Using 21 years of AVHRR data to assess the impact of the North Atlantic Oscillation on European vegetation dynamics

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ABSTRACT - *We have performed a study to assess the relation between satellite-based measures of vegetation greenness and the North Atlantic Oscillation (NAO) over the European region. We have used the 8-km-monthly NDVI and Brightness Temperature (BT) data set retrieved between 1982 and 2002 from the AVHRR instrument. The relationship between vegetation activity and the NAO index were assessed using the Vegetation and Temperature Condition Indices (VCI and TCI) and also the Vegetation Health Index (VHI), proposed by Kogan (Kogan, 1996; 2001). Atmospheric circulation and climatic impacts were assessed by computing maps of correlation coefficient between NAO and six different climatic variables. It is widely accepted that the NAO controls the winter precipitation over the western Mediterranean Sea. Therefore, it seems natural to include an explicit precipitation index when analysing the impacts of the NAO mode on vegetation greenness. It was found that positive (negative) values of* NAO_{JFM} *induce low (high) vegetation activity in the following spring and summer season in the Iberian Peninsula. This fact is associated with the immediate impact of winter NAO in winter precipitation.*

1 INTRODUCTION

The continuous monitoring of vegetation with multiple satellite platforms encouraged new studies to interpret major changes in vegetation as being conditioned by corresponding changes of surface climatic variables, such as temperature, precipitation and snow cover.
Relatively simple vegetation indices, such as NDVI, have been widely used in studies of vegetation phenology and interannual variability. In recent years, different authors have studied the relationship between NDVI and meteorological fields showing the existence of some lag in these relationships, namely with precipitation (Buermann et al., 2003) and temperature (Julien et al., 2006). Moreover, if we normalise NDVI for each individual pixel and for each month then we can compare NDVI values for areas with significant different statistical moments. To implement this idea Kogan (1997) proposed an NDVI and Brightness Temperature (BT) normalization procedure. This author has defined three related vegetation indices; a) the Temperature Condition Index (TCI), b) the Vegetation Condition Index (VCI) and c) the Vegetation Health Index (VHI). These indices have been used recently to investigate the possibility of assessing and monitoring droughts (Kogan, 2001, Kogan et al., 2004).
The North Atlantic Oscillation (NAO) has been recognized for more than 70 years as one of the major patterns of atmospheric variability in the Northern Hemisphere (Walker, 1924). It is within this context, that several studies have established links between the NAO index and winter season precipitation in Western Europe and, in particular, over the Mediterranean basin (e.g. Trigo et al., 2004).
The main objectives of this work are the following:
a) To study the relation between satellite-based indices of vegetation greenness (TCI, VCI and VHI) and the NAO over the European region.
b) To show the sequence of intermediate relevant physical mechanisms responsible for the NAO-induced vegetation changes.
c) To analyse the distinct vegetation response to precipitation and temperature influence between north-eastern Europe and Iberian Peninsula.

2 DATA AND METHODS

2.1 Spectral Indices

We have used the monthly NDVI and BT data set, at 8-km resolution, from the Advanced Very High Resolution Radiometers (AVHRR), provided by the Global Inventory Monitoring and Modelling

System (GIMMS) group. The data for Eurasian and North Atlantic regions (30º W to 60º E and 30º N to 75º N) and covers the 21-year long period from 1982 to 2002. Further details on the quality of the AVHRR dataset can be found in Kaufmann et al. (2000).

As mentioned previously, Kogan (1997) has promoted the use of additional indices in order to describe more comprehensively the vegetation activity over a given area. The TCI is based on the thermal band (channel 4) of the AVHRR and is used to assess temperature-related vegetation stress:

$$TCI = 100*(BT_{MAX} - BT)/(BT_{MAX} - BT_{MIN}) \tag{1}$$

where BT, BT_{MAX} and BT_{MIN} are respectively the monthly, maximum and minimum absolute brightness temperature respecting to the entire period for each pixel and month.

The VCI quantifies the vegetation greenness component and is defined as:

$$VCI = 100*(NDVI - NDVI_{MIN})/(NDVI_{MAX} - NDVI_{MIN}) \tag{2}$$

where NDVI, $NDVI_{MAX}$ and $NDVI_{MIN}$ are respectively the monthly, maximum and minimum absolute NDVI for the entire period for each pixel and month.

Note that TCI and VCI could assume values between 0 and 100, corresponding to variations from stressed to favourable vegetation conditions. Finally, VHI is defined as a combination between the two previous indices:

$$VHI = (VCI + TCI)/2 \tag{3}$$

These three indices were firstly defined on a weekly basis, in order to assess vegetation stress associated with drought events. However, in the present work we propose monthly and seasonal composites of these indices, as this corresponds more closely to the temporal step that is commonly used in NAO studies.

2.2 Large scale climatic data

All meteorological data used in this study are large-scale gridded data retrieved from the National Center for Environmental Prediction (NCEP/NCAR) reanalysis data sets, for the period 1982-2002. Monthly values of precipitation rate, seasonal temperature, net long wave radiation and soil moisture were extracted from NCEP 2.5º latitude by 2.5º longitude grid, with the same window as the satellite data.

Taking into account the poor capability of NCEP/NCAR reanalysis to reproduce accurately the precipitation field over Europe, we have opted to use monthly gridded precipitation data (resolutions 0.5°) from the Global Precipitation Climatology Centre (GPCC). This dataset will be used to derive a Precipitation Index (hereafter PI). Taking into account the definition of TCI (Eq. 1) the PI is defined as:

$$PI = 100*(P_{MAX} - P)/(P_{MAX} - P_{MIN}) \tag{4}$$

where P, P_{MAX} and P_{MIN} are respectively the monthly, maximum and minimum absolute precipitation for the entire period for each pixel and month.

2.3 North Atlantic Oscillation (NAO)

The NAO index used in this study was developed by the Climatic Research Unit (University of East Anglia, UK) and is defined, on a monthly basis, as the difference between the normalized surface pressure at Gibraltar (southern tip of Iberian Peninsula) and Stykkisholmur in Iceland. The NAO index for winter months presents a positive trend over the last 30 years. Therefore its distribution is dominated by positive values, with monthly averages above zero (Jones et al., 1997). Consequently we decided to normalize the entire NAO index on a seasonal basis, having zero mean and one standard deviation. This normalization procedure was based on the computation of seasonal averages and standard deviation between 1982 and 2002.

2.4 Methodology

Monthly and seasonal composites (for the standard seasons: winter (JFM), spring (MAM) and summer (JJA) were computed for all the spectral indices mentioned before (VCI, TCI and VHI) and atmospheric variables. We computed a grid point correlation between seasonal composites of the different variables (VAR) and winter NAO composite (JFM), for the 21 year study period, using contemporaneous (non lagged) and lagged values (with NAO index leading by several months).

In order to estimate the statistical significance for the correlations values, we assume that each season represents an independent event within a Gaussian distribution. For the 21 year study period the corresponding 5% (1%) significance level corresponds to a correlation coefficient of R=0.43 (R=0.55), based on a two tailed t-test statistic, considering 19 degrees of freedom.

3 RESULTS

3.1 NAO and spectral indices

Spatial patterns of simple correlation between the NAO index and the spectral indices were performed over the European continent (Fig. 1). Due the considerable amount of missing values found in Northern Europe in winter, the combinations for this season were removed from further analyses.

Results obtained for NAO-VCI analyses show (Fig. 1a) positive correlation values over Central Europe for spring vegetation (NAO_{JFM}-VAR_{MAM}) with the highest positive values (between 0.6 and 0.8) being observed around the Baltic countries and near the Black Sea. The corresponding largest negative correlations are located over the Iberian Peninsula, Iceland and Russian Federation, with some values being as low as –0.8. Patterns observed for spring VCI are similar to those recently obtained by other authors (with NDVI) on a global scale (e.g. Buermann et al., 2003).

For summer vegetation (NAO_{JFM}-VAR_{JJA}) the analysis shows negative correlations values over Central-Eastern Europe, with the highest positive correlation (~0.6) located north of the Caspian Sea.

The correlation pattern between the NAO_{JFM} index and VHI for spring reveals a similar picture to that obtained between NAO and VCI. However, the latter is characterised by less significant negative correlations over Southern Europe but stronger positive values over central and Eastern Europe. On the contrary, the summer VHI shows higher negative (positive) correlation pattern in Central Europe (Caspian Sea) between NAO_{JFM} and VHI_{JJA}, when compared with the corresponding pattern between NAO_{JFM} and VCI_{JJA}. Taking into account the definition of VHI as a simple average between VCI and TCI, it is understandable that the differences between NAO-VCI and NAO-VHI correlation patterns can be partially evaluated through the analyses of the corresponding NAO-TCI patterns. In particular, it is possible to attribute regions of intensification (attenuation) when we move from the NAO-VCI to the NAO-VHI analyses to the areas where the NAO-TCI correlation present the same (opposite) signal. Iberian Peninsula provides a good example of the intensification, while the Iceland clearly represents a case of attenuation.

Patterns of correlation between the NAO index and these three spectral indices should be analysed carefully, as causal links may not be obvious. We believe that these patterns reflect the strong influence exerted by the NAO circulation mode over relevant climatic variables, particularly in what concerns temperature, precipitation and radiation. VHI presents a strong dependence between NDVI and land surface temperature, where increasing land temperatures will act negatively on vegetation status and consequently origin stress.

3.2 The impact of NAO on climatic variables

Here we compute correlation patterns between seasonal averages of the NAO index and corresponding averages of climatic fields. In Fig. 2 we show results for surface temperature (a), net longwave radiation (b), hereafter called radiation related variables, and precipitation rate (c), soil moisture (d), hereafter called water related variables.

Generally speaking, these figures show a dipolar pattern with maximum positive (negative) correlation values located over Northern Europe (Southern Europe and North Africa) during the winter season.

The results demonstrate the dominant influence of the NAO_{JFM} on surface variables that are key parameters for vegetation growth. The correlation patterns between the NAO_{JFM} index and VCI (and VHI) are consistent with the patterns between the NAO_{JFM} index and relevant meteorological fields. The NAO-VCI patterns are spatially more coherent in spring, when positive NAO_{JFM} induces warm temperatures and highest net long wave radiation in Eurasia are linked to enhanced greenness. Therefore, in areas where the correlation values between VCI and NAO_{JFM} are higher (e.g. Baltic Countries and Sweden) correspond to regions where the influence of the NAO_{JFM} pattern in "water-related" variables is not so relevant. In contrast, positive NAO_{JFM} is linked to the decline of greenness in Central Europe during the summer, as shown in Fig. 1.

The most intense influence of NAO_{JFM} index on meteorological variables occurs in the winter composite. These facts lead us to investigate hereafter, the impact of winter variables with direct impact in vegetation (like precipitation and temperature), on the vegetation composites for the following spring and summer seasons.

3.3 Regionalising NAO-VCI interdependence

With the aim of regionalising the impact of NAO_{JFM} on vegetation status we have looked in more detail over three pre-defined areas, namely over Central and Northern Europe and Iberian Peninsula, (hereafter Baltic, Russia and Iberia). These sub-areas were chosen based on their fairly coherent values of NAO-VCI correlation patterns revealed before (Fig.1). Box plots of NAO_{JFM}-VCI correlation values for each region, in spring and summer are shown in Fig 4 and 5. Positive NAO_{JFM} composite has a positive impact on spring vegetation greenness for both European regions, with median values in the order of 0.5. On the contrary, the influence of NAO_{JFM} on Iberian vegetation status is predominantly negative, with median value in the order of -0.2, but presenting the largest range of values, reaching correlation values of -0.7. For summer, positive NAO_{JFM} values have a negative impact for all the three selected regions (with median values around -0.2), with higher dispersion over Russia and lower dispersion in the Iberian Peninsula.

3.4 The role of precipitation

It is widely accepted that the NAO controls the winter precipitation over the western Mediterranean Sea, an influence that was well depicted here in Figs. 2. Therefore, it seems natural that we include an explicit precipitation index when analysing the impacts of the NAO mode on vegetation greenness. In order to investigate the influence of precipitation on VCI, we used a new Precipitation Index (PI) as shown in section 2.2. Therefore, we have also computed the correlation patterns between seasonal averages of the NAO index and corresponding precipitation composites obtained from the GPCC (Fig 3). It should be noted that the range of the PI varies between 0 (when monthly precipitation equals the maximum) and 100% (when monthly precipitation equals the minimum). Thus, to facilitate the analysis of the correlations, the subsequent comparison with Fig 3 and the scatter plots of Figs. 4 and 5(section 3.5) we decided to represent satellite derived temperature (100-TCI) and precipitation (100-PI), instead of TCI and PI.

3.5 Interdependence between TCI, PCI and VCI

Scatter plots of the relation between TCI and VCI and between PI and VCI values for each area and season are shown in Figs. 4 and 5 for spring and summer respectively. We are particularly interested in pixels with a strong NAO_{JFM} influence on vegetation physiological status. Therefore, we have only represented the pixels with NAO_{JFM}-VCI correlation (Fig. 1) which are corresponding to correlation values higher than the 95th percentile (whenever the selected box presents positive correlation values) or lower than the 5th percentile (whenever the selected box presents negative correlation values). In these figures, pixels in each area were also split in two classes depending on their NAO_{JFM} index values being higher than percentile 75th (red) and lower than percentile 25th (blue), hereafter high NAO and low NAO composites respectively. It should be stressed that throughout these analyses the TCI and PI values were used for winter composites, due the strongest impact of NAO_{JFM} index on the corresponding precipitation and temperature (Fig. 3).

In spring (Fig. 4) and for the European boxes, the years with high NAO_{JFM} values are mostly associated to high vegetation activity and a massively negative high winter temperature and median winter precipitation values, while low NAO_{JFM} values have a negative impact on vegetation greenness, due to the low winter precipitation values. Also in spring but for the Iberian Peninsula it is possible to verify an almost opposite behaviour, with high NAO_{JFM} corresponding to low photosynthetic activity, driven by low winter precipitation and high winter temperature values. On the other hand, for years with low NAO_{JFM}, the vast majority of pixels correspond to high vegetation activity, associated with fairly average values of both winter precipitation and temperature fields.

In the summer (Fig. 5) for the northern European regions, pixels associated with low vegetation activity correspond to seasons with high NAO_{JFM} index values, high winter temperatures and median winter precipitation values, while those associated with high photosynthetic activity correspond to seasons with low NAO_{JFM}, and mostly with low temperature and precipitation values. The impact o NAO_{JFM} on summer vegetation activity in the Iberian Peninsula is very similar to the one previously described for spring (Fig. 4). However, that is not the case for the two northern European areas.

In summary, it is possible to assume that for the northern European boxes there is an obvious dependence of spring and summer VCI on winter temperature and a less obvious dependence on winter precipitation. It should be noted also the distinct impact of NAO_{JFM} on spring or summer vegetation, for these northern European boxes. This inversion is not observed for the Iberian Peninsula box, where the dependence of temperature for spring and summer vegetation activity is small, while the role of precipitation over Iberia is much clearer.

4 CONCLUSIONS

A significant influence of the NAO on the vegetation in the European region was confirmed, but with a great deal of spatial variability, associated with the distinct impact of NAO on the spatial patterns of different meteorological fields. In general, these spatial patterns present a dipolar structure at the European scale, resembling the NAO_{JFM}-precipitation and -temperature spatial patterns previously identified (Trigo et al., 2002). For winter patterns, the areas having highest sensitivity are the Iberian Peninsula, the Northern British Isles, Scandinavia and the Baltic Sea area. For spring patterns, the areas of highest sensitivity are the Baltic Sea area and Central Europe. For the remaining seasons, correlations are weaker and display a less structured spatial pattern, but the Baltic and Black Sea areas, the Iberian Peninsula and Central Europe still displays significant correlations.

During the springtime period, critical for vegetation growth, spatiotemporal structures in hemispheric scale vegetation activity are highly correlated with overlying patterns of surface temperature and potential evaporation rate. The results indicate that hemispheric-scale upper-air circulation patterns associated with NAO_{JFM} are partly responsible for the correlation between year-to-year changes in spring greenness in the northern Europe. During the positive phase of NAO_{JFM}, warmer and greener spring conditions prevail in Eurasia.

In conclusion high (low) values of NAO_{JFM} induce low (high) vegetation activity in the following spring and summer season in Iberia. This impact is associated with the immediate impact of NAO_{JFM} in winter precipitation and relatively insensitivity to winter temperature. The impact of the NAO_{JFM} on the Northern Europe vegetation activity is not so linear, with high NAO_{JFM} inducing high VCI values in spring, resulting from high temperature and low precipitation values for the winter season. On the other hand low NAO_{JFM} could induce high VCI values in summer, if winter temperature is low and winter precipitation was enough in way to have soil moisture and consequently vegetation activity in summer.

For Northern Europe boxes, high NAO_{JFM} values are corresponding to years characterised by soft winters, with more precipitation and more clouds and early melting. In these conditions the maximum of greenness occurs early and intensively, due the high temperature and water availability. However in summer the impact of the NAO_{JFM} index will be negative, because the growth of green vegetation already occurred previously. The growth of green vegetation in the summer occurs only in years of low NAO_{JFM} index and it is only possible, although the low lower values of precipitation, because the melting occurs later and has more radiation availability. For the Iberian Peninsula the maximum of photosynthetic activity occurs in the late spring for the years of low NAO_{JFM}, due the high precipitation values in winter.

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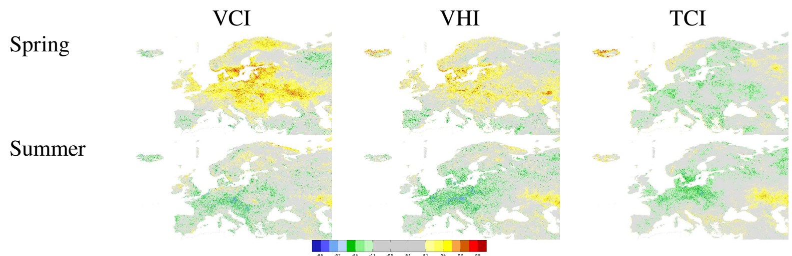

Figure 1. Simple correlation between three months composite of NAO and VCI, VHI and TCI, for spring and summer.

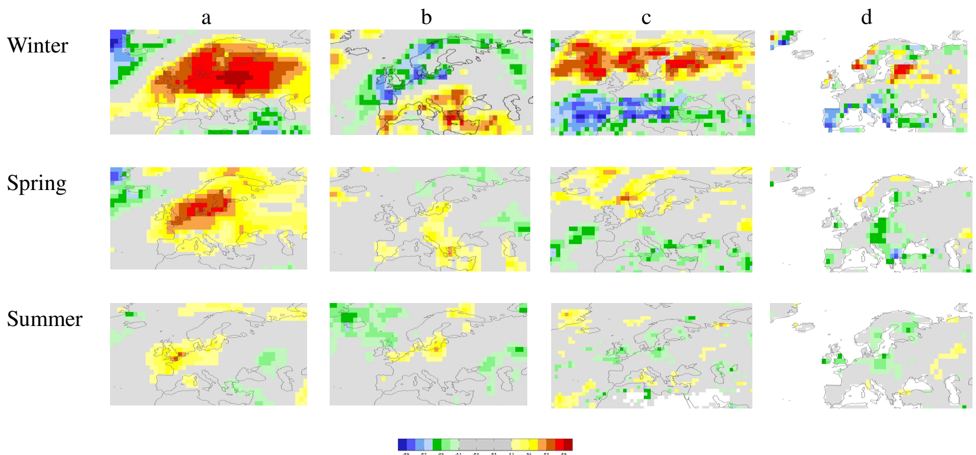

Figure 2. Patterns of simple correlation between three months composite for combinations winter, spring, and summer of NAO and a) seasonal temperature; b) net long wave radiation; c) precipitation rate; d) soil moisture.

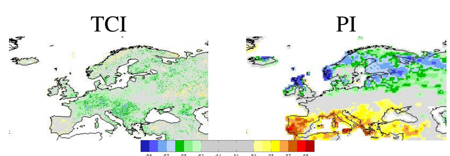

Figure 3. Simple correlation between three month averages of NAO-TCI and -PI, for winter.

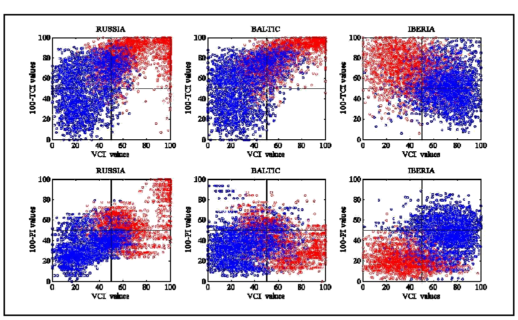

Figure 4. Spring scatter plots, showing the pixels with NAO-VCI correlation larger/smaller than more/less percentile $95^{th}/5^{th}$ of correlation values. Pixels that correspond to NAO larger/smaller than percentile $75^{th}/25^{th}$ are represented in red/blue.

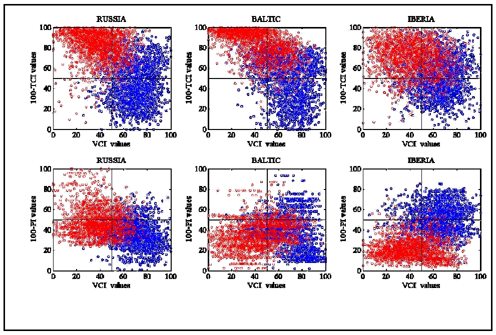

Figure 5. Same of figure 4, bur for summer.