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The North Atlantic Oscillation and European vegetation dynamics

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ABSTRACT: The relationship between vegetation greenness and the North Atlantic Oscillation (NAO) is assessed over Europe. The study covers the 21-year period from 1982 to 2002 and is based on monthly composites of the Normalised Difference Vegetation Index (NDVI) and Brightness Temperature from the Global Inventory Monitoring and Modelling System (GIMMS) as well as on monthly precipitation from the Global Precipitation Climatology Centre (GPCC).

A systematic analysis is first performed of point correlation fields over the 21-year period between the winter NAO index and spring and summer NDVI, followed by an assessment of the vegetation response to precipitation and temperature conditions in winter, over two contrasting regions, namely the Iberian Peninsula and Northeastern Europe. Finally, the impact of NAO on vegetation dynamics over the two regions is evaluated by studying the corresponding annual cycles of NDVI and comparing their behaviour for years associated with opposite NAO phases.

Over the Iberian Peninsula there is strong evidence that positive (negative) values of winter NAO induce low (high) vegetation activity in the following spring and summer seasons. This feature is mainly associated with the impact of NAO on winter precipitation, together with the strong dependence of spring and summer NDVI on water availability during the previous winter. Northeastern Europe shows a different behaviour, with positive (negative) values of winter NAO inducing high (low) values of NDVI in spring, but low (high) values of NDVI in summer. This behaviour mainly results from the strong impact of NAO on winter temperature, associated with the critical dependence of vegetation growth on the combined effect of warm conditions and water availability during the winter season. Copyright © 2008 Royal Meteorological Society

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1. Introduction

Over the last two decades, continuous monitoring of vegetation from space has prompted new studies aiming to relate observed major global changes in vegetation (e.g. trends, variability and extremes) with changes in surface climatic variables, such as temperature and precipitation (Myneni *et al*., 1997; Hansen *et al*., 1999; Zhou *et al*., 2001). In particular, several groups have shown that the recorded temperature increase in the northern latitudes of 0.8 °C in the last 25 years has been accompanied by a significant reduction in annual snow cover, induced by an earlier spring snowmelt (Groisman *et al*., 1994; Vinnikov *et al*., 1999). A longer active growing season has also been reported, as a result of an early spring start and delayed autumn ending (Bogaert *et al*., 2002; Shabanov *et al*., 2002). This change in the annual phenological cycle is associated with an increase in photosynthetic activity of vegetation (Zhou *et al*., 2001), as detected from observed changes in the Normalised Difference Vegetation Index (NDVI). Although no evidence has been given that such changes in NDVI are related to the positive trend in atmospheric concentration of CO_2 (Kaufmann *et al*., 2002), the global carbon cycle certainly has been affected (Keeling *et al*., 1996).

There is a strong need for long-term, large-scale studies aiming to assess the impact of atmospheric circulation variability on surface climate and related vegetation activity. In this respect special attention has been devoted to investigating relationships between vegetation dynamics and the North Atlantic Oscillation (NAO), which is the major pattern of atmospheric variability in the Northern Hemisphere (Hurrell, 1995). A review of the studies considered as especially relevant to the present work will be given in the next section. A number of them have naturally addressed the question of the relationship between NDVI and meteorological fields, namely temperature and precipitation. Vicente-Serrano and Heredia-Laclaustra (2004) have adopted the

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climatological viewpoint and focused their attention on the Iberian Peninsula where the influence of winter NAO on the precipitation regime is especially prominent in the southwest region (Rodriguez-Puebla *et al.*, 1998). They have shown the existence of a positive trend in annual vegetation productivity where the NAO influence is weaker, in strong contrast to the stable or negative trends that were detected in the areas located in the south of Iberia, where precipitation is mostly determined by NAO. However the authors pointed out the need for further studies, at finer temporal scales, namely at the monthly and seasonal ones.

Stöckli and Vidale (2004) have found that spring plant phenology over Europe is well correlated with the winter NAO index. Their study has focused on several geographical sub-domains of Europe that neither reflect any bio-geographical stratification nor any particular sensitivity to the NAO index. The Mediterranean and, in particular, the Iberian Peninsula was not included in the study because their analysis procedure required a large seasonal amplitude in the phenology. The aim of the present work is to fill the gap between the assessment made by land cover experts and by researchers that have looked at the problem from a climatological viewpoint. We will search for relationships between NAO and vegetation activity at the month and seasonal levels over Europe and look for regions where such activity presents a clear dependence on NAO both in spring and summer. We will then investigate how such dependence may be explained in terms of the impact of NAO on relevant surface climate variables, namely temperature and precipitation. We will pay special attention to the Iberian Peninsula and Northeastern Europe because of the distinctive vegetation response to precipitation and temperature. Finally, we will identify, which of the variables have a determinant role on vegetation activity of different regions and make an assessment on the role played by the variables in the annual cycle of vegetation activity.

Accordingly, the main goals of our work are the following:

1. To study the relation between vegetation phenology and NAO over Europe.
2. To characterise the vegetation response to precipitation and temperature in two contrasting areas of Europe, respectively Northeastern Europe and the Iberian Peninsula.
3. To assess the impact of NAO on the vegetative cycle in the two areas, and relate it to the different land cover types and their response to surface climate variability.

2. Rationale

NAO has been known for more than 80 years (Walker, 1924), but it was only in the 1970s that its prime importance as an atmospheric circulation mode of the Northern Hemisphere was recognized and became a subject of wide interest (e.g. van Loon and Rogers, 1978; Rogers, 1984; Barnston and Livezey, 1987). More recently, the work by Hurrell (1995) had a significant impact on the climatological community and was followed by an increasing number of studies, several of them pointing out the existence of links between the NAO index and the winter season precipitation in Western Europe and, in particular, over the Mediterranean basin (Hurrell, 1995; Qian *et al.*, 2000; Trigo *et al.*, 2002, 2004). The control exerted by NAO on the precipitation field over Europe is likely to be related to changes in the activity of North Atlantic storm tracks (Serreze *et al.*, 1997; Trigo, 2006), and the relationship between NAO and precipitation has been used in long-range forecasting models for Iberia (e.g. Gámiz-Fortis *et al.*, 2002; Rodríguez-Fonseca and Castro, 2002). The strong NAO-precipitation link is also likely to have an impact on vegetation greenness (Buermann *et al.*, 2003). In this respect, the use of NDVI to characterise vegetation activity is especially appropriate in the framework of climatological studies, because of the current availability of long-term datasets (>20 years, at present).

The NDVI was designed to capture the contrast between red and near-infrared reflection of solar radiation by vegetation, and is an indicator of the amount of green leaf area (Asrar *et al.*, 1984; Myneni *et al.*, 1995). Despite its simplicity, NDVI has been widely used in studies of vegetation phenology and interannual variability of vegetation greenness. Different authors have looked for relationships between global and regional NDVI and meteorological fields, pointing out the existence of time lags, namely with precipitation (Di *et al.*, 1994; Buermann *et al.*, 2003; Lotsch *et al.*, 2003) and temperature (Buermann *et al.*, 2003; Wang *et al.*, 2003; Julien *et al.*, 2006).

Relationships between NAO and diverse aspects of European vegetation dynamics have been addressed by various authors. D'Odorico *et al.* (2002) showed that spring phenology in the British Isles is influenced by NAO. Dates of leaf unfolding for a mean of nine plant species vary over a 40-day range, from approximately the spring equinox to the end of April. The Julian date of leaf unfolding is inversely correlated with the NAO phase, i.e. leaf unfolding occurs earlier under positive, and later under negative phases of NAO. Similar patterns are reported for Poland, Norway and Sardinia. D'Odorico *et al.* (2002) also found a strong NAO influence on the timing of the pollen season in Europe.

Cook *et al.* (2004) modelled the NAO-dependence of phenological variability in Europe, mediated by the NAO influence on synoptic scale winter temperature variability, and successfully reproduced observed patterns of growing degree-days over Europe. A projection of NAO trends 50 years into the future, based on climate change scenarios, indicated a sustained advance of the growing season start.

Stöckli and Vidale (2004) used advanced very high resolution radiometers (AVHRR) Pathfinder NDVI data, and found that spring phenology correlates well with anomalies in winter temperature and winter NAO index. They established the existence of trends towards an earlier onset and longer duration of the spring vegetation growing period, especially significant over Central Europe.

Vicente-Serrano and Heredia-Laclaustra (2004) analysed the relationship between the NAO index and vegetation productivity (represented by the annual integral of monthly AVHRR Pathfinder NDVI values) trends, for the Iberia Peninsula. Areas of stable or decreasing vegetation productivity were located in southern Iberia, where the NAO influence is stronger. Significant positive productivity trends occur in the north of the Peninsula, where the NAO influence on vegetation dynamics is weaker.

The present study relies on AVHRR NDVI data from the Global Inventory Modeling and Mapping Studies (GIMMS, http://gimms.gsfc.nasa.gov/) group (Brown *et al.*, 2006), which incorporate more thorough and accurate corrections of orbital drift, radiometric degradation, and volcanic aerosol effects than those previously applied to the Pathfinder AVHRR Land (PAL) product, used in earlier works.

3. Data

As pointed out in the introduction, we will look for relations involving large-scale atmospheric variability, vegetation greenness and surface climate. Accordingly, the main sources of information consist of time-series of the NAO index, NDVI and, for surface climate, precipitation (P) and brightness temperature (T), which may be taken as a proxy for land surface temperature.

The NAO index used in this study is based on the one developed by the Climatic Research Unit (University of East Anglia, UK), which was originally defined, on a monthly basis, as the difference between the normalized surface pressure at Gibraltar, in the southern tip of the Iberian Peninsula and Stykkisholmur, in Iceland (Jones *et al.*, 1997). For each year covering the 21-year long period from 1982 to 2002, we have derived a late winter NAO index, defined as the average of the monthly values of January, February and March of the corresponding year. From now on, we will use the term NAO to refer to the three-monthly averaged index and any averaged quantity over January, February and March will be also identified by the subscript NAO (e.g. P_{NAO} and T_{NAO}). The original time-series of winter monthly values of the NAO index presents a positive trend over the last 30 years. Therefore its distribution is dominated by positive values, leading to late winter averages above zero (Jones *et al.*, 1997). Accordingly, we have normalized the derived time-series of NAO indices over the 21-year period (Figure 1) and therefore our three-monthly averages have zero mean and unit standard deviation between 1982 and 2002. We have also identified two classes of years, characterised by extreme NAO indices, respectively above the 3rd and below the 1st quartiles. These two classes, respectively denoted by NAO^+ and NAO^-, are represented, by open and black circles in Figure 1. It may be noted that the NAO^+ years concentrate in the period from 1989 to 1995, a feature of NAO that shows periodic non-stationary oscillations that may give rise to periods of several years of persistence of the NAO in one of its extreme phases (Pozo-Vazquez *et al.*, 2001).

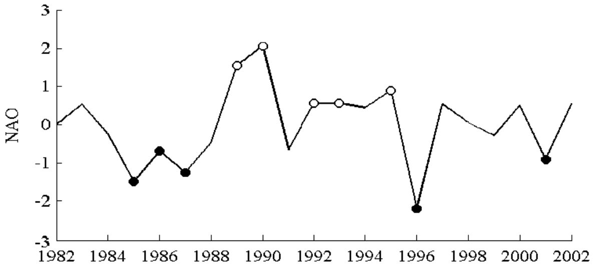

Figure 1. Interannual variability of normalized late winter NAO index over the 21-year long period (1982 to 2002). Open (black) circles indicate years characterised by NAO indices above (below) the 3rd (1st) quartile.

We also used monthly values of NDVI and channel 4 brightness temperature, at 8-km resolution, from the AVHRR, as provided by GIMMS group (Brown *et al.*, 2006). The pre-processing of satellite data involved cloud screening and calibration for sensor degradation and inter-sensor variations (Los, 1998). In particular, the data from April 1982 to December 1984 and from June 1991 to December 1993 were corrected to remove the effects of stratospheric aerosol from El Chichon and Mount Pinatubo eruptions (Tanré *et al.*, 1992). Further details on the quality of the AVHRR dataset may be found in Kaufmann *et al.* (2000) and Zhou *et al.* (2001). Selected data are defined on a window covering the Eurasian and North Atlantic regions, from 23 °W to 27 °E and from 35 °N to 75 °N (Figure 2). Finally, we used monthly precipitation data from the Global Precipitation Climatology Centre (GPCC) (Rudolf and Schneider, 2005). Selected data are defined on a 0.5° latitude by 0.5° longitude grid and cover the same period and window as the satellite data.

For each grid point, we computed spring and summer values of NDVI, T and P, respectively defined as the average of March, April and May and of June, July and August. Spring and summer values of a given quantity will be respectively denoted by the subscripts SPR and SUM. For instance, Figure 2 presents the spatial distribution of the temporal averages of $NDVI_{SPR}$ (left panel) and $NDVI_{SUM}$ (right panel) for the considered period (1982–2002).

4. Results

4.1. NAO and vegetation greenness

Figure 3 displays the spatial patterns, over the selected European window, of point correlation values of NAO *versus* $NDVI_{SPR}$ and NAO *versus* $NDVI_{SUM}$ for the 21-year period. Results show a positive correlation region over Central Europe for spring (left panel), the highest

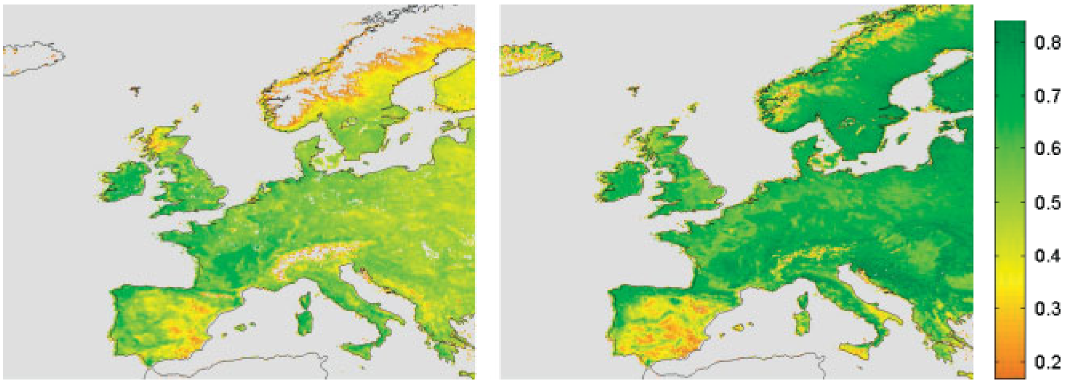

Figure 2. Temporal averages of $NDVI_{SPR}$ (left panel) and $NDVI_{SUM}$ (right panel) for the period from 1982 to 2002 over the selected area covering Eurasia and the North Atlantic.

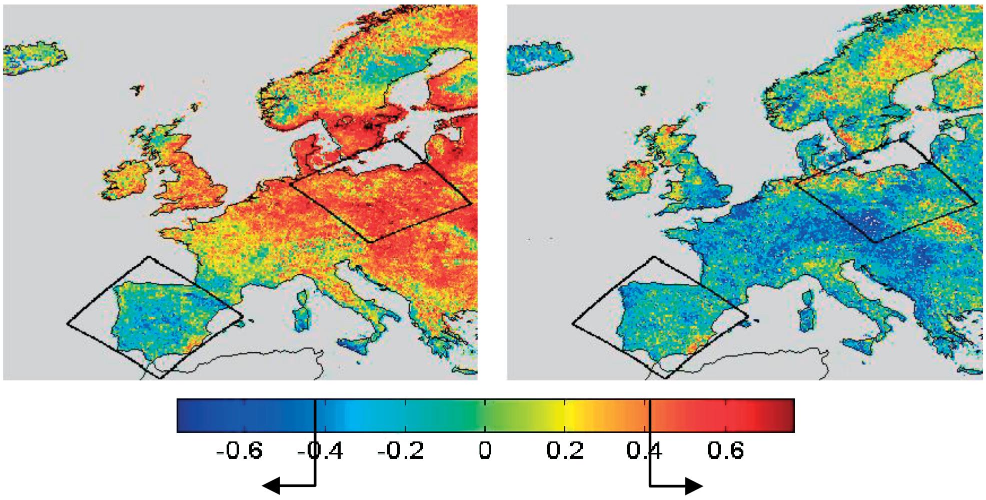

Figure 3. Point correlation fields of NAO *versus* $NDVI_{SPR}$ (left panel) and NAO *versus* $NDVI_{SUM}$ (right panel) over the period from 1982 to 2002. Black frames identify the Northeastern Europe and the Iberian Peninsula. The colorbar shows values of correlation and the two arrows indicate the ranges that are significant at the 5% level.

values (between 0.6 and 0.8) spreading around the north-eastern region. The largest negative correlation regions are located over the Iberian Peninsula and Iceland, some values reaching as low as −0.8. It may be noted that obtained patterns are consistent with the recent findings by other authors, at both the global (Buermann *et al.*, 2003) and the regional (e.g. Vicente-Serrano and Heredia-Laclaustra, 2004) scales. However, we have based our analysis on a much finer spatial resolution than Buermann *et al.* (2003) and, despite the overall consistency, some differences do exist, namely the higher values of correlation that we obtained over the north-eastern sector.

In the case of summer (Figure 3, right panel), the correlation field presents negative values over almost all Central-Eastern Europe. This pattern is also consistent with the finding of Buermann *et al.* (2003), but their maximum core is located towards the northern Black Sea area, whereas ours is confined to the upper Danube region.

The contrasting behaviour of north-eastern and south-western regions of Europe is worth being further investigated. For this purpose we have selected two regions, namely Northeastern Europe (hereafter NE) and the Iberian Peninsula (hereafter IB). These two regions are identified by black frames in Figure 3 and it may be noted that selection was made in such a way to obtain an amount of land pixels of the same order in the two regions, respectively 9639 over NE and 9080 over IB. Both NE and IB show fairly coherent values of correlation of NAO *versus* NDVI for both spring and summer. It is also apparent that over IB, NAO is anti-correlated with vegetation greenness both in spring and summer, whereas over NE the correlation is positive in spring and predominantly negative in summer. During spring, the distribution of correlation values over NE presents a median value about 0.5, whereas the distribution over IB has a median of −0.2 and spans a wide range of negative values, reaching as low as −0.7. During summer, both areas exhibit distributions with similar medians about −0.2, but the lower dispersion is now observed over IB.

The distinctive behaviour of the Iberian Peninsula and Northeastern Europe is to be expected and reflects, on the one hand, the different response of the annual variability of meteorological parameters of the two areas to large-scale atmospheric variability associated to the NAO mode; on the other hand, it reflects the different responses of vegetation to atmospheric variability, in particular changes induced by temperature and precipitation in the annual cycle of heat and moisture. For instance in the case of wheat that is grown in both regions, water is the main limiting factor for growth in IB (Gouveia and Trigo, 2008), whereas it is temperature that limits its growth in NE. The following section will be devoted to characterising the influence of the NAO mode over two atmospheric parameters relevant to vegetation activity, namely surface temperature and precipitation. The analysis will focus on the Iberian Peninsula and Northeastern Europe and the different roles played by temperature and precipitation in the two sub-areas will be emphasized. This section is followed by a final one dedicated to the analysis of the annual cycles of the main land cover types over the two areas and of their different responses to the NAO mode of atmospheric variability.

It may be noted at this point that climate conditions are not the only factor that acts on vegetation dynamics; the nature and quality of the plant substrate, the over-use of agriculture land and the employment of irrigation are important factors linked to the human influence that may disturb the relationship between atmospheric parameters and vegetation activity. With the aim of isolating the effect of natural atmospheric variability, as represented by the NAO, on vegetation dynamics from factors related to the human influence, we have compared the NDVI fields over IB and NE for two years associated to extreme NAO indices. Figure 4 shows a comparison of $NDVI_{SPR}$ for the two chosen years, i.e. 1986 (NAO^-) and 1995 (NAO^+). In the case of IB, anomalies of $NDVI_{SPR}$ present well-defined quasi-meridional dipoles of opposite signs in 1986 (upper left panel) and 1995 (middle left panel). The southern anomaly centre is particularly intense, positive (negative) anomalies being observed in spring 1986 (1995). The dipolar structure is especially apparent when differences are computed between 1995 and 1986 (lower left panel). In the case of NE (right panels) large patterns of negative (positive) anomalies of $NDVI_{SPR}$ may be observed in 1986 (1995). Observed anomalies are particularly intense in 1986 (NAO^-) and this feature is well apparent when

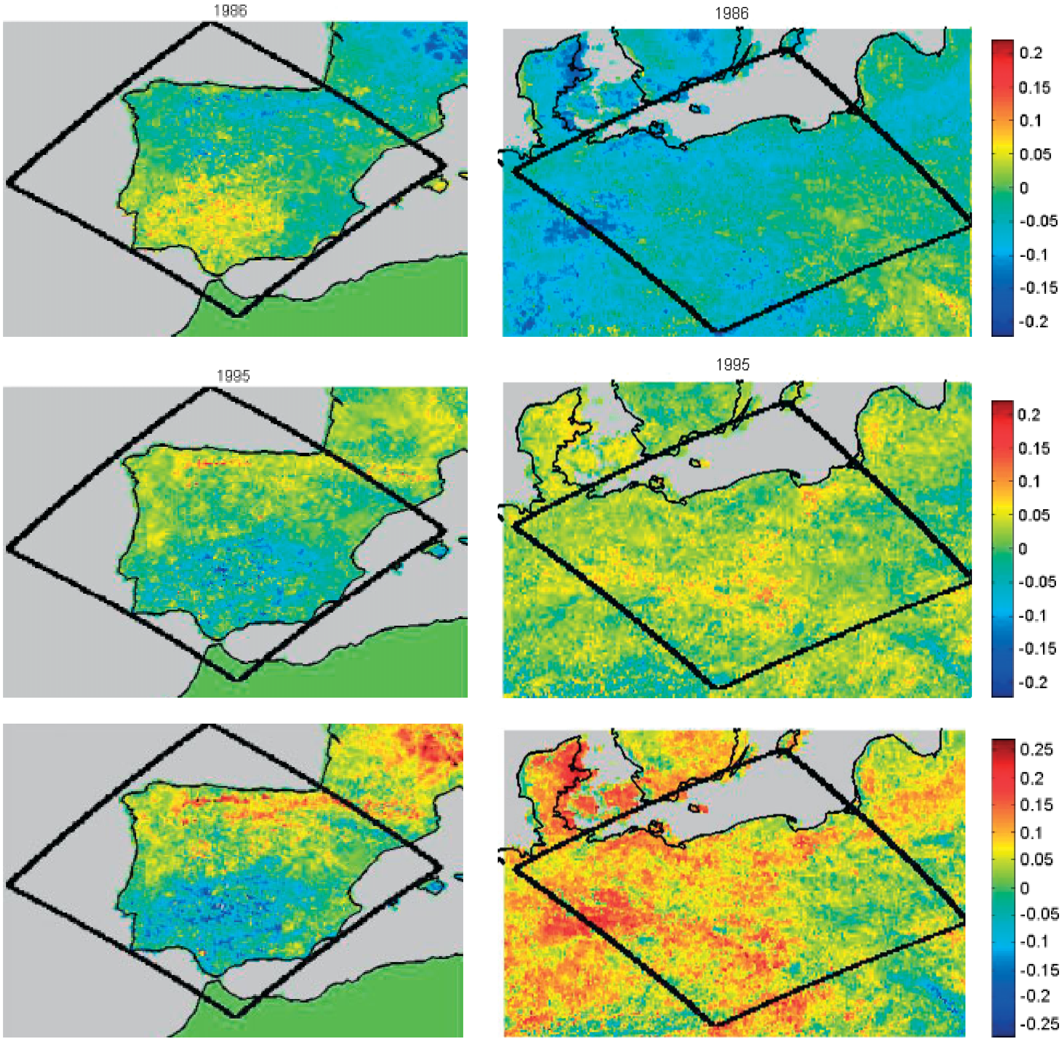

Figure 4. Seasonal anomalies of $NDVI_{SPR}$ for 1986 (NAO^+), 1995 (NAO^-) and differences between 1995 and 1986 (upper, middle and lower panels, respectively) for the IB and NE regions (left and right panels respectively).

analysing differences between 1995 and 1986 (lower right panel).

4.2. NAO and annual variability of atmospheric parameters

Figure 5 shows spatial patterns over the selected European window of point correlation fields between the NAO index and the contemporaneous late winter means of surface temperature and precipitation, i.e. NAO *versus* T_{NAO} and NAO *versus* P_{NAO}. Obtained patterns display the well known response to the NAO signal, of temperature and precipitation over Europe (Hurrell, 1995; Trigo *et al*., 2002). In the case of temperature, a region of positive values over Central and Eastern Europe is well apparent (Trigo *et al*., 2002). Albeit less intense, negative values of correlation may also be identified over the Iberian Peninsula. For precipitation, a well-developed meridional dipolar structure is conspicuous over Europe, delimiting two well-defined zonal bands of positive and negative correlation values, which spread over Northern Europe and along the Mediterranean regions, respectively. These results are in good agreement with those obtained by several authors (e.g. Saénz *et al*., 2001; Castro-Díez *et al*., 2002) who have pointed out that the connection between NAO and Iberian temperature is not as clear-cut as in the case of precipitation. Finally, the intense east–west precipitation gradients observed in southern Norway/Sweden as well as over Ireland and England is worth being point out. These strong precipitation gradients over such short distances are associated with the mountain ranges located in the western sector of these three regions and highlight the lee effect.

Although it is known that the impact of NAO on temperature and precipitation described above is especially prominent in winter (e.g. Trigo *et al*., 2004; Vicente-Serrano and Heredia-Laclaustra, 2004), such behaviour contrasts with that obtained for vegetation activity (Figure 3), where the impact of NAO is clearly apparent both in spring and summer (i.e. NAO *versus* $NDVI_{SPR}$ and NAO *versus* $NDVI_{SUM}$). This gives a strong indication that special attention must be devoted to the relationship between late winter temperature and late winter precipitation, with vegetation greenness in the following spring and summer seasons.

Since we are particularly interested in pixels characterised by the strong influence of NAO on vegetation activity, we will restrict our analysis to IB and NE (as identified in Figure 3), and will focus on those pixels that exhibit the highest (lowest) values of positive (negative) correlations of $NDVI_{SPR}$ and $NDVI_{SUM}$ with NAO. Henceforth, they will be called North Atlantic oscillation high correlation pixels (NHCP).

As pointed out in the previous section, vegetation greenness over the Iberian Peninsula is negatively correlated with NAO, both in spring and summer. Accordingly, we selected, for each one of the two seasons, the 500 highest NHCP. In the case of NE, NHCP were predominantly correlated with NDVI in spring and anti-correlated in summer. Therefore we selected the 500 pixels with the highest (lowest) values of positive (negative) correlation in spring (summer). Figures 6 and 7 show the geographical distribution of the NHCP for spring and summer, respectively over IB and NE. Information about the land cover type associated to each pixel is also provided, as obtained from the Global Land Cover 2000 (GLC2000) database (http://www-gvm.jrc.it/glc2000). Table I shows descriptive statistics of the NHCP associated with the two most common types of vegetation namely in what respects to the distribution of NDVI anomalies for two classes of years, characterised by extreme NAO indices, i.e. the NAO^+ and NAO^-, as described in Section 3. NDVI anomalies in a given pixel are defined as differences from the respective 21-year mean (1982–2002) and the two considered classes of years. For each area and season the statistical distributions of NDVI anomaly values for the two classes of years (NAO^+ and NAO^-) and the two types of vegetation cover are characterised by means of the respective

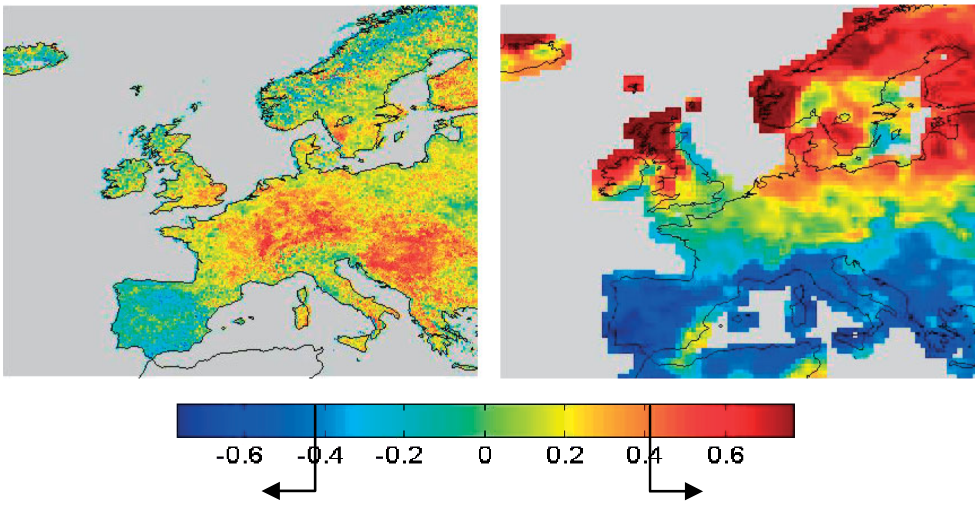

Figure 5. Point correlation fields of NAO *versus* T_{NAO} (left panel) and NAO *versus* P_{NAO} (right panel) over the period from 1982 to 2002. The colorbar shows values of correlation and the two arrows indicate the ranges that are significant at 5% level.

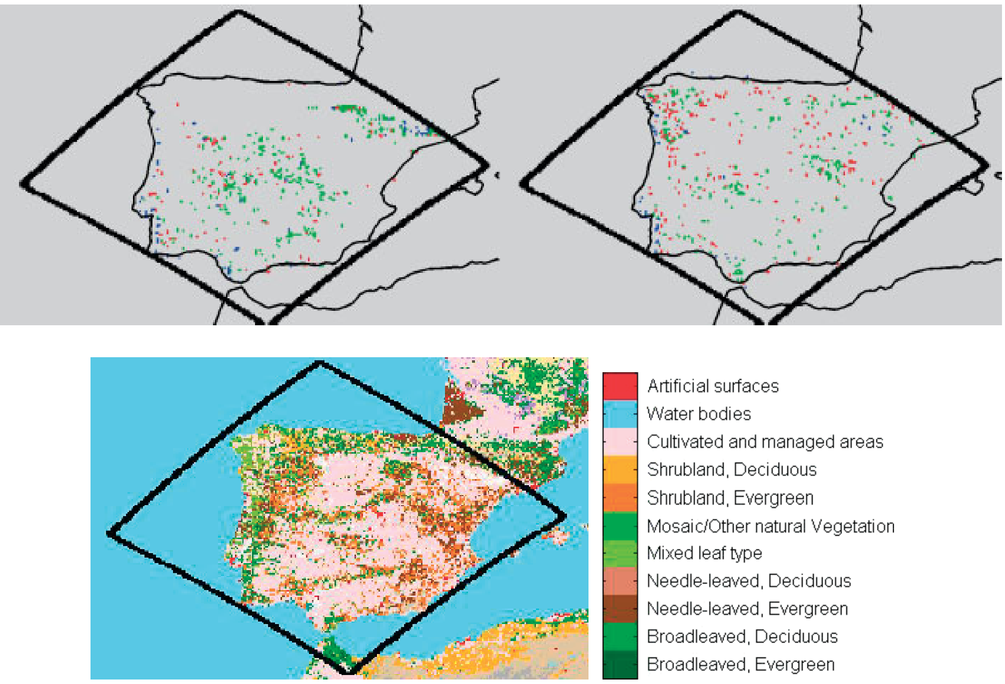

Figure 6. Geographical distribution of NAO High Correlation Pixels (NHCP) sets of selected pixels over IB based on the strong values of correlation of $NDVI_{SPR}$ (left panels) and $NDVI_{SUM}$ (right panels) with NAO. Red, green and blue pixels are respectively associated to forest and shrubland, cultivated areas and other types of vegetation cover. Bottom panel shows the GLC2000 classification for Iberia.

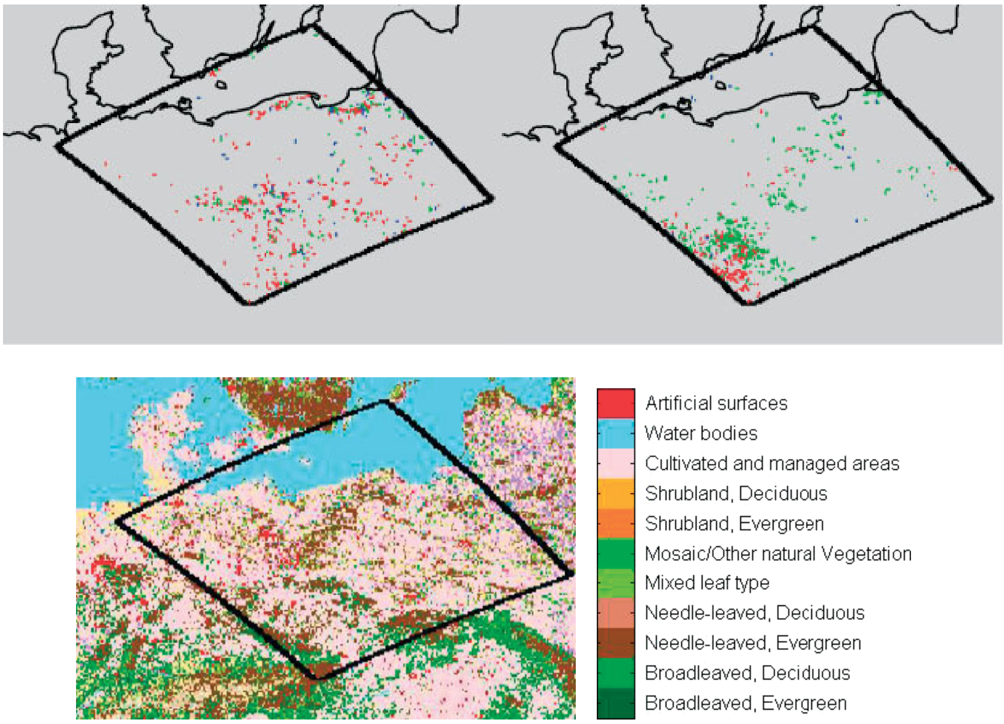

Figure 7. As in Figure 6 but respecting to NHCP over NE. Red, green and blue pixels are respectively associated to needle-leaved, evergreen, cultivated and other types of vegetation cover.

median (Q2), first and third quartiles (Q1 and Q3), and percentiles 1 and 99 (P1 and P99).

As expected, there are marked differences in the obtained distributions of NDVI anomalies for NAO^{+} and NAO^{-} classes for a given type of vegetation, in a given season, over a given region. For instance, it is worth noting that there is no class overlap when restricting to median values between P1 and P99. This feature was taken into account in Figures 8 and 9, where a given year is characterised by its median value.

Differences in the distribution of types of vegetation are also conspicuous for the two regions and the two seasons. In the case of the Iberian Peninsula, almost two thirds (64%) of the NHCP correspond to areas

Table I. Descriptive statistics of the distributions of NDVI anomalies for NAO High Correlation Pixels (NHCP) associated to the two most important vegetation types as found in the cases of spring and summer over IB and NE. P1, Q1, Q2, Q3 and P99 respectively denote percentile one, the first quartile, the median, the third quartile and percentile 99. Percent figures in parenthesis below the types of vegetation indicate the fraction of pixels of the considered NHCP associated to that type.

IB

Spring

	Forest and shrubland (17%)[a]					Cultivated (64%)				
	P1	Q1	Q2	Q3	P99	P1	Q1	Q2	Q3	P99
NAO^{+}	−0.049	−0.030	−0.021	−0.013	0.002	−0.080	−0.041	−0.031	−0.022	−0.004
NAO^{-}	0.004	0.015	0.024	0.033	0.066	0.003	0.019	0.027	0.038	0.071

Summer

	Forest and shrubland (29%)[b]					Cultivated (47%)				
	P1	Q1	Q2	Q3	P99	P1	Q1	Q2	Q3	P99
NAO^{+}	−0.053	−0.031	−0.023	−0.017	0.005	−0.066	−0.036	−0.026	−0.014	0.000
NAO^{-}	−0.001	0.011	0.016	0.022	0.039	0.003	0.012	0.018	0.025	0.054

NE

Spring

	Needle-leaved Evergreen (47%)[c]					Cultivated (25%)				
	P1	Q1	Q2	Q3	P99	P1	Q1	Q2	Q3	P99
NAO^{+}	0.011	0.027	0.033	0.041	0.071	0.009	0.026	0.033	0.044	0.060
NAO^{-}	−0.084	−0.054	−0.043	−0.035	−0.014	−0.072	−0.055	−0.045	−0.037	−0.010

Summer

	Needle-leaved Evergreen (27%)[d]					Cultivated (63%)				
	P1	Q1	Q2	Q3	P99	P1	Q1	Q2	Q3	P99
NAO^{+}	−0.059	−0.037	−0.028	−0.021	−0.008	−0.068	−0.039	−0.030	−0.022	−0.005
NAO^{-}	0.006	0.020	0.025	0.032	0.056	0.009	0.022	0.027	0.034	0.052

[a] Includes 14% of needle-leaved evergreen, 26% of broadleaved deciduous and 60% of Shrubland.

[b] Includes 31% of needle-leaved evergreen, 25% of broadleaved deciduous and 44% of Shrubland.

[c] Includes 12% of needle-leaved evergreen and 88% de broadleaved deciduous.

[d] Includes 35% of needle-leaved evergreen and 65% de broadleaved deciduous.

of spring crops and about one sixth (17%) are forests and shrublands. The relative proportion of the two types undergoes a significant change in summer, when a strong decrease may be observed in the difference between the fraction of NHCP belonging to the two types (29% to forest and shrubland, and 47% to cultivated areas). In the case of NE, there is a dramatic change from spring to summer between the distributions of NHCP of the two types of vegetation; the predominance in spring of forest and shrubland (62%) over cultivated areas (25%) gives way, during the summer, to a predominance of NHCP representing agricultural crops (63%), over those representing forests and shrublands (27%).

The above results may be viewed in terms of the distinct responses of the various vegetation types to moisture and heat conditions prevailing during the previous winter. These conditions, in turn, are determined by the nature of the relationships between the surface annual variability of atmospheric parameters, P_{NAO} and T_{NAO}, and the different phases (NAO^{+} and NAO^{-}) of the NAO atmospheric mode. Figures 8 and 9 show scatterplots, for IB and NE, respectively, of spring and summer anomalies of vegetation greenness against winter anomalies of temperature and precipitation. Each dot represents a pair of median values of a given set of selected 500 NHCP, for a given year of the considered period (1982–2002), of winter anomalies of P_{NAO} (left panels) and T_{NAO} (right panels) *versus* anomalies of $NDVI_{SPR}$ (upper panels) and $NDVI_{SUM}$ (lower panels). Years belonging to the subset of NAO^{+} (NAO^{-}) are marked in dark (light) grey and the variability of the NHCP is characterised by means of horizontal and vertical bars indicating the respective interquartile ranges.

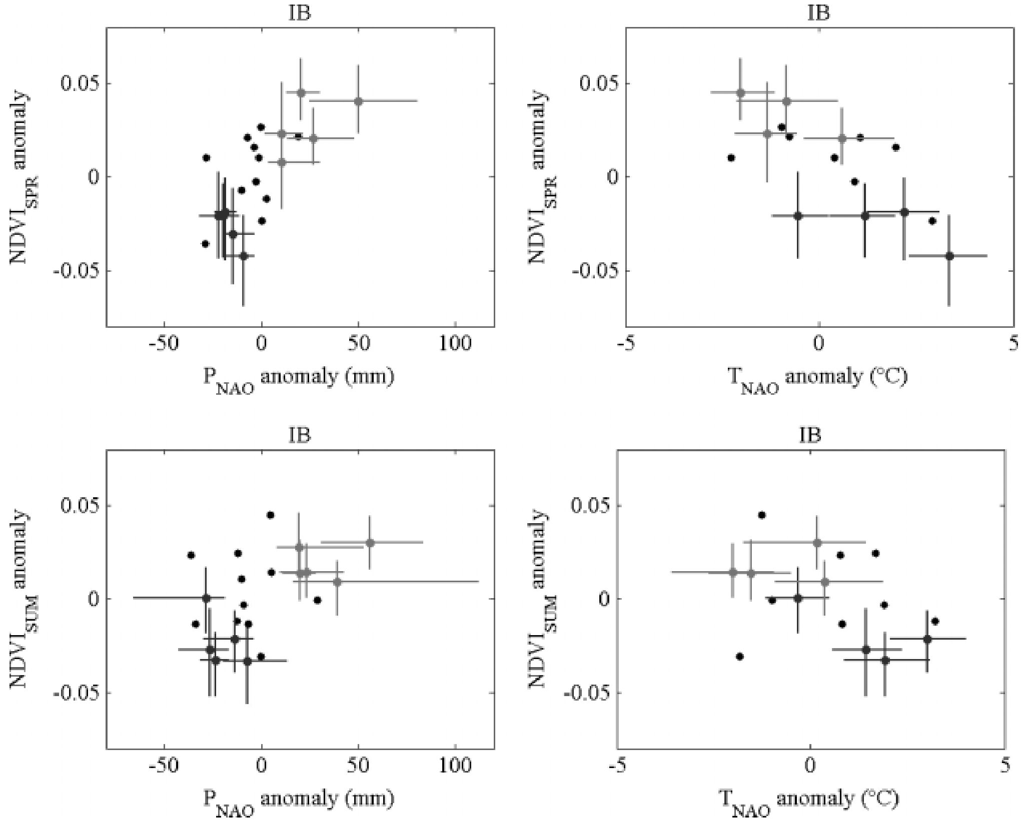

Figure 8. Dispersion diagrams of $NDVI_{SPR}$ (upper panels) and $NDVI_{SUM}$ (lower panels) *versus* P_{NAO} (left panels) and T_{NAO} (right panels) for NAO High Correlation Pixels (NHCP) over IB. Each dot represents a pair of median values of a given set of selected 500 pixels, for a given year of the considered period (1982–2002). Years that belong to the subset of NAO^+ (NAO^-) are marked in dark (light) grey and the respective variability is characterised by means of horizontal and vertical bars indicating the interquartile ranges.

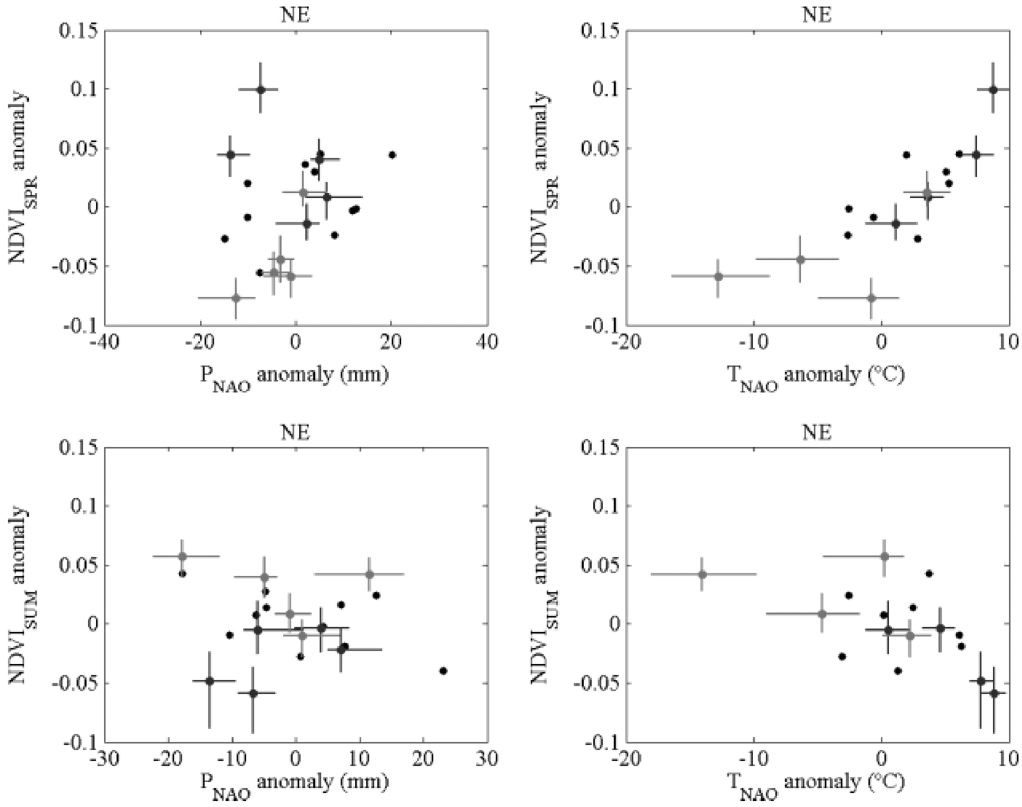

Figure 9. As in Figure 8, but respecting to NE.

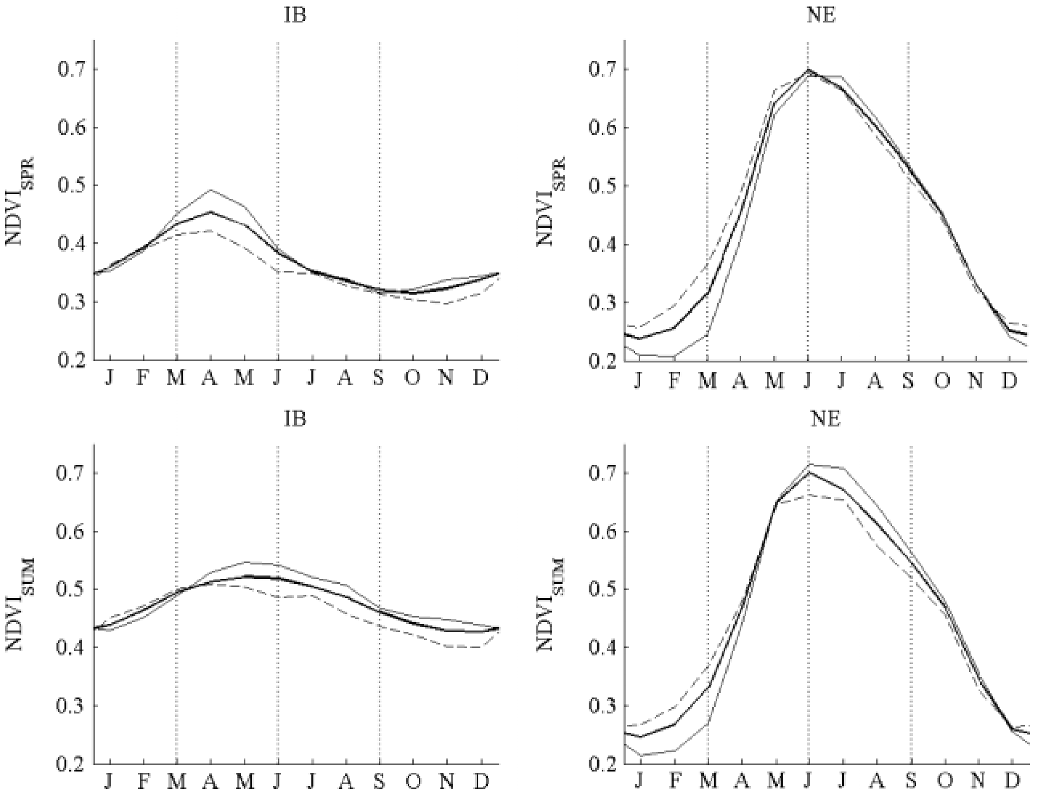

Figure 10. Annual cycles of monthly values of NDVI for NAO High Correlation Pixels (NHCP), for spring (upper panel) and summer (lower panel), over IB (left panel) and NE (right panel). The annual cycles of average NDVI values for the entire period (1982–2002) are represented by thick solid lines, whereas the annual cycles of averages for the NAO^- (NAO^+) subsets are identified by the thin solid (dashed) curves. Vertical dashed curves delimit the season of the year.

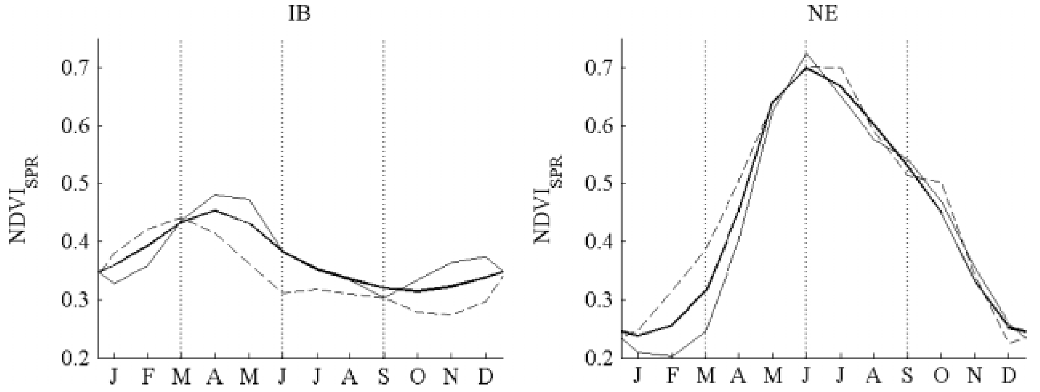

Figure 11. As in Figure 10, but restricting to the annual cycles of NDVI for the individual years of 1986 (NAO^-) and 1995 (NAO^+), respectively represented by the dashed and the solid lines.

The Iberian Peninsula (Figure 8) shows a similar spring and summer vegetation response to precipitation in (left panels), i.e. an increase (decrease) of vegetation greenness for NAO^- (NAO^+) years. In both seasons there is less variability of precipitation in the set of NAO^+ NHCP, in comparison with NAO^-, especially in the spring. A slight dependence of vegetation greenness on temperature is also apparent in the case of spring, with $NVDI_{SPR}$ median values showing a tendency to decrease from NAO^- to NAO^+. It may be noted that the obtained stronger dependence of vegetation on precipitation than on temperature is consistent with the already pointed out fact that over the Iberian Peninsula the influence of NAO is particularly strong on the precipitation regime, whereas the relationship between NAO and temperature is less clear. In the case of NE (Figure 9) there is a marked dependence of vegetation greenness on winter temperature, but the nature of such dependence is reversed from spring to summer. In the first case, $NDVI_{SPR}$ shows a strong increase from NAO^- to NAO^+, whereas a sharp decrease is observed for summer. The lower variability of temperature in the set NHCP for NAO^+ is again evident, when compared with the corresponding set for NAO^-. Concerning winter precipitation, no effects are apparent on vegetation greenness for both spring and summer. Finally, the differences in magnitude of the impacts of NAO on precipitation and temperature in IB and NE is worth being emphasised; the impact on precipitation (temperature) is three times larger over IB (NE) than the corresponding impact over NE (IB), a feature that is in good agreement with the found dependences of NDVI on precipitation (temperature) over IB (NE). This is to be expected, since vegetation growth is much more water-limited in IB than in NE.

4.3. The NAO role on the vegetative cycle

The striking differences that were obtained in the response of vegetation to moisture and heat conditions and to anomalies in P_{NAO} and T_{NAO} associated to the NAO atmospheric mode, warrant further analysis of the NDVI annual cycle for the NHCP over IB and NE. Figure 10 shows the annual cycles of NDVI monthly values for the NHCP, for spring (upper panels) and summer (lower panels), over IB (left panels) and NE (right panels). The annual cycles of mean NDVI for the entire period (1982–2002) are represented by thick solid lines, whereas the annual cycles of averages for the NAO^- (NAO^+) subsets are identified by the thin solid (dashed) curves.

In the case of IB, the most interesting feature for both spring and summer (Figure 10, left panels) is that the highest impact of NAO is observed to occur during the periods of the year characterised by more intense vegetation activity (Ji and Peters, 2003), i.e. around April (June) in the case of the NHCP for spring (summer). During spring, two thirds of the NHCP (Table I) correspond to cultivated areas that mainly consist of crops adapted to the relatively dry Iberian conditions. Owing to the generally observed high temperatures, vegetation has a short growth cycle that starts as soon as water is available, a situation that is especially favoured by NAO^- This is especially apparent in Figure 11 (left panel) where the annual cycles of NDVI are compared for the years of 1986 (NAO^-) and 1995 (NAO^+) that were chosen because of being associated to extreme NAO indices. In the case of summer, the vegetation that is most affected by NAO initiates its growing period late in the year and therefore the response to precipitation tends to extend late in the year.

In the case of NE (Figure 10, right panels), the annual cycles present characteristics that are very different from those observed over IB. The impact of NAO is especially conspicuous during the first months of the year, suggesting that green vegetation growth tends to occur early and intensively, due to the combined effect of warm conditions, especially of the former, since water availability is seldom a problem in NE. This contrast in the response of vegetation during the early months is also well apparent in Figure 11 (right panel) where the years of 1986 (NAO^-) and 1995 (NAO^+) are compared. The distinct behaviour of vegetation in spring (Figure 10, upper panel) and summer (lower panel) is also worth pointing out. In the case of the spring, the NAO impact is almost negligible, whereas in the case of the summer the growth of vegetation is enhanced under NAO^- conditions. This is to be expected, since snow melt is expected to occur later in the year, due to the lower winter temperature. Accordingly, vegetation growth will be reduced in spring, getting delayed until summer, when solar radiation availability increases (Blenckner and Hillebrand, 2002; Menzel, 2003; Wang and You, 2004).

5. Conclusions

We analysed the relationship between the NAO atmospheric mode and vegetation activity (NDVI) over the two contrasting regions of Iberia and Northeastern Europe. As expected the behaviour of vegetation reflects the different response of surface climate to large-scale atmospheric variability associated to the NAO mode. A systematic analysis was performed over two contrasting regions of Europe, namely IB and NE. Over IB there is strong evidence that positive (negative) values of winter NAO induce low (high) vegetation activity in the following spring and summer seasons. This feature is mainly associated with the impact of NAO on winter precipitation, together with the strong dependence of spring and summer NDVI on contemporary water availability. NE shows a different behaviour, with positive (negative) values of winter NAO inducing high (low) values of NDVI in spring, but low (high) values of NDVI in summer. This behaviour mainly results from the strong impact of NAO on winter temperature associated with the critical dependence of vegetation growth on the combined effect of warm conditions and water availability during the winter season. (D'Odorico *et al.*, 2002).

In both spring and summer NHCP over the Iberian Peninsula there is less precipitation variability under NAO^+ than under NAO^-, especially in spring. This feature may be associated with the strong impact of climate variability in semi-arid areas, namely regarding effects of drought conditions on vegetation activity (Vicente-Serrano and Heredia-Laclaustra, 2004), in particular during the intense spring vegetation growth period. A weak dependence of vegetation greenness on temperature is also visible in spring, with median values of spring NVDI tending to decrease from NAO^- to NAO^+ conditions. In the case of NHCP over NE there is a marked dependence of vegetation greenness on winter temperature, but the nature of such dependence is reversed from spring to summer. In spring there is a strong increase of NDVI from NAO^- to NAO^+, whereas a sharp decrease is observed for summer. Again the lower variability of temperature in the set of NHCP for NAO^+, when compared with the corresponding one for NAO^-, is evident.

Finally, the NAO impact on vegetation dynamics over the two regions was evaluated by studying the corresponding annual cycles of NDVI and comparing their behaviour for years associated with opposite NAO phases. In Iberia, the NAO impact is greater on non-forest vegetation, which responds rapidly to spatio-temporal variations in precipitation and soil moisture. During the summer, forests and other dense vegetation areas display the highest sensitivity to NAO dynamics. This vegetation shows slower response to precipitation, and the NAO impacts are delayed until late in the year. Over NE, the NAO impact is especially apparent during the first months of the year, suggesting that green vegetation growth tends to occur early and intensely in NAO$^+$ years due to the relatively warmer conditions associated to the absence of ice cover and early melting. NAO has a strong effect on temperature which, in turn, impacts vegetation activity. The latter impact is well depicted when comparing monthly values of NDVI for the first months of the year, under NAO$^+$ and NAO$^-$ (Figure 10).

The magnitude of the NAO-precipitation relationship in Iberia has been well documented in the literature over the last decade (e.g. Rodó *et al.*, 1997; Trigo *et al.*, 2002, 2004). However, only recently have such connections started to be taken into account when developing precipitation forecast models and predicting precipitation over the Iberian Peninsula with several months in advance (e.g. Gámiz-Fortis *et al.*, 2002; Rodríguez-Fonseca and Castro, 2002). It is highly desirable that such models are implemented at the operational level because of their capacity of providing important seasonal forecasting information to be used by water resources and agricultural managers. However, it should be stressed that our lagged relationships between winter NAO and NDVI values for spring and summer already represent an added value since they allow formulating, by the end of March, simple outlooks of vegetation greenness for certain land cover types over the European region that may provide useful information in a wide range of application encompassing; crop forecasts, long-lead wildfire risk assessment and early warning for public health issues, such as pollen-induced allergies.

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