Interannual Variability in the Summertime Hydrological Cycle over European Regions

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Abstract

A variety of observations-based hydrological variables from different data sets are used to investigate interannual variability and changes in the summertime hydrological cycle over four European regions – Iberian Peninsula (IP), British Isles (BI), Central Europe (CE) and European Russia (ER).

An analysis performed on seasonal means (June, July and August: JJA) suggests that soil moisture variability is impacted almost equally by precipitation and air temperature in BI and ER regions. However, stronger links between soil moisture and precipitation are revealed for CE region and between soil moisture and air temperature for IP region. In all except IP regions summertime interannual variability of column-integrated water vapour is strongly linked to air temperature consistent with the dominating influence of the Clausius-Clapeyron equation. In BI, CE and ER interannual variability of regional precipitation is driven by variations in atmospheric moisture transport into these regions. In IP the link between precipitation and moisture transport is relatively weak.

Based on monthly data, analysis of the lag-lead correlations revealed specific regional relationships between different hydrological variables. In particular, it is shown that in some regions (and months) interannual variability of soil moisture is linked more strongly to precipitation and air temperature anomalies in the previous month, rather than in the coinciding month.

An analysis of the vertical structure of regional atmospheric moisture transport has revealed that the more continental the climate of the region is, the larger deviation from the mean (i.e., climatological) profile might be observed during anomalously dry/wet summers.

1. Introduction

Variability in elements of the European hydrological cycle on different time-scales substantially impacts human activities in this densely populated region. In particular, deficient/excessive precipitation may lead to serious social and economic consequences. During recent years many such climate anomalies in different parts of Europe have resulted in substantial damage to regional economies [e.g., *Christensen and Christensen,* 2003; *Schär et al.,* 2004; *Marsh and Hannaford,* 2007; *Blackburn et al.,* 2008, *Lenderink et al.,* 2009]. Many regional climate extremes occur during summer. One of the most recent examples of such extremes is the anomalously high precipitation over the British Isles during summer 2007 which resulted in extensive flooding across England and Wales [*Marsh and Hannaford,* 2007; *Blackburn et al.,* 2008]. Another remarkable example is the Russian summer heat wave of 2010 [e.g., *Dole et al.,* 2011; *Otto et al.,* 2012] during which a large deficit of precipitation has been observed. In particular, in 2010 monthly July precipitation in the Moscow region amounted only to 12.8mm (which is 13.5% of the climatological value). Nevertheless, compared to winter, significantly less attention has been given during recent years to analysis of the European climate variability during the summer season [e.g., *Colman and Davey,* 1999; *Hurrell and Folland,* 2002; *Zveryaev,* 2004; *Sutton and Dong,* 2012]. In general, summertime climate variability in the European region is not well understood. Therefore, to improve the understanding of regional climate and its extremes, particularly for the warm season, further analysis of the processes driving European climate variability is necessary.

An important role of soil moisture in the climate system is highlighted by *Legates et al.* [2010] who particularly emphasize that the temporal variability of soil moisture in a given region is fundamental to the definition of its climate. Soil moisture is a key climate variable in hydrological processes which also impacts plant growth and carbon fluxes [e.g., *Dirmeyer et al.,* 1999]. Moreover, soil moisture is a critically important variable for weather and climate predictions because it controls local atmospheric water supply and the partitioning of energy flux into sensible and latent heat fluxes at the land surface [e.g., *Albergel et al.,* 2012].

Atmospheric water vapor plays a principal role in the hydrological cycle both at the global and regional scales. The distribution of water vapor and its condensation as cloud is crucial in determining radiative cooling and latent heating of the atmospheric column. Atmospheric water vapor absorbs strongly a portion of the earth's outgoing infrared energy, and radiates energy back to the earth's surface. Thus, water vapor is a primary contributor to the greenhouse effect. During recent decades, analysis of spatial-temporal variability of atmospheric moisture has received considerable attention. A number of recent papers focused on the regional changes in atmospheric water vapor [e.g., *Ross and Elliott,* 1996; *Zhai and Eskridge,* 1997; *Zveryaev et al.,* 2008; *Zveryaev and Rudeva,* 2010]. However, a large degree of uncertainty remains regarding interannual variability of atmospheric water vapor over Europe during the summer season when the leading modes of water vapor variability are not associated with regional atmospheric dynamics [*Zveryaev et al.,* 2008; *Zveryaev and Rudeva,* 2010].

In summer, when the role of atmospheric moisture advection in precipitation variability is diminished, the role of the local land surface processes increases [*Trenberth,* 1999]. Some studies point to the importance of land surface processes in summer precipitation variability [*Koster and Suarez,* 1995; *Schär et al.,* 1999; *Seneviratne et al.,* 2006], whereas other works highlight the role of the summer atmospheric circulation [*Pal et al.,* 2004; *Koster et al.,* 2004]. Although the above mechanisms are not mutually exclusive, their relative roles in summer precipitation variability in the European region are not completely clear.

The present study compares interannual variability in elements of the summertime hydrological cycle over four European regions characterized by contrasting climatic conditions. The climate variables under consideration are precipitation, soil moisture, atmospheric water vapor, horizontal moisture transport and near surface air temperature. While our recent studies [*Zveryaev and Allan,* 2010; *Zveryaev and Rudeva,* 2010; *Allan and Zveryaev,* 2011] explored the leading continental-scale modes of variability in key elements of the hydrological cycle over Europe and their relationships during summer season, the present study examines and highlights regional differences in the hydrological cycle across four European regions. We also examine lag-lead links between soil moisture and precipitation, and between soil moisture and air temperature, thus assessing relative roles of coupling between these two parameters and soil moisture variability. Furthermore, we investigate the highly variable vertical structure of horizontal atmospheric moisture transport and its relation to precipitation anomalies in the regions of interest. The data used and the analysis methods are described in section 2. Interannual variability of the key elements of the hydrological cycle and their relationships during the summer season are analyzed in section 3. In section 4 we explore the vertical structure of horizontal atmospheric moisture transport in four European regions during the summer season. Finally, a summary and discussion are presented in section 5.

2. Data and methods

In this study we use the CRU TS v3.22 monthly precipitation (P) and air temperature (AT) data provided on a 0.5° x 0.5° latitude-longitude grid [*Mitchell and Jones,* 2005; *Harris et al.,* 2013]. This data set has been constructed at the Climatic Research Unit (CRU), University of East Anglia. The data set presents terrestrial surface climate for the 1901-2011 period. The P and

AT data for the European region used in this study were interpolated directly from station observations. Station P and AT records from which the data set was constructed, were obtained from seven sources (see Table 1 in *Mitchell and Jones,* 2005). More details on the data construction method can be found in *Mitchell and Jones* [2005] and *Harris et al.* [2013].

The soil moisture (SM) data used in the present study are provided by the NOAA Climate Prediction Center (CPC) on a 0.5° x 0.5° latitude - longitude grid for the period 1948-present [*Fan and van den Dool,* 2004]. This data set constitutes SM estimated by a one-layer hydrological model [*Huang et al.,* 1996; *van den Dool et al.,* 2003]. The model takes observed P and AT and calculates soil moisture, evaporation and runoff. It should be, therefore, emphasized that this is model-calculated and not directly measured data. More detailed information on the model and the data set construction can be found in *Huang et al.* [1996], van *den Dool et al.* [2003] and *Fan and van den Dool* [2004].

Column Integrated Water Vapor (CWV), near surface atmospheric temperature (T_0), relative humidity (RH) and 500 hPa vertical motion (ω_{500}) fields were extracted from the ERA Interim reanalysis [*Dee et al.,* 2011] produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and covering the period 1979 – present. Note, T_0 is approximately the same as AT, but this is reanalysis product. The data assimilation system used to produce the ERA-Interim includes a 4-dimensional variational analysis (4D-Var) with a 12-hour analysis window. The spatial resolution of the data set is approximately 80 km (T255 spectral) on 60 vertical levels from the surface up to 0.1 hPa. Details on the data set are described in *Dee et al.* [2011].

Additionally, CWV expressed as a fraction (CWVrat) of the approximated maximum potential value (CWVmax) is calculated using CWV, T_0 and ω_{500} fields over the North Atlantic region (0-50°W, 35-60°N). Monthly JJA CWV and T_0 fields over the period 1979-2012 for ocean regions of neutral vertical motion ($\omega_{500}^2 < 0.015$ Pa^2/s^2) were subsequently averaged to form a multi-annual seasonal climatology (grid points were considered only where at least 30% of the values met the neutral vertical motion criteria). A linear least squares fit to the seasonal spatial climatology was applied to produce the resulting relationship: $\ln(CWV) = 0.04T_0 - 8.2$. This methodology ensures that the relationship between CWV and T_0 over the open ocean, where water supply is not limited, is not substantially affected by systematic changes in dynamical regime with temperature [e.g., *Zveryaev and Allan,* 2005]. CWVmax was subsequently calculated for grid points over the four land regions as: $CWVmax = \exp(0.04T_0 - 8.2)$ and CWVrat = CWV/CWVmax.

Further to these monthly means we also calculate the instantaneous horizontal atmospheric moisture transport based on the column integrated water vapor content and wind vectors at each of the lowest 31 vertical levels from the six hourly data of the ERA Interim. These instantaneous data were only available from 1989 until 2008. This is done for each of the individual regions shown in Fig.1 and enables assessment of their individual vertical moisture transport profiles at high temporal resolution, and it also allows averaging of vertical profiles over certain periods of time. The approach and details on how these estimates are derived and applied is published in a series of papers by *Zahn and Allan* [2011, 2013a,b].

We examine summertime variability of the regionally averaged elements of the hydrological cycle over four European regions – Iberian Peninsula (IP), British Isles (BI), Central Europe (CE) and European Russia (ER), which are characterized by the contrasting climatic conditions. Boundaries of these regions are depicted in Figure 1 which also illustrates the substantial differences in seasonal mean CWV across the regions considered.

To assess links between different elements of the regional hydrological cycle we use conventional correlation analysis. According to the Student's *t*-test [*Bendat and Piersol,* 1966], the minimum significant correlation coefficient between the time series analyzed (33 years) is 0.361 for the 95% significance level. The impact of autocorrelation on the estimation of significance of correlation coefficients was found to be trivial in the analyzed time series which is expected since each JJA season is separated by 1 year. It should be emphasized that statistical methods used in this study imply that only linear relationships between analyzed variables are addressed.

3. Interannual variability of the key elements of summertime hydrological cycle over European regions

3.1 Interannual variability of seasonally averaged parameters

To investigate specific regional features of interannual variability in aspects of the hydrological cycle over four European regions during summer, we first examine time series of the normalized (by respective standard deviations) anomalies of seasonally (JJA) and regionally averaged parameters. The time series of P, soil moisture and AT anomalies are shown in Figure 2 and the time series of CWV, moisture transport and CWVrat anomalies are depicted in Figure 3. The correlations between considered parameters are presented in Table 1.

The time series for the IP region (Figure 2a) displays some correspondence between interannual variations of soil moisture and those of P (r=0.34) and AT (r=-0.41). Indeed, in 1988 and 1997 large positive anomalies of P and negative anomalies of AT coincided with large positive anomalies of soil moisture. On the other hand, in 2005 deficient precipitation and high temperatures are linked with anomalously dry soils in the region. This result is consistent with findings of *Garcia-Herrera et al.* [2007] showing that the hydrological year 2004/05 was the driest since the beginning of the precipitation records. However, these relationships do not hold for all years considered. For example, in 1992 a large positive P anomaly (and negative AT anomaly) was not associated with increased soil moisture content (Figure 2a). Indeed, the soil moisture content was even slightly lower than its climatological value. This might be a result of delayed soil moisture response to P and AT anomalies in the preceding season/month (see our analysis in the next section). Our results imply that in the IP region interannual variability of P is weakly linked to that of CWV and moisture transport (Figure 3a); it is more strongly linked with regional AT variability (Figure 2a) as well as to CWVrat and RH variations (Table 1). Table 1 summarizes results of the time series analysis. Negative correlation between summertime P and AT over IP region is indeed rather large (-0.53), which is generally consistent with results presented by *Berg et al.* [2015]. Also, the link between soil moisture and AT is somewhat stronger than that to P (though both are statistically significant). Interestingly, the largest correlation (-0.55) for soil moisture is with atmospheric moisture transport. This somewhat controversial result (i.e., negative correlation between soil moisture and moisture transport) can be at least partly explained by the recent findings of *Gimeno et al.* [2010b] demonstrating that the origin of P is different for different parts of the Iberian Peninsula. In particular this study shows that the two major moisture sources for the IP region, the tropical-subtropical North Atlantic source and the IP – western Mediterranean source play differing roles in different parts of the IP region. Furthermore, analyzing regional surface humidity variability, *Vicente-Serrano et al.* [2014] found constraints on the supply of moisture to the atmosphere from the main (above mentioned) terrestrial and oceanic sources. These constraints are a reduction in precipitation and soil moisture in the case of terrestrial sources, and stable sea surface temperatures that could reduce the flow of atmospheric moisture into the region. Therefore, averaging of the analyzed parameters over the entire region may impact the results of the analysis. It can also be speculated that in the IP region large fractions of precipitation might (especially during the hot season) quickly evaporate not enhancing regional soil moisture content significantly. Furthermore, higher temperatures are associated with lower soil moisture (r=-0.41) due to reduced cooling by surface evaporative fluxes. The warmer land is generally associated with greater convergence yet moisture convergence and P is only enhanced if the air is moisture laden (high CWVrat). Indeed regional P in the IP region is strongly linked (correlation 0.67) to CWVrat and RH (r=0.83) but not to CWV (Table 1). Therefore, the results imply that in this region the hottest conditions are associated with reduced P which is associated with less cloud and more solar radiation while also reducing soil moisture and allowing more of the sunlight to heat the ground rather than evaporate water.

The BI region is characterized by stronger links between soil moisture and P and AT compared to the IP region (Figure 2b, Table 1). In particular, anomalously dry soils were clearly associated with reduced P and higher air AT in 1984, 1995 and 2006. It is interesting that moisture transport into the region was also anomalously low during these years (Figure 3b). On the other hand, in 1985 a positive soil moisture anomaly was clearly associated with increased P (Figure 2b). Similar results are obtained for the recent anomalously moist summer of 2007 [*Marsh and Hannaford,* 2007; *Blackburn et al.,* 2008; *Allan and Zveryaev,* 2011]. In contrast to the IP region correlation between regional P and moisture transport over the BI region is very large (r=0.93; Table 1).

Summertime soil moisture variability in the CE region is characterized by an abrupt decrease of soil moisture in the late 1980s which returns to its former values in the mid 1990s (Figure 2c). Remarkably, time series of P and AT do not reveal such tendencies; rather they show gradual increase of these parameters over the entire period of analysis. However, on shorter (interannual) time scale soil moisture anomalies (especially large ones) are generally in a good agreement with anomalies of P and AT (e.g., 1980, 1987 and 2003 in Figure 2c). The European summer heat wave of 2003 [e.g., *Beniston,* 2004] is well captured by our analysis for the CE region (large anomalies are revealed for soil moisture, P, AT and moisture transport), whereas over the generally drier IP region we detected a large anomaly in that year only for air temperature (Figure 2a). Correlation analysis demonstrates (as in case of the BI region) generally strong links between regional soil moisture, P and moisture transport in the CE region (Table 1). Note however, that the link between soil moisture and AT in this region is weaker than those revealed for the IP and BI regions.

In the continental climate of the ER region our analysis does not reveal any systematic changes in soil moisture, P and AT (Figure 2d). Large anomalies of soil moisture are generally associated with anomalies of like sign in P and moisture transport but opposing anomalies in AT (e.g., 1993, 2002 and 2010, Figures 2d and 3d). As expected, very large anomalies of the considered parameters in ER region are detected in 2010 during the Russian summer heat wave [e.g., *Dole et al.,* 2011; *Barriopedro et al.,* 2011; *Otto et al.,* 2012]. However, in 1984 a large negative soil moisture anomaly was accompanied by a positive anomaly of P and negative anomaly of AT (Figure 2d). Correlations demonstrate very strong links between regional P and moisture transport in the ER region (Table 1). Also, in this region we find the largest (r=0.7) correlation between CWV and AT (which are linked through Clausius-Clapeyron equations) implying limited variation in relative humidity.

3.2 Lag-lead correlations between different elements of the hydrological cycle

Since the time-scales involved in depleting and replenishing soil moisture are not instantaneous this motivated us to examine lag-lead relationships between regional soil moisture, P and AT by analyzing correlations between monthly time series of these parameters. A lag-lead correlation is calculated between a variable at one time step and values of another variable at later or earlier (lagged) time. The lag-lead correlations are shown in Table 2. It should be noted here that besides the impact of P and AT on soil moisture variability, there is also a feedback from soil moisture on both P and AT that can significantly modify variability of these parameters [e.g., *Koster et al.,* 2004; *Seneviratne et al.,* 2006; *Hirschi et al.,* 2011; *Miralles et al.,* 2012; *Berg et al.,* 2013; *Berg et al.,* 2015].

In the IP region significant lag-lead correlations with regional soil moisture are found only for June P (Table 2). Significant correlations are not detected for July and August P since during this part of the summer season P is very low in the IP region and any soil moisture replenishment is rapidly lost through evaporation. Interestingly, for June P simultaneous correlation with June soil moisture (r=0.42) is lower than those with July (r=0.55) and August (r=0.55) soil moisture. One explanation is that rainfall towards the end of the month will not greatly influence the monthly total soil moisture. However, the time-scale for soil moisture depletion following rainfall will also produce a delayed response of soil moisture variability to the impact of P. A similar result is obtained for June AT, for which simultaneous correlation with June soil moisture (r=-0.49) is lower than for July (r=-0.58) and August (r=-0.57) soil moisture. Though the difference is not large, July AT in the IP region shows stronger links to soil moisture in August (r=-0.50) than in July (r=-0.43). In August, however, simultaneous correlation between AT and soil moisture (r=-0.49) is slightly larger than the lagged one (r=-0.40). Note, latter correlation might indicate a soil moisture feedback onto AT. Indeed, in moisture constrained regions large incoming solar radiation cannot result in enhanced latent heat flux (evaporation) due to limited soil moisture content. Instead, it results in enhanced sensible heat flux which in turn increases near surface air AT [e.g., *Berg et al.,* 2015].

Correlations in the BI region do not show statistically significant simultaneous links between regional P and soil moisture in June and July (Table 2). However, August soil moisture is significantly correlated to P in all summer months. We find statistically significant correlation (r=0.57) between June P and July soil moisture, indicative of its lagged response to P impact (precipitation falling at the end of the month will not affect soil moisture for the much that month). AT in June is not correlated significantly to soil moisture in any month (Table 2) suggesting that soil moisture does not generally become limited over the BI region in summer. However, July and August AT both display significant correlations to August soil moisture indicating that warmer prior conditions are able to dry the soils by August.

In the CE region there are no statistically significant simultaneous correlations between soil moisture and P or between soil moisture and AT (Table 2). Moreover, we do not find significant lagged correlations between soil moisture and AT. However, rather large lagged correlations are revealed between June P and July soil moisture and between July P and August soil moisture, implying a delayed response of soil moisture variability to P impact as expected (precipitation late in the month will have a greater influence on soil moisture in the following month).

Lag-lead correlations in the ER region do not show significant simultaneous links between regional P and soil moisture in June and July (Table 2). However, August soil moisture shows significant simultaneous correlation to P (r=0.47). Similar results are obtained regarding regional relationships between soil moisture and AT (Table 2). Consistent with results of the previous subsection (Table 1), this suggests approximately equal roles of P and AT in interannual variability of soil moisture in ER region during summer season. In common with the other regions, the strongest correlations are generally between June (July) P or AT and July (August) soil moisture. This indicates that more cloud and rainfall is associated with lower temperatures (as indicated by negative correlations between P and AT in Table 1) and soil moisture is replenished by the following month.

In summary, coupling between AT and soil moisture variability is strongest in the IP region and weakest for CE. In the BI and the ER regions such influence is detected in late summer (August). Significant correlations (both simultaneous and lagged) between soil moisture and P are also revealed mostly in late summer. The exception is the IP region where June P correlates significantly with soil moisture in all summer months. It is important to emphasize that in many cases we find that lagged correlations are larger than respective simultaneous correlations, thus indicating a delayed response of soil moisture variability to impacts of P and AT.

4. Summertime atmospheric moisture transport over European regions

Since our results presented in the previous sections indicate an important role of moisture transport in determining variability of the key elements of the regional hydrological cycle (P and soil moisture), in this section we examine in greater detail the vertical structure of moisture transport in each region. We focus on climatological (i.e. averaged over the period of analysis) values of the instantaneous transports and on particular years characterized by large positive/negative anomalies of P. Figure 4 shows summer mean moisture transport at different pressure levels averaged over the entire period of analysis. The term “moisture transport” here means the net transport, i.e. the balance between horizontal moisture flux into the region and that out of the region of analysis. The moisture transport is calculated separately at each pressure level. Hence, positive values in Figure 4 indicate a net moisture flux into the region at a given level (the model levels are indicated by the ticks). Figures 5-8 show horizontal moisture transports at different pressure levels estimated along the borders of the different regions for particular years.

The vertical structure of horizontal moisture transport for the IP region demonstrates the largest (compared to other regions) spread of moisture transport at different levels (Figure 4). The major moisture transport into the region is observed at the lower levels (1000-900hPa), whereas large moisture transport at the higher levels between 900-500hPa is directed outward. Note, net moisture divergence out of this region (1.7mm/day) is the greatest of all regions implying significant depletion of soil moisture. Such a low level inflow - upper level outflow profile was found typical for the subtropical moisture transport regimes [*Zahn and Allan,* 2013b].

The profile of the BI region is more complicated (Figure 4). Inward moisture transport is detected at two levels, near the surface (1000-950hPa) and in the layer 800-550hPa. The moisture transport out of the region prevails between 950-800hPa. Except the lower level inflow, this resembles the extra-tropical profile of moisture transports in *Zahn and Allan* [2013a], with upper level inflow and lower to mid level outflow.

Horizontal moisture transport for the CE region shows relatively small moisture flux into the region near the surface. General moisture flux out of the region is seen between 950hPa and

600hPa levels (Figure 4). In the ER region moisture transport is out of the region at all pressure levels with the largest values observed near the surface level (1000-950hPa) indicating that the land surface is a source of moisture during this season through depletion of soil moisture and export out of the region.

We further analyze the mean vertical moisture transport profiles for the driest and the wettest years in terms of precipitation. Moisture transport at different levels in the IP region is shown in Figure 5. Based on the graphs in figure 2a we selected for our analysis two years with large negative anomalies (1994 and 2005) and two years with large positive anomalies (1992 and 1997) of regional P. Moisture transports during dry years (i.e., in 1994 and 2005) are somewhat at odds. While moisture transport into the region at lower levels is close to its climatological values (Figures 5a and 5b), the majority of the variability seems dominated by the upper atmospheric layer between 900-500hPa. In 1994 we find slightly increased moisture flux out of the region (Figures 5a) which is consistent with reduced P in the region. On the contrary, in 2005 the moisture flux out of the region was significantly decreased (Figures 5b) which generally does not agree with reduced regional P. It is also possible that reduced evaporation and local moisture recycling may play a role. We recall here that in the IP region the link between P and moisture transport is indeed rather weak (Table 1). The results for the two wet years (1992 and 1997) are more consistent. For both years we find an increased moisture transport into the region at near surface levels and a decreased moisture transport out of the region in the layer 900-500hPa (Figures 5c and 5d), both resulting in enhanced P during these years (Figure 2a).

Figure 6 shows moisture transport at different levels in the BI region. The selected dry years are 1995 and 2006. In both years we find an increased moisture flux out of the region in the atmospheric layer 950-800hPa (Figures 6a and 6b). The major difference is revealed at the near surface levels where in 1995 we find significantly reduced moisture flux into the region, whereas in 2005 it is close to its climatological value. Indicated moisture transport changes resulted in dry conditions in the region. The selected wet years for BI region are 1998 and 2007. In 1998 moisture transport into the region was not unusual near the surface but was greater than average above the 800hPa level whereas the moisture transport out of the region was below average in the layer 950-800hPa (Figure 6c). In 2007 the moisture transport into the region was approximately twice larger than average above the 800hPa level, whereas the moisture transport out of the region was about half of the average in the layer 950-800hPa (Figure 6d). These changes resulted in anomalously wet conditions in the region. Generally, the BI profiles maintain a similar shape in anomalous precipitation years, which just varies in strength. This is consistent with analysis in Section 3.1 which indicates that positive anomalies in moisture transport into the BI region are associated with greater P (Table 1).

Moisture transport at different levels in the CE region is depicted in Figure 7. Dry conditions in 1994 and 2003 were mostly associated with increased moisture transport out of the region at the lower to mid levels (below 650hPa, Figures 7a and b). In 2003 this increased outflow was so pronounced, that an increased inflow at upper level could not compensate the total budget. Enhanced P in 2002 and 2007 was associated with increased near surface moisture transport into the CE region and decreased moisture transport out of the region in the layer 950-800hPa (Figures 7c and d). For CE the profiles' shapes can deviate considerably from the mean in anomalous P years.

Figure 8 demonstrates moisture transport at different levels in the ER region. The selected dry years for this region are 1992 and 2002. Unfortunately, the instantaneous ERA interim data for 2010 were not available to us. In both years we find an increased moisture flux out of the region in the lower troposphere, especially near the surface (Figures 8a and 8b). Particularly large (twice its climatological value) moisture flux out of the ER region is observed in 2002 (Figure 8b). This coincides with decreased P and generally dry conditions in the region. The selected wet years for the region are 1989 and 2003. In these years substantial changes in regional moisture transport are detected. In both years general climatological moisture flux out of the region has reversed with moisture flux directed into the region. Thus, it appears that the ER is the only region where the moisture flux during anomalous years not only became stronger/weaker, but even changed its resulting direction. This reversal in climatological moisture export lead to enhanced P in the region during 1989 and 2003.

Summarizing results of this section, we note that during summer the vertical structure of the horizontal moisture transport is different over each of the considered regions. Our analysis also revealed contrasting changes in moisture transport at the different atmospheric levels associated with anomalously dry/wet summers in the European regions analyzed in this study, in particular for the BI and CE regions. The IP region is characterized by the largest moisture inflow (near the surface) and outflow (around 750hPa) of all regions considered yet is a net exporter of moisture overall indicating substantial depletion of local soil moisture. Similarly climatological net moisture export over the ER region at all levels also indicates depletion of local soil moisture but this situation reverses during anomalously wet years where a net import of remote moisture leads to greater rainfall totals. Regarding the shape of the vertical profiles we found lower variability in the regimes with a strong coastal influence. Towards more continental climate these profiles get more variable, and can even reverse sign in the whole vertical as in the case of the ER.

5. Summary and discussion

In the present study we analyzed summer season variability in key elements of the hydrological cycle from multiple datasets over four European regions – Iberian Peninsula (IP), British Isles (BI), Central Europe (CE) and European Russia (ER). We also investigated lag-lead relationships between different parameters and examined the vertical structure of atmospheric moisture transport during anomalously dry/wet summers in the respective regions.

It is shown that in all regions considered except the IP region interannual variability of summertime P (and soil moisture) is linked strongly to variations in horizontal atmospheric moisture transport. Regarding the IP region, the detected weak links between the above mentioned parameters were plausible because of the generally low P and prevailing dry conditions in this region during the summer season. Due to these same reasons we also do not find a significant link between AT and CWV in the IP region. Increased AT over the land is not associated with higher CWV since the surface temperature over the ocean source regions [e.g. *Gimeno et al.,* 2010a] is considerably lower and the enhanced evaporation over land is inhibited by low soil moisture content during summer in this region. During the summer season, western and eastern parts of the Iberian Peninsula get moisture from different sources - the tropical-subtropical North Atlantic source and the IP – western Mediterranean source [*Gimeno et al.,* 2010b]. In other regions considered the link between AT and CWV (determined by Clausius-Clapeyron equation) is very strong. Large correlations between summer P and relative humidity (RH) revealed in this study (Table 1) are generally consistent with results of *Ye et al.* [2014] for northern Eurasia which show that in summer RH is the primary contributor to P (and precipitation efficiency) in the region.

Analysis of simultaneous and lag-lead links between soil moisture and P or AT on the other side has shown that, in many cases the lagged correlations are larger than the respective simultaneous correlations. It is expected that precipitation falling toward the end of a month will influence soil moisture in the following month. Yet the time-scales of soil moisture depletion and replenishment also indicate an important role for a delayed response between P or AT and regional soil moisture during the summer season. It is found that AT coupling with soil moisture variability is most important in the moisture limited IP region. On the contrary, in the CE region AT does not appear to be strongly linked with interannual soil moisture variability during the summer season. Regions in which P is re-evaporated and recycled, such as continental interiors in summer, may potentially show stronger relationships with P than with soil moisture; for example rainfall associated with cloudy conditions will reduce the surface heating from absorbed sunlight whilst re-evaporation of any P will further reduce the fraction of surface net radiation that directly heats the atmosphere through sensible heat fluxes.

Our analysis reveals contrasting vertical structures of the horizontal moisture transport across the different regions in summer. We also found differing changes in moisture transport at the different atmospheric levels associated with anomalously dry/wet summers in the European regions analyzed in this study. In particular, the largest changes of moisture transport are detected over the ER region during anomalously wet summers. In these summers climatological moisture flux out of the region has changed to resulting moisture flux directed into the region. The IP region experiences the greatest moisture inflow (at low levels) and outflow (at around 750hPa) yet is the strongest overall net exporter of moisture (1.7mm/day) of all regions considered, indicating substantial depletion of soil moisture over the summer. This suggests that precipitation minus evaporation can be negative over land during the summer season with implications for future changes in aridity [e.g., *Greve and Seneviratne,* 2015].

The present study reveals and compares specific features of summertime interannual variability of the key elements of the hydrological cycle over four European regions. We found differing interannual variabilities as well as different relationships between aspects of the regional hydrological cycles. In particular, different roles of P and AT in soil moisture variability are highlighted. We also found significant changes in atmospheric moisture transport at different pressure levels during anomalously dry/wet years. Further diagnostic studies based on new observational data and involving more parameters (e.g., evapotranspiration) as well as model experiments will enable more accurate assessments of the revealed links and relationships depicting the European hydrological cycle in the summer season.

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Table Captions

Table 1. Correlation coefficients between regional time series of seasonal mean summer precipitation, soil moisture, air temperature, CWV, CWVrat, RH and horizontal moisture transport. Coefficients, shown in color, are statistically significant at the 95% significance level.

Table 2. Correlation coefficients between regional time series of monthly mean soil moisture, precipitation and air temperature. Coefficients, shown in bold, are statistically significant at the 95% significance level.

Figure Captions

Figure 1. Summer (JJA) mean CWV distribution over Europe. Black curves indicate boundaries of the regions under analysis.

Figure 2. Regional time series of normalized anomalies of seasonal mean summer precipitation (blue curve), soil moisture (green curve), and air temperature (red curve).

Figure 3. Regional time series of normalized anomalies of seasonal mean summer CWV (violet curve), CWVrat (green curve), and horizontal moisture transport (blue curve).

Figure 4. Climatological vertical structure of horizontal moisture transport over four European regions. Positive (negative) values indicate resulting moisture flux into (out of) the region.

Figure 5. Vertical structure of horizontal moisture transport over IP region during selected anomalously dry (a, b) and wet (c, d) summers (red) and the JJA mean profile (blue). Positive (negative) values indicate resulting moisture flux into (out of) the region.

Figure 6. Vertical structure of horizontal moisture transport over BI region during selected anomalously dry (a, b) and wet (c, d) summers (red) and the JJA mean profile (blue). Positive (negative) values indicate resulting moisture flux into (out of) the region.

Figure 7. Vertical structure of horizontal moisture transport over CE region during selected anomalously dry (a, b) and wet (c, d) summers (red) and the JJA mean profile (blue). Positive (negative) values indicate resulting moisture flux into (out of) the region.

Figure 8. Vertical structure of horizontal moisture transport over ER region during selected anomalously dry (a, b) and wet (c, d) summers (red) and the JJA mean profile (blue). Positive (negative) values indicate resulting moisture flux into (out of) the region.

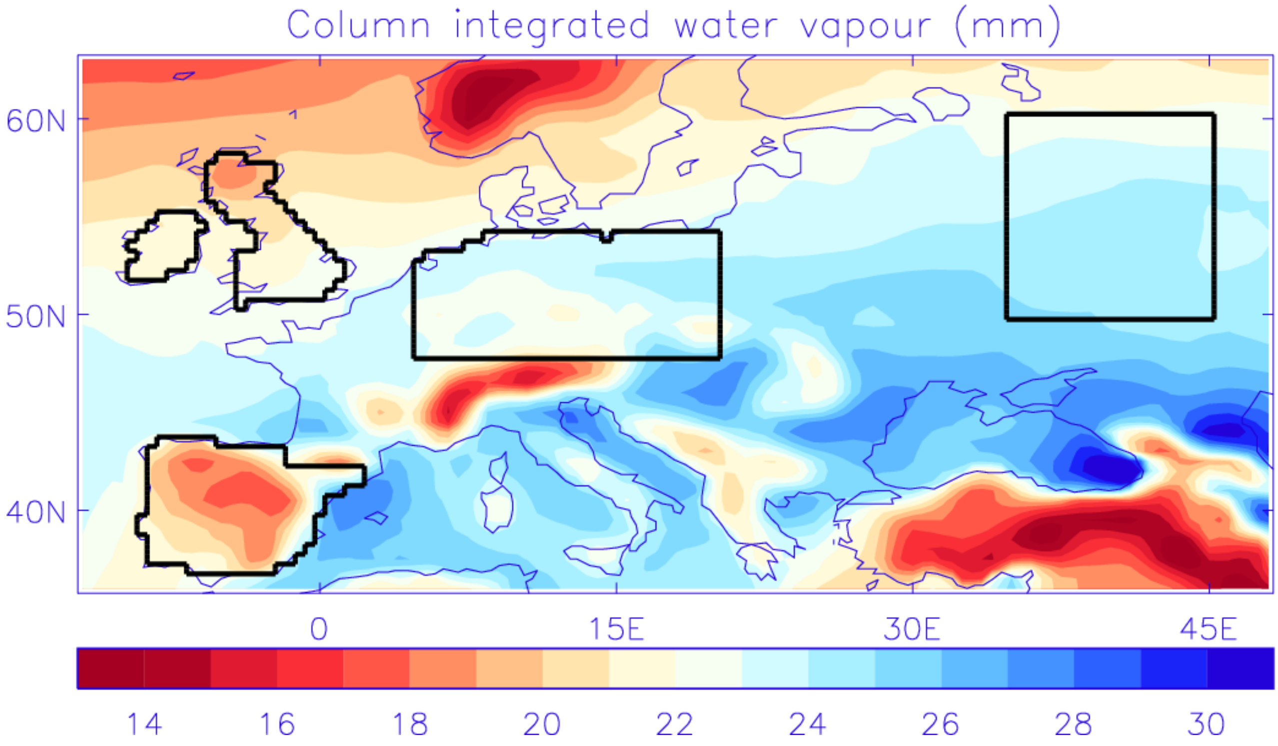

Column integrated water vapour (mm)
60N
50N
40N
0
15E
30E
45E
14
16
18
20
22
24
26
28
30

Figure 1

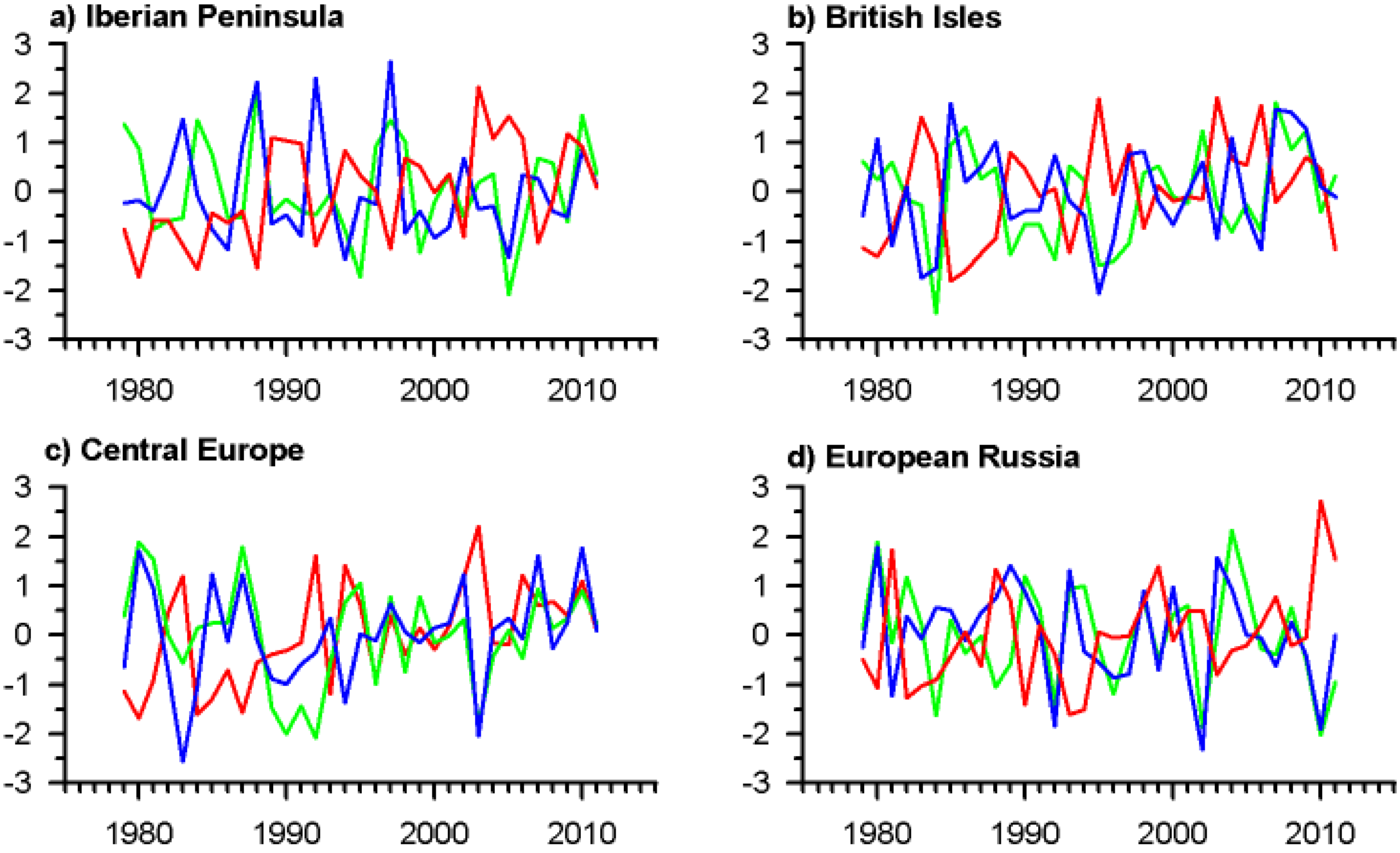
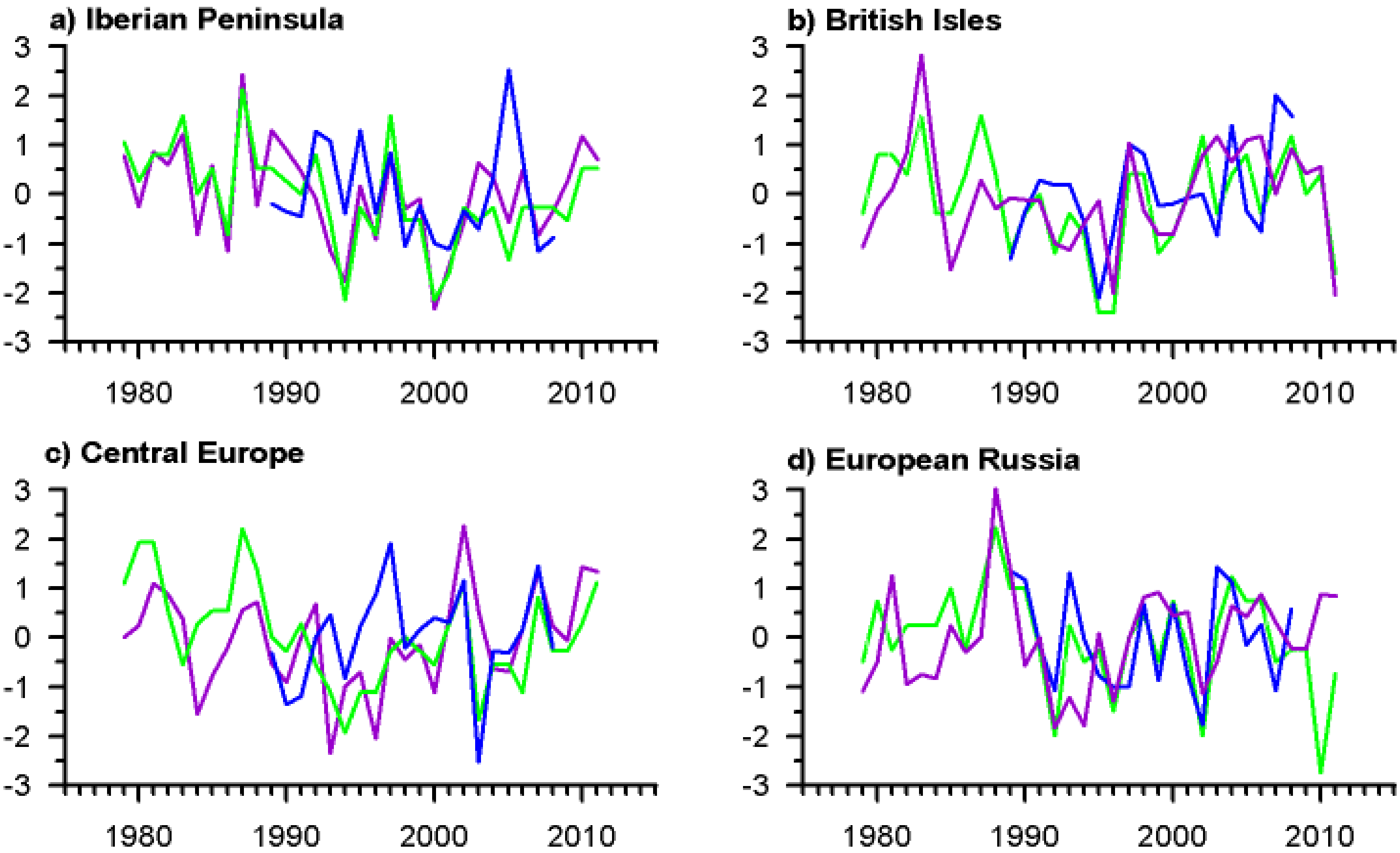

a) Iberian Peninsula
b) British Isles
c) Central Europe
d) European Russia
3
2
1
0
-1
-2
-3
1980
1990
2000
2010

Figure 2


a) Iberian Peninsula
b) British Isles
c) Central Europe
d) European Russia
3
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1980
1990
2000
2010

Figure 3

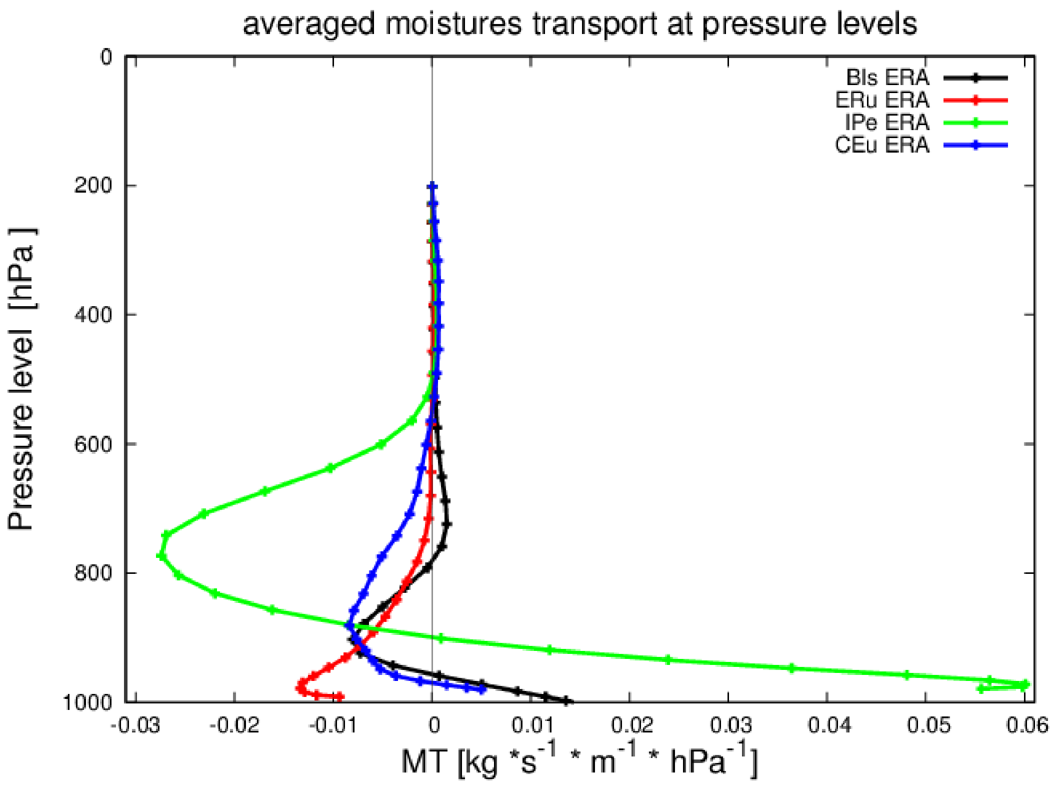

averaged moistures transport at pressure levels
BIs ERA
ERu ERA
IPe ERA
CEu ERA
Pressure level [hPa]
0
200
400
600
800
1000
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
0.05
0.06
MT [kg *s-1 * m-1 * hPa-1]

Figure 4

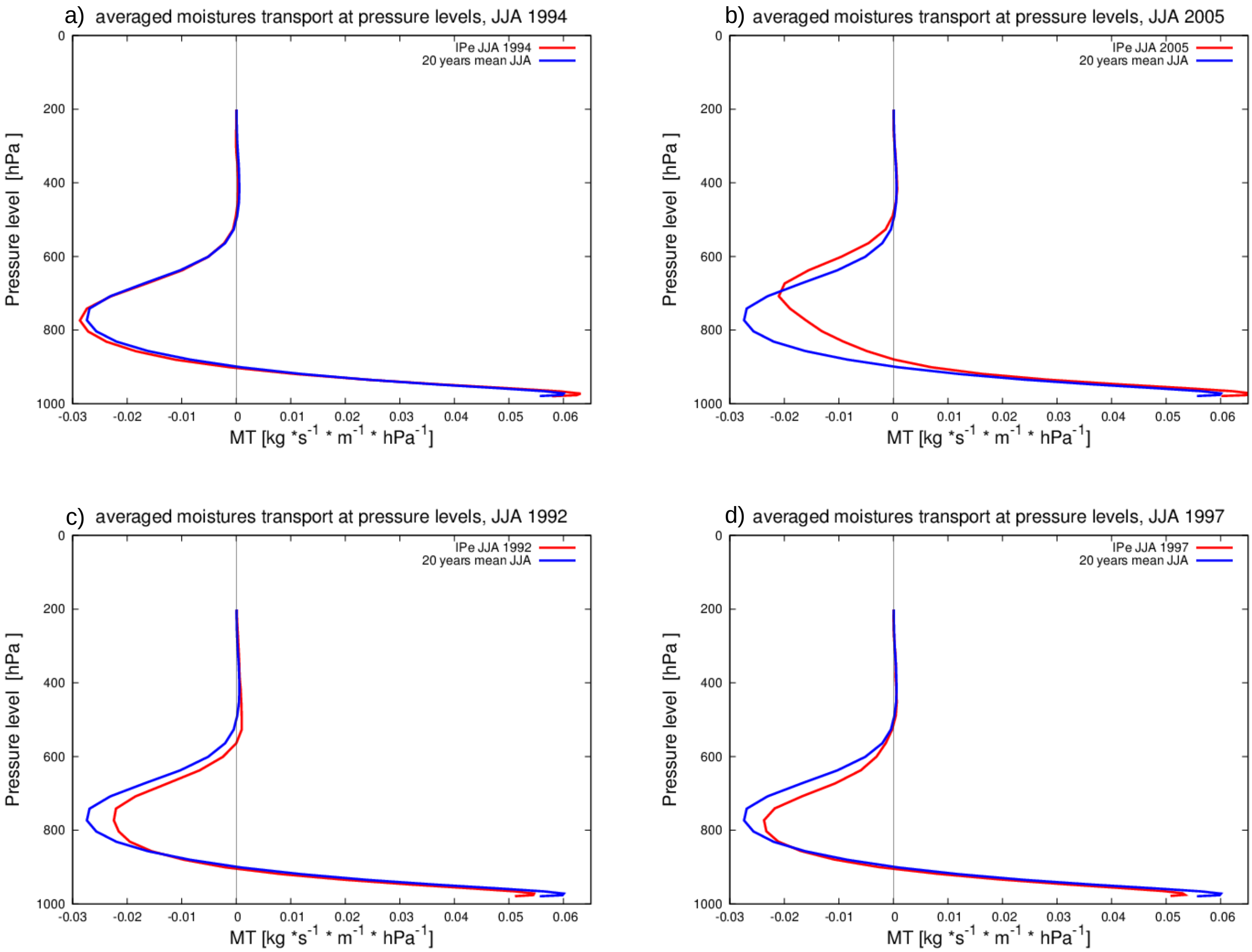
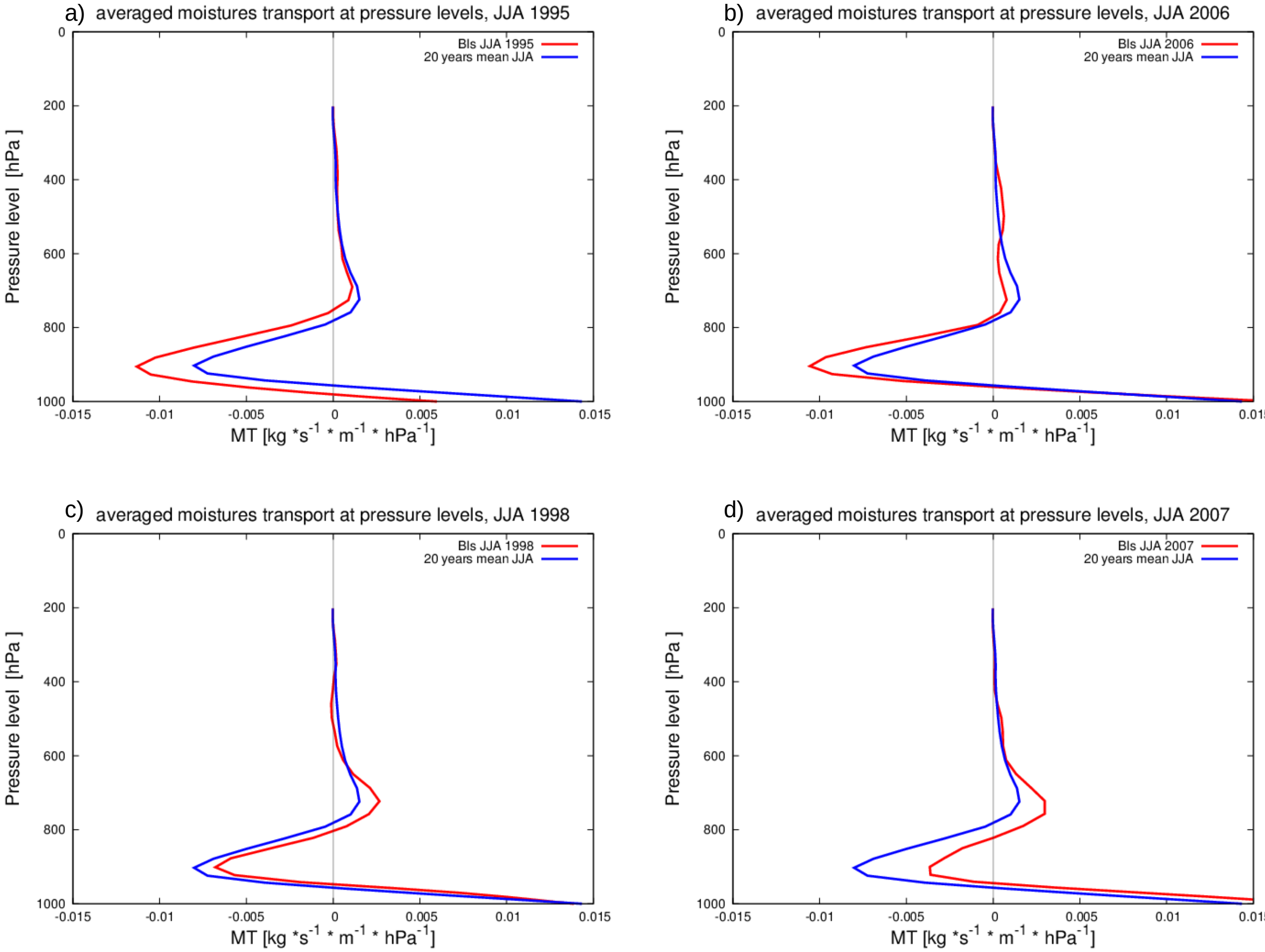

a) averaged moistures transport at pressure levels, JJA 1994
IPe JJA 1994
20 years mean JJA
Pressure level [hPa]
MT [kg *s^-1 * m^-1 * hPa^-1]
0
200
400
600
800
1000
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
0.05
0.06
b) averaged moistures transport at pressure levels, JJA 2005
IPe JJA 2005
20 years mean JJA
Pressure level [hPa]
MT [kg *s^-1 * m^-1 * hPa^-1]
c) averaged moistures transport at pressure levels, JJA 1992
IPe JJA 1992
20 years mean JJA
Pressure level [hPa]
MT [kg *s^-1 * m^-1 * hPa^-1]
d) averaged moistures transport at pressure levels, JJA 1997
IPe JJA 1997
20 years mean JJA
Pressure level [hPa]
MT [kg *s^-1 * m^-1 * hPa^-1]

Figure 5



a) averaged moistures transport at pressure levels, JJA 1995
Bls JJA 1995
20 years mean JJA
b) averaged moistures transport at pressure levels, JJA 2006
Bls JJA 2006
20 years mean JJA
c) averaged moistures transport at pressure levels, JJA 1998
Bls JJA 1998
20 years mean JJA
d) averaged moistures transport at pressure levels, JJA 2007
Bls JJA 2007
20 years mean JJA
Pressure level [hPa]
MT [kg *s-1 * m-1 * hPa-1]
0
200
400
600
800
1000
-0.015
-0.01
-0.005
0
0.005
0.01
0.015

Figure 6

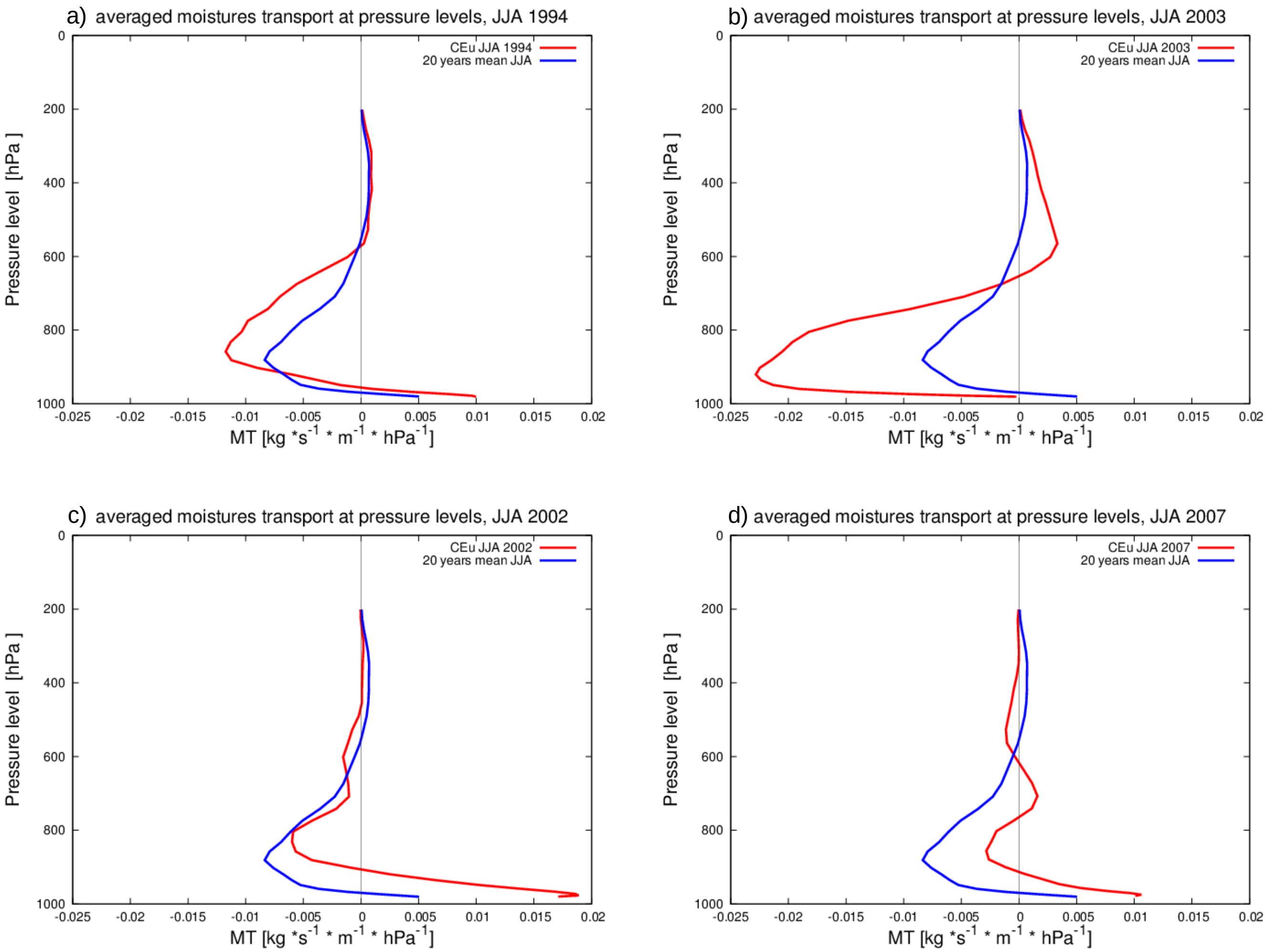

a) averaged moistures transport at pressure levels, JJA 1994
CEu JJA 1994
20 years mean JJA
b) averaged moistures transport at pressure levels, JJA 2003
CEu JJA 2003
20 years mean JJA
c) averaged moistures transport at pressure levels, JJA 2002
CEu JJA 2002
20 years mean JJA
d) averaged moistures transport at pressure levels, JJA 2007
CEu JJA 2007
20 years mean JJA
Pressure level [hPa]
0
200
400
600
800
1000
-0.025 -0.02 -0.015 -0.01 -0.005 0 0.005 0.01 0.015 0.02
MT [kg *s-1 * m-1 * hPa-1]

Figure 7

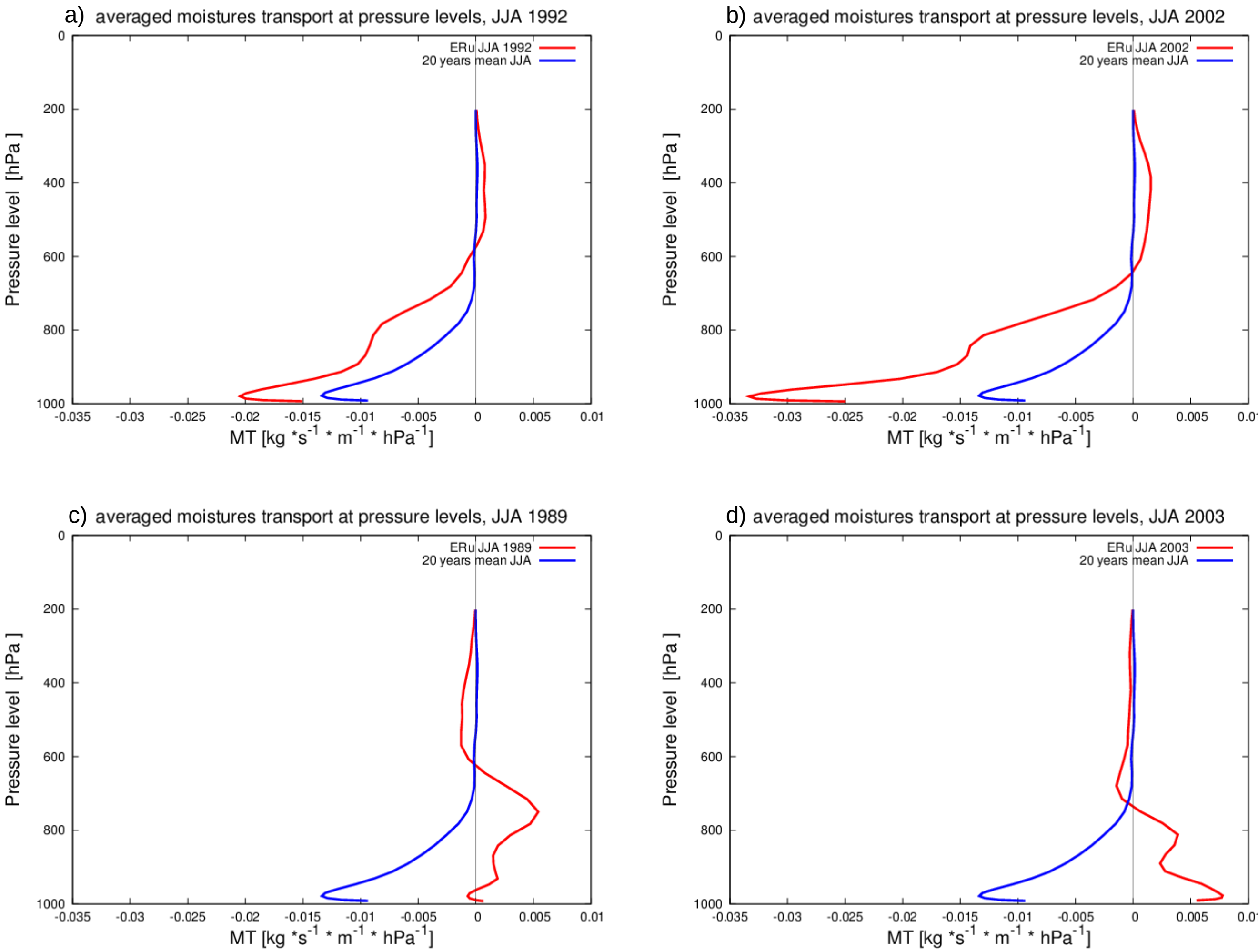

a) averaged moistures transport at pressure levels, JJA 1992
ERu JJA 1992
20 years mean JJA
Pressure level [hPa]
MT [kg *s^{-1} * m^{-1} * hPa^{-1}]
b) averaged moistures transport at pressure levels, JJA 2002
ERu JJA 2002
20 years mean JJA
Pressure level [hPa]
MT [kg *s^{-1} * m^{-1} * hPa^{-1}]
c) averaged moistures transport at pressure levels, JJA 1989
ERu JJA 1989
20 years mean JJA
Pressure level [hPa]
MT [kg *s^{-1} * m^{-1} * hPa^{-1}]
d) averaged moistures transport at pressure levels, JJA 2003
ERu JJA 2003
20 years mean JJA
Pressure level [hPa]
MT [kg *s^{-1} * m^{-1} * hPa^{-1}]

Figure 8

IP region	TMP	SM	CWV	MT	CWVr	RH
PRE	-0.53	0.34	0.36	0.30	0.67	0.83
TMP		-0.41	0.11	0.02	-0.42	-0.52
SM			0.06	-0.55	0.25	0.20
CWV				0.22	0.84	0.70
MT					0.25	0.31
CWVr						0.94

BI region	TMP	SM	CWV	MT	CWVr	RH
PRE	-0.48	0.57	-0.15	0.93	0.38	0.86
TMP		-0.56	0.64	-0.46	-0.16	-0.72
SM			-0.11	0.55	0.43	0.65
CWV				0.19	0.64	-0.16
MT					0.70	0.92
CWVr						0.57

CE region	TMP	SM	CWV	MT	CWVr	RH
PRE	-0.33	0.61	0.28	0.86	0.54	0.56
TMP		-0.31	0.42	-0.24	-0.53	-0.81
SM			0.27	0.59	0.54	0.49
CWV				0.12	0.53	0.16
MT					0.42	0.51
CWVr						0.90

ER region	TMP	SM	CWV	MT	CWVr	RH
PRE	-0.46	0.60	0.16	0.96	0.80	0.80
TMP		-0.55	0.70	-0.46	-0.33	-0.78
SM			-0.09	0.64	0.56	0.62
CWV				0.24	0.43	-0.16
MT					0.79	0.84
CWVr						0.79

Table 1

IP	PRECIPITATION			AIR TEMPERATURE		
SM	JUN	JUL	AUG	JUN	JUL	AUG
MAY	0.21	0.02	-0.19	-0.30	-0.29	-0.34
JUN	**0.42**	0.04	-0.15	**-0.49**	-0.35	-0.37
JUL	**0.55**	0.20	-0.09	**-0.58**	**-0.43**	**-0.40**
AUG	**0.55**	0.32	0.11	**-0.57**	**-0.50**	**-0.49**

BI	PRECIPITATION			AIR TEMPERATURE		
SM	JUN	JUL	AUG	JUN	JUL	AUG
MAY	-0.03	-0.14	-0.01	-0.02	0.07	-0.11
JUN	0.33	-0.14	-0.05	-0.18	-0.06	-0.19
JUL	**0.57**	0.34	0.15	-0.20	-0.38	-0.37
AUG	**0.40**	**0.67**	**0.65**	-0.09	**-0.58**	**-0.62**

CE	PRECIPITATION			AIR TEMPERATURE		
SM	JUN	JUL	AUG	JUN	JUL	AUG
MAY	0.07	-0.03	0.14	-0.03	0.12	-0.12
JUN	0.34	-0.04	0.17	-0.23	0.04	-0.18
JUL	**0.56**	0.39	0.10	-0.24	-0.26	-0.24
AUG	**0.44**	**0.59**	0.37	-0.07	-0.36	-0.35

ER	PRECIPITATION			AIR TEMPERATURE		
SM	JUN	JUL	AUG	JUN	JUL	AUG
MAY	-0.12	-0.08	-0.01	-0.05	0.09	0.12
JUN	0.28	-0.01	0.04	-0.31	-0.07	-0.07
JUL	**0.53**	0.39	0.09	**-0.52**	-0.36	-0.25
AUG	0.39	**0.61**	**0.47**	-0.39	**-0.52**	**-0.45**

Table 2