**ASCAT Metop-A Diurnal Backscatter Observations of Recent
Vegetation Drought Patterns over the Contiguous U.S.: An
Assessment of Spatial Extent and Relationship with
Precipitation and Crop Yield**

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Abstract

We analyzed 4-years of Advanced Scatterometer (ASCAT) incidence angle normalized C-band backscatter, Next-Generation Radar (NEXRAD) precipitation and United States Department of Agriculture (USDA) crop yield data over the contiguous United States (U.S.). Large negative anomalies in backscatter are evident over the U.S. during the 2011 and 2012 growing seasons, coincident with two instances of severe drought. The backscatter anomalies were correlated with diminished growing season precipitation and with reduced crop yields reflecting where drought-induced impacts on above-ground biomass production occurred. During periods of acute drought, differences in diurnal backscatter were reduced and in some cases reversed reflecting diminished nocturnal leaf rehydration. The results indicate that the C-band, VV-polarized ASCAT backscatter data is sensitive to interannual variability in agricultural productivity rather than soil moisture, and can offer an important geophysical monitoring tool capable of identifying and assessing drought-related vegetation responses independent of and complementary to satellite optical/near-infrared remote sensing data. This technique is flexible and adaptable, providing a capability to address region-specific needs. The twice-daily, weather independent and near-real time global monitoring capabilities of ASCAT and similar microwave instruments (e.g. RapidSCAT, Sentinel-1) can help improve drought preparedness and mitigation planning allowing improved water resource management for agriculture on the local as well as the state level.

41 Introduction

42 Spring and summer temperatures during 2011 and 2012 for the contiguous United
43 States (U.S.) were extraordinarily high, setting numerous climatological records [*Karl et*
44 *al.*, 2012]. While July 2012 was the hottest month on record for the U.S., every month
45 from June 2011 through September 2012 exhibited above-normal temperatures, which in
46 itself was unprecedented [*Karl et al.*, 2012]. The unusually warm spring of 2012 led to a
47 false spring (i.e. premature green-up), putting the vegetation at high risk for late frost and
48 drought [*Ault et al.*, 2013]. The unusually hot summer temperatures combined with
49 record low rainfall caused the manifestation of the 2011 southern plains drought and the
50 much worse 2012 summer drought across the U.S. Corn Belt [*Karl et al.*, 2012].

51 Because chlorophyll in productive (i.e. healthy) vegetation has unique absorption
52 and reflection spectra in the visible and near-infrared (NIR) region, the detection of
53 widespread drought patterns has been commonly accomplished using spaceborne, passive
54 optical/NIR instruments. For example, the Drought Severity Index (DSI) of *Mu et al.*
55 [2013] combines the Moderate Resolution Imaging Spectroradiometer (MODIS)
56 Normalized Difference Vegetation Index (NDVI) with the ratio of evapotranspiration
57 (ET) to potential ET in near-real time to inform decision makers on regional drought
58 assessment and mitigation efforts. Likewise, *Ault and Henebry* [2013] calculated the
59 normalized anomalies of Thermal Time to Peak NDVI for the 2012 U.S. summer drought
60 showing that the cumulative effects of anomalous early spring warmth in 2012 were
61 mostly visible across the corn belt. However, while optical/NIR instruments provide
62 invaluable insight into large-scale drought impacts on vegetation greenness, additional
63 lines of remote sensing evidence are needed to enhance optical/NIR satellite-based

drought monitoring capabilities assessing spatial extent and potential cost of drought impacts on agricultural/biomass productivity (i.e. crop yield).

Such evidence can perhaps be provided through application of multiple years of high-frequency active microwave backscatter instruments for the detection, monitoring and quantification of large-scale drought impacts on cropland vegetation [Emmerik and Steele-Dunne, 2014]. Spaceborne K_u- and C-band microwave scatterometers have demonstrated sensitivity to seasonal vegetation dynamics showing moderate to strong correlations with optical/NIR vegetation indices in grasslands, deciduous forests and croplands [FRISON and MOUGIN, 1996; Wagner *et al.*, 1999a; Hardin and Jackson, 2003; Frolking *et al.*, 2006; Naeimi *et al.*, 2009], including the assessment of drought-induced biomass patterns across the U.S. [Frolking *et al.*, 2005], Amazonia [Frolking *et al.*, 2011] and sensitivity to deforestation in pan-tropical humid forests [Frolking *et al.*, 2012].

The sensitivity of radar backscatter to drought arises from the dependence of radar backscatter to water content and structural properties of land surface components [Ulaby *et al.*, 1982], including soil-, leaf-, stalk- and stem moisture content and the size and orientation of vegetation elements. Backscatter modeling has demonstrated the physical link that exists between K_u-band scatterometer data and optical/NIR vegetation indices in deciduous forest and croplands [Frolking *et al.*, 2006]. Similar results were obtained over cropland, forest and grasslands in Spain using the C-band European Remote Sensing (ERS)-1 scatterometer data [Wagner *et al.*, 1999a], whereas C-band backscatter temporal variability was more strongly associated with soil moisture than vegetation dynamics than in the K_u-band case. However, in the West African savanna, ERS-1/2 identified a

systematic backscatter difference between morning and evening overpasses which was explained by diurnal variations in the dielectric properties (i.e. vegetation water content) of the canopy coincident with the onset of water stress [Friesen *et al.*, 2012; Steele-Dunne *et al.*, 2012]. In a dense wheat stand in France, a statistically significant but moderate soil moisture signal was found at C- to K-band provided that low incidence angles were employed for observation [Calvet *et al.*, 2011]. Multiangular backscatter data for the abovementioned ERS studies were normalized to an incidence angle of 40°. Such microwave measurements are generally suitable for surface soil moisture retrieval [Wagner *et al.*, 1999b, 2013; Naeimi *et al.*, 2009].

Here we evaluate the capacity of the European C-band and VV-polarized Advanced Scatterometer (ASCAT) instrument for drought detection over the contiguous U.S. during two instances of severe drought in 2011 [Hoerling *et al.*, 2013] and 2012 [Ault *et al.*, 2013]. We investigate whether the previously demonstrated application of the Ku-band Seawinds-on-QuikSCAT (QSCAT) instrument for the assessment of drought-induced biomass patterns in the U.S. [Frolking *et al.*, 2005] also applies to the longer-wavelength C-band ASCAT. To do so, we first employed a simple method for deriving the normalized backscatter coefficient (σ^0 , sigma-0) at a reference incidence angle of 54°, equal to that of the Ku-band, VV-polarized channel of QSCAT to facilitate comparison with the QSCAT results. We analyzed the data stream of four years of daily, VV-polarized and incidence angle normalized ASCAT backscatter data. We derived annual summer growing season backscatter deviations from the 4-year mean, separately for morning (9:30 Local Solar Time (LST)) and evening (9:30 LST) backscatter observations, and compared the results with annual anomalies obtained from accumulated

growing season precipitation based on data provided by the Next-Generation Radar (NEXRAD). We compared our results to weekly maps of drought conditions produced by the U.S. Drought Monitor in August of 2011 and 2012. A relationship between summer growing season backscatter amplitudes and growing season precipitation, and above-ground biomass production was established using the U.S. Department of Agriculture (USDA) crop yield data as a surrogate for biomass productivity.

Data and Methods

We analyzed four independent data sets for assessing recent drought patterns in the contiguous U.S.:

1) Daily files, December 2008 – September 2012, consisting of 3-minute National Oceanic and Atmospheric Administration (NOAA) Level 2 (L2) ASCAT σ^0 data segments downloaded from the NOAA ASCAT near real-time processing system located at the National Environmental Satellite, Data, and Information Service (NESDIS). We chose the 25-km SZR-type, C-band, VV-polarized ASCAT sigma-0 swath data. A fundamental difficulty with utilizing these data for monitoring drought and associated biomass dynamics is additional variability in the backscatter caused by changes in the angle of incidence [Kennett and Li, 1989; Frison and Mougin, 1996; Wagner *et al.*, 1999a; Pathe *et al.*, 2009]. Following from prior results of Long and Hardin [1994], a method for deriving the normalized σ^0 coefficients at a reference incidence angle of 54° , equal to that of the VV-polarized QSCAT, was developed. The method is based on a simple forward model of the form:

$$\sigma^0(\theta) = \alpha + \beta(\theta - 54^\circ) \quad (1)$$

where $\sigma^0(\theta)$ is backscatter acquired at incidence angle θ , α is the backscatter in dB normalized to 54° and β is a slope factor approximating the change in σ^0 with incidence angle (θ) in dB/ $^\circ$. We combined a 56-day moving window approach with grid cell-wise linear regression analysis to compute time-averaged, daily α and β values by combining σ^0 measurements from each swath, overpass and all antennae regardless of look angle for all ASCAT data collected. Time-window averaged σ^0 values were computed for four 10 degree wide incidence angle bins and aggregated to the 25-km Global Cylindrical Equal-Area Scalable Earth (EASE)-grid [Brodzik and Knowles, 2002] using drop-in-the-bucket averaging (i.e. samples that fell within a grid cell were averaged together). Since σ^0 is a measure on a logarithmic scale, it must be anti-logged prior to calculating arithmetic means. The slope factor β for each day was obtained from binned σ^0 via least-squares linear fits and the resulting slope image from the regression analysis of all grid cells was kept. The resulting time-averaged slope images were input to equation (1) and the VV-polarized and incidence angle normalized backscatter α at 54° for each day, swath and satellite overpass between January 2009 and August 2012 was computed. The output of (1) was gridded to the EASE-grid using drop-in-the-bucket averaging with no swath averaging. The resulting data set was temporally averaged to monthly means for both ascending and descending orbits.

2) Hourly/6-hourly precipitation analysis, January 2009 – August 2012, extracted from NEXRAD and rain gauge observations downloaded from the Earth Observatory Laboratory located at the National Center for Atmospheric Research (NCAR/EOL). This analysis, known as Stage IV, is based on local 4km polar-stereographic grid Stage III data. The National Center for Environmental Prediction (NCEP) mosaicked this product

into a national product (the Stage IV), thereby defining the approximate domain of our study area (25°N- 49°N, 67°W-125°W). We aggregated this data to monthly precipitation totals and gridded the results to the EASE-grid following the L2 ASCAT processing.

3) National drought conditions obtained from the U.S. Drought Monitor for the weeks ending August 30th 2011 and August 28th 2012, provided by the National Drought Mitigation Center at the University of Nebraska-Lincoln, USDA and NOAA (<http://droughtmonitor.unl.edu>). Five drought intensity categories are provided through this product on a weekly basis for a general and up-to-date summary of current drought conditions across the U.S. The categories are based on input from five key indicators and numerous supplementary indicators such as the Palmer drought index, soil moisture, stream flow, precipitation and short and long-term drought indicator blends. Vector data layers for the weeks ending in August of 2011 and 2012 were downloaded to support our analysis.

4) 20 years (1982 – 2012) of U.S. and Texas-based annual corn and hay yield obtained from the USDA's National Agricultural Statistics Service (USDA-NASS). Annual summaries were downloaded directly from Quick Stats at USDA-NASS (<http://quickstats.nass.usda.gov/>).

We defined the summer growing season backscatter as the period between June and August of each year. We defined the annual total growing season precipitation from NEXRAD as all precipitation accumulated from April until August of each year. To evaluate the influence of accumulated winter precipitation on summer growing season backscatter, we combined winter and growing season precipitation, with total annual winter precipitation defined as all precipitation recorded between January and March of

each year. We then computed the average summer growing season backscatter and total growing season precipitation for each grid cell and each year. The resulting data were used to calculate the annual deviations from the 4-year backscatter and precipitation means.

Results

The study domain covers roughly 8 million square kilometer of land comprising approximately 12,800 individual EASE-grid cells (Fig. 1). The Great Plains, eastern Texas and the corn belt of the Midwestern U.S. showed the largest annual deviations from the 4-year mean summer growing season backscatter. We found two distinct, widespread and largely negative (> 0.75 dB) backscatter anomaly patterns in 2011 and 2012 across the southern plains and eastern Texas, and the northern plains and the corn belt, respectively (Fig. 1a-d). The negative backscatter anomaly of 2012 (Fig 1b and d) is also evident in the 2012 normalized peak NDVI anomaly presented by *Ault and Henebry* [2013] showing a very similar spatial pattern and temporal response. A relatively strong but positive backscatter anomaly was also evident across the northern plains in 2011 (Fig. 1a and c). Smaller annual deviations (i.e. < 0.75 dB) were observed in the remaining regions in all years. We note that the negative backscatter anomaly in 2011 and 2012 is more anomalous (by up to 0.5 dB) in the morning (Fig. 1a and b) overpass than the evening (Fig. 1c and d) overpass, consistent with diurnal backscatter observations from QSCAT during persistent drought over tropical forests in Amazonia [*Frolking et al.*, 2011]. The difference is most noticeable in 2012 (Fig. 1b and d), namely in the high

199 plains (e.g. eastern Colorado and western Kansas) and the corn belt (e.g. Illinois, eastern
 200 Iowa and northern Missouri).

201

202 Fig. 1 Grid cell difference between (a) 2011 descending (c) 2011 ascending (b) 2012 descending and (d)
 203 2012 ascending average summer (June, July, August) growing season C-band, VV-polarized and
 204 incidence angle normalized ASCAT backscatter and 4-year (2009-2012) mean; grid cell percent
 205 difference between (e) 2011 and (f) 2012 accumulated growing season (April, May, June, July, August)
 206 Stage IV, NEXRAD precipitation and 2009-12 mean; (g) week ending August 30th, 2011 and (h) week
 207 ending August 28th, 2012 drought conditions as monitored by U.S. Drought Monitor. Grid cell resolution
 208 is ~25-km, except (g) and (h) which are vector-based data. A) and B) indicate the drought-stricken
 209 regions which are outlined by dashed lines.

210 The annual backscatter anomaly patterns of 2011 and 2012 across the plains are
211 largely consistent with the annual deviations in accumulated growing season precipitation
212 (Fig 1e-f). Regions with negative (positive) backscatter anomalies correspond with areas
213 of negative (positive) growing season precipitation anomalies. In other areas, such as in
214 the southern and eastern U.S., the relationship between relatively wetter (drier) growing
215 seasons and relatively larger (smaller) summer growing season backscatter amplitudes is
216 not as clear. For instance, anomalous growing season precipitation stretching from
217 northern Arkansas to New England and Louisiana to Georgia/Florida in 2011 is
218 inconsistent in sign and magnitude with the backscatter deviations in some of these areas
219 (Fig 1a, c and e). The vegetation structure and biomass in these regions likely did not
220 respond as vigorously to the change in total growing season precipitation as did the
221 grasslands of the plains to the west. Other factors include how land management
222 (mowing, harvest) might have affected the backscatter signal in these areas.

223 The negative backscatter anomaly patterns of 2011 and 2012 are largely
224 consistent with the drought conditions indicated by the U.S. Drought Monitor for the
225 weeks ending in August of 2011 (Fig 1g) and 2012 (Fig 1h), respectively. Regions with
226 very negative backscatter anomalies tend to correspond with areas of very severe (i.e.
227 exceptional) drought. However, the negative precipitation anomaly patterns for both
228 years seem to agree more favorably with the patterns from the drought monitor, which
229 was not surprising given that precipitation is an input variable into the generation of the
230 drought monitor conditions while the backscatter observation is not.

231 To better understand the relationship between growing season precipitation and
232 average summer growing season backscatter during drought, we analyzed the monthly

233 time series progression for both observations for all years across two regions. The spatial
234 extents of the two regions are based on the outlined areas A) and B), both showing the
235 largest negative annual backscatter deviations for all years (Fig 1a-1d). To aid in the
236 interpretation of our data and to assess whether the backscatter responses within the areas
237 outlined relate to land cover and associated canopy structural differences, we stratified
238 the backscatter responses within each region based on grid cells dominated (fractional
239 coverage > 50%) by grass and cropland cover. Information regarding the distribution of
240 grass and cropland within each region was provided by the high-resolution (1-km)
241 International Geosphere-Biosphere Program (IGBP) MODIS land cover data set [*Strahler*
242 *et al.*, 1999; *Friedl et al.*, 2002] binned previously to the EASE-grid [*Knowles*, 2004].

243 **Table 1 Drought-stricken region^a A and B, their spatial extent (km²), and the 4-year mean and annual total accumulated NEXRAD growing season**
 244 **precipitation (mm) and summer growing season morning (A.M.) and evening (P.M.) ASCAT backscatter (dB). R² (coefficient of determination) is the**
 245 **relationship between accumulated growing season precipitation and A.M./P.M. summer growing season backscatter.**

Drought-Stricken Region	Areal Extent	4-Year Mean	2009	2010	2011	2012	R²
		Precipitation, A.M., P.M.	Precipitation, A.M., P.M.	Precipitation, A.M., P.M.	Precipitation, A.M., P.M.	Precipitation, A.M., P.M.	
S. Great Plains + E. Texas (A)	918,064	326, -13.32, -13.43	409, -13.05, -13.22	410, -12.69, -12.82	200, -13.99, -14.05	286, -13.54, -13.65	0.91, p<0.001
Cropland (8.1 %)	74,149	364, -12.64, -12.83	405, -12.60, -12.82	489, -11.92, -12.08	203, -13.30, -13.48	359, -12.74, -12.93	0.90, p<0.001
Grassland (59.8 %)	549,205	313, -13.75, -13.87	398, -13.40, -13.58	408, -13.07, -13.21	189, -14.51, -14.55	258, -14.04, -14.14	0.95, p<0.001
N. Great Plains + Midwestern U.S. (B)	2,220,698	434, -12.89, -13.11	429, -12.68, -12.97	507, -12.54, -12.79	510, -12.77, -13.00	290, -13.56, -13.70	0.78, p=0.004
Cropland (37.6 %)	835,118	490, -11.62, -11.84	496, -11.52, -11.79	600, -11.24, -11.47	538, -11.58, -11.81	327, -12.15, -12.29	0.85, p=0.001
Grassland (36.2 %)	803,699	343, -14.85, -15.06	322, -14.47, -14.77	401, -14.44, -14.70	418, -14.66, -14.87	231, -15.81, -15.91	0.67, p=0.013

246

247 ^a Drought-stricken region and sub regions (percent of A or B) based on the IGBP land cover information from MODIS.

248 According to the MODIS land cover classification, region A, stretching from eastern
249 Texas to the southern plains (Table 1), is predominately (68 %) occupied by grassland
250 (60 %, dominating the Texas panhandle) and cropland (8%, dominating parts of
251 Oklahoma, Kansas and eastern Texas). Region B, extending from the midwestern U.S.
252 into the northern plains (Table 1), is predominately (74 %) occupied by grass and
253 croplands both covering approximately equal areas (36 % grassland dominating the
254 northern plains in the west and 38 % cropland dominating the corn belt to the east). We
255 then spatially averaged the monthly backscatter and precipitation data for each region and
256 land cover, and aggregated the monthly values to average summer growing season
257 backscatter and total growing season precipitation for each year (Table 1).

Fig. 2 Average monthly A.M. (descending) and P.M. (ascending) ASCAT backscatter and accumulating winter and growing season precipitation (blue lines, April through August; red lines, January through August), all averaged over drought-stricken regions and sub-regions (see Fig. 1 and Table 1 for domain and spatial extent).

There is a strong seasonal backscatter signal in each region and land cover which cannot be explained by the distribution of monthly precipitation totals from January to August (Fig. 2). Instead, the monthly ASCAT backscatter responses closely follow the seasonal progression of the 8-day QSCAT backscatter and Leaf Area Index (LAI) composites over grasslands in the U.S. [Frolking *et al.*, 2005], linking the backscatter variability of the QSCAT to the seasonal development and senescence of the vegetation canopy [Frolking *et al.*, 2006]. The average summer growing season backscatter

270 amplitudes across the regions correlate well ($R^2 = 0.91$ (region A), $R^2 = 0.78$ (region B),
 271 $p < 0.01$) with accumulated growing season precipitation (Table 1, Fig. 2). Wetter (drier)
 272 growing seasons produced larger (smaller) backscatter amplitudes. However, relatively
 273 wetter winters (e.g. 2012) do not necessarily lead to larger summer backscatter
 274 amplitudes (Fig. 2). Instead, the winter season backscatter was anomalously high during
 275 wetter winters, e.g. across the southern plains and eastern Texas region (Fig. 2).

276
 277 **Fig. 3 30-year record of USDA annual corn (a) and hay (b) yield over the contiguous U.S. (solid line) and**
 278 **Texas (dotted line). Trend lines using least-square distance regression are drawn and annual yields for**
 279 **drought years 2011 (Texas) and 2012 (U.S.) are indicated.**

280 Average summer growing season backscatter variability for region A and B (Fig.
 281 2) also corresponds well with biomass productivity variations as indicated by annual crop
 282 yields for hay and corn in the U.S. and Texas (Fig. 3). Higher (lower) summer
 283 backscatter amplitudes produced higher (lower) crop yields. For instance, the severe
 284 drought of 2011 over the southern plains and eastern Texas yielded 5.8 t ha⁻¹ of corn and

2.7 t ha⁻¹ of hay, a 22-year minimum for corn and a historic 30-year low for hay in Texas. While Texas hay and corn productivity largely recovered the following year, yields in 2012 stayed low relative to 2010, consistent with the summer backscatter amplitudes in 2010 and 2012 for both grass (e.g. hay) and croplands (e.g. corn) in region A.

Grassland summer backscatter in the northern plains consistently peaked before (by approximately 2 months) cropland backscatter in the corn belt (Fig. 2). This pattern does not exist across the southern plains and eastern Texas, where both summer backscatter from grasses and crops generally peaked at once in early summer (May-June) (Fig. 2). However, in 2009, grass and cropland backscatter across the southern plains and eastern Texas peaked late in October (Fig. 2).

The backscatter A.M. (descending) overpass in each region and land cover was generally about 0.1 – 0.6 dB stronger than the P.M. (ascending) overpass (Fig. 2). This diurnal backscatter difference was also observed with QSCAT [Frolking *et al.*, 2011], TRMM [Satake and Hanado, 2004], and Seasat [Birrer *et al.*, 1982] K_u-band backscatter over the Amazon basin, as well as ERS-1/2 [Friesen *et al.*, 2012] C-band backscatter over the vegetated global land surface. Notably, the diurnal backscatter difference in each region and land cover has a characteristic seasonal signal, with general lower values during the summer months and larger differences in spring and fall (Fig. 2). During the drought years (Fig. 1), the diurnal backscatter differences in the summer in both regions vanished almost completely (Table 1), with July morning backscatter being as large as or slightly smaller than evening backscatter for both the grasslands in the northern and southern prairies (Fig. 2). While the 2011 drought have had almost no effect on summer cropland diurnal backscatter differences in the south, the diurnal backscatter difference in

the corn belt abruptly disappeared during drought in July of 2012 (Fig. 2), which was consistent with record heat across the U.S. [Karl *et al.*, 2012].

Discussion

The results of this analysis demonstrate that the incidence angle normalized C-band backscatter data from ASCAT can provide an important geophysical monitoring tool capable of identifying drought-induced impacts on vegetation independent of and complementary to satellite optical/NIR remote sensing data. While optical/NIR instruments used in drought mapping quantify the state and health of the vegetation canopy as indicated through observations of photosynthetically active leaf area, microwave radar backscatter are sensitive to vegetation structural properties and moisture content. We exploited this sensitivity to document the spatial extent and temporal evolution of two recent drought events over the contiguous U.S.

Our assessment showed that the backscatter anomaly patterns observed over the U.S. during drought were consistent with late-summer patterns of drought documented by the U.S. Drought Monitor in 2011 and 2012. The A.M. backscatter data acquired during drought events showed a more pronounced anomaly than the P.M. observations, and is consistent with the K_u-band-supported detection of drought patterns over Amazonia [Frolking *et al.*, 2011]. The summer backscatter anomalies for 2011 and 2012 correlated well with diminished growing season precipitation and reduced crop yield, indicating that the backscatter signal is related to a difference in biomass and is drought-induced [Farooq *et al.*, 2009].

Wetter winters produced higher winter season backscatter amplitudes which could indicate enhanced backscatter sensitivity to soil moisture as was shown here across the southern plains and eastern Texas region during the 2012 winter. The grassland summer backscatter maximum in the northern plains preceded the cropland backscatter peak in the corn belt, suggesting that wet biomass for grasses in the northern prairies peaks before crops in the corn belt. In the southern plains and eastern Texas, grass and cropland backscatter peaked at once in early summer, except in 2009 when both grass and cropland backscatter peaked late in October. The precipitation record from October and September in 2009 indicated extreme high precipitation totals (255 mm for cropland and 204 mm for grassland) relative to the following years. This finding could indicate enhanced backscatter sensitivity to surface soil moisture, particularly during periods of persistent rainfall and generally lower vegetation density in September and October in the region. The presence of lower vegetation density likely results from a seasonal increase of the bare soil (due to harvest and plowing) and dry vegetation (due to senescence) fraction [Calvet *et al.*, 2011].

The C-band backscatter normalized to 40° has shown sensitivity to vegetation biomass and soil moisture dynamics in areas with moderate-to-low vegetation density [Wagner *et al.*, 1999a]. Normalizing the backscatter coefficient to 54° is within the range of ASCAT incidence angles (25°-65°) and makes the normalized backscatter more susceptible to variations in the slope factor (c.f. Pathe *et al.* [2009]). Wagner *et al.* [1999b] showed that the temporal variation of the slope factor is directly related to the change in vegetation water content which varies seasonally with the development and senescence of a vegetation canopy. Thus, as the drought conditions worsened and the

transmissivity of the vegetation canopy increased, the slope likely steepened causing the normalized backscatter to decrease.

We found a 0.1 – 0.6 dB diurnal backscatter difference between morning and evening overpasses which is consistent with the general higher vegetation water content in the canopy in the morning [*Larcher*, 1995], or the potential formation of morning dew in the canopy [*Satake and Hanado*, 2004]. Capillary action, whereby groundwater can be drawn upward to the soil surface through very small pores, could be a possible cause of diurnal backscatter differences as well. However, limited water availability during persistent droughts and interference with the overlying vegetation canopy are likely to prevent the detection of capillary rises which is consistent with our observations of early season diurnal backscatter differences and reduced backscatter amplitudes during drought. The seasonality of diurnal backscatter differences across the regions and land covers examined cannot be explained by the data we have studied. However, a possible explanation for the disappearance of diurnal backscatter differences during the 2012 drought in the corn belt could be cessation of leaf transpiration and water uptake following depletion of root zone water in July, resulting in no difference between morning and evening plant water storage [*Steele-Dunne et al.*, 2012]. As the drought conditions relaxed, e.g. due to a combination of rainfall and lower maximum daytime air temperatures, soil water in the root zone could have become increasingly available, restoring root-to-leaf water transport and transpiration of that water through the leaf stomata. Nocturnal leaf wetting through suppressed nighttime transpiration could have led to an increase in morning leaf water content, contrasting the afternoon when leaves experience mid-day wilting (i.e. evaporative water loss through the leaves exceeded

water uptake from the roots) [Ulaby and Batlivala, 1976; McDonald *et al.*, 1991; Way *et al.*, 1991; Larcher, 1995]. The ability to gradually recover from mid-day wilting through the process of nocturnal rehydration was consistent with the steady increase in the diurnal backscatter differences from summer to fall (Fig. 2). Similarly, the diurnal backscatter difference in each year decreased from spring to summer (Fig. 2), suggesting that the vegetation canopy was increasingly unable to recover leaf moisture content overnight. This finding is consistent with the progressive decline of ERS-1/2 diurnal backscatter differences in the West African savanna following the onset of water stress during the transition from the wet to the dry season [Friesen *et al.*, 2012; Steele-Dunne *et al.*, 2012].

Because the A.M. summer backscatter anomaly during drought was more pronounced than the P.M. anomaly, we hypothesize that the A.M. backscatter anomaly is sensitive to the inability of the canopy to fully recover overnight from mid-day growing season rainfall deficits, hence indicating a drought-induced effect [Frolking *et al.*, 2011]. This response shows a clear relationship with land cover, with grasslands showing larger morning summer backscatter anomalies than croplands. We speculate that irrigation of farmland could be responsible for these differences. While equal morning and evening backscatter amplitudes in croplands could suggest cessation of leaf transpiration and water uptake, reversed diurnal backscatter differences, as those observed during drought in grasslands in July, do not. For this instance, it is likely that a drought-induced plant water conservation strategy such that leaf transpiration occurred only very early in the day, e.g. during lower air temperatures between dawn and the early morning hours (prior to 9:30 A.M. LST), whereas cessation of leaf transpiration and leaf rehydration took place during the remainder of the day (9:30 A.M. LST – Dawn). This stomatal response

could be triggered by either limited water availability in the root zone and/or anomalous high daytime temperatures and vapor pressure deficits and/or other environmental controls. Ground-based testing of these hypotheses would involve summer growing season measurements of leaf relative water content, water potential, conductance and transpiration during normal and drought-ridden summer conditions [Way *et al.*, 1991; Frolking *et al.*, 2011].

Conclusion

With more ASCAT data available in the future (2006-present, acquisitions ongoing), the scatterometer record from QSCAT (1999-2009) and ERS-1/2 (1991-2000), sufficient global-scale acquisitions are available to support this drought detection method and adapt it to region-specific needs. Because of the insensitivity to cloud cover and solar illumination, the coarse spatial resolution and resulting high temporal resolution of these microwave instruments (e.g. ASCAT 2-day or better repeat-visit), the combined scatterometer record provides an important complementary tool for detecting, monitoring and quantifying large-scale drought impacts on croplands. This can help improve drought preparedness and mitigation planning allowing improved water resource management for agriculture on the local as well as the state level. However, more research is needed to enhance the use of ASCAT in this capacity, within the U.S. and elsewhere.

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Author Contributions

R. Schroeder conceived and designed this study in consultation with K. C. McDonald and R. Zimmermann for partial fulfillment of the requirements for the PhD degree. R. Schroeder assembled the satellite data and other datasets employed, carried out all analyses including derivation and assessment of results and development of conclusions, and authored the manuscript. M. Azarderakhsh processed and provided the NEXRAD data in collaboration with R. Schroeder. All co-authors provided feedback on and worked to mature the final manuscript.

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Figure Captions

Fig. 1 Grid cell difference between (a) 2011 descending (c) 2011 ascending (b) 2012 descending and (d) 2012 ascending average summer (June, July, August) growing season C-band, VV-polarized and incidence angle normalized ASCAT backscatter and 4-year (2009-2012) mean; grid cell percent difference between (e) 2011 and (f) 2012

accumulated growing season (April, May, June, July, August) Stage IV, NEXRAD precipitation and 2009-12 mean; (g) week ending August 30th, 2011 and (h) week ending August 28th, 2012 drought conditions as monitored by U.S. Drought Monitor. Grid cell resolution is ~25-km, except (g) and (h) which are vector-based data. A) and B) indicate the drought-stricken regions which are outlined by dashed lines.

Fig. 2 Average monthly A.M. (descending) and P.M. (ascending) ASCAT backscatter and accumulating winter and growing season precipitation (blue lines, April through August; red lines, January through August), all averaged over drought-stricken regions and sub-regions (see Fig. 1 and Table 1 for domain and spatial extent).

Fig. 3 30-year record of USDA annual corn (a) and hay (b) yield over the contiguous U.S. (solid line) and Texas (dotted line). Trend lines using least-square distance regression are drawn and annual yields for drought years 2011 (Texas) and 2012 (U.S.) are indicated.