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Correspondence to:
Michael N. Styllas
mstyllas@gmail.com

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RELATIONSHIP BETWEEN WINTER OROGRAPHIC PRECIPITATION WITH SYNOPTIC AND LARGE-SCALE ATMOSPHERIC CIRCULATION: THE CASE OF MOUNT OLYMPUS, GREECE

Michael N. Styllas[1], Dimitrios G. Kaskaoutis[2]

[1]**Geoservice LTD. Eirinis 14 Street, 55236, Panorama, Thessaloniki, Greece,** mstyllas@gmail.com
[2]**Institute for Environmental Research and Sustainable Development, National Observatory of Athens, 11810 Athens, Greece**, dkask@noa.gr

Abstract

The relationship between the winter (DJFM) precipitation and the atmospheric circulation patterns is examined around Mount Olympus, Greece in order to assess the effects of orography and atmospheric dynamics over a small (less than 100 x 100 km) spatial domain. Winter accumulated rainfall datasets from 8 stations spread along the eastern (marine) and western (continental) sides of the Mount Olympus at elevations between 30 m and 1150 m are used during the period 1981 to 2000. Synoptic scale conditions of mean sea-level pressure and geopotential heights at 850 hPa and 500 hPa, were used to explain the multiyear rainfall variability. High pressure systems dominated over the central Mediterranean and most parts of central Europe during the late 1980's and early 1990's, are associated with minimum winter rainfall along both sides of Mount Olympus. The winter of 1996 was associated with peak in rainfall along the marine side of the mountain and was characterized by enhancement of upper level trough over the western Mediterranean and increased low tropospheric depressions over the southern Adriatic and the Ionian Seas. This atmospheric circulation pattern facilitated a southeasterly air flow that affected more (less) the marine (continental) sides of the mountain. In contrast, dominance of low pressure systems with cores over the Gulf of Genoa and the Central Mediterranean affect the study area mostly from west/southwest revealing *higher correlations with the precipitation in the continental side of the mountain (r= -0.80; Elassona station) and considerably lower correlations with the marine side (r = -0.67; Katerini station). This highlights the orographic barrier of the Mount Olympus revealing large differences between the upward and leeward sides. Large scale atmospheric patterns like the North Atlantic Oscillation and the Arctic Oscillation seem to influence the winter rainfall in the lowlands along the continental side of the mountain.*

Keywords: *Winter rainfall, atmospheric circulation, North Atlantic Oscillation, Arctic Oscillation, orographic effect, Mount Olympus.*

Περίληψη

Στην παρούσα εργασία εξετάζονται οι σχέσεις μεταξύ της ατμοσφαιρικής κυκλοφορίας και της χειμερινής (Δεκέμβριος – Μάρτιος) βροχόπτωσης στην περιοχή του Ολύμπου. Απώτερος σκοπός της εργασίας είναι η αξιολόγηση της επίδρασης του ορεινού όγκου του Ολύμπου στη χωρική κατανομή της βροχόπτωσης σε μία μικρής έκτασης περιοχή (100 x 100km2) κατά τη χειμερινή περίοδο. Η εργασία βασίζεται σε βροχομετρικά δεδομένα από 8 σταθμούς, που βρίσκονται περιμετρικά του Ολύμπου, σε υψόμετρα μεταξύ 30 και 1150 μέτρων για την περίοδο μεταξύ 1981 και 2000. Η πολυετής μεταβλητότητα της χειμερινή βροχόπτωσης περιγράφεται από τις συνοπτικές συνθήκες της ατμοσφαιρικής πίεσης στη στάθμη της θάλασσας και από τα γεωδυναμικά ύψη στα επίπεδα των 850 hPa and 500 hPa, αντίστοιχα. Τα συστήματα υψηλής ατμοσφαιρικής πίεσης στην περιοχή της Μεσογείου, μεταξύ των δεκαετιών 1980 και 1990, συνδέονται με τις ελάχιστες τιμές χειμερινής βροχόπτωσης στην περιοχή του Ολύμπου κατά τη διάρκεια των παρατηρήσεων. Το χειμώνα του 1996, η προσθαλάσσια πλευρά του Ολύμπου χαρακτηρίστηκε από πολύ υψηλές τιμές χειμερινής βροχόπτωσης, οι οποίες συνδέονται με μία αυλώνα χαμηλών πιέσεων πάνω από τη Δυτική Μεσόγειο, αλλά και από αυξημένες τροποσφαιρικές υφέσεις στη νότια Αδριατική και το Ιόνιο Πέλαγος. Αυτός ο τύπος της ατμοσφαιρικής κυκλοφορίας δημιουργεί μία ροή αέρα νοτιοανατολικής διεύθυνσης στο Αιγαίο, η οποία επηρεάζει περισσότερο (λιγότερο) τη χειμερινή βροχόπτωση στην προσθαλάσσια (ηπειρωτική) πλευρά του Ολύμπου. Εν αντιθέσει, η επικράτηση υφέσεων στην κεντρική Μεσόγειο και πάνω από τον Κόλπο της Γένοβας, δημιουργεί

ατμοσφαιρική κυκλοφορία νότιας / νοτιοδυτικής διεύθυνσης και επηρεάζει περισσότερο τη χειμερινή βροχόπτωση στην ηπειρωτική πλευρά του Ολύμπου (r= -0.80, Σταθμός Ελασσόνας) και λιγότερο την προσθαλάσσια πλευρά του Ολύμπου (r= -0.67; Σταθμός Κατερίνης). Η κατάσταση αυτή τονίζει την επίδραση του ορεινού όγκου του Ολύμπου στην κατανομή της χειμερινής βροχόπτωσης, με μεγάλες παρατηρούμενες διαφορές μεταξύ της ηπειρωτικής και προσθαλάσσιας πλευράς. Μεγάλης κλίμακας φαινόμενα, όπως η ταλάντωση του Βόρειου Ατλαντικού ή του Αρκτικού, επηρεάζουν περισσότερο τη χειμερινή βροχόπτωση στην ηπειρωτική πλευρά του Ολύμπου.

Λεξεις κλειδιά: *Ολύμπος, βροχόπτωση, βροχομετρικά δεδομένα, ατμοσφαιρική κυκλοφορία, χειμερινή βροχόπτωση.*

1. Introduction

Orographic precipitation is defined as any precipitation (rainfall, sleet, snowfall, etc.) that is either modified or produced by the interaction of atmospheric processes with the mountainous terrain. In the Mediterranean Basin, the coastal mountains contribute 50–90% to the total runoff, whereas in sub-humid regions the particular contribution varies from 20% to 50% (e.g. Viviroli and Weingartner, 2004; Viviroli et al., 2007). The Mediterranean climate is variable and complex and is determined to a significant extent by the generation of local low pressure systems, cyclogenesis, and also by large-scale atmospheric circulation patterns, like the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AOD) (Marquina, 2004; Lionello and Giorgi, 2007; Flocas et al., 2010; Campins et al., 2011). Cyclogenesis along the Mediterranean basin mainly originates by the intense sea-air thermal contrasts and by the interaction of cold air masses with the orography (Flocas and Karakostas, 1996). In karstic mountainous areas, which constitute the majority of the Mediterranean mountains, the amount of snow is equally important to winter rainfall, since snowpack characteristics (distribution, thickness, duration, albedo etc.) drive the main hydrological processes responsible for surface runoff and underground aquifer recharge. Therefore, the relationship between large-scale climate dynamics, cyclogenesis and coastal relief has a direct impact on the Mediterranean rainfall, which occurs mainly during the wintertime (Xoplaki et al., 2004). The decline in Mediterranean precipitation during the last decades of the 20th century is partially explained by the observed positive trends of the NAO, AO and the EA/WRUS patterns (Krichak and Alpert, 2005). In general, the NAO appears to play a major role in controlling the winter precipitation over the Mediterranean basin, through a southward migration of the storm systems (Quadrelli et al., 2001). Xoplaki et al. (2004) found that 30% of the total wet season (October – April) Mediterranean precipitation is linearly explained by four geopotential height fields and by the mean sea-level pressure (MSLP). According to their study, the large-scale influence on Mediterranean wet-season precipitation is expressed by the negative modes of the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO) and the Eastern Atlantic Western Russia (EA/WRUS) pressure dipoles during the second half of the twentieth century (1950 – 1999).

Maheras et al., (1999), investigated the wet and dry monthly anomalies across the Mediterranean Basin and their relationships with large-scale atmospheric circulation over the past 130 years. Those findings revealed that the reduction in winter rainfall was also associated with a decline in winter temperatures, resulting in cold and dry winters due to an enhanced frequency of the northern continental dry and cold airflows. The advection of continental air during the winter and spring months, is connected to the presence of high-pressure systems over the northern Balkans, eastern and/or western Europe (Bartzokas et al., 2003). These anomalous mid-tropospheric northerly to northeasterly air currents mostly from the northern Balkans and western Russia result to an overall lack of precipitation over Greece (Xoplaki et al., 2000). Xoplaki et al. (2000) concluded that a raise in the 500 hPa geopotential heights and in MSLP during the second part of the 20th century was connected with enhanced atmospheric stabilization and anomalous advection of continental cold and dry air over Greece. The observed decreasing trend of winter rainfall over Greece during the same period was also verified by other studies (e.g. Feidas et al., 2007 and references therein), but statistically significant decrease was found only in the northern and eastern parts of Greece (Xoplaki et al., 2000). Along the northern part of Mediterranean basin, winter rainfall accounts for 60% of the total annual amounts (Trigo et al., 2000) and is very important for the overall assessment of the water resource availability during the summer and fall seasons. Therefore, there is an increasing need and interest to understand the influence of the coastal orography on the distribution of winter precipitation (rainfall and snow), which has serious socio-economic impacts on the natural resources (water, forests, wood) exploitation practices, agricultural production (amount and types of cultivated crops), flood warning, landslide and avalanche forecasting, and tourism (e.g. touristic and recreational activities and infrastructures) on the mountain environments along the Mediterranean coastline. The fact that winter rainfall across the Mediterranean basin is strongly influenced by its complex coastal mountainous relief, which ultimately reinforces thermal and orographic forcing with a large spatio-temporal variability (Xoplaki et al., 2004), calls for more local studies focusing on small areas of 1.0° x 1.0° (~100 x 100 km) in order to evaluate the orographic effects on rainfall distribution. This study is driven by the climatic partitioning between the marine and continental sides of Mount Olympus, evident from highly variable elevation of the tree line among the two sides. The tree line in the marine side of reaches at 2400 m and is considered the highest in Europe, while on the continental side is located below 1800 m. The focus of this study is to assess the interactions between the orography of Mount Olympus, with low pressure systems from areas along the Mediterranean basin and with specific large-scale atmospheric circulation patterns that affect the winter rainfall. The temporal extend of the study includes a 20-year long period (1981 – 2000). This is achieved through correlations (Pearson's correlation coefficients) and other basic statistical analyses, between middle (500 hPa) and low (850 hPa) geopotential height fields and MSLP at 1000 hPa from the Mediterranean basin and the winter (December – March, DJFM) rainfall amounts, following previous studies (Flocas, 1996; Xoplaki et al., 2000; Feidas et al., 2007; Zappa et al., 2015). The large-scale circulation effects on the local distribution of the wintertime rainfall are achieved through correlations between teleconnection indices of continental and hemispheric patterns including the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO) and the Eastern Atlantic/Western Russia (EA/WRUS) atmospheric pressure dipoles, which control the winter rainfall distribution over Greece.

2. Study area, datasets and methodology

2.1 General setting

Frequent cold invasions from the high latitudes interact with the complex Mediterranean coastal topography causing increased cyclogenesis across the basin. The most important centers of cyclogenesis within the Mediterranean basin (Fig. 1), which exert controls on the winter rainfall over northern Greece, are the Atlas Mountains lee area (Sharav cyclones; Bou Karam et al., 2010), the central Mediterranean region, the Gulf of Genova and the Black Sea (e.g. Xoplaki et al., 2000; Bartzokas et al., 2003; Feidas et al., 2007). The depressions originating in the eastern basin, such as the Cyprus low pressure systems, influence the precipitation in the southeastern Aegean Sea (Maheras 1982) and they are not considered in this study. Due to its small intensity and duration, the Aegean cyclogenesis (Flocas and Karakostas, 1996) is frequently underestimated but is considered here, since the study area (black box in Fig. 1) is located on the northwest margin of the Aegean Sea.

In terms of large-scale circulations, the observed decrease in winter rainfall over Greece during the last decades was linked to a positive trend of the NAO, AO and EA/WRUS indices (Xoplaki et al., 2004; Krichak and Alpert, 2005; Feidas et al., 2007), which has also led to a decrease of Mediterranean cyclogenesis through a northward shift of the eastern Atlantic storm tracks (Trigo and Davies, 2000).

In the light of such positive trending of these three major large-scale circulation patterns and reduced Mediterranean cyclogenesis during the second half of the 20th century, this study attempts to assess the effects of coastal orography on the winter (DJFM) rainfall at a local scale across a 80 km transect that extends from the Aegean Sea coast, past the orographic barrier of Mount Olympus, to the interior of the Greek mainland (black box in Fig. 1).

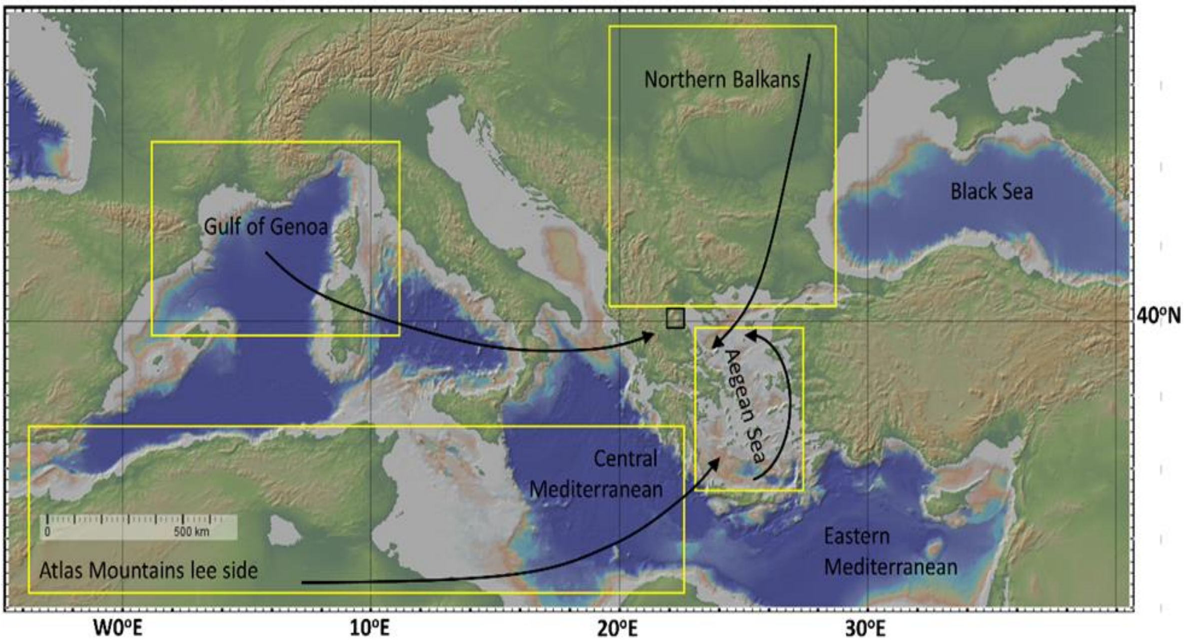

Fig. 1: Geographic location of the study area (black rectangle), in relation to the main cyclones' trajectories (black arrows) and areas of cyclogenesis (yellow rectangles) across the Mediterranean basin. Topographic and bathymetric background are provided by Geomapapp® (http://www.geomapapp.org ; Ryan et al., 2009).

Mount Olympus is the highest mountain in Greece with an elevation of 2918 m. Its summit Mytikas or Pantheon is distanced 18 km from the Aegean coastline (Fig. 2). This particular setting constitutes Mount Olympus an orographic barrier, with different climatic and vegetational characteristics between the eastern (marine) and western (continental) sides. The geologic structure of the massif is dominated by calcareous types of rocks (Triassic and Cretaceous limestones), with a general tilt to W-SW directions that form a highly karstic system, where all major springs are located at an elevation of 1000 m. The overall low annual surface runoff (no available measurements) peaks during the late spring/early summer season, as a result of the increased snowmelt and the high infiltration rates of the carbonate formations. This voluminous karstic aquifer provides water to the broader region of Pieria through an extended network of groundwater channels. Snow accumulation on Mount Olympus starts in late October – early November and lasts until July (direct observations 2003 – 2017), whereas permanent snowfields and ice patches still survive in sheltered locations along the base of headwalls of the NW-oriented Megala Kazania cirque and are considered to be the remnants of the late Holocene (Little Ice Age) small maritime glaciers that occupied the part of the cirque (Styllas et al., 2016, 2018).

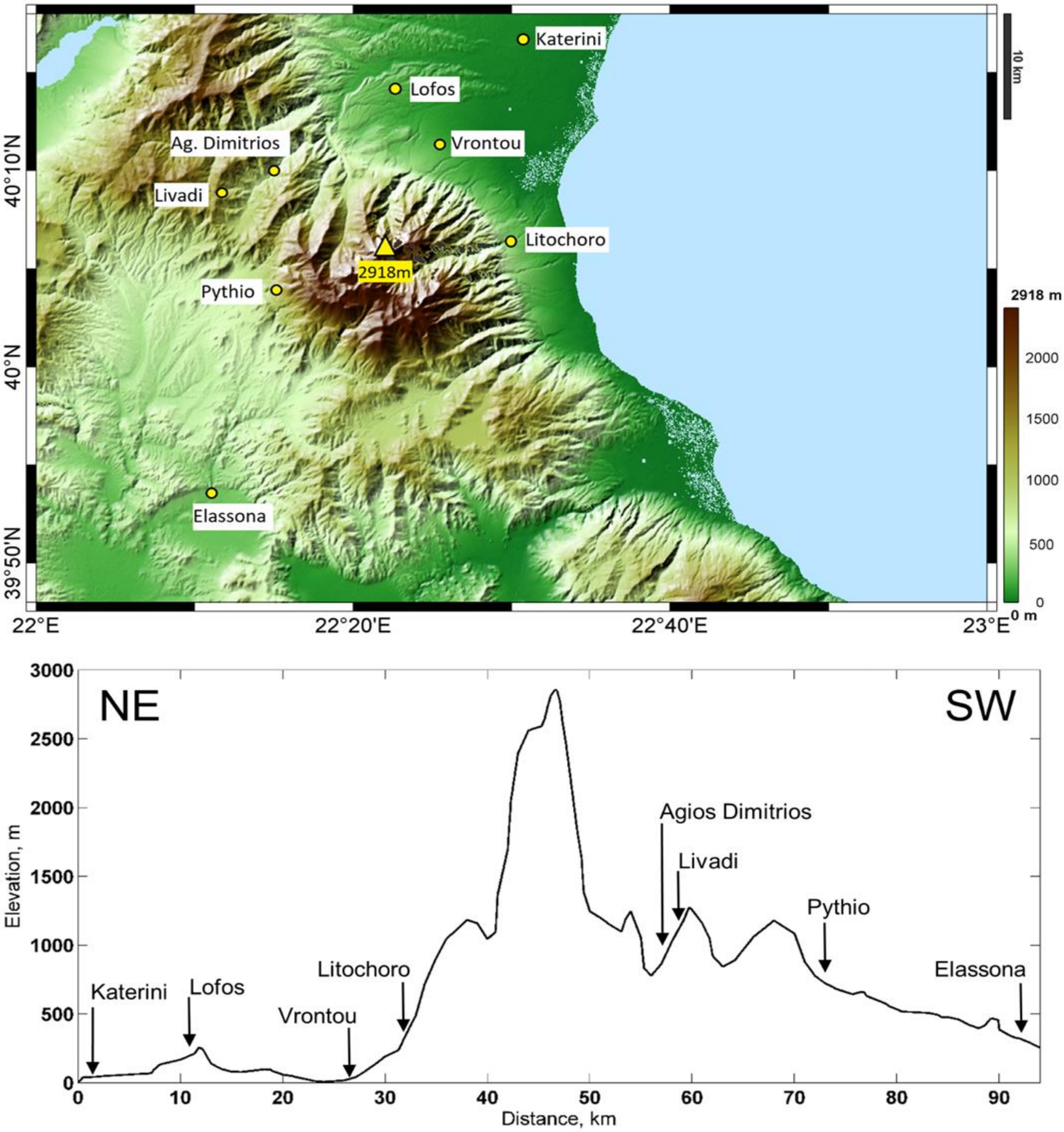

Fig. 2: SRTM topographic data image with the general setting of the study area (black rectangle Fig. 1), and the respective locations of the 8 meteorological stations (*upper panel*). (*lower panel*) The topographic transect considered in the study to assess the effects of orography on winter rainfall in the vicinity of Mount Olympus.

2.2 Winter rainfall datasets

The first part of the study examines basic similarities and differences of the winter rainfall patterns between the marine and continental sides of the Mount Olympus. To achieve this, wintertime (DJFM) rainfall amounts from eight (8) stations were selected. The data were downloaded from Hydroscope, the National Depository of Hydrological and Meteorological Data (http://hydroscope.gr/). The stations used in this study have different temporal coverage (Fig. 3, Table 1) with a common period for all between 1980 and 2001. Four of the stations (Katerini, Lofos, Vrontou and Elassona) are located at the alluvial valleys of both sides of the Mount Olympus while the rest are located at higher elevations on the eastern (Litochoro), northwestern (Agios Dimitrios, Livadi) and western slopes (Pythio) of the mountain along an 80 km transect (Fig. 2).

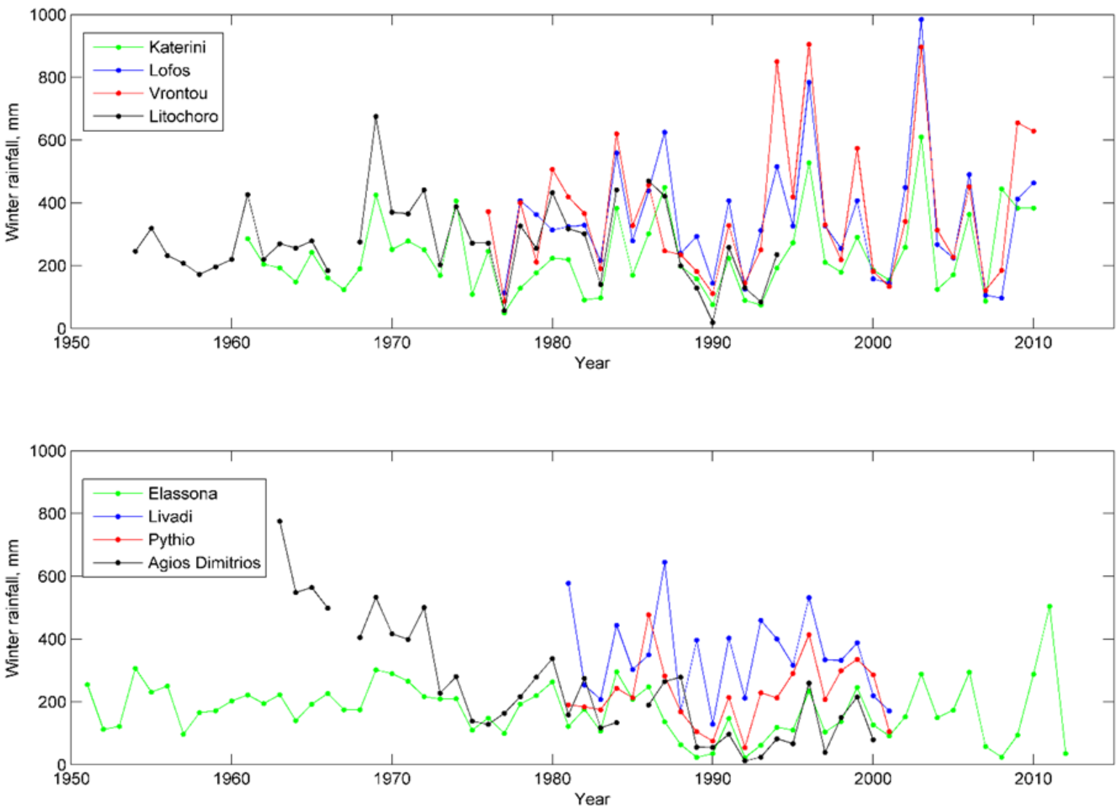

Fig. 3: Wintertime (DJFM) rainfall amounts for the stations along the eastern (marine) side of Mount Olympus (*upper panel*), and along the western (continental) side of the massif (*lower panel*).

The time frame of the observations from each station varies considerably, with the lower elevation stations (Katerini and Elassona) covering longer periods, while the stations closer to the mountain capture shorter periods of time and two of them (Litochoro and Agios Dimitrios) contain several gaps in their records (Fig. 3). In order to examine the controls of the large-scale atmospheric modes (NAO, AO) on interannual time scales, the longest available time series of winter rainfall from Katerini and Elassona stations are used, which cover the 50-year period 1961 - 2010.

Table 1. Topographic characteristics and time periods of rainfall recordings at each station.

Station	**Katerini**	**Lofos**	**Vrontou**	**Litochoro**	**Agios Dimitrios**	**Livadi**	**Pythio**	**Elassona**
Lat	40.27°N	40.24°N	40.18°N	40.01°N	40.15°N	40.12°N	40.06°N	39.88°N
Long	22.51°E	22.37°E	22.49°E	22.51°E	22.23°E	22.15°E	22.23°E	22.19°E
Elevation	30.40m	250.0m	182.0m	300.0m	808.2m	1150.4m	708.8m	270.3m
Time coverage	01/1959 – 12/2012	02/1974 –02/2011	02/1974 – 02/2011	03/1953 –04/1994	01/1958 –12/2012	10/1980 –09/2001	10/1980 –09/2001	06/1950 – 11/2012

2.3 NCEP/NCAR re-analysis and climatic indices

The National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) re-analysis database (Kalnay et al. 1996) was also used to assess the synoptic meteorological conditions on certain winter periods of increased or decreased rainfall amounts at the leeward and upward sides of the Mount Olympus. NCEP/NCAR reanalysis has been extensively used over the Mediterranean and other parts over the globe for examining or even classifying the atmospheric circulation patterns that are associated and/or facilitate specific meteorological and atmospheric phenomena like abnormal rainfall, aerosol episodes, dust storms, etc (Houssos et al., 2008; Kaskaoutis et al., 2014, 2015, 2018; Gkikas et al., 2014). In this study, we used the NCEP/NCAR products of MSLP at 1000 hPa, as well as the geopotential heights at 850 hPa and 500 hPa levels, along with rainfall anomalies for certain years of peaks or gaps in rainfall around the Mount Olympus. The study domain covers the whole Mediterranean Basin and Europe with a spatial resolution of 2.5° lat. x 2.5° long. The NCEP/NCAR reanalysis data are produced by NOAA/ESRL and were downloaded from http://www.esrl.noaa.gov/psd/data/timeseries/. The second part of the analyses, involves correlations between large-scale atmospheric patterns and geopotential height variability from certain regions with the DJFM rainfall amounts. The synoptic meteorological conditions during periods of peak DJFM rainfall, or during periods of pronounced DJFM rainfall deficit are both examined.

The area-averaged monthly geopotential height fields for the middle (500 hPa) and lower (850 hPa) troposphere at MSLP dataseries were obtained for the four regions that are illustrated in Fig.1 (yellow rectangles). These regions include (i) the Gulf of Genoa (0° – 10° E, 37.5° – 45° N), the lee side of the Atlas Mountains and the central Mediterranean (5° W – 25° E, 30° – 37.5° N), the Aegean Sea (22.5° – 35° E, 27.5° – 40° N) and the northern Balkans (17.5° – 27.5° E, 40° – 47.5 °N). The scope of these correlations is to test separately the influence of the Mediterranean low-pressure systems on the precipitation in the marine and continental sides of Mount Olympus and to assess the impact of orography. In addition to the Mediterranean, the Aegean and the northern Balkan pressure systems, the winter-rainfall time series were also tested against large-scale atmospheric circulation indices.

These indices include the dataseries of the Hurrell-NAO obtained from NCAR/UCAR database (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based), the Arctic Oscillation (AO) and the Eastern Atlantic Western Russia (EA/WRUS) patterns that were obtained from the NOAA’s Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/teledoc.shtml).

3. Results

3.1 Temporal evolution of the rainfall between marine and continental sides

The marine side of Mount Olympus receives more winter rainfall compared with the continental side, but also demonstrates higher inter-annual variability (Figs. 3, 4; Table 2). These stations also exhibit the highest winter rainfall amounts, approaching or even overcome the 800 mm at Lofos and Vrontou in 1996.

Along the marine side there is an increasing trend of winter rainfall (see Fig. 3) during the last decades, especially for the stations located closer to the mountain (Vrontou), pointing out the influence of local orography on the spatial distribution of winter rainfall.

Table 2. Wintertime (DJFM) rainfall statistics in the six stations during the 1981-2000 period.

	Marine side of Mount Olympus			**Continental side of Mount Olympus**		
Station	**Katerini**	**Lofos**	**Vrontou**	**Livadi**	**Pythio**	**Elassona**
Mean (mm)	219.7	353.4	367.9	353.7	233.0	136.3
Std (mm)	123.3	167.0	221.0	136.2	103.3	78.2
Max (mm)	527.5	784.2	904.5	644.9	477.1	295.5
Min (mm)	75.0	125.5	111.5	129.2	54.5	22.5

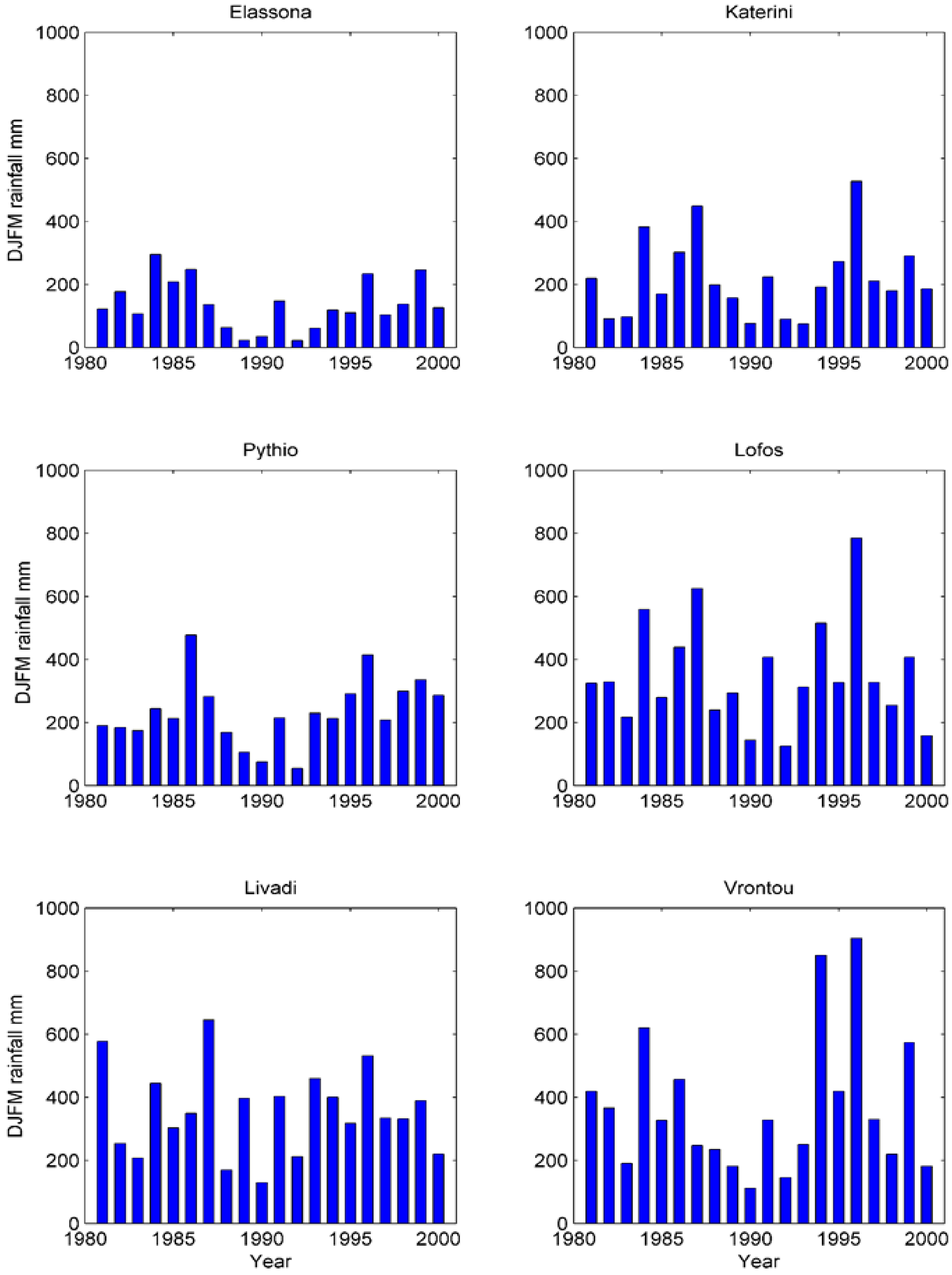

Fig. 4: Winter (DJFM) rainfall time-series for the six stations that do not contain gaps in the records spanning the period from 1981 to 2000.

3.2 Synoptic conditions during the highest and the lowest winter precipitation years

As previously seen in Figs. 3 and 4 and summarized in Table 2, the six stations display different rainfall characteristics, in terms of their evolution and basic statistics. The highest winter rainfall on the marine side between 1981 and 2000 occurred in 1996, with maximum values for Katerini, Lofos and Vrontou stations reaching 527.5 mm, 784.2 mm and 904.5 mm, respectively (Table 2). On the continental side of Mount Olympus, 1996 was also characterized by high amounts of winter rainfall, but the highest values of the record for Livadi (644.9 mm) and Pythio (477.1 mm) were recorded in 1987 and for Elassona station (295.5 mm) in 1984, with 1987 being the second highest year (248 mm) of the record. The driest year for almost all stations was the winter of 1990.

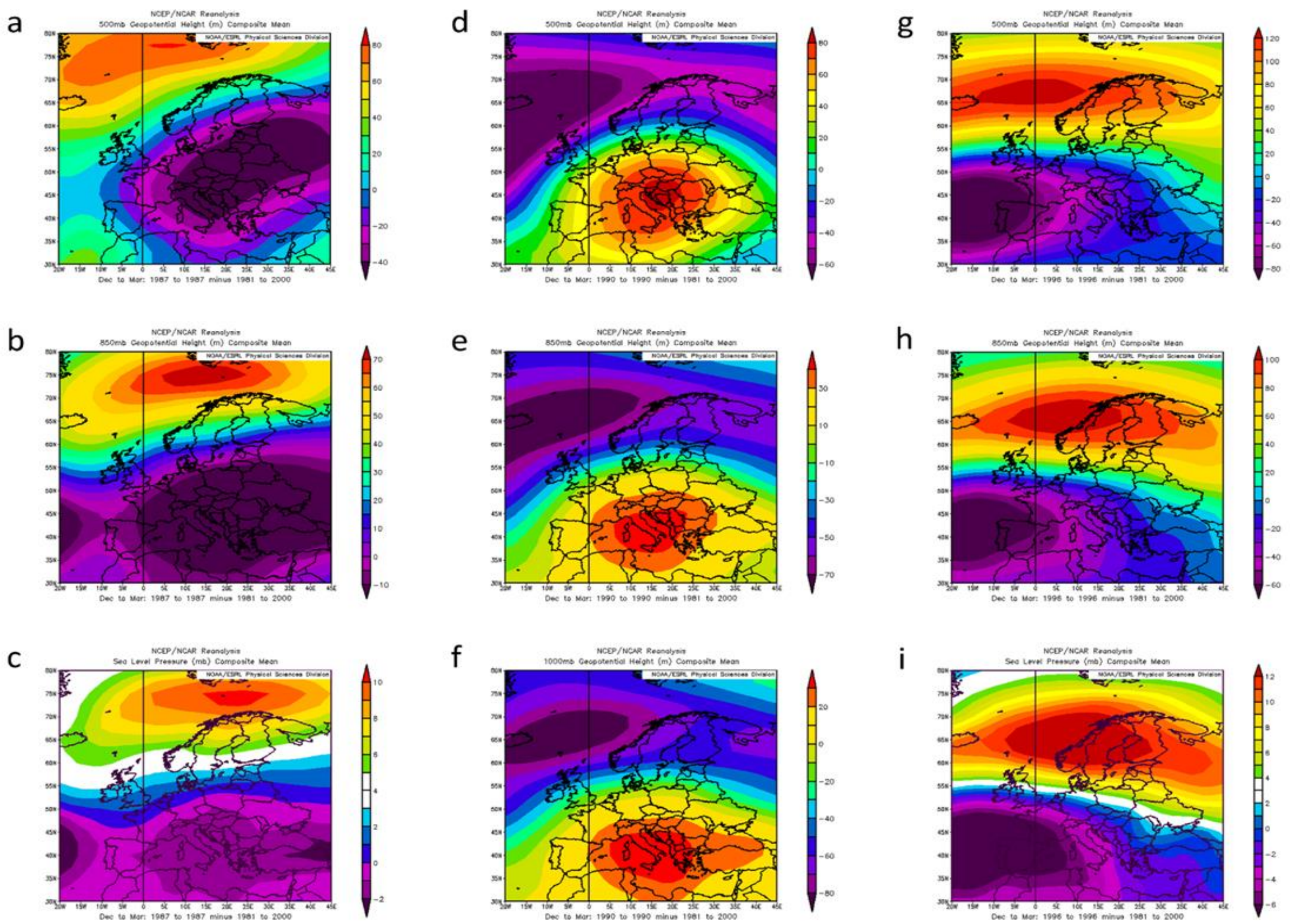

Fig. 5: NCEP/NCAR composite mean maps for geopotential heights at 500 hPa (a, d, g) at 850 hPa (b, e, h) and surface MSLP (1000 hPa; c, f, i) for the winter periods of 1987 (left column), 1990 (center column) and 1996 (right column).

In order to get a view of the synoptic conditions associated with these extreme wet and dry years for each side, composite maps from the NCEP/NCAR reanalysis are examined. The wet winters of 1987 for the continental side and of 1996 for the marine side, show a different pattern in the middle and low troposphere and in MSLP as well. During the winter of 1987, in the middle and lower troposphere an upper trough was dominant over central Europe (Fig. 5a) and its corresponding surface expression involves two low pressure centers; one is located off the west coast of Portugal, and the other one over eastern Turkey, whereas the Arctic was dominated by a high-pressure center (Fig. 5a, b, c). This synoptic pattern resulted in positive precipitation anomalies over western Great Britain, central Europe, the Gulf of Genoa and western Greece (Fig. 6a), and had a greater influence on the western continental side of Mount Olympus.

According to Bartzokas et al. (2003), the positive precipitation anomalies in the continental side of Mount Olympus during the winter of 1987, were associated with positive vorticity anomalies over the Tyrrhenian Sea and with depressions formed over the Gulf of Genoa that led to a south-southwesterly flow that caused higher precipitation amounts over western Greece (Fig. 6a) and the continental side of Mount Olympus.

Large negative MSLP and geopotential height anomalies over the most part of the central and eastern Europe, as in the case of winter 1987 (Fig. 5, left column) were found to be strongly associated with marine air masses from the Atlantic that traversed the Mediterranean Basin before reaching over Greece (Kaskaoutis et al., 2012). These are masses are humid and fast moving, especially during the wintertime, and are associated with clean atmospheres over Greece.

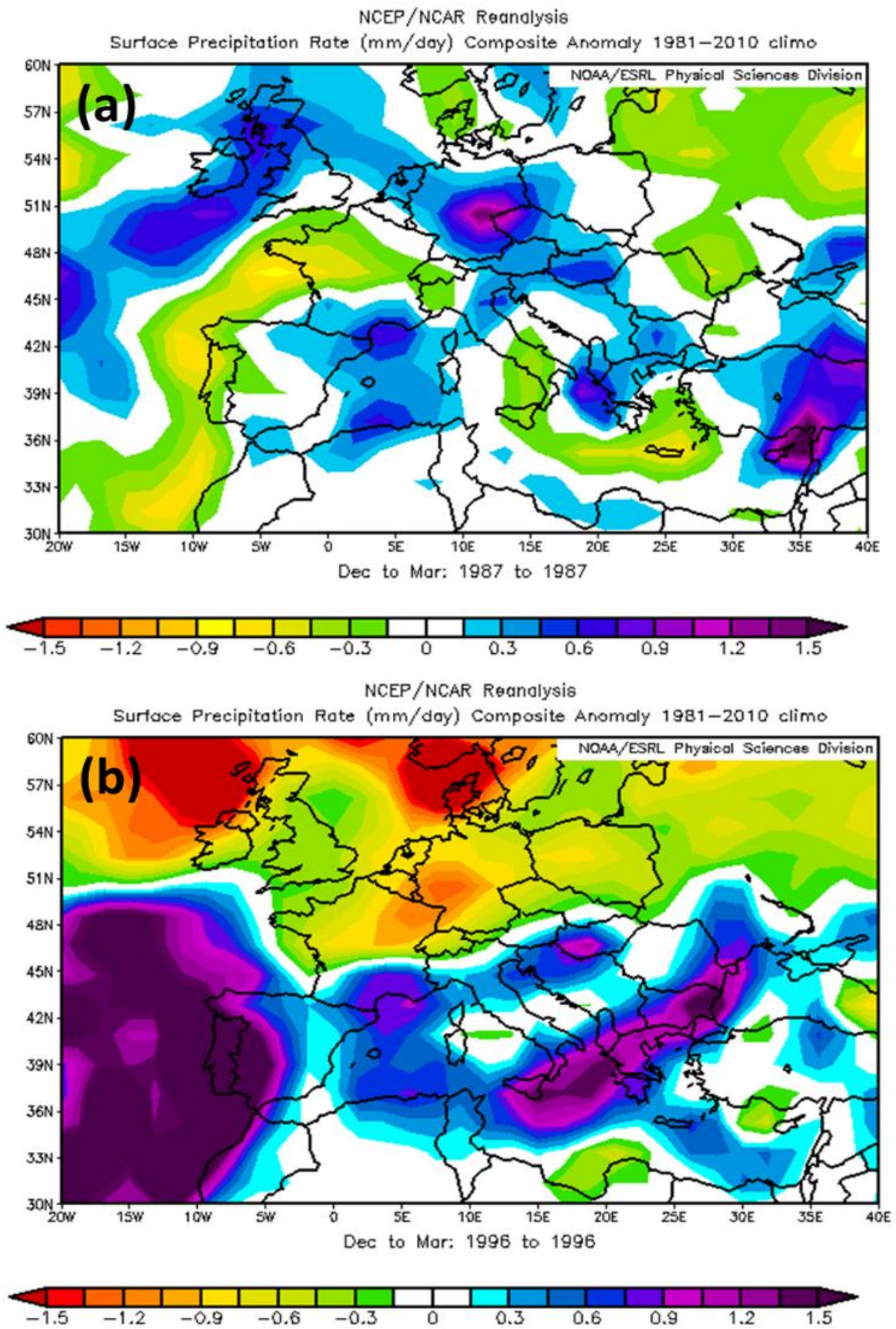

Fig.6: NCEP/NCAR surface precipitation anomalies from the 1981-2010 climatology for the winter of 1987 (a), with higher precipitation along the continental side of Mount Olympus and, (b) for the winter of 1996, when the marine side of Mount Olympus received the highest precipitation.

During the winter of 1996, positive tropospheric and surface anomalies occurred in the north Atlantic between Iceland and western Scandinavia, whereas a well-established trough was located over the eastern Atlantic, extended as far as the western Mediterranean. High positive precipitation anomalies occurred over the west coast of Portugal, while slightly lower positive precipitation anomalies were observed south of Sicily, in northern Greece and eastern Bulgaria (Fig. 6b). The surface expression of this pattern (Fig. 5i) was likely associated with lower tropospheric depressions and potential cyclogenesis over southern Italy, a pattern which has been found to cause a dominant southeasterly flow resulting to extreme precipitation amounts in Thessaloniki, located 80 km northeast of Katerini (Houssos et al., 2008). Additional evidence for a dominant southeasterly flow during the winter of 1996, come from the positive low tropospheric vorticity anomalies (850 hPa) over the entire Mediterranean Sea that caused depressions to move along the Mediterranean axis, passing through southern Greece enhancing the southeasterly flow (Bartzokas et al., 2003). This southeasterly air flow driven by low pressure systems in the vertical over the most art of the Mediterranean, is responsible for the highest rainfall amounts along the marine side of Mount Olympus in the winter of 1996. The driest period was observed during the late 1980's and early 1990's (Fig. 4), and is well-known for a general drought over the Mediterranean basin (Kutiel et al., 1996; Maheras, 2000). The minimum rainfall for almost all the stations was recorded in the winter of 1990, which was characterized by the dominance of a high pressure center over the central Mediterranean at all atmospheric levels (Fig. 5d, e and f) that prevented the development and eastward movement of the winter cyclones, thus resulting in deficit of precipitation (Fig. 6c). This blocking high intercepted the low pressure systems originating in the Atlantic domain to cross the Mediterranean, with the atmospheric stability and subsidence leading to below normal precipitation, especially on the western coasts of the Dinarides and Pindos mountains (Xoplaki et al., 2006).

3.3 Correlation between winter rainfall and atmospheric circulation

A better insight on the main controls that drive the positive and negative winter rainfall anomalies between 1981 and 2000, can be obtained by assessing the effects of the geopotential heights and MSLP from the areas defined in Fig. 1 for each station separately. This is achieved through correlations. (Pearson's correlation coefficients) between the winter rainfall amounts in the six stations and the spatially averaged geopotential heights and MSLP data series, which are summarized in Table 3.

Table 3. Pearson's correlations coefficients between the DJFM rainfall at four stations and the spatially averaged geopotential heights at 500 hPa, 850 hPa and MSLP (from top to bottom). The statistically significant correlations at the 1% significance level (a=0.01; *p*<0.01) are shown in bold.

Station / Region	Aegean Sea	Northern Africa – Central Mediterranean	Gulf of Genoa	Northern Balkans
Katerini	0.01 -0.50 **-0.58**	**-0.57** **-0.66** **-0.65**	**-0.65** **-0.67** **-0.66**	-0.54 **-0.58** -0.50
Lofos	0.08 -0.48 **-0.59**	**-0.62** **-0.73** **-0.73**	**-0.70** **-0.73** **-0.73**	-0.43 -0.51 -0.44
Vrontou	0.21 0.42 **-0.56**	**-0.51** **-0.65** **-0.66**	**-0.58** **-0.65** **-0.67**	-0.34 -0.50 -0.50
Livadi	-0.13 -0.49 -0.50	**-0.63** -0.55 -0.47	-0.48 -0.42 -0.36	-0.41 -0.37 -0.26
Pythio	0.10 -0.39 -0.49	-0.49 **-0.58** **-0.57**	**-0.61** **-0.65** **-0.65**	-0.52 **-0.56** -0.51
Elassona	0.15 -0.53 **-0.67**	**-0.70** **-0.78** **-0.76**	**-0.83** **-0.81** **-0.78**	**-0.62** **-0.68** **-0.60**

All stations show negative correlations between rainfall amount and geopotential height or MSLP variations, indicating that the low-pressure systems at the surface and the troughs (low geopotential height values) in the low and mid troposphere show a positive feedback in precipitation over the northern Greece. Statistically significant correlations between the Aegean Sea

MSLP data series and winter rainfall are observed only for the stations located below 300 m of elevation, along both the marine side and the continental sides of Mount Olympus. Low pressure systems generated in the Gulf of Genoa and in the broad area including the lee side of the Atlas Mountains and central Mediterranean, show the highest correlations with Lofos and Elassona stations and the lowest correlations with Vrontou, Pythio and Livadi stations (statistically significant at the most of the cases). Depressions generated over the north Balkans also show significant negative correlations with winter rainfall in Elassona. Therefore, Elassona station shows the highest negative correlations with the middle and low tropospheric geopotential height fields and with the MSLP, despite the fact that is characterized by the lowest mean and least variable winter rainfall (Fig. 4, Table 2). The stations along the marine side of Mount Olympus show significant but lower correlations with the low pressure systems generated in northern Africa – Central Mediterranean and in the Gulf of Genoa (Table 3).

The stations above 700 m of elevation show nearly no significant correlation with the geopotential height fields of the selected areas. This suggests that along the marine side and mainly in the higher (>700 m) elevations, local and small-scale mechanisms influenced by the orographic effects become more important in controlling the distribution of the winter rainfall on the Mount Olympus.

3.4 Large-scale atmospheric circulation relationships with winter rainfall

From the previous considerations it becomes apparent that the low-pressure systems over the Mediterranean Basin are related to increased winter rainfall in the lower elevations, a relationship that appears to be more pronounced on the continental side of mountain. In addition, the impacts of the large-scale atmospheric circulation on the winter rainfall are assessed. For the time frame of this analysis (1981 – 2000), negative correlations between the AO and rainfall are statistically significant ($p<0.01$) only for the Katerini, Elassona and Pythio stations, whereas the EA/WRUS pattern shows moderate-to-weak correlations with Mount Olympus winter rainfall (Table 4).

Table 4. Pearson's correlations coefficients between the DJFM rainfall amounts in the six stations, with the mean DJFM indices of the Arctic Oscillation (AO), the Hurrell-NAO, and the EA/WRUS for the 20-year period between 1981–2000. Bold indicates statistically significant correlations at 0.01 confidence level (p<0.01).

Station / Region	AO	NAO	EA / WR
Katerini	**-0.62**	**-0.64**	-0.43
Lofos	-0.55	**-0.63**	-0.40
Vrontou	-0.45	-0.43	**-0.60**
Livadi	-0.36	-0.39	-0.01
Pythio	**-0.61**	**-0.57**	-0.23
Elassona	**-0.70**	**-0.58**	-0.52

From a statistical point of view, the effects of large-scale atmospheric modes such as the AO, NAO and EA/WRUS, cannot be securely assessed in the rainfall amounts at stations around the Mount Olympus, since the large-scale atmospheric variability is more pronounced on interannual time scales and mostly affects wide areas, like parts of the Mediterranean and Europe (e.g. Xoplaki et al., 2004; Trouet et al., 2009, and references therein). For example, by considering the longest available period of observations for Katerini and Elassona stations (1961 – 2010) and the NAO and AO winter (DJFM) indices, the correlation coefficients for the two stations change to -0.3 and -0.56 and -0.29 and -0.64, respectively. The EA/WRUS pattern showed low correlations for both Katerini (-0.20) and Elassona (-0.29) stations, despite the longer time series used. The 8-year running means of winter rainfall for the Katerini and Elassona stations displayed the highest correlation coefficients with the 8-year NAO and AO DJFM running means, e.g. -0.62 / -0.58 and -0.87 / -0.89 (Fig. 7). The fact that on longer time-scales the continental side of Mount Olympus demonstrates considerably higher correlations with the NAO and AO indices in comparison to the marine side, emphasizes the importance of Mount Olympus orographic barrier in modulating the effect of the large-scale atmospheric circulation patterns as well. Small scale processes, land sea effects and orographic interactions, appear to play a dominant role on winter precipitation along the marine side of Mount Olympus. Correlation coefficients between rainfall anomalies and NAO, AO and EA/WRUS indices were found to be *r* = -0.66, *r* = -0.55 and *r* = -0.50, respectively (Xoplaki et al., 2004), which are similar to the current findings.

Overall, when the NAO, AO and EA/WRUS systems are in the negative mode, higher than normal precipitation (rainfall and snow) occurs over most parts of the Mediterranean, due to a southward shift of the storm tracks from western Europe to the Mediterranean. On those cases the highest precipitation occurred over the western coasts of the Italian and Greek peninsulas and the lowest at the southeastern part of the Levantine basin (Xoplaki et al., 2004).

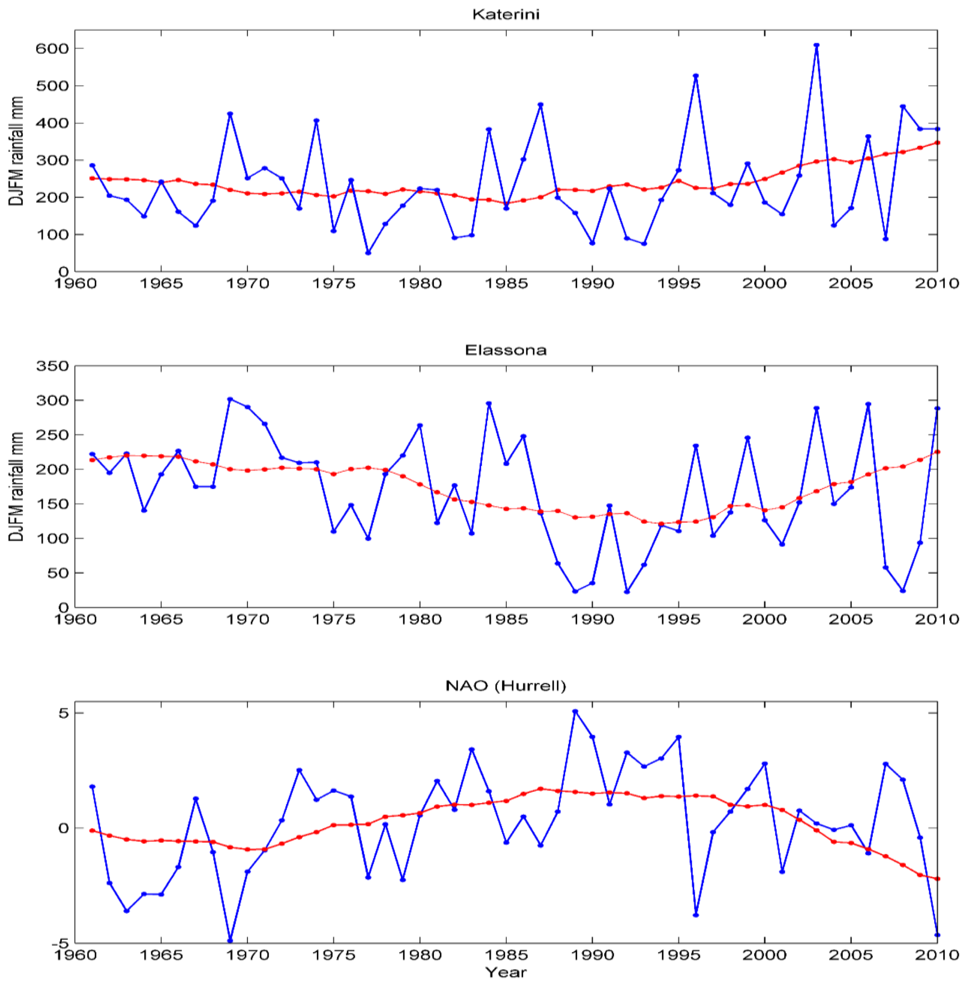

Fig.7: Interannual variability of winter rainfall in Katerini and Elassona stations and the North Atlantic Oscillation Index. Red lines are the 8-year running means.

4. Conclusions

As the increasing pressure to the water resources in the broader region of Mount Olympus continues due to intensive agriculture practices and increasing touristic activities, a better understanding of the mechanisms that control winter rainfall on annual and interannual time scales is necessary and comprises a baseline for future assessments on the proper planning of the water resources. Herein, a general assessment of the factors that drive the winter (DJFM) rainfall in the broader region of Mount Olympus is presented.

Low pressure systems generated along the Mediterranean basin control the winter rainfall over the study area, but are more pronounced on the continental side of the massif. Furthermore, the large-scale atmospheric patterns such as the Arctic and the North Atlantic Oscillation, exert significant high correlations ($r > 0.85$) that control the rainfall on the continental side of Mount Olympus on interannual (8-year) time-scales.

More specifically, the 850 hPa and the 500 hPa geopotential heights and MSLP over Northern Africa – Central Mediterranean and the Gulf of Genoa, as well as the low-pressure systems generated in the Aegean Sea showed the highest correlations with rainfall at the low elevation (<300 m) stations. Despite the lower mean winter rainfall amounts and variability in the Elassona station, it was found that this region (low elevation valley southwest of Mount Olympus) is influenced to a greater extent from the Mediterranean and Aegean low pressure systems on an annual basis due to a dominant southwesterly flow associated with these patterns. The stations located at higher elevations (>700 m) showed much lower correlations with the geopotential height and surface pressure fields, highlighting the role of orography and local processes in the winter orographic precipitation modulation.

The large-scale atmospheric annual and interannual variability, expressed by the NAO and AO indices, also showed the highest correlation coefficients with Elassona station. This is also linked to a dominant westerly - southwesterly flow, which is less pronounced on the stations located along the marine side of Mount Olympus. These stations systematically displayed lower, albeit significant, correlations with the middle and low tropospheric geopotential height fields, the MSLP and the NAO and AO indices. This can be partial explained by the orographic blocking of the south-southwesterly flow from Mount Olympus itself.

Maximum winter rainfall amounts in 1987 along the continental side and in 1996 along the marine side of Mount Olympus were linked to different synoptic conditions. The prevalence of easterly – southeasterly flow during the winter of 1996, originated from an upper level trough in eastern Atlantic and western Mediterranean and deep depressions in southern Italy resulted in the highest winter rainfall amounts. Suppressing conditions caused by positive geopotential height anomalies over the central Mediterranean and central Europe during the late 1980's and early 1990's, caused deficit of precipitation over the stations as well as over the most part of the eastern Mediterranean basin.

In the light of climatic model predictions for a declining trend in Mediterranean cyclogenesis and rainfall and for a positive trend in the NAO, significant changes are expected in the distribution of winter rainfall in the vicinity of many Mediterranean coastal massifs, including Mount Olympus, which according to results of this study will be linked with drier conditions especially along the upwind side of the mountain. However, the tendency in the winter precipitation and snow cover on the higher parts of Mount Olympus remains elusive as it is mostly influenced by local scale meteorological dynamics.

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