

1                   **The 2010 Pakistan Flood and the Russia Heat Wave:**

2                   **Teleconnection of Extremes**

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26 **The Pakistan flood and the Russia heat wave/wild fires of the summer of 2010 were two of**

27 **the most extreme events in the histories of the two countries occurring at about the same**

28 **time. To a casual observer, the timing may just be a random coincidence of nature, because**

29 **the two events were separated by long distances, and represented opposite forces of nature,**

30 ***i.e.*, flood vs. drought, and water vs. fire. Here, we present evidences showing that the two**

31 **events were indeed physically connected. Our results show that the root cause of the 2010**

32 **Russia heat wave/wild fires was an atmospheric blocking event in high latitudes which,**

33 **through the excitation of a large-scale atmospheric Rossby wave, was instrumental in**

34 **affecting the rainfall evolution of the South Asian summer monsoon, including triggering the**

35 **development of a mid-tropospheric cyclone that was responsible for the torrential rain over**

36 **Pakistan.**

37 During July and August, 2010 Pakistan suffered the worst flood in 100 years. Over 1500

38 people and 1 million homes perished and 20 million were rendered homeless, or displaced from

39 their homes by the floodwater. The total economic lost from property and crop damage, loss of

40 businesses was in the tens of billions. At about the same time, Russia was stricken by a record

41 heat wave, with temperature in Moscow rising above 40° C for a prolonged period in July and

42 August 2010, and the entire western Russia region (including western Siberia) was suffering

43 from a prolonged drought. Intense and extensive wild fires raged over more than 5000 km<sup>2</sup> of

44 forested area. The Russia heat wave, drought and forest fires might have taken over 5,000 lives

45 and cost the economy loss more than 15 billion. By any measure, the Pakistan flood and the

46 Russian heat wave /wild fires were super extreme events, both from the perspectives of

47 meteorology and society impacts. Already, the media, pundits and some scientists were  
48 wondering aloud whether the Pakistan flood and Russia heat wave and many of the extreme  
49 weather events experienced around the world in 2010 were the results of global warming.  
50 However, while the 2010 extreme events will likely add to the statistics of extreme events  
51 consistent with projections of global warming, no attribution can be made based on a single  
52 event. From past experience, an extreme event is seldom the result of a singular cause, but  
53 rather the end product of positive feedback from an alignment of multiple factors, on both  
54 large and small scales. In this study, we focus on such an alignment of factors leading to the  
55 Russian heat wave and the Pakistan flood. Our paper differs from previous studies of extremes  
56 in that we identify not only the causes of each event, but also the possible physical connection  
57 between them. Methodology and data used for this study are described in the Method Section  
58 at the end of the manuscript.

#### 59 **The Pakistan flood**

60 Tucked away in the northwestern corner of the Indian subcontinent, and bounded on the  
61 northeast by the high mountains of Karakoram, on the west by the arid regions and deserts of  
62 Afghanistan, Syria and Iran, and on the south by the Arabian Sea, Pakistan is a relative dry  
63 region compared to monsoon India. Even during the peak of the monsoon season, July-August,  
64 the average total rainfall over the wettest part of the country (northern Pakistan) is of the  
65 order of 160-180 mm – a scanty amount compared to rain total of 1600-2000 mm for the same  
66 months over the wettest monsoon regions of northeastern India and the Bay of Bengal. Based  
67 on the NOAA Climate Prediction Center rainfall station data<sup>1</sup>, during the 2 week period, July 25-  
68 August 8 2010, torrential rain of approximately 500 mm fell in about 10 days in the northern

69 Pakistan Swat Valley, exceeding more than 70% of the total *annual* mean rainfall over the same  
70 region. As shown in rainfall anomaly field in Fig. 1a, the heavy rain over northern Pakistan was  
71 not isolated geographically, but appeared to be connected to excessive monsoon rainfall over  
72 northern and northeastern India along the foothills of the Himalaya, and central and  
73 northeastern Arabian Sea. Reduced rainfall was found over most part of central and southern  
74 India, and the southern Bay of Bengal, and along the coast of Myanmar. The widespread  
75 rainfall anomaly suggested that the Pakistan heavy rain was a part of a major shift in the entire  
76 monsoon rainfall pattern, which normally has the heaviest rainfall over Bangladesh and Bay of  
77 Bengal in August.

#### 78 **The Russian heat wave**

79 Russia is a vast country, covering northeastern Europe and Siberia, stretching from the  
80 Arctic Circle southward to Ukraine and Kazakhstan, southeastward to Mongolia and  
81 northeastern China. The dominant vegetation is tundra in the extreme northern regions  
82 around the Arctic Circle, tiaga (boreal forest) in northern and central Siberia, and temperate  
83 forest and steppe grassland in the south. In western Russian, climatologically July-August is the  
84 rainy season, with mean monthly rainfall of 75-85 mm. However, atmospheric blocking  
85 condition which slows or prevents the passage of rain storms, may develop and last for weeks,  
86 leading to dry conditions and wild forest fires<sup>2-4</sup>. During July-August 2010, a record heat wave  
87 and drought developed and prevailed over western Russia. Temperature in Moscow in August  
88 soared to a record daily high of 40° C (about 10 degree above the climatological mean). Prior to  
89 2010, the highest temperature record in Moscow was set at 36.8° C in August, 1920. During  
90 the two-week period coinciding with the Pakistan flood, the heat wave expanded to cover

91 western Russia, western Siberia, and Eastern Europe (Fig. 1b). The extreme hot and dry weather  
92 spurred ferocious forest fires over the vast taiga regions of western Russia and Siberia, and  
93 Ukraine, as evidence in the density of the satellite fire counts. Also noteworthy is that  
94 temperature contrast, with much cooler temperature prevailed in the adjacent regions to the  
95 heat wave, over central and eastern Siberia, and western Europe.

#### 96 **Teleconnection**

97 Figure 2 shows the time series of rainfall from TRMM over northern Pakistan [32-35N, 70-  
98 73E] and surface temperature from AIRS and fire count from MODIS over western Russia [45-  
99 65N, 30-60E]. Very heavy rain fell over northern Pakistan intermittently in clusters of 3-4 days  
100 during the two-week period from July 25- August 10, following a period of steadily increasing  
101 rainfall beginning in mid-June. Surface temperature over western Russia rose rapidly around  
102 June 20; remained at a high level for the next 10 days or so, and soared from around July 18 to  
103 reach a very high-level, with maximum area-averaged temperature exceeding nearly 9° C above  
104 the seasonal mean, during a 2-week period contemporaneous with the heavy rain over  
105 Pakistan. The Russia forest fire activity, as evident from the MODIS fire count, was near  
106 normal or slightly elevated about the same time as the heat wave emerged, but dramatically  
107 intensified around July 25 and remained at a very high level till August 10, and dropped off  
108 rapidly, as a cold front passed through and brought rain to the area. The correlation between  
109 surface temperature and fire count is 0.70, and between fire count, surface temperature and  
110 Pakistan rainfall is 0.50 and 0.37, respectively. All correlations are statistically significant at the  
111 95% level. The high correlation between heat wave and forest fire is expected, because the  
112 abnormally hot and dry air associated with the heat wave is conducive to forest fire. However,

113 the significant correlations of Russian surface temperature and forest fire count with Pakistan  
114 rainfall hint at a more profound teleconnection between the extratropics and tropics. In the  
115 following, we explore the physical basis for such a teleconnection. To facilitate the discussion  
116 of the evolution of the teleconnection pattern, we carry out separate but identical analyses for  
117 the 15-day period (Period II: July 25- August 8) for the Pakistan heavy rain, and for the 15-day  
118 antecedent period (Period I: June 10- 24).

119 *Period I: July 10- July 24*

120 This period characterized the development of the Russian heat wave and large-scale  
121 circulation and moisture conditions leading to, but *before* the Pakistan heavy rain. A  
122 pronounced blocking high, with 500 hPa geopotential height anomaly exceeding 120 -140 m  
123 was found over northern Europe and western Russia (Fig. 3a). The blocking high was coupled to  
124 a deep trough to its west, and another high pressure feature further east over western Siberia.  
125 The trough displayed a pronounced southwest-to-northeast tilt, penetrating into the subtropics  
126 with a cut-off low to the north of Pakistan. This pattern resembled that of a dispersive Rossby  
127 wave-train<sup>6</sup> emanating from the blocking high over western Russia, and propagating towards  
128 the east and southeast directions. As will be shown later, the penetrating trough and cut-off  
129 low (marked **L** in Fig. 3a) were associated subsequently with the formation of a mid-  
130 tropospheric cyclone (MTC) which was responsible for the heavy rain over Pakistan. An MTC is  
131 a hybrid midlatitude-tropical, rain bearing weather system commonly found in the South Asian  
132 monsoon region<sup>7-8</sup>.

133 Coupled to the 500 hPa blocking high was a lower troposphere large-scale anticyclone  
134 (Fig3b). The southerly flow on the west side of the anticyclone, brought warmer and moister

135 (rising) air to central and northern Europe, while the northerly flow on the eastern side  
136 brought widespread cooler (sinking) and drier air over western Siberia to regions further south.  
137 [See Fig. S1 in Supplementary Material for a description of the 500 hPa vertical motion pattern].  
138 Over the mountainous region of Afghanistan and Pakistan, the low level flow was not well  
139 organized. However, over the larger South Asian monsoon region, two distinct branches of  
140 anomalous low-level flow could be identified. A strong low-level easterly flow from the Bay of  
141 Bengal was found over northern India. This flow opposed the climatological low level westerly  
142 monsoon flow, and implied an anomalous transport of moisture from the Bay of Bengal to  
143 northwestern India/northern Pakistan and the northern Arabian Sea. Additionally, an  
144 anomalous southerly low-level flow was found over northern Arabian Sea. Our analysis (figure  
145 omitted) showed that the northern Arabian Sea was warmer than normal at this time. The  
146 warmer Arabian Sea could increase evaporation, allowing more moisture transport by the  
147 anomalous southerlies into the Gulf of Oman and southern coast of Pakistan (Fig. 3b).

148 *Period II: July 25 – Aug 7*

149 During this period, the heat wave soared and the Russian wild fires grew in area coverage  
150 and intensity. At 500 hPa, the blocking high shifted about 20° eastward in longitude, and grew  
151 to a very impressive size, with anomaly at the center exceeding 180 m (Fig. 3c). Examination of  
152 the daily variability of the 500 hPa geopotential height revealed that during the first week of  
153 this period, the slow eastward movement of the blocking high coupled with the rapid westward  
154 retrogression of the penetrating trough in the Rossby wave resulted in a separation of the cut-  
155 off low from the main trough. An explosive cyclogenesis of the low into a full-blown MTC west  
156 of northern Pakistan (marked C<sub>1</sub> in Fig. 3c) ensued. The strong mid-tropospheric ascent east of

157 the 500 hPa vortex - an evidence of the baroclinic structure of the MTC, was the reason for the  
158 heavy rain over northern Pakistan [See Fig. S1b in Supplementary Material]. Notice that  $C_1$  was  
159 only a part of the large-scale anomalous circulation pattern of the entire South Asian monsoon  
160 system, which included the development of a secondary MTC (marked  $C_2$  in Fig. 3c) over  
161 southern Pakistan and northeastern Arabia Sea, and an anomalous anticyclonic over western  
162 China, northeast of the Tibetan Plateau.

163 In the lower troposphere, contemporaneous with the mid-tropospheric development, the  
164 low level anticyclone over northern Europe and Russia shifted eastward to western Siberia (Fig.  
165 3d). Strong southerly flow on the west of the anticyclone advected more warm and moist air  
166 to northern Europe and the Arctic. On the southeastern side of the anticyclone, the low level  
167 northeasterly, and northerly flow brought a tongue of dry and cold (sinking) air from Siberia to  
168 Iran, and eastern Pakistan, setting the stage for a confrontation with the warm, moist (rising)  
169 air from the north Arabian Sea to Pakistan, eventually leading to the MTC cyclogenesis.  
170 Computations of the wind divergence (figures omitted) indicated that the MTCs were  
171 associated with strong upper level wind divergence east of the mid-tropospheric low center.  
172 The combination of strong mid-troposphere ascent and upper level divergence associated with  
173 the MTCs would act like a pump drawing the low level southeasterly flow over northern India,  
174 along the Indian/Nepal Himalayas, and transporting additional moisture from the Bay of Bengal  
175 to Pakistan (Fig. 3d). The moist southeasterly flow along the Himalayas foothills could lead to  
176 orographically forced heavy rain along the foothills region. The north and northwesterly flow  
177 from an anomalous anticyclone over the southern tip of the India subcontinent could also have  
178 contributed additional low-level moisture from the Arabian Sea, fueling the development of the



179 secondary MTC ( $C_2$  in Fig. 3c). Overall, the large-scale circulation, the MTCs, and associated  
180 large-scale vertical motion and upper wind divergence are dynamically consistent with the  
181 rainfall anomaly over Pakistan, the Indian/Nepal Himalaya foothills, and the northeastern  
182 Arabian Sea as shown in Fig. 1a.

### 183 **Jetstream modulation**

184 During Period-I and -II, the strength of atmosphere blocking and the accompanying  
185 Rossby wave were such that they distorted the flow of the powerful jetstream in the upper  
186 troposphere, which in turn altered the steering of storm tracks. Climatologically, the boreal  
187 subtropical jetstream comprises of a belt of fast moving westerly in the upper troposphere  
188 around the global, centered around 35-40°N, with compensating easterlies over the tropics.  
189 Storms with mid-latitude origins are generally confined to the vicinity just south of the  
190 jetstream maximum, and north of the zero-wind (zonal) line. During Period-I (figure omitted),  
191 associated with the blocking development, there was a strengthening of the climatological  
192 subtropical jetstream, and a new, weaker polar jetstream emerged over Scandinavia. During  
193 Period-II, the Rossby wave influence on the jetstream was very pronounced. Here, the split  
194 polar jetstream was displaced eastward from Period-I and found over northwestern Siberia and  
195 the Arctic region of Eurasia (Fig. 4a). The subtropical branch, where the climatological westerly  
196 belt was normally located (line contours in Fig. 4a), showed a highly wavy pattern spanning  
197 southern Europe, the Mediterranean/North Africa, the Caspian Sea, Syria, northwestern China  
198 and Mongolia, with the southernmost extent of the main jetstream hanging northwest of  
199 Pakistan (Fig.4a). The signature of the Rossby wavetrain was even more pronounced in the 200  
200 hPa meridional wind component (Fig.4b), showing a northern component around the Arctic

201 circle of Eurasia and a subtropical component from the Mediterranean to the western Pacific.  
202 The magnitude of the subtropical branch was much stronger than climatology (line contours in  
203 Fig. 4b), and the phase of the Rossby wave was almost in quadrature, with a westward phase  
204 shift relative to that from climatology. The anomalous southerlies and the northerlies at 35-40°  
205 N west of Pakistan, indicated cyclonic circulation, consistent with the MTC formed over the  
206 region. Given the planetary scale of the jetstream anomalies, it is conceivable that these  
207 anomalies are connected to other major extreme weather events from Europe to Asia, in both  
208 the tropics and extratropics during the summer of 2010.

### 209 **Conclusion and discussion**

210 We have presented preliminary evidences suggesting that the two record setting extreme  
211 events in the summer of 2010, *i.e.*, the Russia heat wave/wild fires and the Pakistan flood are  
212 meteorologically connected. The prolonged atmospheric blocking situation associated with the  
213 extreme heat wave/drought and wild fires over western Russia is instrumental in forcing a  
214 large-scale atmospheric Rossby wave train connecting western Russia to the South Asian  
215 monsoon region. A deep trough in the Rossby wave penetrating from the mid-latitudes to the  
216 tropics may have triggered the explosive cyclogenesis of a subtropical MTC, spawning the  
217 extreme rainfall events over Pakistan, the Indian/Nepal Himalayas, and northeastern Arabian  
218 Sea. The MTCs are known rain activators in the South Asian monsoon region, with both  
219 midlatitude (baroclinic) and monsoonal (condensational heating) characteristics, including  
220 warm core structure above 600 hPa, pronounced cyclonic structure in mid-troposphere, and  
221 strong upper level divergence<sup>7,9-10</sup>. Further studies of the causes of the Pakistan flood should  
222 revive the attention to the MTC as an important heavy rain-bearing monsoon weather system.

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223           The present results raise important unanswered questions. For the South Asian  
224 monsoon region, rainfall is generally enhanced by La Nina, *i.e.*, below normal sea surface  
225 temperature (SST) in the eastern tropical Pacific, and above normal SST in the western Pacific  
226 and Indian Ocean. During the summer of 2010, a weak La Nina condition was brewing over the  
227 central eastern Pacific. Did the La Nina condition in 2010, including the warmer Arabian Sea,  
228 further add to the alignment of factors, favoring more rainfall over Pakistan? Could the  
229 Pakistan flood have occurred, if there were no Rossby wave forcing? Or with Rossby wave  
230 forcing but no pre-conditioning of the tropics, such as La Nina and warmer Arabian Sea? For  
231 the Russia heat wave and wild fires, the key question is : what caused the prolonged blocking  
232 situation that led to the unprecedented severity of the drought and west Russian forest fires?  
233 Previous studies showed that soil moisture and land surface processes played a vital role in the  
234 blocking event associated with severe summer heat waves, such as that occurred over Europe  
235 in 2003<sup>11</sup>. Are the 2010 and 2003 heat waves similar or different in terms of forcing and  
236 responses? The exceptional large amount of aerosols emitted from the 2010 Russia wild fires  
237 during Period-II (see Supplementary Material Fig. S2) would certainly have affected the surface  
238 and atmospheric energy budget over the west Russia and adjacent regions. Did aerosols from  
239 the forest fires play a role, via radiative heating and feedback processes in the atmosphere and  
240 at the surface, in amplifying and/or sustaining the atmospheric blocking? If so, this raises the  
241 intriguing possibility that the Russia wild fires may have contributed to the Pakistan flood!  
242 Finally, is this extraordinary teleconnection of extremes a sign of a changing atmospheric  
243 general circulation associated with global warming, favoring more extratropical-tropical

244 interaction? These are important and urgent questions that the scientific communities have to  
245 provide answers, the sooner the better.

## 246 **Methods**

247 For this investigation, we used a combination of in-situ, satellite and reanalysis data to  
248 carry out correlative and diagnostic analyses. Anomalies were defined as the deviations from  
249 the climatology of each dataset. We used the satellite rainfall, fire count, and surface  
250 temperature to examine the spatial patterns of the Pakistan heavy rain, and the Russian heat  
251 wave and wild fires, and establish the temporal correlations among these variables. We then  
252 defined two 15-day periods to identify the quasi-stationary features in the geopotential, wind  
253 and moisture teleconnection patterns, prior to, and during the Russian heat wave and the  
254 Pakistan flood. We seek physical and dynamical consistency among these independent data  
255 with respect to evolving coherent spatial patterns during the two periods. For rainfall, we used  
256 daily gridded rain gauge data from NOAA Climate Prediction Center (CPC)<sup>1</sup>, as well as daily  
257 rainfall product (3B42) on 0.25 x 0.25 degree latitude-longitude grid from the Tropical Rainfall  
258 Measuring Mission (TRMM)<sup>5</sup>. Surface temperature was estimated from the Advanced Infra  
259 Red Sounder (AIRS), fire counts and aerosol optical thickness from the Moderate Resolution  
260 Imaging Spectro-radiometer (MODIS) on board the NASA Aqua and Terra satellites. AIRS is a  
261 high spectral resolution spectrometer on board Aqua satellite with 2378 bands in the thermal  
262 infrared (3.7 - 15.4  $\mu\text{m}$ ) and 4 bands in the visible (0.4 - 1.0  $\mu\text{m}$ ). The MODIS Fire Pixel Count  
263 has a spatial resolution of 1kmx1km and is determined by a significant increase in radiance at  
264 4 $\mu\text{m}$  compared to 11 $\mu\text{m}$  radiance. It is available from the Terra and Aqua satellites twice daily,  
265 night and day. Locations of fire pixel from all four daily measurements are used in Fig. 1 and

266 Fig. 2. Data and meta-data for AIRS and MODIS fire count were obtained from at the Goddard  
267 Earth Sciences Data and Information Service Center (<http://disc.sci.gsfc.nasa.gov/AIRS>) and  
268 MODIS Hotspots/Active Fires Text file FTP site (<ftp://mapsftp.geog.umd.edu>), respectively. For  
269 geopotential height, wind, and moisture, we used the National Center for Environmental  
270 Prediction (NCEP) reanalysis data available from (<http://ftp.cdc.noaa.gov>).  
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303 Measuring Mission (TRMM).

304 **Author contributions**

305 W.K.M.L. led the study and wrote the manuscript. K.M.K. carried out the data analyses. Both  
306 authors collaborated in the discussion of the results and writing.

307 **Additional information**

308 The authors declare no competing financial interests.

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313 **Figure Captions**

314 Figure 1 Spatial distribution of a) TRMM rainfall anomaly over Pakistan and the South Asian  
315 monsoon region for period July 25 – Aug 8, 2010, b) AIRS surface temperature  
316 anomaly, and MODIS daily fire count (green dots) for the same period. The rainfall  
317 anomaly ( $\text{mm day}^{-1}$ ) was derived from the base period of 1988-2009, and the surface  
318 temperature anomaly ( $^{\circ}\text{C}$ ) from the base period of 2003-2009.

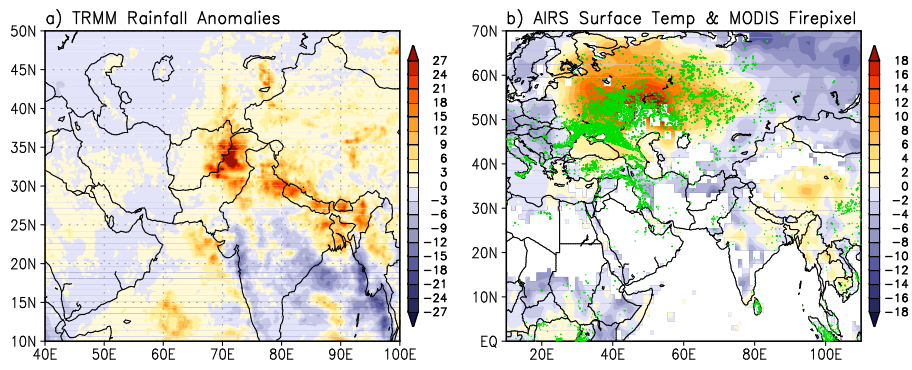
319 Figure 2 Time series of AIRS daily surface temperature ( $^{\circ}\text{C}$ ) averaged western Russia [ $45\text{-}65^{\circ}\text{N}$ ,  
320  $30\text{-}60^{\circ}\text{E}$ ], with positive (negative) deviations from climatology shaded red (blue),  
321 MODIS fire count per day (right ordinate) over the same domain, and TRMM daily  
322 rainfall ( $\text{mm day}^{-1}$ , left ordinate) over northern Pakistan [ $32\text{-}35^{\circ}\text{N}$ ,  $70\text{-}73^{\circ}\text{E}$ ], for the  
323 June 1 - August 27, 2010.

324 Figure 3 Spatial patterns of a) 500 hPa geopotential height and wind anomalies during  
325 Period-I, b) 850 hPa wind and moisture anomalies during Period-I, c) 500 hPa  
326 geopotential height and wind anomalies during Period-II, and d) 850 hPa wind and  
327 moisture anomalies during Period-II. The geopotential height (m) and wind ( $\text{ms}^{-1}$ ) data  
328 were from the NOAA National Center for Environmental Prediction (NCEP). Centers of  
329 the blocking high (H), and low (L) and the mid-tropospheric cyclones ( $C_1$  and  $C_2$ ) are  
330 marked. Anomalies were computed based on the climatology of 1979–2009.

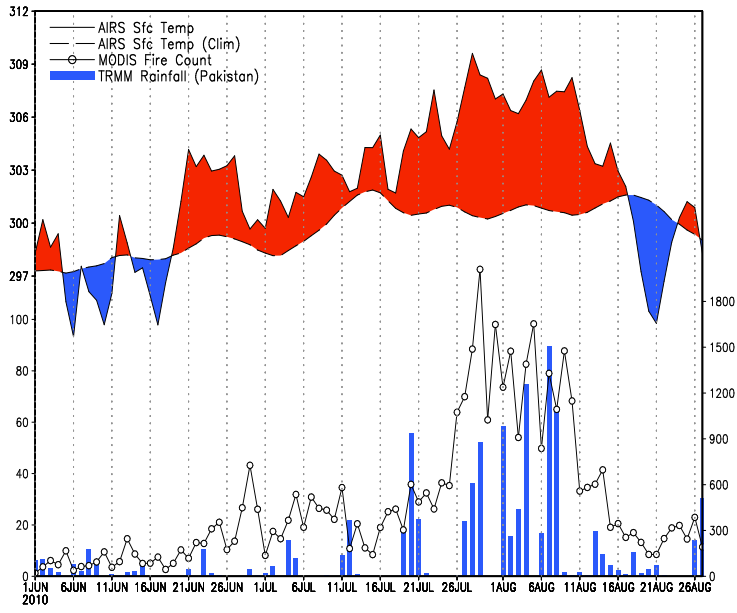
331 Figure 4 Spatial pattern of a) 200 hPa zonal wind anomaly and climatology (shown in green  
332 line contours) showing the influence of Rossby waves on the jetstream flow, b) 200hPa  
333 meridional wind anomaly and climatology (shown in green line contours), showing the



334 Rossby wave signature at the jetstream level. Anomalies were computed based on the  
335 climatology of 1979-2009.



338 Figure 1



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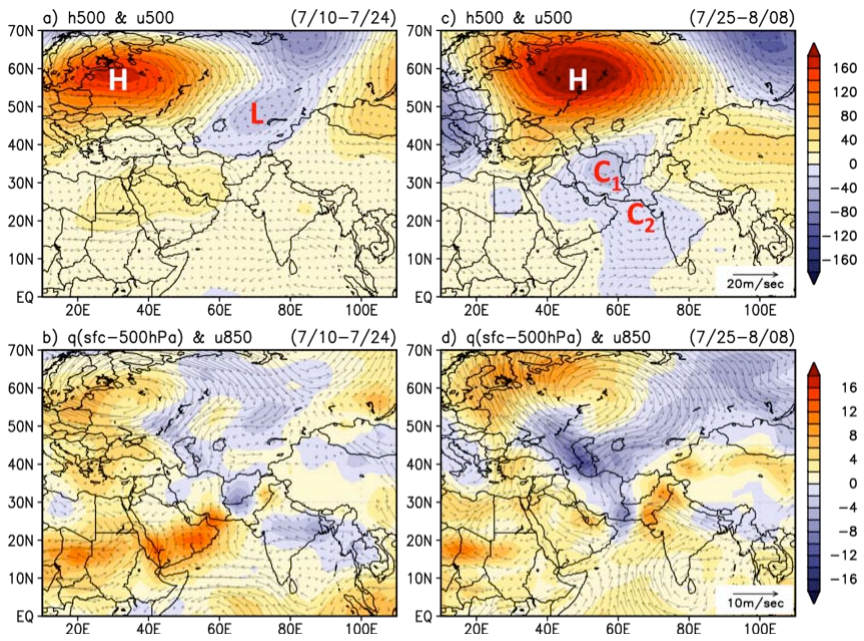
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Figure 2

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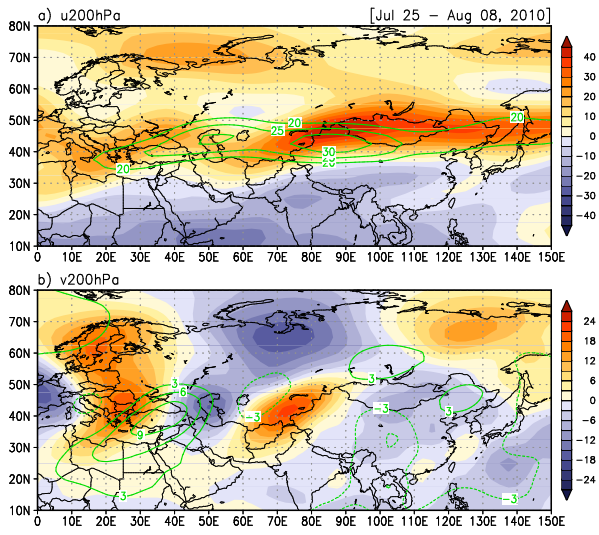
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Figure 3

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348 Figure 4

349 **Supplementary Material**

350 **Mid-tropospheric vertical motion**

351 During Period-I, wide-spread large-scale sinking motion (negative anomaly) was found  
352 east of, and rising motion (positive anomaly) west and southwest of the blocking high (H) (Fig.  
353 S1a). The vertical motion pattern was consistent with the anticyclonic flow associated with the  
354 blocking, having subsiding colder air moving toward the subtropics and poleward moving  
355 warmer air towards western Europe. Strong sinking motion was also noted over western  
356 Afghanistan and Iran, probably associated with a large-scale anomalous anticyclone found over  
357 Saudi Arabia and Iran (see Fig. 3a). With respect to the mid-tropospheric low (L), rising motion  
358 was found to its southeast, and sinking motion to its northwest, typical of the baroclinic  
359 structure of a developing low in mid-latitudes. In the tropics, rising motion was found over  
360 northern Pakistan, northern India, and the northern Arabian Sea, coupled to sinking motion  
361 over the Bay of Bengal, and Indo-China. The rising motion, though still moderate in magnitude  
362 provided vertical transport of moisture to the lower and middle troposphere, ready to be  
363 tapped for MTC development. During Period-II (Fig. S1b), the subsiding (colder) air over  
364 western Siberia east of the blocking high (H) became more expansive and amplified, with the  
365 southern tip of the sinking air reaching below 30N over Iran. At the same time, eastern and  
366 northern Europe experienced generally rising motion as the block shifted eastward. In the  
367 subtropics and tropics, the MTCs ( $C_1$  and  $C_2$ ) were fully developed over Iran/Afghanistan, and  
368 the northern Arabia Sea. Clearly from the vertical motion field, strong upward motion  
369 coinciding with the Pakistan flood was found to the east, and sinking motion to the west of the  
370 primary MTC ( $C_1$ ), which was the primary weather system that caused the heavy rain over

371 northern Pakistan. For  $C_2$ , the rising motion was more coincident with the vortex center, more  
372 representative of a monsoon weather system. It should be pointed out that the vertical  
373 motion fields were derived from rather coarse resolution ( $2.5^\circ \times 2.5^\circ$  latitude-longitude) wind  
374 analyses, and therefore reflected only the large-scale vertical motion pertaining to the synoptic  
375 scale forcing associated with the blocking in high latitudes and the rainfall in the monsoon  
376 region. The convective scale vertical motions directly associated with updrafts in the heavy rain  
377 were not resolved in the analysis.

378

### 379 **Aerosol distribution**

380 The 2010 Russia wild fires emitted abundant smoke, noxious gases ( $CO_2$ , CO,  $CH_4$ ,  $NO_x$ ,  
381 and others) and aerosols (black carbon and organic carbon) harmful to human health, and  
382 possibly alter the land surface and atmospheric heat balance, depending on the radiative  
383 properties of the gases and aerosols. These gases and aerosols were transported by the  
384 atmospheric circulation to high elevations and regions far from the forest fire. During Period-I  
385 (July 10-24), atmospheric loading of aerosols over Russia and Siberia was actually slightly below  
386 normal over vast regions of Eurasia and the Asian monsoon region (Fig. S2a). During Period-II  
387 (July 25- August 8), as the heat wave soared and the forest fire raged, the aerosol loading in the  
388 atmosphere increased dramatically (Fig. S2b). Maximum high level of aerosol concentration  
389 ( $AOD > 1$ ) was found over a large region, near but slightly offset to the west of the center of  
390 surface anticyclone, and downwind of the region of maximum fire count (See Fig. 1b in main  
391 text). High-to-moderate aerosol concentrations ( $AOD > 0.5$ ) were found over northwestern  
392 Europe, the Arctic circle, regions north of the Caspian Sea, western Russia in conjunction of

393 the slow eastward migration, and growth in size and magnitude of the blocking event. Large  
394 negative AOD (<0.6-0.8) anomaly was found over Pakistan, northwest India and the Indo-  
395 Gangetic Plain. This was associated with the wash-out, by the excessive rain, of the dense  
396 aerosol (mostly dust and black carbon) which accumulate in the region during the early  
397 monsoon season<sup>1,2</sup>. The strong contrast between the large areas of high aerosol loading over  
398 western Russia, and the overall reduced aerosol loading over the pan-continental regions of  
399 Eurasian, Mediterranean, Africa and monsoon Asia would most likely have affected the  
400 energy balance through the direct and semi-direct effects<sup>3</sup>, and thus could play a role in  
401 sustaining and/or amplifying the Russian heat wave, the blocking high and indirectly the  
402 Pakistan flood, through the Rossby wave teleconnection.

403



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405 **References for Supplementary Material**

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415 | **Figure Caption for Supplementary Material**

416 | Figure S1. Spatial pattern of vertical motion at 500 hPa for a) Period-I and b) Period-II.

417 | Ascending (descending) motion is shaded red (blue). Labels denote position of low

418 | centers at 500 hPa. Sign of the vertical motion is reversed, and the unit is  $\text{Pa s}^{-1}$

419 | The centers of the 500 hPa blocking high (H) and low (L), and the MTC's ( $C_1$  and  $C_2$ ) are

420 | marked to show their relative positions with respect to the vertical motion field.

421 | Figure S2 Spatial patterns of a) MODIS Aerosol Optical Depth (AOD) and 850 hPa wind

422 | anomalies ( $\text{ms}^{-1}$ ) during Period-I, and b) Same as in a), but for Period- II.

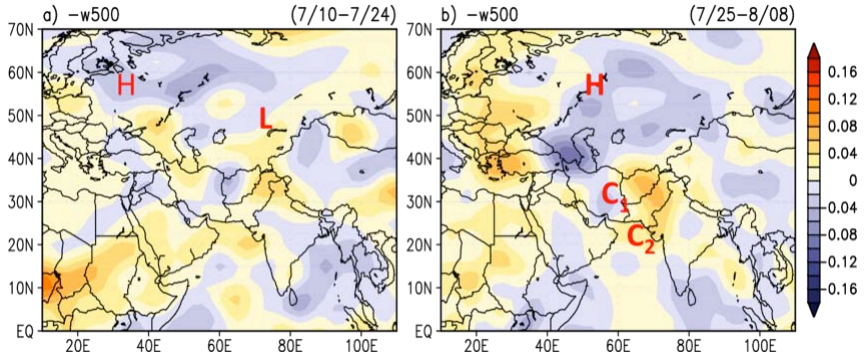
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424 Figure S1

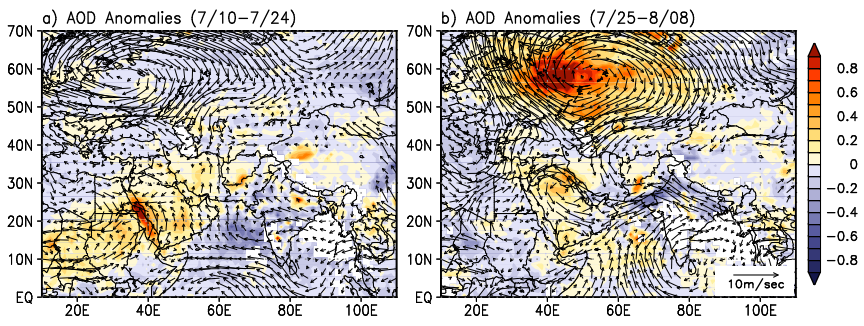
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429 Figure S2

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