMORPH) Precipitation Product for the 2003-2010 period [Joyce et al. 2004]. GPCP (a merging of rain gauge data with satellite geostationary and low-orbit infrared and passive microwave information) and TRMM data sets (specifically the TRMM_3B42 set) were chosen for their temporal extension (29 and 13 years, respectively). All of these precipitation products had a 0.25ºx0.25º horizontal resolution facilitating a comparison with model output. Figure S4 shows time series of monthly rainfall anomalies for each of the data sets.

A comparison of the CMORPH and TRMM data sets (Figs. S3) reveals considerable differences in the magnitude of estimates of precipitation during the third precipitation pulse of July 2010 that occurred over the higher terrain of northern Pakistan (panel 3, Fig. S2d). The TRMM rainfall estimate was considerably higher than CMORPH by about a factor of two consistent with the discussion of Gopalan et al [2010] who suggested that TRMM may overestimate precipitation rates over substantial terrain. Comparisons during earlier periods, when the precipitation maxima occurred over the plains of southern Pakistan and northwestern India are more comparable (Fig. S2). Consequently, we use CMORPH as the principal data set for determining the sequence of events during 2010 and also as the principal agent for the statistical rendering of the quantified precipitation forecasts.

The ECMWF EPS forecasts consist of 51 ensemble members initialized twice per day (00 and 12 UT), each ensemble member having a 15-day forecast horizon. The horizontal resolution of the model is 50 x 50 km from 0 to 10 days and then 80 km x 80 km from day 10-15 [Buizza et al. 2007]. For this initial study, model forecast precipitation for the months of July and August from 2007 to 2010 was converted into daily cumulative amounts. To minimize systematic model bias differences between the distributions of the ECMWF forecasts and the observed rainfall, a quantile-to-quantile (*q-to-q*) mapping technique was implemented following Hopson and Webster [2010] and Webster et al. [2010] (see method description in supplementary document). All rainfall forecasts presented here are adjusted using the *q-to-q* technique.

3. Results:

Beginning in early July 2010, there were six major pulses of torrential rainfall occurring over Pakistan, each separated by about a week (Fig. 1b). One of the most intense periods occurred between July 27-30 over the mountainous regions of the north. Figure S2 shows the distribution of rainfall for the major pulses of monsoon rain. The earlier rainfall events caused flooding in Balochistan in central Pakistan. Flooding followed across northern Pakistan in the Kyhber-Paktunkhwa province with the later July rains extending to the Punjab in late July/early August[2]. Here we address the uniqueness and predictability of the floods.

3.1 Uniqueness:

There have been 67 reported flooding events in Pakistan occurring since 1900 with a clustering of 52 events of various severity in the last 30-40 years[3] . Some of these events (e.g., 1950, 1973, 1976, 1977, 1992, 2001, 2007 and 2008) were also accompanied with large loss of life and property. This recent increase is consistent with the increase in intensity of the global monsoon accompanying the last three decades of general global warming [Wang et al. 2010] or perhaps changes in water management strategies, increases of damage due to a rapidly growing population or improved reporting through advances in communication.

Figure S4 shows the temporal variability of seasonal (MJJA) precipitation averaged in Pakistan [62°-74°E, 24°-36°N, blue rectangle in Fig. 1a] and northern Pakistan [70°E-74°E, 30°N-36°N, red rectangle in Fig.1a] relative to the seasonal climatology for each of the data sets: GPCP and CMORPH. While there are amplitude differences between datasets, each shows substantial variability, with seasons of excessive rainfall and drought occurring irregularly over the past 30 years (Fig. S3 and Fig. S4).

Were the rainfall events of 2010 worse than previous extreme events? Using a 13-year TRMM precipitation record, extreme events can be counted. An extreme event is defined here to occur when the two-days accumulated rainfall exceeds over 10 mm over

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[2] http://unosat.web.cern.ch/unosat/asp/prod_free.asp?id=85

[3] International Disaster Data Base, http://www.emdat.be

all Pakistan and 20 mm over the northern Pakistan (Fig. 1c-d). Note that the chosen thresholds for this analysis are much smaller than maximum daily rainfall measurements at specific stations (see http://www.pakmet.com.pk/FFD/index_files/rainfalljuly10.htm) due to a broader averaging area. Although there is considerable interannual variability, the number of extreme events over entire Pakistan, so defined, is larger in 2010 than in previous years, greater, for example than in 2008. In summary, 2010 stands out as a period of above average rainfall events over northern Pakistan. The number of extreme events over northern Pakistan is far more unique which, based on the very limited TRMM data set would have return periods of > 30 years. Long-term variability for extreme events is calculated with GPCP pentad data set from 1981 (Fig. S5) to 2007 overlapped with CMORPH pentad from 2003 to 2010. Although, there are differences between data sets, the high occurrence of Northern Pakistan extreme events in 2010 is relatively rare. Rainfall data is not sufficiently reliable prior to 1987 when GPCP data was generated on a daily basis. However, we do have CMORPH and TRMM data for 2008. As shown in figure S6, the cumulative July- August rainfall for northern Pakistan is larger in 2010 than 2008, with values larger than 0.5 m in several areas.

3.2 Predictability:

The next step is to examine the predictability of the rainfall events depicted in Figure 1b. Figure 2a shows the total average precipitation [mm/day] for July 28-29, based on the CMORPH observational dataset and the ECMWF forecast ensemble mean initialized 4 days before the event (Fig. 2b). The *q-to-q* correction was applied to the precipitation forecast data. The forecasts compare well with the observed rainfall with ECMWF slightly underestimating the rainfall intensity in the northern part of the region. The

ECMWF forecast showed average precipitation larger than 40 mm/day in some areas which is over 3 times larger than the CMORPH climatological average for the region.

Figure 2c and 2d shows the temporal evolution of the ECMWF forecast commencing on 22nd and 24th July, 2010 through August 9, 2010 for the Khyber-Pakhtunkhwa province, located in the north west of the country (red rectangle in Fig. 1a). The diagram shows the probability distribution of precipitation based on the 51 ensemble members with the ensemble mean plotted as the black dotted line. The blue line represents the CMORPH observed rainfall. Good predictive skill of the July 28-29 event is found up to 6 days in advance. The same analysis done for various other monsoon pulses have resulted in similar conclusions (Fig. 3).

Figure S7 shows an assessment of precipitation predictability in northern Pakistan using all available hindcast data. Predictability is shown as correlations between predicted and observed CMORPH rainfall values as a function of lead time for July based on 2007-2010 period. Note that for 2007, the model prediction extends only up to 10 days but up to 15 days for the 2008- 2010 period. Correlations ≥ 0.7 were found for predictions 5 days in advance indicating useful predictive skill. Thus, the quantitative rainfall forecasts could be used as a robust variable in a flood forecasting scheme for Pakistan region.

In order evaluate whether the model can provide useful information with regards to the actual severity of the major rainfall events of July-early August 2010, all ECMWF forecasts made during the period were extracted and bias corrected. Then, the probability that the predicted rainfall would exceed the observed climatological average plus 1 standard deviation was computed. In other words, for each forecast, at each lead time, the percentage of ensemble members exceeding the threshold was computed. The exceedance threshold is calculated using 2003- 2010 CMORPH data, with mean and standard deviation based on July-August daily average data. Results are shown in Figure 3 as shaded contours. The blue line represents the observed CMORPH rainfall averaged for the same region and the same time period. For example, the July 28 event was predicted almost 8 days in advance with a probability >60% over the climatological average plus 1 standard deviation (Fig. 3). All the other events appear to have similar skill at the 8 to 10 day horizon.

4. Conclusions

From a climatological perspective, July and August precipitation rates were above average in Pakistan although not exceptionally so. However, in terms of rainfall rate, the monsoon pulses were extreme events compared to other years in the period 1998-2010. The devastating flooding occurred from a conspiracy of events. The summer of 2009 was a severe drought period with rainfall well below average.(http://www.pakmet.com.pk/monsoon2009ver.pdf) so that vegetation may have been sparser during 2010. The region is mountainous with steep valleys and ridges. Furthermore, deforestation in northern Pakistan has been severe [e.g., Ali et al. 2006]. Deforestation and sparse undergrowth would exacerbate runoff through the steep valleys of the heavy rains that occurred during the month of July and early August.

The major result of the study is that the heavy rainfall pulses throughout July and early August were predictable with a high probability 6-8 days in advance. If these forecasts had been available to the regions of northern Pakistan, government institutions and water resource managers could have anticipated rapid filling of dams, releasing water ahead of the deluges. A high probability of flooding could have been anticipated.

Finally, it appears that Pakistan would benefit from a hydrological forecasting scheme similar to that developed for Bangladesh [Hopson and Webster 2010, Webster et al. 2010]. The Bangladesh system incorporates the same form of statistically rendered ensemble precipitation forecasts as discussed above but coupled to a hybrid hydrological model. Working with Government of Bangladesh authorities, these 10-day river forecasts were communicated to the union (county) and village level allowing time to prepare for the floods for three major Brahmaputra floods during 2007/8allowing the saving of household and agricultural effects and the successful evacuation of those in peril [ADPC 2009, Webster et al. 2010, Webster and Jian 2010].

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References

Adler, R.F., G.J. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, and P. Arkin, 2003: The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present). *J. Hydrometeor.,* 4,1147-1167. Data obtainable at: (http://www.esrl.noaa.gov/psd/)

ADPC, 2009: Flood Forecasts Application for Disaster Preparedness: Post Flood Forecasts Assessment 2008: Community Response to CFAN Forecasts. Available at http://www.adpc.net/v2007/ and http://pacific.eas.gatech.edu/~pjw/FLOODS.

Ali, Y., B. Shahbaz, and A. Suleri, 2006: Analysis of myths and realities of deforestation in Northwest Pakistan: Implications for forestry Extension, *Int. J. Agri.Bio,* 8:1, 107-110.

Buizza, R., J.-R. Bidlot, N. Wedi, M. Fuentes, M. Hamrud,G. Holt, and F. Vitart, 2007: The new ECMWF VAREPS (Variable Resolution Ensemble Prediction System).

Quart. J. Roy. Meteor. Soc., 133, 681–695.

Gopalan, Kaushik, Nai-Yu Wang, Ralph Ferraro, Chuntao Liu, 2010: Status of the TRMM 2A12 Land Precipitation Algorithm. *J. Atmos. Oceanic Technol.*, **27**, 1343–1354.doi: 10.1175/2010JTECHA1454.1

Hopson, T. M., P. J. Webster, 2010: A 1-10 day ensemble forecasting scheme for the major river basins of Bangladesh: forecasting severe floods of 2003–2007. *J. Hydromet.*, 11, 618-641.

Hoyos, C. D. and P. J. Webster, 2007: The Role of Intraseasonal Variability in the Nature of Asian Monsoon Precipitation. *J. Climate*, 20 (17), 4402-4424.

R. A. Houze, Jr., K. L. Rasmussen, S. Medina, S. R. Brodzik, and U. Romatschke, 2010: Anomalous Atmospheric Events Leading to the Summer 2010 Floods in Pakistan, Submitted to the *Bull. Amer. Meteor. Soc.*

Huffman, G. J., R. F. Adler, S. Curtis, D. T. Bolvin, and E. J. Nelkin, 2005: Global rainfall analyses at monthly and 3-hr time scales. *Measuring Precipitation from Space: EURAINSAT and the Future*, V. Levizzani, P. Bauer, and J. F. Turk, Eds., Springer, 722 pp.

Huffman,G J, D. T. Bolvin, E. J. Nelkin, D. B. Wolff, R. F. Adler, G. Gu, Y. Hong, K. P. Bowman, E. F. Stocker, 2007: The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combinedsensor precipitation estimates at fine scales. *J. Hydrometeor.*, 8, 38–55.

Joyce, R. J., J. E. Janowiak, P. A. Arkin, and P. Xie, 2004: CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution.. *J. Hydromet*., 5, 487-503. Data available at (ftp.cpc.ncep.noaa.gov/precip/global_CMORPH/daily_025deg/)

Kumar K. K., Rajagopatan B, Hoerling M., Bates G, Cane M (2006), "Unraveling the Mystery of Indian Monsoon Failure During El Niño", *Science* 314 (5796): 115–119,

Lawrence, D. M., and P. J. Webster, 2001: Interannual variations of the intraseasonal oscillation in the South Asian summer monsoon region. *J. Climate,* 14, 2910–2922.

Madden R. and P. Julian, 1972: Description of global-scale circulation cells in the tropics with a 40-50 day period*. J. Atmos. Sci.,* 29, 1109-1123.

Shukla, J. and D. A. Paolina, The southern oscillation and long range forecasting of the summer monsoon rainfall over India, *Mon. Weather Rev*., 111, 1830-1837, 1983.

Stephens, G. L., P. J. Webster, R. H. Johnson, R. Engelen and T. L'Ecuyer, 2004: Observational Evidence for the Mutual Regulation of the Tropical Hydrological Cycle and Tropical Sea Surface Temperatures. *J. Climate*: 17(11), 2213–2224

Wang, B., P. J. Webster and H. Teng, 2005: Antecedents and self-induction of active-break south Asian monsoon unraveled by satellites, *Geophys. Res. Lett*., 32, L04704, doi: 10.1029/2004GL020996.

Wang, B., P. Webster, K. Kikuchi, T. Yasunari and Y. Qi, 2006: Boreal summer quasi-monthly oscillation in the global tropics, *Clim. Dyn*. 27, 661-675.

Wang, B. J. Liu, H-J Kim, P. J. Webster and T. A. Schroeder, 2010: Recent Intensification of Global Monsoon and Precipitation, submitted to *Nature.*

Webster, P. J. and C. D. Hoyos, 2004: Prediction of Monsoon Rainfall and River Discharge on 15-30 day Time Scales. Bull. Amer. Met. Soc., 85 (11), 1745-1765

Webster P. J. and J. Jian 2010: Probability, Uncertainty and prediction: A pathway towards the alleviation of poverty in the developing world. To appear *Phil. Trans. Roy. Soc.*

Webster, P.J., J. Jian, T. M. Hopson, C. D. Hoyos, J., H-R. Chang, P. Agudelo, J. A. Curry, T. N. Palmer, A. R. Subbiah, R. L. Grossman, 2010: Extended-range probabilistic forecasts of Ganges and Brahmaputra floods in Bangladesh. In press November issue: *Bull. Amer. Meteor. Soc.*

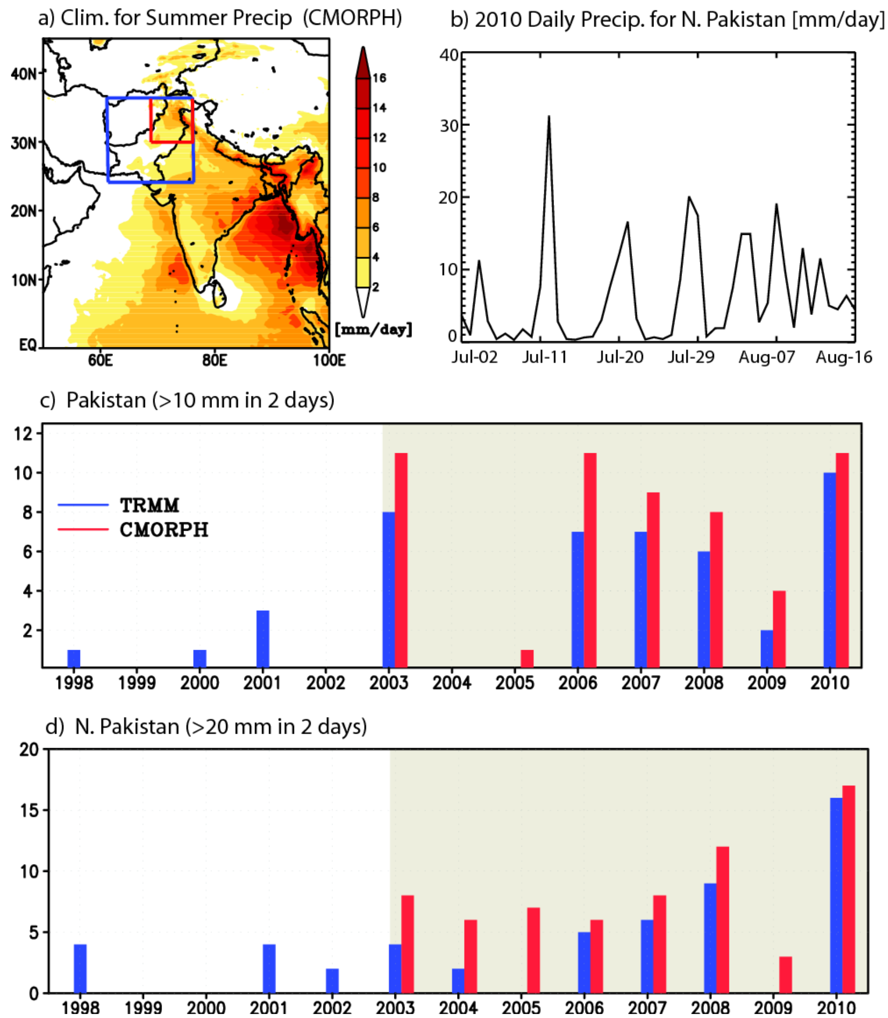


Figure 1. a) May-August CMORPH precipitation [mm/day] climatology for 2003-2010. b) The observed CMORPH rainfall averaged for the Northern Pakistan [70°N-74°N; 30°E-36°E, red rectangle]. c)-d) Number of heavy rainfall events over the summer (May-August) in TRMM (blue) and CMORPH (red). The events are defined when two-day accumulated rainfall exceeds (c)10 mm over entire Pakistan [62°N-74°N; 24°E-36°E, blue rectangle in Fig. 1a] and (d)20 mm over the northern Pakistan [70°E-74°E, 30°N-36°N, red rectangle in Fig.1a]. Years with available CMORPH data are shaded in gray.

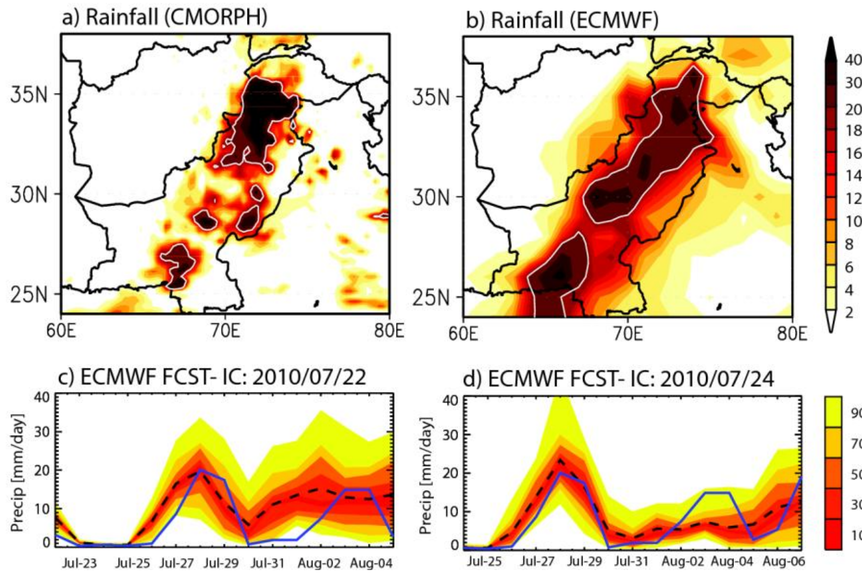


Figure 2. Total precipitation [mm/day] for a) CMORPH over 28-29 July 2010 and b) ECMWF ensemble mean of the forecast initialized four days previously (July 24, 2010) for the same time period. White contour shows 20 mm/day. c) ECMWF 15-day forecast of the precipitation [mm/day] in the red rectangle (Fig. 1a) initialized on July 22nd, and (d) 24th, 2010. Black dashed line shows the ensemble mean. Colored shading depicts the probability of precipitation rate based on the 51 ensemble members. Dark blue line represents the observed CMORPH precipitation averaged for the same region.

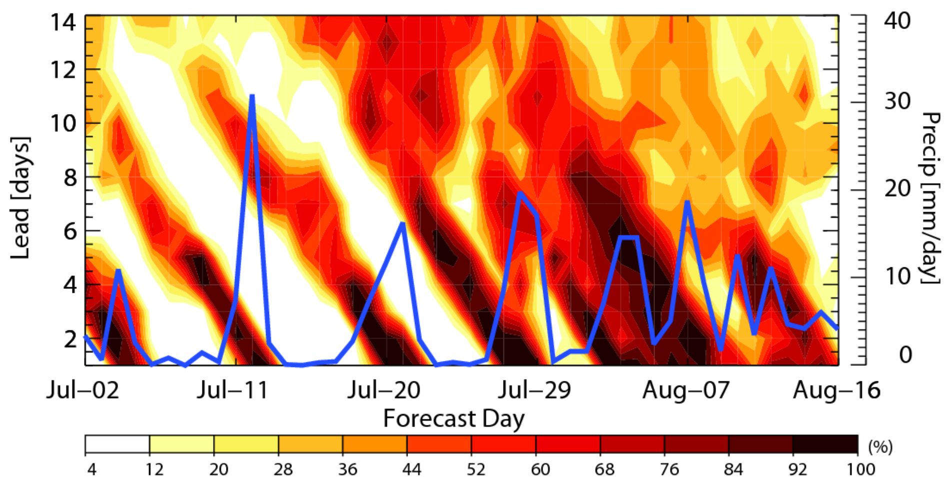
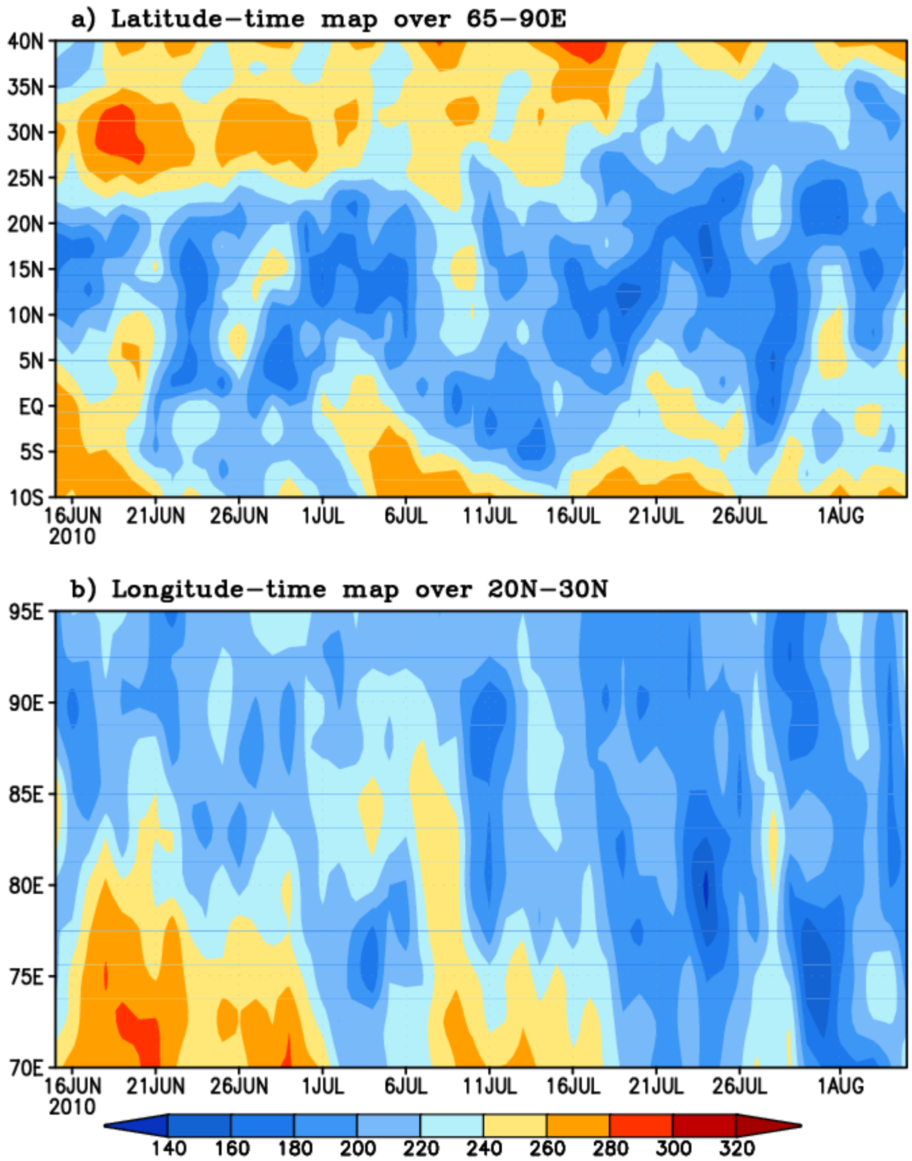


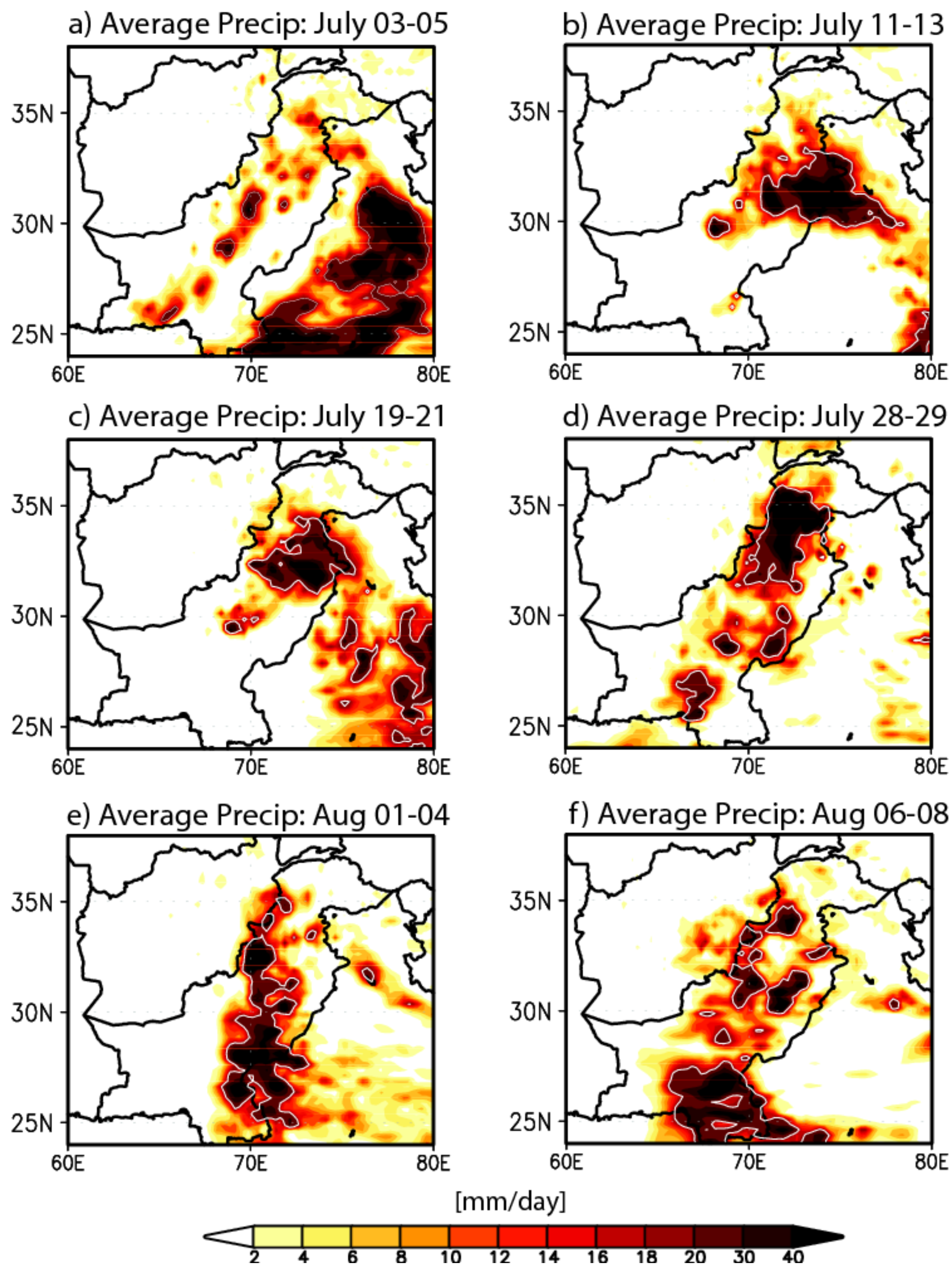
Figure 3. Forecast lead time diagram of the probability that the ECMWF forecast for the red region (Fig. 1a) exceeds the observed CMORPH July-August climatology plus 1 standard deviation. The blue line represents the observed CMORPH rainfall [mm/day] averaged for the same region and the same time period (units on the left axis). The July 12 and June 21 events were forecast at 50% probability level to exceed observed climatology plus 1 standard deviation, at least 10 days in advance. An additional 2 days of predictability is evident at the 50% level for the July 28 event. All events were forecast at >70-80% level of probability 6 days in advance. Note that the ECMWF forecast is adjusted using the *q-to-q* technique.

Auxiliary Material:

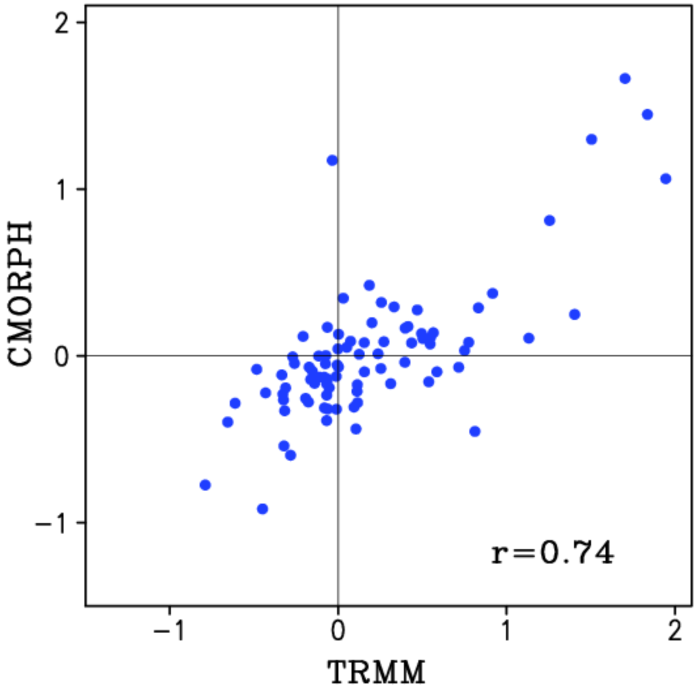
Quantile-to-quantile bias correction: To minimize systematic model bias between the ECMWF forecasts and the observed rainfall, a quantile-to-quantile (*q-to-q*) mapping technique was implemented following Hopson and Webster [2010] and Webster et al. [2010]. Specifically, two sets of cumulative density functions (CDFs) were constructed, one for the observed CMORPH data and the second for the forecasts field, at each lead time (e.g., 24 hr, 48 hr, and etc.) arranged in ascending quantiles. CDFs were constructed for each point in the domain of interest at a common 1°x1° resolution. The quantile of the CMORPH CDF was matched to the corresponding quantile of the forecast field, at each lead time, providing a correction $a(x,y)$ such that the observed precipitation was mapped against the forecast data quantile as $p_i(observed)= a(x,y)p_i(modeled)$ where p_i is i^{th} quantile of precipitation for the observed and modeled fields. The mapping is applied to all the 51 ensemble members for the period May to August, in the 2007-2009 period. The result of the *q-to-q* correction system is a quantile correspondence between the model and the observed precipitation. This method has the advantage of producing the same number of no-rain events as the observations. All modeled result presented in this paper are bias corrected using the *q-to-q* technique.



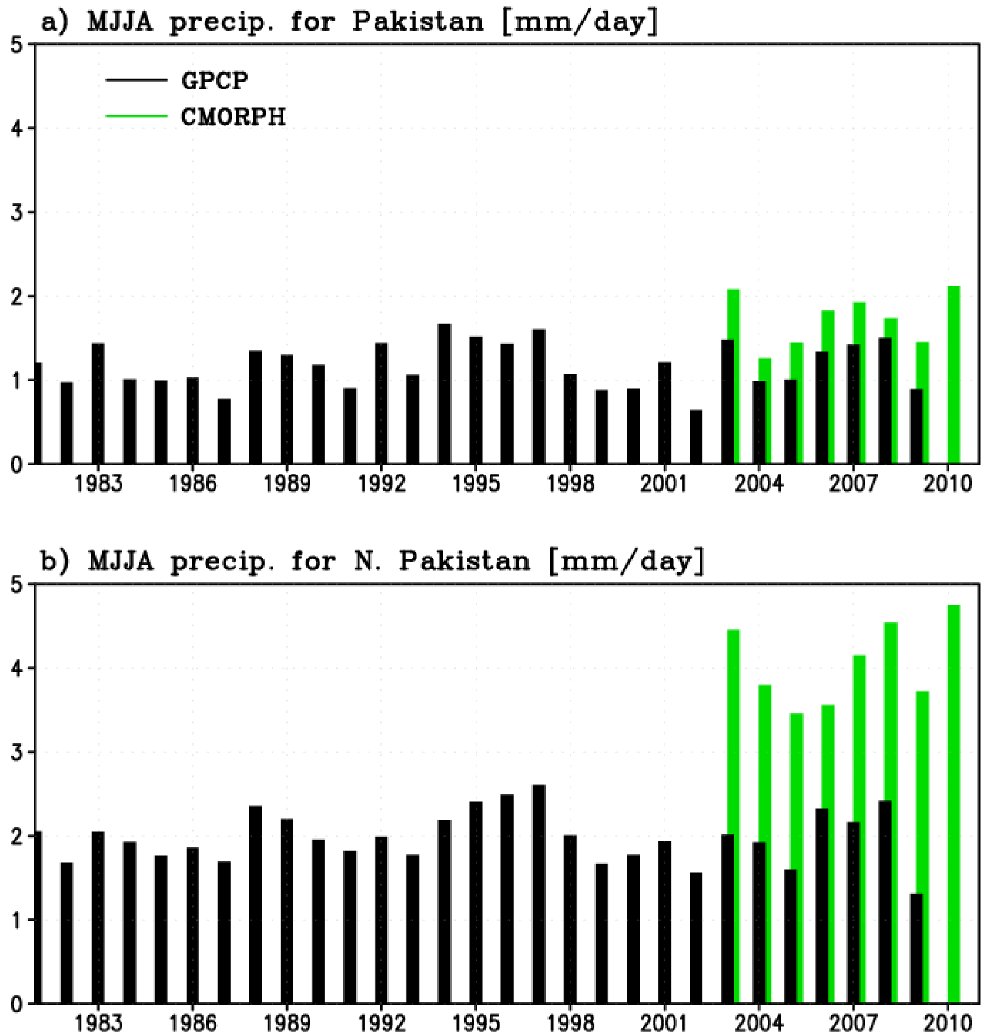
Auxiliary Material Figure S1: a) Latitude-time (averaged over 65-90°E) and b) Longitude-time (averaged over 20-30°N) cross section for observed outgoing longwave radiation [OLR, W/m^2] during June-July 2010. Low values of OLR are indicative of a measure of deep convection. OLR data is from NOAA (http://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html). Note the northward propagation for the equatorial regions to 20-30°N (panel a) and the east to west propagation across northern India and Pakistan (panel b).



Auxiliary Material Figure S2: Observed CMORPH precipitation [mm/day] for the 6 monsoon pulses during July-August 2010. White contours outline precipitation exceeding 20 mm/day.



Auxiliary Material Figure S3: Scatter diagram of monthly precipitation anomaly (mm/day) between CMORPH and TRMM over the period from 2003 to 2010. Correlation coefficient between two variables is 0.74.



Auxiliary Material Figure S4: Seasonal mean (MJJA) precipitation [mm/day] for GPCP (black) and CMORPH (green) averaged over (a) the Pakistan and (b) northern Pakistan.

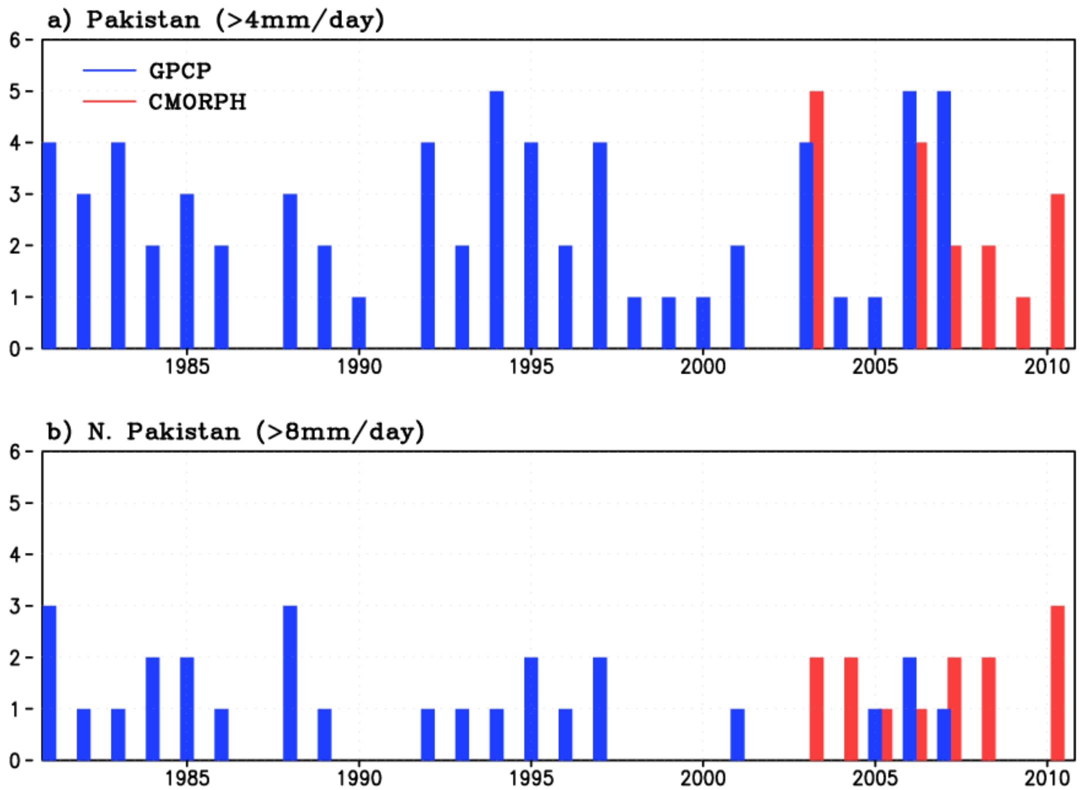
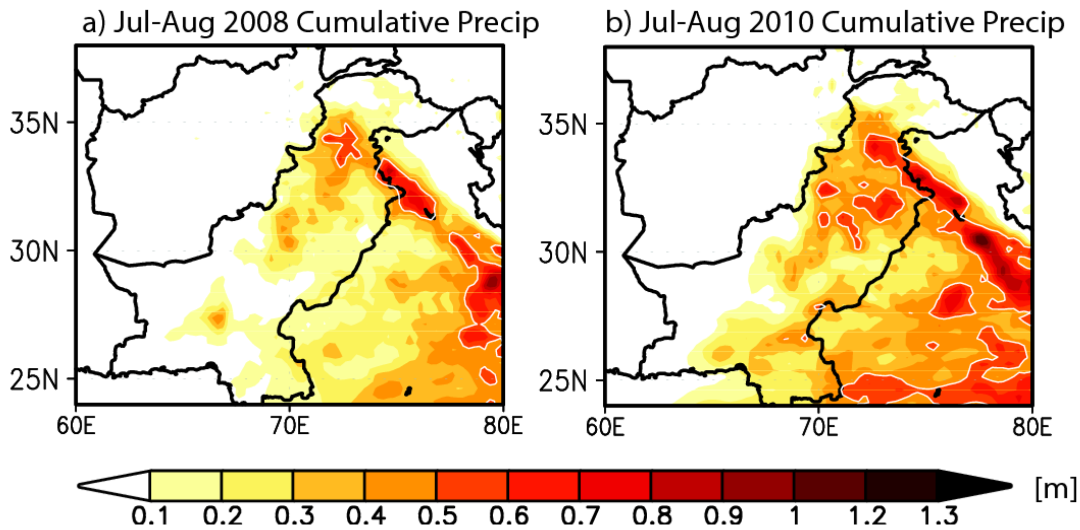
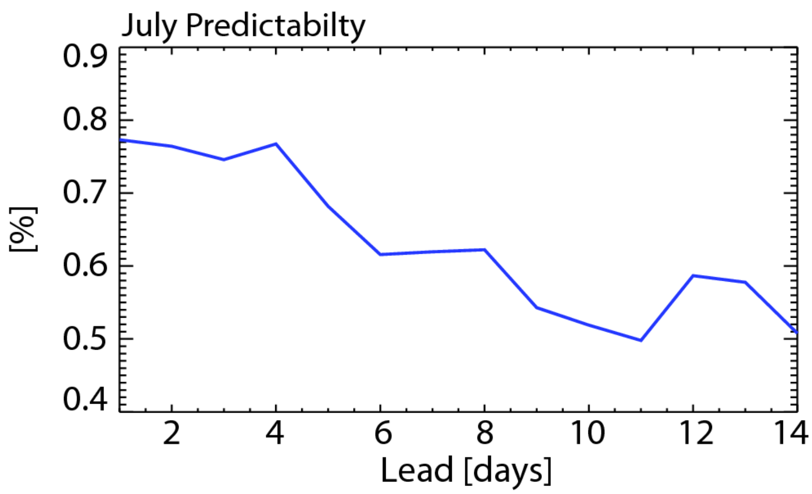


Figure S5. Number of heavy rainfall events over the summer (May-August) in GPCP (blue) and CMORPH (red). The events are defined when pentad rainfall exceeds (a) 4 mm/day over entire Pakistan and (d) 8mm/day over the northern Pakistan.



Auxiliary Material Figure S6: Observed July-August cumulative CMORPH precipitation [m] for years 2008(a) and 2010(b). White contours outline total precipitation exceeding 0.5 m.



Auxiliary Material Figure S7: Overall estimates of the predictability of precipitation in the Pakistan region [blue rectangle in Fig.1a] versus lead-time for July based on 15-day forecasts from 2007-2010. Correlations between ECMWF ensemble mean forecast and observed CMORPH rainfall are presented. 124 (31 days x 4 years) forecasts are used for lead 1 to 10 and 93 (31days x 3 years) forecasts are used for lead 11 to 14, since the 2007 model prediction extends only up to 10 days.