Extreme Precipitation events over North China in August 2010 and their link to eastward-propagating wave-trains across Eurasia: observations and monthly forecasting

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ABSTRACT

Over the Far East in summer, climate is strongly influenced by the fluctuating western Pacific subtropical high (WPSH), and strong precipitation is often associated with southeasterly low-level wind that brings moist air from the southern China seas. The WPSH intra-seasonal variability is partly influenced by quasi-stationary wave-trains propagating eastwards from Europe across Asia along the two westerly jets: the Silk-Road wave-train along the Asian jet at mid-latitudes and the polar wave-train along the sub-polar jet. In the unusual summer of 2010, Northeast China experienced its worst seasonal flooding for a decade, triggered by unusually severe precipitation. That summer was also characterized by a record-breaking heat wave over Eastern Europe and Russia, whose impact on the precipitation further east over China has been little explored. Here, we examine the role of the Silk-Road and polar wave-trains, and their impact on precipitation over Northeast China throughout August 2010, using station precipitation data and re-analyses. We found that there is a strong link between the Silk-Road wave-train and extreme precipitation events; associated with a strong occasional influence of the polar wave-train, these two modulate the northward and westward shifts of the WPSH.

Forecasting such regional precipitation events at the sub-seasonal timescale remains a big challenge for operational global prediction systems. In this study, we use high-resolution forecasts with the atmospheric model of the ECMWF, and demonstrate that the monthly forecast failure with regard to extreme precipitation over North and Northeast China in August 2010 is linked to the failure to represent intra-seasonal fluctuations of the Silk-Road and polar wave-trains and the associated modulation of the WPSH.

1. Introduction

Over the heavily-populated Far East region, extreme summer precipitation events can have dire societal consequences. Devastating floods have occurred in China in summertime, such as the Great Yangtze River flood in 1998 or, more recently in 2010, when Northeast China had its worst seasonal flooding for a decade, triggered by unusually prolonged and severe monsoonal rains. The floods left thousands of people dead or missing country-wide, necessitated the evacuation of million others, and caused tens of billions of dollars in damage. In the second half of August 2010 more specifically, parts of North and Northeast China and the Korean Peninsula were affected by extreme precipitation and flooding. In Liaoning Province, the precipitation in August was the highest since 1961, leading to flooding in two rivers of the Northeast China. The Yalu River, which is the national boundary between China and North Korea, experienced severe flooding on 23 August, 2010, ranking fourth among all the historical records. 250,000 people were forced to leave their homes (Sun and Zhao, 2011).

Over the Far East in summer, precipitation is strongly influenced by the East Asian Summer Monsoon (EASM), which displays strong inter-annual and intra-seasonal variability (e.g. Wang et al., 2013; Schubert et al., 2014). Over Eastern China in particular, a strong EASM and high precipitation events are often brought by the westward migration of the western Pacific subtropical high (WPSH), and southeasterly low-level winds that bring moist-laden air from the southern China seas to the land (Ding and Wang, 2005; Cha et al., 2011; Zeng et al., 2012). The inter-annual WPSH variability is affected by air-sea interaction in the tropical western Pacific and Indo-Pacific regions, notably by ENSO in both developing El Niño and La Niña, and by the Pacific-Japan (PJ) meridional teleconnection pattern (Kosaka et al., 2012; 2013; Wang et al., 2013). The ENSO influence is such that the WPSH is strengthened during summers when El Niño is decaying.

On the other hand, the intra-seasonal variability of the WPSH, and hence of precipitation, is also influenced by quasi-stationary, hemispheric-scale wave-trains (WTs) propagating eastwards from Europe across Asia. Such WTs play an important role in the boreal summer subseasonal variability (Ding and Wang, 2005; Schubert et al., 2011). They tend to develop in the North Atlantic and then split in the jet exit region, further propagating along the two westerly jets across Asia: the Silk-Road (S-R) WT along the Asian jet at mid-latitudes and, on a more northern route, the polar WT along the sub-polar jet (Kosaka et al., 2009; Enomoto, 2004; Ding and Wang, 2005, 2007; Zhu et al., 2010; Schubert et al., 2014). Vorticity sources associated to transient eddies in the Euro-Atlantic sector tend to trigger both WTs with a modulation brought by the summer North Atlantic Oscillation (Bothe et al., 2010; Linderholm et al. 2011; Schubert et al., 2014). Along the WTs, anticyclones bring diabatically compressed dry, warm air masses, providing conditions for heat waves and drought if they remain stationary for a prolonged period. Opposite regional-scale anomalies in surface wetness or dryness can hence appear under the alternating quasi-stationary cyclonic or anticyclonic centers aligned in a near-zonal direction along these WTs. For example, a wet Tibet and a dry North China would be associated with a particular phase of the S-R WTs (Bothe et al., 2010; Zhu et al., 2010). Opposite anomalies in surface wetness or dryness can similarly appear in the meridional direction, under the out-of-phase cyclonic or anticyclonic centers within the S-R WT to the south and the polar WT to the north. In such as case, Siberia can be anomalously wet while Northeast Asia is anomalously dry (Iwao and Takahashi, 2008). Examples of such WTs across Eurasia in the summers 2003 or 2010, both characterized by prominent heat waves have been described (Kosaka et al., 2012; Orsolini and Nikulin, 2007; Schneidereit et al., 2012).

The S-R WT is also under the influence of the Indian summer monsoon (Ding and Wang, 2005; 2007). Recently, Saeed et al. (2011) used simulations with the ECHAM atmospheric model to show that anomalous convection and large-scale ascent over the Indian sub-continent influenced the S-R WT downstream, triggering precipitation anomalies over China about ten days later.

In addition to these floods in China, the summer 2010 was remarkable in other ways: it was record-breaking hot over Eastern Europe and Russia, where a pronounced blocking and a concomitant heat wave peaked in early August (Schneidereit et al., 2012). Pakistan also witnessed catastrophic monsoonal floods in July (Hong et al, 2011; Trenberth and Fasullo, 2012). While the connections between the Russian blocking, the excitation of WTs across Eurasia and the anomalous Pakistan monsoon in the summer 2010 have been made (e.g. Lau and Kim, 2012), yet its links with the S-R WT and anomalous precipitation further east over North China have been little explored. A first goal of this article is to establish the role of the eastward-propagating WTs in the WPSH intensification and the extreme precipitation events that occurred over North China in August 2010. Our diagnostic study aims to complement previous studies by linking the Russian blocking with developing WTs downstream and precipitation into the Far East.

The extreme heat wave over Russia and the Pakistan extreme monsoonal precipitation of summer 2010 were reasonably well-predicted 5-6 days in advance (Matsueda, 2011; Webster et al., 2011). Matsueda (2011) further noted that the forecast deteriorated near the blocking termination date. The development of reliable, skilful sub-seasonal forecasts beyond the well-established synoptic time scale of weather forecasts, would be of great societal value. While the development of seamless weather-to-climate forecasts is a prioritized research topic, skilful, reliable forecasts of regional precipitation events at the sub-seasonal timescale remain at the present time a big challenge for operational global prediction systems. Successful prediction of precipitation events would require first skilful forecast of relevant dynamical patterns, and then translation of model dynamical predictability into precipitation predictability. Sub-seasonal to seasonal prediction of summer climate is particularly limited over the Far East. Kosaka et al. (2012) showed that, in the summer 2010, many coupled seasonal forecast models predicted a cool summer in developing La Nina conditions. Yet, they missed the interfering role of the S-R WT, which brought a record-high hot summer over the Far East (Otomi et al., 2013; Kosaka et al., 2012). From the two above-mentioned factors influencing the summer climate over the Far East, the PJ teleconnection appears to some extent (but not entirely) predictable on the seasonal time scale, through its link with ENSO. The predictability of the WTs on the other hand is low on the seasonal time scale, and the WTs show no clear linkages to sea surface temperatures (SSTs) (Kosaka et al., 2012).

To our knowledge, there has been no study of the diagnostics and predictability of the August 2010 precipitation events over the Far East on a monthly time scale, using state-of-the-art operational prediction systems. On the seasonal timescale, such systems need to rely on coupled ocean-atmosphere models, given the importance of air-sea interactions in the EASM region (Wang et al., 2005). On the monthly timescale however, the predictability needs to be examined first with atmosphere-only models, with the atmospheric forcing of SSTs being neglected on that short time scale. A second goal of this paper is to examine the predictability of the S-R WT and the polar WT in August 2010, using a high-resolution, initialised forecast model in a near-operational prediction context. For the diagnostics and forecasts verification, it is also necessary to use the best available precipitation station data, as well as the state-of-the-art re-analyses. In this study, we use precipitation data provided by the China Meteorological Administration, and ERA-Interim re-analyses provided by the ECMWF. Sections 2 and 3 present an observational study of precipitation and circulation anomalies in August 2010, with section 3 specifically focused on WTs across Asia. Forecast results are described and analysed in Section 4, while a summary and concluding remarks are presented in Section 5.

2. Precipitation anomalies and WPSH over North China in August 2010: data and analyses

Observational data: Several datasets are used for the subsequent analyses: (i) Daily station precipitation from 1961 to 2010 is provided by the National Meteorology Information Center, China Meteorological Administration (CMA). Most stations have been established in the 1950s, but there are many missing data in this period, therefore, we consider only 573 stations for the entire China spanning from 1961 to

2010. (ii) Geopotential height, wind fields, specific humidity and precipitation data are taken from ERA-Interim reanalysis dataset covering the period 1979-2010. Meridional winds at 200hPa over the region (30°E-130°E; 30°N-50°N) were used in an Empirical Orthogonal Function (EOF) analysis to identify the Silk-Road pattern (S-R WT) spatial and temporal variability in August. In the rest of this paper, observational anomalies are calculated with respect to the 1979-2009 climatology.

Precipitation: The geographical distribution of precipitation anomalies (mm/month) in August 2010 over China is shown in Figure 1, based on station observations (Fig1 Left) and ERA-Interim re-analyses (Fig1 Right). An elongated, tilted pattern of anomalously high precipitation (e.g. over 50 mm) extends from Southwest to Northeast China in both data sets. We furthermore characterize precipitation at each station using the Standardized Precipitation Index (SPI, Bordi et al., 2009). For each station, an extreme wet event is considered to occur if SPI>2.0. Following this criterion, the extreme wet stations are represented by black dots in Fig. 1a. Hereafter, we refer to this region of extreme precipitation (110.0°E-127.0°E, 32.5°N-45°N) as North China (NC). The daily rainfall (mm/day) in August 2010, averaged over all the extreme wet stations is displayed for both observations and ERA-Interim re-analyses in Figure 2 (Left and Right, respectively). For the collocation, grid boxes in ERA-Interim comprising each individual station were used. Five extreme precipitation events appear clearly in the station-averaged data, exceeding two-standard-deviation above climatologically: on the 5th, 8th-9th, 14th , 19th-22th, and finally 27th-29th. Despite a negative anomaly bias by ERA-Interim, the number and duration of the extreme precipitation events are well-captured, with the exception of the duration of the last event. In summary, there is a broad spatial agreement between the observations based on station data and the ERA-Interim re-analyses over NC, despite an underestimation of precipitation in the latter.

Moisture flow: High summer precipitation over China is often related to an intensification and westwards displacement of the WPSH (e.g. Zeng et al., 2012), which leads to northward flow of moisture-enriched air over coastal areas and into the eastern part of mainland China. Mid-tropospheric winds are an indicator of the WPSH influence, and in the rest of this paper, we will use 500 hPa as a characteristic level to diagnose the WPSH. Figure 3a,b shows the anomalous WPSH during August 1-15 and August 16-31, in maps of geopotential height (gpm) and wind (m/s) at 500 hPa. In the first half of the month, the WPSH is already displaced northward from its climatological position at 30°N, and it further intensifies and shifts further westwards by about 20 degrees toward mainland China in the second half of the month. Figure 3c,d also shows the vertical integral of water vapor flux vector anomalies in these two periods. The grey areas showing anomalies higher than 90 kg/m/s indicate strong moisture transport into the coastal areas from Southwest to the Northeast of China, along the northwest boundary of the strengthened anticyclone.

Dynamics and climatological setting: Figure 4 shows the daily ERA-Interim meridional wind anomalies averaged over NC (as defined above) throughout August 2010. At 200 hPa, four bursts of northward wind can be identified in excess of 10 m/s, each of those coinciding with an extreme wet event (see Figure 2). We note that all but one of these wind bursts are of short duration (approximately 2-3 days) and have a near-barotropic structure from the 200 hPa down to near 500 hPa. Only the wind burst corresponding to the longer precipitation event of August 19-22 extends down to the lower troposphere, where it did appear first.

As mentioned in the Introduction, the WPSH falls under the influence of the PJ pattern, of ENSO and of eastward-propagating WTs. The PJ pattern was not anomalously strong in August 2010 (not shown for brevity, see Kosaka et al. 2012). The summer 2010 was sandwiched between a preceding El Niño and a developing La Niña event, with Niño-3.4 SST anomalies being 1.4°C in NDJ 2009/2010 and -1.64°C in NDJ 2010/2011. Hence, statistically, both the NDJ Niño-3.4 SST preceding and following the summer 2010 provide positive contributions to the strengthening of the summer-mean WPSH (Sui et al, 2007; Chou et al., 2009). We now examine in greater detail the sub-monthly variability of the WTs across Asia in August 2010.

3. Wave-trains across Asia in August 2010

As noted by Kosaka et al. (2012), the upper-level Silk-Road (S-R) and polar WTs were anomalously pronounced during that summer. We first extract the S-R pattern are using an EOF analysis of monthly-mean meridional wind (V) at 200hPa, in the latitude band (30°N-50°N) and between longitudes of 30°E to 130°E. The EOF analysis is carried out for the month of August in the period 1979-2010. After extracting the two leading EOFs (akin to two forms of S-R WT), we regressed meridional winds onto the two principal components to obtain the hemispheric meridional wind signature of these S-R modes (Figure 5). The two regional EOFs appear clearly as parts of hemispheric-scale WTs. On their path from the North Atlantic to the Far East, their follow a near-zonal route along the Asian jet region where the EOFs are defined, but they also contain out-of-phase polar WT along the sub-polar jet across northern Eurasia. The EOF daily principal components throughout August 2010 (Figure 5, Bottom) show that the second half of August is characterized by a negative phase of the EOF-1 followed by a positive phase of both EOFs. We next reconstruct the 200hPa-meridional wind from the sum of the two EOFs over the previously-defined NC region and compare it to ERA-Interim (Figure 6). Among the four observed pulses of northward winds with values exceeding approximately 10 ms^{-1}, the timing of three pulses and approximately half of their amplitudes are captured by the reconstructed wind based on the two EOFs. Only the wind pulse around August 21 is not. Hence, the meridional wind fluctuations over the NC region are to a large extent related to S-R WTs.

A Hovmöller plot of 200 hPa meridional wind anomalies, averaged over the latitude band 40°N-45°N, is shown in Figure 7. Four, slowly eastward-propagating S-R WTs are highlighted in green. There is some subjectivity in identifying these WTs and their full longitude span, but we have highlighted major WTs extending over at least 120 degrees of longitude. They are associated with northward meridional winds at the longitude of NC (near 120°E), around approximately August 5 th, 7-8 th, 12-17 th and 23-30 th, the last one being the most prominent. In between the later two, there is a weaker meridional wind dipole with a northward wind at 120°E and a southward wind near 150°E. The dipole structure is found only for a few days around August 21, and does not have the longitudinal extent of a typical, near-zonally propagating S-R pattern.

The different nature of the event around August 21 can be linked to the decaying stages of the blocking high over Russia that persisted from mid-July through August 18 (Lau and Kim, 2012). To demonstrate that, we present in Figure 8 several 3-day averages of the horizontal Plumb vector at 200 hPa, a diagnostic commonly used to investigate horizontal propagation of near-stationary waves (e.g. Schneidereit et al., 2012 for an application to the summer 2010). The 3-day averages are centered on August 15, August 21 and August 27 to cover the two pulses of S-R WT and the dipole anomaly in the second half of August (Figure 7). The 200-hPa geopotential height anomalies (color shading) further illustrates the near-zonal S-R WTs or the strong polar WTs. The NC region is clearly under the influence of wave trains emanating slightly east of the Caspian Sea and propagating near-zonally along the S-R WT route on August 15 th and 27 th. On August 21 however, the WT over NC is seen to emanate from the Euro-Atlantic and Western Russia region at much higher latitudes (55°-60°N), and it veers south only above China. In the Hovmöller plot at 40°N-45°N (Figure 7), the WT hence shows no signature at longitudes west of about 100°E around August 21. The meridional wind dipole in Figure 7 hence reflects a polar WT event and is not part of a typical longitudinally-oriented S-R WT.

4. Monthly forecasts of wave trains across Asia in August 2010

4.1. ECMWF Forecast model

We now turn to the forecast of the anomalous circulation in August 2010, using atmosphere-only retrospective forecasts carried out by the KNMI with the IFS model of the European Centre for Medium-Range Weather Forecasts (ECMWF). These runs expand on a previous set of simulations described in van den Hurk et al. (2012), and are carried out over the period 2000-2010. While we focus on August 2010, model anomalies are computed using the runs over the 10-year period 2000-2009. In this article, we only use the first month of the seasonal forecasts starting on August 1.

These runs were made with a recent cycle (Cy36R4) of the atmospheric model, with 62 levels, an upper boundary near 5 hPa, and a spatial resolution of 1 degree by 1 degree (T255). The realistic initial atmospheric states are derived from ERA-Interim re-analyses. They have realistic land states and improved soil moisture initialisation. The initial land states are derived from ERA-Interim, and the soil moisture variables are realistically initialized from an off-line run of the land module HTESSEL forced by ERA-Interim. SSTs are prescribed, i.e. realistically initialized and progressively relaxed to climatology allowing for some persistence (Koster et al., 2011; van den Hurk et al., 2012). These simulations are hence true forecasts, and make no use of prior information during the forecast period.

Ensembles consist of 10 members each and mostly ensemble-means are used here. The ensemble members are generated from perturbed initial atmospheric states using the singular vector approach.

4.2. Monthly forecast results

A Hovmöller plot of the 200-hPa meridional wind anomalies in the ensemble-mean forecast, averaged over the latitude band 40°N-45°N, is shown in Figure 9 (Top). The forecasts capture meridional wind fluctuations associated with the S-R WT during the first 10 days of August, as expected given that the realistic initialization should give good predictability on the synoptic time scale. However, it is quite striking that ensemble-mean forecasted wind anomalies become unrealistic after that, remaining near-stationary for 2 weeks around 30°E over the Eastern Mediterranean and around 120°W over the

Western US. Hence, a key point is that the ensemble-mean forecast model missed the development of the S-R WT pulses and the intensified northward flow over NC in the second half of August. There is, on the contrary, rapid change in the re-analyses after August 10 with the development first of the slowly eastward-propagating pulse of S-R WT across Eurasia around approximately August 12-17, then the dipole noted above, followed by the strong pulse in the S-R WT after August 21. The ensemble-mean forecasts missed these three events. This is despite the model being initialized with the blocked conditions at the start of August, incl. anomalously low soil moisture over Russia where the heat wave was prevailing. However, a closer examination of individual forecast members reveals that some do show some S-R WTs in late August, the coherence of which is lost in the ensemble-mean: Figure 9 (Bottom) also shows two prominent S-R WTs after August 21 in one particular member (#4). While not in agreement with the observed S-R WTs with regard to phase propagation or wavelength, the forecast is nevertheless able to capture developing S-R WTs spanning at least 120° across Eurasia.

The monthly ensemble-mean forecast fails to reproduce the necessary dynamical conditions of developing WTs and WPSH intensification during the 2nd half of August 2010. Hence it is no surprise that the ensemble-mean forecast of precipitation is poor given the influence of these conditions on the strong moisture transport toward in-land China, which we have demonstrated in the sections 3 and 4. For a qualitative comparison with station data, we show on Figure 10 shows forecasted total precipitation (mm per day) over North China (NC region defined as before) throughout August. Note that the model precipitation has not been collocated with station data as in Figure 2. Figure 10 shows the ensemble-mean forecast as well as the specific member (#4) that produced S-R WTs near the end of the month. It also shows model climatology and its two-standard-deviation exceedance. Comparing Figs 2 and 10, one readily sees that the model has a significant negative climatological bias as commonly found in forecast models (e.g. Webster et al., 2011). The first precipitation event on August 5 is well predicted in both the ensemble-mean and the particular member. The ensemble-mean forecast shows extreme precipitation (i.e. exceeding two standard deviations from climatology) on 9 days throughout the month, and the particular member only on 4 days; in either case, the days do not match days when extreme precipitation was observed over the region (Figure 2).

5. Summary and Concluding Remarks

Eastward-propagating wave-trains across the Eurasian continent, which induce extreme weather patterns in Far East, are an important summertime climatic feature (e.g. Bothe et al. 2010; Schubert et al., 2014). They are also relevant for the interpretation of extremes in future climate scenarios (Bothe et al. 2011). In this paper, we have focused on the extreme precipitation events of summer 2010 over North and Northeast China, and how these are affected by such WTs. Five precipitation events were identified over Northeast China (NC) in August 2010, and characterized using a unique rain data set from a set of stations over China as well as ERA_Interim re-analyses. We showed a good coherence between the two sources of data, but an underestimation of precipitation in the latter. We showed that the WPSH displaced northward and shifted westward brought bursts of northward meridional winds and huge rainfall in the second half of August over NC. This displacement of the WPSH is associated with hemispheric-scale WTs originating from the west, namely the S-R WT and the polar WTs.

The ability of monthly forecasts to predict such summertime precipitation events over the Far East has (to our knowledge) not been investigated. Realistically initialized monthly forecasts with assimilated initial conditions and made with a high-resolution atmospheric model were only able to capture such WTs in the first 10 days. However, the forecasts failed to predict intra-monthly variability of the WTs later in the month, during the break-up phase of the Russian blocking, hence missing the dynamical developments that were so critical in bringing high precipitation to the NC region.

The representation of such upper-level WTs and their intra-monthly variability in forecast models appears to depend on the cooperation of many effects, such as wave-breaking processes in the North

Atlantic sector or the conditions at the lower boundaries, that is the sea surface temperatures (see e.g. Raible and Luksch, 2004) and land surface conditions, such as soil moisture. The upper boundary condition in the lower stratosphere may also modulate baroclinic synoptic perturbations which, in turn, feedback onto the mid-latitude jet (Bordi et al., 2009). Although we expect less vertical coupling to the stratosphere in the summer season, when a westward stratospheric zonal wind regime is found, previous studies have shown that such hemispheric WTs do extend in the lower stratosphere (Orsolini et al., 2006).

There is a need to identify how sub-seasonal forecasts of such precipitation events could be improved. A first hurdle in predicting the precipitation events is hence to model these WTs correctly. The lack of predictability of the S-R at seasonal timescale was previously noted in Kosaka et al. (2012), but it appears clearly here even after 10 days. It is encouraging that individual members actually predicted developing S-R WTs at lead times beyond 10 days, indicating that S-R WT is an intrinsic mode of model variability (Figure 9). The main issue seems to lie with the forcing. Since transient eddies and blockings in the North Atlantic and European sector may be important in forcing the S-R and the polar WTs (e.g. Bothe et al., 2010; Linderholm et al., 2011; Schubert et al., 2014), their evolution might be difficult to predict beyond the synoptic time scale. Another forcing could arise from land-atmosphere coupling through soil moisture feedbacks, which has been recognized as a modest source of skill (Koster et al., 2011). Atmospheric GCM simulations with and without this feedback in Schubert et al. (2014) suggest that across the mid-latitude belt of Eurasia where the S-R WT propagates, surface temperature is influenced by soil moisture. Since the energetics of the S-R WT in Kosaka et al. (2009) indicates that the WT extracts baroclinic energy from the mean flow in that sector, soil moisture anomalies in that region may be important for the S-R WT maintenance through their modulation of the north/south surface temperature gradients. Nevertheless, our forecasts with realistic soil moisture initialization show no improvement in terms of forecasts of upper-level WTs compared to similar forecasts without realistic soil moisture initialization (not shown). Hence, while the slowly-varying land conditions might influence the atmospheric state, it is not clear that they strongly affect actual predictability of these WTs. Probabilistic approaches that exploit ensemble forecasts with large ensemble sizes need to be further developed.

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Fig. 1: Geographical distribution of precipitation anomalies (mm/month) in August 2010 over China from observations (left) and ERA-Interim (right). The extreme wet stations (see text for definition) are indicated as black dots.

Fig.2: Regional mean daily rainfall (mm/day) in August 2010 over North China from observations (top) and ERA-Interim (bottom) as a black line with dots. Black line is climatology for August, and grey line is climatology plus two times the standard deviation.

Fig.3: Geopotential height (gpm) and wind fields (m/s) anomalies at 500hPa in August 2010: a) August 1-15; b) August 16-31. Vertical integral of water vapor flux vector anomalies (grey area is moisture transport anomalies more than 90 kg/ m/ s) in August 2010: c) August 1-15; d) August 16-31.

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