### Contrasting Interannual variability of Atmospheric Moisture over Europe during Cold and Warm Seasons

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| Complete List of Authors: | Zveryaev, Igor; P.P. Shirshov Inst. of Oceanology, air-sea interaction lab.  
Wibig, Joanna; University of Lodz, Dept. of Meteorology and Climatology  
Allan, Richard; University of Reading, Environmental Systems Science Centre |
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Contrasting Interannual variability of Atmospheric Moisture over Europe during Cold and Warm Seasons

Igor I. Zveryaev, Joanna Wibig¹ and Richard P. Allan²

P.P. Shirshov Institute of Oceanology, RAS, Moscow, Russia

¹Department of Meteorology and Climatology, University of Łódź, Łódź, Poland

²Environmental Systems Science Centre, University of Reading, Reading, UK

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Address for correspondence:

Dr. Igor I. Zveryaev, P.P. Shirshov Institute of Oceanology, RAS

36, Nakhimovsky Ave., Moscow, 117997, Russia

Telephone: 7 (495) 1247928

Telefax: 7 (495) 1245983

Email: igorz@sail.msk.ru
Abstract

Seasonality in interannual variability of the atmospheric moisture over Europe is investigated using precipitable water (PW) from the NCEP/NCAR Reanalysis dataset for 1979-2004. Over Europe the summer PW and its interannual variability (expressed by standard deviations) are essentially larger than those of the winter season. The largest seasonal differences are found over eastern Europe and European Russia, where the summer PW climatology and magnitudes of its interannual variability exceed respective winter characteristics by a factor of 2.5-3.8.

The first and second EOF modes of winter PW over Europe are associated, respectively, with the North Atlantic Oscillation (NAO) and the East Atlantic teleconnection pattern. During summer the leading EOFs of PW are not linked to the known regional teleconnection patterns. Our analysis revealed that EOF-1 of summer PW is associated with sea level pressure (SLP) pattern characterized by two action centers of opposite polarity over northwestern Siberia and over broad region including southern Europe, Mediterranean Sea and part of northern Africa. The EOF-2 of summer PW is associated with SLP pattern resembling Rossby wave structure and implying possible influence of the tropical Atlantic on the regional PW variability.

It is shown that PW and precipitation variability are positively coupled during cold season but not for the warm season. Instead, during warm season we found a link between leading EOFs of regional PW and air temperature.
1. Introduction

It is well known that during the cold season the North Atlantic Oscillation (hereafter NAO) is the major driver of the European climate variability (e.g., van Loon and Rogers 1978; Rogers 1984; Hurrell 1995, Seager et al., 2000). Since the NAO is linked to sea surface temperature variations in the North Atlantic (e.g., Rodwell and Folland, 2002), potentially this provides some seasonal predictive skill for regional climate. The NAO determines the intensity and the location of the mid-latitudinal jet stream, steering the heat and moisture transport from Atlantic to Europe and forming European climate conditions. Many studies (e.g., Hurrell 1995; Wibig 1999; Cassou and Terray 2001; Gulev et al. 2002) analyzed this mechanism for the cold season. Less is done so far for the analysis of European climate variability during warm season when zonal heat and moisture transport is diminished and the relative role of local processes in regional climate variability is increased. As a result, major mechanisms driving European climate variability during warm season are not well understood. Moreover, these mechanisms might be different for different climatic variables. For example, recent studies show that during summer precipitation variability over Europe is associated with the summer NAO (Zveryaev, 2004, 2006), whereas the NAO is not the major driver of air temperature variability during this season (Zveryaev and Gulev, 2007).

Atmospheric water vapour plays a key role both in radiative and dynamic processes of the climate system. It is the most important greenhouse gas, absorbing strongly a portion of the Earth's outgoing thermal energy and radiating a substantial fraction of this energy back to the surface. As water vapor condenses into clouds, cooling effects become important also. The amount of moisture in the atmosphere, is
strongly related to air temperature according to the Clausius–Clapeyron equation, and is expected to rise as climate warms thus strengthening the greenhouse effect. Water vapor content is also crucial for precipitation, and through latent heat, is driving dynamical processes in the troposphere. Because of a great number of feedbacks in which water vapor is involved it is a source of strong uncertainty when predicting future climate. That is why during the past two decades, analysis of spatial-temporal variability of the atmospheric moisture has received considerable attention. A number of papers focused on the regional changes in atmospheric water vapor (e.g., Flohn and Kapala, 1989; Ross and Elliott, 1996, 2001; Zhai and Eskridge, 1997; Trenberth et al. 2005). Several other studies considered global distribution of the atmospheric moisture and its variability (Oort, 1983; Peixoto and Oort, 1992; Gaffen et al., 1991). Although PW variability is linked to variations of air temperature and precipitation, character and strength of these links vary significantly both in time and space (e.g., Zveryaev and Allan, 2005). Therefore, understanding of mechanisms driving PW variability and its links to other key climatic variables is crucial for correct modeling of the regional hydrological cycle. Thus, along with analysis of major features of PW variability over Europe, examining of the above links for winter and summer seasons is another aim of this study.

In the present study we analyze interannual PW variability over Europe during cold and warm seasons on the basis of relatively continuous-in-time and spatially homogeneous data available from the National Centers for Environmental Prediction - National Center for Atmospheric Research (hereafter NCEP/NCAR) reanalysis (Kalnay et al., 1996). Several studies show that interannual variability of PW is well captured in the NCEP/NCAR reanalysis (Trenberth and Guillemot, 1998; Allan et al., 2002; Sudradjat et al., 2005). More specifically, Trenberth and Guillemot (1998) compared
PW from the NCEP/NCAR reanalysis with that from the National Aeronautics and Space Administration (NASA) Water Vapor Project (NVAP) (Randel et al., 1996) and found essential biases in the tropics, whereas they revealed excellent agreement (both in terms of climatologies and characteristics of variability) between the two datasets over regions of spatially dense radiosonde observations (particularly, over Europe). Results of Allan et al. (2002) also suggest that PW from the NCEP/NCAR reanalysis has sufficient quality for climate variability studies. Another reason for choosing NCEP/NCAR reanalysis for this study is its longer time series compared to those from the ERA40 reanalysis (Uppala et. al., 2001) but similar PW variability over land (Allan, 2007). The data used in the present study and analysis methods are described in section 2. Characteristics of PW variability during the two seasons for 1979-2004 are described in section 3. Section 4 examines links between PW variability and regional atmospheric circulation, as well as with some other key climatic variables. Finally, concluding remarks are presented in section 5.

2. Data and methods

The main data source for this study is the NCEP/NCAR reanalysis (Kalnay et al., 1996; Kistler et al., 2001), which is the result of the outstanding project to produce dynamically consistent synoptic scale resolution fields of the basic atmospheric quantities and computed parameters for the needs of climate studies. NCEP/NCAR reanalysis provides parameters with 6-hours temporal resolution and 2.5° latitude by 2.5° longitude spatial resolution for a period 1948 - present. The reanalysis project uses a frozen assimilation technique to analyze past data and gives the possibility to explicitly describe short and long-term climate variability within the uncertainties.
introduced by the changes in the input data. Pressure-level data as well as surface data at 2.5° grid are considered to be instantaneous values at the reference time. In our analysis we used monthly precipitable water content (i.e., the total column water vapour; hereafter PW) from NCEP/NCAR reanalysis for 1979-2004.

To reveal the dynamical context of the leading PW modes over Europe, we used monthly sea level pressure (hereafter SLP) data and 700 hPa vertical motion fields from the NCEP/NCAR reanalysis (Kalnay et al., 1996) for the period analyzed (i.e., 1979-2004).

In the present study we also used indices of the major teleconnection patterns that have been documented and described by Barnston and Livezey (1987). These indices are regularly updated and available from the Climate Prediction Center (CPC) website (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html). The data cover the period 1950 - present. Details on the teleconnection pattern calculation procedures can be found in Barnston and Livezey (1987).

In our study we consider the climatologies of winter (DJF) and summer (JJA) seasonal mean PW and its standard deviations (STD) as a measure of the total year-to-year variability. To examine spatial-temporal structure of the long-term variations of seasonal mean PW over Europe, we applied empirical orthogonal functions (EOF) analysis based on the covariance matrix (Wilks, 1995; von Storch and Navarra, 1995). Before the EOF analysis the annual cycle was removed from all grid point time series by subtracting from each seasonal value the respective season’s long-term mean. In order to account for the latitudinal distortions, each grid point of the large-scale field anomalies was weighted by the square root of cosine of latitude to ensure that equal areas are afforded equal weight in the analysis (North et al., 1982). The long-term
stationarity of the time series is preserved for the calculation of EOF through detrending of the time series with a linear least square fit. Spatial patterns and respective principal components (hereafter PCs) of the leading modes of the winter and summer PW are discussed in detail.

To ascertain relationship of the leading modes of seasonal mean PW to variations of the regional atmospheric circulation, we performed singular value decomposition (SVD) of the covariance matrix between PW fields over Europe and the SLP fields in the North Atlantic – European sector. SVD is a fundamental matrix operation, a generalization of the diagonalization method that is performed in principal component analysis to matrices that are not square or symmetric. A unique benefit is that SVD of a cross-covariance matrix identifies, for instance, from two data fields, pairs of spatial patterns that explain as much as possible of the mean-squared temporal covariance between the two fields. Detailed descriptions of SVD analysis can be found in Bretherton et al. (1992), and von Storch and Navarra (1995). To assess links to teleconnection patterns we used conventional correlation analysis. No lead or lag relationships were taken into consideration for this work; our analysis was restricted to simultaneous connections between winter and summer PW fields over Europe and major teleconnection patterns.

3. Interannual variability of PW

3a. Climatologies and standard deviations of the seasonal mean PW

The largest (reaching 17kg/m²) climatological seasonal mean winter (December - February, hereafter DJF) PW values (Figure 1a) are observed over the oceanic/marine regions, surrounding Europe (i.e. eastern Atlantic, Bay of Biscay, Mediterranean and
Black Seas). These regions are characterized by the large latent heat fluxes during winter. Note PW is significantly lower (8-11kg/m²) over the Baltic and the North Sea. The lowest values of winter PW (less than 6kg/m²), however, are detected over Scandinavia and northeastern European Russia. The standard deviation (STD) of the time series of the seasonal mean DJF PW is a measure of its total year-to-year variability (Figure 1a). This variability is the largest (reaching 1.5kg/m²) over southern Iberian Peninsula and southwestern Scandinavia, thus, being consistent with the largest variability of the winter precipitation detected in these regions (Zveryaev, 2004) from analysis of the data from the Climate Prediction Center Merged Analysis of Precipitation (hereafter CMAP) dataset (Xie and Arkin, 1997). The smallest magnitudes of the winter PW variability are found over the Alps and the Caucasus in agreement with local minima of climatological PW in these regions. There are two reasons for climatological minima of PW over high mountains. First, the atmospheric layer over mountains is thinner and colder compared to other regions, and therefore can hold less water vapour under the same conditions. Second, much of the water vapour advecting from lower levels is lost via precipitation which is heavy over the orography.

The climatology of the summer (June-August, hereafter JJA) seasonal mean PW and its standard deviations over Europe are depicted in Figure 1b. The largest PW values (reaching 28kg/m²) are detected over the northwestern Mediterranean, eastern Europe, southern European Russia and the Black Sea regions. Thus, the pattern is essentially different from that for summer precipitation (Zveryaev, 2004) where precipitation maxima were found over the Alps, western Scandinavia and the Caucasus. Spatial structure of year-to-year variability of JJA PW over Europe, presented by its STDs, reveals the largest magnitudes of PW variability over eastern Europe and
European Russia (Figure 1b). Enhanced variability of PW is also detected over the Mediterranean – Black Sea region. Overall the spatial structure of both climatologies and STDs of summer PW is essentially different from that for the winter season (Figure 1a).

To emphasize seasonal differences in PW climatologies and STDs we estimated ratios between respective summer and winter characteristics. Figure 1c shows that over the entire domain of analysis, summer PW values are larger than the winter ones. The largest seasonal increase of PW is revealed over European Russia and eastern Scandinavia where the ratio is as high as 3.0-3.8. The increase in ratio from west to east is explained primarily by the thermodynamic relationship between saturated vapour pressure and temperature. To illustrate this point, the PW summer/winter ratio is calculated using a thermodynamic relationship derived over the oceans, \( \ln(PW)=-14.0+0.059T_{1.5} \) (Zveryaev and Allan, 2005) where \( T_{1.5} \) is the NCEP 1.5m air temperature. Ratios ranging from below 2 over the oceans to above 5 over European Russia (Fig 1e) are explained by the larger seasonal changes in \( T_{1.5} \) over the continental interior. The expected changes are broadly consistent with the directly calculated values in Figure 1c, although the theoretical changes are larger to the east, explained by the lack of an open water moisture supply, resulting in reduced summer relative humidity compared to the winter.

Interannual variability of PW over Europe is also intensified significantly during the summer season (Figure 1d). The largest ratios between summer and winter STDs reach values of 2.0-2.6 over northeastern European Russia and eastern Scandinavia. The smallest seasonal increase of both PW climatologies and STDs is detected over the eastern Atlantic and Mediterranean region. Over some eastern Atlantic regions
magnitudes of interannual variability of summer PW are even lower than those of winter PW. We note, however, that revealed seasonal intensification of interannual variability of PW is associated with a seasonal increase of mean PW values. When variability is assessed in terms of coefficients of variation (i.e., standard deviations normalized by mean values) the ratio between respective summer and winter coefficients shows weaker (compared to the cold season) interannual variability of PW during the warm season (Figure 1f).

3b. Leading modes of PW variability

To reveal the dominant modes of year-to-year variability of PW over Europe and analyze their seasonal differences, we applied EOF analysis to the time series of the seasonal (winter and summer) mean PW. Only the first two EOF modes are separated reasonably well with respect to sampling errors (North et al., 1982). These two EOFs jointly explain more than 40.0% of the total variance of PW in both seasons. Spatial patterns of the first two EOF modes are presented in Fig. 2. Time series of the respective PCs are depicted in Fig. 3.

The first EOF mode accounts for 34.7% of the total variance of winter mean PW. Its spatial pattern (Figure 2a) shows two major action centers of opposite polarity with the largest loadings over western Scandinavia and Iberian peninsula, and reflects opposite DJF PW variations over northern and southern Europe. The pattern is similar to the first EOF mode pattern of the winter precipitation (e.g. Hurrell, 1995; Zveryaev, 2004). The explained variance, however, is lower than that obtained from analysis of CMAP precipitation (42.1%) presented by Zveryaev (2004). This EOF mode is linked to the major climatic signal in the region – the North Atlantic Oscillation (hereafter...
NAO) which is the major driver of the wintertime atmospheric moisture transport into European region. The PC-1 (Figure 3a), displaying temporal behaviour of this mode, demonstrates close relationship with the winter NAO index (R=0.74).

The second EOF mode explains 17.7% of the total variance of winter PW. The respective spatial pattern (Figure 2b) depicts coherent PW variations over almost all of Europe, showing the largest loadings over eastern Europe/western Baltic region. Weak PW variations of opposite sign are detected only over Turkey and Caucasus region. In contrast to the first EOF mode, this pattern differs significantly from the meridional tripole pattern of the second EOF mode of the winter CMAP precipitation (Zveryaev, 2004). Since the PC-2 shows large (R=-0.57) correlation (Figure 2b) to the index of the East Atlantic (hereafter EA) pattern, this mode of winter PW might be associated with the above mode of the regional atmospheric circulation. Although the second EOF mode explains relatively low percentage of winter PW variance, the local effect of this mode might be essential in the regions characterized by the large loadings (e.g., western Baltic region).

During summer the first EOF mode accounts for 28.2% of the total variance of seasonal mean PW. Similar to the second EOF mode of winter PW, spatial pattern of this mode (Figure 2c) reflects coherent PW variations over entire Europe. However, the largest loadings are detected over eastern Europe and European Russia. During recent decades principal components (Figure 3c) of this mode demonstrate decadal-scale variations with multi-year periods of predominantly positive (1984-1991) and negative (1992-1996) PW anomalies. This feature of decadal scale variability has also been revealed in summer (July-August) time series of sea level pressure over northeast Atlantic presented by Hurrell and Folland (2002) (see their Figure 1).
The second EOF has a different structure from the first mode and explains 18.5% of the total variance of summer PW over Europe. Its spatial pattern is characterized by the prominent southwest-northeast oriented dipole (Figure 2d), with the strongest signal being in the Mediterranean region, and opposite PW variations evident over European Russia and eastern Scandinavia. Principal components of this mode (Figure 3d) demonstrate interannual variability of summer PW that is not associated with known regional teleconnection patterns. It is worth noting that compared to the principal components of the first EOF mode (Figure 3d), PC-2 represents shorter-term interannual variability of summer PW over Europe.

It is interesting to note that the leading EOFs of PW from present analysis and precipitation from Zveryaev (2004) are strongly linked during the cold season, and not linked during warm season. Correlations between respective PCs are 0.91 for winter and 0.16 for summer. However, during summer PC-1 of PW is strongly correlated (R=-0.69) to the PC-1 of regional air temperature presented in Zveryaev and Gulev (2007). This is another important feature of seasonality in PW variability over Europe.

4. Links to atmospheric circulation

4a. Leading SVD modes

To explore links between PW variability over Europe and regional atmospheric circulation, we performed conventional SVD analysis (Bretherton et al., 1992) on the de-trended seasonal mean PW and SLP data. Linear coupled dominant modes between fields of PW over Europe and SLP in the North Atlantic – European sector were defined for winter and summer seasons. We limit our analysis to consideration of the first SVD
mode only since each of the subsequent modes explains very small fractions of the total covariance of PW and SLP in both seasons. The eigenvalues of the considered SVD modes are well separated from higher-order patterns.

The first SVD mode (SVD-1) between winter mean PW and SLP fields explains 80% of the total covariance. The SVD-1 spatial pattern for the winter SLP (Figure 4a) is characterized by the meridional dipole with the largest loadings over broad region extending from Greenland to Scandinavia (first action center), and over Azores – western Mediterranean region (second action center with opposite SLP variations). The obtained pattern is typical for the positive phase of NAO that is characterized by below normal SLP in the region around Iceland, and above normal SLP in the extensive region around Azores. This SLP pattern results in anomalous atmospheric moisture advection into the region and excessive (deficient) precipitation over northern (southern) Europe (e.g., Hurrell, 1995; Zveryaev, 2004). The SVD-1 spatial pattern for winter PW (Fig. 4c) shows opposite PW variations over northern and southern Europe, thus, being consistent with above mentioned NAO-associated winter precipitation pattern over Europe. Time series of expansion coefficients of SLP and PW patterns (Figure 4a) are strongly linked (correlation is 0.91) to each other and to the winter NAO index (Table 1). Thus, being consistent with earlier studies, our results imply that during winter the major driver for the PW variability over Europe is the NAO.

During summer the SVD-1 mode explains only 38% of the total covariance between seasonal mean PW and SLP fields. In general that means relatively weak links between interannual variations of the respective climatic parameters. The SVD-1 spatial pattern for the summer SLP (Figure 4b) is characterized by the zonal dipole with the strong PW variations over Scandinavia and northern European Russia (first action
center) and opposite intensive PW variability over Greenland (second action center). Thus, this pattern is completely different from the respective winter pattern (Figure 4a). The associated SVD-1 spatial pattern for summer PW (Figure 4d) shows coherent opposite PW variations throughout much of Europe with the largest loadings over southern Europe and Mediterranean region. Note this is somewhat different from the summer EOF-1 pattern of PW (Figure 2c) where the largest PW variability has been found over European Russia. Also local PW variability of the opposite sign is evident over northeastern European Russia. Correlation (0.71) between time series of expansion coefficients of SLP and PW patterns is essentially lower than that obtained for the winter season (0.91).

4b. Summertime links to SLP fields

Since we did not find significant links between leading EOF modes of summer PW over Europe and regional teleconnection patterns and SVD analysis revealed relatively weak association between summertime variability of PW over Europe and SLP in Atlantic-European sector, we extend our analysis to the wider region of the northern hemisphere. Figure 5 depicts correlations between PC-1 and PC-2 of summer PW and SLP fields over northern hemisphere as well as their significance at the 95% level according to Student’s $t$-test (Bendat and Piersol, 1966).

There are several regions in the northern hemisphere where correlations between PC-1 of summer PW are relatively high and statistically significant (Figure 5a). However we focus only on the two centers of high correlations that are more relevant to our analysis. The first center, where correlations reach 0.6, covers extensive region including southern Europe, Mediterranean Sea, and essential portion of northern Africa.
The second center, showing negative correlation (exceeding -0.4) is located over northwestern Siberia. Thus, these two centers form southwest-northeast oriented dipole, resulting in advection of relatively dry (and cold) air from the northwest into the European region. The above advection of dry air forms negative PW anomalies throughout Europe (Figure 2c).

Figure 5b shows correlations between PC-2 of summer PW and SLP fields over the northern hemisphere. The largest negative correlations (reaching -0.6) are detected over Scandinavia/northeastern European Russia, whereas the largest positive correlations of the same magnitude are found over northern margin of Siberia and the Kara Sea. Weaker, but statistically significant positive correlations are also found over southwestern Europe. Further southwest the extensive region of significant negative correlations is revealed over the tropical Atlantic. Two of the above correlation centres, namely Scandinavia and Iberia, are responsible for the formation of the EOF-2 dipole pattern of summer PW (Figure 2d). The entire chain of the above detected centres of high correlations is structurally reminiscent of a Rossby wave pattern emanating from the tropical Atlantic through the European region to the Arctic. It is worth noting that the correlation pattern presented in Figure 5b generally implies possible influence of the tropics on the second EOF mode of summer PW. That is not the case for the EOF-1 of summer PW (Figure 5a).

In section 3 we noted strong correlation between summer PC-1 of PW and the PC-1 of regional air temperature presented in Zveryaev and Gulev (2007). To examine this link further, we estimated correlations between PC-1 of summer PW and air temperature from NCEP/NCAR reanalysis. Figure 6a shows large correlations over European Russia and eastern Scandinavia, meaning enhanced (decreased) PW in this
region is associated with above (below) normal air temperatures. We also examined links to vertical velocity at 700hPa level (Figure 6b). Although the signal is rather weak, the correlation pattern generally implies that over the region of interest summer PW increase is associated with intensification of upward motion, indicative of low-level moisture convergence. It is worth noting that in the region of our study, convective processes and vertical motion in the atmosphere are not as strong as in the tropical regions (over Maritime continent, for example). Consequently, magnitudes of variability of the respective parameters are not large. That is why correlations presented in Figure 6b are rather low.

5. Concluding remarks

In the present study we analyzed climatic variability of the seasonal (winter and summer) mean PW (tropospheric precipitable water) over Europe based on data from the NCEP/NCAR reanalysis (Kalnay et al., 1996). Major seasonal difference in climatologies of PW is that during winter the largest PW values are detected over oceanic/marine regions surrounding Europe, whereas the largest summer PW values are found over land, in particular, over eastern Europe and European Russia. The largest variability (expressed in STDs) of winter PW is attributed to effects of orography (e.g., Iberian Peninsula, western Scandinavia). The summer PW variability is most intensive over northeastern European Russia. In general, both climatological PW values and STDs over Europe are essentially larger during summer season. The largest seasonal differences of both characteristics are found over eastern Scandinavia and northeastern European Russia.
Being consistent with results obtained from analysis of regional precipitation variability (Zveryaev, 2004), the first and second EOFs of winter PW over Europe are associated, respectively, with the NAO and East Atlantic teleconnection patterns. The NAO is the major driver of the winter climate variability over Europe and, therefore, NAO-associated zonal transport of the atmospheric moisture into Europe is crucial in formation of regional anomalies of winter PW.

In contrast to winter, PW variability over Europe during summer is not associated with the NAO (as well as with other regional teleconnection patterns). Moreover, it is not linked with summer precipitation variability over Europe. Our analysis shows that the first EOF mode of summer PW is associated with SLP pattern characterized by two action centers of opposite polarity. One of them extends over extensive region from southern Europe to the Mediterranean Sea and northern Africa. Another center is located over northwestern Siberia. The entire pattern implies advection of relatively dry and cold oceanic/marine air from the northwest into Europe. Note, the principal difference from the winter season is that the enhanced transport of the oceanic/marine air during summer results in negative PW anomalies over Europe, suggesting, along with the strong links to regional air temperature variations, the important role of intense summer heating and associated local convective processes in formation of positive PW anomalies when horizontal moisture transport is diminished. In general, our results are in line with the findings of Trenberth (1999), showing significant seasonal (from cold to warm season) increase of the “moistening efficiency” (i.e., fraction of moisture evaporated from a region to that flowing through) in the northern hemisphere extra-tropics.
Our analysis did not reveal significant links between the second EOF mode of summer PW over Europe and known regional teleconnection patterns. Instead, our results suggest that this mode might be associated with the processes in the tropical Atlantic through the Rossby wave emanating from this region. This possible link, however, needs further investigation.

An important feature of seasonality in regional PW variability, revealed in the study, is that during the cold season PW variability is strongly coupled with the variability of precipitation, which is not the case for the warm season. Instead, during the warm season we found rather strong link between leading EOFs of regional PW and air temperature.

Summarizing results of the present study we note that this is the first time the seasonal PW variability over Europe has been studied in reanalyses, focusing on the contrasts in regional PW variability between cold and warm seasons. Our results highlight essential seasonality in characteristics of PW variability over Europe. Moreover, the present study reveals differing physical mechanisms that drive regional PW variability during cold and warm seasons. While wintertime PW variability is well studied and generally well understood, analysis of the more complicated variability of summer PW deserves further investigation. In particular, analysis (based on observations and model simulations) of the relative role of local convective processes in summer PW variability over Europe looks very promising.

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CIRES Climate Diagnostics Center.

References

Allan, R. P. 2007. Improved simulation of water vapour and clear-sky radiation using
0870.2007.00229.x

the European Centre for Medium-Range Weather Forecasts 15-year reanalysis over

Barnston, A.G., and Livezey, R.E. 1987. Classification, seasonality and persistence of


atmospheric variability in the North Atlantic European sector: a study with the APREGE
30-year period. Nature 338, 244-246.

tropospheric moisture. J. Climate 4, 989-1008.

Gulev, S.K., Jung, T., and Ruprecht, E. 2002. Interannual and seasonal variability in the
intensities of synoptic scale processes in the North Atlantic mid latitudes from the


over the North Atlantic. CLIVAR Exch. 7(3-4), 52-54.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M.,
Saha, S., White, G., Wollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W.,
77, No. 3, 437-471.

Kistler, R., Collins, W., Saha, S., White, G., Wollen, J., Kalnay, E., Chelliah, M.,
Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R., Fiorino, M.
2001. The NCEP/NCAR 50-year reanalysis: monthly means CD-ROM and

North, G.R., Bell, T.L., and Calahan, R.F. 1982. Sampling errors in the estimation of


Figure Captions

Figure 1. Climatologies (in shading) and standard deviations (in solid curves) of the winter (a) and summer (b) PW (1979-2004). Ratios between climatologies (c) and standard deviations (d). Ratios between thermodynamic PW components (e) and coefficients of variation (f). Dashed curves and shading in (d) indicate ratio values <1.0.

Figure 2. Spatial patterns of the first (a,c) and second (b,d) EOF modes of winter (a,b) and summer (c,d) PW. Dashed curves indicate negative values. The period of analysis is 1979-2004.

Figure 3. Principal components of the first (a,c) and second (b,d) EOF modes of winter (a,b) and summer (c,d) PW. Dashed curves indicate the NAO (a) and EA (b) indices. The period of analysis is 1979-2004.

Figure 4. The SVD-1 mode spatial patterns (a-d) and expansion coefficients (e,f) obtained for pairs of winter (a,c,e) and summer (b,d,f) PW and SLP fields. Expansion coefficients are normalized by their standard deviations. In (a-d) dashed curves indicate negative values. In (e,f) solid (dashed) curve denotes PW (SLP) variations.

Figure 5. Correlations between PC-1 (a) and PC-2 (b) of the summer PW and northern hemisphere SLP fields. Shaded areas indicate 95% significance level.

Figure 6. Correlations between PC-1 of the summer PW and regional surface air temperature (a) and vertical velocity at the 700hPa level (b). Shaded areas indicate 95% significance level.
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Figure 4. The SVD-1 mode spatial patterns (a-d) and expansion coefficients (e,f) obtained for pairs of winter (a,c,e) and summer (b,d,f) PW and SLP fields. Expansion coefficients are normalized by their standard deviations.
Figure 5. Correlations between PC-1 (a) and PC-2 (b) of the summer PW and northern hemisphere SLP fields. Shaded areas indicate 95% significance level.
**Figure 6.** Correlations between PC-1 of the summer PW and regional surface air temperature (a) and vertical velocity at the 700hPa level (b). Shaded areas indicate 95% significance level.