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Investigating Response of Global Vegetation to ENSO Events Between 1987 and 1997 Using NDVI Data

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Abstract

El Niño Southern Oscillation (ENSO) influences extensive regions around the globe causing global weather changes and affecting both marine and land ecosystems. ENSO events are also frequently held responsible for much of the variation in carbon fixation by terrestrial biosphere pool. The timing and size of the response of eight global vegetation biomes to ENSO events between 1987 and 1997 were investigated employing monthly Normalized Difference Vegetation Index (NDVI), temperature and precipitation data and monthly anomalies of sea surface temperature in the tropical Pacific. Lagged correlation analyses were used to identify times when the relationship between vegetation condition and ENSO is most robust and standardized NDVI departures were computed to estimate the size of vegetation response to ENSO. Warm ENSO phases appear to have delayed (7~17 months) and protracted negative impacts on vegetation in all biomes related in most cases to a decrease in precipitation but rarely to an increase of temperature. This impact starts earlier in the tropical and subtropical regions but delays in the temperate and cold regions. Positive/negative impacts of warm/cold ENSO phases on global vegetation are instantaneous and brief. Interestingly, the result also indicates that ENSO has significant impacts on Boreal forests which were previously considered to have little or weak association with ENSO. Almost in all biomes, warm ENSO phases tend to result in below average NDVI while cold and neutral phases tend to result in above average NDVI with significant departures being more frequent during cold and neutral phases.

Keywords

ENSO, Climatic Parameters, Terrestrial Vegetation, NDVI, Lagged Correlation

1. Introduction

El Niño Southern Oscillation (ENSO) influences extensive regions around the globe deriving large-scale precipitation and temperature patterns causing global weather changes and affecting both marine and land ecosystems [1]. Of particular importance the fact that ENSO events are frequently held responsible for much of the variation in carbon fixation by terrestrial biosphere pool ([2], [3]) by reducing plant photosynthesis and increasing biomass burning especially in the tropics [4].

El Niño is an irregular event that occurs every 3-6 years associated with the emergence of warm water mass in the equatorial Pacific alternating with the opposite La Niña that is allied with the emergence of cold water mass in the equatorial Pacific. During El Niño events some regions suffers precipitation that is four to ten times higher than average while others are hit by draught [1]. Opposite patterns are observed in these regions during La Niña phases.

Impacts of El Niño events on marine environment are well studied however, effects on terrestrial ecosystems are poorly explored [1]. Among the few attempts made substantial effects were found at regional to continental scale but few were obvious at global scale [5]. Previously, consequences of ENSO events have been learned by comparing climatic records [6] but recently satellite–based vegetation indices (the Normalized Difference Vegetation Index, NDVI, of the Advanced Very High Resolution Radiometer, AVHRR, on board the National Oceanic and Atmospheric Administration's, NOAA satellites) became widely used. They provide high spatial and temporal resolution coverage which allows monitoring dynamics of global and regional vegetation condition. NDVI is computed as the ratio between the difference between energy reflectance in the near-infrared waveband and the visible waveband and the sum of energy reflectance in both wavebands (NDVI=NIR-VIS/NIR+VIS). Infrared emission is directly dependent on the structure of vegetation canopy and indirectly on water content in the plant therefore, this ratio provides an indicator of vegetation condition or vigor such that the higher the NDVI value the greener the vegetation and the greater the level of photosynthetic activity of the cover type [7]. The multi-temporal NDVI data are, thus, useful in studying temporal variation in phenology of natural vegetation due not only to seasonal and annual climatic variation but also to episodic events such as El Niño.

The relationship between AVHRR-NDVI and ENSO indices was frequently investigated in various regions of the world for example in Africa ([8], [9]), in South America and Brasil ([10], [11) and in North America [12]. Kogan [6] examined the association between sea surface temperature anomalies in the equatorial Pacific and a vegetation health index derived from NDVI for the entire world. Generally, a comprehensive understanding of ENSO effects on most terrestrial ecosystems is lacking [1]. The objective of this study is to investigate the response of major global vegetation biomes to ENSO events during one-decade period (1987~1997). NDVI and sea surface temperature in the El Niño 3.4 region of the equatorial Pacific together with long-term precipitation and temperature record are used to (1) characterize correlation patterns between ENSO and vegetation of various terrestrial ecosystems, (2) identify teleconnections between ENSO-induced weather anomalies and vegetation condition and to (3) better understand the size and timing of ENSO impacts on different vegetation biomes.

2. Materials and Methods

2.1. NDVI and Climatic Data

Monthly NDVI measured by AVHRR on board NOAAA 9, NOAA 11 and NOOA 14 polar-orbiting satellites and monthly mean temperature and precipitation derived from global meteorological observations over land which are compiled by the Office of Statistics in the Japan Meteorological Agency were used. Here, a sub-set (1987~1997) of the C-level monthly NDVI data of the third generation version was used. This data has been obtained from NOAA/NESDIS's Office of Research and Application (ORA), Climate Research and Application Division (CRAD), Land Surface Team with a spatial resolution (pixel size) of 0.144° latitude by 0.144° longitude (16 Km). The C-level data was derived from the weekly B-level data by monthly averaging cloud screened observations, spatial interpolation and smoothing. Due to satellite failure, the 1995, 1996 and 1997 data was amended using the new post-launch calibration equations [13]. Seven-month data from August 1994 to February 1995 was excluded from the analysis (NOAA afternoon satellites were inoperative).

Table 1. *Annual mean NDVI, temperature and precipitation of eight global vegetation biomes. Bracketed values are no. of pixels or Standard Deviations.*

Biome code	Biome type	Mean NDVI	Mean Temp.	Mean Prec.
TEG (64p)	Tropical evergreen forests	0.35 (0.03)	25.4 (0.6)	125 (30.5)
TDC (52p)	Tropical deciduous forests	0.28 (0.02)	23.4 (1.8)	64.1 (38.4)
TMF (116p)	Temperate forests	0.27 (0.02)	11.47 (6.9)	73.3 (28.1)
BOR (53p)	Boreal forests	0.23 (0.02)	0.8 (11.9)	43.9 (18.2)
WOO (131p)	Woodlands	0.24 (0.01)	12 (7.5)	65.7 (24.3)
SAV (166p)	Savanna	0.25 (0.02)	24.7 (1.1)	52.1 (11)
TMG (51p)	Temperate grassland	0.21 (0.01)	8 (6.7)	37.9 (20.7)
DES (103p)	Deserts	0.14 (0.01)	18.7 (2.3)	20.2 (12.1)

Grid cells of NDVI data (16 Km) which spatially overlap with meteorological stations on land were extracted and the corresponding meteorological measurements (temperature, precipitation) were taken to represent mean values of each cell. Grid cells with meteorological station(s) positioned at or near the center were preferential. Generally, within a single pixel, maximum of two stations were located from which mean values of climatic parameters were computed. A total of 736 pixels were found to include meteorological stations with complete data record of 11 years. Pixels of NDVI data with their meteorological variables were then aggregated into global land cover classes based on the vegetation map described in Chen et al. [14]. They were further regrouped into 8 broad vegetation classes adapted from IPCC [15] (see Table 1). No pixels including meteorological stations were found in tundra class while pixels located in deserts and semi-deserts were grouped into one class. Five-month running mean was applied on NDVI, temperature and precipitation data in order to smooth out any intra-seasonal variations (outliers). Such frequent and fast changes for example, in NDVI are usually not coherent with the regular slower change in vegetation greenness and health in response to weather variations [6]. Because time series data contain seasonality that is usually much stronger than the inter-annual signal probably associated with an ENSO-induced type of variation, NDVI and meteorological variables were deseasonalized using Ratio-to-Moving Average method. Therefore, pixels in each class were taken to represent sample measurements of the specific vegetation biome. Monthly NDVI, temperature and precipitation were obtained by averaging data pixels within each vegetation biome. Table (1) summarizes simple statistics of NDVI and meteorological variables in all biomes.

2.2. ENSO Index

Sea surface temperature (SST) in the El Niño 3.4 region (120° W-170° W, 5° N-5° S)of the equatorial Pacific (1950~2001) was obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) website (http://www.cpc.ncep.noaa.gov/data/indices/index.html).
SSTs in the El Niño 3.4 region are recently being widely used [16] and known to detect the first signs of ENSO events. SST anomalies were computed according to the method of [16]. Anomalies were obtained by subtracting the monthly SST mean from the monthly SST time series. The monthly SST mean was derived from a base period of 1950-1979. This 30-year base period is considered representative for the record of this century whereas the period after 1979 has been biased warm and dominated by El Niño events [17]. Five-month running mean of SST anomalies were then calculated in order to smooth out the possible intra-seasonal variations in the tropical ocean (Figure 1). Warm (El Niño) and cold (La Niña) phases are defined as SST anomalies greater or smaller than ±0.4°C, respectively, for at least six consecutive months. The neutral phase is defined when SSTs are within the range of ±0.4°C. Four warm phases, three neutral phases and two cold phases were identified which assumed to impact global vegetation between 1987 and 1997 (Figure 1).

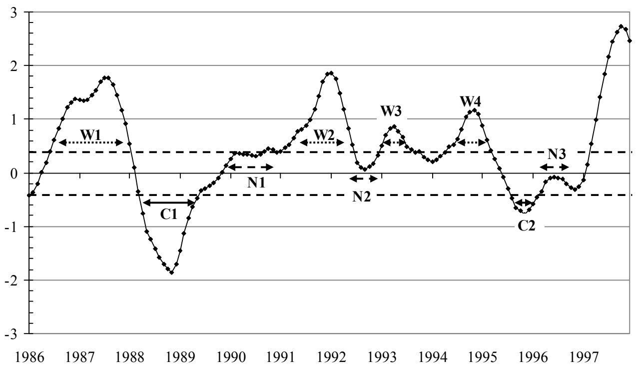

Figure 1. *Time series of SST anomalies in the El Niño 3.4 region of the tropical Pacific (1986~1997). Correlations between bold dashed lines are statistically insignificant (P>0.05). W over dotted arrows indicates warm ENSO phases, N over dashed arrows indicates neutral ENSO phases and C over solid arrows indicates cold ENSO phases. Note the timing of events` peaks. Impacts from the strong El Niño of 1997 were not included in the analysis of standardized departure.*

2.3. Lagged Correlation Analyses

Previously, regional and global studies ([18], [19]) have reported delayed vegetation responses to ENSO events as frequent as immediate responses. However, the degree and extent of temporal correlation between ENSO events and global vegetation biomes are not well characterized. Lagged correlation analyses between monthly SST anomalies and monthly NDVI, precipitation and temperature were performed within each biome group. Precipitation and temperature were included in the lagged correlation analyses since climatologists determined typical precipitation and temperature anomaly patterns from one ENSO event to another (e. g. [20], [16]). Correlations between SST anomalies and these climatic parameters are expected to help understanding the conditions associated with significant relationships between SST anomalies and NDVI, if found. For all data sets, statistically significant trends were removed to produce approximately stationary time series. Since lagged correlations could arise either from coordinated changes or spuriously from periodicity in the data [21], autocorrelations of monthly ENSO index, NDVI, temperature and precipitation were performed. The seasonal adjustment and detrending, however, should have accounted for much of the periodicity in the data. Autocorrelation analyses used only data from before August 1994. In the case of lagged cross correlations, lag periods were matched in advance before removing the 7-month period from the data set. This allowed the use of maximum number of data pairs (125) throughout the analyses maintaining the same significance level of correlation coefficient (r) at P=0.05.

2.4. Standardized Departures

In order to view patterns of change in vegetation condition during ENSO phases, standardized departure of NDVI was used. This is defined as the difference between mean NDVI during the impact period of an ENSO phase and mean NDVI of the study period (1987~1997, excluding the seven-month period from Aug. 1994 to Feb. 1995) divided by the standard deviation of the time series. The impact period is defined as the four-month period delayed from the peak of the event by a certain time lag. It was assumed that impact which correspond to the peak of an ENSO event shall be more evident. The month with the maximum positive or negative SST anomaly is taken to represent the peak of a warm or a cold ENSO event, respectively. The peak of a neutral phase is defined as the month with the closest SST anomaly to zero. Events` peaks are also recognizable in Figure1. The time lag is decided based on the result of lagged correlation between ENSO index and NDVI for each specific vegetation biome. The time lag corresponds to the four-month lags characterized by the strongest correlation between ENSO index and NDVI.

3. Results and Discussion

3.1. Response of Global Vegetation to ENSO Events

Investigation of autocorrelograms and time series plots of deseasonalized and detrended NDVI, temperature and precipitation displayed an apparent oscillation pattern emerging every 1.5 to 3 years, probably associated with ENSO phases. The rapid causi-periodic behavior observed in some temperature and precipitation time series are attributed to more local or regional factors and are incompatible with the observed lagged correlations (Figure 2).

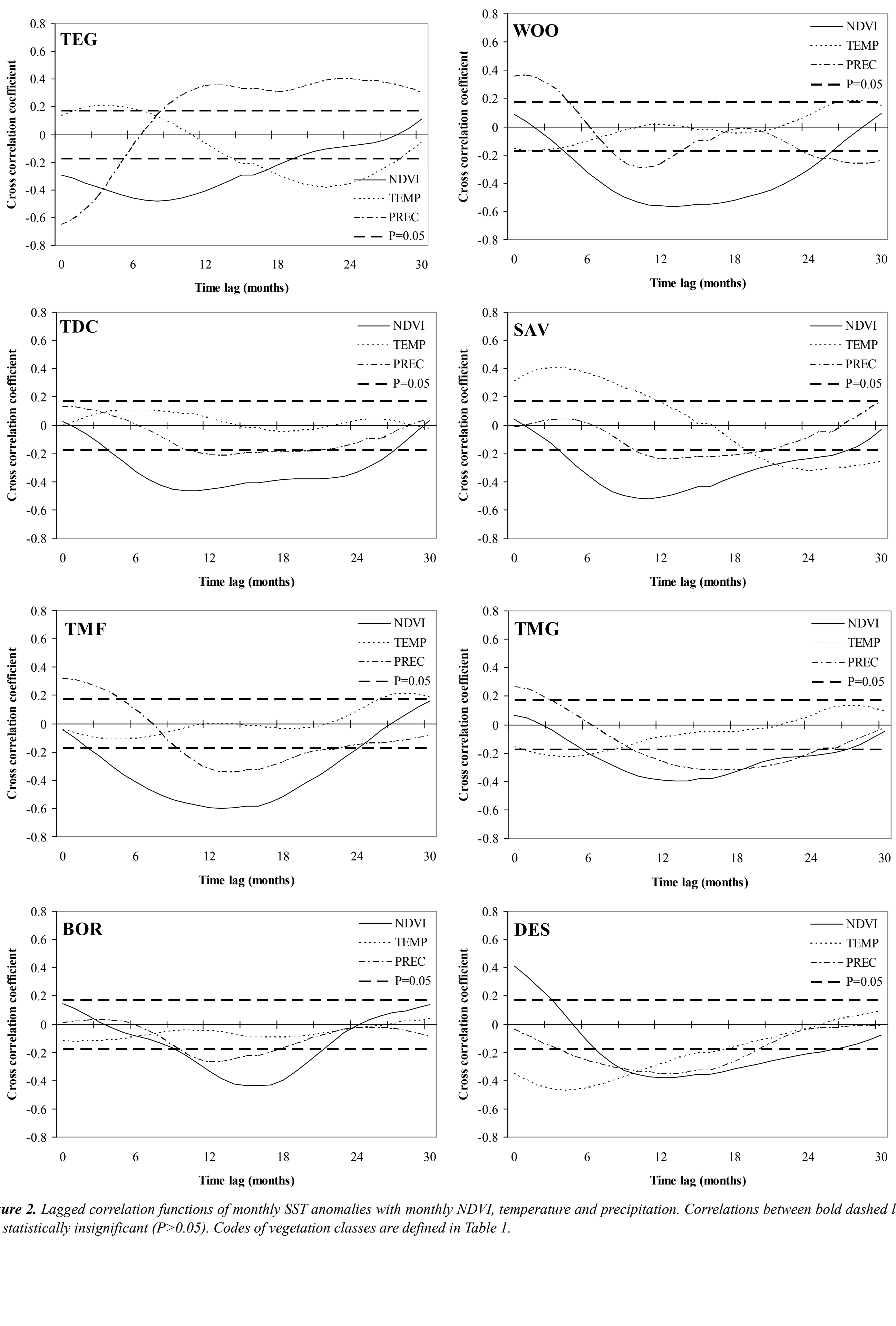

Figure 2. *Lagged correlation functions of monthly SST anomalies with monthly NDVI, temperature and precipitation. Correlations between bold dashed lines are statistically insignificant (P>0.05). Codes of vegetation classes are defined in Table 1.*

Significant immediate and lagged correlations of different magnitudes were observed between ENSO and NDVI, temperature and precipitation (Figure 2). Warm ENSO phases have delayed negative impacts on vegetation condition in all biomes and an immediate positive impact on desert biomes. The later was associated with a corresponding decrease of air temperature which should have resulted in the reduction of water stress. Instead, the negative correlation at longer time lags was associated with a decrease of precipitation. In tropical evergreen forest significant correlation with ENSO was observed at zero-lag and continues to increase with time lag. The initial impact was associated with a decrease in precipitation and increase of temperature. The negative correlation between NDVI and ENSO becomes stronger even when ENSO relations with temperature and precipitation becomes insignificant or change sign. This together with the persistent negative correlation in tropical deciduous forests could indicate the high sensitivity, weaker physiological adjustment [19] and slow recovery of tropical vegetation.

The negative impact of warm ENSO phases on vegetation condition is frequently related to a decrease in precipitation (e.g. temperate forests, temperate grasslands and deserts) but rarely to an increase in temperature (tropical evergreen savanna, and deserts) agreeing with the reported observations at local and regional scales ([6], [11]). This explains the substantial impacts of El Niño on tropical and arid ecosystems where the increase of temperature typically intensifies the water stress.

In most cases correlation between ENSO index and temperature and precipitation are weak or rather insignificant. This might be partly attributed to the averaging which blurs locally significant anomalies [21]. Nevertheless, ENSO was found to be modulated by a climatic oscillation of a longer term, known as Pacific Decadal Oscillation (PDO) [22]. Positive phases of PDO have a stronger relationship with ENSO than negative phases. PDO phase was also found to impact the intensity of teleconnections between ENSO and regional rain [23]. Hare and Mantuna [24] speculated a PDO phase change from positive to negative starting around 1989 which suggests that precipitation would be expected to become more linked to local or regional factors than to ENSO.

For a single cross correlation function lags of maximum correlation indicate the period where the relationship between ENSO and NDVI is most pronounced. As discussed by Kogan [6] the timing of the most pronounced differences in vegetation response to ENSO coincides in some regions and shifts to earlier or later months in others. In order to better see the response of different vegetation biomes to ENSO events, this criterion was used to define the maximum impact period for every biome. The peak of an ENSO phase was assumed to lag the maximum impact period on vegetation by a number of time lags (months) corresponding to the four maximum correlation coefficients in the cross correlation function. The impact period lags the peak of an ENSO phase by 7~10 months in the tropical evergreen forests, 9~12 months in the tropical deciduous forests and savanna, 11~14 months in deserts and woodlands, 12~15 months in temperate forests and grasslands and 14~17 months in Boreal forests. Typically, the maximum impact period of ENSO occurs earlier in the tropical and subtropical region compared to the temperate and cold regions. This result is in harmony with a previously reported one year lagged correlation between ENSO and NPP (Mohamed et al., 2004).

3.2. Spatial Variability in Vegetation Response to ENSO

Results presented at the biome level reflect an average response of a spatially variable phenomenon. Therefore, monthly SST anomalies were lag correlated with each pixel's monthly NDVI. The frequency (as percentage of the total number of pixels in each biome) of the occurrence of positive and negative significant (P=0.05) correlations at representative seven-time lags was obtained as shown in Figure (3). This would permit viewing the degree of spatial variability of vegetation response to ENSO events particularly wide regions of the same biome might be subjected to opposite patterns of ENSO-induced weather anomalies. All pixels, consistently showed larger frequency of negative correlations between SST anomalies and NDVI at 6~18-month time lag in harmony with the result obtained at the biome level. Data from Boreal forests and arid and temperate grasses (deserts, savanna, woodlands and temperate grassland) displayed an opposite pattern at zero-time lag indicating an immediate positive/negative impact of warm/cold ENSO phases on vegetation in many locations and enhancement of vegetation production may be by increase of precipitation and/or decrease of temperature. As well this might imply an immediate positive impact and a delayed negative impact of El Niño on the vegetation of these biomes. A greater grazing pressure of large ungulate grazers following an enhanced production in Savannas and grasslands [19] are likely to reduce land cover which in turn might lower the NDVI several months later. In the case of Boreal forests, previous studies presented little or inconsistent responses to ENSO. A Boreal deciduous forest in Saskatchewan, Canada, was found to sequester more carbon during strong El Niño years as the ecosystem photosynthesis substantially increased due to a warmer spring and early leaf emergence [25]. Chen et al. [14] noted that although area cover of Boreal forests considerably decreased during the long El Niño of 1991~1994, they generally seem to have a weaker association with ENSO events. Kogan [6] performed simultaneous correlation analyses at global scale between SST anomalies in the tropical Pacific and an NDVI-based vegetation condition index. He has reported that four out of six regions which displayed statistically significant correlations are more likely to have poor vegetation condition during cold SSTs (La Niña) and good condition when SSTs are warm (El Niño). This implies that positive impacts of El Niño (or negative impacts of La Niña) are likely to be rapid and brief while negative effects are usually late and prolonged. Poveda and Salazar [11] reported that the extended dryness associated with El Niño in

Amazonia is reflected in a more spatially coherent NDVI field whereas during La Niña there is more variability associated with positive precipitation anomalies.

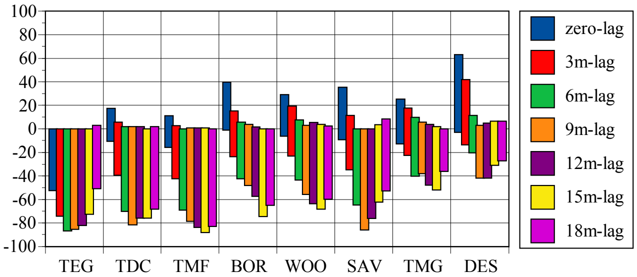

Figure 3. *Frequency of either positive or negative significant correlation coefficients for lagged correlation at seven time lags (zero, 3, 6, 9, 12, 15 and 18 months). Negative values indicate the number of significant anti-correlations. Codes of vegetation classes are defined in Table 1.*

3.3. NDVI Departure During ENSO Phases

Table (2) shows pattern of standardized NDVI departure during ENSO phases in the different vegetation biomes between 1987 and 1997. Almost in all biomes, warm ENSO phases tend to result in below average NDVI while cold and neutral phases tend to result in above average NDVI. Significant departures (≥ |1|) are more frequent during cold and neutral phases than during warm phases particularly, in the last cold and neutral phases around the end of the study period (C2 and N3). This might indicate significantly favorable growth conditions following the release from the prolonged poor conditions associated with the 1991~1994 El Niño (W2~W4). In the tropical forests (TEG and TDC) standardized NDVI departures during ENSO phases reflect delayed impacts from earlier events as well as current impacts from developing phases. The image is more complicated in the case of deserts (and to a lesser extent; savanna, woodlands and temperate grasslands) because the vegetation responds differently to the same ENSO phase at different time lags. This explains for example, the positive NDVI departures in tropical forests and close to zero NDVI departures in woodlands, savanna and temperate grasslands during W4 where the impact period overlap with the developing cold phase (La Niña) of 1995. The prompt positive impact of warm ENSO (El Niño) on desert biomes was also investigated by calculating standardized NDVI departures at zero to 2 months time lags from event's peak. The following departures were obtained; -0.75, -0.13, -0.56, -0.33, -0.18, 0.03, -0.08 and 0.92 for W1, C1, N1, W2, N2, W3, C2 and N3, respectively. NDVI departure at W4 was not computed (7-month data, Aug. 1994~Feb. 1995, was removed). Although many departures decreased or became less significant the general pattern of ENSO impacts on deserts` vegetation did not drastically changed. The neutral phase of 1992 (N2) seems to be overwhelmed by the prolonged warm phase W2~W4 showing below average NDVI in tropical forests, temperate forests, woodland and savanna. Actually, from the perspective of some ENSO indices, the 1990~1995 period could be treated as one long event [16]. In the eight vegetation biomes, the mean NDVI during warm, neutral and cold ENSO phases was compared (Figure 4). In all biomes, warm ENSO phases are characterized by low mean NDVI with considerable deviation observed in tropical forests (see Standard Deviations, Figure 4). Both neutral and cold ENSO phases seem to provoke more favorable conditions resulting in a slightly higher mean NDVI. The large Standard Deviations, however, indicates that none of the two phases is specially favored by vegetation. This result agrees in some parts and disagrees in others with previous studies ([6], [10], [26]). According to Peters et al., [26] this is primarily due to the fact that these relationships are not linear i.e. both warm and cold ENSO phases induce less favorable climate for vegetation with the warm phase having the greater negative effect. Special attention should also be paid to understand how and when different ecosystems physiologically respond to ENSO-induced weather anomalies. A phenomenon such as the Seed Hydration Memory (SHM) allows the seed to retain physiological changes induced by initial hydration during long dehydration periods [12], therefore complicating impacts from ENSO-induced weather anomalies. This capacity of desert plants preserves the internal changes induced by a hydration period allowing them to withstand longer dehydration periods and germinate later originating high NDVI during driest periods.

Table 2. *Series of standardized departures of NDVI during warm, neutral and clod ENSO phases. Dark shaded cells indicate negative departures, light shaded cells indicate positive departures and clear cells indicate departures close to zero. Departures in bold are significant (>1). Codes of vegetation biomes and ENSO phases are in Table 1 and Fig.1, respectively.*

	W1	C1	N1	W2	N2	W3	W4	C2	N3
TEG	-0.4	1.0	0.7	-0.4	-0.3	-1.0	0.7	1.1	0.9
TDC	-0.5	0.5	0.5	-0.6	-0.4	-1.4	0.6	0.9	1.7
TMF	-0.6	1.6	0.4	-0.8	-0.3	-0.9	-0.3	0.9	1.5
BOR	-1.1	1.6	0.3	-0.3	0.2	0.1	-0.2	1.2	1.6
WOO	-0.9	0.7	0.4	-1.3	-0.4	-0.3	-0.1	1.3	1.7
SAV	-1.0	0.4	0.3	-0.4	-0.6	-1.3	0.0	1.2	2.1
TMG	-0.5	-0.0	-0.2	-0.6	0.8	-1.2	0.0	1.0	1.8
DES	-1.2	-0.8	-0.2	-0.0	0.3	-0.6	-0.6	1.5	2.6
1987--1997									

4. Conclusion

The timing and size of the response of eight global vegetation biomes to ENSO events between 1987 and 1997 were investigated employing monthly NDVI, temperature and precipitation data and monthly anomalies of SST in the tropical Pacific. Lagged correlation analyses were useful in identifying times when the relationship between vegetation condition and ENSO is most robust.

This is crucial to understand the variation in terrestrial carbon cycle and for projecting future atmospheric CO_2 levels.

Warm ENSO phases appear to have delayed (by 7 to 17 months) and protracted negative impacts on vegetation in all biomes related in most cases to a decrease in precipitation but rarely to an increase of temperature. This impact starts earlier in the tropical and subtropical regions but delays in the temperate and cold regions. Positive/negative impacts of warm/cold ENSO phases on global vegetation are instantaneous and brief. The extended negative impact on tropical forests reflects the high sensitivity, weaker physiological adjustment and slow recovery of tropical vegetation. Arid semi-arid biomes (desserts, savanna, woodlands and temperate grasslands) displayed a higher frequency of data samples with immediate direct relationship with SST anomalies attributed either to the spatial variability of ENSO impacts and/or to regulation by other factors (intensive grazing). Our result also indicates that ENSO has significant impacts on Boreal forests which were previously considered to have little or weak association with ENSO events.

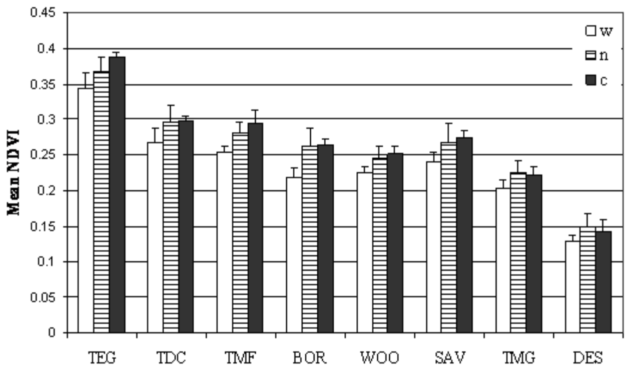

Figure 4. *Comparison of mean NDVI during impact periods of warm, neutral and cold ENSO phases. Error bars represent 1 Standards Deviation, SD. Means and SDs were calculated from deseasonalized data series of each biome. Codes of vegetation classes are defined in Table 1.*

Almost in all biomes, warm ENSO phases tend to result in below average NDVI while cold and neutral phases tend to result in above average NDVI. Significant departures (≥ |1|) are more frequent during cold and neutral phases than warm phases particularly, around the end of the study period (1995~1996) following the release from the prolonged poor conditions associated with the 1991~1994 El Niño. In the tropical forests (TEG and TDC) standardized NDVI departures during ENSO phases reflect delayed impacts from earlier events as well as current impacts from developing phases. The image is more complicated in the case of deserts (and to a lesser extent; savanna, woodlands and temperate grasslands) because the vegetation responds differently to the same ENSO phase at different time lags. Generally warm ENSO phases are characterized by low mean NDVI while both neutral and cold ENSO phases seem to provoke more favorable conditions resulting in a slightly higher mean NDVI. The large Standard Deviations, however, indicate that none of the two phases is specially favored by vegetation.

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