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Detecting drought impact on terrestrial biosphere carbon fluxes over contiguous US with satellite observations

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Abstract

With projections of increasing drought in the future, understanding how the natural carbon cycle responds to drought events is needed to predict the fate of the land carbon sink and future atmospheric CO2 concentrations and climate. We quantified the impacts of the 2011 and 2012 droughts on terrestrial ecosystem CO2 flux and uptake anomalies over the contiguous US (CONUS) relative to non-drought years during 2010–2015 using satellite observations and the carbon monitoring system—flux inversion modeling framework. Soil moisture and temperature anomalies are good predictors of gross primary production anomalies ($R^2 > 0.6$) in summer but less so for net biosphere production (NBP) anomalies, reflecting different respiration responses. We showed that regional responses combine in complicated ways to produce the observed CONUS responses. Because of the compensating effect of the carbon flux anomalies between northern and southern CONUS in 2011 and between spring and summer in 2012, the annual NBP decreased by 0.10 ± 0.16 GtC in 2011, and increased by 0.10 ± 0.16 GtC in 2012 over CONUS, consistent with previous reported results. Over the 2011 and 2012 drought-impacted regions, the reductions in NBP were ~40% of the regional annual fossil fuel emissions, underscoring the importance of quantifying natural carbon flux variability as part of an overall observing strategy. The NBP reductions over the 2011 and 2012 CONUS drought-impacted region were opposite to the global atmospheric CO2 growth rate anomaly, implying that global atmospheric CO2 growth rate is an offsetting effect between terrestrial biosphere carbon uptake and emission, and enhancing the understanding of regional carbon-cycle climate relationship is necessary to improve the projections of future climate.

1. Introduction

Between 1990–2009, the North American (NA) terrestrial biosphere absorbed ~0.9 ± 0.5 GtC/year from the atmosphere, contributing 15% to 35% of the land carbon sink (King et al 2015, Le Quéré 2016), and offsetting ~25%–50% of NA fossil fuel emissions (~1.8 GtC). This carbon sink comes primarily from the contiguous US (CONUS) (Peters et al 2007), and it has significant interannual variability that may be especially sensitive to drought and heat (e.g., Ciais et al 2005, Doughty et al 2015). With the projection of increasing drought and heat events in the future (Easterling et al 2000, Meehl and Tebaldi 2004), quantifying how the terrestrial biosphere responds to drought events is important for predicting the fate of land carbon sinks and resulting atmospheric CO2 concentrations and climate.

Intense drought events also provide testbeds for emerging satellite observations, such as column CO2 ($X_{CO2}$) and solar induced chlorophyll fluorescence (SIF). In this study, we focus on two drought events that occurred over CONUS during the Greenhouse Gases Observing Satellite (GOSAT) CO2 observational...
record which began in 2009 (Yokota et al 2009): the 2011 Texas drought (Seager et al 2014) and the 2012 Midwest drought (Rippey 2015).

These two droughts differ in their causes, seasonal progression, and impact on the carbon cycle. The 2011 drought was centered in the south-central US and affected part of Mexico, and was caused by a combination of a La Niña and the negative phase of the North Atlantic Oscillation (Parazoo et al 2015). It started in late 2010 and lasted through 2011. The 2012 Midwest drought, centered in the central US, was caused by a combination of sea surface temperature anomalies over the Pacific and Atlantic ocean basins, and amplified by land-atmosphere interactions (Seager and Hoerling 2014, Rippey 2015). The drought stress likely caused changes in biosphere activity and impacted net biosphere productivity (NBP) and its component fluxes: gross primary production (GPP) and ecosystem respiration (Reco). With a terrestrial biogeochemical model, Parazoo et al (2015) estimated that extremely hot and dry conditions during the 2011 drought could have reduced NBP over Texas-Mexico by 0.23 GtC, which would have been the largest reduction over the area since the 1950s. Using in situ observations from flux towers, Wolf et al (2016) showed that the higher spring temperature in 2012 enhanced carbon uptake, which partially compensated for the reduction of net carbon uptake that resulted from the severe summer drought.

Complementing studies using models and in situ measurements, satellite measurements of CO₂ provide a top-down constraint on the net exchange of carbon, and solar induced fluorescence provides a top-down estimate of photosynthesis, or GPP, allowing studying large regional climate anomaly impacts on the carbon cycle in new ways (Liu et al 2017, Sun et al 2017). We used the NASA Carbon Monitoring System Flux (CMS-Flux) inversion and optimization framework (Bowman et al 2017, Liu et al 2014, 2016, 2017) to quantify the impact of these two drought events on NBP, GPP, and Reco over CONUS. NBP and GPP were optimized independently, but consistently, through the assimilation of XCO₂ and SIF from GOSAT (Frankenberg et al 2011). Due to dense spatiotemporal coverage, satellite XCO₂ observations have shown potential in quantifying the regional carbon flux interannual variability (e.g., Basu et al 2014, Detmers et al 2015, Bowman et al 2017, Liu et al 2017), in spite of uncertainty in the absolute net flux estimates (e.g., Feng et al 2016). Within any 4° × 5° grid box, there are annually ~200 GOSAT XCO₂ observations, with denser coverage over mid-latitudes (figure S1 is available online at stacks.iop.org/ERL/13/095003/mmedia), providing increased spatial and temporal coverage relative to surface flask observations, albeit with lower accuracy.

The GOSAT record extends from 2009 to the present with carbon fluxes calculated through 2015. Based upon this record, we use the mean carbon fluxes over non-drought years (2010, 2013–2015) as a baseline to investigate the impact of these two droughts on terrestrial carbon flux anomalies. We further discuss the impact of these drought events in the context of carbon-climate interannual variability, with the objective to inform the mechanistic understanding of carbon–climate interactions and improve terrestrial biosphere carbon cycle predictions. CONUS spans a large range of climate zones, with warmer semi-arid climate in the south and a temperate climate in the north. The terrestrial biosphere has different limiting factors over these regions, being limited primarily by soil moisture to the south and a combination of vapor pressure deficit and temperature to the north (e.g., Nemani et al 2003, Madani et al 2017). We therefore separate CONUS into the southern (S) and northern (N) regions with 38°N as the separating line, representing warm (i.e., annual mean temperature is above 15 degrees) and cool climate respectively, to quantify the response of terrestrial biosphere carbon fluxes over these two zones to drought.

Specifically, we focus on four scientific questions: (1) what are the impacts of the 2011 and 2012 drought events on regional NBP relative to the non-drought years during 2010–2015, and which component flux was the driver for the NBP anomaly over CONUS? (2) How do these two drought events differ in their seasonal progression in terms of climate drivers and carbon flux responses? (3) How significant are drought effects on carbon fluxes relative to the region’s overall carbon budget? (4) What are the general relationships between carbon flux anomalies and climate state anomalies?

2. Methods

2.1. Net biosphere production quantification and attribution system

Net biome production between land and atmosphere, NBP (fNBP), is the net effect of photosynthesis (fGPP), and total ecosystem respiration (fReco),

\[ f_{\text{NBP}} = f_{\text{GPP}} - f_{\text{Reco}} \]  

where positive indicates that the carbon is absorbed from the atmosphere.

We quantified NBP, GPP, and their uncertainties by statistical optimization approaches that are briefly described in the following. The respiration term is calculated as a residual. Note that the \( f_{\text{Reco}} \) here includes autotrophic and heterotrophic respiration, and carbon losses to disturbance, such as fire, harvest, clearing, and land cover change. However, the \( f_{\text{Reco}} \) here only includes carbon losses that go into the atmosphere during the time and place of the disturbance, not the portion of carbon loss that goes elsewhere, e.g., food harvest transported somewhere else. We quantified carbon loss due to fire using carbon monoxide observations from measurement of pollution in the
troposphere (Jiang et al 2017), and found that the 2011 and 2012 drought had negligible impact on biomass burning carbon flux anomalies over the region (not shown). In the later discussion, we use $f_{\text{Reco}}$ to represent the total carbon loss to the atmosphere.

2.1.1. Estimating NBP and its uncertainties with atmospheric CO2 flux inversion and NBP validation

We optimized $f_{\text{NBP}}$ by assimilating ACOS-GOSAT (O’Dell et al 2012) b7.3 $X_{\text{CO2}}$ retrievals into the CMS-Flux 4D-Var inversion framework, which uses the GEOS-Chem adjoint model (Henze et al 2007). GEOS-Chem (http://geos-chem.org) is a global chemical transport model that uses GEOS (Goddard Earth Observing System) assimilated meteorological fields from the NASA Global Modeling Assimilation Office (Rienecker et al 2008). We run the model at a horizontal resolution of $4^\circ$ (latitude) $\times 5^\circ$ (longitude). The model has 47 vertical levels, with the top up to 0.01 hPa.

When optimizing monthly $f_{\text{NBP}}$ from July 2009 to December 2015, we assume that uncertainties in fossil fuel emissions are much smaller than the expected variability of the biosphere (Deng et al 2014, Liu et al 2014, Liu et al 2016). The prior biosphere fluxes (including fire) were based on model simulations from CASA-GFED3 (van der Werf et al 2010). Fossil fuel emissions were from FFDAS (Asfei-Najafabady et al 2014), and ocean fluxes were from ECCO2-Darwin (Menemenlis et al 2008, Dutkiewicz et al 2009, Brix et al 2015).

We calculated the NBP posterior uncertainties with a 60-member Monte Carlo approach (Liu et al 2014, 2016). Each ensemble member has a different set of perturbed prior fluxes and simulated observations to represent the prescribed prior flux uncertainties and observation errors. The spread among 60-member posterior fluxes represents the posterior flux uncertainties. The uncertainties of flux anomalies discussed in section 3 are $\sqrt{2}$ times of the mean posterior flux uncertainty. Note that the impact of any structure errors in atmospheric transport model and biases in the assimilated observations have not been taken into account in the quantification of posterior flux uncertainties.

To examine whether flux anomalies discussed in section 3 could be due to changes in observation coverage or accuracy, we calculated the annual total number of observations and compared the posterior CO2 concentrations to independent aircraft observations over NA. The annual total number of observations was similar from 2010 to 2014, while 2015 had 10% fewer observations compared to previous years (figure S1). Due to the high annual total number of ACOS-GOSAT observations ($\sim 35,000$), the observational constraint is high despite a 10% reduction (not shown). The posterior CO2 concentrations closely track the ACOS-GOSAT b7.3 (figure S2), and have stable RMS statistics ($\sim 1.3$ ppm) compared to aircraft CO2 observations over NA (figure S3), which indicates that the ACOS-GOSAT 7.3 over NA do not show time dependent drift. The stability in terms of observation coverage and relative difference from the independent observations over NA indicate that the flux anomalies discussed in section 3 are not an artifact of the changes in observation characteristics.

2.1.2. GPP and total ecosystem respiration

We used a Bayesian analysis framework to estimate monthly average GPP at $4^\circ \times 5^\circ$ grid spacing (consistent with CMS-Flux grid) that optimally accounts for uncertainties in predictions of GPP from terrestrial biosphere models, satellite observations of GOSAT SIF (Frankenberg et al 2011), and relationships between SIF and GPP (Parazoo et al 2014). The Bayesian analysis framework calculates the mean GPP as well as its uncertainties. Monthly prior GPP was from the average of ten land biosphere models (CLM4.5, ISAM, JULES, LPIG, LPI, LPX, OCN, ORCHIDEE, VEGAS, VISIT) from the TRENDY model intercomparison project over the period 2009–2012 (http://dgvm.ceb.ac.uk/node/9). Due to the highly linear correlations between SIF and GPP, SIF has been used as a proxy of GPP to investigate photosynthetic activities in a number of studies (Guanter et al 2014, Joiner et al 2014, Zang et al 2014, Sun et al 2015, Yang et al 2015). The SIF optimized GPP product (SIF-GPP) has been used to study the 2011 Texas-Mexican drought (Parazoo et al 2015), 2010 Amazonia drought (Lee et al 2013, Parazoo et al 2013, Bowman et al 2017), and the impact of 2015–2016 El Niño on tropical terrestrial biosphere carbon cycle (Liu et al 2017). The GPP products show good correspondence to flux tower observations (Parazoo et al 2014, 2015). The SIF-GPP products used here are the same as in Liu et al (2017) and Bowman et al (2017).

We calculated $f_{\text{Reco}}$ as a residual term between $f_{\text{NBP}}$ and $f_{\text{GPP}}$ based on equation (1). We also propagated the uncertainties from $f_{\text{NBP}}$ to $f_{\text{GPP}}$ to $f_{\text{Reco}}$ based on equation (2):

$$\sigma^2_{\text{Reco}} = \sigma^2_{\text{GPP}} + \sigma^2_{\text{NBP}}$$

Therefore, the uncertainties of $f_{\text{Reco}}$ are larger than those of GPP and NBP.

2.2. Definition of drought

‘Meteorological’ and ‘agricultural’ drought are two common drought types according to the National Center for Environmental Information website (http://drought.unl.edu/DroughtBasics/TypesOfDrought.aspx). The intensity of meteorological drought is often defined by the amount and duration of precipitation, while agricultural drought is defined by the soil moisture state. Here, we define drought using soil moisture instead of precipitation following the criteria of ‘agricultural drought’, since vegetation growth is directly related to soil moisture availability (Williams and Albertson 2004). We used the
combined satellite soil moisture product from the European Space Agency Climate Change Initiative (ESA CCI), which spans from 1978 to 2015. The product has been validated against surface observations (e.g., Dorigo et al 2015, Dorigo and de Jeu 2016), and has been used in studying drought impacts on vegetation growth (e.g., Yu et al 2017).

We used the mean conditions averaged over 2010 and 2013–2015 as the baseline to define drought, the same period as we used for fluxes. We define drought as where the soil moisture deficit was larger than \( \sqrt{2\sigma^2} \), where \( \sigma \) is the standard deviation over the four baseline years.

3. Results

3.1. Drought characteristics during springs and summers in 2011 and 2012

Figure 1 shows the soil moisture anomaly for 2011 (a and b) and 2012 (c and d) spring (March, April, and May (MAM)) and summer (June, July, and August (JJA)). The shaded area is the region with soil moisture deficit larger than \( \sqrt{2\sigma^2} \). Figures 1(e)–(h) shows the corresponding surface temperature anomalies, and the shaded area is the region with temperature anomaly larger than \( \sqrt{2\sigma^2} \). The surface temperature is from ERA interim reanalysis (Dee et al 2011). During both drought events, summer had more severe soil moisture deficits than did spring. The 2012 summer drought covered a larger area than the 2011 drought. The S-CONUS, especially the northern part of Texas, experienced both droughts. Along with soil moisture deficit, temperatures were also much higher (c, d, g, and h). Positive temperature anomalies occurred primarily over the S-CONUS during 2011, whereas they covered both the N-CONUS and S-CONUS during the 2012 drought, especially during MAM 2012.

3.2. Seasonal responses of terrestrial biosphere carbon fluxes to 2011 and 2012 droughts over CONUS

In this section, we discuss the NBP and GPP responses to climate state anomalies in spring (MAM) and summer (JJA) separately. Figure 2 shows the NBP and GPP anomaly over CONUS in spring and summer 2011 and 2012. The NBP value at each grid point is an average of nine points centered at that grid to remove the spatial noise. For the points along the coast, it is the average over the land grid points. Figure 3 shows the monthly NBP, GPP, respiration, and their anomalies over N-CONUS and S-CONUS in 2011 and 2012.

Figure 2 shows that, in spring 2011, the NBP and GPP reduction primarily occurred over Texas, the NBP anomaly was close to neutral and the GPP anomaly was slightly positive over the rest of CONUS (figures 2(a) and (c)), corresponding to similar spatial patterns in soil moisture and temperature anomaly (figures 1(a) and (c)). As a result of the relatively small area of drought in the spring of 2011 (figure 1(a)), NBP was close to neutral in S-CONUS (–0.04 ± 0.08 GtC). Over N-CONUS, NBP was reduced by 0.12 ± 0.14 GtC (figures 3(a) and (b)), which was larger than the 0.06 GtC interannual variability, and was primarily driven by an increase in respiration (figures 3(c) and (e)).

By contrast, the NBP was increased (figure 2(b)), along with the enhanced photosynthetic activity (figure 2(d)) over the southeast CONUS in spring 2012, which was consistent with MODIS-GPP and CarbonTracker (Peters et al 2005) net flux anomaly patterns discussed in Wolf et al (2016), even though the baseline years used were different between our study and Wolf et al (2016). Wolf et al (2016) argued that the increase of plant growth and net carbon uptake were due to warmer temperatures (figure 1(g)) in spring 2012. The positive temperature anomaly occurred a.e. east of Rocky Mountain in MAM 2012 (figure 1(g)). The temperature anomaly was 1.65 ± 0.36 °C and 2.96 ± 0.96 °C (figures 4(c) and (d)) over the S- and N-CONUS respectively, and the corresponding GPP was increased by 0.12 ± 0.34 GtC and 0.12 ± 0.30 GtC (figures 4(c) and (d)). The GPP uncertainty derived from the optimal estimation approach (Parazoo et al 2014) is much larger than the interannual variability, which was 0.03 GtC over both S- and N-CONUS in spring. Besides warmer temperatures, the much stronger GPP enhancement over the S-CONUS may be also due to the close-to-neutral soil moisture anomaly (figure 4(a)).

Positive temperature anomalies can enhance plant growth in spring, while at the same time accelerating plant and soil decomposition and increasing respiration. A positive NBP anomaly only occurred over the S-CONUS in 2012 (figure 2(b)), while the GPP enhancement and increase in respiration were cancelled over N-CONUS in 2012 (figures 3(c)–(f)). Regionally, the net uptake was increased by 0.16 ± 0.08 GtC over the S-CONUS in MAM 2012, much larger than the 0.08 GtC interannual variability. The N-CONUS had near neutral changes in MAM 2012 (figures 3(a) and (b)). Over CONUS, our results showed that the NBP was increased by 0.15 ± 0.11 GtC and GPP was increased by 0.24 ± 0.35 GtC in spring 2012, which are close to the 0.23 GtC and 0.27 GtC estimates by Wolf et al (2016).

Both drought events had maximum impact on soil moisture anomalies and terrestrial biosphere carbon fluxes in summer, but the NBP and GPP reduction over CONUS was much stronger in summer 2012 than in summer 2011. NBP was decreased by 0.19 ± 0.12 GtC over CONUS in JJA 2012, dominated by a reduction in GPP (0.29 ± 0.63) (figures 3(a)–(d)). Both the NBP and GPP reductions over CONUS were larger than their interannual variability, which are 0.12 GtC and 0.06 GtC, respectively. In JJA 2011, CONUS NBP decreased only by 0.03 ± 0.12 GtC, which was
due to regionally compensating NBP anomalies: NBP decreased by 0.11 ± 0.40 GtC over S-CONUS, while increased by 0.09 ± 0.14 GtC over N-CONUS (figures 2(b) and (d)). Increased net carbon uptake over the N-CONUS in 2011 may be related to the much wetter conditions during spring and near normal soil moisture during summer (figures 4(a) and (d)). The much stronger NBP and GPP reduction in summer 2012 also occurred over much larger areas (figures 2(e)–(h)), corresponding to the soil moisture deficit spanning over both N-CONUS and S-CONUS in JJA 2012.

3.3. The drought impact on annual biosphere carbon fluxes and regional contributions to atmospheric CO2 growth

Figure 5 summarizes the anomalies of annual net and gross carbon fluxes over the regions with drought either
in 2011 or 2012 (shaded area in figures 5(a) and (b) respectively). The drought regions are defined as where the annual mean soil moisture deficit is larger than $\sqrt{2}\sigma^2$. Also shown in the figure is the mean annual fossil fuel emissions (black) averaged between 2010 and 2015 over the same regions. Over the drought-impacted regions (i.e., the pixels with brown shaded color), annual NBP decreased by 0.20 ± 0.10 GtC and 0.30 ± 0.16 GtC respectively in 2011 and 2012, equal to ~40% of the mean annual fossil fuel emission over these regions. About half of the NBP reduction was due to a decrease of GPP, and the other half was due to an increase in respiration. The regional contribution to the atmospheric CO$_2$ growth, which is the sum of fossil fuel emissions and the net biosphere uptake, increased by more than a factor of 2 over the 2011-drought-impacted region from an average of 0.06 GtC net uptake (2010, 2013–2015) to 0.14 GtC net release into the atmosphere, and it was increased by a factor of 2.5 from an average of 0.22 GtC net release to 0.52 GtC over the 2012 drought-impacted region. The large magnitudes of natural biosphere carbon flux anomalies relative to regional fossil fuel emissions indicate that any mitigation policy to reduce regional contributions to atmospheric CO$_2$ growth needs to consider the interannual variability and long-term trend of the natural carbon cycles.

Figure 2. The NBP (a), (b), (c), (d) and GPP anomalies (unit: GtC) (e), (f), (g), and (h) during spring (MAM) (a)–(d) and summer (JJA) (e)–(h) over CONUS in 2011 and 2012. The NBP values are nine-point averages centered at each grid point. For the points at the coastal region, it is the average only over land grid points.
Due to the temporal or spatial compensating effects, the annual NBP anomaly was much smaller over the whole of CONUS than over the drought-impacted regions. Annually, the NBP was decreased by $0.10 \pm 0.16$ GtC in 2011, but was increased by $0.10 \pm 0.16$ GtC in 2012 over CONUS. The 2012 annual net flux anomaly estimate is consistent with Wolf et al. (2016), reinforcing net biosphere flux anomalies inferred from satellite XCO2 observations.

On the global scale, the terrestrial biosphere absorbed $1.0 \pm 0.59$ gigaton more carbon from the atmosphere in 2011 than the baseline years, primarily from the Southern Hemisphere (SH) semi-arid region (e.g., Poulter et al. 2014), which resulted in $\sim 1.6$ GtC lower atmospheric CO2 growth in 2011 (Le Quéré et al. 2016). The NBP reduction over the 2011 CONUS drought-impacted region was $\sim 12.5\%$ of the atmospheric CO2 growth difference between 2011 and the baseline, but in the opposite direction. In 2012, the global atmospheric CO2 growth rate was lower than the baseline by $\sim 0.25$ GtC, which has the same magnitude but in the opposite direction from the NBP reduction ($0.30 \pm 0.16$ GtC) over the CONUS drought-impacted region. The opposite directions between the global CO2 growth rate anomalies and the drought-induced carbon flux anomalies in these two years imply a regional compensating...
effect of biosphere carbon flux anomalies, and indicate that a single box model used to represent the relationships between CO$_2$ growth rate anomalies and climate state anomalies may not be sufficient (Cox et al 2013, Wang et al 2013) to represent a more complex regional forcing-response relationship (Jung et al 2017). Enhancing the understanding of the regional carbon-cycle climate relationship is then necessary to improve the projections of future climate.

3.4. Understanding the 2011 and 2012 drought events in the context of carbon-climate interannual variability

The results from the previous two subsections show that carbon flux anomalies respond to climate state anomalies. In this subsection, we will discuss the general relationships between carbon flux anomalies and climate state anomalies that underlie the 2011 and 2012 drought impact. Figure 6 shows the regression between climate and carbon flux anomalies over N- and S-CONUS in summer. The anomalies were calculated relative to the baseline years. Table 1 lists the linear regression slopes, $R^2$, and p-values of the slopes. The slopes of linear regression are computed using a least square fit, representing the sensitivities of carbon flux anomalies to climate state anomalies. The significance of the slope (i.e., p-value) is determined using the effective sample size and a t-test. The smaller the p-value is, the more significant is the linear regression slopes differing from zero. For example, a p-value equal to 0.05 indicates that the linear regression slope differs from zero at more than 95% of probability.

Both the GPP (dark green) and NBP (blue) anomalies are positively correlated with soil moisture anomalies and anti-correlated with temperature anomalies (figure 6). Soil moisture variability explains $\sim 85\%$ (i.e., $R^2 \sim 0.85$) while temperature explains $\sim 60\%$ of GPP variability over both regions. The p-values for the linear regression slopes between climate state anomalies and GPP anomalies are smaller than 0.05 except the linear regression slope between GPP and T over S-CONUS ($p = 0.07$) (table 1). The linear relationship between NBP and climate anomalies is weaker over both regions, especially over N-CONUS, due to compensating GPP and $R_{eco}$ effects, consistent with the spatial patterns shown in.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{The mean monthly soil moisture (a) and (b) (unit: m$^3$/m$^3$) and temperature (c) and (d) (unit: K) from the baseline and its variability (grey shaded area), and the 2011 (red) and 2012 (green) monthly mean values over S-CONUS (left panel) and N-CONUS (right panel). The bottom two panels in each sub figure is the 2011 and 2012 monthly anomaly relative to the baseline year. The numbers are the mean seasonal anomalies and the corresponding variability.}
\end{figure}
The p-values for the linear regression slopes between climate state anomalies and NBP anomalies are between 0.04 and 0.24 (table 1). The anti-correlation between NBP and temperature during summer is consistent with Wunch et al (2013), which show that $X_{CO2}$ drawdown over the NH Total Carbon Column Observing Network sites reduces with the increase of temperature in summer.

The linear regression slopes indicate that the sensitivities of GPP and NBP anomalies to temperature over the S-CONUS are about half of those over the N-CONUS,
while the sensitivity of NBP to soil moisture is about 30% higher over S-CONUS than over N-CONUS. The linear regression slopes representing the sensitivities of GPP anomalies to soil moisture and temperature are more than half of those for NBP anomalies, implying that GPP variability is the dominant driver of NBP variability over both regions in general, though it may not be the case for a specific year (figure 5). Plant growth and net carbon uptake were lowest over the S- and N-CONUS in 2011 and 2012, respectively, as a result of the driest and hottest climate conditions (figure 6).

In spring (figure S5), soil moisture anomalies and carbon flux anomalies are almost independent, but temperature still can explain 68% of GPP variability in S-CONUS (p-value = 0.04), and 59% of GPP variability in N-CONUS (p-value = 0.07). Over both regions, the plant net uptake increases with temperature, which is consistent with enhanced plant growth and net uptake in spring 2012.

4. Conclusion and discussions

In this study, with satellite observations and CMS-Flux inversion and optimization system, we quantified the impact of the 2011 and 2012 drought events on the terrestrial biosphere NBP and its component fluxes including GPP and respiration over CONUS. We showed that regional responses combine in complicated ways to produce the observed CONUS responses. Because of the compensating effect of the carbon flux anomalies between N- and S-CONUS in 2011 and between spring and summer in 2012, annual net carbon flux anomalies over CONUS were not significant. Annually, the NBP was decreased by $0.10 \pm 0.16$ GtC in 2011, but was increased by $0.10 \pm 0.16$ GtC in 2012 over CONUS. The 2012 annual net flux anomaly estimate is consistent with Wolf et al. (2016), which is an indirect validation of the net biosphere flux anomalies inferred from satellite XCO2 observations. We showed that the seasonal NBP anomalies in 2012 constrained by satellite XCO2 were consistent with the flux tower observations shown in Wolf et al. (2016), despite the large difference in terms of spatiotemporal scale between the top-down atmospheric flux inversion results ($4^\circ \times 5^\circ$) and flux tower observations ($\sim 1$–$10 \text{ km}^2$, Running et al. 1999). This implies that the 2012 drought had a consistent impact throughout the region. The consistency between the two observing strategies provides evidence that satellite XCO2 observations are sensitive to regional carbon responses from large-scale climate variability, and argues for a synthesis of continental scale flux tower observations and atmospheric inversion results for quantifying and understanding dominant patterns of net carbon flux interannual variability.

The 2011 drought was primarily over S-CONUS, while the 2012 drought covered both N-CONUS and S-CONUS. The peaks of both droughts’ impact were in summer. We found that the sensitivities of GPP and NBP anomalies to temperature over S-CONUS are about half of those over the N-CONUS, while the sensitivity of NBP to soil moisture is about 30% higher over S-CONUS than over N-CONUS in summer. The soil moisture variability explains $\sim 85\%$ of the SIF-GPP variability, while temperature explains $\sim 60\%$. Because of these general linear relationships between carbon flux anomalies and climate state anomalies, plant growth and net carbon uptake were the lowest over S- and N-CONUS in 2011 and 2012, respectively, as a result of the driest and hottest climate conditions.

We illustrated the importance of accurately quantifying the natural carbon flux interannual variability in order to quantify the impact of any emission mitigation policy on regional contributions to atmospheric CO2 growth. Over the drought-impacted regions, the reductions of net carbon uptake from the 2011 and 2012 drought were $\sim 40\%$ of the regional annual fossil fuel emissions. The net carbon uptake reductions from the 2011 and 2012 drought and the predicted increase in drought frequency over the southern Great Plains (Meehl and Tebaldi 2004) implies a positive carbon cycle feedback that may reduce the ability of the terrestrial biosphere to mitigate fossil fuel emissions in the future. In both 2011 and 2012, the global atmospheric CO2 growth rate was lower than the baseline, opposite to the flux anomalies over the drought-impacted regions. Quantifying regional fluxes is essential for understanding the relationships between climate forcing and carbon flux response as the global atmospheric CO2 growth rate reflects offsetting enhanced uptake and emission.
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