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Response of terrestrial ecosystems to recent Northern Hemispheric drought

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[1] Satellite normalized difference vegetation index (NDVI) observations reveal large and geographically extensive decreases in vegetation activity in Eurasia and North America between 1999 and 2002. In 2001, 73% of central southwest Asia exhibited NDVI anomalies that were more than one standard deviation below 21-year average conditions, and in 2002, fully 95% of North America exhibited below-average NDVI. This episode of large-scale vegetation browning coincided with a prolonged period of below-normal precipitation in the Northern Hemisphere, which limited moisture availability for plant growth. Spatio-temporal dynamics of NDVI, precipitation, and sea surface temperature data reveal that synchronous patterns of ocean circulation anomalies in the Pacific, Atlantic, and Indo-Pacific are strongly correlated with observed joint variability in NDVI and precipitation in the Northern Hemisphere during this period. **Citation:** Lotsch, A., M. A. Friedl, B. T. Anderson, and C. J. Tucker (2005), Response of terrestrial ecosystems to recent Northern Hemispheric drought, *Geophys. Res. Lett.*, *32*, L06705, doi:10.1029/2004GL022043.

1. Introduction

[2] Improved knowledge of ecosystem response to climate variability is important to understand changes in spatio-temporal patterns of biosphere-atmosphere interactions that may arise from climate changes, including fluxes of carbon, water and energy [*Bonan*, 2002]. In particular, future climate perturbations are likely to result in substantial changes, both globally and locally, to precipitation regimes [*Intergovernmental Panel on Climate Change*, 2001; *Trenberth et al.*, 2003], and may therefore alter exchange processes at the biosphere-atmosphere interface.

[3] Terrestrial ecosystems show significant response to inter-annual fluctuations in precipitation patterns associated with perturbations in the ocean-atmosphere circulation system [*Nemani et al.*, 2003]. Specifically, global climate in recent years was characterized by a period of geographically extensive and prolonged drought episodes in the Northern Hemisphere, which limited moisture availability for plant growth, and affected primarily central southwest (CSW) Asia [*Barlow et al.*, 2002] and North America [*Hoerling and Kumar*, 2003]. Because of the potential sensitivity of the global hydrologic cycle to climate change, this period of extreme drought provides a unique natural experiment to help scientists understand how perturbations in the ocean-atmosphere system affect terrestrial ecosystems, and by extension, agricultural production and food security of entire countries.

[4] At global scales the response of vegetation to climate perturbations has been widely observed using satellite-based measurements of normalized difference vegetation index (NDVI) [*Lucht et al.*, 2002], which is proportional to the amount of photosynthetically active radiation absorbed by vegetation [*Asrar et al.*, 1984] and indicative of terrestrial ecosystem productivity [*Myneni et al.*, 1995; *Tucker*, 1979].

[5] We hypothesized that observed patterns of reduced plant growth between 1999 and 2002 were related to a recent hemispheric-scale drought caused by anomalies in global sea surface temperatures (SST). To test this hypothesis, we examined (1) spatio-temporal correlation between 1981–2002 NDVI time series produced from National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data and global precipitation, and (2) the link of principal modes of precipitation variability with SSTs.

2. Data and Methods

2.1. NDVI

[6] The raw NOAA-AVHRR sensor data at 8-km spatial and 15-day temporal resolution has been reprocessed by the National Aeronautics and Space Administration (NASA) Global Inventory Monitoring and Modeling Studies (GIMMS) group to provide a spatially and temporally consistent representation of global vegetation for climate studies, and to remove effects associated with calibration changes, orbital drift and aerosol contamination of the atmosphere [*Tucker et al.*, 2004]. For this study, the data was aggregated to 1 degree spatial and 1 month temporal resolution to minimize the effect of spatial and temporal autocorrelation. Anomalies were calculated relative to 1981–2002 June–August (JJA) means and normalized by the standard deviation estimated from 21 seasonal observations for the same season.

2.2. Precipitation

[7] The precipitation time series used in this analysis are based on monthly land observations from weather stations included in the Global Historical Climatology Network and the Climate Anomaly Monitoring System spanning the period from 1948 to 2002 [*Chen et al.*, 2002].

[8] To investigate how recent changes in plant growth are related to spatial and temporal patterns of precipitation we constructed time series of the standardized precipitation index (SPI) based on monthly observations of precipitation

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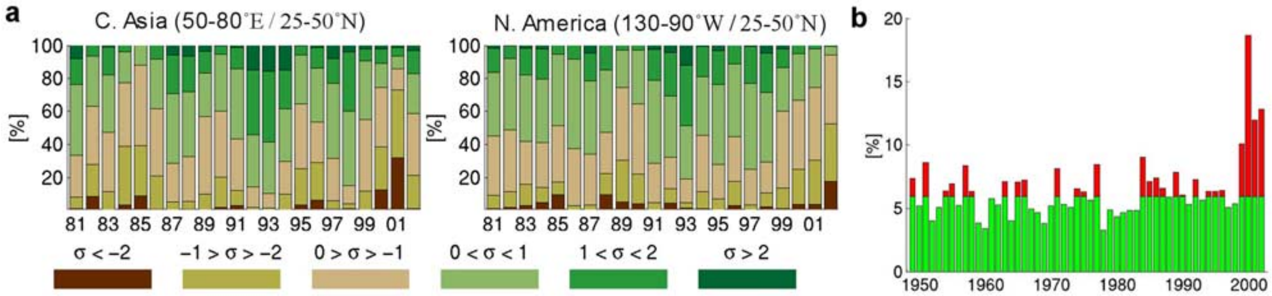

Figure 1. (a) Fractional land area showing NDVI deviations from 1981–2002 mean conditions. Fractional land area (in percent) is shown as positive (green) and negative (brown) standardized departures (σ) of NDVI from the 1981–2002 (x-axis) summer (July–August) mean. This graph summarizes anomalies for CSW Asia (50°–80°E, 25°–50°N; left panel) and western North America (130°–90°W, 25°–50°N; right panel). Anomalies were binned into moderate ($0 \leq |\sigma| < 1$), strong ($1 \leq |\sigma| < 2$) and extreme ($2 \leq |\sigma|$) deviations from the mean. Particularly extreme reductions in vegetation greenness (dark brown) occurred in 2001 in central southwest Asia and in 2002 in western North America. (b) Northern Hemispheric (20°–50°N) fractional land area affected by severe seasonal drought (1948–2002). Severe seasonal drought is defined as 6-month SPI values smaller than −1.5. The red portion of the bars indicates above average fractional area of severe droughts for the period from 1948–2002. Annually (October–September) averaged percentage of land area affected by severe drought increases sharply from a multi-decadal average of 5–10% to nearly 19% in 2000.

[*McKee et al.*, 1993]. This index captures the accumulated deficit (SPI < 0) or surplus (SPI > 0) of precipitation over a specified period of time and provides a normalized measure (i.e. spatially invariant Z score) of relative precipitation anomalies at multiple time scales. Because the SPI is normalized using climatological mean values, it is equally effective at representing dry and wet anomalies. For this study, a 6-months time scale was chosen based on previous analyses of NDVI-SPI covariability [*Lotsch et al.*, 2003].

2.3. SSTs

[9] To investigate inter-annual fluctuations in SSTs, data from the National Center for Environmental Prediction (NCEP) reanalysis are used [*Kalnay et al.*, 1996]. This data is used to characterize the leading modes of SST variability in each ocean basin according to well-known patterns of ocean-atmosphere interactions.

3. Results

[10] Figure 1a shows JJA standard deviations (σ) from NDVI for mid-latitudes in North America and CSW Asia for 1981–2002 expressed as the spatially averaged fraction of total land area. CSW Asia (left panel) shows pronounced year-to-year variability with a 4–5 year cycle and exhibits significant negative departures from mean NDVI (olive to dark brown colours) in 1999–2001. Most notably, 2001 shows the largest anomaly for the 21-year period, with nearly 40% and 33% of CSW Asia having strong ($-2 < \sigma < -1$) and extreme ($\sigma < -2$) deviations from the mean, respectively, and reflecting the significant deficit in rainfall during this period [*Barlow et al.*, 2002]. Similarly, an increase in the area of below-normal NDVI patterns was observed for western North America (middle panel) in 1999–2002, with 95% of land area exhibiting below average NDVI values in 2002 (33% with $-2 < \sigma < -1$ and 18% with $\sigma < -2$). This level of browning is unparalleled in the 21-year NDVI record. Northern Hemisphere maps of JJA NDVI anomalies for 1998, 2001 and 2002 are shown in Figure 2 and illustrate the geographic extent of areas in the Northern Hemisphere that were affected by reduced plant activity.

4. Conclusions

[18] The results presented in this paper reveal strong empirical evidence of joint variability in the ocean-atmosphere-biosphere system. It is becoming increasingly evident that large-scale perturbations of the terrestrial biosphere such as those described here can propagate into other components of the climate system, with important implications for the direction and magnitude of biosphere-atmosphere fluxes of water and carbon [*Prentice and Fung*, 1990; *Koster et al.*, 2000]. Globally, dry and warm conditions are associated with a net release of carbon, whereas wet and cool years tend to increase terrestrial carbon uptake [*Schimel et al.*, 2001]. While increases in growing season temperatures have caused increased carbon uptake by boreal forests [*Myneni et al.*, 2001], warmer temperatures associated with precipitation deficits have negative consequences for plant growth, especially in semi-arid ecosystems such as those affected by the 1998–2002 drought. Positive trends in precipitation associated with warmer temperatures, on the other hand, will tend to increase ecosystem productivity and can result in terrestrial carbon uptake [*Nemani et al.*, 2002]. Finally, a variety of recent evidence suggests that land-atmosphere coupling [*Deser and Timlin*, 1997; *Pielke et al.*, 1998] provides an important positive feedback within the climate system, which can lead to catastrophic droughts such as the one experienced in the Great Plains of North America in the 1930's [*Schubert et al.*, 2004]. Indeed, such feedback mechanisms may explain much of the variance in precipitation and NDVI that is not accounted for by SST anomalies in this work.

[19] In conclusion, the recently observed patterns of below-normal NDVI reveal terrestrial ecosystem dynamics that are strongly correlated with unique and synchronous ocean-atmosphere fluctuations in the Pacific, Atlantic, and Indo-Pacific. Because spatial and temporal patterns in global precipitation regimes are expected to change as a consequence of an intensified global hydrological cycle, a better understanding of the causal mechanisms and effects of such droughts on global ecosystems and society is important for appropriate climate change policy formulation.