

# Teleconnection between Pakistan Flooding and European Heatwave, 2010 & 2022

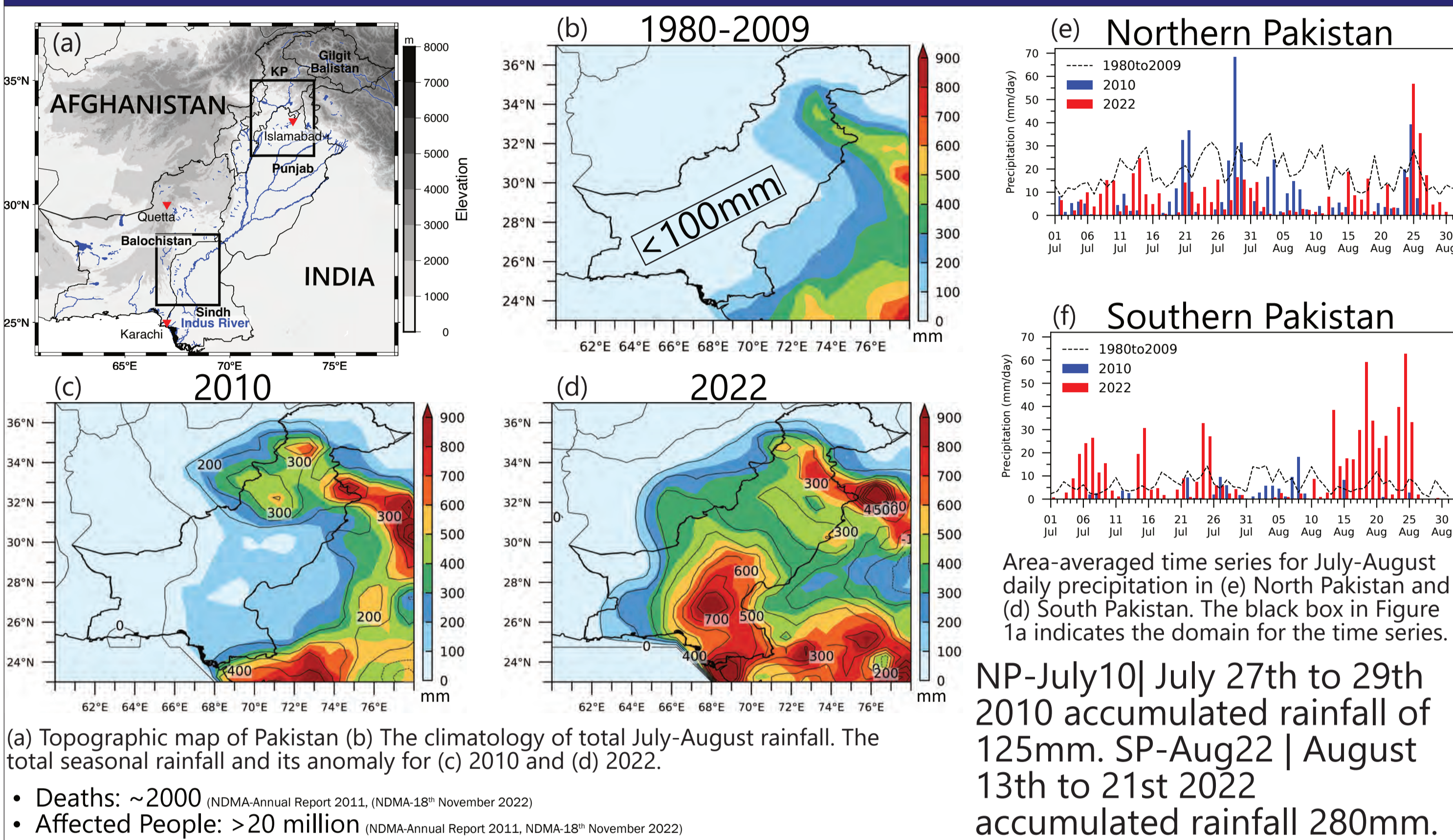
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This study aims to investigate the spatial-temporal rainfall patterns, moisture transport across Pakistan, and the impact of extratropical atmospheric blocking on the major flood events in July 2010 and July-August 2022, which led to over 1,500 fatalities. It focuses on the occurrence of blocking highs over Europe during these periods.

## Pakistan Rainfall: July-August 2010 vs. 2022



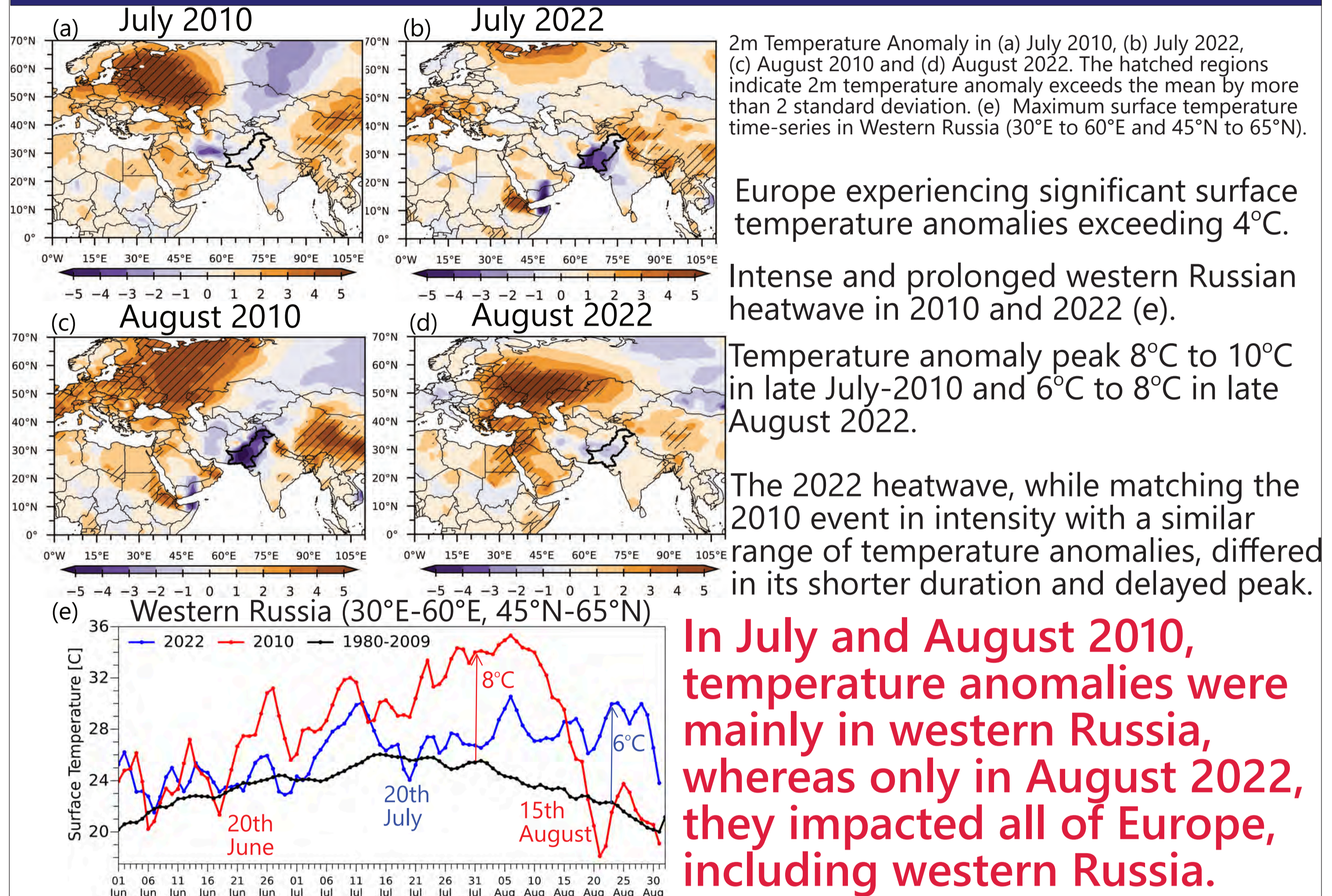
(a) Topographic map of Pakistan (b) The climatology of total July-August rainfall. The total seasonal rainfall and its anomaly for (c) 2010 and (d) 2022.

• Deaths: ~2000 (NDMA Annual Report 2011, NDMA-18<sup>th</sup> November 2022)  
• Affected People: >20 million (NDMA Annual Report 2011, NDMA-18<sup>th</sup> November 2022)

**In 2022, Arid Southern Pakistan Received over 600mm of anomalous rainfall during the July-August season.**

Area-averaged time series for July-August daily precipitation in (e) North Pakistan and (f) South Pakistan. The black box in Figure 1a indicates the domain for the time series.  
NP-July10| July 27th to 29th 2010 accumulated rainfall of 125mm. SP-Aug22 | August 13th to 21st 2022 accumulated rainfall 280mm.

## European Summer Heatwave: 2010 vs. 2022



2m Temperature Anomaly in (a) July 2010, (b) July 2022, (c) August 2010 and (d) August 2022. The hatched regions indicate 2m temperature anomaly exceeds the mean by more than 2 standard deviation. (e) Maximum surface temperature time-series in Western Russia (30°E to 60°E and 45°N to 65°N).

Europe experiencing significant surface temperature anomalies exceeding 4°C.

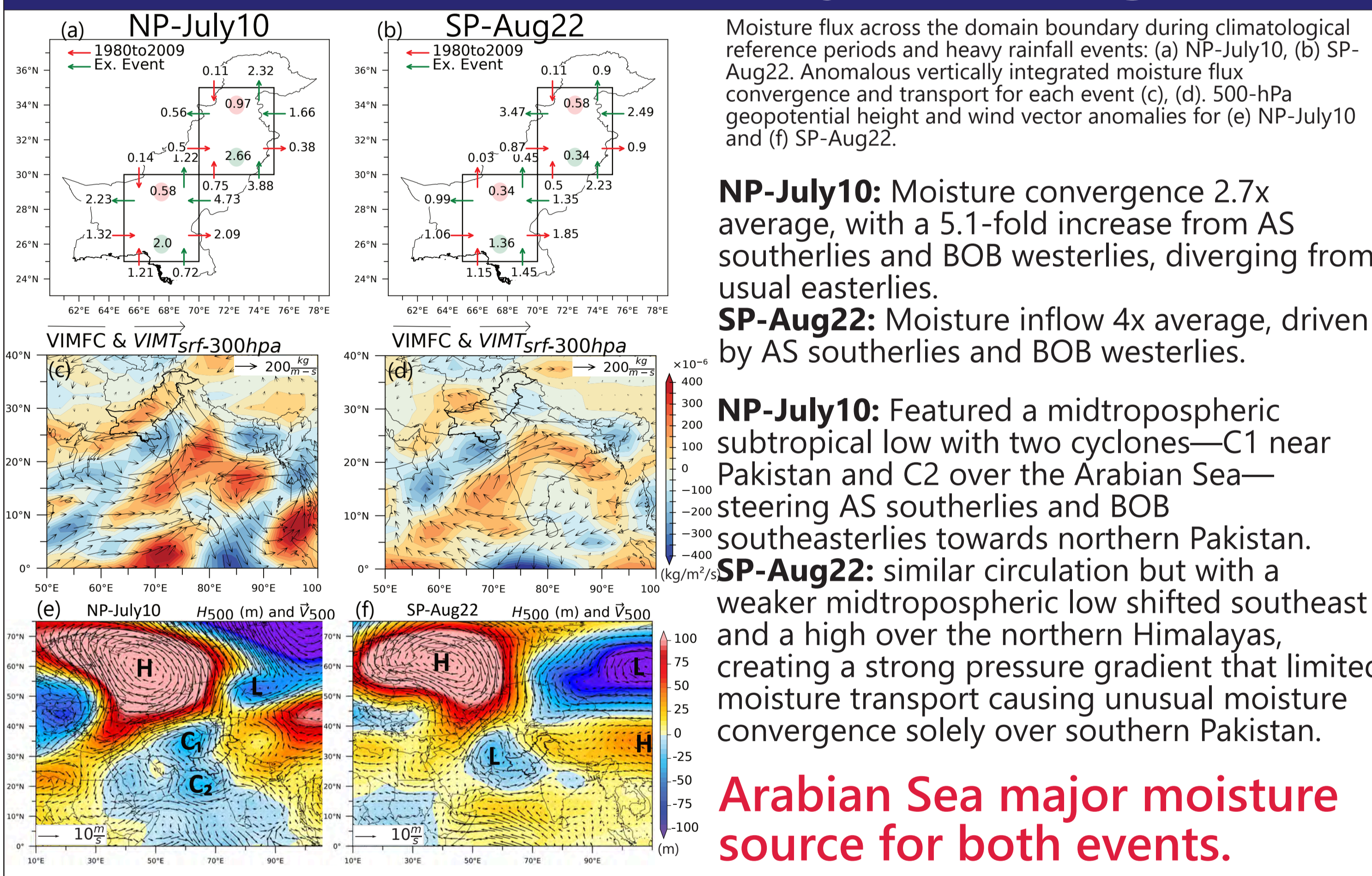
Intense and prolonged western Russian heatwave in 2010 and 2022 (e).

Temperature anomaly peak 8°C to 10°C in late July-2010 and 6°C to 8°C in late August 2022.

The 2022 heatwave, while matching the 2010 event in intensity with a similar range of temperature anomalies, differed in its shorter duration and delayed peak.

**In July and August 2010, temperature anomalies were mainly in western Russia, whereas only in August 2022, they impacted all of Europe, including western Russia.**

## Moisture Source Arabian Sea vs. Bay of Bengal



Moisture flux across the domain boundary during climatological reference periods and heavy rainfall events: (a) NP-July10, (b) SP-Aug22. Anomalous vertically integrated moisture flux convergence and transport for each event (c), (d). 500-hPa geopotential height and wind vector anomalies for (e) NP-July10 and (f) SP-Aug22.

**NP-July10:** Moisture convergence 2.7x average, with a 5.1-fold increase from AS southerlies and BOB westerlies, diverging from usual easterlies.

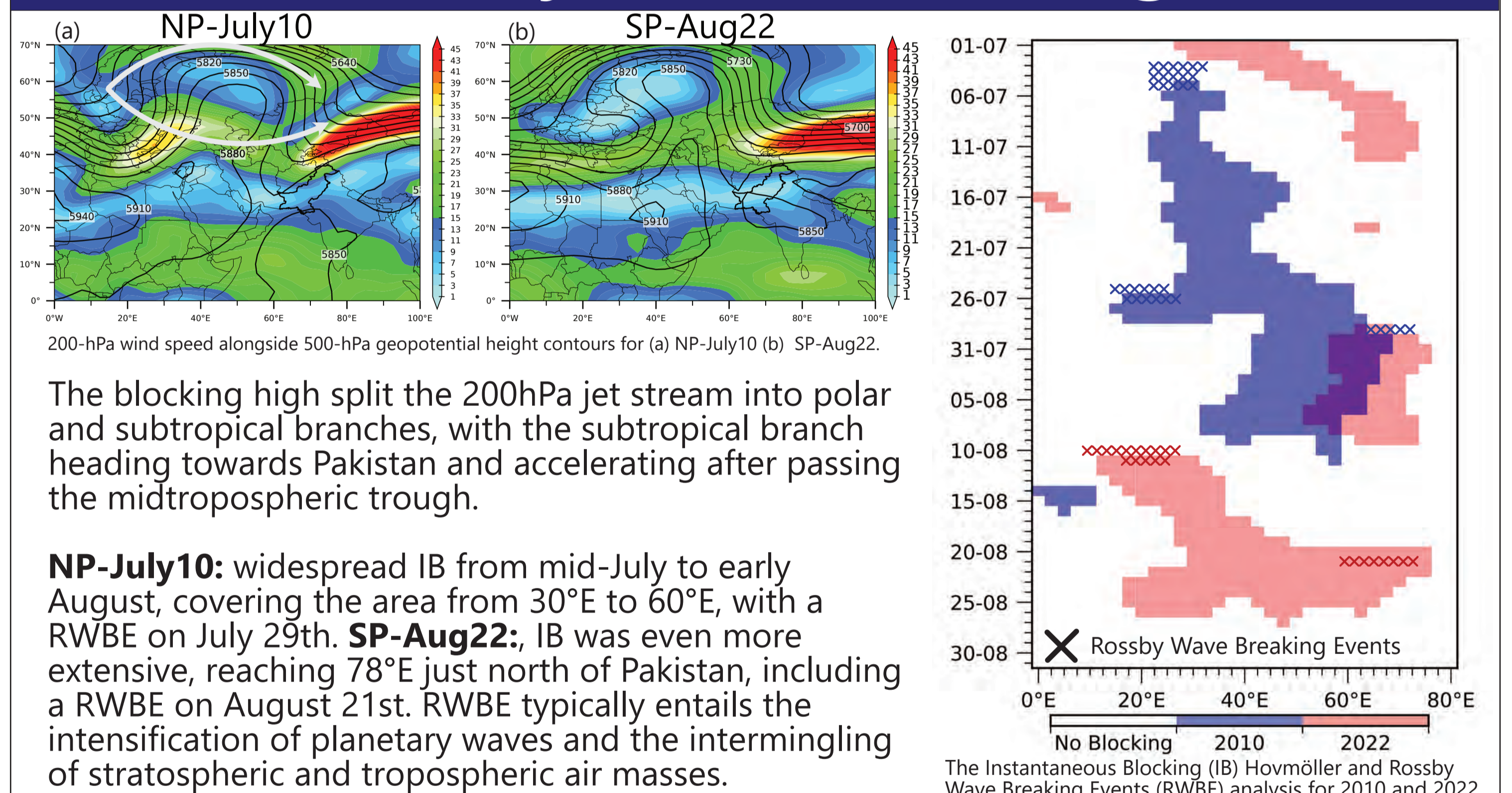
**SP-Aug22:** Moisture inflow 4x average, driven by AS southerlies and BOB westerlies.

**NP-July10:** Featured a midtropospheric subtropical low with two cyclones—C1 near Pakistan and C2 over the Arabian Sea—steering AS southerlies and BOB southeasterlies towards northern Pakistan.

**SP-Aug22:** similar circulation but with a weaker midtropospheric low shifted southeast and a high over the northern Himalayas, creating a strong pressure gradient that limited moisture transport causing unusual moisture convergence solely over southern Pakistan.

**Arabian Sea major moisture source for both events.**

## Atmospheric Blocking | Rossby Wave Breaking

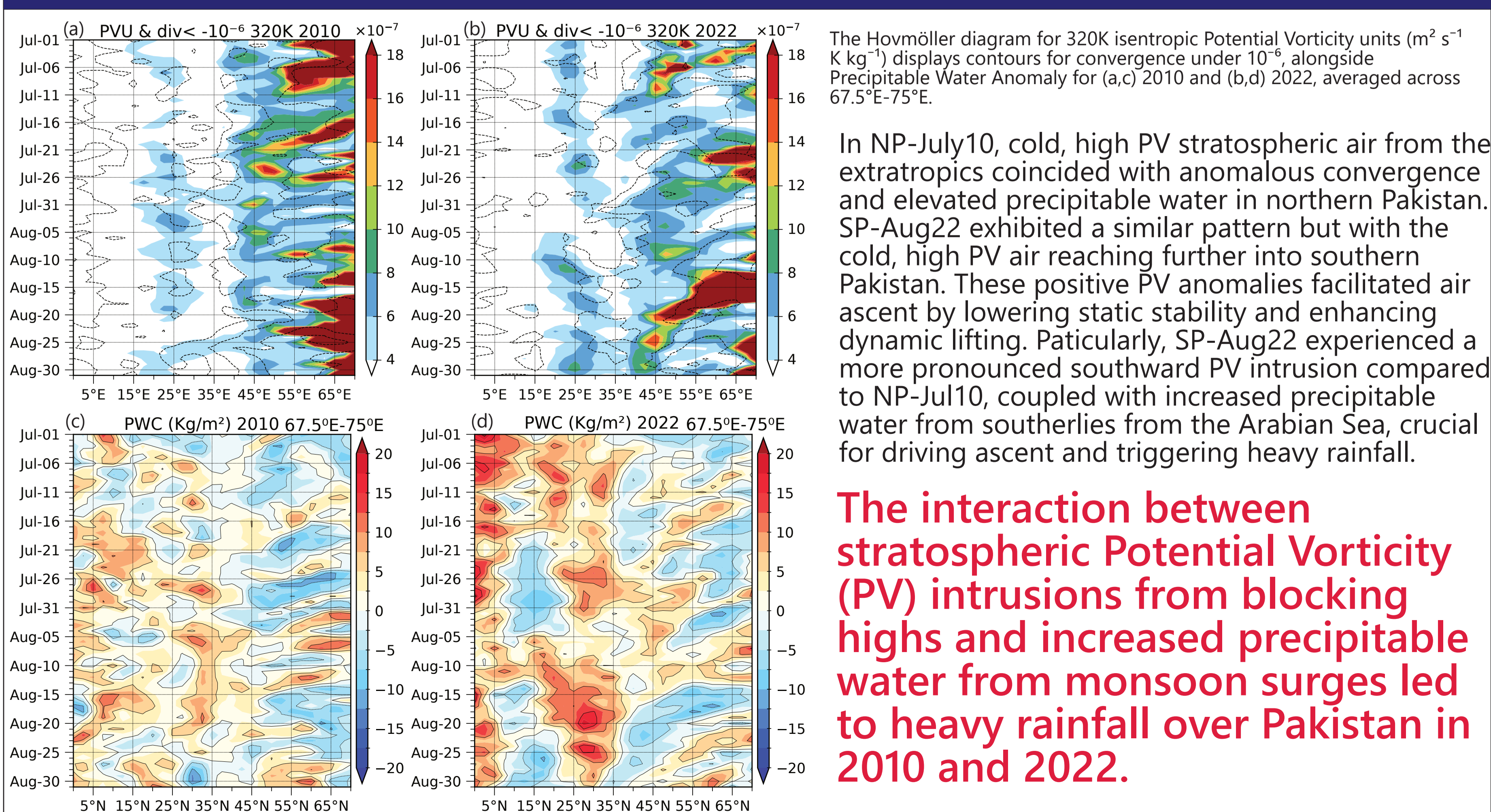


200-hPa wind speed alongside 500-hPa geopotential height contours for (a) NP-July10 (b) SP-Aug22.

The blocking high split the 200hPa jet stream into polar and subtropical branches, with the subtropical branch heading towards Pakistan and accelerating after passing the midtropospheric trough.  
**NP-July10:** widespread IB from mid-July to early August, covering the area from 30°E to 60°E, with a RWBE on July 29th. **SP-Aug22:** IB was even more extensive, reaching 78°E just north of Pakistan, including a RWBE on August 21st. RWBE typically entails the intensification of planetary waves and the intermingling of stratospheric and tropospheric air masses.

**Mid-Latitude Rossby Wave Breaking Events coincided with the onset of heavy rainfall in Pakistan in both 2010 and 2022.**

## Tropical-Extratropical Interactions



The Hovmöller diagram for 320K isentropic Potential Vorticity units ( $\text{m}^2 \text{s}^{-1} \text{K kg}^{-1}$ ) displays contours for convergence under  $10^{-6}$ , alongside Precipitable Water Anomaly for (a,c) 2010 and (b,d) 2022, averaged across 67.5°E-75°E.

In NP-July10, cold, high PV stratospheric air from the extratropics coincided with anomalous convergence and elevated precipitable water in northern Pakistan. SP-Aug22 exhibited a similar pattern but with the cold, high PV air reaching further into southern Pakistan. These positive PV anomalies facilitated air ascent by lowering static stability and enhancing dynamic lifting. Particularly, SP-Aug22 experienced a more pronounced southward PV intrusion compared to NP-July10, coupled with increased precipitable water from southerlies from the Arabian Sea, crucial for driving ascent and triggering heavy rainfall.

**The interaction between stratospheric Potential Vorticity (PV) intrusions from blocking highs and increased precipitable water from monsoon surges led to heavy rainfall over Pakistan in 2010 and 2022.**

## Summary

The study found distinct spatio-temporal rainfall patterns between 2010 and 2022, with Southern Pakistan receiving five times its usual rainfall in late August 2022. Both periods saw Tropical-Extratropical interactions, where Rossby Wave breaking events caused high potential vorticity (PV) stratospheric air to penetrate into lower altitudes, prompting atmospheric ascent. Notably, in August 2022, these PV intrusions extended into Southern Pakistan. These high PV anomalies coincided with strong southerly winds from the northern Arabian Sea, bringing large moisture to the affected areas.