Linkage between Record Floods in Pakistan and a Severe Heatwave in China in the Boreal Summer of 2022

Huang-Hsiung Hsu (✉ hhhsu@gate.sinica.edu.tw)  
Academia Sinica  https://orcid.org/0000-0001-9919-4404

Chi-Cheng Hong  
University of Taipei

An-Yi Huang  
University of Taipei  https://orcid.org/0000-0003-2872-2294

Wan-Ling Tseng  
National Taiwan University  https://orcid.org/0000-0002-6644-9965

Mong-Ming Lu  
National Taiwan University  https://orcid.org/0000-0003-1694-034X

Chih-Chun Chang  
University of Taipei

Article

Keywords:

Posted Date: December 29th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2353452/v1

License: ☕ ☀ This work is licensed under a Creative Commons Attribution 4.0 International License.  
Read Full License
Abstract

In the boreal summer of 2022, Pakistan suffered record rainfall that led to severe flooding and left more than 30 million people homeless. At the same time, a severe heatwave persisted over central China. The concurrence of these extreme events suggests a possible linkage. Our analysis of climatic data indicated that the record rainfall was triggered by an extratropical cold-dry northerly associated with European blocking interacting with an unusually strong warm-moist southerly flow from the Arabian Sea at Pakistan. Both flows joined with an easterly anomaly induced by La Niña over the northern Indian subcontinent, which resulted in strong convergence. Wave activity flux analysis indicated that the European blocking, flooding in Pakistan, and heatwave in China were teleconnected by a stationary Rossby wave-like pattern. The rainfall in Pakistan may have induced diabatic heating that forced an upper-level anomalous anticyclone downstream and strengthened the heatwave in central China.

Introduction

In 2022, a sequence of unusual intense monsoon surges struck Pakistan from mid-June to late August. The extreme rainfall led to widespread landslides along the Indus River basin that induced flooding across one-third of the country and left more than 30 million people homeless and more than 1000 deaths. The accumulated rainfall was three standard deviations above the climatological mean, which was higher than the previous flooding in 2010 that caused significant socioeconomic losses and nearly 3000 deaths. Concurrently, an extreme heatwave persisted over central China, which seriously affected its agriculture and power supply. The concurrence of these extreme events suggests a possible linkage.

The year 2022 was characterized by a long-enduring La Niña that was initiated in 2020. The 2022 La Niña was accompanied by a negative Indian Ocean Dipole (IOD), which comprised positive and negative sea surface temperature anomalies (SSTAs) in the southeastern and western Indian Ocean (IO), respectively. Previous studies have indicated that the Western North Pacific Subtropical High (WNPSH) tends to strengthen in La Niña summers and that it can be further intensified by a negative IOD$^{1-5}$. This seems to have been the case in 2022: an unusually strong WNPSH extended northwestward to central China with a negative IOD, which was accompanied by a mid- to upper-level persistent positive height anomaly. At the mid-latitudes, a persistent heatwave is usually accompanied by a stationary positive height anomaly in the upper troposphere$^{6-9}$. Thus, the WNPSH and accompanying anomaly likely contributed to the heatwave in central China. Similarly, La Niña was concurrent with a negative IOD and enhanced WNPSH in 1998$^{5,10}$, but this year instead saw severe flooding in the Yangtze–Huai River valley and central China. This inconsistency suggests that factors other than the WNPSH may have helped induce the heatwave in 2022.

The 2010 flooding in Pakistan was attributed to a tropical–extratropical interaction between a mid-latitude blocking high and Indian summer monsoon flow in the western IO$^{11-13}$. In 2022, a strong blocking high over Europe (45°–60°E) and an intense Indian summer monsoon were identified from mid-June to late August. It seems likely that a similar tropical–extratropical interaction may have contributed
to the 2022 flooding in Pakistan. In addition, atmospheric internal dynamics and the increasing sea surface temperature (SST) in recent decades may have intensified extreme rainfall and heatwaves\textsuperscript{8,9,14,15}. The SST in the IO has exhibited a significant increasing trend since 1980\textsuperscript{16,17}. A higher SST provides more moisture, which may have enhanced the rainfall that led to the flooding in 2022.

In this study, we explored the physical processes that led to the record rainfall in Pakistan and its potential influence on the concurrent heatwave in central China in 2022. In particular, we focused on the linkage between these two extreme events and the factors that led to the record rainfall. We hypothesized that the flooding was caused by compounding factors: the tropical–extratropical interaction, SSTAs associated with the La Niña and negative IOD, and increasing SST. We also explored the effect of diabatic heating induced by extreme rainfall on a persistent anticyclone downstream, which may explain the heatwave.

**Results**

**Features of the record rainfall in Pakistan**

Figure 1 presents the features of the 2022 rainfall in Pakistan and the associated large-scale circulations. In boreal summer, Pakistan and northwestern India received above-normal rainfall exceeding the 99th percentile for 1979–2022. Downstream of Pakistan, central China received below-normal rainfall and an above-normal near-surface temperature (T2m) exceeding the 99th percentile (Fig. 1a, b). The extreme rainfall extreme in Pakistan was accompanied by an enhanced southwesterly flow in the Arabian Sea, and the unusually warm conditions in central China were accompanied by an enhanced WNPSH and weakened WNP monsoon flow. An easterly anomaly associated with the WNPSH extended from the WNP to northwestern India and converged with the enhanced southwesterly flow from the Arabian Sea over Pakistan, which contributed to the record rainfall. The time series of the rainfall (PKT index) shows that an unusually strong monsoon started in early July and persisted through late August (Fig. 1c). During this period, three strong southerly flows in the Arabian Sea (dashed box in Fig. 1a) reached Pakistan and led to monsoon surges (Fig. 1d). The first surge occurred in early to mid-July; the second happened in late July; and the third was the strongest and most persistent from early to late August. The three monsoon surges accounted for 32.4%, 14.5%, and 45.6%, respectively, of the rainfall from June to August and together comprised more than 90% of the accumulated rainfall. They resulted in a record accumulated rainfall of 500 mm that was four times more than observed since 1979 and was much more than in 2010. We investigated the possible contribution of tropical cyclones to the rainfall in 2022. However, we only found one TC that occurred in the Arabian Sea in 12–13 August and that did not made landfall. Thus, we concluded that the record rainfall was primarily caused by the monsoon surges.

Figure 2 shows that the 2022 flooding in Pakistan was accompanied by La Niña and a moderately negative IOD structure: a negative SSTA in the central-eastern Pacific Ocean (PO) and western IO and a positive SSTA in the eastern IO and western PO. A mid- to upper-level blocking high over Europe was also observed, similar to 2010. The anomalous trough downstream of the blocking high transported cold and
dry air southward to Pakistan and created a convection-favorable environment (i.e., unstable atmosphere) when it met the tropical warm-moist southerly flow from the Arabian Sea. Such a tropical–extratropical interaction was also observed in 2010 and thus may have a significant role in inducing extreme rainfall. Figure 3 shows that the first and third monsoon surges occurred concurrently with the arrival of the northerly wind anomaly at Pakistan from the deepened trough downstream of the European blocking high. In contrast, the blocking index was not as high during the second surge. Further analysis suggested that a westward-moving Rossby wave was initiated from the northern part of a twin cyclone straddling the equator in the eastern IO (not shown), which may have contributed to the second surge. The southerly associated with the second surge was not rooted in the deep tropics but was instead confined between 15° and 30°N, which is characteristic of a westward-moving off-equator disturbance.

The 2010 and 2022 events differed as follows. First, a basin-wide warm SSTA occurred in the western IO in 2010, but a negative IOD-like SSTA occurred in 2022. Second, an unusually persistent upper-level anticyclone anomaly occurred over central China in 2022. In 2010, a positive anomaly near Japan characterizing an enhanced Bolin high was observed instead (Fig. 2e). Third, the persistent anomalous anticyclone in 2022 was accompanied by a serious heatwave, but no heatwave was observed in 2010. During the 1998 La Niña, no blocking signal was observed over Europe, and the tropical–extratropical interaction seen in 2010 and 2022 was not evident (Fig. 3a, b). Additionally, Pakistan received a normal amount of rainfall in summer of 1998 (Fig. 3c). These differences suggest that the European blocking high was more crucial than the La Niña SSTA to the extreme rainfall in Pakistan, even though the Indian monsoon flow should be strong in a La Niña summer. The 2010 and 2022 events differed as follows. First, a basin-wide warm SSTA occurred in the western IO in 2010, but a negative IOD-like SSTA occurred in 2022. Second, an unusually persistent upper-level anticyclone anomaly occurred over central China in 2022. In 2010, a positive anomaly near Japan characterizing an enhanced Bolin high was observed instead (Fig. 2e). Third, the persistent anomalous anticyclone in 2022 was accompanied by a serious heatwave, but no heatwave was observed in 2010. During the 1998 La Niña, no blocking signal was observed over Europe, and the tropical–extratropical interaction seen in 2010 and 2022 was not evident (Fig. 3a, b). Additionally, Pakistan received a normal amount of rainfall in summer of 1998 (Fig. 3c). These differences suggest that the European blocking high was more crucial than the La Niña SSTA to the extreme rainfall in Pakistan, even though the Indian monsoon flow should be strong in a La Niña summer.

Table 1 compares the extreme events in 1998, 2010, and 2022. The WNPSH was enhanced for all three events, but it exhibited a northward extension in 2010 and northwestward in 2022 with no clear shift in 1998 (Fig. 2). A blocking high over Europe and intense Pakistan rainfall were both identified in 2010 and 2022 but not in 1998, which indicates that the blocking high and associated tropical–extratropical interaction are crucial to inducing extreme rainfall in Pakistan (Fig. 3). The La Niña-associated SSTA in the eastern equatorial PO is known to enhance the WNPSH. The easterly anomaly extending from the WNP to IO signals a weakened southwesterly monsoon flow, which would increase rainfall in Pakistan and northwestern India. An anomalous easterly was observed in all three years, but rainfall only increased in 2010 and 2022 concurrent with a more active tropical–extratropical interaction. These results indicate that La Niña did not have as direct an effect on the rainfall in Pakistan as the tropical–extratropical interaction. It is unclear why the accumulated rainfall was much more in 2022 than in 2010.

Table 1. A comparison of large-scale atmospheric and oceanic conditions between 1998, 2010, and 2022.
<table>
<thead>
<tr>
<th>August</th>
<th>1998</th>
<th>2010</th>
<th>2022</th>
</tr>
</thead>
<tbody>
<tr>
<td>WNPSH (low level)</td>
<td>Strong, southern China</td>
<td>Strong, northward expansion (Japan)</td>
<td>Strong, westward expansion (Southern China)</td>
</tr>
<tr>
<td>Monsoon</td>
<td>Indian</td>
<td>Strong</td>
<td>Strong</td>
</tr>
<tr>
<td>WNP</td>
<td>Weak</td>
<td>Weak</td>
<td>Weak</td>
</tr>
<tr>
<td>Easterly anomaly</td>
<td>10°N–20°N (position)</td>
<td>15°N–25°N</td>
<td>20°N–30°N</td>
</tr>
<tr>
<td>over NIO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropical SST</td>
<td>Pacific</td>
<td>Strong La Niña</td>
<td>La Niña</td>
</tr>
<tr>
<td></td>
<td>Atlantic</td>
<td>Warm</td>
<td>Not evident</td>
</tr>
<tr>
<td>Mid-latitude</td>
<td>Siberian blocking</td>
<td>European blocking, anticyclone anomaly</td>
<td>European blocking, anticyclone anomaly</td>
</tr>
<tr>
<td>disturbance</td>
<td></td>
<td>over Japan</td>
<td>over central China</td>
</tr>
<tr>
<td>(mid-upper level)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropical-extratropical interaction</td>
<td>Not evident</td>
<td>Strong</td>
<td>Very strong</td>
</tr>
<tr>
<td>Trend effect</td>
<td>Not evident</td>
<td>Weak</td>
<td>Strong</td>
</tr>
</tbody>
</table>

**Linkage between the flooding in Pakistan and heatwave in central China**

Figure 4 shows Hovmöller diagrams (averaged over 25°–35°N) of anomalous T2m and precipitation in 2022. The flooding in Pakistan was accompanied by a negative T2m anomaly. In contrast, the opposite situation occurred in central China. The rainfall time series in the two regions also showed negative correlation (not shown). This suggests that the flooding in Pakistan and heatwave in central China were probably linked. Regression analysis was performed to obtain any correlations of the T2m, precipitation, and geopotential height data for the Eurasian content with the rainfall index over Pakistan (PKT: 22°–32°N, 63°–73°E). A teleconnection pattern of the temperature and geopotential height was shown to extend from Europe to East Asia (Fig. 4c, d). The rainfall in Pakistan was also significantly correlated with negative precipitation anomalies in western Europe and central-eastern China and with positive anomalies in South/Southeast Asia and northern China. The teleconnection pattern showed a close resemblance to observed anomalies in 2022, and it indicates that the climate anomalies in Europe and Asia are connected. This pattern initially appeared to be the Scandinavia pattern, which was previously reported to affect the heatwave in northeast Asia (Supplementary Fig. 1b). However, the teleconnection pattern showed an eastward shift compared with the Scandinavia pattern. Additionally, the Scandinavia pattern was accompanied by wet conditions in southern China and no significant rainfall in Pakistan. In contrast, the teleconnection pattern (Supplementary Fig. 1a) was accompanied by dry conditions in southern China and above-normal rainfall in Pakistan. The correlation coefficient (r = 0.17, p = 0.27) indicates that the teleconnection and Scandinavia patterns are not temporally correlated. The teleconnection pattern associated with the rainfall in Pakistan seems like a new pattern that warrants further investigation.

Analysis of the wave activity flux indicated a stationary Rossby wave-like perturbation that originated from European blocking and emanated southeastward to central Asia and central China and then
northeastward to the extratropical north PO (Fig. 5). Positive streamfunction anomalies (i.e., blocking or ridges) were associated with heatwaves in Europe and China, whereas negative anomalies (i.e., deepened troughs) were associated with flooding in Pakistan. These results indicate that the heatwaves and flooding in 2022 were linked by the anomalous Rossby-wave-like activity.

The extreme precipitation near Pakistan may have acted as a large diabatic heating source that further triggered perturbations downstream. We used a linear baroclinic model (LBM) to conduct numerical experiments on the possible downstream impact of diabatic heating over Pakistan\textsuperscript{26–28}. The heating may have induced a positive H200 anomaly over central China (Supplementary Fig. 2a) as well as perturbations dissimilar to the anomalies observed over other regions. This suggests that the diabatic heating was likely a response to upstream wave activity from Europe and in turn helped sustain the ridging activity and heatwave over central China. The regression analysis and numerical experiments indicate that diabatic heating in Pakistan and wave activity over Eurasia jointly induced the mid-upper level anticyclone over central China that resulted in the unusually strong and persistent heatwave.

**Influencing factors**

Climate extremes such as the record rainfall in Pakistan are usually induced by compounding factors\textsuperscript{29,30}.

**Tropical–extratropical interaction and topography effect**

The tropical–extratropical interaction likely played a dominant role in inducing the record rainfall (Table 1, Fig. 3). The first and third monsoon surges occurred when the northerly wind associated with upstream blocking met the southerly flow over Pakistan. These two surges accounted for approximately 80% of the total rainfall in June–August (Fig. 1c). The diabatic heating associated with heavy rainfall also had a positive feedback loop with the tropical–extratropical interaction by enhancing the extratropical northerly and tropical southerly flow (Supplementary Fig. 2b). Figure 6 reveals that the easterly anomalies in northern India were equivalent in 2010 and 2022, but the southerly over the Arabian Sea was much stronger in 2022. The convergence of the enhanced warm-moist southerly and cool-dry northerly in Pakistan (Fig. 3h) was a key feature that was much weaker in 2010. This distinction may help explain the much greater rainfall in 2022. This large-scale moisture convergence, together with the lifting effect of the topography in Pakistan, likely played an essential role in inducing the record rainfall (not shown).

**La Niña-associated SSTAs**

La Niña is associated with a negative SSTAs in the equatorial eastern PO, which could force an anticyclonic anomaly (i.e., a typical Gill-type response) in the WNP and in turn substantially strengthen the WNPSH and weaken the southwesterly in South Asia\textsuperscript{11,31–33} (Table 1, Fig. 6a, b). This would block the southwesterly flow in the Arabian Sea and provide favorable conditions for heavy rainfall in the northwestern Indian subcontinent (Fig. 1a). However, La Niña occurred in both 2010 and 2022 (Fig. 2b, c), so it cannot explain why the total rainfall was so much greater in 2022.
The southwesterly flow in the Arabian Sea was much stronger in 2022 than in 2010 (Fig. 6). In 2010, La Niña was accompanied by basin warming in the IO, but in 2022, La Niña was accompanied by a negative IOD (Fig. 2b, c). The major distinction between 2010 and 2022 is the negative IOD, which is associated with a negative SSTA in the western IO and is accompanied by a strong southwesterly anomaly (Fig. 1a). However, regression analysis of the 850 hPa horizontal wind onto the IOD index did not yield a good correlation between the southerly in the Arabian Sea and the negative IOD (not shown). Therefore, the enhanced southwesterly cannot be attributed to the IOD. The numerical experiments suggest that the diabatic heating induced by the rainfall in Pakistan may have further enhanced the lower-level southerly in the Arabian Sea (Supplementary Fig. 2b). We hypothesize that a positive feedback loop between the heating-induced southerly and precipitation in mountainous Pakistan contributed to the record rainfall.

**Upper-level anticyclone associated with the heatwave in central China**

One major distinction between 2010 and 2022 was the northwestward extension of the enhanced WNPSH to central China in the latter year (Table 1, Fig. 2), which was coupled with the upper-level anticyclone anomaly that led to the severe heatwave. This anticyclone exhibited an equivalent barotropic structure in which the associated easterly anomaly extended from the upper troposphere to the lower troposphere (Fig. 6d). This easterly anomaly enhanced the low-level easterly associated with La Niña in the north Indian subcontinent and shifted it closer to Pakistan (Fig. 6a, b). In 2010, this enhancing effect was not observed, and the equivalent barotropic structure was much weaker. Instead, a dominant baroclinic vertical structure appeared over the subtropical north PO. The enhanced easterly shifted northward, enhanced southerly from Arabian Sea, and northerly anomaly associated with European blocking converged near Pakistan and contributed to the record rainfall. The equivalent barotropic vertical structure is typical for Rossby-wave-like perturbations and suggests the extratropical origin of the anomalous anticyclone as part of the teleconnection pattern in Fig. 4d, whose upper-level component can be enhanced by diabatic heating associated with precipitation near Pakistan. The compounding effect of the extratropical and La Niña-associated perturbations was not seen in 2010, which may help explain why the rainfall was much greater in 2022.

**Intensifying southerly**

Another possible factor for the intensified monsoon flow over the Arabian Sea is its intensifying trend. Although the summer rainfall in Pakistan did not exhibit a significant trend (Fig. 7a), the 850 hPa horizontal wind revealed a significant intensifying trend of the southerly in the Arabian Sea over 1979–2021 (Fig. 7b), especially in August (not shown). Anticyclonic and warming trends were also observed over western Eurasia and northern continental East Asia. The anticyclonic trend at 850 hPa can be associated with mid-level trends such as European blocking (Fig. 7c). The southerly trend in the Arabian Sea and blocking trend in Europe for 1979–2021 favor the tropical–extratropical interaction. Removing the linear trend from the 2022 anomalies yielded a much weaker southerly in the northern Arabian Sea and extratropical circulation, including the anomalous highs over Europe and central China.
(Supplementary Fig. 3). This indicates the marked contribution of recent trends to the observed anomalies and the strong tropical–extratropical interaction in 2022 to the extreme rainfall in Pakistan.

The intensifying trend of the southerly over the Arabian Sea likely resulted from the enhanced land–sea contrast in recent decades (Fig. 7b). The extratropical land has warmed faster than the ocean, particularly in central Asia, the Arabian Peninsula, and the Arabian Sea. A stronger land–sea contrast may create a stronger southerly flow over the Arabian Sea and enhance its intrusion into central Asia and the Arabian Peninsula.

**Discussion**

In this study, we investigated the linkage between record rainfall in Pakistan and a severe heatwave in China in 2022 and the possible physical processes behind them. Our analysis revealed that the record rainfall in Pakistan was caused by several compounding factors. The record rainfall in Pakistan was triggered by the interaction between an unusually warm-moist southerly flow from the Arabian Sea and an extratropical cold-dry northerly anomaly associated with European blocking. The enhanced convergence favored the development of strong convection and heavy rainfall, which were further enhanced by an easterly anomaly over the northern Indian subcontinent induced by La Niña and the lifting effect of the topography of Pakistan. Wave activity flux analysis indicated that the European blocking, flooding in Pakistan, and the heatwave in China were linked together though a stationary Rossby wave-like perturbation originated from the European blocking and emanated southeastward to central Asia and central China and then northeastward to the extratropical North PO. These results might be used in the hazard warning and prediction. Further analysis (Supplementary Fig. 1a) revealed that the stationary Rossby wave, differing from the Scandinavia patterns, was likely a new teleconnection. The characteristic of teleconnection pattern associated with the rainfall in Pakistan and the possible impact on the climate warrants further investigation.

The concurrence of flooding in Pakistan and heat wave in central China indicated that the wet and dry extremes might be mutually enhanced. Our analysis showing the potential positive feedback between two extremes confirmed this hypothesis (Fig. 6 and Supplementary Fig. 2). In the meantime, whether the concurrence of two extremes was related with recent warming, and how their intensity and frequency will change in future under global warming need further investigation.

Several studies reported that the weather and climate extreme events will occur with higher frequency and intensity under a warming climate\(^{34,35}\). It seems that the record Pakistan rainfall in 2022 is a footprint of warming climate. Figure 7 reveals that a large part of enhanced southwesterly flow over the Arabian Sea, which played a critical role in establishing strong moisture flux convergence, was largely contributed by the recent enhancing trend. Under an extreme warming climate (i.e., future projection), the potential change of the southwesterly flow over the Arabian Sea and its possible impact on the tropical–extratropical interaction and extreme weather events are under investigation.
Methods

Data

We used the daily precipitation data from the Climate Prediction Center Global Unified-Based Analysis of Daily Precipitation\(^{36}\) and monthly precipitation data from the Global Precipitation Climatology Project\(^{37}\) (GPCP, version 2.3). Monthly precipitation and T2m gridded time series datasets from Climatic Research Unit\(^{38}\) (CRU, version 4.06) were also analyzed. We utilized the ERA5 daily and monthly data\(^{39}\) of the European Centre for Medium-Range Weather Forecasts for upper-level diagnostics including horizontal winds (U and V), geopotential height (Z), and specific humidity (Q).

Blocking index

The blocking index\(^{40}\) is used to identify atmospheric blocking, which is a steady atmospheric condition that often accompanies prolonged extreme weather (e.g., heatwaves). For the Northern Hemisphere, the blocking index is calculated by using the 500 hPa geopotential height (for details, please refer to https://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/block.shtml).

Regression analysis

We calculated regression coefficients to estimate the relationship between two monthly-mean time series. The linear regression model can be expressed as \(Y_i = \alpha + \beta X_i + \varepsilon\), where \(X_i\) and \(Y_i\) are two time series we expect to know their relationship, \(\alpha\) is the intercept, \(\beta\) is the slope (regression coefficient), and \(\varepsilon\) is the residual.

Percentile rank

The percentile rank is expressed as a whole number between 1 and 99 and is used to evaluate the precipitation intensity and T2m as the percentage of scores in a reference group that is lower than a given score of interest.

Idealized heating experiments

We used an LBM to conduct idealized heating experiments\(^{26}\). The model was forced by an idealized heating center in Pakistan (approximately 29°N, 68°E) with the August climatological field. The 200 and 850 hPa geopotential heights and the 850 hPa horizontal winds from the day-30 output were analyzed.

Declarations

DATA AVAILABILITY

The CPC and GPCP precipitation data were provided by NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their websites at https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html and https://psl.noaa.gov/data/gridded/data.gpcp.html, respectively. The CRU precipitation and 2m temperature data are from https://crudata.uea.ac.uk/cru/data/hrg. The ERA5 reanalysis data was
obtained from Copernicus Climate Change Service (C3S) Climate Data Store (CDS) and available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form.

**CODE AVAILABILITY**

All the computer codes used to generate the results and figures of this study are available from the authors upon request. All figures were generated by using the MATLAB and Statistics Toolbox Release 2021b version 9.11.0.1769968 with the M_MAP mapping package version 1.4m (https://www.eoas.ubc.ca/~rich/map.html), and the NCAR Command Language (NCL) (https://www.ncl.ucar.edu/) version 6.3.0.

**ACKNOWLEDGEMENTS**

This study was in memory of Dr. Masao Kanamitsu, who gave C.-C.H a crucial push in his first research visit. This study was supported by the National Science and Technology Council (NSTC), Taiwan (R. O. C.), under grant numbers 109-2111-M-845-001 and 110-2111-M-845-001. The authors are grateful to the National Center for High-Performance Computing (NCHC), National Applied Research Laboratories (NARLabs) for providing computer facilities. This manuscript was edited by Wallace Academic Editing.

**AUTHOR CONTRIBUTIONS**

C.-C.H. and H.-H.H. conceptualized the study. A.-Y.H. and C.-C.C. contributed to data collection and analysis. W.-L.T. carried out the model experiments. C.-C.H. drafted the manuscript, and H.-H.H., A.-Y.H., and M.-M.L. were involved critical revisions. All authors contributed to review and improve the manuscript, and approve the final manuscript.

**COMPETING INTERESTS**

The authors declare no competing interests.

**References**


**Figures**

**Figure 1**

**Large-scale conditions during the 2022 extreme Pakistan extreme rainfall events.** (a) July–August averaged anomalous precipitation (PR, shading; unit: mm·day$^{-1}$) and 850 hPa moisture flux (UqVq850, vectors; unit: m·s$^{-1}$ g·kg; minimum vector: 15). Blue solid and dash boxes indicate the regions for Pakistan (PKT; 22°N–32°N, 63°E–73°E) rainfall index and monsoon flow (V850; 10°N–20°N, 50°E–65°E) index, respectively. Shading with white hatched regions indicates the signals exceeding the 99th percentile during 1979–2022. (b) Same as in (a), except the shading represents the near surface temperature (T2m) anomaly. (c) Bars and lines represent daily and accumulated PKT rainfall during June–August 2022, respectively. The colored bars indicate three waves of extreme rainfall periods (7/1–7/18, 7/23–7/30, and 8/4–8/30). The numbers above three colored bars are the percentage of the accumulated rainfall in each period against total period (6/1–8/31). (d) Blue and black lines represent the 2022 and climatological monsoon flow during June–August, respectively.
Figure 2

Comparisons of boreal summer SST and large-scale circulations during La Niña events in 1998, 2010, and 2022. (a) July–August averaged anomalous sea surface temperature (SST, shading; unit: °C) and 850 hPa streamfunction (PSI850, contour; unit: 10^6 m^2·s^-1; interval: 1.5) in 1998. (b, c) Same as (a), but for 2010 and 2022, respectively. (d) July–August averaged anomalous outgoing long-wave radiation (OLR, shading; unit: W·m^-2) and 200 hPa streamfunction (PSI200, contour; unit: 10^6 m^2·s^-1; interval: 1.5) in 1998. (e, f) Same as (d), but for 2010 and 2022, respectively.
Figure 3

Daily tropical-extratropical interactions during La Niña events in 1998, 2010, and 2022. (a) North Hemisphere blocking index (Hovmöller diagram), (b) 10m meridional wind (V10m) averaged over 50°E–65°E (Hovmöller diagram), and (c) daily (bars) and accumulated (lines) PKT rainfall during June–August 1998, respectively. (d–f) Same as (a–c), but for 2010. (g–i) Same as (a–c), but for 2022.

Figure 4
Linkage between Pakistan rainfall and central China heatwave. (a) Hovmöller diagram of daily 2m temperature (T2m) anomaly averaged over 25°N–35°N during June–August 2022. (b) Same as (a), but for precipitation. (c) Regression of July–August averaged T2m (shading) on normalized PKT index during 1979–2021. Black dots indicate the regression coefficients exceeding 90% confidence level based on Student’s $t$-test. (d) Same as (c), but for precipitation (shading) and 500 hPa geopotential height (contour; interval: 2.5). Shadings and slashed regions indicate the regression coefficients exceeding 90% confidence level based on Student’s $t$-test.

![Figure 5](image)

**Figure 5**

Teleconnection pattern and wave activity anomalies in August 2022. Shadings represent the 200hPa streamfunction (unit: $10^7$ m$^2$·s$^{-1}$) and vectors are wave activity flux (unit: m$^2$·s$^{-2}$).
Figure 6

Comparisons of large-scale circulations between two extreme Pakistan events in 2010 and 2022. (a, b) July–August averaged anomalous precipitation (PR, shading; unit: mm/day), 850 hPa moisture flux (UqVq850, vectors; unit: m·s⁻¹·g·kg; minimum vector: 15), and 500 hPa geopotential height (H500, contour; unit: m; interval: 10) in 2010 and 2022. (c, d) Cross section of July–August averaged anomalous zonal wind (U-wind: unit: m/s) and geopotential height (H; unit: m; interval: 40) along 25°N (vertical profile) in 2010 and 2022.
Figure 7

The long-term linear trends. (a) Climatology of boreal summer (JJA) 850hPa wind and precipitation during the period 1979–2021. The precipitation marked by red (blue) dot indicate the yearly precipitation with significantly upward (downward) trend during 1979–2021. (b) The linear trend of near surface temperature at 2m (T2m) (shadings), and 850hPa wind (streamline). Only the trend (T2m, SST) exceeding the 90% confidence test was plotted. As for the trend of winds that exceed the 90% confidence
test was displayed in blue vectors. (c) Same as in (b) except for the 500hPa geopotential height (shadings) and wind (streamline and vectors).

**Supplementary Files**

This is a list of supplementary files associated with this preprint. Click to download.

- npjsupplementary.docx