Effects of the North Sea Caspian pattern on surface fluxes of Euro-Asian-Mediterranean seas

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[1] The influence of the North Sea Caspian Pattern (NCP) on marine basins of the Euro-Asian-Mediterranean region (Mediterranean, Black and Caspian Seas) is investigated by making use of Empirical Orthogonal Functions (EOF) analysis. The effect of the NCP on surface fluxes of momentum and heat, as well as on curl and divergence of wind stress is evident in all of the studied basins. In particular, the Aegean and southern Black Sea heat fluxes are significantly affected by NCP. The processes underlying the demonstrated effects of the NCP on the Mediterranean Sea deserve further attention, especially as they relate to the so-called Eastern Mediterranean Transient (EMT), a recent event that resulted in abrupt changes in the marine climate.

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1. Introduction

[2] Besides localized surface processes, large-scale patterns, especially mid and upper level tropospheric circulation patterns are known to strongly influence regional climate. There is ample evidence for this to be especially true in the Euro-Asian-Mediterranean region [*Corte-Real et al.*, 1998; *Özsoy*, 1999; *Xoplaki et al.*, 2000; *Brunetti et al.*, 2002; *Bartzokas et al.*, 2003; *Rodionov*, 1994; *Malanotte-Rizzoli*, 2004].

[3] Among the various climate patterns of the northern hemisphere near the Atlantic sector is the extensively studied North Atlantic Oscillation (NAO). The influence of NAO on the Euro-Mediterranean region in winter is well known [*Hurrell*, 1995; *Marshall et al.*, 2001]. *Paz et al.* [2003] alternatively identify a North-Africa-West Asia (NAWA) sea-level pressure pattern, which they directly associate with inter-annual climate variability and change in the Eastern Mediterranean. An alternative pattern known as the North Sea Caspian Pattern (NCP) based on mid-tropospheric geopotential height difference between North Sea and Caspian Sea regions has been proposed by *Kutiel and Benaroch* [2002], and has been previously referred to as the East Atlantic/Western Russian (EA/WR) pattern by *Barnston and Livezey* [1987]. Both of the above patterns characterize the motions of mid-tropospheric jet-stream over Europe, and therefore represent eastward extension of the NAO pattern originating in the Atlantic sector.

[4] The winter (October to March) NCP index in Figure 1 is the standardized 500 hPa geopotential height difference between the averages in 0–10°E, 55°N and 50–60°E, 45°N (see boxes in Figure 4). *Kutiel et al.* [2002] have found air temperature and rainfall especially in the Balkans and the Eastern Mediterranean region to be highly correlated with the NCP, which appeared to characterize the anomalous circulation in the region. The positive phase of the NCP, with a positive geopotential height anomaly (GHA) difference (high over North Sea and low over Caspian Sea) typically corresponds to northwesterly winds over the region of interest, while the negative phase NCP corresponds to southwesterly winds.

[5] The Aegean Sea is a small, partly shallow sub-basin of the Mediterranean, believed to be the main site for massive winter convection and deep water formation during the early nineties, contributing to the deep waters of the Eastern Mediterranean basin as opposed to the previously accepted source of dense water in the Adriatic Sea. The phenomenon has been referred to as the Eastern Mediterranean Transient (EMT) [*Roether et al.*, 1996; *Lascaratos et al.*, 1999]. Although changes in Aegean Sea wind and cooling patterns [*Stratford and Haines*, 2001; *Samuel et al.*, 1998], and to some extent, large scale atmospheric controls [*Josey*, 2003] have been identified as factors leading to EMT, comprehensive analysis establishing the roles of continental/regional climate patterns on the EMT has not yet been produced. The present paper contributes to this end.

2. Data and Methods

[6] Our analyses have been based on the ERA40 Re-Analysis global data set produced by the European Center for Medium Range Weather Forecasts (ECMWF) for the period from January 1958 to December 2000 at 6 hour temporal and 1° spatial resolution. Monthly mean values of surface variables and geopotential height at 500 hPa for the extended winter months (October-March) are used in all of our analyses.

[7] Correlations between NCP and surface atmospheric variables have been calculated for the 42 year window of the available data. Empirical Orthogonal Functions (EOFs) Analysis [*Preisendorfer*, 1988; *Venegas*, 2001] has been performed for the total Euro-Med marine area (shown in Figure 2) and separately for each of the marine basins of the region with the NWM, LVT, ADR, AEG, BLK and CAS sub-basins represented by 35, 47, 15, 16, 49 and 40 grid points respectively (abbreviations for sub-basins given in Table 1), but only the results for the Aegean Sea, where the most significant correlations are found are discussed here. Anomaly fields were first constructed by subtracting long-term monthly means from each month before the EOF analysis and October to March months were used for EOF

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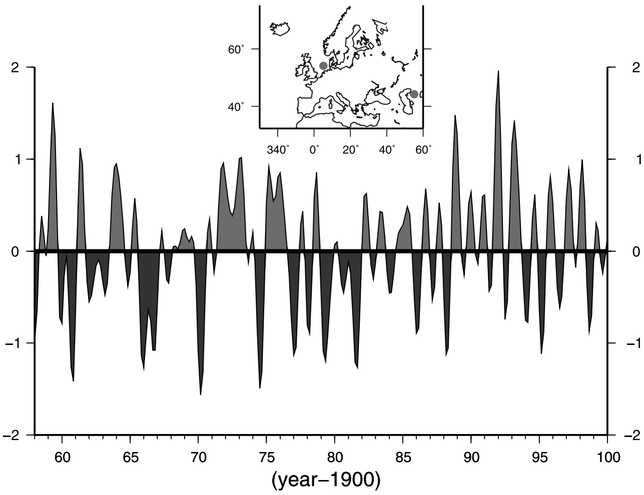

Figure 1. October-March NCP index (monthly series low pass filtered with a 5 month boxcar window) and the locations of its two poles (inset). See color version of this figure in the HTML.

calculations. The NCP index has been obtained from *Kutiel and Benaroch* [2002].

3. Results and Discussion

3.1. Correlation Analysis

[8] To investigate the domains of influence of the NCP on different marine and terrestrial regions, correlation coefficient was computed between surface variables and the NCP index to yield the spatial distributions shown in Figure 2 and the average values in Table 1. Remarkable correlation is found between the NCP index and sensible, latent and net heat fluxes, specific humidity and air temperature in the Balkans, Middle East and the Caucases regions.

[9] Sensible and latent heat fluxes correlate negatively around the eastern Mediterranean, Black and Caspian Seas region, with significant values over the Aegean and eastern Black Sea and positive correlation over the western Mediterranean. Specific humidity and air temperature show similar behavior, with high negative correlation in a wide region encompassing the eastern Mediterranean, Black and Caspian Seas. Precipitation shows a clear contrast between negative correlation over continental Europe including western Anatolia, and positive correlation in the Asian region including Aral and Caspian Sea areas and the central Mediterranean.

3.2. Empirical Orthogonal Function Analysis

[10] Results of the EOF Analysis for October-March time series of surface fluxes are summarized in Table 1. For each of the marine basins, first column in Table 1 is the correlation coefficient between NCP and the area averaged time series (ts) of surface variables, while the second column is the correlation coefficient with the most correlated EOF mode (eof), this mode (m) being shown in the third column and the percent contribution to variance (%) in the fourth column. The first mode air temperature, specific humidity, sensible and latent heat flux, curl and divergence of the wind stress over the Eastern Mediterranean and Black Sea are highly correlated with NCP. The correlation coefficient values computed between NAO and the EOF modes (not shown) are not nearly as significant as those computed for NCP in the same regions. The correlations with NAO appear significant only in the western and central Mediterranean regions, with generally lower values than those observed for the NCP in the eastern region.

[11] Figure 3a shows the first mode of air temperature over the Aegean Sea, explaining about 97% of the total variance, and a principal component that closely tracks the NCP (Figure 3c, upper panel) with a correlation coefficient of −0.63. The first mode of sensible heat flux (Figure 3b) similarly accounts for about 92% of the total variance, with its principal component time series tracking the NCP (Figure 3c, lower panel) with a correlation coefficient of 0.60. Other surface variables like latent heat flux, zonal and meridional component of the wind stress are also highly correlated with the NCP index (correlations are given in Table 1).

4. Conclusions

[12] Based on our analysis of marine and atmospheric surface variables, the important atmospheric climate pattern affecting the entire Euro-Asian Mediterranean region, and especially the Eastern Mediterranean and Black Sea, appears to be the North Sea Caspian Pattern.

[13] While the NAO has been attributed a stronger role in influencing the climates on both seaboards of the Atlantic Ocean and especially Europe on its downstream, its influence appears more confined in the western Mediterranean, while the NCP better accounts for the climatic variability of the Eastern Mediterranean, Black and Caspian Seas region.

[14] There is a strong relation between October-March averaged NCP index and the Arctic Oscillation (AO) (alternatively the Northern Annular Mode, NAM) index with a correlation coefficient of 0.69, while a weaker relationship is obtained with the NAO, with a correlation coefficient of 0.44. It is therefore suggested that the NCP

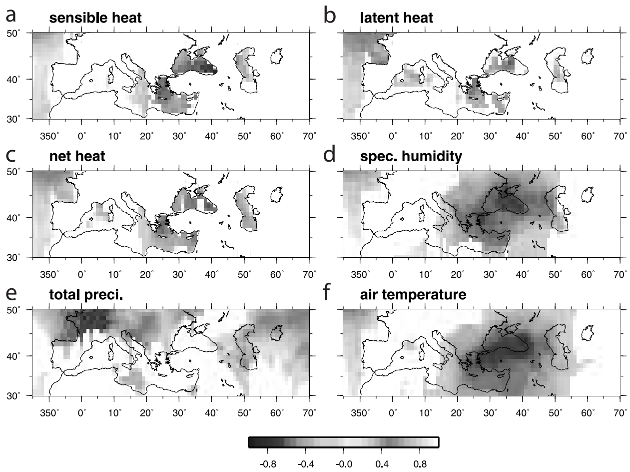

Figure 2. Correlation coefficient of October-March averaged NCP index with surface variables [(a) sensible, (b) latent heat and (c) net heat flux, (d) specific humidity, (e) total precipitation, (f) air temperature] in the Euro-Asian Mediterranean region. Only the correlation values satisfying $p < 0.05$ significance level according to Student's t-test are plotted. See color version of this figure in the HTML.

Table 1. Correlation Coefficient Between NCP and Area Averaged Surface Variables Time Series (ts), Correlation Coefficient Between NCP and Most Correlated Mode of These Variables (eof), Correlated Mode (m) and Explained Variance of the Most Correlated Mode (%) for Each of the Marine Basins[a]

	NWM				LVT				ADR				AEG				BLK				CAS			
	ts	eof	m	%	ts	eof	m	%	ts	eof	m	%	ts	eof	m	%	ts	eof	m	%	ts	eof	m	%
T	0.06	−0.52	3	2	−0.16	−0.57	1	93	−0.09	−0.36	2	6	−0.24	−0.63	1	97	−0.27	−0.69	1	95	−0.12	−0.38	1	86
H	0.09	−0.29	3	1	−0.22	−0.54	1	90	−0.11	−0.39	2	7	−0.27	−0.56	1	96	−0.30	−0.67	1	95	−0.15	−0.39	1	82
S	0.17	−0.52	3	3	−0.40	−0.50	1	88	−0.10	0.30	2	11	−0.50	−0.60	1	92	−0.57	−0.67	1	88	−0.30	−0.36	1	79
L	0.27	0.33	1	83	−0.35	−0.42	1	84	−0.04	−0.04	1	84	−0.50	−0.54	1	90	−0.40	−0.57	1	85	−0.21	−0.36	1	75
C	−0.42	−0.58	3	16	0.34	0.34	2	30	−0.22	−0.56	2	19	−0.05	0.63	1	68	0.24	−0.69	2	26	−0.48	−0.61	1	42
D	−0.43	−0.66	1	53	−0.09	−0.43	1	36	0.45	−0.56	1	58	0.55	−0.65	1	54	−0.38	−0.44	1	37	−0.38	0.65	2	22
X	−0.68	−0.70	1	74	−0.05	0.47	3	5	−0.49	−0.46	1	84	−0.60	−0.60	1	82	0.24	−0.57	2	13	0.50	0.52	2	20
Y	0.07	−0.57	3	5	−0.46	0.47	1	72	−0.46	0.51	2	16	−0.65	−0.67	1	89	−0.56	−0.61	1	81	−0.59	−0.61	1	70

[a]Higher correlations are statistically significant according to the students's t test with significance level 0.05. NWM, North Western Mediterranean; LVT, Levantine Sea; ADR, Adriatic Sea; AEG, Aegean Sea; BLK, Black Sea; CAS, Caspian Sea; T, temperature; H, specific humidity; S, sensible heat flux; L, latent heat flux; C, curl of wind stress; D, divergence of wind stress; X, zonal component of wind stress; Y, meridional component of wind stress.

can be viewed as a regional signature of AO/NAM which is the dominant mode of variability in the northern extra-tropical atmosphere. *Kutiel and Benaroch* [2002] have concluded that NCP is partly responsible for the Mediterranean dipole-like behavior known as the Mediterranean Oscillation (MO).

[15] In addition to our main results, if the real cause of the EMT is sustained anomalous heat loss over the Aegean Sea, NCP could play a significant role in the EMT, since the sensible, latent heat fluxes, and wind stress are found to be significantly related to the NCP over the Aegean Sea.

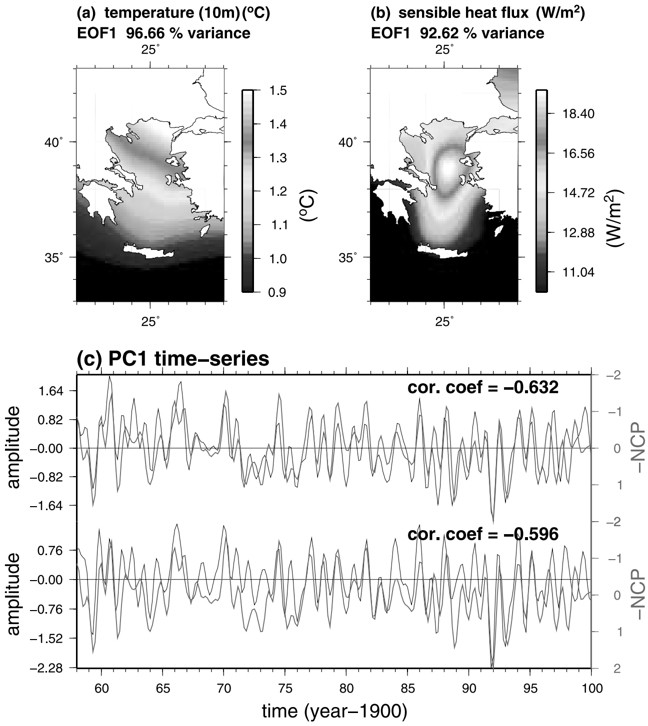

Figure 3. The leading spatial modes of (a) air temperature and (b) sensible heat flux over the Aegean Sea and (c) the comparison of corresponding principal component time series of air temperature (upper panel) and sensible heat flux (lower panel) with the NCP index (red). The time series are low pass filtered with a boxcar window of 5 months window length. See color version of this figure in the HTML.

[16] Figure 4 shows the composite map of the geopotential height at 850 hpa during the years when annual average net heat flux from the Aegean Sea to the atmosphere exceeds 40 Wm^2. In Figure 4, the two poles of the NCP (orange bands over the North Sea and north Caspian - Aral regions) coincide respectively with the positive pole and the zero contour of the net heat flux distribution for years corresponding to a positive NCP index. During the EMT period (early 1990s), the NCP index shows persistent positive anomalies in Figure 1.

[17] In their investigation of anomalous rainfall variability in the Eastern Mediterranean, *Eshel and Farrell* [2000] defined 5 most dry (1959, 1964, 1972, 1973, 1990) and 5 most wet years (1963, 1969, 1980, 1981, 1988) and found links of dry/wet years with the NAO. Our simple checks suggest that the dry periods of the Eastern Mediterranean typically correspond to the 'positive phase' and the wet periods correspond to the 'zero phase' of the NCP (with the exception of the wet year 1981) in Figure 1. Average GHA fields (not shown here) computed for the corresponding five year periods indicate a typical zonal wave pattern with anomaly maximum at the North Sea and minimum at the Caspian Sea poles (positive NCP) in the case of dry years

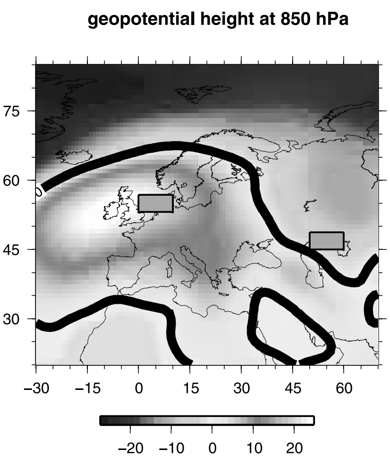

Figure 4. Geopotential height at 850 hpa when annual average net heat flux over the Aegean Sea is greater then 40 Wm^2 (i.e. 1964, 1975, 1976, 1992, 1993). The zero contour is indicated by the heavy black line. See color version of this figure in the HTML.

and one with smoother pattern with a zero line passing through both poles in the case of wet years (zero NCP).

[18] It is also noted that the NCP index has a period with persistent positive values in the mid 1970's, similar to the case in the early 1990's. Although there may be a lack of simultaneous oceanographic data, it is conceivable that the early 1970's could have been another deep water formation period in the Aegean Sea [*Josey*, 2003], signs of which have been found in the southern Aegean by *Miller* [1974]. These results suggest persistent periods of positive phase NCP could possibly correspond to deep water formation, a possibility that could have led to the amplified EMT event in the nineties.

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