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Heavy Rains and Historic Flooding over Pakistan in Late July 2010: Synoptic Conditions and Physical Mechanisms

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Support provided by CIRES Postdoctoral Fellowship

Introduction

Historic Flooding Over Pakistan

- Widespread extremely heavy rains (> 200 mm) and historic flooding occurred in the Indus River basin throughout Pakistan during 24–31 July 2010
- Heaviest rains fell on 28–29 July, where many stations in the northern provinces and tribal areas received over well over 150% of their climatological July precipitation in less than 48 hours
- The high-impact flooding affected nearly 17 million people, resulted in over 1500 fatalities, and left over 4 million people without homes

Fig. 1: Geography of Pakistan

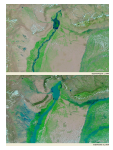

Fig. 2: MODIS image of the Indus river basin from (top) 1 Aug 2009 and (bottom) 31 Jul 2010.

Table 1: Total rainfall (mm) at selected stations during 27–30 Jul 2010.

- Although the heaviest rains fell on 28–29 July, there were several periods of heavy rain during the last ten days of July and much of the first half of August

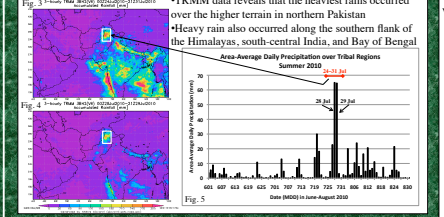

Fig. 3

Fig. 4

Fig. 5

- TRMM data reveals that the heaviest rains occurred over the higher terrain in northern Pakistan
- Heavy rain also occurred along the southern flank of the Himalayas, south-central India, and Bay of Bengal

Goals

- Examine large-scale antecedent conditions
- Investigate subsynoptic-scale processes relevant to production of heavy rainfall
- Examine the forecastability of heavy rainfall in the ECMWF ensemble prediction system

Data Sources

- 2.5° NCEP/NCAR Reanalysis (for composites)
- 1.0° GFS Analyses (for synoptic analysis)
- TRMM rainfall data
- NCDC GIBBS satellite archive
- ECMWF ensemble prediction system (EPS) from TIGGE archive
  - 50 members + control run
  - Spectral truncation of T639 (~32 km resolution)
  - 62 vertical levels

Synoptic Analysis

Large-Scale Overview

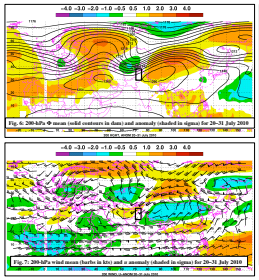

Fig. 6: 200-hPa Φ mean (solid contours in dam) and anomaly (shaded in sigma) for 20–31 July 2010

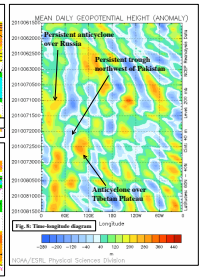

Fig. 8: Time-longitude diagram

Fig. 7: 200-hPa wind mean (barbs in kts) and σ anomaly (shaded in sigma) for 20–31 July 2010

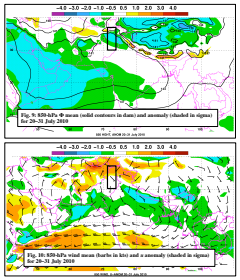

Fig. 9: 850-hPa Φ mean (solid contours in dam) and anomaly (shaded in sigma) for 20–31 July 2010

Fig. 10: 850-hPa wind mean (barbs in kts) and σ anomaly (shaded in sigma) for 20–31 July 2010

- High-latitude blocking over eastern Europe and western Asia, responsible for producing record heat over Russia, helped anchor an anomalously deep trough northwest of Pakistan throughout much of June and July (Figs. 6 and 8)
- Downstream amplification contributed to ridge building over the Tibetan Plateau during 20–31 July (Fig. 6 and 8)
- Anomalous +2 to +3 sigma ridging (–1 to –2 sigma troughing) over the Tibetan Plateau (northwest of Pakistan) contributed to an intense upper-level jet and jet-entrance region over northern Pakistan during 20–31 July (Fig. 7)
- Anomalous low-level southeasterly upslope flow over northern India and eastern Pakistan was prevalent during 20–31 July (Figs. 9–10)

Subsynoptic-Scale Analysis

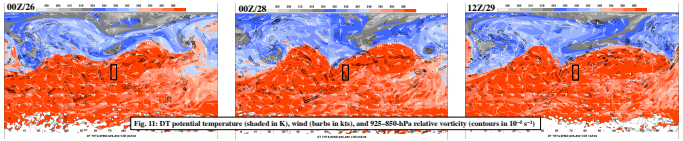

Fig. 11: DT potential temperature (shaded in K), wind (barbs in kts), and 925–850-hPa relative vorticity (contours in 10^{-5} s^{-1})

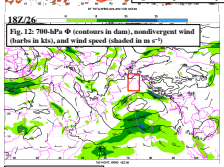

Fig. 12: 700-hPa Φ (contours in dam), nondivergent wind (barbs in kts), and wind speed (shaded in $m\ s^{-1}$)

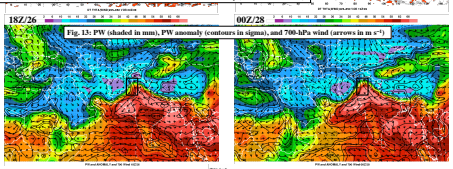

Fig. 13: PW (shaded in mm), PW anomaly (contours in sigma), and 700-hPa wind (arrows in $m\ s^{-1}$)

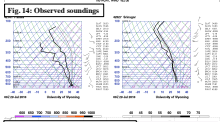

Fig. 14: Observed soundings

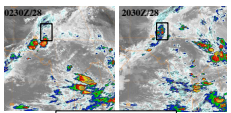

Fig. 16: METEOSAT-7 IR imagery

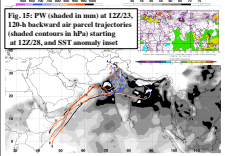

Fig. 15: PW (shaded in mm) at 12Z/23, 120-h backward air parcel trajectories (shaded contours in hPa) starting at 12Z/28, and SST anomaly inset

- Subsynoptic-scale transient disturbances helped reinforce trough north of Pakistan (Fig. 11)
- Monsoon low contributed to enhanced moist SE flow over N India and E Pakistan (Fig. 12-14)
- Moist SE upslope flow and weak WAA contributed to extended period of active convection (Figs. 13, 14, 16)
- Moist air originated in monsoon southwesterlies over anomalously warm SSTs in western Indian Ocean (Fig. 15)

Historical Comparison

Large-Scale Composite Analysis of Historical Cases

- TRMM data was used to compute the daily area-average precipitation over northern Pakistan for June–August 1998–2010 (Fig. 17)
- The top 2% wettest days (> 20 mm of area-average rainfall) over northern Pakistan during 1998–2010 were selected for composite analysis
- 200 & 850-mb fields were composited for comparison with July 2010
- Since 8 of the top 24 (2%) wettest days occurred in July and August 2010, the composites were computed with 2010 days removed

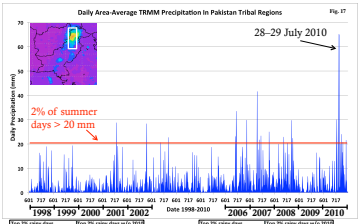

Fig. 17

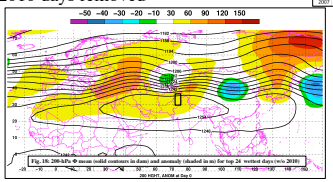

Fig. 18: 200-hPa Φ mean (solid contours in dam) and anomaly (shaded in m) for top 24 wettest days (w/o 2010)

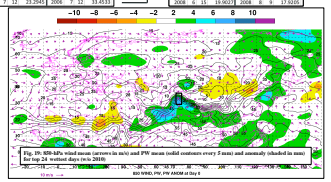

Fig. 19: 850-hPa wind mean (arrows in m/s) and PW mean (solid contours every 2 mm) and anomaly (shaded in mm) for top 24 wettest days (w/o 2010)

- Composite 200-hPa height suggests that a blocking anticyclone over western Asia may be instrumental in locking in a weak trough northwest of Pakistan during heavy rainfall events similar to the pattern observed in 2010 (Fig. 18)
- Composite 850-hPa winds and precipitable water show that low-level weak upslope southeasterly flow (enhanced by the passage of a monsoon low to the south in some cases) may help advect deep tropical moisture from India into northern Pakistan (Fig. 19)

Ensemble Prediction

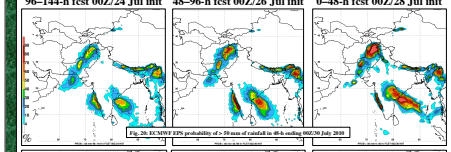

Fig. 20: ECMWF EPS probability of > 50 mm of rainfall in 48-h ending 00Z/30 July 2010

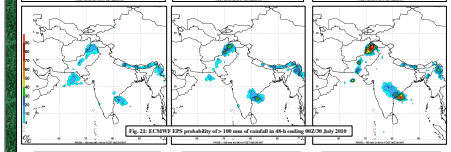

Fig. 21: ECMWF EPS probability of > 100 mm of rainfall in 48-h ending 00Z/30 July 2010

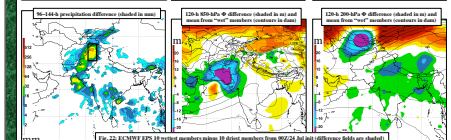

Fig. 22: ECMWF EPS 10 wettest members minus 10 driest members from 00Z/24 Jul init (difference fields are shaded)

- ECMWF EPS initialized 00Z/24 indicated 50% (10%) probabilities of > 50 mm (100 mm) of rainfall over in N Pakistan during days 4–6
- Probabilities for > 50 and 100 mm of rainfall over N Pakistan increased markedly at shorter lead times (i.e, the 00Z/26 and 00Z/28 init) (Figs. 20, 21)
- Top 10 "wettest" and "driest" members from 00Z/24 run are compared in Fig. 22
- Note that the "wettest" EPS members have relatively lower 850-hPa Φ over S Pakistan inferring stronger SE upslope flow in NE India and Pakistan
- "Wettest" EPS members have relatively deeper 200-hPa trough NW of Pakistan highlighting the importance of upper-level trough forcing and jet-entrance region dynamics in focusing heavy rainfall