11-2005

Interannual variability in North American grassland biomass/productivity detected by SeaWinds scatterometer backscatter

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Recommended Citation

Frolking, S., M. Fahnestock, T. Milliman, K. McDonald, and J. Kimball (2005), Interannual variability in North American grassland biomass/productivity detected by SeaWinds scatterometer backscatter, Geophys. Res. Lett., 32, L21409, doi:10.1029/2005GL024230.

Interannual variability in North American grassland biomass/productivity detected by SeaWinds scatterometer backscatter

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Received 2 August 2005; revised 13 September 2005; accepted 6 October 2005; published 9 November 2005.

[1] We analyzed 2000–2004 growing-season SeaWinds Ku-band microwave backscatter and MODIS leaf area index (LAI) data over North America. Large anomalies in mid-growing-season mean backscatter and LAI, relative to 5-year mean values, occurred primarily in the western Great Plains; backscatter and LAI anomalies had similar spatial patterns across this region. Backscatter and LAI time series data for three $\sim 10^3$ km^2 regions in the western Great Plains were strongly correlated ($r^2 \sim 0.6$–0.8), and variability in mid-growing season values was well-correlated with annual precipitation (October through September). The results indicate that SeaWinds backscatter is sensitive to interannual variability in grassland biomass/productivity, and can provide an assessment that is completely independent of optical/near-infrared remote sensing instruments. **Citation:** Frolking, S., M. Fahnestock, T. Milliman, K. McDonald, and J. Kimball (2005), Interannual variability in North American grassland biomass/productivity detected by SeaWinds scatterometer backscatter, *Geophys. Res. Lett.*, *32*, L21409, doi:10.1029/2005GL024230.

1. Introduction

[2] Grassland annual net primary productivity (NPP) across the central U.S. strongly correlates with annual precipitation, and the relative interannual variability in NPP increases with decreasing precipitation [*Sala et al.*, 1988]. Grassland ecosystems have larger relative and absolute interannual variability in aboveground net primary productivity than forest, desert, or arctic/alpine sites [*Knapp and Smith*, 2001]. In a field manipulation study in Kansas, *Fay et al.* [2003] found that native tallgrass prairie aboveground NPP was reduced by either decreased total rainfall during the growing season or by increased intervals between rainfalls with no change in total growing-season rainfall.

[3] Space-borne optical/near-infrared (NIR) remote sensing has been used in many studies to evaluate regional vegetation productivity [e.g., *Hicke et al.*, 2002]. Optical/NIR vegetation indices (e.g., the normalized-difference vegetation index or NDVI) exhibit significant sensitivity over a range in annual precipitation. *Wang et al.* [2001, 2003] found a strong correlation between mean annual precipitation and the NDVI gradient across Kansas (precipitation range $\sim$ 450–1200 mm/y), and that most of the year-to-year variation in spatial patterns of growing season average NDVI was explained by precipitation during the growing season and the previous seven months.

[4] Optical/NIR reflectances have been combined with radiative transfer modeling to estimate vegetation structural properties such as LAI [*Myneni et al.*, 2002]. *Fensholt et al.* [2004] found that the seasonal pattern and interannual variability in the MODIS LAI product matched field LAI data from grassland/savanna sites in Senegal (annual precipitation $\sim$ 200–500 mm y^{-1}), though MODIS LAI magnitude was higher than measured in the field.

[5] Ku- and C-band microwave scatterometers have demonstrated sensitivity to the spatial variability and temporal dynamics of soil moisture [e.g., *Magagi and Kerr*, 1997; *Wagner et al.*, 1999; *Wagner and Scipal*, 2000] and growing season vegetation dynamics [e.g., *Frison and Mougin*, 1996; *Magagi and Kerr*, 1997; *Hardin and Jackson*, 2003; S. Frolking et al., Evaluating SeaWinds scatterometer backscatter sensitivity to growing season vegetation dynamics across a range of ecosystem types, submitted to *Journal of Geophysical Research*, 2005, hereinafter referred to as Frolking et al., submitted manuscript, 2005]. This sensitivity arises from the strong dependence of microwave backscatter to surface dielectric properties, which are highly correlated with the water content of vegetation and surface soil layers, and to the fact that Ku- and C-band wavelengths (2.1 cm and 5.7 cm, respectively) are similar to characteristic leaf lengths, increasing the interaction strength between the electromagnetic field and the leaves, and hence the radar backscatter sensitivity to the canopy [*Ulaby et al.*, 1982; *Elachi*, 1987].

[6] *Hardin and Jackson* [2003] analyzed year 2000 SeaWinds Ku-band data for five large savanna sites in South America, and found that monthly mean backscatter and NDVI were well correlated. The correlations were improved somewhat by adding precipitation and soil type in a multiple linear regression; temperature had no significant impact on the correlation. Frolking et al. (submitted manuscript, 2005) analyzed multiyear SeaWinds backscatter data for 27 sites representing a range of ecosystem types around the world; for most deciduous vegetation sites there was a clear growing-season response of backscatter to vegetation that correlated with 8-day interval MODIS-derived LAI. Analysis of multi-year backscatter and LAI data across North America showed moderate to strong correlations between the two time series for broadleaf vegetation across eastern North America (Frolking et al., submitted manuscript, 2005). Seasonality in grassland backscatter has also been observed with the ERS-1 C-band scatterometer [*Frison and Mougin*, 1996; *Abdel-Messeh and Quegan*, 2000; *Wagner et al.*, 1999]. None of these studies quantified interannual variability in backscatter.

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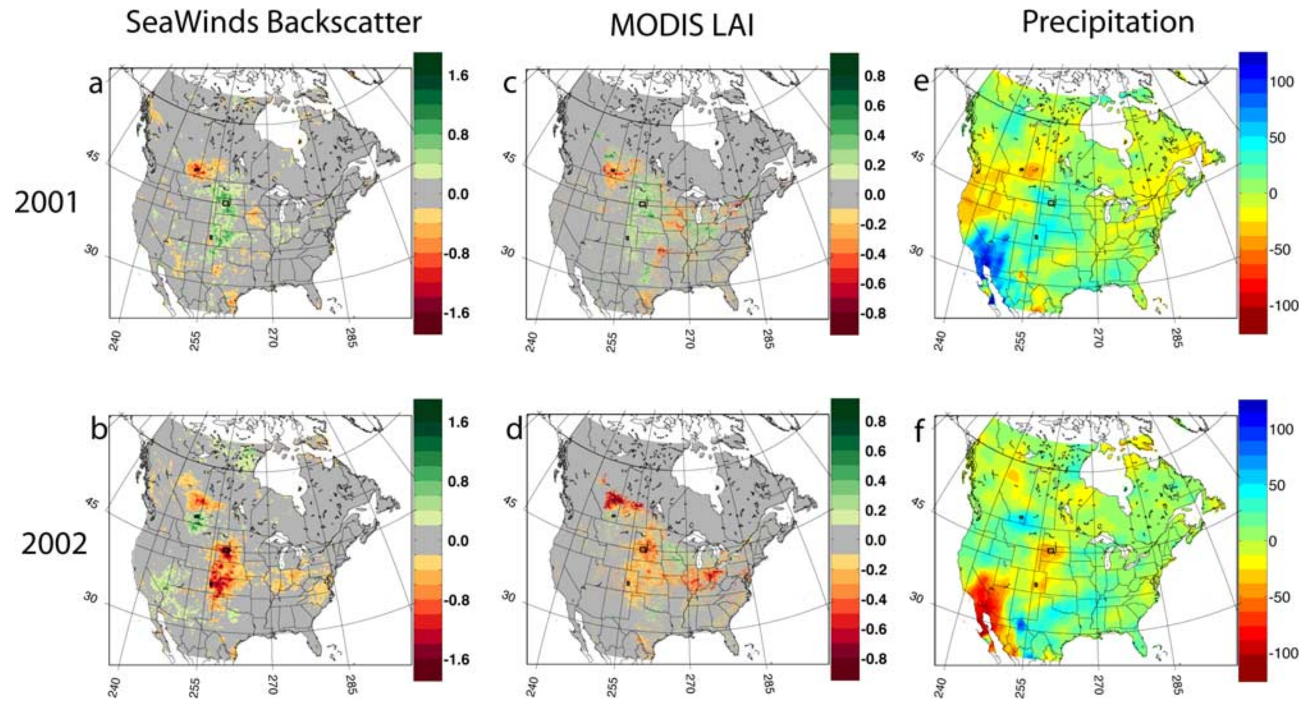

Figure 1. Grid cell difference between (a) 2001 and (b) 2002 growing season mean SeaWinds backscatter (dB) and 5-yr (2000–04) mean (dB); grid cell difference between (c) 2001 and (d) 2002 growing season mean MODIS LAI and 2000–04 mean, normalized by 5-year mean value (dimensionless); and grid cell percent difference between (e) 2001 and (f) 2002 accumulated precipitation (Nov.–Aug.) and 3-year mean (2000–02). Grid cell resolution for all panels is ~4.5 km.

[7] We analyzed multi-year SeaWinds backscatter and MODIS-derived LAI data for North America to determine if there are coherent spatial patterns in interannual variability in these datasets. Annual deviations in growing-season radar backscatter and LAI were assessed for 2000–04, and the relative impact of precipitation variability on sensor retrievals was evaluated.

2. Data and Methods

[8] We processed three data sets for North America:

[9] 1) SeaWinds backscatter ($\sigma°$) data, 2000–04, from the NASA Scatterometer Climate Record Pathfinder database (scp.byu.edu). We used the resolution-enhanced Scatterometer Image Reconstruction 'egg' images, which incorporate both ascending and descending orbital passes and are a composite 4-day average backscatter time series [*Early and Long*, 2001]. This dataset defined the spatial domain and grid cell size (~4.5 km) (Figure 1), and was temporally averaged to 8-days to match the MODIS LAI data.

[10] 2) MODIS-derived 8-day composite 1-km resolution LAI (MOD15A2), 2000–04, from the NASA Earth Observing System Data Gateway (delenn.gsfc.nasa.gov; *Myneni et al.* [2002]). For spatial aggregation, the center of each 1-km MODIS pixel was identified within its associated SeaWinds grid cell. We averaged only LAI values with a quality control flag ≤ 1, obtaining a single LAI value for each SeaWinds grid cell and 8-day composite during 2000–2004.

[11] 3) Six-hourly surface air temperature and precipitation data, from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA–40 reanalysis for Oct. 1999–Aug. 2002 (ecmwf.int/products/data/archive/). Temperature was averaged to daily means and precipitation was accumulated to a 10-month total (e.g., growing season 2000 total equaled the sum of Nov. 1999 through Aug. 2000) for each ERA-40 grid cell ($\sim 2° \times 2°$), and these were spatially disaggregated by two-dimensional cubic interpolation to the center of each SeaWinds grid cell.

[12] Daily average ERA-40 temperature was used to approximate the non-frozen seasons for each grid cell from Jan. 2000 through Aug. 2002. For Sept. 2002 through Dec. 2004, with no ERA-40 data, we used an average non-frozen period from fall 1999 through spring 2002. We defined the mid-growing season as the middle half of the interval between the onset and end of the growing season. We then calculated mid-growing season average backscatter and LAI for each grid cell, and annual deviations of these results from the 5-year (2000–04) mid-season means.

3. Results

[13] The domain had 829,709 land grid cells (Figure 1). Large deviations from the 5-yr mean mid-growing season backscatter (i.e., >0.6 dB) were most evident in the western Great Plains in all years, and had a distinct reversal in sign between 2001 and 2002 (Figures 1a and 1b). Throughout eastern, western, and northern North America, annual deviations from the 5-yr mean mid-growing season backscatter were generally small (i.e., <0.4 dB) in all years. A similar spatial pattern and temporal response (intensity and sign) was also evident as the dominant signal of deviations in mid-growing season LAI (Figures 1c and 1d). The spatial

Table 1. Total Annual Precipitation[a] and Percent Difference From 6-Year Mean

Region	Domain	1999	2000	2001	2002	2003	2004
Southern Alberta[b]	110.8°–111.5°W; 50.0°–50.5°N	317 (+0%)	205 (−35%)	177 (−44%)	544 (+72%)	272 (−14%)	384 (+21%)
Western Dakotas[c]	101.0°–102.2°W; 44.6°–45.5°N	615 (+44%)	400 (−6%)	496 (+16%)	286 (−33%)	377 (−12%)	386 (−10%)
Southeastern Colorado[d]	104.0°–104.3°W; 38.2°–38.9°N	532 (+36%)	344 (−12%)	431 (+10%)	234 (−40%)	391 (+0%)	412 (+5%)

[a]October–September in mm.
[b]Precipitation is the average of monthly data from Lethbridge, AB, and Medicine Hat, AB, airport weather stations; http://climate.weatheroffice.ec.gc.ca/climateData/canada_e.html.
[c]Precipitation is the average of monthly values for climatic divisions 7 and 8 in North Dakota and 1 and 2 in South Dakota; http://lwf.ncdc.noaa.gov/oa/climate/onlineprod/drought/ftppage.html#dd.
[d]Precipitation is the average of monthly values for the Colorado climatic divisions 1 and 3; http://lwf.ncdc.noaa.gov/oa/climate/onlineprod/drought/ftppage.html#dd.

pattern of negative and positive backscatter and LAI deviations for the Great Plains region (Figures 1a–1d) were largely consistent with precipitation anomalies (Figure 1e and 1f). Areas with positive (negative) precipitation anomalies showed positive (negative) LAI and backscatter responses relative to 5-yr averages.

[14] We selected 3 regions ($\sim 10^3 - 10^4$ km^2) in southeastern Colorado, the western Dakotas, and southern Alberta (Table 1), showing relatively strong annual deviations in backscatter, LAI, and precipitation; all are classified as predominantly grassland in the MODIS-derived land cover product [*Friedl et al.*, 2002]. We spatially averaged 8-day backscatter and LAI within each sub-region, and aggregated monthly station precipitation data to annual totals (Table 1); for each region, annual precipitation varied by at least ±35% from the 6-year mean (1999–2004). We used station data for this small-scale study to avoid any precipitation biases that might be introduced in a global re-analysis.

[15] There is a strong correlation between growing season backscatter and LAI time series for all 3 regions (Figure 2; r^2 = 0.75, 0.59, and 0.80 for southern Alberta, western Dakotas, and southeastern Colorado, respectively; $p < 0.0001$ in all cases), also evident in mid-season (peak) values for all 3 sites. This variability corresponds directly to the accumulated precipitation of the growing season and the previous winter (Figure 2). In a dry year (2002) for southeastern Colorado and the western Dakotas, LAI values were about half those of the preceding wet years and backscatter values were about 2 dB lower than the preceding wet years (Figure 2b and 2c). However, 2002 was a wet year in southern Alberta, and LAI doubled and backscatter increased by 3 dB over the preceding dry years (Figure 2a).

[16] A positive precipitation anomaly in 2002 in southern Alberta/Northern Montana seems to have generated a stronger backscatter than the LAI anomaly (Figures 1b, 1d, and 1f). However, closer examination of the southern Alberta region (Table 1) shows that the pattern and magnitude of the LAI and backscatter signals are very similar (Figure 2). For the larger surrounding region, despite the difference in magnitude, there is a similar spatial pattern (difficult to see in Figure 1). The magnitude difference cannot be explained by the data we have examined. While the stronger backscatter response could indicate greater sensitivity to soil moisture, vegetation in a semi-arid region also responds vigorously to increased soil moisture, and therefore so should LAI (see Figure 2). Other factors that might contribute to the difference include any differences in how agricultural land management (grazing, mowing, harvest) affects the two signals, or different responses of vegetation biomass (microwave sensitivity) and vegetation color (optical/NIR sensitivity).

[17] For the southern Alberta region, October–June accumulated precipitation in 2002–03 and 2003–04 was 50% higher than in 1999–2000 and 2000–01, which can explain the higher LAI and backscatter values in early summer in 2003 and 2004. July–August precipitation in the southern Alberta region in 2002 was 106 mm, while in

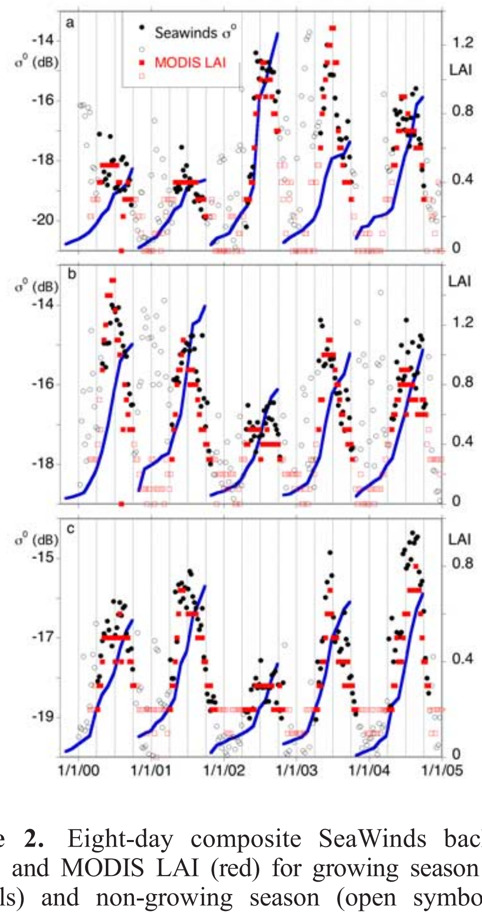

Figure 2. Eight-day composite SeaWinds backscatter (black) and MODIS LAI (red) for growing season (closed symbols) and non-growing season (open symbols) and accumulating monthly precipitation (blue lines; October through September), all averaged over regions in (a) southern Alberta, (b) the western Dakotas, and (c) southeastern Colorado (see Table 1 for domains and precipitation data sources). Full-scale precipitation is 600 mm for all panels.

2003 it was 11 mm. Both backscatter and LAI maintained high values in 2002 from June through early September, while in 2003 both backscatter and LAI declined significantly during the second half of July (Figure 2a). However, monthly precipitation totals cannot explain why summer 2003 backscatter and LAI were as high as in 2002, and significantly higher than in 2004, as 2002–03 precipitation was much less than 2001–02 (Figure 2a); these differences in LAI and backscatter may be due to the distribution of precipitation during the summer months [*Fay et al.*, 2003], and/or to other factors.

[18] In the southwestern U.S., the precipitation anomaly correlates with the LAI anomaly signal and not the backscatter signal (Figure 1). Growing season LAI and backscatter are not temporally correlated in this arid, mountainous region (Frolking et al., submitted manuscript, 2005); this may be due sparse vegetation cover and associated signal complications arising from exposed bare soil, or to the inadequacy of defining growing season only by temperature and not precipitation. To the extent that there is a vegetation canopy dynamics signal in arid regions, the scatterometer does not seem to be able to identify it clearly.

4. Discussion

[19] Despite a strong growing season signal in SeaWinds backscatter across most of central and eastern North America (Frolking et al., submitted manuscript, 2005), mean mid-growing season backscatter showed little interannual variability across most of this region during 2000–04. Only the western Great Plains had large interannual variability in backscatter, consistent with the ecosystem productivity analysis by *Knapp and Smith* [2001] that showed grassland having the greatest interannual variability. It is also generally consistent with the observed pattern of interannual variability in mid-growing season MODIS-derived LAI. The spatial coherence of LAI and backscatter variability generally matched the sign and pattern of interannual variability in precipitation, consistent with precipitation being a dominant control on grassland productivity [*Sala et al.*, 1988].

[20] This variability can have socio-economic as well as eco-climatic implications. In Colorado, 2002 hay production was only 65% of the 1999–2001 mean, due to reductions in both yield (down 25%) and harvested area (down 13%), while in South Dakota, 2002 hay production was 56% of the 1999–2001 mean; hay prices in these states were 36% higher in 2002 than the 1999–2001 mean (http://www.nass.usda.gov/QuickStats/#top). This is consistent with the low backscatter and LAI values in 2002 relative to 2000 and 2001 for the southeastern Colorado and western Dakota regions (Figure 2).

[21] Both SeaWinds backscatter and MODIS LAI originate from the interaction of electromagnetic radiation with the vegetated land surface. However, the instruments measure within distinctly different frequency spectra (frequencies differ by $\sim 10^5$), so each provides unique measures of land surface attributes. Optical/NIR sensors provide measures of photosynthetic leaf area associated primarily with vegetation chemistry and color, whereas microwave radar backscatter is sensitive to vegetation canopy structure (e.g., sizes, shapes, number density and spatial distribution of canopy constituents) and moisture (i.e., dielectric constant) [*Elachi*, 1987]. The two instruments provide completely independent measures of the regional impact of precipitation variability on grassland phenology and relative productivity, increasing confidence in the data and interpretation.

[22] Microwave backscatter is largely insensitive to cloud cover and atmospheric aerosols that constrain optical/NIR remote sensing over much of the globe. It is, however, still relatively untested for terrestrial growing season applications, and its spatial resolution is not optimal for observing human land use impacts. The synergy of coincident MODIS and SeaWinds observations offers the potential for more comprehensive global monitoring of vegetation, with a combined sensitivity to surface moisture, vegetation biomass and photosynthetic leaf area.

[23] The results here suggest that semi-arid ecosystems such as grasslands and dryland agriculture are ideal targets for exploiting this synergy. It may be possible to design observational strategies to define the impact of drought on these areas as the condition progresses. Further research is needed at this point to define the global range of Ku-band backscatter sensitivity to vegetation canopy dynamics and the relative contributions of vegetation properties to the aggregate radar backscatter temporal response.

[24] **Acknowledgments.** Resolution-enhanced SeaWinds backscatter data were from the NASA Scatterometer Climate Record Pathfinder project (www.scp.byu.edu). This work was supported by NASA's Terrestrial Ecology Program (NAG5-1126), and the NASA Interdisciplinary Science Program (NAG5-10135).

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