Chapter 3

Relations between Variability in the Mediterranean Region and Mid-latitude Variability

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3.1. Introduction

The Mediterranean climate is under the influence of both tropical and mid-latitude climate dynamics, being directly affected by continental and maritime air masses with significant origin differences (Barry and Chorley, 2003). In this region, most of the precipitation occurs from October to March (Xoplaki, 2002). The peak of the winter season occurs between December and February, when the mid-latitude cyclone belt has usually reached its southernmost position (e.g. HMSO, 1962). However, spring and autumn also contribute to a significant amount of precipitation (Fig. 54).

Being located at the southern limit of the North Atlantic storm tracks, the Mediterranean region is particularly sensitive to interannual shifts in the trajectories of mid-latitude cyclones that can lead to remarkable anomalies of precipitation and, to a lesser extent, of temperature. Given the seasonal characteristics of the Atlantic storm-tracks, this is particularly true in winter when the influence of mid-latitude variability is at its greatest. In the transition seasons, and especially in summer, this influence needs to be considered along with other factors including that of tropical climate. Storm-track variability impacts primarily the western Mediterranean, but it has also a signature clearly detected in the eastern Mediterranean as well. The complex orography that characterizes most regions surrounding the Mediterranean basin can modulate and even distort climate anomaly patterns that otherwise would be geographically much more homogenous. For instance, the interplay between orography and thermal contrast between advected Atlantic air masses and Mediterranean temperatures has a huge impact on the development of Mediterranean storms (Trigo et al., 2002a), which can produce violent precipitation extremes at the end of the summer season.

Observational studies indicate significant climate trends on different time scales in the Atlantic–European area, including the larger Mediterranean area. The physical processes responsible for these trends and changes seem to be hemispheric to global (such as external forcings and changes in the large-scale

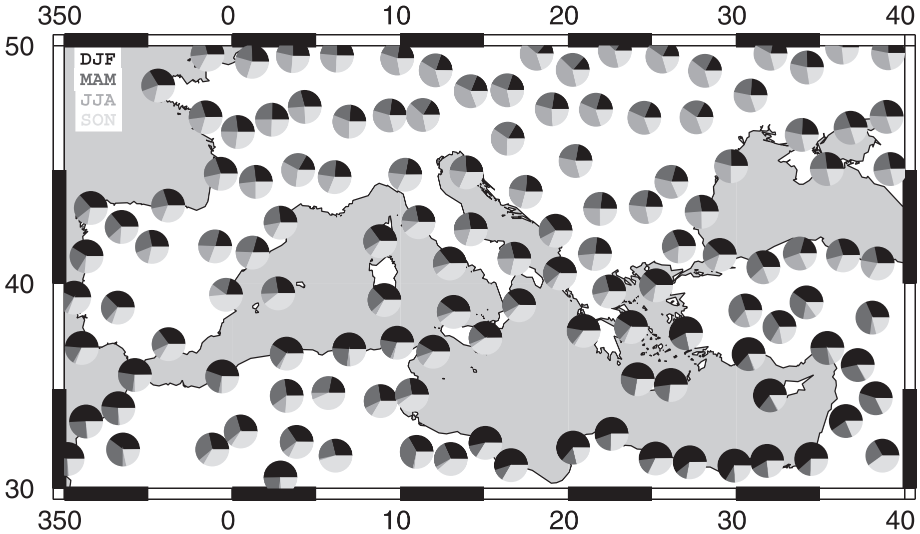

Figure 54: Seasonal distribution of precipitation over the entire Mediterranean Basin according to the monthly database from the Global Historical Climatology Network (GHCN). The stations from GHCN were randomly subsampled to evenly cover the area and the common period 1948–1990 was used (Adapted from Fernández et al., 2003).

atmospheric circulation) as well as local/regional (such as changes in land surface and use). It is one of the main challenges to understand the recent trends and changes over the Mediterranean region, both in space and time. Furthermore, it is necessary to study these relatively recent trends within a larger temporal framework. Such analyses was performed in Chapter 1 of this book.

Why is it so relevant to study the physical mechanisms responsible for variability and trends of both temperature and precipitation over the Mediterranean? There is evidence that major changes on the strength of some of these circulation modes have already made their impact on the living conditions of many people around the Mediterranean basin (see Chapter 1) and that future changes on these patterns will probably produce significant changes in the regional climate in the future (see Chapter 8). Furthermore, it must be stressed that there has always been a considerably large number of people living in this area with a strong dependence on regional agriculture and availability of water resources. Agriculture still constitutes a major economic activity in the Mediterranean region, particularly for southern Mediterranean countries, precisely those countries that are most affected by the variability of water availability. Critical situations of water shortages and extended droughts are mostly due to high values of seasonal and year-to-year variability of precipitation. The impact of temperature and precipitation on most crop yields is mostly dependent on changes in the seasonal cycle of these parameters, rather than on fluctuation of their annual average value (Rötter and van de Geijn, 1999). In this temperate climate, the most important variable is related to the presence or lack of water. Lack of water in winter and spring will be reflected in the crop yield. However, too much water in winter can be harmful by drowning the seeds and retarding root development (Xoplaki et al., 2001). The variability of precipitation plays a crucial role in the management of regional agriculture, in environment, in water resources and ecosystems as well as social development and behaviour (Xoplaki, 2002).

3.2. Mid-latitude Modes of Atmospheric Variability and their Impact

It is now widely accepted that most large-scale modes of atmospheric circulation in the Northern Hemisphere have been described previously in literature (Wallace and Gutzler, 1981; Barnston and Livezey, 1987). It should be stressed that the relevance of these modes is seasonally dependent, i.e. they have a signature only during part of the year (Barnston and Livezey, 1987). Different approaches have been developed over the last decade to assess the impact of the most relevant modes on the Mediterranean climate, mostly in terms of precipitation and temperature fields. Generally speaking, these studies can be clustered within two different approaches (Yarnal, 1993):

(a) Studies based on atmospheric circulation indices independently from surface climate parameters. These include the pioneering work on blocking episodes by Rex (1950a,b, 1951) and, more recently on the North Atlantic Oscillation pattern (Hurrell, 1995). At shorter spatio-temporal scales, there are various regional classification schemes such as the Lamb Weather Types for the UK (Lamb, 1972) and the Grosswetterlagen catalogues (Hess and Brezowski, 1977) for central Europe.
(b) Methods that incorporate both atmospheric circulation and surface climatic fields, often based on eigenvalue techniques (e.g. CCA, SVD). Some of these works have focused on the Mediterranean basin (e.g. Corte-Real et al., 1995; Dünkeloh and Jacobeit, 2003; Xoplaki et al., 2000, 2003a,b, 2004; Valero et al., 2004).

Despite their different methodologies, these studies tend to agree that the most important mid-latitude modes for the Mediterranean climate at the monthly time-scale are: (a) the North Atlantic Oscillation (NAO), (b) the Eastern Atlantic

(EA) pattern and Eastern Atlantic/Western Russia pattern (EA/WR; EU2 of Barnston and Livezey, 1987), and (c) the Scandinavian pattern (SCAND; EU1 of Barnston and Livezey, 1987). Naturally we will focus our analysis on the impact of these modes that affect most significantly the Mediterranean Basin. It is worth noticing that the impact of the most important circulation patterns on the Mediterranean climate in historical times was addressed in Chapter 1 of this book.

Traditionally, studies on large-scale patterns and climate trends have been carried out by slightly different research communities, with the former being mostly developed by dynamical meteorologists and the latter mainly by climatologists and geographers. This framework has changed considerably in the last two decades, but it is still reflected in the way this chapter was organized, with some issues analysed from more than one viewpoint. Section 3.2 describes the most important large-scale modes that have been recognized to impact significantly the climate of the Mediterranean region. Sections 3.3 and 3.4 analyse the influence of these circulation modes in the variability throughout the twentieth century of the temperature and precipitation fields. Section 3.5 addresses again the impact of these patterns to account for the observed trends of climatic variables within the Mediterranean basin. Despite our best efforts, we acknowledge that with this sequential approach, some repetitions of issues have become inevitable.

3.2.1. The North Atlantic Oscillation Pattern

The North Atlantic Oscillation has been identified for more than 70 years as one of the major patterns of atmospheric variability in the Northern Hemisphere (Walker, 1924). However, it has only become the subject of a wider interest in recent years (e.g. van Loon and Rogers, 1978; Rogers, 1984; Barnston and Livezey, 1987; Lamb and Peppler, 1987; Hurrell, 1995; Hurrell and van Loon, 1997; Wanner et al., 2001). This mode is associated with the strength of the meridional pressure gradient along the North Atlantic sector (Fig. 55, top). Some authors consider the NAO mode as a regional manifestation of the hemispheric Arctic Oscillation (Thompson and Wallace, 1998). This discussion is out of the scope of this chapter, nevertheless, it highlights how climate anomalies in the Mediterranean region need to be considered in the larger context of global climate variability – and that we should look at the larger picture when evaluating the impact of the NAO on the Mediterranean climate. Moreover, Xoplaki (2002) has shown that the impact of the NAO and the AO patterns in Mediterranean winter precipitation and temperature fields is quite similar.

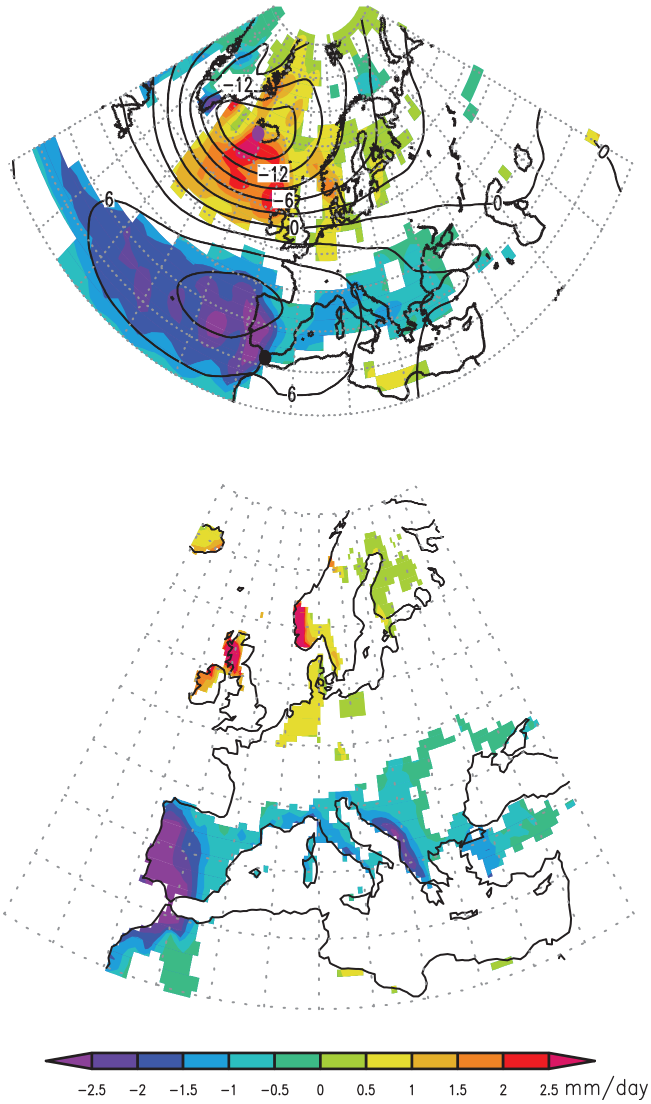

Figure 55: Top: difference in SLP (hPa, solid contours) and NCEP precipitation rate (mm/day, colour) between winter months with a NAO index >1 and months with an NAO index <−1 (period 1958–1997). Precipitation rate differences are represented only if significant at the 5% level. Bottom: as in top but with high resolution precipitation field (mm/day) of New et al. (2000) (represented only if significant at the 5% level) (Adapted from Trigo et al., 2004a).

Since the pioneering work by Lamb and Peppler (1987), most works for the Mediterranean area have been focused on the impact of the NAO during the winter season (December to March) when its impact is greatest, particularly for precipitation (Rodríguez-Fonseca and Castro, 2002). This control exerted by NAO on the precipitation field is related to corresponding changes in the associated activity of North-Atlantic storm tracks that affect most of western Europe (Osborn et al., 1999; Ulbrich et al., 1999; Goodess and Jones, 2002; Trigo et al., 2002b) and the Eastern Mediterranean such as in Turkey (Türkeş and Erlat, 2003, 2005). Using high and (low) NAO index composites, Trigo et al. (2002b, 2004a) have shown anomaly fields of climate variables and their associated physical mechanisms for the entire Europe (Figs. 55 and 56). While

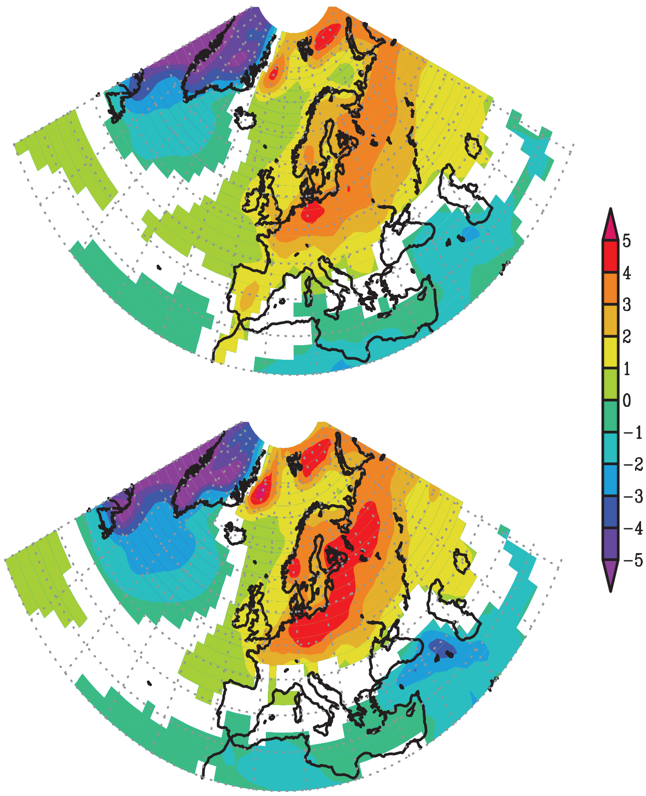

Figure 56: Top: difference in maximum temperature (°C) between winter months with an NAO index >1 and months with an NAO index <−1 (period 1958–1997). Differences are represented only if significant at the 5% level. Bottom: as in top but with minimum temperature. Data from NCEP/NCAR reanalyses.

the impact of the NAO on precipitation shows a decreasing influence in the eastern and southern sector of the Mediterranean basin (Mariotti et al., 2002b), it can still impact significantly on precipitation variability and water resources over Turkey (Cullen and de Menocal, 2000; Struglia et al., 2004; Türkeş and Erlat, 2003, 2005). The influence of the NAO on the variability of the whole Mediterranean sea–fresh water cycle is linked to the precipitation anomalies since no significant correlation is found with evaporation (Mariotti et al., 2002b). This NAO-precipitation control is associated with the steering of storm-track paths over the entire North-Atlantic sector, but also influences cyclogenesis in the Mediterranean (Trigo et al., 2000). This issue is further developed in Chapter 6 in this book.

It has been shown that the NAO does not play a relevant role in terms of western Mediterranean winter temperature variability (Sáenz et al., 2001b; Pozo-Vazquez et al., 2001a; Castro-Díez et al., 2002) and a minor, but discernible, one for the eastern Mediterranean temperature field (Cullen and de Menocal, 2000; Ben Gai et al., 2001; Xoplaki, 2002). Generally, the influence of the positive (negative) winter NAO on the Mediterranean is warmer (cooler) conditions over the northern part and cooler (warmer) over the southern part (Hurrell, 1995; Trigo et al., 2002b; Xoplaki, 2002). Interestingly, the impact of the NAO in daily extreme temperatures is unequal, with large asymmetries between minimum and maximum temperatures (Fig. 56), and more significantly, between positive and negative phases of NAO (Trigo et al., 2002b). The differences in maximum and minimum temperatures between months of high and low NAO index are shown in Fig. 56. The amplitude of the differences over Europe is larger for minimum than for maximum temperatures. However, the spatial extension of statistically significant differences for Iberia and southern Europe in general is larger for maximum than for minimum temperature. It is worth noting that maximum temperature values are usually recorded during daylight while minimum temperature values are usually observed towards the end of the night. Thus, during daytime, enhanced solar short wave radiation is capable of partially offsetting the advection of cold polar air to yield small maximum temperature anomalies, while during the night, the strong clear sky emission of long wave radiation further cools the lower troposphere (Trigo et al., 2002b). The large-scale mean temperature anomalies can be mostly explained by heat transport by the corresponding anomalous mean atmospheric flow, modified and partially offset by the heat transported by transient eddies. However, there is a third process: the modulation by anomalous cloud cover (associated with anomalous atmospheric circulation) of the radiative transfer of heat to and from the Earth's surface. These radiative and cloud cover influences modulate the response to NAO mainly in terms of generating different day and night-time temperature anomalies (Trigo et al., 2002b, 2004b).

3.2.2. The Eastern Atlantic and Eastern Atlantic/Western Russia Patterns

Several authors have shown that modes other than NAO play an important role in shaping the European precipitation variability, including sectors of the Mediterranean Basin (Zorita et al., 1992; von Storch et al., 1993; Qian et al., 2000; Quadrelli et al., 2001; Krichak et al., 2002; Xoplaki, 2002). However the NAO pattern is sufficiently well established and has been derived through different methods for every month of the year. The remaining modes of atmospheric circulation over Europe present a less clear picture, because they are of a more regional nature, their index may not be so unambiguous and finally, because some of these modes have a signature only during part of the year (Barnston and Livezey, 1987). In particular, the Eastern Atlantic (EA) pattern depends crucially on the procedure used to derive it. Still, the kind of variability associated with this pattern seems important and physically real, as it is also detected in studies using alternative techniques, like cluster analysis (Kimoto and Ghil, 1993). According to Wallace and Gutzler (1981), the EA corresponds to an index, defined in terms of the geopotential height anomalies of the 500 hPa surface at three different points. Other definitions of the same index and ''similar'' patterns have been provided through the years, including the indices from rotated EOF analysis (Barnston and Livezey, 1987). These authors (Barnston and Livezey, 1987) have identified two patterns, the Eastern Atlantic and the Eastern Atlantic/Western Russia (EA/WRUS). The East Atlantic/Western Russia pattern is one of the two prominent patterns that affect Eurasia during most of the year presenting its east Atlantic anomaly centre located further east than the EA (over western Europe) and an opposite centre located north of the Caspian region. This pattern is prominent in all months except June–August, and has been referred to as the Eurasia-2 pattern by Barnston and Livezey (1987). Correlation coefficients obtained between monthly time series of the EA_{WG} (defined by Wallace and Gutzler, 1981) and EA_{BL} or EA/WRUS (as defined by Barnston and Livezey, 1987) are statistically significant but relatively low. For instance, the correlation value between monthly winter (D,J,F) of EA_{WG} and EA_{BL} is -0.54 (significant at the 95% level) and between EA_{WG} and EA/WRUS is -0.46. Therefore, results of impact studies that use slightly different indices are bound to obtain different correlation. Here, we decided to adopt a broad perspective on this issue, making an effort to include results obtained by authors that have used both EA as well as the EA/WRUS indices. The subscripts from EA_{WG} and EA_{BL} are dropped in the following, because different studies adopt one of the definitions for the EA index they use.

Recent works have shown that the EA and EA/WRUS patterns represent a significant contribution for the precipitation over northern Iberia (Sáenz et al., 2001a) as well as parts of the eastern Mediterranean areas (Quadrelli et al., 2001;

Xoplaki et al., 2000, 2004; Krichak et al., 2002). Using station data, Xoplaki (2002) shows the spatial correlation between the EA/WRUS and winter (NDJF) precipitation in the Mediterranean basin (Fig. 57, top). Significant positive correlation is visible between EA/WRUS and winter precipitation over north-eastern Africa, the Near East, eastern Turkey and the Black Sea region. Significant negative correlations are found generally north of 40°N with a maximum over France. Anomalous positive pressure over northwestern Europe and the central and western Mediterranean area lead to subsidence and stability conditions and reduced precipitation over continental Europe and the northern coast of the Mediterranean (Xoplaki, 2002). The advection of humid and warm air by EA/WRUS to certain Mediterranean regions is associated with

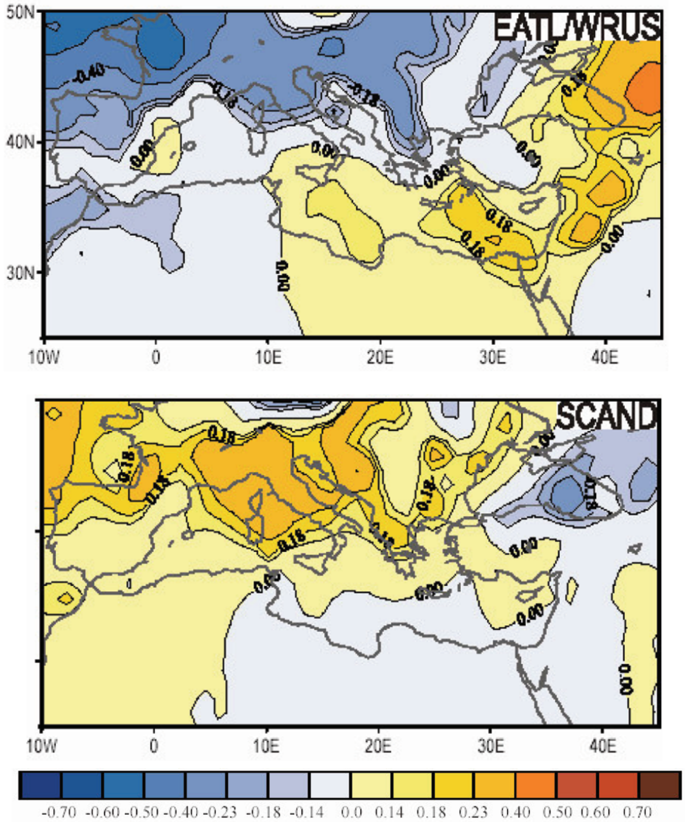

Figure 57: Spatial Spearman correlation between the patterns EA/WRUS and SCAND patterns and winter (NDJF) Mediterranean station precipitation for the period 1950–1999. Correlations $|r| \geq 0.14$ indicate significance at the 95% level, $|r| \geq 0.18$ at the 99% level and $|r| \geq 0.23$ at the 99.9% level ($n = 4 \times 50 = 200$ months), respectively (Adapted from Xoplaki, 2002).

the southward shifts of storm tracks from western Europe towards the Mediterranean. This effect, combined with the local cyclogenesis, is the main physical mechanism responsible for increased precipitation values in the Mediterranean (Xoplaki et al., 2004). In the case of winter (DJF) temperature variability, it has been shown that for the western Mediterranean region, the fraction of variance explained by the EA mode is higher than the one explained by the NAO pattern. This result is linked to the sensible heat fluxes by the mean circulation anomalies driven by the EA pattern (Sáenz et al., 2001b). A recent work has shown that the EA also plays a remarkable role in shaping daily temperature variability over most of north-eastern Spain throughout the year, particularly over coastal areas (Sigró, 2004), with the correlation coefficient reaching its maximum value in February (0.70). However, results as high as these are not observed for the eastern Mediterranean (Hasanean, 2004).

3.2.3. The Scandinavian and Blocking Patterns

The Scandinavian (SCAND) pattern consists of a primary circulation centre, which spans Scandinavia and large portions of the Arctic Ocean north of Siberia (Xoplaki, 2002). Two additional weaker centres with opposite sign to the Scandinavian centre are located over western Europe and over the Mongolia/western China sector. The SCAND pattern is a prominent mode of low frequency variability in all months except June and July, and has been previously referred to as the Eurasia-1 pattern by Barnston and Livezey (1987). The SCAND pattern is associated with important precipitation anomalies in both western and eastern Mediterranean regions (Corte-Real et al., 1995; Wibig, 1999; Xoplaki, 2002; Quadrelli et al., 2001). Using station data, Xoplaki (2002) obtained the spatial pattern of correlation between the SCAND mode and winter (NDJF) precipitation in the Mediterranean basin (Fig. 57, bottom). A strong positive pressure anomaly centered over Scandinavia and western Russia and negative anomalies over the Iberian Peninsula cause anomalous easterly to southeasterly airflow over the eastern basin and anomalous southwesterlies to southerlies over the central basin. The combined effect of these air masses connected with the relatively warm Mediterranean Sea leads to distinct cyclogenesis connected with high precipitation amounts over Italy, along the eastern Adriatic coast and the southern part of the Alps.

Interestingly, the SCAND circulation mode reveals a spatial pattern similar to the European blocking pattern, usually described in studies using sub-monthly scales (e.g. Tibaldi et al., 1997). Therefore, we believe that it is appropriate to describe the impacts of the well-established blocking pattern (Rex, 1950b, 1951) simultaneously with those associated with the SCAND mode. In fact, a recent study has quantified the impact of the SCAND pattern winter blocking variability over the European sector (Barriopedro et al., 2005).

The frequency of blocking events over Europe presents a marked seasonal cycle with higher values in winter and spring (Tibaldi et al., 1997; Trigo et al., 2004b). Blocking episodes are known to produce significant impacts on both the precipitation and temperature fields of the Mediterranean Region (Trigo et al., 2004b). Figure 58 (top) shows differences between the mean 500 hPa geopotential height composites for winter blocking and non-blocking episodes, and the corresponding difference for the 850 hPa temperature composites (represented only if significant at the 1% level). The corresponding differences for precipitation rate (represented only if significant at the 5% level) are shown in Fig. 58 (bottom). Blocking episodes usually last between 5 and 20 days, but their fingerprint is sufficiently intense to be noticed at the monthly scale

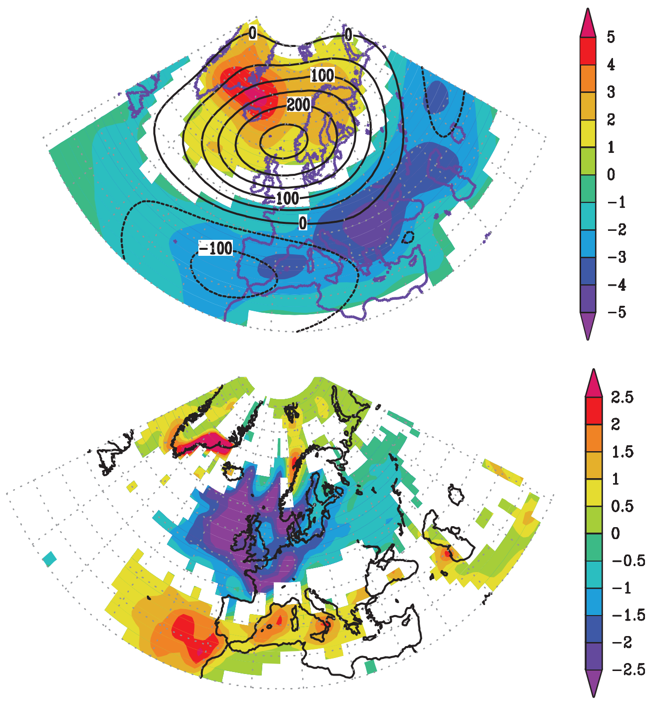

Figure 58: Top: Differences between the mean 500 hPa geopotential height (gpm, contour) composites for winter blocking and non-blocking episodes, and the corresponding difference for the 850 hPa (°C, colour) temperature composites (represented only if significant at the 1% level). Bottom: Corresponding differences of precipitation rate (mm/day) are represented (only if locally significant at the 5% level). Data from NCEP/NCAR reanalyses (Adapted from Trigo et al., 2004b).

(Quadrelli et al., 2001). The most important feature corresponds to the intensification of the meridional component of the mid-troposphere circulation that is perfectly visible during blocked situations, up and downstream of the British Isles. This configuration is usually associated with the split of the jet stream in two distinct branches, a feature that is widely accepted as a trademark of European blocking episodes (Rex, 1950a). The impact of these events for the low tropospheric temperature field at 850 hPa extends from Iberia to the Black Sea with the most intense values being observed over the Balkans (Fig. 58, top). On the other hand, the significant impact of these blocking episodes on the Mediterranean precipitation is confined to the western sector (Fig. 58, bottom).

3.2.4. Other Modes

A regional manifestation of the NAO is given by the Mediterranean Oscillation (Conte et al., 1989) implying opposite pressure (especially at upper levels) and surface climate conditions between the western to central and the southeastern Mediterranean basin. Thus, the most important canonical correlation pattern between the large-scale circulation and Mediterranean precipitation in winter being significantly correlated ($r = 0.72$) with the NAO during the October–March period is strongly related with various indices of the Mediterranean Oscillation (Dünkeloh and Jacobeit, 2003). A similar result arises even for the case of a non-seasonal whole-year analysis at monthly scales (Corte-Real et al., 1995). Therefore, such a high correlation coefficient between NAO and the Mediterranean Oscillation seems to imply that these two phenomena are not independent.

Another dominant circulation mode (present at 1000 and 500 hPa) coupled with Mediterranean climate variability is the Mediterranean Meridional Circulation (MMC) pattern consisting of two opposite anomaly centres west of the Bay of Biscay and in the central Mediterranean implying preferred meridional flows around this area (Dünkeloh and Jacobeit, 2003). It shows some relation with the hemispheric-scale EA pattern at the 500 hPa level (NOAA-CPC, 2005a) and often recurs in dynamical studies linked to the Mediterranean area, e.g. as second mode of the non-seasonal analysis by Corte-Real et al. (1995) or as first mode of the Greek winter rainfall analysis by Xoplaki et al. (2000).

Another mode of low-frequency variability affecting the Mediterranean area is the East Atlantic Jet pattern (EA-JET, see NOAA-CPC, 2005a). It is among the ten leading teleconnection patterns from April to August (NOAA-CPC, 2005b) revealing a N–S dipole of anomaly centres with one centre over the northeastern North Atlantic and western Scandinavia, the other centre over Northwest Africa and large parts of the Mediterranean region. Thus, its positive mode reflects intensified mid-latitude westerlies, whereas its negative mode represents particular blocking configurations. During spring, there is a moderate correlation ($r = 0.44$) with a canonical correlation pattern (CCP) whose rainfall part explains some 16% of Mediterranean precipitation variability, however, during summer the EA-JET pattern is strongly related ($r = -0.66$) to the most important CCP including nearly 30% of explained summer precipitation variability in the northern and western Mediterranean regions (Dünkeloh and Jacobeit, 2003). Thus, blocking configurations of an EA-JET type in its negative mode are especially important for above-average summer rainfall in these areas. Touchan et al. (2005) recently have also found a significant positive correlation between the EA-Jet and May–August precipitation over the southeastern Mediterranean area for the 1948–2000 period. However, they also report on instationarities in those relationships using reconstructed precipitation several centuries back in time.

A last mode, the Polar Eurasian pattern (NOAA-CPC, 2005a), is particularly important during the winter season (NOAA-CPC, 2005b). It reflects variations in the strength of the circumpolar vortex and affects the Mediterranean region by its European anomaly centre which extends up to the northern and western parts of the Mediterranean area. Increased anticyclonicity in these regions represents an enhanced polar vortex and vice versa. This pattern has been found being moderate negatively correlated (−0.42) with the second CCP of wet season Mediterranean precipitation connected with below normal precipitation over the western Mediterranean and above normal precipitation over the eastern part of the basin (Xoplaki et al., 2004).

3.3. Temperature Variability

It is widely accepted that the frequency of large-scale circulation patterns has a major impact on monthly/seasonal surface climate characteristics. In fact this link was explored in Chapter 1 of this book to evaluate the evolution of Mediterranean winter climate since the early sixteenth century. However, until the mid-twentieth century, virtually all large-scale circulation data is referent to sea level pressure, limiting the extent of those historical circulation-climate studies (except for Schmutz et al., 2000, Luterbacher et al., 2002 and Brönnimann and Luterbacher, 2004, who provide mid and upper tropospheric fields further back in time). Nowadays, the generalized use of multi-variable and multi-level reanalyses datasets has allowed the use of more appropriate variables (e.g. 300 hPa or 500 hPa geopotential height) to establish those relationships.

Xoplaki et al. (2003b) using a multi-component CCA in the EOF space, investigated the relationships between the large-scale atmospheric circulation and the Mediterranean summer (June to September) temperature. The authors show that 56% of the summer Mediterranean temperature variability during the second half of the twentieth century can be explained by making use of the first two canonical modes. The most important of the canonical modes (Fig. 59) reveals a dipole configuration in the North Atlantic. In the positive phase of the dipole, a deep centre with positive 300 hPa geopotential height anomalies is located over central Europe; an area of negative anomalies presents higher values south of Iceland and surrounding northward, the positive anomalies extends up to the western Ural mountains and the northern Caspian Sea. SSTs and surface temperatures reveal higher values in the northwestern part of the Mediterranean under the high pressure region. This dynamic configuration strengthens the zonal flow over northern Europe and easterly–northeasterly flow over the Mediterranean. The increased stability leads to clear sky conditions and maximum insolation in the area.

The CCA mode described above agrees well with the second mode in the study of Xoplaki et al. (2003a) on summer temperatures over Greece. Thus, it seems plausible to extend the reasoning in their work to the entire Mediterranean area. From this perspective, the variability of summer temperatures in the Mediterranean would be well described with a parsimonious conceptual model invoking two modes, the "high-index" type and the "low-index" type, which picture transitions from the zonal to the meridional flow.

3.4. Precipitation Variability

Most Mediterranean countries experience frequent drought episodes, which may cause water shortages and disrupt agricultural and industrial activities, such as hydroelectric power generation. Köppen's (1936) definition of Mediterranean climate is, in simple terms, one in which winter rainfall is more than three times the summer rainfall. Summer in many regions located in the southern Mediterranean coast is characterized by lack of rain, long periods of drought and high temperatures that lead to a marked summer aridity. The strong summer–winter rainfall contrast that characterizes the Mediterranean climate is associated with pronounced seasonal cycles in most climatic variables. During a typical year, rain occurs most frequently during the winter half-year over most of the land area surrounding the Mediterranean, mainly in the southern and eastern parts. In addition, the winter half-year precipitation accounts for between 30% (western and northern Mediterranean lands) and 80% (eastern-southeastern parts) of the annual total amounts (Xoplaki et al., 2004). In general, there exists a clear deficit of water during the summer half-year, when only sparse storms and convective systems produce rainfall (Trigo et al., 1999).

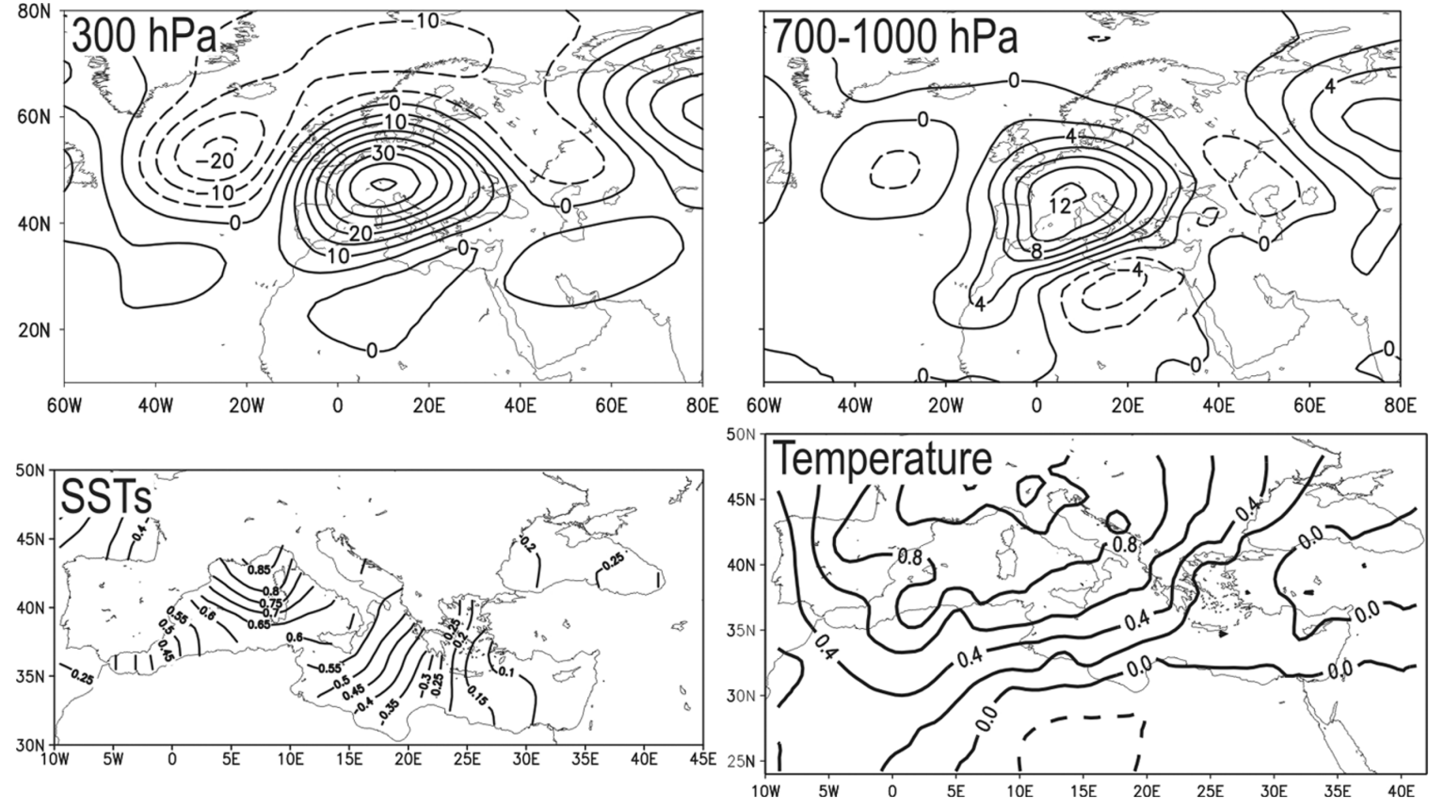

Figure 59: Canonical spatial patterns of the first multi-component CCA. The canonical correlation patterns reflect the typical strength of the signal, with 300 hPa, 700–1000 hPa, SST, air-temperature anomalies in °C (adapted from Xoplaki et al., 2003b).

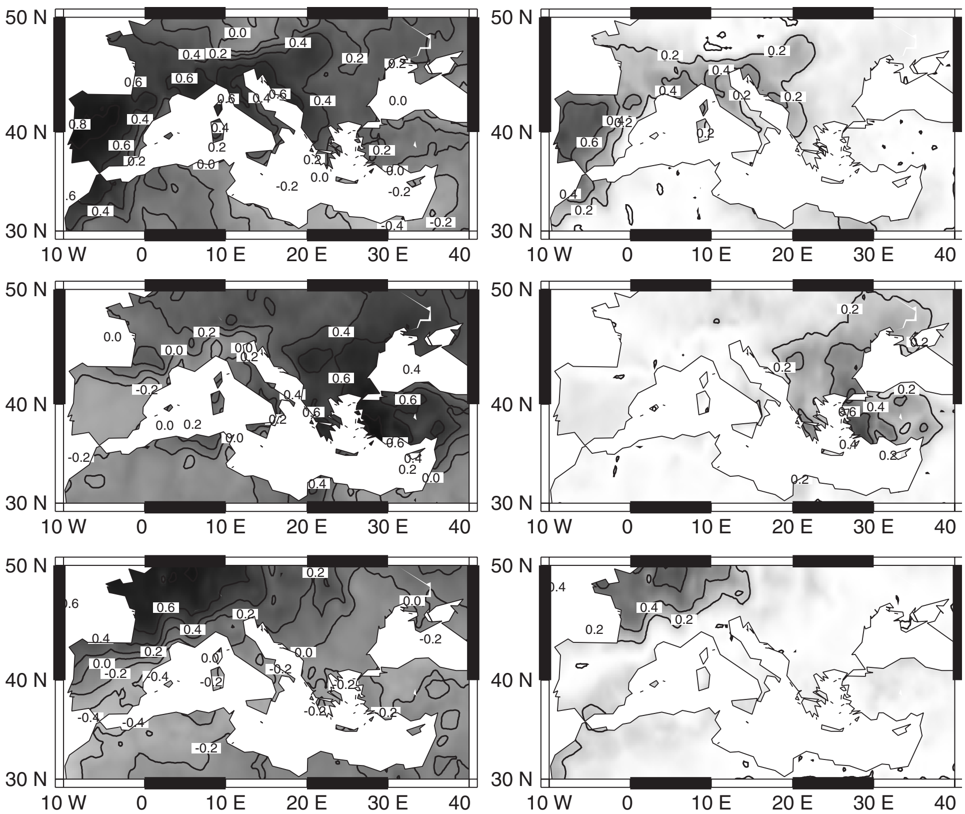

Figure 60: Left: From top to bottom: The 3 leading EOFs from the New et al. (2000) precipitation field expressed as correlation of the corresponding PC with the precipitation series at each grid point. Right: From top to bottom: The variance fraction of the precipitation series explained by the 3 leading PCs. (Adapted from Fernández et al., 2003).

Therefore, it is necessary to use appropriate statistical tools to assess the spatio-temporal variability of the precipitation field throughout the yearly cycle, but particularly during the winter season. Figure 60 shows the approach developed for the Mediterranean basin by Fernández et al. (2003) in which PCA was applied to the linearly detrended monthly precipitation over the area given by the high resolution ($0.5^\circ \times 0.5^\circ$) gridded data from New et al. (2000) for the period 1948–1996. The 3 leading EOFs are represented as the correlation of the corresponding PC with the precipitation series at each gridpoint. These three patterns explain around 50% of the total detrended field. It is worth mentioning that the first EOF (22% of variance) shows the typical precipitation fingerprint of the NAO, controlling the rainfall variability in western Mediterranean sector (see Fig. 55). The second EOF (16% of variance) shows high loading values over the eastern Mediterranean sector while the third EOF (11% of variance) shows a north–south dipole with particularly high loadings over France. The spatial pattern of the third EOF is related with the patterns of precipitation impact of the EA or the EA/WRUS already mentioned (Fig. 57, left).

The average flux of atmospheric water vapour through the boundary is shown in Fig. 61. Since the outflow is selected as positive flux, the negative values along the western boundary represent the inflow of humidity coming from the Atlantic Ocean. An average inflow of 494 Pg mo^{-1} crosses this boundary while the main outflow from the basin takes place through the eastern boundary (Fernández et al., 2003). The precipitation variability is closely related to the structure of the vertically integrated moisture transport fluxes, inside the domain and at the borders. As an example, the principal components of precipitation are regressed over the moisture transport at each NCEP/NCAR Reanalysis grid point over the area in Fig. 61B–D. The leading model (Fig. 61B) shows for positive phases an intensification of the transports of moisture arriving to the area from the Atlantic through the lateral western boundary. The second model

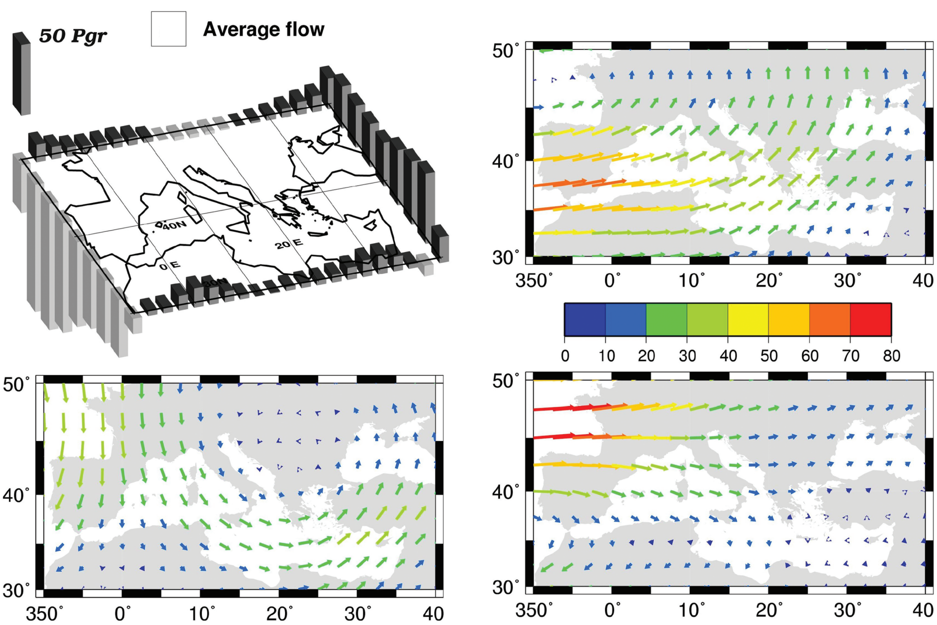

Figure 61: (A) Average moisture flux through the boundaries according to NCEP data (in Pg mo^{-1}). (B–D) Regression of the precipitation PCs (1st–3rd PC, respectively) over the vertically integrated moisture transport derived from NCEP/NCAR Reanalysis in kg m^{-1} s^{-1}. (Adapted from Fernández et al., 2003).

(Fig. 61C) shows an important contribution of moisture to the atmosphere from the western Mediterranean sub-basin and its transport to the eastern areas. Finally, the third EOF (Fig. 61D) is closely linked to the barrier effect of orography (mainly over the Alps) over the vertically integrated moisture transports.

Xoplaki et al. (2004) used a multi-component Canonical Correlation Analysis (CCA) in the Empirical Orthogonal Function (EOF) space to identify the most important circulation patterns, at the sea level as well as at mid- and upper atmospheric levels, associated with the wet season (October to May; 1949–1999) Mediterranean station precipitation. Standard CCA technique relates one large-scale pattern with one regional precipitation pattern (e.g. Corte-Real et al., 1995). However, Xoplaki et al. (2004) have shown that a combination of large-scale fields of predictors can achieve better results than the use of a single predictor. Four large-scale circulation modes accounted for 30% of the overall precipitation variability. It should be stressed that the CCA method maximizes the explained variance that links patterns of precipitation and large scale fields previously considered. Of course, there is a part of the variability linked to local factors and not related to these large-scale fields and, thus, the variance explained by these patterns (constrained to be related to the pre-defined large scale circulation patterns) is lower than the one associated with the first 3 EOFs by Férnandez et al. (2003). The first canonical pair (Fig. 62) is connected with the NAO and

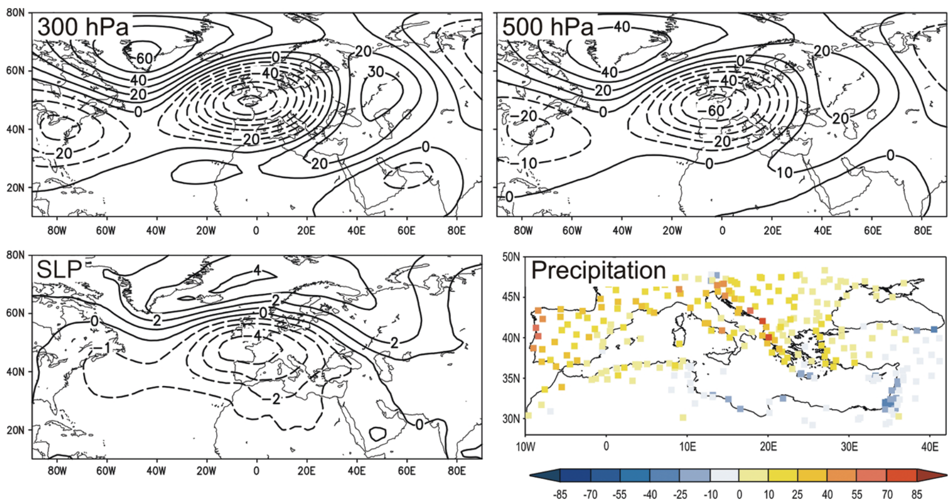

Figure 62: Canonical spatial patterns of the first CCA between the wet season Mediterranean station precipitation (predictand) and 300 hPa, 500 hPa and SLP (predictors); wet season precipitation anomalies in mm (Adapted from Xoplaki et al., 2004).

the EA/WRUS (correlates at −0.66 and −0.50, respectively). These patterns are connected with above normal precipitation over the western, central and northern Mediterranean area and drier conditions over the remaining region. These results are quite well in agreement with Dünkeloh and Jacobeit (2003) for a similar analysis using gridded precipitation data over the Mediterranean coast. A regional study focused on the eastern Mediterranean supports that stronger westerlies over the eastern North Atlantic and the rising 500 hPa height (and the sea level pressure) over continental Europe during the last few decades were connected with enhanced atmospheric stabilization and anomalous advection of cold dry air from northerly directions. This led to the winter dryness over the eastern Mediterranean (Xoplaki et al., 2000).

3.5. Trends

A comprehensive analysis of Mediterranean climate trends over the last 500 years has been presented in Chapter 1 of this book. Here, we focus on trends observed over shorter time scales (decadal) during the twentieth century. After describing the most important characteristics of temperature and precipitation trends for different parts of the Mediterranean region, we describe the most important physical mechanisms associated with them and driven by the large-scale atmospheric patterns described in the previous sections.

3.5.1. Temperature Trends

Giorgi (2002) analysed the surface air temperature variability and trends over the larger Mediterranean land-area for the twentieth century based on gridded data of New et al. (2000). He found a significant warming trend of 0.75°C, mostly from contributions during the early and late decades of the century. Slightly stronger warming was observed for winter and summer. Spring reveals important trends over the last half century, mainly in the northern part of the Mediterranean while Autumn presents a warming trend in the western basin and a slight decrease in the eastern sector.

The structure of climate series can differ considerably across regions showing variability at a range of scales in response to changes in the direct radiative forcing and variations in internal modes of the climate system (New et al., 2001; Hansen et al., 2001; Giorgi, 2002). Therefore, it is of no surprise, that based on the same data as Giorgi, Jacobeit (2000) found a distinct summer warming between 1969 and 1998 (a short period), being more distinct in the western than in the eastern part; seasonal cooling trends exist in some eastern areas, mainly in spring, in some cases also in winter. Figure 63 (left) presents the linear trends of summer

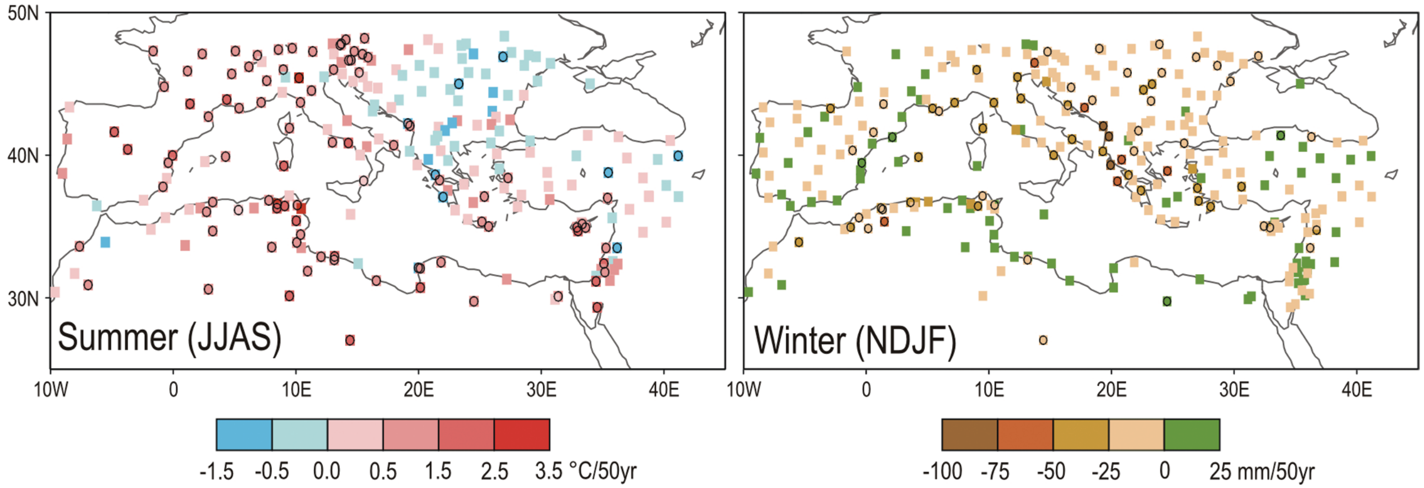

Figure 63: Right: Linear trends of winter (NDJF) station precipitation (mm/50 year). Left: Summer (JJAS) station air temperatures (°C/50 year) for the period 1950–1999. Stations with a significant trend (90% confidence level, based on the Mann–Kendall test) are encircled (from Xoplaki, 2002).

station air temperatures (°C/50 year) for the period 1950–1999 based on the results of Xoplaki et al. (2002). It also shows the stations which experienced a significant trend. A clear east–west differentiation in Mediterranean summer air-temperature trends is visible. Negative values over the Balkans and eastern basin can be observed, however many are not significant. In the other areas, there is a significant warming trend of up to 3°C/50 year. However, the warming in these regions did not occur in a steady or monotonic fashion. Over most of western Mediterranean for instance, it has been mainly registered in two phases: the early years of twentieth century up to the mid-century warm phase and from the earliest 1970s onwards (Fig. 64). These rising episodes in temperatures were particularly well depicted over the entire Iberian Peninsula (e.g. Brunet et al., 2001; Galan et al., 2001) and over Italy (Brunetti et al., 2006). A glance at the summer air-temperature trends for the period 1900–1949 reveals that warming, though less extreme as in 1950–1999, was experienced in the western basin (not shown). A cooling trend over 1900–1949 was only prevalent over Libya and Egypt. The trend of winter temperature over 1900–1949 indicates a general cooling in the central basin but a warming in the east and west (not shown). For the 1950–1999 period, except for the eastern part, there was warming experienced (not shown). Xoplaki (2002) found a significant cooling trend of Mediterranean winter Sea Surface Temperatures (SSTs) east of 20°E over the period 1950–1999, while the western basin SST experienced a positive trend.

Xoplaki et al. (2003b) showed that the 300 hPa geopotential height, 700–1000 hPa thickness and Mediterranean SST large-scale fields account for more than 50% of the Mediterranean summer temperature variability over the period 1950–1999. The most important summer warming pattern is associated with

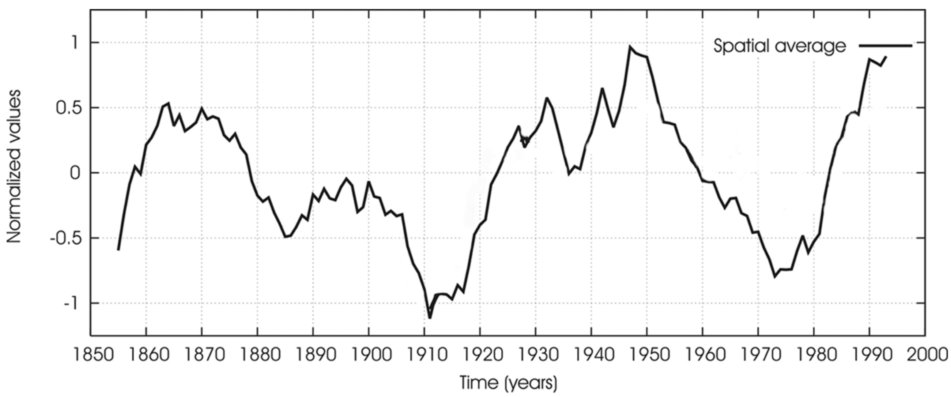

Figure 64: The curve corresponds to standardized values of the spatial average of Mediterranean summer temperatures for the period 1850–1999. All time series are outputs of a 10-year centred moving average filter (Adapted from Xoplaki et al., 2003b).

blocking conditions, subsidence and stability. This mode is responsible for the 0.4°C (0.5°C) warming during the period 1950–1999 (1900–1999). The spatial average for summer (June to September) Mediterranean station temperatures (Fig. 64) shows high values during the 1860s, comparable to those during the 1950s and 1990s. For the period 1850 to 1999, a trend of 0.018°C/decade is found (significant at the 95% level). For the period 1900 to 1999, a change of 0.05°C/decade is found. This fact points to an increase in temperature of about 0.27°C in the 1850–1999 period, and of 0.5°C in the twentieth century (Xoplaki et al., 2003b).

For the eastern part of the Mediterranean, no significant linear trend in the averaged summer months (June to September) and entire summer mean air temperature could be detected (Xoplaki et al., 2003a). The most remarkable features concerning trends are on decadal time scales: the cooling trend at the beginning of the 1960s and the warming at the end of the 1980s (Fig. 65).

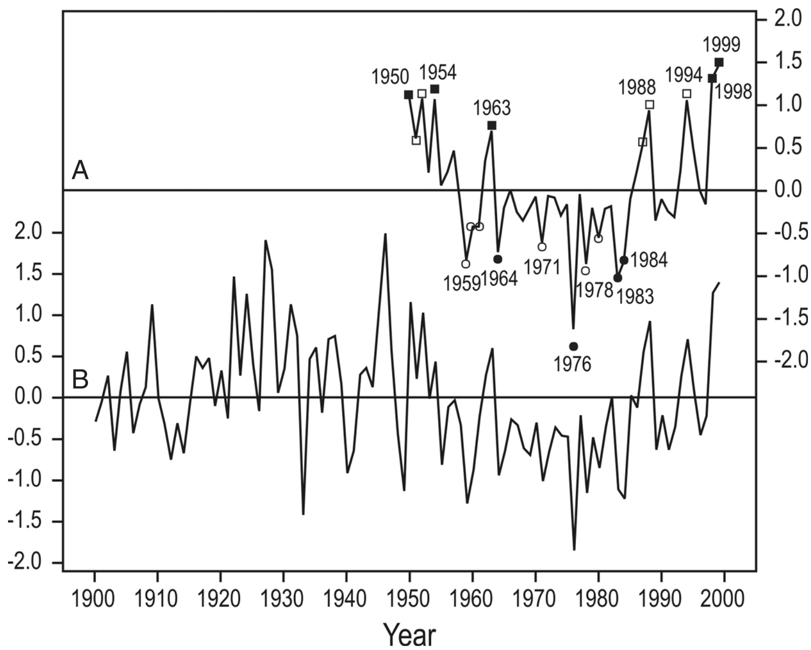

Figure 65: (A) Spatially weighted mean of summer (JJAS) air temperature anomalies from Greece and western Turkey from 1950 to 1999. Circles: 10 coolest summers. Squares: 10 warmest summers. Solid symbols correspond to the extreme summers, in which at least three single months are characterized by ''extreme'' air temperature conditions. (B) Spatially weighted mean of summer (JJAS) air temperature anomalies (Thessaloniki, Larissa, Athens and Patra) from 1901 to 1999 (From Xoplaki et al., 2003a).

Türkeş et al. (2002) found general increasing trends in annual, winter and spring mean temperatures particularly over the southern regions of Turkey, for the period 1929–1999. On the other hand, these authors found decreasing trends for summer and autumn mean temperatures over the inner continental and northern regions. In general, summer night-time warming, temperature rates were found to be larger than corresponding night-time rates for spring and autumn. Furthermore, during spring and summer night-time warming, temperature rates were generally stronger than daytime temperature rates. Recently, Türkeş and Sümer (2004) showed that the diurnal temperature ranges significantly decreased for most urban stations of Turkey throughout the year, but less explicitly in winter.

3.5.2. Precipitation Trends

It is a well-known fact that precipitation throughout the Mediterranean basin is highly concentrated in time between late autumn and spring (i.e. between October and April). Therefore, the relatively vast amount of literature on the subject is bound to reflect this imbalance, with very few studies focusing the drier half of the year. Recent studies revealed that the twentieth century was characterized by significant precipitation trends at different time and space scales (e.g. Folland et al., 2001; New et al., 2001). Giorgi (2002) found negative (positive) winter precipitation trends over the eastern (western) Mediterranean land-area for the twentieth century. The two other important seasons for precipitation present a different picture, with negative trends concentrated over Iberia and central Mediterranean areas (Schönwise et al., 1993). This is confirmed with more regionalized studies, such as the one undertaken by González-Rouco et al. (2001) for the Iberian Peninsula, showing positive seasonal trend for this time interval in winter and negative trends in spring and autumn. In Italy, the significant negative trend observed in total annual precipitation amount is mainly due to the spring season, even if negative but not significant trends were observed also for winter, summer and autumn (Brunetti et al., 2006). Studies on precipitation trends must be analysed carefully as they crucially depend on the length of time-series analysed. Using the same data as Giorgi, Jacobeit (2000) showed for the last three decades some rainfall increases in autumn (western Iberia and southern Turkey), but dominating decreases in winter and spring. For the period 1951–2000, opposite to the prevailing decreasing trend, there is some increase in winter precipitation from southern Israel to northern Libya in accordance with increased positive modes of the Mediterranean Oscillation (Jacobeit et al., 2004). Nevertheless, the prevailing trends for the second half of the twentieth century are negative in winter and spring, although areas with significance are relatively restricted, depending on the month (Norrant and Douguédroit, 2005). A glance at the Mediterranean regional winter precipitation trends reveals a more detailed picture of the general findings. Sub-regional variability is high, particularly in areas with contrasted topography near coastland where also significant trend in precipitation variability and totals have been observed (e.g. Türkeş, 1996, 1998). The evaluation of regional data series (Fig. 63, right) indicate that the trend towards reduced winter precipitation trends in many regions are not statistically significant in view of the large variability (Xoplaki, 2002; Norrant and Douguédroit, 2005). However, significant decreases are prevalent in western and central Mediterranean.

For the Mediterranean Sea, precipitation variability and water budget have been investigated using gauge-satellite merged products and atmospheric re-analyses (Mariotti et al., 2002b). NCEP re-analyses show that during the last 50 years of the twentieth century Mediterranean averaged winter precipitation has decreased by about 20%, with the decrease mostly occurring during the period late 1970s to early 1990s. This implies a similar increase in the Mediterranean atmospheric water deficit with potentially important impacts on the Mediterranean Sea circulation as stressed in other chapters of this book.

Xoplaki et al. (2004) in Fig. 66 show the monthly time evolution of the spatially averaged precipitation anomalies both for the instrumental data ($\sim$300 stations equally distributed around the Mediterranean; upper panel) and the NCEP/NCAR re-analysis data (lower panel); their 4-year moving average low pass filtered time series are also shown to aid comparison at longer time scales. There is good agreement between the NCEP and station data (correlation 0.78). The plot highlights the underestimation of variability by the NCEP/NCAR reanalysis data: the ratio of variance of observations vs. NCEP is 3.11. Decadal changes show good agreement between both datasets in depicting relatively wet and dry periods (see filtered data): relative maxima take place in the early 1950s, 1960s, late 1970s to early 1980s and late 1990s while relative minima occur in the late 1950s, early 1970s and early 1990s. The decadal changes are superimposed upon a long-term negative trend of 2.18 $\mathrm{mm \cdot month^{-1} \cdot decade^{-1}}$ (station data; 1.5 $\mathrm{mm \cdot month^{-1} \cdot decade^{-1}}$ for the reanalysis), significant at the 0.05 level.

Naturally, negative trends of winter precipitation over western and central Mediterranean are probably linked with trends in cloud cover. In fact, recent studies for Portugal (Santos et al., 2002) and Italy (Maugeri et al., 2001), both using station-based data, have detected negative trends of winter cloud cover for the second part of the twentieth century. The results show that there is a highly significant negative trend in total cloud amount all over Italy. It is evident in all seasons and is particularly steep in winter where both in northern and southern Italy, the decrease exceeds 1 okta in 50 years (Maugeri et al., 2001).

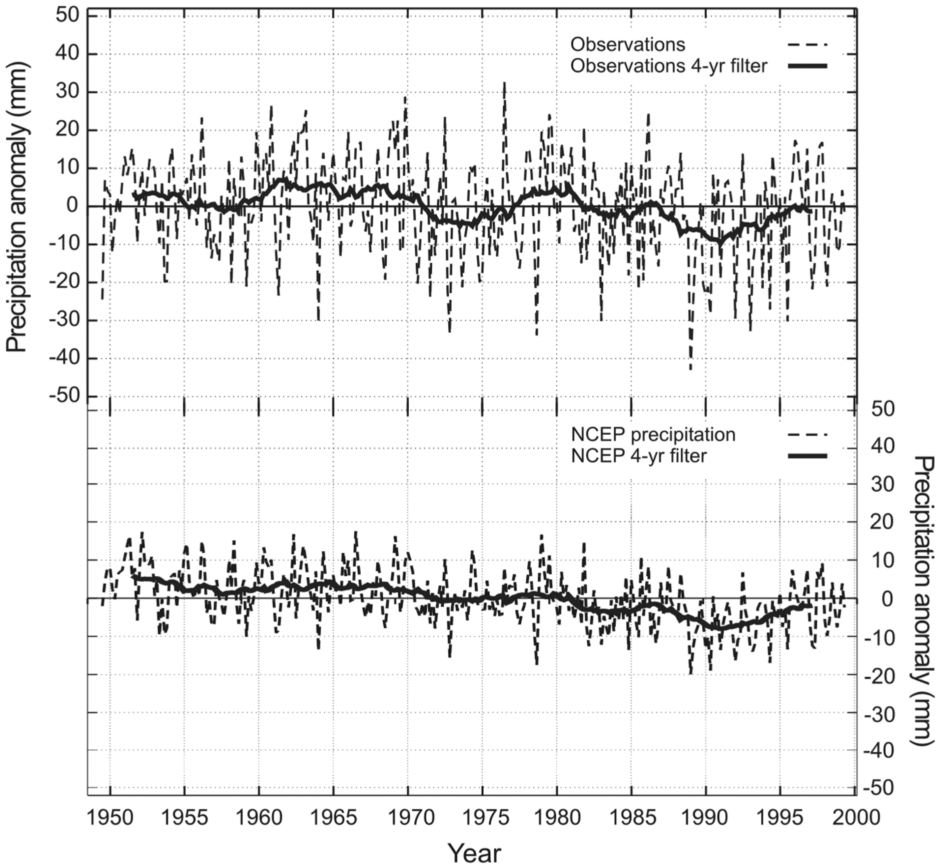

Figure 66: Upper panel: Wet season (October–March) precipitation anomalies (with respect to the 1950–1999 reference period) averaged over 292 sites in the Mediterranean (dashed line) and 4-year low pass filter (solid line); Lower panel: Wet season precipitation anomalies averaged over NCEP reanalysis data (dashed line) and 4-year low pass filter (solid line) (Adapted from Xoplaki et al., 2004).

3.5.3. Contributing Factors for Observed Temperature and Precipitation Trends

After assessing the impact of several large-scale atmospheric circulation patterns in terms of Mediterranean climate, it is natural to expect that any major trends in the intensity of these circulation modes may impact directly on the observed climate. This is particularly true for the winter NAO index, that has revealed a strong positive trend throughout most of the 1980s and 1990s (Hurrell, 1995). However, over the last few winters a downward trend of the NAO has been observed (Overland and Wang, 2005). The observed decreasing precipitation in northern Mediterranean and increasing Mediterranean fresh water deficit has been linked to trends of the NAO index in winter (Quadrelli et al., 2001; Mariotti et al., 2002b) influenced by corresponding trends in Atlantic storm-track paths and Mediterranean cyclogenesis (Trigo et al., 2000). On a monthly scale, probably the most significant precipitation trend can be found over the entire Iberian Peninsula for the month of March with a continuous monotonic decrease of up to 70% between the late 1950s and the 1990s (Trigo and DaCamara, 2000; Paredes et al., 2005). The spatial extent of those regions with significant trends (Fig. 67, top) is particularly coincident with the NAO impact region shown in Fig. 55. Moreover, the associated trend of cyclone densities for March shows a remarkable decrease near the Iberian Peninsula while northern Europe presents significant increase of cyclones and precipitation (Paredes et al., 2005). Recent studies have shown that throughout the latest two decades, the northern centre of the NAO dipole (the Icelandic low) has moved closer to Scandinavia (Jung and Hilmer, 2001). This shift has major implications for the Northern Hemisphere climate, in general, (Lu and Greatbatch, 2002) and for the precipitation field over Iberia, in particular (Rodó et al., 1997; Goodess and Jones, 2002). This observed trend in storm-track paths (Fig. 65, right) has been reinforced with observational studies showing a simultaneous coherent trend in blocking activity over the Atlantic sector (Barriopedro et al., 2005). It is not obvious if this variability is natural or induced itself by climate change.

Recent works have shown that the significant winter precipitation decline that took place over the Mediterranean region during the last decades of the twentieth century results from the combined effect of trends of the NAO and the EA/WRUS patterns (Krichak and Alpert, 2005a,b). These authors separated the Mediterranean basin in three target areas in order to identify the different trend effects of the NAO and EA/WRUS patterns. The area 7°E–10°E; 44°N–46°N was selected to represent the northwestern Mediterranean region. The target area for the northeastern Mediterranean region is located between 37°E–40°E; 35°N–37°N, while that for the southeastern part of the basin is defined by 35°E–37°E; 31°N–34°N. Krichak and Alpert (2005a,b) based their analysis on a determination of the typical for winter months (DJF) circulation patterns over the northwestern, northeastern and southeastern Mediterranean area during the 15-year periods that are characterized by high and low NAO and EA/WRUS indices (1958–1972 and 1979–1993, respectively). The circulation patterns in the Figs. 68–70 illustrate the differences between the two 15-year periods. During the high phase period the typical for the northwestern part composite vortex is to be found positioned much further to the southeast (inland) than in the low phase case (Fig. 68). The difference explains the observed precipitation decrease during the last several decades of the past century by a decrease in the moisture content

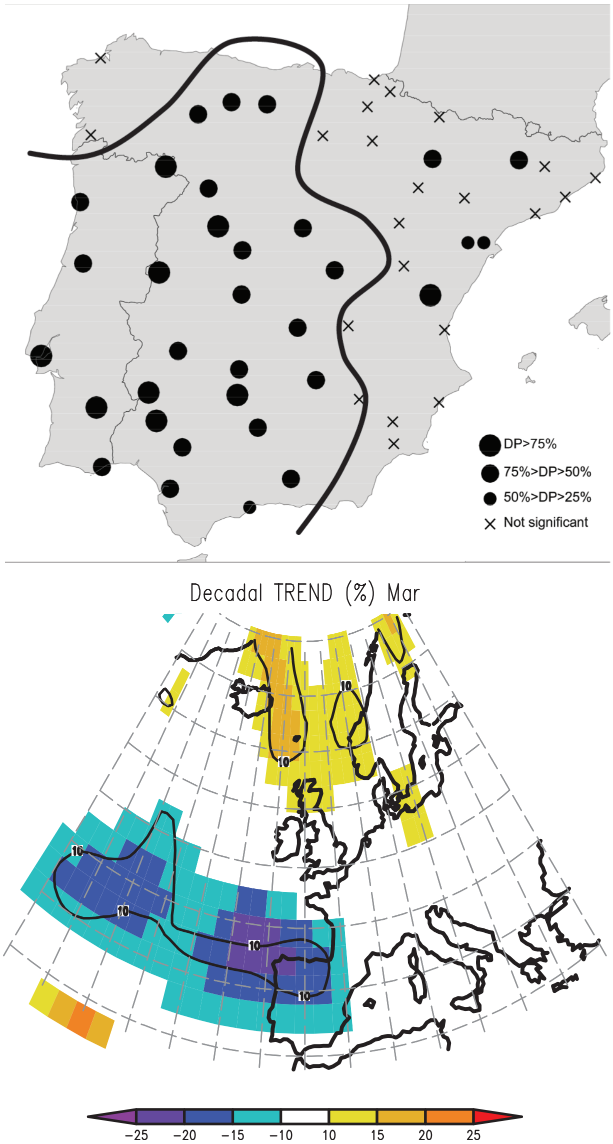

Figure 67: Top: Decreasing Precipitation (DP) trends in March for the period 1941–1997. The different sizes of black dots depict the relative change in precipitation for the complete period after fitting March time series to a linear model. "Crosses" correspond to non-significant or positive trends, while the dots represent stations with declining precipitation at less than the 10% level (Mann–Kendall test). Bottom: Decadal trends (% relative to the mean over the study period) of the average number of cyclones detected in March for the period 1960–2000, computed on cell boxes with 10° longitude by 10° latitude and normalized for a standard latitude of 50°N. The solid line indicates the grid cells with significant trends at least at the 10% level (from Paredes et al., 2005).

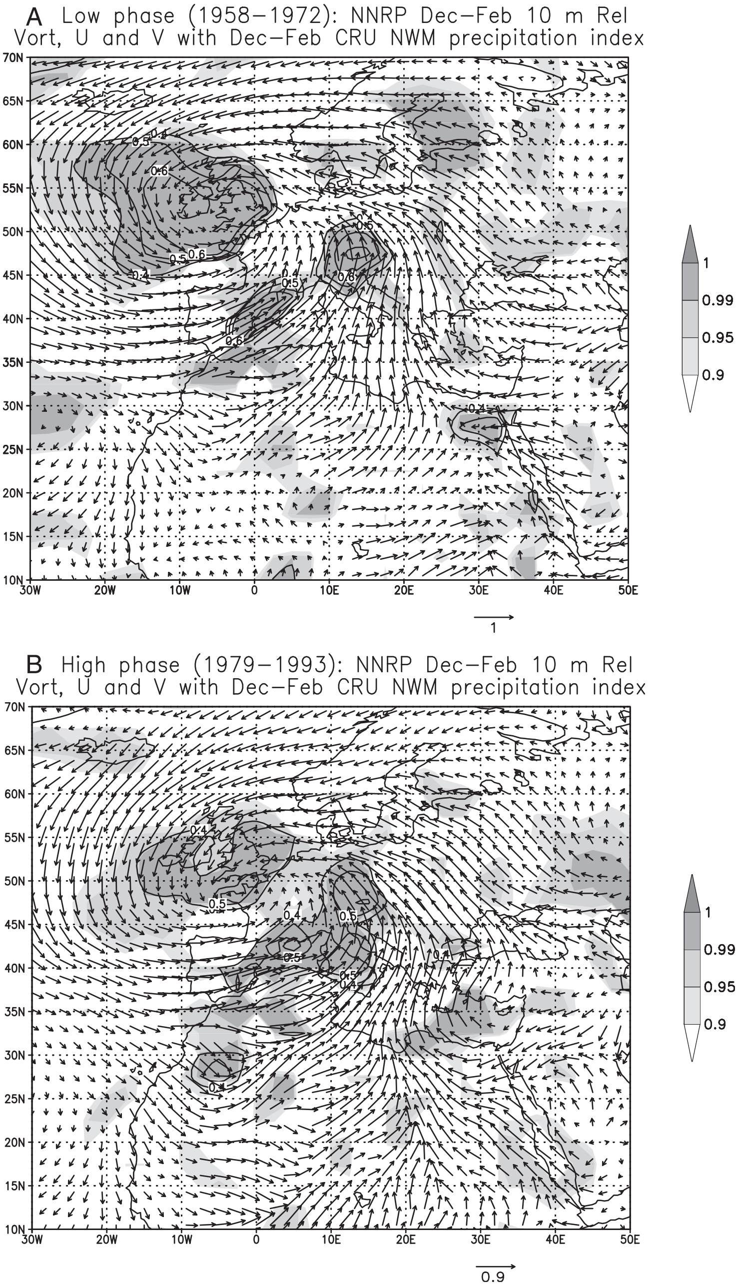

Figure 68: Correlations between precipitation index over the northwestern Mediterranean target area and the *u,v* wind components at 850 hPa isobaric surface, during DJF months for (A) low six-year mean NAO-EA/WRUS; (B) high six-year mean NAO-EA/WRUS. The wind vectors represent the magnitudes of the wind-precipitation correlations obtained. The isolines and shaded areas in the figures represent the correlations and statistical significances (above 0.90) of the dependencies between relative vorticity and precipitation respectively (From Krichak and Alpert, 2005b).

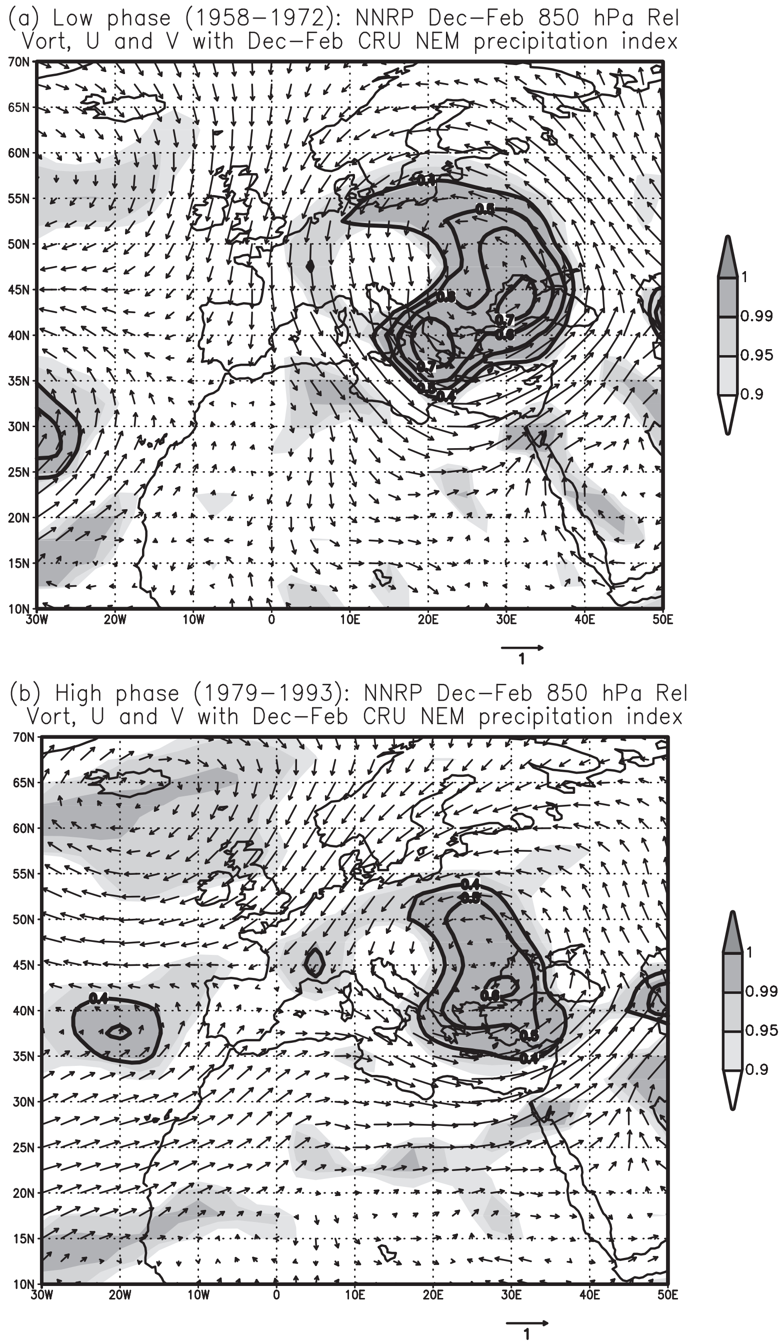

Figure 69: Same as in Fig. 68 but for the northeastern Mediterranean target area (From Krichak and Alpert, 2005b).

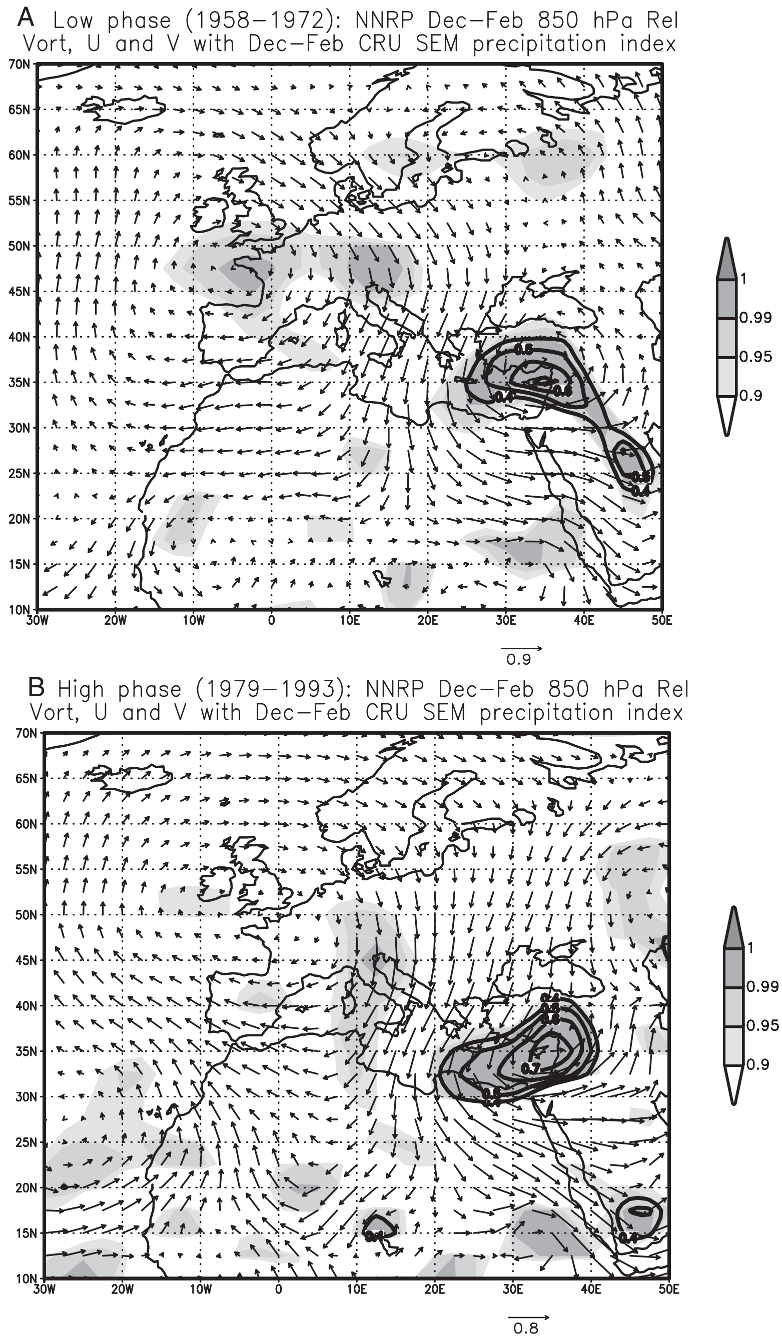

Figure 70: Same as in Fig. 68 but for the southeastern Mediterranean target area. (From Krichak and Alpert, 2005b).

of the air masses due to the stronger westerlies which characterize the high NAO months. Another physical mechanism appears to be linking the positive NAO-EA/WRUS trend with the precipitation decline over the northeastern and southeastern Mediterranean regions (Figs. 69 and 70). The low-phase wet DJF months in the eastern Mediterranean (both northeastern and southeastern parts) are characterized by the circulation patterns with the northwesterly airflow (i.e. from the Atlantics towards the eastern Mediterranean) in the lower troposphere. One may expect that the moisture plays an important role in the intensification of the low troposphere northerly flows as well as stratospheric air intrusions and potential vorticity (PV) streamer systems over the southern Europe (Massacand et al., 1998). These processes significantly contribute to the cyclogenetic activity in the region. Additional analyses are required however for a better understanding of the physical mechanisms involved. On the contrary, the high phase years are characterized by a northeasterly airflow in the vicinity of the eastern Mediterranean. The increase in the role of the relatively dry continental air masses during the eastern Mediterranean wet months explains the precipitation decline over the eastern Mediterranean during the positive phase periods. Due to an evident relationship of the eastern Mediterranean synoptic processes with those associated with the development and consequent decay of the Asian–African monsoon (Webster et al., 1998) most of the precipitation of the southeastern Mediterranean region takes place during the cool season. The fact contributes to a noticeable focusing of the analyses on the winter-time processes.

Figure 71 adapted from Xoplaki et al. (2004) presents standardized values of October–March precipitation anomalies over 110 Mediterranean stations for the 1900–1999 (RR 1900) period and the Gibraltar–Iceland NAO (Jones et al., 1997) with reversed sign. For the first half of the twentieth century, RR 1900 indicates the relatively dry early 1900s, early 1920s and 1940s and the wet periods 1910s and 1930s. RR 1900 suggests that the decreasing trend highlighted in Fig. 63 is not part of a centenial trend but a feature of the second half of the twentieth century and that the 1960s and late 1970s were actually the wettest intervals since the 1850s. This reasoning can be supported by the evolution of the large-scale circulation during the twentieth century shown in Fig. 71. The time series labelled as Cs1 (Fig. 71) shows the regressed time series (4-year moving average filter) between the NCAR SLP dataset (Trenberth and Paolino, 1980; 1900 to 1999) and the first canonical pair SLP pattern (presented in Fig. 62). Cs1 and RR 1900 show similar decadal changes since the beginning of the twentieth century (correlation 0.76). The correlation of NAO time series with Cs1 is 0.70, suggesting that the North Atlantic climate variability plays a crucial role in driving long-term trends in the Mediterranean. After (before) 1960, both Cs1 and -NAO show negative (positive) trends supporting the idea that the negative precipitation trends after the 1950s are dynamically induced and a feature of the second half

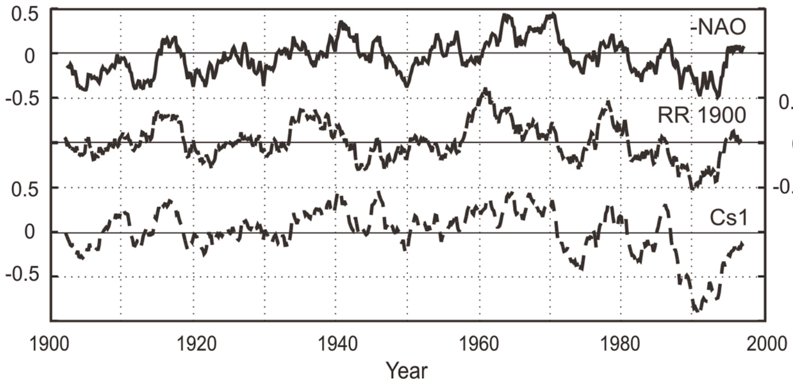

Figure 71: NAO: Gibraltar–Iceland NAO index (Jones et al., 1997) with reversed sign. RR 1900: spatial average over all Mediterranean sites with available data for the period 1900–1999. Cs1: regressed time series (4-years moving average filter) between the NCAR SLP dataset (Trenberth and Paolino, 1980) and the first canonical pair SLP pattern in Fig. 62 (Adapted from Xoplaki et al., 2004).

of the twentieth century. These results suggest that wet season Mediterranean precipitation increased since the second half of the nineteenth century and experienced a downward trend through the second half of the twentieth century (Xoplaki et al., 2004; see also Fig. 62). Further, the NAO index correlates at 0.72 with a large-scale Mediterranean Oscillation pattern during October–March (Dünkeloh and Jacobeit, 2003).

The recently observed trend towards drier Mediterranean winter conditions is linked to particular circulation pattern changes including increased pressure south of 45°N–50°N since the 1970s, a weakening of the central Mediterranean trough since the late 1980s, and a long-term rising trend in the Mediterranean Oscillation pattern (higher pressure in western and central Mediterranean) being connected to the NAO (Dünkeloh and Jacobeit, 2003). Though the NAO mode plays an important role in driving temperature and precipitation trends in the Mediterranean, its influence varies through different time periods. Thus, there are other modes which are of relevance for explaining seasonal sub-Mediterranean climate variability (e.g. Kutiel and Benaroch, 2002; Kutiel et al., 2002; Dünkeloh and Jacobeit, 2003; Xoplaki et al., 2003a,b, 2004; Valero et al., 2004) or indirectly through the effect over sea level pressure patterns (Ribera et al., 2000).

The nature of different rates of rainfall decrease in the east coast of Iberian Peninsula and parts of Italy (Brunetti et al., 2001, 2004) might be related to the observed increasing precipitation intensity, owing to a general enhancement of the hydrological cycle (caused by an increase in surface temperature), and the reduction of the number of wet days which are consistent with the variation of the atmospheric circulation (Brunetti et al., 2002, 2004). Minimum winter extreme temperatures across Peninsular Spain for the period 1955–1998 indicate that most of the extremes occurred under six synoptic patterns. A generalized decreasing trend in the annual frequency of extreme events is detected for most of the studied observatories. Prieto et al. (2004) showed that it is due to a non-linear shift in the annual mean minimum temperatures associated with a generalized warming in the area. An explanatory hypothesis of the differential diurnal warming observed over the western Mediterranean can be found in Fernandez-Garcia and Rasilla (2001). They showed an increase of the geopotential height over the region, particularly intense during the second half of the twentieth century. This was associated with increasing solar radiation, higher maximum temperatures and an intensified radiative loss at night, which have smoothed rising in daily minimum temperatures.

3.6. Other Important Forcing Factors

3.6.1. Tropical and Extratropical SST

The direct influence of tropical climate variability on the Mediterranean region has long been debated and is discussed in Chapter 2 of this book. Here, the focus is on the link between mid-latitude circulation anomalies and tropical climate variability. In recent years, there has been a healthy and unclosed debate on the influence of the indirect effect, via extratropical modes, of El-Niño-Southern Oscillation (ENSO) on climate patterns and precipitation in the Mediterranean region. A number of studies report that ENSO-related winter circulation anomalies in the Atlantic/European sector have a pattern similar to that of the NAO (Ribera et al., 2000; Pozo-Vazquez et al., 2001b; Mathieu et al., 2004). In particular, Pozo-Vazquez et al. (2001b) find that this is true but only for la Niña events. There is still no general agreement on the extent of the ENSO influence in seasonal Mediterranean climate. Some studies suggest that the ENSO influences on the Mediterranean spring and autumn precipitation regime (Mariotti et al., 2002a), while others state that this influence is confined to the eastern Mediterranean in winter (Price et al., 1998). Rodo et al. (1997) instead find the ENSO signature over parts of southern Europe but only in areas where the NAO influence is weaker. However, others find no influence of ENSO on winter rainfall (Quadrelli et al., 2001).

Some studies pointed to the large-scale changes induced by tropical processes and the role they might play in the modulation of either oceanic/atmospheric responses in certain mid-latitude areas. Of particular relevance appear to be the changes induced by the modulation of the local Hadley cell over the

Atlantic and the alteration of the ascending branch of this circulation, which affects the Mediterranean sea and in particular, the southern part. These dynamics have been traced by means of upper tropospheric humidity changes and varying heat fluxes (Fig. 72), as inferred from both cloud cover changes and absorbed solar radiation (Rodó, 2001). Mariotti et al. (2002a, 2005) show an anomalously weaker (stronger) Azores anticyclone in connection with autumn (spring) rainfall anomalies in the Western Mediterranean. How these changes alter the net heat fluxes both in the tropical north Atlantic and the Mediterranean sea (particularly the western basin) and which might be their ultimate effects on Mediterranean climate is the subject of active research and current debate. A cooling of the western Mediterranean Sea appears to take place linked to a sequence of atmosphere–ocean couplings that initiate in the warm tropical Pacific during an El Niño event (Klein et al., 1999; Rodó, 2001).

Several authors have suggested the role played by ocean dynamics (Sutton and Allen, 1997; Rodwell et al., 1999) as potential sources of variability affecting the North Atlantic climate with impacts on the Mediterranean regions. Hoerling et al. (2001) found that observed long-term changes in the NAO during winter since 1950 are recoverable from tropical SST forcing alone. Latif (2001) show some skill in predicting long-term changes in the NAO based on tropical SSTs. Recent numerical experiments by Hoerling et al. (2004) and Hurrell et al. (2004) indicate that tropical SST variations, particularly in tropical Indian and western Pacific Ocean, have significantly controlled recent North Atlantic circulation anomalies.

While the underlying mechanisms behind these tropical–extratropical connection remain to be explained, these studies suggest a potential for predicting changes such as the dryness observed in the Mediterranean region in connection to the trend in the NAO based on tropical SST anomalies. Effects of other tropical systems like, Asian (Indian) Monsoon, African Monsoon, Hurricanes and Saharan dust on the Mediterranean climate were also reported in many studies and are summarized in Chapter 2 of this book.

3.6.2. Solar Variability

Solar variability and troposphere–stratosphere interaction (Perlwitz and Graf, 1995, 2001; Shindell et al., 1999) have been recognized to impact the North Atlantic climate. Solar influence on the Earth's climate is a long-discussed topic and it has produced controversial scientific opinions. In general terms the solar cycle relationship is viewed as just a statistical fluctuation, however the solar–climate relationship could be strongly nonlinear. An example of this nonlinearity is the problem of the spatial structure of the NAO according to the solar cycle.

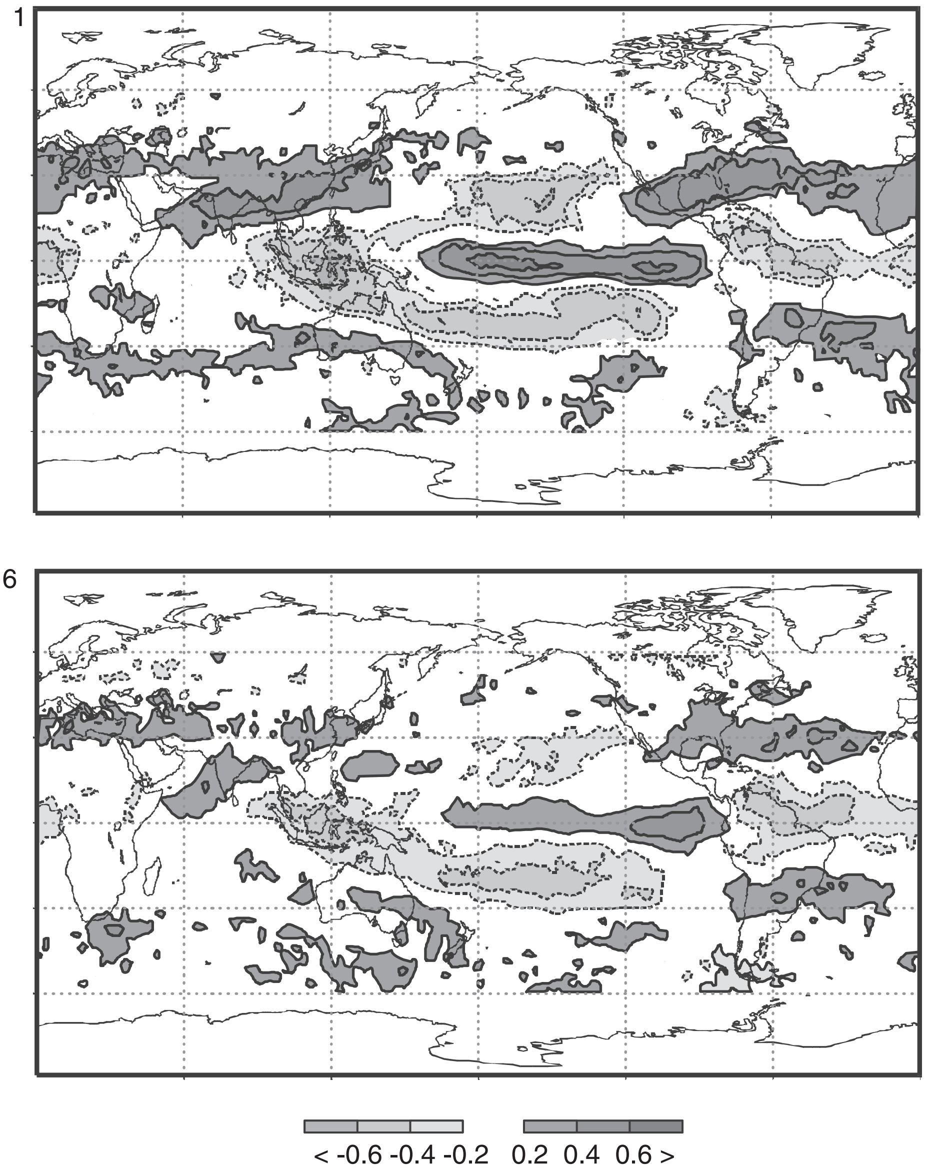

Figure 72: Correlation fields between an ENSO index and Upper-tropospheric humidity, at lags 1 and 6 months. Contoured areas indicate a significance higher than $p < 0.001$. Continuous lines indicate positive values and dotted line refers to negative ones. (Adapted from Rodó, 2001).

Kodera (2002, 2003) demonstrated that the spatial structure of the NAO during the winter is very different during low solar activity (NAO confined in the Atlantic sector) than during high solar activity (hemispherical structure extending into the stratosphere). This difference has important consequences as the modulation of the winter and summer circulation linkage (Ogi et al., 2003) or the modulation of the relationship between NAO and the northern hemisphere surface air temperature (Gimeno et al., 2003). Very recently, Kodera and Kuroda (2005) have proposed a possible mechanism to explain the solar modulation of the spatial structure of the NAO. They suggest that the solar activity influence originates in the stratopause region from a change in the seasonal march of the jet. The leading mode of the interannual variation of the zonal–mean zonal wind in the stratopause region has a meridional dipole-type anomaly structure in high solar activity winters. This structure extends into the troposphere by changes in the meridional propagation of planetary waves giving a hemispherical structure to the NAO. During low solar activity, the downward extension of the zonal–mean zonal wind anomalies is weak, so regional scale variations are dominant in the troposphere and NAO is confined in the Atlantic sector. It has been shown that when the long-term solar activity is high, then the smoothed NAO index is low and vice-versa (Kirov and Georgieva, 2002). Is the strength of the NAO–solar connection sufficiently strong to impact directly the Mediterranean climate? We believe that it is. A recent study on the frequency and magnitude of flood episodes in Iberian rivers over the last millennium shows that periods of high frequency in floods are well associated with periods of high solar activity (Vaquero, 2004).

3.7. Future Outlook

In the twentieth century the Mediterranean was characterized by positive trends of temperature in every season but particularly in winter and summer. However, if one restricts the analysis to the last three or four decades, the positive trend is prominent in the summer (particularly in the west), while areas of negative trend can be observed in spring. On the other hand, the twentieth century precipitation regime was characterized by negative (positive) winter precipitation trends over the eastern (western) Mediterranean regions, while autumn and spring reveal mostly negative trends in Iberia and central Mediterranean regions. Over the last 50 years, there has been a significant decrease of precipitation in winter and spring, with a conspicuous decline of March precipitation throughout the western Mediterranean sector.

The physical processes responsible for these trends and changes seem to be partially of a hemispheric nature (such as external forcings and changes in the large-scale atmospheric circulation) as well as local/regional (such as changes in earth surface and land use). In fact, temperature and precipitation trends over the Mediterranean, during the twentieth century, are shown to be directly linked to changes in phase of some of the major large-scale circulation modes previously mentioned, particularly for NAO and EA/WRUS patterns during the winter season.

It should be stressed that most studies on variability and trends of precipitation over the Mediterranean region and associated atmospheric circulation patterns focus on the winter part of the year. Some of these studies use the standard winter 3 months (DJF), others also incorporate the months of March (e.g. Trigo et al., 2002b, 2004a), some even use the wet season concept between October and March (e.g. Xoplaki et al., 2004). In any case, the highly seasonal behaviour of the precipitation regime is reflected in a bias towards winter on the number of scientific works published. We acknowledge that such bias is also present in this chapter. Studies on trends of temperature cover more evenly the various seasons of the year, with slightly more focus on the two extreme seasons, i.e. summer and winter.

As we have shown in this chapter, considerable research has been carried out produced in recent years linking the most relevant large-scale atmospheric circulation modes with Mediterranean climate variables. In particular, it is now clear that twentieth century trends of precipitation, temperature, cloud cover can be attributed, at least partially, to corresponding trends of well-established circulation patterns. Nevertheless, there are still *grey* areas, and different issues require further analysis in the near future. Here we provide a list of issues that in our view should be dealt explicitly during the next decade:

(1) There are large gaps between datasets for the northern and southern margins of the Mediterranean basin. Therefore, it is necessary to assemble more reliable and consistent climate datasets (both at the daily and monthly scale) over the entire Mediterranean basin. Among other initiatives, it would be particularly helpful to contribute to the production of a high resolution regional reanalyses dataset.

(2) Despite the large amount of work already done on climate trends, we acknowledge that there is still scope for further work. Therefore, it is necessary to confirm the role played by important large-scale modes to explain regional temperature and precipitation variability and trends for different periods and seasons within the instrumental period using sophisticated statistical methods. It is necessary to characterize the climatic impact imposed by these atmospheric circulation modes on a month-by-month basis and to assess precisely where these impacts are significant. Furthermore,

especial attention should be devoted to characterize changes of the annual cycle in Mediterranean temperature and precipitation through the instrumental period.

(3) Climate change scenarios obtained with different General Circulation Models (GCMs) reveal that there is a general agreement towards a significant decrease of precipitation for this region among most GCMs (Folland et al., 2001). In fact, this is the region of the planet that shows a more consistent signal towards a dry future as shown by the analysis of climate model simulations regarding the reproducibility of the main characteristics of the extra tropical modes, including its impact on the precipitation field and cyclonic activity (Osborn et al., 1999; Ulbrich and Christoph, 1999; Trigo and Palutikof, 2001). However, present climate models are still unable to replicate the observed amplitude of the interannual variability and of the multidecadal trends of some modes, e.g. the NAO (Osborn, 2004). Therefore, this work should be continued and intensified with the aim of determining to what extent climate models yield a realistic picture of the variability in the present climate and quantifying, if possible, the amount of expected regional climate change that can be ascribed to future trends in extra tropical modes, since these modes will probably be responsible for regional differences in the future climate.

(4) Trends in the large-scale driving patterns are especially relevant since they may enhance or dampen the warming caused by increasing greenhouse gas concentrations. However, to our knowledge, work has just begun in this direction. Relevant questions in this context are the possible changes of these extra tropical modes under global climate change. The results to date seem to indicate that the so-called Annular Modes – the Arctic Oscillation and the Antarctic Oscillation – to which the NAO is linked will tend to become more intense in the future (Guillet et al., 2000), although the signal-to-noise ratio may be not very large (Zorita and González-Rouco, 2000). In a more regional basis, some work has been reported for the Western Mediterranean (González-Rouco et al., 2000) and the Balkans (Busuioc et al., 1999). These issues are further stressed in Chapter 8 of this book.

(5) Many studies have underlined the role of several teleconnection patterns (NAO, EA/WRUS, EA, EA-Jet, SCAND) over different parts of the Mediterranean basin. However, in general it is not clear whether there are significant differences in the physical mechanisms for the generation and dissipation of these planetary regimes, or whether the only difference lies simply in the geographical location of their centres of action. Furthermore, the underlying physical mechanisms (moisture and enthalpy advection,

cyclogenesis and storm tracks, vertical stability, radiation and cloud cover, oceanic processes etc.) that give rise to these statistical connections are not always completely understood.

This question is three-fold relevant:

- in the context of changes in the intensity of these circulation patterns under global climate change. Only with a sufficient understanding of the physical mechanisms will it be possible to estimate the effect of changes of extra tropical modes on the Mediterranean climate.
- For understanding the variability at decadal time scales (where persistent deviations of atmospheric indices have been observed), and estimate their influence on low-frequency changes in temperature and precipitation, in the frame of other possibly competing effects, such as land use changes.
- Seasonal climate prediction would greatly benefit from research in this direction. A substantial fraction of the climate variability of the Mediterranean basin may be explained in terms of a few planetary flow regimes. Their predictability, though, is not well quantified, and their origin and possible relationship with oceanic process is very uncertain. Possibly, in order to make accurate predictions of variables like precipitation, some kind of downscaling method would be necessary to fill the gap between the large and the regional scales.

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