The 2010 Pakistan Flood and the Russia Heat Wave:

Teleconnection of Extremes

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The Pakistan flood and the Russia heat wave/wild fires of the summer of 2010 were two of the most extreme events in the histories of the two countries occurring at about the same time. To a casual observer, the timing may just be a random coincidence of nature, because the two events were separated by long distances, and represented opposite forces of nature, \( \textit{i.e.,} \) flood vs. drought, and water vs. fire. Here, we present evidences showing that the two events were indeed physically connected. Our results show that the root cause of the 2010 Russia heat wave/wild fires was an atmospheric blocking event in high latitudes which, through the excitation of a large-scale atmospheric Rossby wave, was instrumental in affecting the rainfall evolution of the South Asian summer monsoon, including triggering the development of a mid-tropospheric cyclone that was responsible for the torrential rain over Pakistan.

During July and August, 2010 Pakistan suffered the worst flood in 100 years. Over 1500 people and 1 million homes perished and 20 million were rendered homeless, or displaced from their homes by the floodwater. The total economic lost from property and crop damage, loss of businesses was in the tens of billions. At about the same time, Russia was stricken by a record heat wave, with temperature in Moscow rising above 40\( ^\circ \) C for a prolonged period in July and August 2010, and the entire western Russia region (including western Siberia) was suffering from a prolonged drought. Intense and extensive wild fires raged over more than 5000 km\(^2\) of forested area. The Russia heat wave, drought and forest fires might have taken over 5,000 lives and cost the economy loss more than 15 billion. By any measure, the Pakistan flood and the Russian heat wave/wild fires were super extreme events, both from the perspectives of
meteorology and society impacts. Already, the media, pundits and some scientists were wondering aloud whether the Pakistan flood and Russia heat wave and many of the extreme weather events experienced around the world in 2010 were the results of global warming. However, while the 2010 extreme events will likely add to the statistics of extreme events consistent with projections of global warming, no attribution can be made based on a single event. From past experience, an extreme event is seldom the result of a singular cause, but rather the end product of positive feedback from an alignment of multiple factors, on both large and small scales. In this study, we focus on such an alignment of factors leading to the Russian heat wave and the Pakistan flood. Our paper differs from previous studies of extremes in that we identify not only the causes of each event, but also the possible physical connection between them. Methodology and data used for this study are described in the Method Section at the end of the manuscript.

The Pakistan flood

Tucked away in the northwestern corner of the Indian subcontinent, and bounded on the northeast by the high mountains of Karakoram, on the west by the arid regions and deserts of Afghanistan, Syria and Iran, and on the south by the Arabian Sea, Pakistan is a relative dry region compared to monsoon India. Even during the peak of the monsoon season, July-August, the average total rainfall over the wettest part of the country (northern Pakistan) is of the order of 160-180 mm – a scanty amount compared to rain total of 1600-2000 mm for the same months over the wettest monsoon regions of northeastern India and the Bay of Bengal. Based on the NOAA Climate Prediction Center rainfall station data¹, during the 2 week period, July 25-August 8 2010, torrential rain of approximately 500 mm fell in about 10 days in the northern
Pakistan Swat Valley, exceeding more than 70% of the total annual mean rainfall over the same region. As shown in rainfall anomaly field in Fig. 1a, the heavy rain over northern Pakistan was not isolated geographically, but appeared to be connected to excessive monsoon rainfall over northern and northeastern India along the foothills of the Himalaya, and central and northeastern Arabian Sea. Reduced rainfall was found over most part of central and southern India, and the southern Bay of Bengal, and along the coast of Myanmar. The widespread rainfall anomaly suggested that the Pakistan heavy rain was a part of a major shift in the entire monsoon rainfall pattern, which normally has the heaviest rainfall over Bangladesh and Bay of Bengal in August.

The Russian heat wave

Russia is a vast country, covering northeastern Europe and Siberia, stretching from the Arctic Circle southward to Ukraine and Kazakhstan, southeastward to Mongolia and northeastern China. The dominant vegetation is tundra in the extreme northern regions around the Arctic Circle, tiaga (boreal forest) in northern and central Siberia, and temperate forest and steppe grassland in the south. In western Russian, climatologically July-August is the rainy season, with mean monthly rainfall of 75-85 mm. However, atmospheric blocking condition which slows or prevents the passage of rain storms, may develop and last for weeks, leading to dry conditions and wild forest fires\(^2\)\(^-\)\(^4\). During July-August 2010, a record heat wave and drought developed and prevailed over western Russia. Temperature in Moscow in August soared to a record daily high of 40\(^\circ\) C (about 10 degree above the climatological mean). Prior to 2010, the highest temperature record in Moscow was set at 36.8\(^\circ\) C in August, 1920. During the two-week period coinciding with the Pakistan flood, the heat wave expanded to cover
western Russia, western Siberia, and Eastern Europe (Fig. 1b). The extreme hot and dry weather spurred ferocious forest fires over the vast taiga regions of western Russia and Siberia, and Ukraine, as evidence in the density of the satellite fire counts. Also noteworthy is that temperature contrast, with much cooler temperature prevailed in the adjacent regions to the heat wave, over central and eastern Siberia, and western Europe.

**Teleconnection**

Figure 2 shows the time series of rainfall from TRMM over northern Pakistan [32-35N, 70-73E] and surface temperature from AIRS and fire count from MODIS over western Russia [45-65N, 30-60E]. Very heavy rain fell over northern Pakistan intermittently in clusters of 3-4 days during the two-week period from July 25- August 10, following a period of steadily increasing rainfall beginning in mid-June. Surface temperature over western Russia rose rapidly around June 20; remained at a high level for the next 10 days or so, and soared from around July 18 to reach a very high-level, with maximum area-averaged temperature exceeding nearly 9° C above the seasonal mean, during a 2-week period contemporaneous with the heavy rain over Pakistan. The Russia forest fire activity, as evident from the MODIS fire count, was near normal or slightly elevated about the same time as the heat wave emerged, but dramatically intensified around July 25 and remained at a very high level till August 10, and dropped off rapidly, as a cold front passed through and brought rain to the area. The correlation between surface temperature and fire count is 0.70, and between fire count, surface temperature and Pakistan rainfall is 0.50 and 0.37, respectively. All correlations are statistically significant at the 95% level. The high correlation between heat wave and forest fire is expected, because the abnormally hot and dry air associated with the heat wave is conducive to forest fire. However,
the significant correlations of Russian surface temperature and forest fire count with Pakistan rainfall hint at a more profound teleconnection between the extratropics and tropics. In the following, we explore the physical basis for such a teleconnection. To facilitate the discussion of the evolution of the teleconnection pattern, we carry out separate but identical analyses for the 15-day period (Period II: July 25- August 8) for the Pakistan heavy rain, and for the 15-day antecedent period (Period I: June 10- 24).

**Period I: July 10- July 24**

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

Coupled to the 500 hPa blocking high was a lower troposphere large-scale anticyclone (Fig3b). The southerly flow on the west side of the anticyclone, brought warmer and moister.
(rising) air to central and northern Europe, while the northerly flow on the eastern side
brought widespread cooler (sinking) and drier air over western Siberia to regions further south.
[See Fig. S1 in Supplementary Material for a description of the 500 hPa vertical motion pattern].
Over the mountainous region of Afghanistan and Pakistan, the low level flow was not well
organized. However, over the larger South Asian monsoon region, two distinct branches of
anomalous low-level flow could be identified. A strong low-level easterly flow from the Bay of
Bengal was found over northern India. This flow opposed the climatological low level westerly
monsoon flow, and implied an anomalous transport of moisture from the Bay of Bengal to
northwestern India/northern Pakistan and the northern Arabian Sea. Additionally, an
anomalous southerly low-level flow was found over northern Arabian Sea. Our analysis (figure
omitted) showed that the northern Arabian Sea was warmer than normal at this time. The
warmer Arabian Sea could increase evaporation, allowing more moisture transport by the
anomalous southerlies into the Gulf of Oman and southern coast of Pakistan (Fig. 3b).

Period II: July 25 – Aug 7
During this period, the heat wave soared and the Russian wild fires grew in area coverage
and intensity. At 500 hPa, the blocking high shifted about 20° eastward in longitude, and grew
to a very impressive size, with anomaly at the center exceeding 180 m (Fig. 3c). Examination of
the daily variability of the 500 hPa geopotential height revealed that during the first week of
this period, the slow eastward movement of the blocking high coupled with the rapid westward
retrogression of the penetrating trough in the Rossby wave resulted in a separation of the cut-
off low from the main trough. An explosive cyclogenesis of the low into a full-blown MTC west
of northern Pakistan (marked C1 in Fig. 3c) ensued. The strong mid-tropospheric ascent east of
the 500 hPa vortex - an evidence of the baroclinic structure of the MTC, was the reason for the heavy rain over northern Pakistan [See Fig. S1b in Supplementary Material]. Notice that C1 was only a part of the large-scale anomalous circulation pattern of the entire South Asian monsoon system, which included the development of a secondary MTC (marked C2 in Fig. 3c) over southern Pakistan and northeastern Arabia Sea, and an anomalous anticyclonic over western China, northeast of the Tibetan Plateau.

In the lower troposphere, contemporaneous with the mid-tropospheric development, the low level anticyclone over northern Europe and Russia shifted eastward to western Siberia (Fig. 3d). Strong southerly flow on the west of the anticyclone advected more warm and moist air to northern Europe and the Arctic. On the southeastern side of the anticyclone, the low level northeasterly, and northerly flow brought a tongue of dry and cold (sinking) air from Siberia to Iran, and eastern Pakistan, setting the stage for a confrontation with the warm, moist (rising) air from the north Arabian Sea to Pakistan, eventually leading to the MTC cyclogenesis.

Computations of the wind divergence (figures omitted) indicated that the MTCs were associated with strong upper level wind divergence east of the mid-tropospheric low center. The combination of strong mid-troposphere ascent and upper level divergence associated with the MTCs would act like a pump drawing the low level southeasterly flow over northern India, along the Indian/Nepal Himalayas, and transporting additional moisture from the Bay of Bengal to Pakistan (Fig. 3d). The moist southeasterly flow along the Himalayas foothills could lead to orographically forced heavy rain along the foothills region. The north and northwesterly flow from an anomalous anticyclone over the southern tip of the India subcontinent could also have contributed additional low-level moisture from the Arabian Sea, fueling the development of the
secondary MTC ($C_2$ in Fig. 3c). Overall, the large-scale circulation, the MTCs, and associated large-scale vertical motion and upper wind divergence are dynamically consistent with the rainfall anomaly over Pakistan, the Indian/Nepal Himalaya foothills, and the northeastern Arabian Sea as shown in Fig. 1a.

**Jetstream modulation**

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

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

Conclusion and discussion

We have presented preliminary evidences suggesting that the two record setting extreme events in the summer of 2010, *i.e.*, the Russia heat wave/wild fires and the Pakistan flood are meteorologically connected. The prolonged atmospheric blocking situation associated with the extreme heat wave/drought and wild fires over western Russia is instrumental in forcing a large-scale atmospheric Rossby wave train connecting western Russia to the South Asian monsoon region. A deep trough in the Rossby wave penetrating from the mid-latitudes to the tropics may have triggered the explosive cyclogenesis of a subtropical MTC, spawning the extreme rainfall events over Pakistan, the Indian/Nepal Himalayas, and northeastern Arabian Sea. The MTCs are known rain activators in the South Asian monsoon region, with both midlatitude (baroclinic) and monsoonal (condensational heating) characteristics, including warm core structure above 600 hPa, pronounced cyclonic structure in mid-troposphere, and strong upper level divergence $^{7,9,10}$. Further studies of the causes of the Pakistan flood should revive the attention to the MTC as an important heavy rain-bearing monsoon weather system.
The present results raise important unanswered questions. For the South Asian monsoon region, rainfall is generally enhanced by La Nina, i.e., below normal sea surface temperature (SST) in the eastern tropical Pacific, and above normal SST in the western Pacific and Indian Ocean. During the summer of 2010, a weak La Nina condition was brewing over the central eastern Pacific. Did the La Nina condition in 2010, including the warmer Arabian Sea, further add to the alignment of factors, favoring more rainfall over Pakistan? Could the Pakistan flood have occurred, if there were no Rossby wave forcing? Or with Rossby wave forcing but no pre-conditioning of the tropics, such as La Nina and warmer Arabian Sea? For the Russia heat wave and wild fires, the key question is: what caused the prolonged blocking situation that led to the unprecedented severity of the drought and west Russian forest fires? Previous studies showed that soil moisture and land surface processes played a vital role in the blocking event associated with severe summer heat waves, such as that occurred over Europe in 2003\textsuperscript{11}. Are the 2010 and 2003 heat waves similar or different in terms of forcing and responses? The exceptional large amount of aerosols emitted from the 2010 Russia wild fires during Period-II (see Supplementary Material Fig. S2) would certainly have affected the surface and atmospheric energy budget over the west Russia and adjacent regions. Did aerosols from the forest fires play a role, via radiative heating and feedback processes in the atmosphere and at the surface, in amplifying and/or sustaining the atmospheric blocking? If so, this raises the intriguing possibility that the Russia wild fires may have contributed to the Pakistan flood! Finally, is this extraordinary teleconnection of extremes a sign of a changing atmospheric general circulation associated with global warming, favoring more extratropical-tropical
interaction? These are important and urgent questions that the scientific communities have to provide answers, the sooner the better.

Methods

For this investigation, we used a combination of in-situ, satellite and reanalysis data to carry out correlative and diagnostic analyses. Anomalies were defined as the deviations from the climatology of each dataset. We used the satellite rainfall, fire count, and surface temperature to examine the spatial patterns of the Pakistan heavy rain, and the Russian heat wave and wild fires, and establish the temporal correlations among these variables. We then defined two 15-day periods to identify the quasi-stationary features in the geopotential, wind and moisture teleconnection patterns, prior to, and during the Russian heat wave and the Pakistan flood. We seek physical and dynamical consistency among these independent data with respect to evolving coherent spatial patterns during the two periods. For rainfall, we used daily gridded rain gauge data from NOAA Climate Prediction Center (CPC)¹, as well as daily rainfall product (3B42) on 0.25 x 0.25 degree latitude-longitude grid from the Tropical Rainfall Measuring Mission (TRMM)⁵. Surface temperature was estimated from the Advanced Infra Red Sounder (AIRS), fire counts and aerosol optical thickness from the Moderate Resolution Imaging Spectro-radiometer (MODIS) on board the NASA Aqua and Terra satellites. AIRS is a high spectral resolution spectrometer on board Aqua satellite with 2378 bands in the thermal infrared (3.7 - 15.4 μm) and 4 bands in the visible (0.4 - 1.0 μm). The MODIS Fire Pixel Count has a spatial resolution of 1kmx1km and is determined by a significant increase in radiance at 4μm compared to 11μm radiance. It is available from the Terra and Aqua satellites twice daily, night and day. Locations of fire pixel from all four daily measurements are used in Fig. 1 and
Data and meta-data for AIRS and MODIS fire count were obtained from the Goddard Earth Sciences Data and Information Service Center (http://disc.sci.gsfc.nasa.gov/AIRS) and MODIS Hotspots/Active Fires Text file FTP site (ftp://mapsftp.geog.umd.edu), respectively. For geopotential height, wind, and moisture, we used the National Center for Environmental Prediction (NCEP) reanalysis data available from (http://ftp.cdc.noaa.gov).
References


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Author contributions

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

Additional information

The authors declare no competing financial interests.
Figure 1  Spatial distribution of a) TRMM rainfall anomaly over Pakistan and the South Asian monsoon region for period July 25 – Aug 8, 2010, b) AIRS surface temperature anomaly, and MODIS daily fire count (green dots) for the same period. The rainfall anomaly (mm day⁻¹) was derived from the base period of 1988-2009, and the surface temperature anomaly (°C) from the base period of 2003-2009.

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

Figure 3  Spatial patterns of a) 500 hPa geopotential height and wind anomalies during Period-I, b) 850 hPa wind and moisture anomalies during Period-I, c) 500 hPa geopotential height and wind anomalies during Period-II, and d) 850 hPa wind and moisture anomalies during Period-II. The geopotential height (m) and wind (ms⁻¹) data were from the NOAA National Center for Environmental Prediction (NCEP). Centers of the blocking high (H), and low (L) and the mid-tropospheric cyclones (C₁ and C₂) are marked. Anomalies were computed based on the climatology of 1979–2009.

Figure 4  Spatial pattern of a) 200 hPa zonal wind anomaly and climatology (shown in green line contours) showing the influence of Rossby waves on the jetstream flow, b) 200hPa meridional wind anomaly and climatology (shown in green line contours), showing the
Rossby wave signature at the jetstream level. Anomalies were computed based on the climatology of 1979-2009.
Figure 1
Figure 2
Figure 3
Supplementary Material

Mid-tropospheric vertical motion

During Period-I, wide-spread large-scale sinking motion (negative anomaly) was found east of, and rising motion (positive anomaly) west and southwest of the blocking high (H) (Fig. S1a). The vertical motion pattern was consistent with the anticyclonic flow associated with the blocking, having subsiding colder air moving toward the subtropics and poleward moving warmer air towards western Europe. Strong sinking motion was also noted over western Afghanistan and Iran, probably associated with a large-scale anomalous anticyclone found over Saudi Arabia and Iran (see Fig. 3a). With respect to the mid-tropospheric low (L), rising motion was found to its southeast, and sinking motion to its northwest, typical of the baroclinic structure of a developing low in mid-latitudes. In the tropics, rising motion was found over northern Pakistan, northern India, and the northern Arabian Sea, coupled to sinking motion over the Bay of Bengal, and Indo-China. The rising motion, though still moderate in magnitude provided vertical transport of moisture to the lower and middle troposphere, ready to be tapped for MTC development. During Period-II (Fig. S1b), the subsiding (colder) air over western Siberia east of the blocking high (H) became more expansive and amplified, with the southern tip of the sinking air reaching below 30N over Iran. At the same time, eastern and northern Europe experienced generally rising motion as the block shifted eastward. In the subtropics and tropics, the MTCs (C_1 and C_2) were fully developed over Iran/Afghanistan, and the northern Arabia Sea. Clearly from the vertical motion field, strong upward motion coinciding with the Pakistan flood was found to the east, and sinking motion to the west of the primary MTC (C_1), which was the primary weather system that caused the heavy rain over
northern Pakistan. For \( C_2 \), the rising motion was more coincident with the vortex center, more representative of a monsoon weather system. It should be pointed out that the vertical motion fields were derived from rather coarse resolution (2.5\(^\circ\) x 2.5\(^\circ\) latitude-longitude) wind analyses, and therefore reflected only the large-scale vertical motion pertaining to the synoptic scale forcing associated with the blocking in high latitudes and the rainfall in the monsoon region. The convective scale vertical motions directly associated with updrafts in the heavy rain were not resolved in the analysis.

Aerosol distribution

The 2010 Russia wild fires emitted abundant smoke, noxious gases (CO\(_2\), CO, CH\(_4\), NOx, and others) and aerosols (black carbon and organic carbon) harmful to human health, and possibly alter the land surface and atmospheric heat balance, depending on the radiative properties of the gases and aerosols. These gases and aerosols were transported by the atmospheric circulation to high elevations and regions far from the forest fire. During Period-I (July 10-24), atmospheric loading of aerosols over Russia and Siberia was actually slightly below normal over vast regions of Eurasia and the Asian monsoon region (Fig. S2a). During Period-II (July 25- August 8), as the heat wave soared and the forest fire raged, the aerosol loading in the atmosphere increased dramatically (Fig S2b). Maximum high level of aerosol concentration (AOD>1) was found over a large region, near but slightly offset to the west of the center of surface anticyclone, and downwind of the region of maximum fire count (See Fig. 1b in main text). High-to-moderate aerosol concentrations (AOD>0.5) were found over northwestern Europe, the Arctic circle, regions north of the Caspian Sea, western Russia in conjunction of
the slow eastward migration, and growth in size and magnitude of the blocking event. Large
negative AOD (<0.6-0.8) anomaly was found over Pakistan, northwest India and the Indo-
Gangetic Plain. This was associated with the wash-out, by the excessive rain, of the dense
aerosol (mostly dust and black carbon) which accumulate in the region during the early
monsoon season\(^1,2\). The strong contrast between the large areas of high aerosol loading over
western Russia, and the overall reduced aerosol loading over the pan-continental regions of
Eurasian, Mediterranean, Africa and monsoon Asia would most likely have affected the
energy balance through the direct and semi-direct effects\(^3\), and thus could play a role in
sustaining and/or amplifying the Russian heat wave, the blocking high and indirectly the
Pakistan flood, through the Rossby wave teleconnection.
References for Supplementary Material


Figure Caption for Supplementary Material

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

Ascending (descending) motion is shaded red (blue). Labels denote position of low centers at 500 hPa. Sign of the vertical motion is reversed, and the unit is Pa s\(^{-1}\).

The centers of the 500 hPa blocking high (H) and low (L), and the MTC’s (C\(_1\) and C\(_2\)) are marked to show their relative positions with respect to the vertical motion field.

Figure S2. Spatial patterns of a) MODIS Aerosol Optical Depth (AOD) and 850 hPa wind anomalies (ms\(^{-1}\)) during Period-I, and b) Same as in a), but for Period-II.
Figure S1

a) -500 (7/10–7/24)

b) -500 (7/25–8/08)

Legend:

-0.16
-0.12
-0.08
-0.04
0
0.04
0.08
0.12
0.16
Figure S2