ENSO Impact on the Australian vegetation
A satellite diagnostic from 1998 - 2006

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EXTENDED ABSTRACT

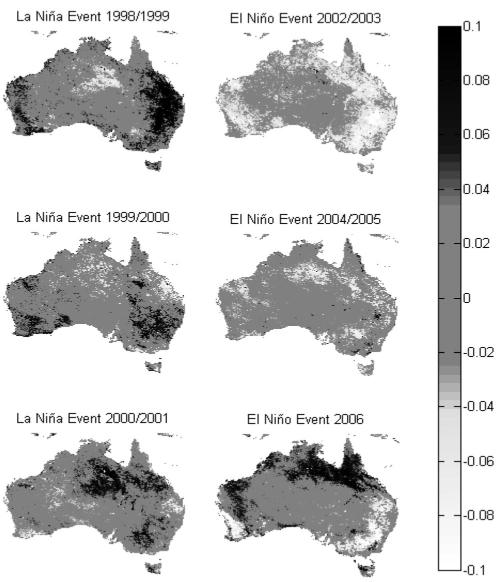

Figure 1. NDVI anomalies in Australia during El Niño and La Niña events from 1998 to 2006.

The modelling of water and energy exchanges between Soil-Vegetation and the ATmosphere (SVAT) often assimilates remotely sensed time series of Vegetation Indices (VIs). At first order, spectral combinations like the Normalized Difference Vegetation Index (NDVI) are known for their ability to witness the geographic and seasonal distribution of greenness on continental surfaces. Another usual combination is the ShortWave Vegetation Index (SWVI), which is more sensitive to the vegetation structure and water content than NDVI (Gao et al. 1996). According to recent published studies (e.g. Maki et al. 2006), the difference between **NDVI** and **SWVI** (Δ hereafter) should theoretically relate to the vegetation water stress.

In the present study, we evaluate the ability of these indices to monitor the Australian vegetation behaviour to **ENSO** induced precipitation anomalies (Figure 1). Thanks to **9 year time series** of **SPOT/VEGETATION** kilometric imagery (1998-2006), we calculate the standard seasonality for these 3 spectral indices and we compare it with ENSO quantitative indices like the Southern Oscillation Index (SOI) proposed by Troup (1965). Although the SOI is only a temporal index, we use it as a general indicator for the water stress probability.

According to our results, Δ presents a better correlation with SOI than NDVI or SWVI anomalies at seasonal time scale (1 to 3 years considered at the monthly time step).

In 2005, a field campaign named NAFE (National Airborne Field Experiment) was carried on in a specific region of New South Wales. In this region, our results concerning Δ are confirmed and further investigations are now planed in order to take advantage of the NAFE in situ measurements (like soil moisture and vegetation water content). By that time the SPOT VEGETATION archive is still growing since SPOT5/VEGETATION2 should operate until late 2011 and a project for a VEGETATION Follow-On mission is under study at French and European Space Agencies.

1. INTRODUCTION

The El Niño Southern Oscillation (ENSO) phenomenon produces an important interannual variability of oceanic and atmospheric conditions with irregular periods and amplitudes (Cobb et al., 2003) in many regions of the world. On the Australian continent, El Niño events are generally associated to droughts (Potgieter et al., 2005; Suppiah, 2004; Ropelewski & Halpert, 1987), while La Niña events produce above normal rainfall (Suppiah, 2004). Several authors showed that the strongest connections between Southern Oscillation and Australian rainfall occur in northern and eastern Australia (McBride & Nicholls, 1983; Ropelewski & Halpert, 1987), whereas being more important in Southern Hemisphere spring (McBride & Nicholls, 1983; Drosdowsky & Williams, 1991). As plant growth in this region is assumed to be mainly limited by water availability, an equal connection should be found between ENSO events and remotely sensed vegetation indices, e.g. NDVI or SWVI. The typical reflectance spectrum of vegetation (Figure 2), in which red light is absorbed for photosynthesis purposes and midinfrared radiation is absorbed by the present water while nearinfrared radiation is mostly reflected, shows that these three spectral bands can be used to determine the amount of photosynthetically active vegetation, vegetation water content and soil moisture in a specific region. For this purpose, several vegetation indices have been proposed by different authors.

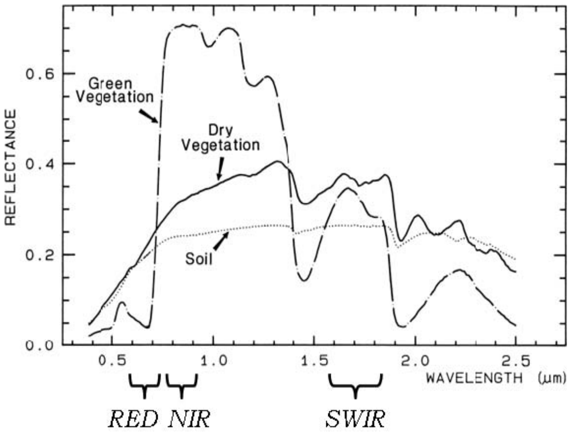

Figure 2. Spectral signature of dry vegetation, green vegetation and bare soil.

The most common is the Normalized Difference Vegetation Index (NDVI), defined as difference between surface reflectances (ρ) in the nearinfrared (NIR) and red channels normalized (divided) by their sum.

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \quad (1)$$

This index has widely been used as an indicator of vegetations' leaf area index (LAI) and thus plants' potential to intercept and use photosynthetically active radiation.

As its capability for estimating vegetation water content is limited (Jackson et al., 2004), the Short Wave Vegetation Index (SWVI) which benefits from water absorption in the shortwave infrared (swir) section is commonly used. To calculate the SWVI, the red channel in Eq. (1) is to be replaced by the SWIR section,

$$SWVI = \frac{\rho_{swir} - \rho_{red}}{\rho_{swir} + \rho_{red}} \quad (2)$$

We suppose that a water stress in vegetated areas has an immediate impact on SWVI values since they partly depend on SWIR reflectances, spectral region where water absorption occurs. Conversely, NDVI behaves more slowly, since it does only "see" the water stress when the surface of green leaves is modified. Thus, we compute a variable Δ as the difference between NDVI and SWVI (Equ. 3), and we investigate its capabilities to determine the plant water status. A similar index called NDDI has recently been proposed by Gu et al. (2006) as a drought indicator.

$$\Delta = NDVI - SWVI \quad (3)$$

In order to evaluate and compare the relative performance of these 3 indices, we use a quantitative index for ENSO events (Southern Oscillation Index or SOI) as a general indicator for the water stress probability. This ENSO indicator is compared to the remotely sensed spectral indices of our interest. Our exercise is performed on 2 scales. First we consider the continental scale; second, we focus on the regional scale, choosing an area where an Airborne and Field Experiments was carried on in 2005.

The ongoing evaluation of NDVI, SWVI and Δ will take advantage of this experiment (named NAFE05 - http://www.nafe.unimelb.edu.au), which will provide us with complementary in situ information on the vegetation water status.

2. AVAILABLE INFORMATION

2.1. El Niño and Precipitation

To identify the different ENSO periods, values for the Southern Oscillation Index (SOI) often referred to as Troup index (cf. Troup (1965)) are taken. This index describes a standardised anomaly of the Mean Sea Level Pressure difference between Tahiti and Darwin. Sustained and strong negative and positive values of this index are respectively considered as an indicator of El Niño and La Niña events. The evolution of SOI from 1998 to 2006 (our time period of interest) is visualized in Figure 3. The data are obtained from the website of the National Climate Centre, Australian Bureau of Meteorology (http://www.bom.gov.au/climate/current/soihtm1.shtml). This Centre does also provide maps of Australian seasonal rainfall and anomalies at (http://www.bom.gov.au/silo/products/ClimMaps.shtml) that we did also consult for the analysis of our results.

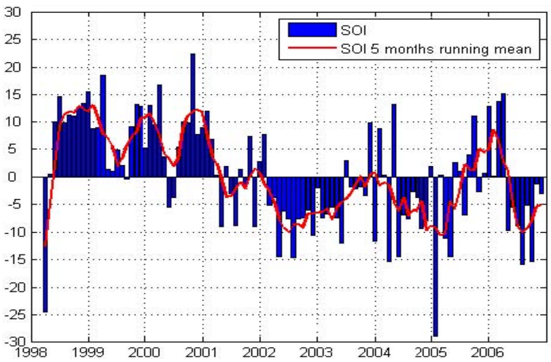

Figure 3. Monthly evolution of the Troup Southern Oscillation Index from 1998 to 2006.

Figure 4. Annual precipitation (mm/year).

2.2. The SPOT/VEGETATION dataset

The present study is based on data acquired by the SPOT4/VEGETATION1 and SPOT-5/VEGETATION2 missions (VGT1 & VGT2) which both map surface reflectances in red (0.61-0.68 µm), NearInfraRed (0.78 0.89 µm) and ShortWave InfraRed (1.58-1.75 µm) spectral bands for vegetation index determination, the blue spectral band (0.43-0.47 µm) for cloud detection as well as the viewing zenith angle. The SPOT/VEGETATION mission performs a daily global monitoring of continental surfaces at the kilometric resolution. On the principle of maximum NDVI selecting, 10-day composite images are built after correction for atmospheric effects. This entire processing chain is made at CTIV (Centre de Traitement des Images VEGETATION) and resulting 10-day synthesis (S10 products) are available free of charge at http://free.vgt.vito.be (see Maisongrande et al. 2004 for details on products).

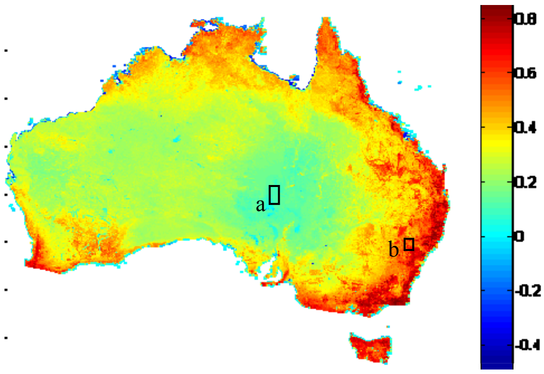

Figure 5. Average annual NDVI of Australia on the basis of SPOT/VEGETATION data acquired from 1998 to 2006. Areas named (a) and (b) present specific regions of interest that are respectively an arid surface and a region covered with pasture and open woodland (NAFE 2005 region).

From April 1998 to April 2002 (SPOT4/VGT1) and May 2002 to December 2006 (SPOT5/VGT2), we ordered and transferred successive S10 composite images for Australia. Figure 5 illustrates the 9 year average NDVI calculated from the resulting time series. The geographic distribution of NDVI is highly correlated to the patterns of annual precipitation (Figure 4). This first comparison obviously shows that the water availability is the prime factor driving the plant development all over Australia. Rainfall anomalies due to ENSO event are then likely to impact NDVI seasonality and geography.

3. RESULTS OBTAINED FROM VI'S TIME SERIES ON A REGIONAL SCALE

Having now presented the context of the study and the available dataset, we focus on the analysis of regional samples of the Australian continent and their vegetation's behaviour. We present now zonally average time series of NDVI, in the aim of comparing their trends to the interannual SOI patterns shown on Figure 3.

3.1. Getting a first impression on the NAFE -2005 territory

A first look is taken on a 100km*100km geographic window around a territory that has been investigated during the NAFE 2005 field campaign (see Figure 5 for geolocation). Located in New South Wales, the land cover of this region is mixture of shrublands, woodlands and forest. The temporal evolution of NDVI and SWVI spatial mean values can be seen in Figure 6. In most of cases, the seasonal variability in this region presents peak values during austral winters which can be understood as a season of no water limitation for the plants. NDVI and SWVI curves are strongly correlated and a strong interannual variability of both NDVI and SWVI is observed. During the SPOT4 period (1998 to 2002), a decreasing trend of the two curves can be noticed, followed by a strong boost at the beginning of the SPOT5 measurements. Subsequently, two negative successive trends can be detected over the considered nine years, the first one from 1998 to 2002, the second one from 200" to 2006. The Interannual variations in NDVI and SWVI values reach amplitude of 0.15, an order of magnitude comparable to the seasonal variations which oscillate by 0.2 to 0.3 or both indices. Besides their similarities, NDVI and SWVI time series also present slight differences that we analyse and discuss in §3.3.

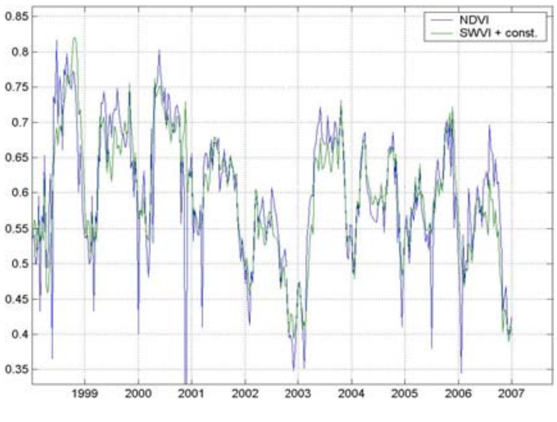

Figure 6. NDVI and SWVI 9 year time series in the NAFE05 region.

As the abrupt change in NDVI and SWVI values is located exactly at the moment of the "switch" from VEGETATION1 to VEGETATION2, a lack of calibration consistency between the two sensors might be the explanation for the twofold pattern of VIs time series. Such an artefact could interfere with the interpretation of NDVI and its anomalies compared to SOI.

Therefore, we paid attention to the calibration issue by considering VIs time series on arid and flat surfaces where NDVI signal should present a long term horizontal trend. On a 100 km x 200 km region in the Simpson Desert (zone b on Figure 5) we observed steady NDVI time series with a law NDVI level (around 0.09) and very weak seasonal cycles that might be due a mixture of directional effects and episodic blooms of greenness after rare precipitation. In 2003, the transition from VGT1 to VGT2 caused a slight change in the average level of the signal (0.01) which is very small compared to the magnitude of NDVI presented on Figure 5 for the NAFE2005 region. To the light of this checking of the NDVI time consistency, and acknowledging the radiometric high quality of the SPOT/VEGETATION data, we considered the time consistency of our time series for granted (see http://www.spot-vegetation.com/ for more details on the data processing at the ground segment level).

3.2. Vegetation Indices vs El Niño index

As calibration reasons can not be considered as responsible for the important interannual variability observed for both NDVI and SWVI values on Figure 6, an attempt is made to evaluate the influence of ENSO on observed Vegetation Indices. In order to calculate a correlation between SOI values describing the actual ENSO state and its eventual impact on vegetation, we paid a particular attention on NDVI anomalies. The retrieval of anomalies was performed by taking away the principal seasonal variability on VIs time series. Therefore, a standard annual behaviour is calculated and removed from the NDVI and SWVI signals.

Resulting curves for the NAFE 2005 territory are displayed on Figure 8. For this region, interannual variability of vegetation indices can be largely explained by ENSO influence. More precisely, in the observed south-east Australian regions, high SOI values (i.e. La Niña conditions) provoke vegetation prosperity while the reverse is true for El Niño conditions. This general result corresponds very well with what has been shown for the entire continent by different authors (McBride & Nicholls, 1983; Drosdowsky &

Williams, 1991) for rainfall. However, besides the general positive correlation between curves on a large time scale, we notice weaker correlation between SOI and NDVI when considering the seasonal time scale.

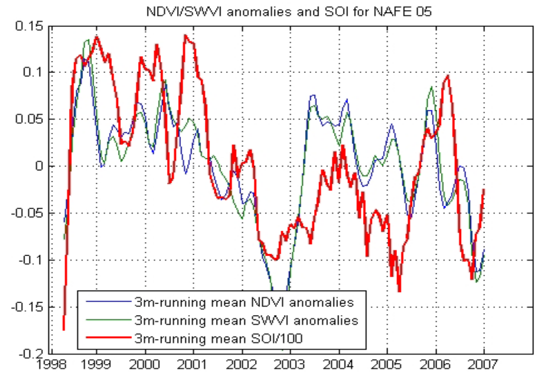

Figure 7. Time series of NDVI anomalies (blue) and SWVI anomalies (green) averaged in the NAFE 2005 region compared with ENSO index (SOI according to Troup (1965) in red colour).

Conversely, when replacing NDVI and SWVI by their difference Δ in the comparison exercise with SOI, Figure 8 shows that Δ presents a very good negative correlation with SOI at the annual time scale while the general correlation (i.e. on the whole time series) is weaker than the one observed on Figure 7. This short term correlation between Δ and SOI is an interesting result which suggests that Δ could be used as a spectral indicator for the Vegetation water status in SVATS modelling. This issue deserves further investigations, for example at regional scale where the land cover is known as well as the vegetation water content and soil moisture. These informations are available in the NAFE region on which we plan to focus our next efforts.

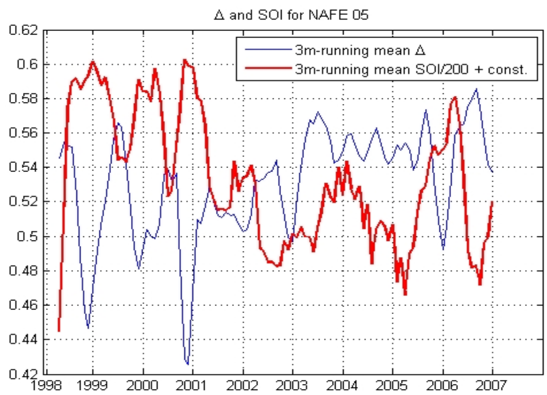

Figure 8. Time series of Δ=NDVI(t)-SWVI(t) (blue) compared with ENSO index (SOI according to Troup (1965) in red colour).

By that time, in order to get a broader view on the spatial distribution of the observed variables, we devote the next paragraph to the scale of entire Australia.

4. ZOOMING OUT – THE CONTINENTAL SCALE

4.1. Geographic Patterns of correlation with SOI

In an attempt to verify the geographical patterns of ENSO influence on Australia shown by different authors who generally find, high (low) ENSO influence on northern and eastern (southern and western) regions (Potgieter et al., 2005; McBride & Nicholls, 1983; Drosdowsky & Williams, 1991), the same calculation the one presented by Figures 7&8 is realized on NDVI, SWVI and Δ for each pixel of a map of the entire continent. The results are given in Figure 9.

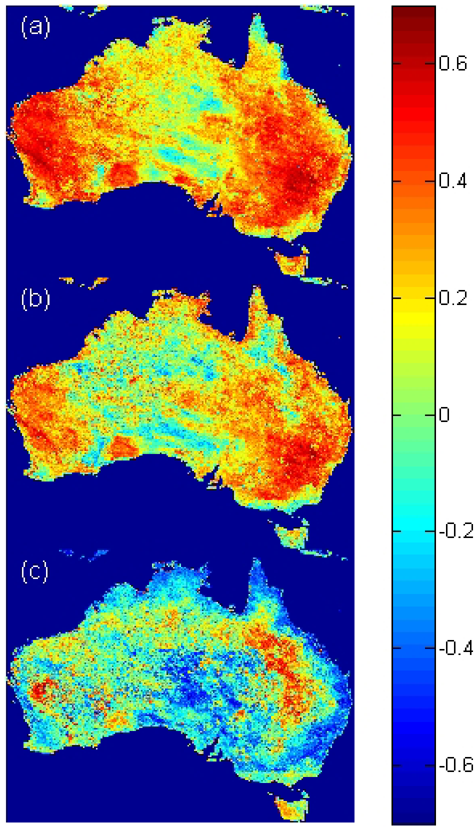

Figure 9. Spatial distribution of correlations between SOI values and (a) NDVI anomalies, (b) SWVI anomalies, (c) Δ.

We first notice that the positive correlation previously found for the NAFE region is verified. However, in other parts of the continent a different behaviour is observed. At first, one can see that positive correlations with SOI evolution are often important for NDVI and SWVI anomalies.

For these two indices, positive correlations dominate, especially in western and eastern Australia. Meanwhile in the centre and on the east coast, very small and even negative correlations can be observed.

On the other hand, on different geographic patterns, Δ often present important negative correlation but also positive ones. As an indicator for water stress, Δ should negatively correlate with the SOI. This is the case in some eastern, northern and central regions, but not generally. Although any direct interpretation of Δ remains difficult and disserves further developments, we notice that these strong negative correlations occur in region where rainfalls and vegetation are usually abundant (Figure 9c vs Figures 4&5).

4.2. Mapping of VIs anomalies during ENSO events

The results of § 4.1 give a good idea on the geographic patterns of ENSO impact on Australia, but possible differences between the influence in the course of time, e.g. between El Niño and La Niña events, cannot be observed this way. Thus, further attention is paid on the temporal dimension. So, our approach now consists in focusing on the time scale of ENSO events in order to consider them separately. In agreement with Figure 3, during the nine years informed with SPOT/VEGETATION observations, six events occurred, among which three are positive and three others are negative (see Table 1). This table is quite consistent with what has been declared as ENSO events by the NOAA/National Weather Service considering sea surface temperature anomalies in the Pacific Ocean.

Event's type	Period
La Niña 98/99	Jun 1998 Apr 1999
La Niña 99/00	Oct 1999 Apr 2000
La Niña 00/01	Aug 2000 Mar 2001
El Niño 02/03	Mar 2002 Jun 2003
El Niño 04/05	Jun 2004 May 2005
El Niño 06	May 2006 Dec 2006

Table 1: Southern Oscillation events from 1998 to 2006.

Considering separately these six events, we did calculate the deviation between the measured VIs during the event and their average value usually measured during the same season for the 9 considered years. The result of this calculation for NDVI values is given in Figure 10.

The fact that El Niño events involve negative anomalies (in yellow) while La Niña involve positive ones (in green) is confirmed, but the geographic pattern of these impact vary a lot form event to event.

For example, the highest positive departures during La Niña 98/99 and 99/00 are found in eastern and western Australia, while central and northern regions show even slight negative anomalies. NDVI values during El Niño events equally show most negative anomalies in the eastern and western vegetated mid-latitude areas. The last El Niño observed, the one in 2006, however, is atypical as vegetation index is higher than normal in large areas in the north and in the west. The unusual comportment of vegetation during the last El Niño could be due to the fact that the observation period ended in the middle of the event, data for 2007 should be used to verify the results. However, it may be retained that geographical patterns of vegetation index anomalies in Australia vary from event to event while in most cases the impact on eastern and western regions is stronger than on central and northern regions. A study of VIs evolution on a finer timescale is considered hereafter.

Comparison with precipitation anomalies described at the monthly time step for the 9 years explained very well the "interENSO" variability highlighted by Figure 8. This last result also reminds the limitation we have to cope with when working with SOI. Indeed, this index is generic for the entire southern hemisphere while we are interested in intercontinental variability of ENSO and its impact plants water status.

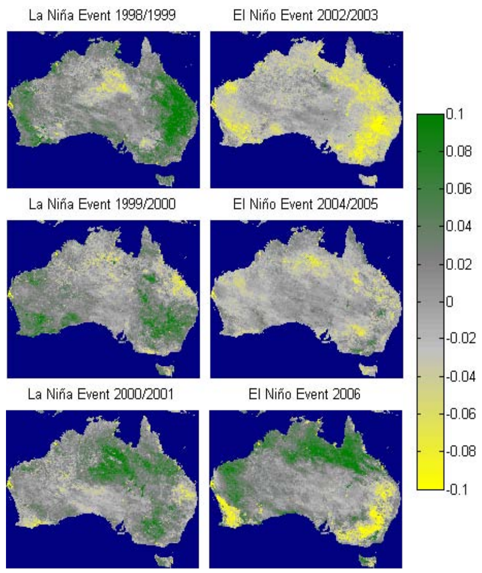

Figure 10. Geographic distribution of NDVI anomalies during the ENSO events that occurred from 1998 to 2006.

CONCLUSION

This study has taken advantage of the available time series of SPOT/VEGETATION data. Thanks to the geometric and radiometric quality of VEGETA TION products delivered free of charge at CTIV (Centre de traitement des données VEGETATION) at http://free.vgt.vito.be, we built a nine years time series (1998-2006) for Normalized Difference Vegetation Index, Short Wave Vegetation Index and their difference Δ for the entire Australian continent. This archive made possible our investigation on the way ENSO events impact the behaviour of the vegetation seasonal cycle and its geographic distribution. Moreover, we did also investigate the relevancy of Δ as an original spectral index that could provide SVAT models with maps of plant water status, faster than classical NDVI would do (i.e. without having to wait for leaves senescence due to long water stress).

Many teaching emerge from this study. **On the continental scale**, we clearly show the geographic patterns of the highest sensitivity to El Niño or La Niña. We also illustrate the interannual variability of these events in term of magnitude and geographic distribution. This variability is clearly explained by precipitation anomalies in relationship with ENSO events. **On the regional scale**, we found that NDVI and SWVI anomalies correlate very well with the Troup Southern Oscillation index when considering the entire 9-year time period. Conversely, Δ presents an interesting negative strong correlation with SOI at short time frequency (i.e. 2-3 years seasonal variability).

In order to analyse and explain these last results further investigations are now planed on the regional scale of the National Airborne Field Experiment was carried on in 2005 (NAFE - http://www.nafe.unimelb.edu.au) where airborne and ground measurements of different variables like soil moisture and vegetation water content were performed.

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