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# Impact of 1998–2002 midlatitude drought and warming on terrestrial ecosystem and the global carbon cycle

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[1] A rare drought occurred from 1998 to 2002 across much of the Northern Hemisphere midlatitude regions. Using observational data and numerical models, we analyze the impact of this event on terrestrial ecosystem and the global carbon cycle. The biological productivity in these regions was found to decrease by 0.9 PgC $yr^{-1}$ or 5% compared to the average of the previous two decades, in conjunction with significantly reduced vegetation greenness. The drought led to a land carbon release that is large enough to significantly modify the canonical tropically dominated ENSO response. An atmospheric inversion reveals that during the 1998–2002 drought period, Northern Hemisphere midlatitude changed from a 1980–1998 average of 0.7 PgC $yr^{-1}$ carbon sink to nearly neutral to the atmosphere, while a forward model suggests a change of 1.3 PgC $yr^{-1}$ in the same direction. This large $CO_2$ source may explain the consecutive large increase in atmospheric $CO_2$ growth rate of about 2 ppmv $yr^{-1}$ in recent years, as well as the anomalous timing of events. This Northern Hemisphere $CO_2$ anomaly was largely caused by reduced vegetation growth due to less precipitation, but also with significant contribution from higher temperature that directly increases respiration loss and indirectly further reduces soil moisture. Since the Northern Hemisphere midlatitude landscape has been significantly modified by agriculture, grazing, irrigation and fire suppression, the strong signature in the global carbon cycle of a drought initiated by changes in tropical oceanic temperatures is a remarkable manifestation of climate variability, with implications for carbon cycle response and feedback to future climate change. **Citation:** Zeng, N., H. Qian, C. Roedenbeck, and M. Heimann (2005), Impact of 1998–2002 midlatitude drought and warming on terrestrial ecosystem and the global carbon cycle, *Geophys. Res. Lett.*, *32*, L22709, doi:10.1029/2005GL024607.

## 1. Introduction

[2] The atmospheric $CO_2$ concentration observed at Mauna Loa, Hawaii (MLO) experienced a period of large growth from 2001 to 2003 [*Jones and Cox*, 2005] (Figure 1a). The growth rate of over 2 ppmv $yr^{-1}$ for the consecutive years of 2002–2003 is unprecedented so that the atmospheric $CO_2$ reached a new height of 376 ppmv for 2003. Although the yearly growth rate is somewhat smaller than during the short-lived 1997–98 El Niño event, the 2001–2003 growth was sustained longer so that the bi-yearly peak is highest ever when the data is smoothed with a 24 month running mean.

[3] In the meantime, the 1998–2002 drought spanned much of the Northern Hemisphere midlatitudes, with most severity in the regions of western US, southern Europe, Southwest Asia, eastern Asia and Siberia [*Waple et al.*, 2002; *Hoerling and Kumar*, 2003] (Figure 2a), with wide spread impacts such as wildfires in western US. In the following, we attempt to establish a relationship between the drought and the anomalous behavior in the carbon cycle. We use the terrestrial carbon model Vegetation-Global-Atmosphere-Soil (VEGAS) [*Zeng*, 2003; *Zeng et al.*, 2004] forced by observed precipitation [*Xie and Arkin*, 1996] and temperature [*Hansen et al.*, 1999] from Jan 1980–Apr 2004 (referred to as the forward model here). The model was run at daily time step with a horizontal resolution of 1° × 1°. The model considers only natural variability with fixed $CO_2$ and without land use. The model simulation started in 1901 with observed climate forcing and the analysis focuses on recent two decades. The forward model results are compared to atmospheric $CO_2$ inversion results of *Roedenbeck et al.* [2003], and satellite observed vegetation index NDVI [*Tucker et al.*, 2005].

## 2. Drought and $CO_2$

[4] The interannual variability in the atmospheric $CO_2$ growth rate is dominated by tropical land response to the El Niño Southern Oscillation (ENSO) due to the constructive plant and soil physiology and the spatially coherent tropical climate anomalies [*Bousquet et al.*, 2000; *Zeng et al.*, 2005] (Figure 1c). On the contrary, changes in the carbon sources and sinks in midlatitude regions tend to cancel each other, so that the overall variability is weakly correlated with ENSO and it contributes only a small fraction of the interannual variability in atmospheric $CO_2$. The modeled global land-atmosphere carbon flux variability shows general agreement with MLO $CO_2$ growth rate (Figure 1b), as well as the global flux from an atmospheric inversion study [*Roedenbeck et al.*, 2003] (Figure 1d). On regional scale, both tropical and Northern Hemisphere midlatitude show overall agreement with inversion results.

[5] However, in the drought period of 1998–2002, midlatitude land regions are largely $CO_2$ sources to the atmosphere (Figure 2b). The most pronounced source

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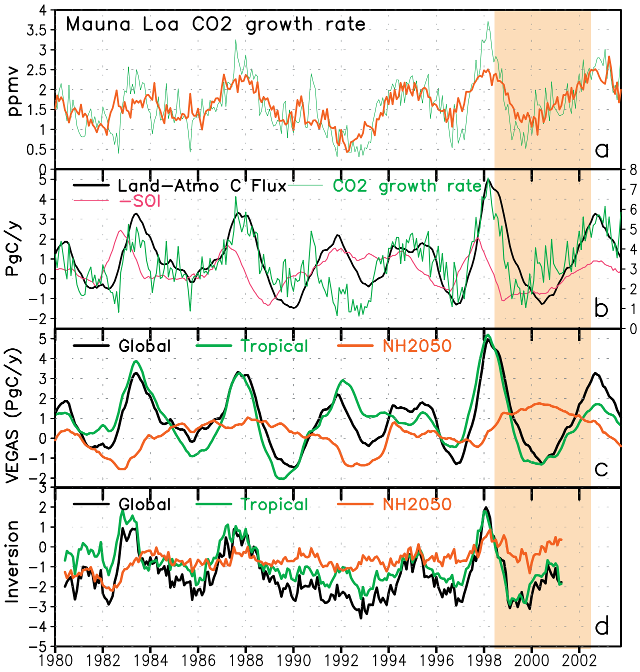

**Figure 1.** (a) Growth rate of atmospheric $CO_2$ observed at Mauna Loa, Hawaii from January 1980 to October 2003; a 12 month running mean (green) was used to remove the seasonal cycle, and a 24 month running mean (red) was used to emphasize the lower frequency variability. (b) Model simulated total land-atmosphere carbon flux (black), compared to Mauna Loa $CO_2$ growth rate (green, labeled on the right) and the negative southern oscillation index (-SOI in purple; mb labeled on the left). (c) Model simulated total land-atmosphere carbon flux (black), contribution from the tropics (20S to 20N, in green) and Northern Hemisphere midlatitude (20N to 50N, in red). (d) Same as in (c) but from the atmospheric inversion of *Roedenbeck et al.* [2003]. Seasonal cycle has been removed from all figures except otherwise noted. Shading is for the June 1998–May 2002 period during which Northern Hemisphere midlatitude released anomalously large amount of $CO_2$, modifying the normally tropically dominated ENSO response both in terms of amplitude and phasing.

anomalies are in western US, Southwest Asia and Northeast Asia, while only small sinks are found in Canada and northern Europe. Although the detailed spatial pattern of these anomalies varied somewhat over time (not shown), the persistence of this midlatitude drought and carbon cycle response is striking, as during the same 4 year period, the tropics switched sign from the large 1997–98 El Niño to 1999–2001 La Niña and back to the modest 2002–2003 El Niño (Figure 1c).

[6] Over most of the period, the Northern Hemisphere land between 20N and 50N is a nearly constant source releasing 1.3 PgC $yr^{-1}$ more relative to the 1980–98 average. The inversion for the same region (Figure 1d) shows similar trend, with an anomalous flux from 1998–2001 larger than any other time during the 22 year period of the inversion. In particular, carbon flux changed from a 1980–98 mean sink of 0.7 PgC $yr^{-1}$ to nearly neutral for 1998–2001, with excursions as source in 1998 and 2001. Part of the forward-inversion difference may be that drought impact was partially alleviated by heavy land management such as irrigation in these regions. Since the forward model did not include anthropogenic $CO_2$ emission and uptake nor oceanic effects, the modeled total land-atmosphere flux is overall shifted compared to inversion so that only the relative changes are comparable.

[7] Another clue of the importance of the midlatitude drought on the carbon cycle comes from the timing of the events. Typically, MLO $CO_2$ growth rate correlates well with the southern oscillation index (SOI, an atmospheric pressure index for ENSO) with maximum correlation 0.59 at a lag of 5 months [*Zeng et al.*, 2005] (Figure 1b). This lag is due to the delayed response in hydrology and biological activity to ENSO climate anomalies in the tropics. During 1998–2003, this normality was disrupted by the midlatitude carbon release so that $CO_2$ recovery to higher values after 1999–2001 La Niña was several months earlier than usual. For instance, there is an early rise in MLO $CO_2$ growth rate in 2000, and the peak during 2002–2003 slightly leads SOI, rather than the normal 5 month lag. Should the Northern Hemisphere anomalies be zero during 1998–2002, the tropical anomaly alone would have produced a significantly smaller $CO_2$ increase (Figure 1c), whereas observation shows 2–3 year unprecedented growth in $CO_2$.

## 3. Regional Contributions and Mechanisms

[8] The overall agreement between model simulated land-atmosphere carbon flux and MLO $CO_2$ growth rate (Figure 1b) suggests the usefulness of further analysis of regional characteristics and mechanisms. The modeled leaf area index (LAI; Figure 3a) follows precipitation closely with reduction in western US and northern Mexico, Southwest Asia and East Asia, while LAI increased in northeastern Canada and central Europe. The LAI increase in the latter two regions, is partly due to warming (Figure 3f) because temperature is a limiting factor for growth, especially in northeastern Canada. The modeled LAI shows a general agreement with the satellite observed normalized

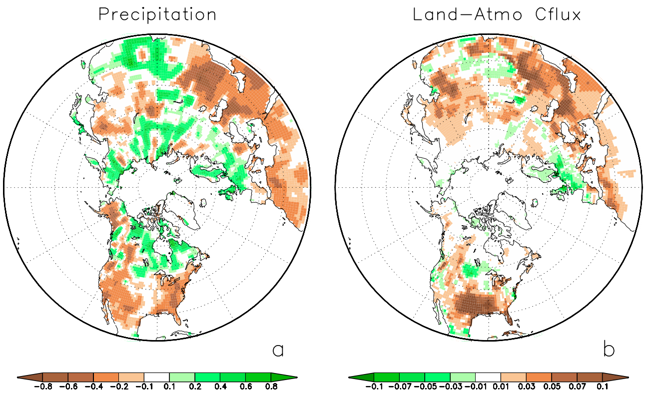

**Figure 2.** Anomalies for the period June 1998–May 2002 relative to the climatology of Jan 1980–Dec 2003 for (a) precipitation [*Xie and Arkin*, 1996] normalized by local standard deviation, (b) VEGAS modeled land-atmosphere $CO_2$ flux (kgC $m^{-2}$ $yr^{-1}$).

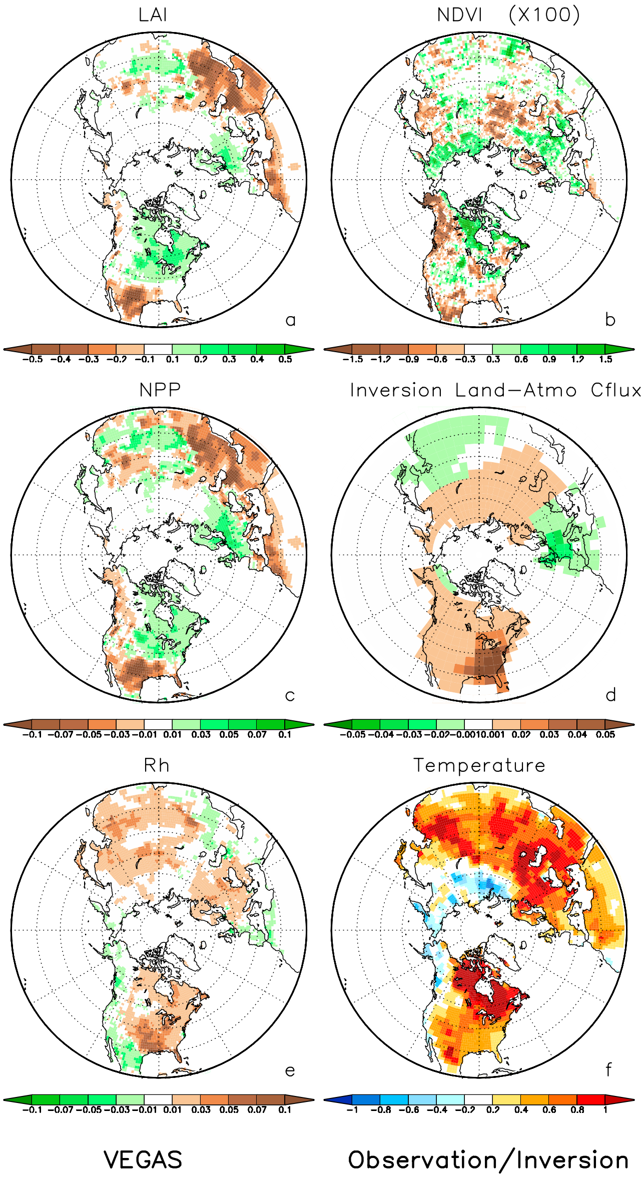

**Figure 3.** Anomalies of the period June 1998–May 2002 for (a) modeled leaf area index (LAI); (b) observed normalized difference vegetation index (NDVI); (c) modeled net primary production (NPP, kgC $m^{-2}$ $yr^{-1}$); (d) land-atmosphere flux from inversion of *Roedenbeck et al.* [2003] with 11 $CO_2$ stations (kgC $m^{-2}$ $yr^{-1}$) for 1998–2001; (e) modeled soil respiration ($R_h$, kgC $m^{-2}$ $yr^{-1}$); (f) observed surface air temperature (Kelvin).

difference vegetation index [*Tucker et al.*, 2005] (NDVI), but some differences exist particularly in Southwest Asia where reduced NDVI is somewhat north of the modeled LAI. Because the spatial anomaly patterns varied over time [*Lotsch et al.*, 2005], modeled LAI and NDVI may compare better on a year to year basis. More importantly, land use and management that was not included in the model likely have modified the natural response significantly. The general agreement in these regions is in a sense remarkable, suggesting natural climate variability nonetheless manifests itself prominently.

[9] The simulated anomalies in net primary productivity (NPP) in the Northern Hemisphere midlatitude largely follow the precipitation change. However, the spatial extent of regions with reduced NPP is larger while the area with positive NPP anomalies shrank (see Figures 3c and 2a). This is mostly due to the enhanced autotrophic respiration in response to general warming over this period (Figure 3f). This tendency is further enhanced in the total land-atmosphere carbon flux (Figure 2b) because heterotrophic soil respiration (Figure 3e) also increased in response to the warming. As a result, the Northern Hemisphere midlatitude was predominantly a $CO_2$ source to the atmosphere during 1998–2002 with a spatial extent larger than the area affected by reduced precipitation.

[10] Regional patterns from the inversion [*Roedenbeck et al.*, 2003] (Figure 3d) indicate that from May 1998 to October 2001, most of North America is a carbon source especially in the US, and a moderate carbon sink in central Europe, consistent with our forward model (Figure 2c). The inversion also shows a band of source covering southwest to central and East Asia, albeit very weak compared to modeled anomalies. The inversion may not resolve the sub-continental variations especially in Eurasia due to the lack of $CO_2$ station there.

[11] From 1980 to 2003, the VEGAS land-atmosphere carbon flux shows high correlation with precipitation

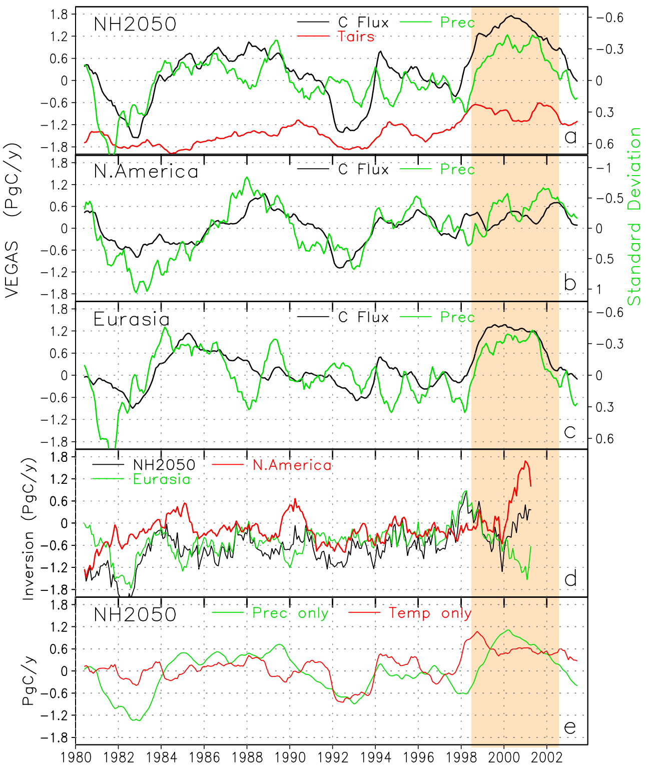

**Figure 4.** Observed precipitation (normalized by standard deviation; green) and temperature (red; not labeled: the range from minimum to maximum is 1.6 Kelvin), and VEGAS modeled land-atmosphere carbon flux (black) for (a) Northern Hemisphere midlatitude (20N–50N); (b) North America 20N–50N; (c) Eurasia 20N–50N. Also plotted in (d) is carbon flux for the same three regions from the inversion. (e) Modeled Northern Hemisphere midlatitude C flux from two sensitivity experiments using precipitation only or temperature only as forcing.

(Figures 4a–4c), and different regions differ in their detailed temporal evolutions. The drought in Eurasia (Figure 4c) started early and peaked in 1999–2000, with largest contribution from Southwest Asia for the first half, and significant contribution from Northeast Asia for the latter half (not shown). In contrast, drought in western US occurred between 2000 and 2003. Similar to the forward model, the atmospheric inversion shows an anomalous increase early in 1998 from Eurasia and another increase from North America in 2000–2001. However, these two events are further apart in time in the inversion, so that the total flux has a minimum in 1999, while the forward model has a more sustained peak from 1998 to 2002.

[12] Temperature also played an important role during 1998–2002 and in the overall evolution. For instance, the total midlatitude carbon flux during 1998–2002 is 0.7 PgC $yr^{-1}$ larger than the period 1984–1989, while precipitation is only modestly smaller (Figure 4a). This is partly because the recent drought hit the more sensitive semi-arid regions, and partly because the long-term warming trend leads to more respiration in the 1998–2002 period so that the net carbon flux is significantly higher. The importance of warming on carbon loss can be seen more clearly in two model sensitivity experiments in which either precipitation or temperature alone was used to force the physical land-surface and the carbon model (Figure 4e). During the 1998–2002 period, temperature-induced carbon release had a somewhat smaller peak amplitude but lasted longer than the precipitation-induced anomalies. Interestingly, temperature effect was significantly smaller during previous periods such as 1984–1989, another indication that the recent drought was unusual. The pathway by which warming influences carbon flux is through the direct effect of more respiration loss, and an indirect effect as higher temperature leads to larger evaporation and more severe drought [*Wetherald and Manabe*, 1995].

## 4. Conclusions

[13] While climate models generally predict midlatitude drying under global warming [*Wetherald and Manabe*, 1995], the changes in precipitation patterns and subsequent terrestrial carbon response are highly uncertain [*Zeng et al.*, 2004]. Our results suggest that the 1998–2002 midlatitude drought was a response to reduced precipitation and increased temperature, with widespread consequences to the terrestrial ecosystem and the global carbon cycle, highlighted by the anomalous increase in atmospheric CO2 growth rate in recent years.

[14] The spatial extensiveness of 1998–2002 midlatitude drought has been attributed to a synergy of surface temperature changes across the tropical oceans. In addition to the usual changes associated with a La Niña cold event in the eastern Pacific ocean, this wide-spread drought was significantly influenced by warming in the western Pacific and the Indian ocean [*Hoerling and Kumar*, 2003]. Although not a perfect analog of global warming, since such conditions may become more likely [*Stott et al.*, 2004], this event provides a glimpse into the possible future carbon cycle response to climate change.

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