El Niño–Southern Oscillation influences on the interannual variability of leaf appearance dates in central Siberia

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[1] This paper analyses the role of the El Niño–Southern Oscillation (ENSO) on the interannual variability of the leaf appearance dates of boreal forests in the Northern Hemisphere (1982–2004). We find significant negative correlations between the ENSO, quantified by means of the Southern Oscillation Index (SOI), and the leaf appearance dates in central Siberia with up to 9 months lag. The correlations between leaf appearance dates and summer Sea Surface Temperatures (SST) show a pattern that resembles the ENSO phenomena with positive and significant correlations in the East Pacific and negative in the West. These findings are explained by the role of SOI on Sea Level Pressures, 500 hPa Geopotential and the wind flow direction and intensity during the months of leaf appearance (April and May) and on average temperatures, which determine noticeably the date of leaf appearance.

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1. Introduction

[2] Phenology is an important parameter for environmental processes. Deciduous plant phenology, taken as the timing of foliage appearance and senescence, influences the annual carbon uptake by vegetation as photosynthesis requires the presence of leaves. CO₂ fluxes measurements show that differences in phenology explains 83% of the variance of the annual uptake of forests located at ten sites [Baldocchi *et al.*, 2001]. One day change in phenology is said to modify the annual CO₂ exchanges by 5.7 g C m⁻² on average and the net ecosystem productivity by 1.6% [White *et al.*, 1999]. Phenology appears so to belong to a feedback loop including atmospheric CO₂ concentration, temperature and ecosystem carbon uptake.

[3] Therefore, it is very important to understand the factors affecting the interannual variability of leaf appearance at global scale. Various studies provided evidence about the important role of atmospheric circulation on plant phenology in Europe [i.e., Aasa *et al.*, 2004]. Nevertheless, these studies do not cover large geographic regions and, at present, the influence of the most important atmospheric

circulation patterns at global and hemispheric scale is still unknown. El Niño–Southern Oscillation (ENSO) is one of the main sources of climatic variability at global scale [Trenberth, 1997]. ENSO affects the climate of large areas [Ropelewski and Halpert, 1987], but also the ecosystems and interannual variability of vegetation activity. Different studies have shown the ENSO effects on the Normalized Difference Vegetation Index (NDVI), obtained from remote sensing data [i.e., Kogan, 2000]. These studies were focused on the analysis of the role of ENSO on vegetation activity, and they showed that large regions of the southern Hemisphere have significant differences as a function of El Niño and La Niña years.

[4] Nevertheless, although remote sensing data have been used to analyse the ENSO impacts on the vegetation activity, the role of ENSO on the plant phenology has not been yet addressed.

[5] In this paper we analyse the role of the main source of atmospheric circulation variability at global scale, the ENSO phenomenon, on leaf appearance timing of boreal forested areas, which are key-regions for global change processes.

2. Methodology

2.1. Leaf Appearance Date Estimation From Remotely Sensed Data

[6] Remote sensing satellite data have often been used to provide estimates of phenological dates [i.e., Zhang *et al.*, 2004], and to study phenological interannual variations [Myneni *et al.*, 1997]. However different methods gave significantly different results [Schwartz *et al.*, 2002], and it is difficult relating the remote sensing estimate to a particular phenological status. In boreal regions, one additional problem arises from the presence of snow: the NDVI, commonly used to derive phenology, is also affected by snowmelt and consequently, the observed phenological variations may be partially related to snowmelt date variations [Dye and Tucker, 2003].

[7] A methodology to overcome this problem and provide accurate estimates of spring phenological date in boreal regions is described by Delbart *et al.* [2005a]. For the years 1998–2004, the phenological date is calculated using the Normalised Difference Water Index (NDWI) from SPOT-VEGETATION (VGT). This index has the advantage of separating the phenology from the snowmelt signal. An increase in the NDWI, built from a combination of near and middle infrared bands, can be uniquely attributed to the leaf appearance.

[8] The methodology used to measure phenology before 1998 relies on the fact that both SPOT-VGT data and Pathfinder AVHRR Land (PAL) data [James and Kalluri,

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Figure 1. Spatial distribution of correlations between the leaf appearance dates and the Southern Oscillation index of (a) the previous summer (Jun, Jul, Aug), (b) autumn (Sep, Oct, Nov), and (c) winter (Dec, Jan, Feb).

1994] are available in 1998–2001. For each pixel and each year (1998–2001, except 1999), the NDVI value from the PAL dataset at the leaf appearance date derived using SPOT-VGT is recorded. Then, the three NDVI values are averaged to give a threshold value specific to each pixel. For the period 1982–1997 (and 1999), the date of onset of greening is taken as the date at which the PAL NDVI value equals the threshold (see details in the work of *Delbart et al.* [2005b]).

[9] Preliminary to the phenology retrieval, both SPOT-VGT data and PAL were reprojected to a common geographic plate carre projection at a 0.1 degree resolution. Both data sets have a compositing period of 10 days.

[10] The two methods (SPOT-VGT and NOAA) were validated using in situ determination of the date of leaf appearance of deciduous trees at eight sites in Siberia. The estimation of the phenological dates proved not to be affected by snow as it is very close to the observed date of leaf appearance (NDWI method: $N = 21$, $R^2 = 0.83$, $RMSE = 6.65$ days, $Bias = 0.55$ days. NDVI method: $N = 81$, $R^2 = 0.75$, $RMSE = 7.75$ days, $Bias = 0.34$ days). In Canada, the NDWI data results were validated on 68 sites in 2002–2004 (deciduous tree phenology data from <http://www.naturewatch.ca/english/plantwatch/>). The results are slightly worse than in Eurasia, ($N = 68$, $R^2 = 0.48$, $RMSE = 9.77$, $Bias = 2.95$ days), very probably because of the dominance of evergreen species which makes the retrieval more difficult. However, in all cases, the remote sensing estimates are significantly correlated to the in situ dates.

2.2. El Niño–Southern Oscillation Quantification

[11] Various indices have been proposed to quantify the ENSO [*Hanley et al.*, 2003]. One of the most widely used is the SO index, a measure of the intensity of the coupled atmosphere–ocean mode in the South Pacific based on the surface pressure gradient between the western and eastern areas of the South Pacific [*Ropelewski and Jones*, 1987]. Seasonal averages of summer (Jun, Jul, and Aug), autumn (Sep, Oct, Nov) and winter (Dec, Jan, Feb) were calculated to relate to leaf appearance data.

3. Results

3.1. Relationships Between Leaf Appearance Dates and SOI

[12] Correlations between the leaf appearance dates and the seasonal SOI were calculated for each pixel of the boreal regions in the Northern hemisphere between 1982

Figure 2. Evolution of the leaf appearance dates in central region of Siberia (area with significant correlations in Figure 1a) and the SOI of the previous summer.

and 2004. Figure 1 shows the spatial distribution of correlations between the leaf appearance and the SOI of the previous summer (Figure 1a), autumn (Figure 1b) and winter (Figure 1c). Negative significant correlations are found over large areas in Central Siberia. The spatial patterns for the different seasons are similar as a consequence of the low differences in the SOI between consecutive months due to the fact that the positive and negative ENSO phases tend to maintain during several months. The ENSO phenomena usually change phase between spring and summer [*Trenberth*, 1997]. For further analysis we selected the previous summer SOI because it could be more useful for predictive purposes.

[13] Figure 2 shows the temporal evolution of the summer SOI and the average leaf appearance date over the areas of negative and significant correlations ($p < 0.05$) indicated in Figure 1a. There is an opposite behaviour of both series ($R = -0.67$, $p < 0.01$), which indicates that high SOI values during the previous summer are related to earlier leaf appearance in large areas of central Siberia.

[14] We also calculated the correlations between the average leaf appearance dates in the areas with significant correlations in Figure 1a and the previous summer Sea Surface Temperature (SST, Figure 3). The SST data were obtained from ftp://podaac.jpl.nasa.gov/pub/sea_surface_temperature/reynolds/oisst/doc/oisst.html, based on NOAA-AVHRR thermal data [*Reynolds and Smith*, 1995]. The spatial patterns of correlation show important differences in the correlations within the Pacific Ocean. They resemble the SST pattern corresponding to the ENSO phenomenon. In fact, we found positive correlations in the center and East Pacific and negative correlations in the West Pacific. This indicates that warm conditions in the East Pacific, which characterises El Niño phases and low SOI

Figure 3. Correlation between the leaf appearance date in central Siberia and the Sea Surface Temperature of the previous summer at global scale (1982–2004). Black lines isolate areas with significant correlations.

Figure 4. Correlation (1982–2004) between the average April–May sea level pressures and (a) the previous summer SOI, (b) the leaf appearance date in central region of Siberia and correlation (1982–2004) between the average April–May 500 hPa Geopotential and (c) the previous summer SOI, (d) leaf appearance in central region of Siberia. Dotted lines indicate areas with significant correlations. Arrows show the wind vectors obtained from correlations between the u and v wind components and the previous summer SOI and the leaf appearance in central region of Siberia for c) and d) respectively.

values, causes, on average, a later leaf appearance in central Siberia. On the contrary, cold SST in the East, that characterises La Niña and high SOI values, are associated with an earlier leaf appearance.

3.2. Remote Climate Connections Explaining the SOI Influence on Leaf Appearance Dates in Central Siberia

[15] A significant connection between ENSO and the atmospheric anomalies in North America and Europe was reported by several authors [i.e., *Trenberth and Hurrell*, 1994]. Therefore, we also analysed the role of the summer SOI on the Sea Level Pressures (SLP), 500 hPa Geopotential and the 500 hPa wind direction and magnitude in the Northern Hemisphere during the following April–May, months in which leaf appearance happens in central Siberia. We used the monthly Northern Hemisphere atmospheric datasets of NCEP-NCAR (from <http://dss.ucar.edu/datasets/>). Figure 4 shows the spatial distribution of correlations between Northern Hemisphere April–May SLP and the previous summer SOI (Figure 4a) and the leaf appearance dates in the central Siberia areas shown in Figure 1a between 1982 and 2004 (Figure 4b). In the same figure we also show the correlations between the April–May 500 hPa Geopotential and the previous summer SOI (Figure 4c) and the leaf appearance in the same region (Figure 4d). Also the magnitude and direction of the wind vectors associated with these relationships were obtained for the 500 hPa Geopotential. This was analysed by means of the correlations between the average April–May u and v wind components, the summer SOI and the leaf appearance dates in central Siberia.

[16] We found significant positive correlations between the summer SOI and the SLP in central-South Siberia

during April–May of the following year and negative significant correlations are on the Arctic Ocean and West Russia. The opposite pattern (negative correlation to SLP in central-South Siberia and a positive with SLP in the Arctic area) was found considering correlations between leaf appearance dates in central Siberia and the Northern Hemisphere SLP in April–May. These results indicate that the most important SLP gradient related to the SOI influence is recorded in central Siberia. This behaviour is clearer considering the 500 hPa Geopotential. Higher correlation values have been obtained in April–May with the previous summer SOI and also with the leaf appearance dates in Central Siberia. This pattern of influence is well explained considering the direction of the flows in central Siberia. High SOI values (characteristics of La Niña phases) cause high pressures (in the surface and in the medium troposphere) in central-South Siberia and low pressures over the Arctic Ocean. This configuration causes dominant South-western flows that affect central Siberia. Therefore, Western flows induce an earlier leaf appearance than Eastern flows. On the contrary, negative pressures in central-South Siberia and positive pressures in the Arctic Ocean are associated to dominant North-east flows, which cause a later leaf appearance in central Siberia.

[17] The influence of ENSO on leaf appearance dates by means of the SLP, Geopotential patterns and wind flows can be interpreted by their direct influence on temperatures. Therefore we also analysed the role of the summer SOI on April–May temperatures in central Siberia. For this purpose, the CRU monthly temperature grids at 0.5° (TS 2.0 data set) were used [*Mitchell et al.*, 2003]. The data set finished in 2002 but the decrease in degrees of freedom does not sensibly affect the robustness of the results.

[18] The SOI is positively and significantly correlated to the average temperature in Central Siberia ($R = 0.56$, $p < 0.01$). Therefore, Western flows, associated to positive SOI, causes higher temperatures than eastern flows. This favours an earlier leaf appearance given the high negative correlation between the April–May temperatures and the date of leaf appearance ($R = -0.84$, $p < 0.01$).

[19] Figure 5 shows the spatial distribution of correlations between the previous summer SOI and the average temperatures in April–May between 1982 and 2002. Correlations are positive and significant ($p < 0.01$) in large areas of

Figure 5. Correlations between the previous summer SOI and the average temperatures in April–May of the following year (1982–2002).

central Siberia, favouring the positive (negative) SOI values early (late) leaf appearance as a consequence of the ENSO control of temperatures in this region during spring, conducted by West (East) flows.

4. Discussion and Conclusions

[20] This paper shows that the ENSO phenomenon has an important role on the interannual variability of leaf appearance dates over large areas in central Siberia. Warm SST in the East Pacific, characteristics of El Niño phenomena, are associated with a delay of leaf appearance, whereas the opposite phenomenon, La Niña (cold SST in the East Pacific) causes an earlier leaf appearance. This is explained by the influence of ENSO on surface pressure patterns and flows that control the surface temperature in central Siberia, temperature being the main driving factor for vegetation activity in this region [Suzuki *et al.*, 2001].

[21] Thompson *et al.* [2002] indicated that warm and cold ENSO events have an important impact on winter temperatures and the frequency of extreme cold events in the Eurasian continent. This is due to the fact that the structure of the Northern Hemisphere Annular mode is significantly different during warm and cold ENSO events [Quadrelli and Wallace, 2002] affecting the climatology of large areas of Siberia. Nevertheless, these studies were conducted in the winter season, showing the opposite role of the ENSO on temperatures than that observed in this paper for April–May, in which warm episodes have been prone to cause colder temperatures than cold episodes. It is well known that the ENSO effects can vary noticeably between seasons regarding both temperature conditions and vegetation [Buermann *et al.*, 2003], and are often subjected to time lags [Gong and Ho, 2003]. It is important underlying that the influence of ENSO on leaf appearance in central Siberia has been identified considering the Pacific atmosphere-ocean coupled mode 8–9 months prior the leaf appearance. This is very important for predictive purposes related to the vegetation-atmosphere CO₂ interchange.

[22] Future changes in the ENSO phenomena could produce important modifications in the Siberian boreal ecosystems, which are especially sensitive to climatic change due to the limiting climatic conditions. This could have important consequences on global change processes. In fact according to Net Primary Production (NPP) calculations by the LPJ (Lund-Potsdam-Jena) model [Sitch *et al.*, 2003] the areas in which leaf appearance is highly affected by ENSO shown in Figure 1a account for 7.6% of the NPP for the whole Northern Hemisphere above 50°N and 16% in Boreal Eurasia.

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