South European Rain Rate Modulation by NAO and Atmospheric Circulation Regimes

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Abstract
The aim of this study is to classify circulation patterns in Atlantic-European sector and to reveal linkages between anomalies in pressure field over North Atlantic (e.g. NAO) and respective circulation pattern occurrence over continent on one hand and rain fields on other hand. Changes in atmospheric circulation over Europe during the past 50 years were examined using both objective (modes of low-frequency variability inferred by regression analysis and objective cluster classification of circulation types – fuzzy logic) and subjective (Hess-Brezowsky classification of weather types) methods. The grid monthly geopotential H700, wind zonal and meridional velocity components U850 and V850 as well as the surface atmosphere pressure (SAP), and precipitation fields acquired from NCEP/NCAR reanalysis dataset (for 1948-1998) were employed in this study. Joint regression analysis of and fuzzy logic classification of these fields was a basic to reveal major circulation regimes. The fuzzy set analysis of these fields revealed the major circulation regimes over eastern North Atlantic and Europe to be determined in summer by three vorticity polar: 1) North-Western (Scandinavia), 2) Western Mediterranean and 3) Caucasian. It is necessary to note that anticyclone was found in western part of North Atlantic for both seasons. Scandinavia cyclone area explains rain rate maximums located in 50^o-60^o latitude European area and lower rain rate in Southern Europe because of hot and dry African air inflow. In late fall and winter we revealed a vorticity system comprised by three other polar: 1) North-Western, 2) Northern Africa and 3) Northern Russia (Cara Sea). The zonal circulation type dominates in this case and more precipitations are delivered from Atlantic. Rain rate is more uniformly distributed in various latitude belts across Europe than in summer, but more intensive precipitations are occurred in Southern Europe because of moisture transport strengthening to this area from Atlantic. NAO as well as AO (Arctic Oscillation) indexes substantially increased their magnitudes in late eighties and nineties during global warming. The atmospheric circulation patterns, which transported very wet Atlantic air, moved northward during last two decades. As a consequence, the climate in Southern Europe has been becoming drier and respective rain amounts reducing primary in warm part of year. In contrast, the rain rate increased here in cold part of the year. It leads to wetter climate in winter.

Keywords*: monthly wind and precipitation, atmospheric circulation regimes, low frequency oscillation, fuzzy logic*

Introduction
Changes in stream flow patterns over Europe have serious consequences for a wide range of human activities in this densely populated region. An appearance of the extreme events such as floods or droughts is caused in many cases by persistence of some circulation type(s). The climate of the European-Atlantic sector exhibits considerable variability on a wide range of time scales. A substantial portion is associated with the North Atlantic Oscillation (NAO), a hemispheric meridional oscillation in atmospheric mass with centers of action near Iceland and over the subtropical Atlantic. NAO related impact on the winter climate extends from the East coast of the United States to Eurasia and from Northern Africa and the Middle East to the Arctic regions (Wallace, and Thompson, 2002a, b; Trenberth, et al, 1998; Hurrell, 1995, and references therein; James, and James, 1989). The analysis of proxy data of the NAO shows phases of enhanced (active) and reduced (passive) decadal variability (Appenzeller et al., 1998). The growing interest in the NAO is partly explained by the fact that the spatial signature of the observed climate warming over the last century (with a significant increase over the last three decades) resembles the surface temperature anomalies associated with the NAO. The current climate trend could be partly explained by human activities and by their related increase of greenhouse gases concentrations (Raible, et al, 2001). The understanding of the mechanisms sustaining the NAO and their link to global climate change is thus crucial to detect and clearly identify the signature of the latter (Halliwell, 1997). In addition, climate fluctuations at shorter timescales (from week to season) that are related to the NAO (in terms of temperature, precipitation anomalies or preferred storm tracks) affect a large number of human activities, such as the management for energetic and hydraulic resources, the agriculture and the fishery industry. Therefore, understanding the origin of the NAO and predicting its temporal fluctuations also correspond to such a

social and economical demand. The aim of this study is to classify the atmospheric circulation patterns in Atlantic-European sector and to reveal linkages between anomalies in pressure field over North Atlantic (e.g. NAO) and respective circulation pattern occurrence over continent on one hand and rain fields on other hand. Changes in atmospheric circulation over Europe during the past 50 years were examined using both objective (modes of low-frequency variability by regression analysis and objective cluster classification of circulation types – fuzzy logic) and subjective (Hess-Brezowsky classification of weather types) methods.

Methodology and data

Statistical analyses provide an empirical knowledge that can lead to more skillful forecasts in the absence of explicit physical understanding. Additionally, acquired information may provide guidance towards identification of the physical process, contributing to or limiting the predictability. The choice to use an empirical approach reflects the fact that both simple and complex general circulation models (GCMs), either with prescribed boundary conditions or with actual oceanic coupling, currently do not adequately reproduce the processes of the real atmosphere in the mid and high latitudes at the lead times an averaging periods of concern here. It is not surprising that the seasonal skill score of GCMs may not be the best (Van den Dool, 1994). One of the main difficulties is actually to validate GCM forecasts since a large number of independent prediction cases (al least, equal to a number of the independent grid variables in model) is required to fully assess their skill. We hope and assume that eventually, with advances in physical understanding, dynamic prediction approaches will outperform statistical ones. Prediction of time-averaged surface climate has received considerable attention over last two decades. First, the potentially predictable portion of the total variability of a given predictand has been empirically estimated using ratios of predictand variability at different frequencies (Trenberth, 1984). Second, direct attempts at forecasting and verification have been made using analog approaches (Wallace, Gutzler, 1981) and linear statistical approaches with either several pre-selected predictor elements or whole predictor fields (Barnett, 1981). The empirical orthogonal functions (EOFs) and singular value decomposition (SVD) are the most commonly used techniques (Fraedrich and Wang, 1993, Vautard et al, 1996) to build a phase space. EOFs are the eigenvectors of the covariance matrix obtained from calculating covariances of time series at different spatial points. EOFs are optimal in explaining as much total variance as possible with any specific number of spatial patterns. The first EOF explains most of the temporal variance in the dataset among all possible spatial fields. The subsequent EOFs are mutually orthogonal (in space and time) and successfully explain less variance. The EOF analysis is non-local in that the loading values at two various spatial points in an EOF do not simply depend on the time series at those two points but depend on the whole dataset. This contrasts with the one-point correlation analyses used to define teleconnections, for which the patterns can be interpreted locally. The SVD approach provides the retrieval of both the temporal and spatial modes, simultaneously (Cherry, 1996). The EOFs or SVD serve here only to prescribe a coordinate basis for phase space, containing all the observed states of SST or other fields. There is a difference in implication of above techniques. EOFs are used for analysis of anomaly fields attributed to a given time index (e.g. a month or a season). The SVD might be applied to spatial-temporal observed fields distributed over some time window of predictor (e.g. few months, seasons or year). Thus, any SST or other predictor (predicand) field might be projected on the *m*-dimensional phase space and represented as a state point in this vector space. When we use SVD phase space with a year time window, such state point is equivalent to a coherent space-time structure in physical space, describing the statistics for the past 12 months. However, leading EOF or SVD vectors usually tend to have the largest spatial scales, whereas fairly small anomalies may be predictable (Montroy, 1997). Fuzzy set approach is more appropriate to approximate them in low dimensional phase space (Pokrovsky et al, 2002). Certainly, there are atmosphere-ocean interactions generating a set of forward and feedback links. Some of them are nonlinear and cannot be described by simplified statistical models based on the linear regression. Therefore, a multivariate self-learning neural network model was developed (Pokrovsky, 2000) to describe the predictive relationships between evolving large-scale patterns in Northern Hemisphere sea surface temperature (SST), surface atmosphere pressure (SAP), the wind zonal and meridional velocity components U850 and V850, surface atmosphere temperature (SAT) fields (predictors) and subsequent patterns in the Northern Europe SAT and precipitation (predictands). A lead interval of varying length (from 1 to 6 months) is placed between a series of consecutive predictor periods and a single predictand period. Objective evaluation of strength of such relationships is a primary aim of this study.

The global month mean SST, SAT and SAP grid fields used in present study were derived from NCEP/NCAR reanalysis data set. The original daily data were provided by NCEP and then averaged over monthly intervals. The dataset covers a period from January 1948 to December 1998. The annual cycle and inter-annual linear trend were removed from predictor and predicand fields. The anomalies (departure from climate means) were used in all prediction model modifications. The data used were divided into learning and verification sets. All calculations for subsequent model building were derived from learning set only. The data contained in verification set were used only for evaluation the predictive skill. It should be pointed out that linear trend, calculated on each grid after annual cycle removal is related either to artificial factors (measurement errors) or to variability having large time scale (equivalent or larger than a century), which is not relevant to predictive problem concerned here. The amplitude of the linear trend is very small. However, it may give rise to a trajectory shifting in phase space and thus affect the selection of nearest fuzzy set activated in nonlinear model. Therefore, this filtering procedure might be considered as necessary step in present context.

Low oscillation dynamic and predictability of precipitation rate

The NAO exerts a dominant influence on wintertime temperature and precipitation across the North Atlantic basin and thus has major impacts on marine and terrestrial ecosystems. Linear regression analysis shows that a considerable portion of the climatic fluctuations in surface temperatures and sea surface temperatures is directly related to the NAO index. Changes of more than 1^{o} C associated with a one standard deviation change in the NAO index occur over the northwest Atlantic and extend from northern Europe across much of Eurasia (James, and James, 1989; Deser, and Blackmon, 1993; Fraedrich et al, 1993; Sutton, and Allen, 1997). The changes in the mean circulation patterns over the North Atlantic are accompanied by pronounced shifts in the storm tracks and associated synoptic eddy activity (Sickmoller, et al, 2000; Walter, et al, 2001), which affect the transport and convergence of atmospheric moisture and can, therefore, be directly tied to changes in regional precipitation. Hurrell (1995) has shown that drier conditions during high NAO index winters occur over much of central and southern Europe and the Mediterranean, while wetter than normal conditions occur from Iceland through Scandinavia. This has been the case for much of the past two decades. In contrast, increases in wintertime precipitation over Scandinavia may be related to recent positive mass balances in the maritime glaciers of southwest Norway, one of the few regions of the globe where glaciers are not retreating. Beniston(1997) showed that snow depth and duration in Switzerland is correlated with the NAO. Beniston and Rebetez (1996) found that snow depth and duration over the past several winters have been among the lowest recorded this century, causing economic hardships on those industries dependent on winter snowfall. However, as 1996 was a low NAO index winter, Europe experienced a severe winter with record low temperatures and heavy snowfalls in many parts of Southern Europe. Let us consider some results of our correlation analysis aimed to reveal hidden linkages between NAO and precipitation rate in Southern Europe. We present here several figures described a case when NAO is considered to be a predictor of precipitation rate with the lead time equal to two months. We used monthly fields acquired from NCEP-NCAR reanalysis dataset for 1948-1998. Seasonal prediction of SAT from winter to spring is most reliable (Luksch, 1996; Czaja, A., Frankignoul, C., 2002). Therefore, it is not surprising that the winter NAO index values provide very high correlation (up to 0.9) with the precipitation rate in following spring (fig.1). Highest correlation can be found in Western

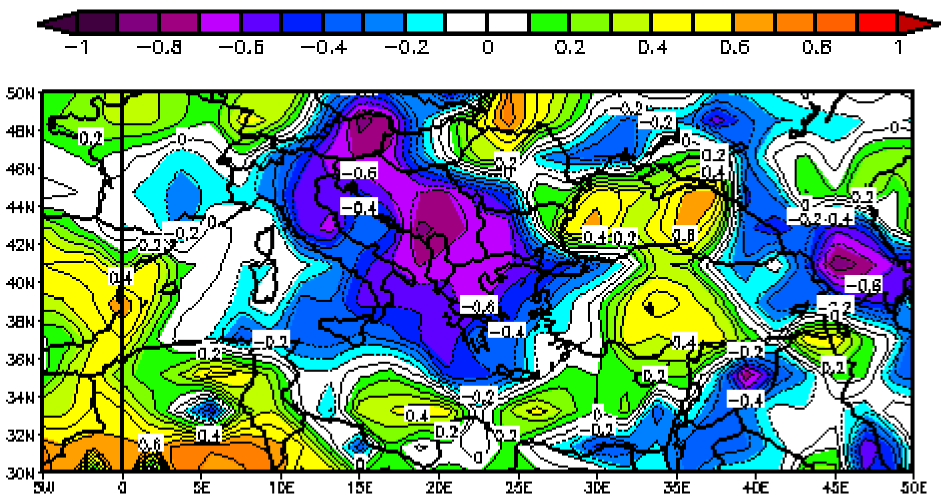

Figure 1. Seasonal correlation of April-May (1995-2005) precipitation rate with February-March NAO (index leads by 2 months) in Mediterranean area

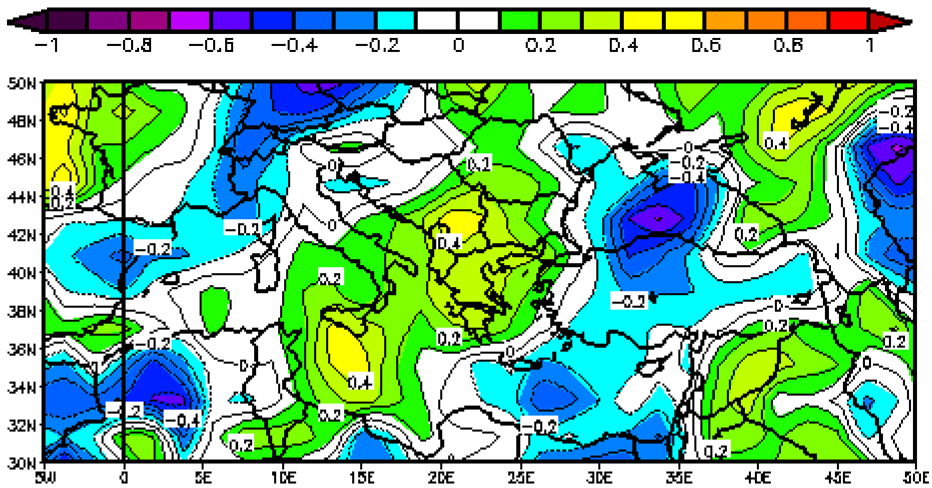

Figure 2. Seasonal correlation of April-May (1965-1975) precipitation rate with February-March NAO (index leads by 2 months) in Mediterranean area

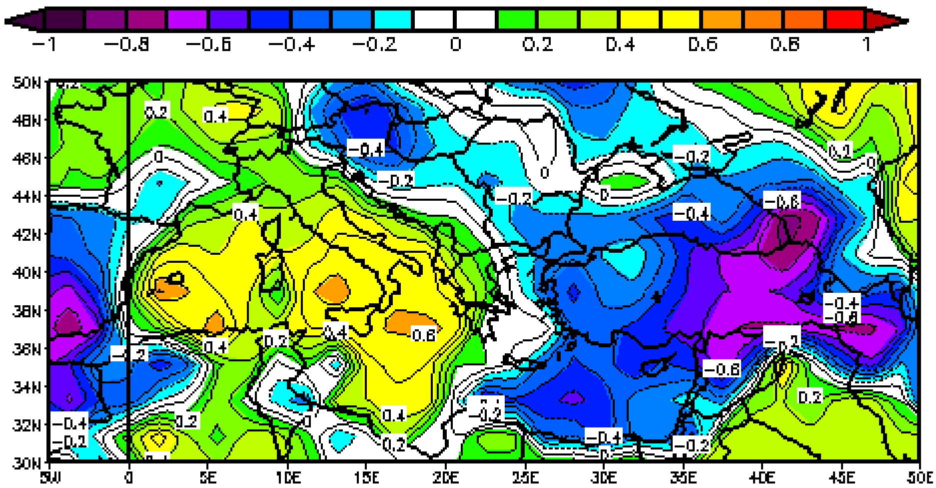

Figure 3. Seasonal correlation of June-July (1995-2005) precipitation rate with April-May NAO (index leads by 2 months) in Mediterranean area

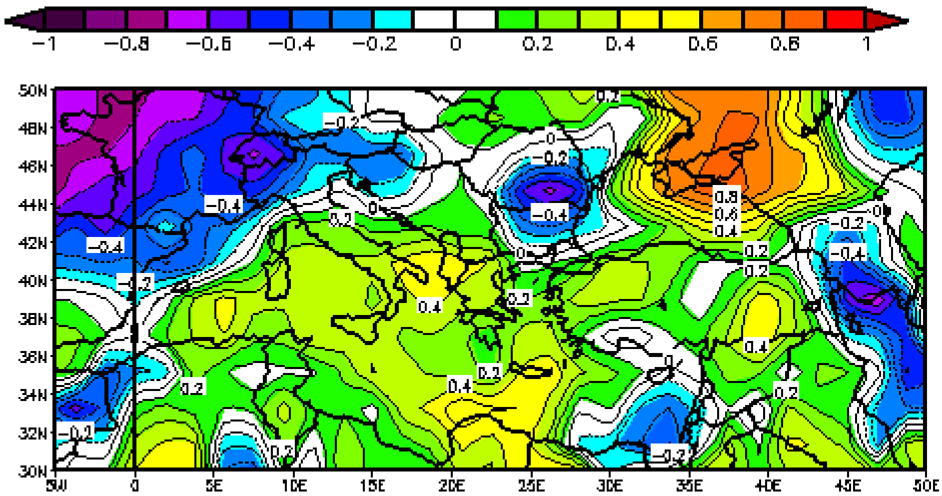

Figure 4. Seasonal correlation of September-October (1995-2005) precipitation rate with July-August NAO (index leads by 2 months) in Mediterranean area

Balkans and Italy as well as in Southern Caucasian area. It is necessary to underline that the map at fig.1 is responded to period 1995-2005, which is might be attributed to the climate warming time.
The NAO seems not to be a stationary stochastic (or deterministic) process in the time scales that are common in climate research. Appenzeller et al. (1998) showed by means of wavelet analysis that in a 1400-year simulation of the ECHAM3 GCM developed at the Max-Planck Institute in Hamburg, as well as in ice-core data, the dominant frequencies of the NAO-index changes in time. One frequency in the NAO-index of ECHAM3 could be attributed to a coupled ocean-atmosphere mode, which projects into the NAO index. Another indication that the NAO can change its regime is the strong positive trend of the index since the late 1960s. During this latter part of the record, an 8-year oscillation may be observed (Latif, 1998; Stephenson, and Xoplaki, 2001). This trend in the index may come from a very significant mechanism in a changing climate, which GCM must reproduce if climate projections in the North Atlantic region are to have any meaning. Our calculations confirmed major conclusion of past papers that NAO does not behavior like a stationary process. Moreover, not only its trends are distinctive before and after 1975, which is considered as beginning of global warming in atmosphere, but also its correlation to other meteorological parameters sharply changed manner. In particular, relationship with the precipitation rate became much more strong with account to previous time (fig.2).
The NAO-precipitation rate cross-correlation was rather weak even in the most promising couple season “winter-spring”. The highest magnitude (0.5) was achieved at Balkans area. Rain rate reliable prediction for summer time is of practical value for most countries of Southern Europe and Northern Africa. Our study showed (fig.3) that there is strong cross-correlation between spring NAO values and summer precipitation rate in some areas of Mediterranean: Spain, Western Africa, Southern Italy, and East domain including South Caucasian. Autumn is the next important season for the rain amount investigation. Its successful prediction depends mainly on the cross-correlation between summer NAO (predictor) and precipitation rate in September-October. Our calculations (fig.4) exhibit that most promising autumn rain amount seasonal forecast is related to France, Northern Africa, Balkans, Southern Russia and Eastern Mediterranean. Our study demonstrated that the explained variance for prediction based on the regression model also delivers very high level of statistical confidence for obtained guesses. Finally, it is necessary to add here that very strong correlations were found with Arctic Oscillation (AO) index magnitudes obtained in similar investigation mode.

Classification of regime circulation and rain rate spatial distribution

It is well known that wind field probability distribution function (PDF) has multimode signature (Trenberth, 1984). Vector character of horizontal wind field complicates a task to approximate this PDF by standard model functions. More promising approach is related to slitting the multidimensional wind velocity phase space into several sub-domains in such a way that wind velocity PDF has a one-

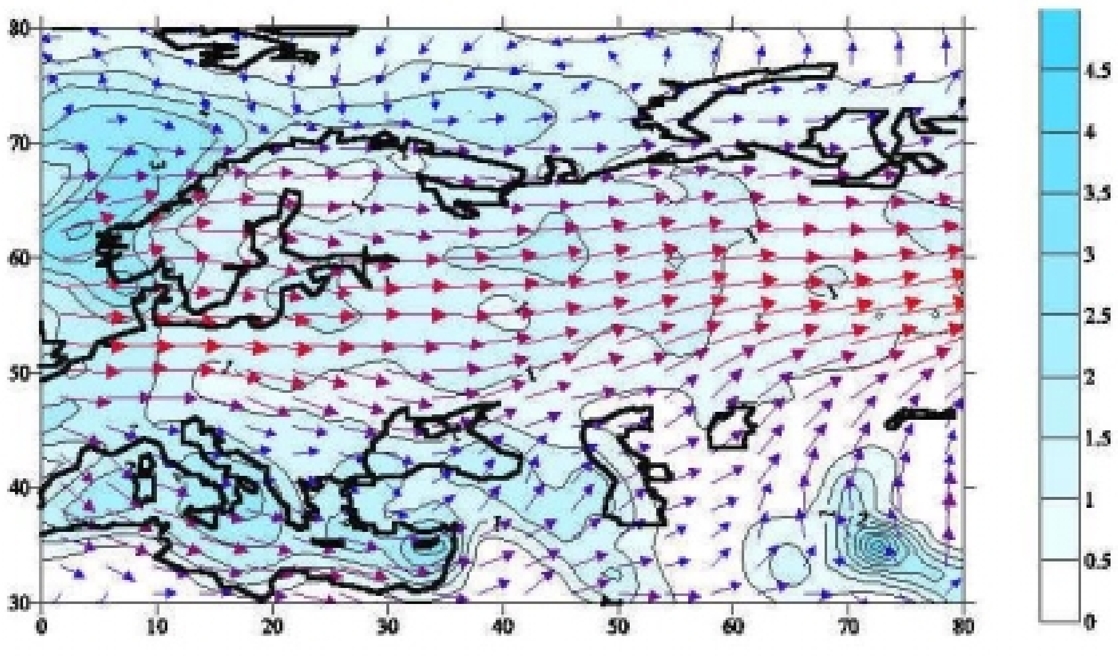

Figure 5. Monthly circulation regime 1 (winter and early spring): the joint pattern for U850-V850 and responding precipitation rate (mm/day) fields marked by blue color

modular structure within each of them. Every obtained one-modular PDF might be approximated by some of standard models (Gaussian, log-normal et al). Recently (Pokrovsky, et al, 2002) we successfully used the fuzzy logic technique to classify spatial meteorological fields. In fuzzy set clustering, we are given a set of N points in d-dimension space R^d and we have to arrange them into a number of groups (called clusters). In *k-means* clustering, the groups are identified by a set of points that are called the cluster centers. The data points belong to the cluster whose center is closest. Existing algorithms for k-means clustering suffer from three main drawbacks, (i) the algorithms are slow and do not scale to large number of data points, (ii) these are restricted by low dimensionality of phase space "d", and (iii) they converge to different local minima based on the initializations. To overcome these disadvantages we applied new recurrent algorithms recently developed by Pelleg and Moore (1998). It permits us to increase the dimensions "d" up to 800-900. Here we considered joint

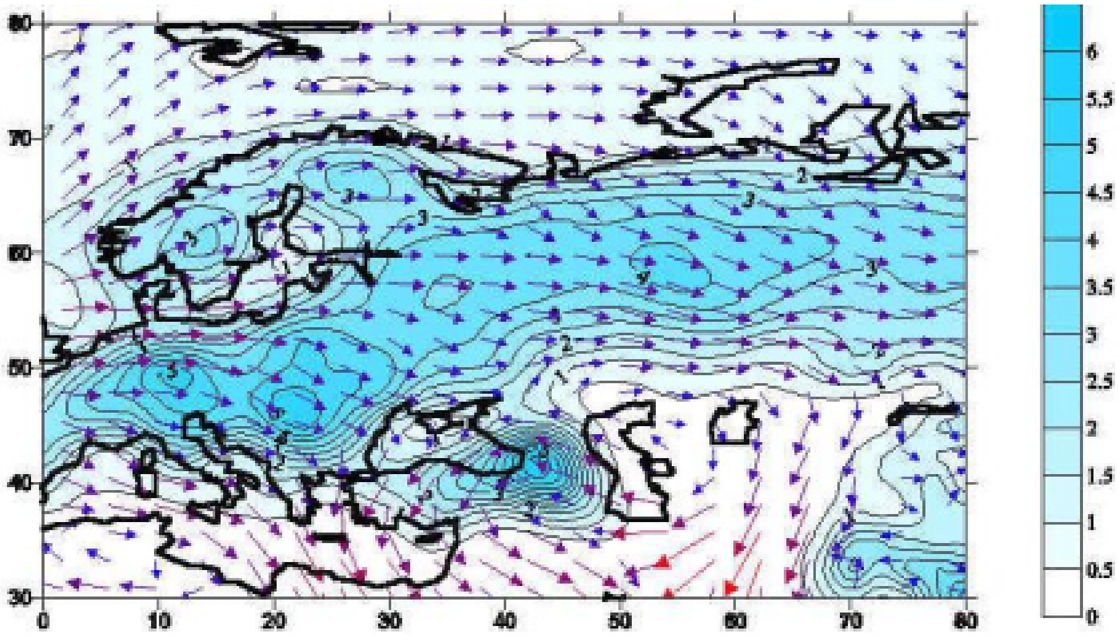

Figure 6. Monthly circulation regime 2 (summer): the joint pattern for U850-V850 and responding precipitation rate (mm/day) fields marked by blue color

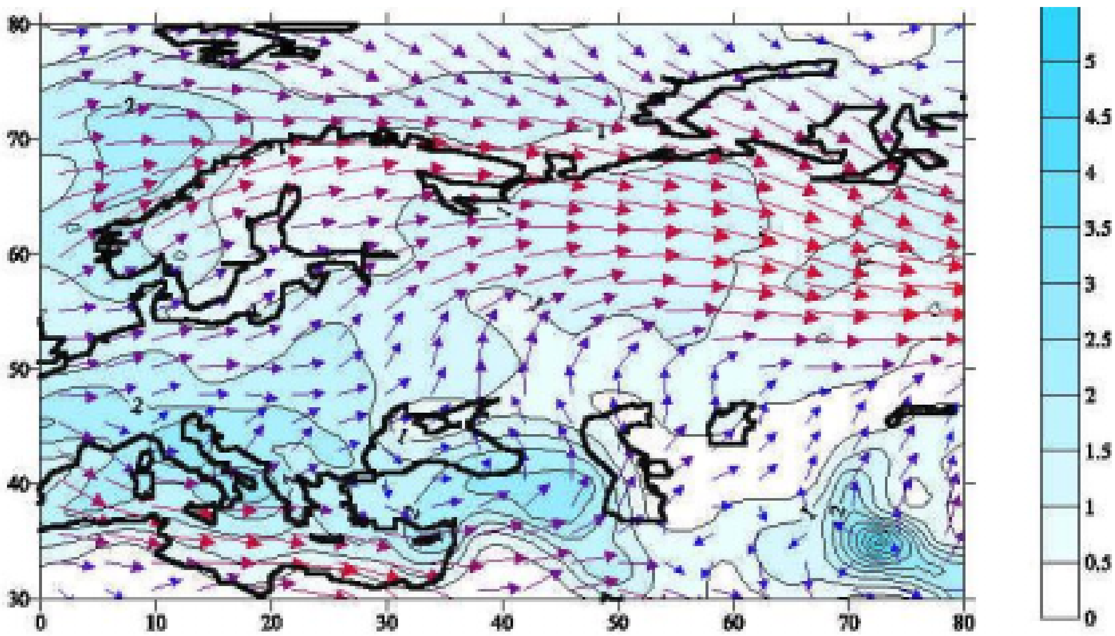

Figure 7. Monthly circulation regime 3 (autumn and early winter): the joint pattern for U850-V850 and responding precipitation rate (mm/day) fields marked by blue color

distribution of three fields U850, V850 and precipitation in a domain with 300 grid points. Therefore, general dimension "d" was equal to 900. Joint analysis permits us to investigate not only atmospheric circulation patterns responded to major the SAP low oscillations in Atlantic-Europe area, but also find related spatial anomaly of the rain rate fields during all seasons. The fuzzy set analysis of these fields revealed the major circulation regimes over eastern North Atlantic and Europe. It turned out that here is three main regimes responded to seasons (fig.5-7): 1) winter and early spring; 2) summer, and 3) autumn. First regime (fig.5) is primary zonal and closely related to type *W* in Hess-Brezowsky classification. Therefore, major anomaly of rain rate might be found in mountain areas around Europe including Alps, Balkans and Apennines Peninsulas in Southern Europe. Summer airflow regime (fig.6) substantially deviates from zonal regime and to be determined by three vorticity polar system: 1) North-Western (Scandinavia), 2) Western Mediterranean and 3) Caucasian. Non-zonal circulation in Middle Asia is closely related to precipitation filed anomaly in Caucasian domain. This circulation type has some similarity with type *E* in Hess-Brezowsky classification. It is necessary to note that anticyclone was found in western part of North Atlantic for both (warm and cold) seasons. Scandinavia cyclone area explains rain rate maximums located in 50^o-60^o latitude European area and lower rain rate in Southern Europe because of hot and dry African air inflow. In late fall and early winter (fig.7) we revealed a vorticity system comprised by three other polar: 1) North-Western, 2) Northern Africa and 3) Northern Russia (Cara Sea). The zonal circulation type dominates in Southern Europe and more precipitations are delivered from Atlantic. Winter rain rate is more uniformly distributed in various latitude belts across Europe than in summer, but more intensive precipitations are occurred in Southern Europe because of moisture transport strengthening to this area from Atlantic. Another important rain formation mechanism is non-zonal meridian airflow in Eastern Mediterranean and Caucasian area. NAO as well as AO (Arctic Oscillation) indexes substantially increased their magnitudes in late eighties and nineties during global warming. The atmospheric circulation patterns have been moving northward during this time. As a consequence, the climate in Southern Europe became drier and respective rain amounts reducing primary in warm part of year. In contrast, the rain rate has been increasing here in cold part of the year. It led to wetter climate in winter and drier one in summer.

Discussion

The overall of this paper was to propose a novel approach for atmospheric circulation patterns over Europe. The new method was validated and compared to conventional low oscillation approach based on regression technique. It is known (Cherry, 1996) that the main problem with linear regression, EOF or SVD approach in statistical prediction is the over-fitting problem. Fuzzy technique permits to reveal separate clusters in multidimensional phase space describing quasi-stationary circulation regimes. Points in phase space traced between them may be considered as transition states of weather system subjected by stochastic factors. In contrast, points located within clusters describe well-established circulation regimes discussed above. Each atmospheric regime generates particular air and moisture transport and, therefore, determines rain probability distribution. Topology of each fuzzy set displays its low-dimension structure and small diameter. Fuzzy metric introduction allowed us to establish links between the associated predictor to the predicand sets (instead of the SVD or EOF modes). Therefore, rain prediction skill is found to be significant for winter, spring and summer while it is much weaker for autumn. Both correlation and fuzzy analysis manifested that the winter prediction provides a useful skill score over the Southern Europe. Climate change is a major cause of precipitation deficit in Southern Europe appeared in eighties and nineties. We showed that this phenomenon is related to northward displacement of major route of the airflow transport of Atlantic moisture in summer, spring and autumn.

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References:

Appenzeller, C., Stocker, T.F., Anklin, M., 1998. North Atlantic oscillation dynamics recorded in Greenland ice cores. *Science* 282, 446–449.

Barnett, T.P., 1987. Variations in the near-global sea level pressure. *J. Atmos. Sci*. 42, 478–501.
Beniston, M. and M. Rebetez, 1996: Regional Behavior of Minimum Temperatures in Switzerland for the Period 1979--1993. *Theor. Appl. Climatol*., 53, 231-243
Beniston, M., 1997: Variations of snow depth and duration in the Swiss Alps over the last 50 years: links to changes in large-scale climatic forcings. *Climatic Change*, 36, 281-300
Cherry S., 1996, Singular value decomposition analysis and canonical correlation analysis, *J. Climate*, v.9, p. 2003-2009.
Czaja, A., Frankignoul, C., 2002. Observed impact of Atlantic SST anomalies on the North Atlantic oscillation. *J. Clim*. 15, 606–623.
Deser, C., Blackmon, M.L., 1993. Surface climate variations over the North Atlantic ocean during winter: 1900–1989. *J. Clim.* 6, 1743–1753.
Fraedrich, K., Bantzer, C., Burkhardt, U., 1993. Winter climate anomalies in Europe and their associated circulation at 500 hPa. *Clim. Dyn.* 8, 161–175.
Fraedrich K., and R. Wang, 1993, Estimating the correlating dimension from noisy and small data set base on re-embedding. *Physica D*, v.65, p. 373-398.
Halliwell, G.R., 1997. Decadal and multidecadal North Atlantic SST anomalies driven by standing and propagating basin-scale atmospheric anomalies. *J. Clim*. 10, 2405–2411.
Hurrell, J.W., 1995. Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. *Science*, 269, 676–679.
James, I.N., James, P.M., 1989. Ultra-low-frequency variability in a simple atmospheric circulation model. *Nature* 342, 53–55.
Latif, M., 1998. Dynamics of interdecadal variability in coupled ocean–atmosphere models. *J. Clim*. 11, 602–624.
Luksch, U., 1996. Simulation of North Atlantic low-frequency SST variability. J. Clim. 9, 2083–2092.
Montroy D.L., 1997, Linear relation of central and eastern North American precipitation to tropical sea surface temperature anomalies, *J. Climate*, v.10, p.541-558.
Pelleg D. and A. Moore, 1998. Cached sufficient statistics for efficient machine learning with large datasets. *Journal of Artificial Intelligence Research*, 8, 67-91.
Peng, S., Whitaker, J.S., 1999. Mechanisms determining the atmospheric response to midlatitude SST anomalies. *J. Clim*. 12, 1393–1408.
Pokrovsky O.M., 2000. Land Surface Energy Exchange Simulation Based on Combined "Fuzzy Sets and Neural Networks" Approach. *Proceedings of Second Conference on Artifical Intelligence*, AMS, Boston, MA, p.21-26.
Pokrovsky O.M., Roger H.F. Kwok and C.N. Ng , 2002, Fuzzy logic approach for description of meteorological impacts on urban air pollution species: a Hong Kong case study, *Computers and Geosciences*, v. 28, p. 119-127.
Raible, C.C., Blender, R., 2004. Northern hemisphere midlatitude cyclone variability in GCM simulations with different ocean representations. Clim. Dyn. 21, in press.
Raible, C.C., Luksch, U., Fraedrich, K., Voss, R., 2001. North Atlantic decadal regimes in a coupled GCM simulation. Clim. Dyn. 17, 321–330.
Sickmoller, M., Blender, R., Fraedrich, K., 2000. Observed winter cyclone tracks in the northern hemisphere in re-analysed ECMWF data. Q. J. R. Meteorol. Soc. 126, 591–620.
Stephenson, D.B., Xoplaki, E., 2001. North Atlantic oscillation: concepts and studies. *Survey Geophys*. 22, 321–382.
Sutton, R.T., Allen, M.R., 1997. Decadal predictability of the North Atlantic sea surface temperature and climate. Nature 388, 563–567.
Trenberth, K.E., Branstator, G.W., Karoly, D., Kumar, A., Lau, N.-C., Ropolewski, C., 1998. Progress during TOGA in understanding and modelling global teleconnections associated with tropical sea surface temperatures. *J. Geophys. Res.* 103, 14291–14324.
Trenberth K.E., 1984. Some effect of finite sample size and persistence on meteorological statistics, Part 2: Potential predictability, *Mon. Weather Rev*., v.112, p. 2369-2378.
Van den Dool H.M., 1994, Long-range weather forecast through numerical and empirical methods, *Dyn. Atmos. Ocean*, v.20, p. 247-270.
Vautard R, G.Plaut, R.Wang, and G.Brunet, 1999, Seasonal prediction of North American surface air temperatures using space-time principal components., *J. Climate*, v.12, p.380-394.
Wallace, J.M., Gutzler, D.S., 1981. Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev*. 109, 782–812.
Wallace, J.M., Thompson, D.W.J., 2002a. Annular modes and climate prediction. *Phys. Today,* 55, 28–33.

Wallace, J.M., Thompson, D.W.J., 2002b. The Pacific center of action of the Northern Hemisphere annular mode: real or artifact? *J. Clim*. 15, 1987–1991.
Walter, K., Luksch, U., Fraedrich, K., 2001. A response climatology to idealized midlatitude thermal forcing experiments with and without a storm track. *J. Clim*. 14, 467–484.