Response to referee comments (in red):

Anonymous Referee #3

Received and published: 17 March 2016

This paper uses the results from two atmospheric inversion models and long-term surface temperature and NDVI records to compute trends in the CO2 fluxes in the Arctic and Boreal regions (excluding Europe). The authors conclude that the Boreal region has become an increasingly large sink for CO2, with no statistically significant change in the Arctic, even though the seasonal cycle amplitude in CO2 in both regions has increased. The authors argue that this is due to the balance between increased summertime uptake and fall CO2 emissions. The paper is well-written and clear, and suitable for publication in ACP. I recommend that this paper is published after addressing the following comments.

Main Comments:

I would recommend that the authors look at the more recent solar-induced fluorescence (SIF) measurements (e.g., GOME-2, GOSAT, OCO-2) in their analyses. SIF is reported to be more directly related to photosynthesis than greenness indices are, and show some significant differences in the Boreal and Arctic regions (e.g., Joiner et al. 2013). GOME-2 has the longest time series (launched in 2006), and I recognize that this does not cover the main time period of the inversions, but it should be helpful to determine whether NDVI is fully capturing the productivity cycle in the Boreal region.

We are also excited about the potential of SIF in quantifying carbon fluxes in the high northern latitudes. However, an analysis of SIF and changes in growing season length are outside the scope of this study. This comment was a good reminder to discuss the possible disconnect from NDVI and GPP on a seasonal time scale. This was added: *"Comparisons with recent satellite measurements of solar induced fluorescence show that the seasonality of NDVI may not capture the seasonality in GPP (Walther et al., 2015), but we focus on interannual variability of growing season sums and maximum July values in this study."*

In this study, NDVI was not used as a model input, so bias in the seasonal cycle will not affect the inversion fluxes calculated.

This analysis does not directly consider the timing of the onset of the growing season, but it is obvious in Figure 3a that even between the two models using the same CO2 concentration data, the phase and duration of the growing season are inconsistent. This raises several questions: Are monthly fluxes temporally fine enough for this analysis (i.e., would the results change if you were to look at, say, bi-weekly fluxes)? Do the two inversions show a similar change in the timing of the onset of the growing season over time? Do they show consistent changes in the length of the growing season?

This disagreement between the models at the beginning and end of the growing season does raise some interesting questions. The phase of the fluxes is not fixed (held constant) in either model, so there is no obvious explanation for why they would differ, other than the two models are entirely independent of each other. There are other metrics of season start/end such as NDVI and SIF that are better suited to identifying trends in the shoulder seasons if your focus is on productivity (GPP) and not the net CO_2 fluxes (which include respiration contributions). The decades long focus of this study limits the spatial and temporal coverage of atmospheric CO_2 observations. In the future, including the denser network of atmospheric observing stations, spatially and temporally, should improve the power of atmospheric inversions to quantify start/end of the net CO_2 uptake season.

Minor Comments:

Title: I suggest you clarify the title by specifying that the inversions use surface concentrations and that the remote sensing is of NDVI and temperature

Excellent point. Changed the title.

P2L22:... trigger *a* massive...

Corrected.

P2L35: Is (1997) referring to a paper?

Citation error. Fixed it.

P5L2: Be careful to state that GLOBALVIEW-CO2 isn't "data". From the ESRL webpage (http://www.esrl.noaa.gov/gmd/ccgg/globalview/co2/co2_intro.html): "GLOBALVIEWCO2 is derived from atmospheric measurements but contains no actual data."

Agreed. Deleted 'data'.

P6Para24: Please clarify. I find the first two sentences very confusing.

Changed this text to: *"The atmospheric inversion approach taken in this study is unlikely to reliably separate influences from different longitudinal regions within the latitude bands discussed here. Our focus on the longest records possible, from sparse atmospheric CO_2 observations starting in the 1980s, compromises the spatial resolution of the inversion fluxes. Rapid atmospheric mixing of a few weeks around latitude bands makes it hard to separate fluxes for example from North America and Eurasia."*

P9L25: In order *to* investigate...

Corrected.

P10L6: You show the average growing season NDVI. Would the integrated NDVI over the growing season be better correlated with CO2 uptake?

In this analysis, the "growing season" is defined as April through October, everywhere, so the mean and the integrated NDVI would have the identical correlation.

P10L13: How does the month of the maximum NDVI change over time? Is there a trend?

While the maximum value of NDVI changes, the timing of the maximum does not change. The focus of this study is really the CO2 fluxes. Figure 3 shows no indication that the timing of the maximum CO_2 uptake has shifted either.

P10L27: How is significance defined here?

We added a paragraph on the statistical methods used in section 2.3. "*Trends were considered significant if they passed the 90% confidence level (p-values < 0.1).*"

P12L28: ... warm summers may *be* driven...

Corrected.

P12L27: Schneising et al. (2014) also came to a similar conclusion.

Added this reference.

P13L22: ... to different *latitude* bands...

Corrected.

Figure 3: The two inversions differ in their mean seasonal cycle amplitudes by a factor of two in the Arctic, and they have significantly different onsets of the growing season in the Boreal zone. Can you explain why?

They are 2 entirely independent inversion models and it is not surprising that there are some differences. The modelers involved in this study have not identified a specific cause of the differences, but it likely is related to different prior fluxes and atmospheric transport models. Also, a simple explanation for some of the model differences is how they split fluxes between boreal and temperate zones. This makes the fluxes in either zone, and particularly in the arctic zone, with smaller fluxes, somewhat less robust. A variable amount of leakage of boreal fluxes into the arctic could lead to large changes in the arctic CO_2 amplitude. The inversions are much stronger constraints on interannual variability and trends in the fluxes than on the shape of the CO_2 flux seasonality. Added: " *These differences are not unexpected given the differences in atmospheric transport (including vertical mixing and leakage across latitudes), a priori fluxes, observational network inputs, and model structure between the inversion models. In this analysis we try to focus on the most robust features were the models do tend to agree on the interannual trends in anomalies from the mean."*

References:

Joiner, J., Guanter, L., Lindstrot, R., Voigt, M., Vasilkov, A. P., Middleton, E. M., Huemmrich, K. F., Yoshida, Y., and Frankenberg, C.: Global monitoring of terrestrial chlorophyll fluorescence from moderate-spectral-resolution near-infrared satellite measurements: methodology, simulations, and application to GOME-2, Atmos. Meas. Tech., 6, 2803-2823, doi:10.5194/amt-6-2803-2013, 2013.

Schneising, O., M. Reuter, M. Buchwitz, J. Heymann, H. Bovensmann, and J. P. Burrows (2014), Terrestrial carbon sink observed from space: variation of growth rates and seasonal cycle amplitudes in

response to interannual surface temperature variability,
Atmos. Chem. Phys., 14(1), 133–141, doi:10.5194/acp-14-133-2014.

Response references:

Walther, S., Voigt, M., Thum, T., Gonsamo, A., Zhang, Y., Koehler, P., Jung, M., Varlagin, A. and Guanter, L.: Satellite chlorophyll fluorescence measurements reveal large-scale decoupling of photosynthesis and greenness dynamics in boreal evergreen forests, Global Change Biology, doi:10.1111/gcb.13200, 2015.