Response to referee comments (in red):

Anonymous Referee #1
Received and published: 29 March 2016

This paper is competently written, and I don't find obvious errors in method, analysis, or results. My main complaint has to do with context and integration of results into previous results.
The authors spend some time reviewing previous, sometimes contradictory studies of the boreal and arctic regions
- conflicting browning/greening NDVI studies
- the 'carbon bomb' vs. the authors' results that don't show a large carbon efflux from permafrost regions
- high northern latitudes have decreasing sink, or even becoming a net source vs. the present study that disagrees with this result

After multiple readings of the paper, I'm not sure how far this work goes towards resolving any of these questions, but I think potential is there to do so. The basic result, that there is increasing CO2 uptake in the boreal region (not in the arctic) while the amplitude of arctic CO2 cycles has increased, seems reasonably well established by the results of their study. What I don't really get is a sense of how these results fit into the literature to confirm or deny other hypotheses as a means to clarify our understanding of this admittedly complex region.

In the introduction the authors say that "The net carbon balance of increased plant growth and increase soil respiration is unclear, but has important consequences for predicting carbon-climate feedbacks." By the end of the paper, I don't get the feeling that the authors make a definitive statement addressing this one way or the other. I believe this study has merit, and that any flaws are not fatal. A more rigorous organization of previous literature and the place of this study within our understanding would be helpful. Also, it seems that perhaps the authors are being too passive and 'nice' here, and are just presenting their results without directly confirming or refuting the work of others. Be bold! In the conclusion, state who among your predecessors you agree with, who you disagree with, and say why. You take the risk of perhaps ruffling a few feathers, but you will ensure response, and that's a very effective way to move science forward. (I'm reminded of a current disagreement between a group that hypothesizes that the Amazon experiences greenup during drought, and the group that believes this isn't the case. The issue has not been resolved, but there have been some very interesting studies that have come out of the dispute.)

We appreciate the reviewer's encouragement to take a stronger position on how our findings relate to the existing body of literature. We find no trends towards the carbon release that is often predicted for this region. Our limited temporal study is however unable to weigh in on whether that carbon release will ever occur in the future. We simply can say it hasn't happened yet. We can say that as a whole, the boreal region is maintaining carbon uptake strength in spite of the often discusses drought effects in Alaska and Canada. It could be that opposite trends in Eurasia are offsetting drought effects in North America. We do not feel comfortable using the inversion fluxes to attribute flux trends longitudinally between NA and EU. There aren't enough CO2 observation stations to constraint this well. We have expanded the conclusions section to draw the reader's attention to areas of conflict with previous literature. Including: "*Furthermore, our atmospheric inversions results show no evidence of an overall trend towards increasing CO_2 releases in either the boreal or Arctic zone over the 1985-2012 period. This is an important check for process-based biospheric models which have been challenged to predict the timing of an incipient 'carbon bomb' from the high northern latitudes (Treat and Frolking, 2013). At the moment, the increase in biomass productivity has appeared to be outpacing CO_2 losses from warming northern carbon-rich soils. Time will tell whether this trend continues, or whether it will reverse, due to nutrient or water limitations, etc., and become a net carbon source in a few decades as predicted by popular opinion among the community of experts (Abbott et al., 2016).*"

Some specific comments:
- Author is not listed in reference in the 4th paragraph of the introduction.

Fixed.

- The Jena inversion uses LPJ land flux and Mikaloff Fletcher/Takahashi ocean flux. What does the RIGC inversion use?

Added these details to the model description.

How are these surface fluxes similar/different, what might that mean for inversion results? Could these differences be the source of the RIGC peak CO2 uptake being double that of Jena (section 3.1.1)?

These priors are used as a starting point and allowed to change based on the inversion residual minimization. They could contribute to the differences in the inversion results. They also use different atmospheric transport models and entirely different model configurations. It is hard to identify one cause of the differences. The fact that they share many similar trends gives us some confidence that those trends are robust. Inversion models are known to vary widely in their magnitude of the fluxes. For that reason, interannual variability is the focus of our study (Baker et al., 2006).

- Section 3.3: the authors claim that the flux amplitude increase, shown in figures 3cd, is larger in the arctic than in the boreal regions. This is clearly true in the RIGC product, especially with regard to SON efflux. However, I'm not sure I agree that this is true for Jena. To my (subjective) eye, the summer uptake and fall/winter efflux amplitude increase is larger for both Jena products in the boreal region than in the arctic.

It's roughly the same absolute increase in the flux amplitude, but that's on top of very different mean seasonal cycles. It's the percentage increase that larger in the Arctic region.

- I'm a bit confused about the results shown in sections 3.5 and 3.6, Figure 11. Figure 3 clearly displays a strong amplification of July CO2 uptake, and Figure 8 shows a clear upward trend in JJA temperatures over the period of study. But Figure 11 (and references to studies in the text) correlate cooler summertime temperatures with increased uptake. What am I missing here? These seem contradictory. Is the moisture component the more important than the temperature?

The difference is that the records were detrended before the correlation analysis in Fig 11. There may be different drivers of long-term trends and short-term interannual variability.

"In this analysis, all data sets were de-trended using a stiff spline to remove long-term trends, thus emphasizing processes controlling interannual variability (IAV)."

- Section 3.5: Russell and Wallace (2004) and Schaefer et al. (2002) looked at carbon flux in relation to modes of climate variability such as the annular modes. Hurrell et al. (2001) discussed trends in the NAO itself. Would studies such as these help provide context here, or are they unrelated?

The annual modes are related in that they correspond to temperature and precipitation anomalies, but I don't think it's necessary to include them in the discussion. The analysis of temperature controls on NEE and NDVI is fundamental regardless of whether the temperature anomaly is caused by an annual mode or not. We did add a statement related to the Russell and Wallace findings…

"The RIGC inversion shows significant correlation between warm winters and increased CO_2 *uptake the following growing season (negative correlation), consistent with Russell and Wallace* (2004)*, but this relation did not appear in the Jena correlation."*

- Is the last paragraph of section 3.6 necessary?

It seems important for completeness, and it's interesting that the same patterns don't hold in the northern region.

- Figure S1: RIGC BA+BNA fossil fuel (ORNL/EDGAR) is about half the Jena anthropogenic flux for the same region (also EDGAR, but apparently different version.
Intuitively, I would expect that Jena uptake would have to be larger than RIGC to resolve observed CO2 concentration with these anthropogenic fluxes. Why isn't this the case?

"The RIGC and Jena inversions use different fossil-fuel emissions datasets to isolate the net land surface fluxes related to biology. Comparing fossil-fuel emissions for the EU and BA+BNA Arctic and Boreal zones used in each inversion (SI Fig. 1) shows that while the mean emissions were lower in the RIGC inversion,

the IAV and trends in absolute fluxes were similar in each inversion. Differences in the fossil emissions are therefore unlikely to contribute significantly to trends in the biological land fluxes of the BA+BNA Arctic and Boreal zones."

Remember that the long-term means have been removed in this analysis because of offsets like this among models.

- Patra et al. (2008) and Parazoo et al. (2008) discuss model resolution in relation to simulations of CO2. I wonder if advection of the effect of large surface CO2 flux into boreal/arctic regions is a partial (or dominant?) cause of the increasing amplitude of high-latitude CO2 concentrations? Or is Graven et al. (2013) the last word? What role might model resolution play? Are these issues not germane to this manuscript?

There is a body of literature suggesting that many transport models under estimate the vertical mixing, which would directly affect these inversion predictions, in particular when the measurement sites are located close to the intense source regions, e.g., the land biosphere or industrial centers. However, the fact that 2 different transport models produce similar CO_2 flux trends is reassuring. This consistency between the two inversions is obtained because the measurement sites used in both inversions are remotely located and designed to sampling marine air. Patra et al. (2008) have shown that the so called “site representation error” is high for the coastal or continental sites.

- Figure 11: There are significant correlations out to two years for RIGC and 4 years for Jena that are not discussed in the text. What might these long time-lag correlations mean?

Added this paragraph: *"Our analysis found significant correlations out to 2 to 4 years prior, suggesting that temperature anomalies could have an impact on NEE after several years delay. While there have been studies suggesting that multi-year lags between climate and CO_2 fluxes are important (e.g. Bond-Lamberty et al., 2012), these correlations were not consistent between the inversion models, preventing us for speculating as to the cause. "*

References
Hurrell, J.W., Y. Kushnir, M. Visbeck 2001: The north atlantic oscillation. Science, Vol. 291, No. 5504 (Jan 26 2001), p603-605.
Parazoo, N.C., A.S. Denning, S.R. Kawa et al., 2008: Mechanisms for synoptic variations of atmospheric CO2 in North America, South America, and Europ. Atmos. Chem. Phys., 8, 7239-7254.
Patra, P.K., R.M. Law, W. Peters, et al., 2008: TransCom model simulation of hourly atmospheric CO2: Analysis of synoptic-scale variation for the period 2002-2003. Glob. Biogeochem. Cy., 22, GB4013, doi:10.1029/2007/GB003081.
Russel, J. and J.M. Wallace, 2004: Annual carbon dioxide drawdown and the northern annular mode. Glob. Biogeochem. Cy., 18, GB1012, doi:10.1029/2003/GB002044.
Schaefer, K. A.S. Denning, N. Suits et al., 2002: Effect of climate on interannual variability of terrestrial CO2 fluxes. Glob. Biogeochem. Cy., 16(4), 1102, doi:10.1029/2002GB001928.

Response references:

Baker, D. F., Law, R. M., Gurney, K. R., Rayner, P., Peylin, P., Denning, A. S., Bousquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fung, I. Y., Heimann, M., John, J., Maki, T., Maksyutov, S., Masarie, K., Prather, M., Pak, B., Taguchi, S. and Zhu, Z.: TransCom 3 inversion intercomparison: Impact of transport model errors on the interannual variability of regional CO_2 fluxes, 1988–2003, Global Biogeochemical Cycles, 20(1), GB1002, doi:10.1029/2004GB002439, 2006.

Bond-Lamberty, B., Bunn, A. G. and Thomson, A. M.: Multi-year lags between forest browning and soil respiration at high northern latitudes, edited by G. Bohrer, PLoS ONE, 7(11), e50441, doi:10.1371/journal.pone.0050441.t002, 2012.

Patra, P. K., Law, R. M., Peters, W., Rodenbeck, C., Takigawa, M., Aulagnier, C., Baker, I., Bergmann, D. J., Bousquet, P., Brandt, J., Bruhwiler, L., Cameron-Smith, P. J., Christensen, J. H., Delage, F., Denning, A. S., Fan, S., Geels, C., Houweling, S., Imasu, R., Karstens, U., Kawa, S. R., Kleist, J., Krol, M. C., Lin, S. J., Lokupitiya, R., Maki, T., Maksyutov, S., Niwa, Y., Onishi, R., Parazoo, N., Pieterse, G., Rivier, L., Satoh, M., Serrar, S., Taguchi, S., Vautard, R., Vermeulen, A. T. and Zhu, Z.: TransCom model simulations of hourly atmospheric

CO_2: Analysis of synoptic-scale variations for the period 2002-2003, Global Biogeochemical Cycles, 22(4), n/a–n/a, doi:10.1029/2007GB003081, 2008.

Russell, J. L. and Wallace, J. M.: Annual carbon dioxide drawdown and the Northern Annular Mode, Global Biogeochemical Cycles, 18(1), n/a–n/a, doi:10.1029/2003GB002044, 2004.

Response to referee comments (in red):

Anonymous Referee #2
Received and published: 25 March 2016

This study takes an important step beyond the well-documented increase in atmospheric CO2 seasonal amplitude at Arctic monitoring sites and asks whether this amplitude increase actually reflects a net gain in CO2 uptake in boreal and Arctic regions. The methodology involves exploring trends in NEE fluxes inferred from 2 different inversion systems over the common period 1986-2006 (and also 1985-2012 for one of the inversions). In general, the study is well presented and documented and I support publication with minor revision. Some of my more important (although still relatively minor) concerns are that the results differ substantially between the two inversions in many aspects, leading to doubts about the robustness of either.

Added: " *These differences are not unexpected given the differences in atmospheric transport 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 trends in anomalies from the mean."*

Also, the Arctic zone>60N is the region with the most unequivocal increase in CO2 amplitude, yet the inversions estimate significant trends in net CO2 uptake mainly in the boreal zone (50-60N), not the Arctic zone. The CO2 amplitude increase at Barrow, AK (71N) in particular has been the subject of much attention, yet it doesn't seem to be associated with an actual increase in CO2 uptake in the surrounding region. A particularly interesting result is that the inversions suggest that increased CO2 respiration and release in fall may largely balance increased CO2 uptake in summer (although they don't agree where the increased fall respiration is occurring). I am curious about the heavy focus on midsummer (July) at the expense of late spring/early summer, when the CO2 cycle (e.g., at Barrow) indicates an earlier onset of photosynthesis. Could this be when some of the net gain in CO2 uptake is occurring?

I think the reviewer is confusing trends in concentration amplitude with flux amplitude. The inversion should be able to separate influence in the spring from the mid-summer.

Re: the 2 time periods chosen: 1986-2006 and 1985-2012. I suggest making the second period 1986-2012, to remove ambiguity about why the results differ between the 2 periods. With the 1985 start year, we don't know whether the changes in the trends are due to the influence of starting in 1985 vs. 1986 or due to more recent changes from 2006-2012. The latter possibility seems more relevant to global change, therefore I suggest eliminating this ambiguity by starting both periods in 1986. Trend calculations of this sort can be sensitive to the starting year, especially when operating on the margins of statistical significance, as is the case here. On a related note, is the legend in Fig 3b (86-12) a typo?

Regarding the start year and periods of trend calculations, we agree with the reviewer's comments about sensitivity to start year. That's why we think it is a more robust estimate to use the longest records possible. It is not our intension to comment on the difference between 86-06 and 85-12 as a measure of processes from 06-12. Rather, the intension to use as much information as possible to examine the longterm trends. Fixed the 86-12 typo. Should be 85-12.

Some specific comments
Abstract, there are a couple of grammatical errors or typos that interfere with smooth reading:
AbL17-18 "Here we examine CO2 fluxes from northern boreal and tundra from 1986 to 2012 ..."

edited

AbL29-31 sentence beginning with "Meanwhile . . .

edited

P2L35 (1997)?

citation fixed

P3L20-26 Please define what exactly is meant by "browning" and "greening," e.g., does this refer to changes in seasonality of NDVI, or does it refer to an annual mean index?

Some studies examine maximum and others the growing season integrated NDVI. This comment was added.

The Introduction in general is quite good and informative, but is marred by the paragraph on L8-17. I have several suggestions for improving it:
P4 L8-17 The emphasis on aboveground vs. belowground in the first sentence seems incongruous because it is

not mentioned earlier as a strength of inversions. Perhaps start this paragraph with a more general statement about the strengths of forest inventories.

The reviewer's comment was valid. We edited the entire paragraph to improve the context with the rest of the introduction.

P4 L13 For clarity, should “several studies” be “several process-based model studies”?

change made

P4 L11-17 Can we believe these results? What are the weaknesses of process-based model studies? (Referring back to earlier statement that, “Each of these methods has its strengths and weaknesses.”)

The models need to be validated and atmospheric inversions can help in that effort.

P4L18 “. . .50N, using the atmospheric inversion method.”

Moved the second sentence forward to introduce the inversion method at the start.

P4L35 What is “It” ?

RIGC

P5L7 What period?

1985-2006

P5L9 Temporal coverage of what? Years, months, weeks? What is the time resolution?

It varies by station and time period, but at least monthly resolution was the aim.

P5L21 What is LPJ?

The Lund-Potsdam-Jena model is commonly referred to a LPJ in the literature.

P5L30 What are the units of NDVI? Are they mass units, e.g., kg/m2 or flux units, e.g., in kg/m2/s?

Unitless. It's a ratio of light reflectance in different wavelengths. This is described briefly now.

P6L10- Perhaps I am missing something, but I don’t see the 2 different analysis methods for trends and significance reported in Table 2 described anywhere in this section. There is only a brief mention of them in the Table 2 caption, which is not very informative.

We added a paragraph in section 2.3, Analysis Approach, that describes each of these statistical methods and cites the sources.

P6L15 In Figure 1 the boreal forest stippling extends well north of 60 degrees. Does this mean that the so-called Arctic zone consists largely of boreal forest? This is somewhat confusing and perhaps should be noted here. Other parts of the text seem to suggest the Arctic zone is mainly tundra, but later p.12 mentions that tundra covers only 25% of the Arctic zone.

Added a comment on this.

Figure 3c,d. Should the Y-axis units be gC/m2/day per year?

Yes. Fixed.

P7L33. Probably should note that $P < 0.1$ is significant at only 10% level, which is a weak standard. In general $p < 0.05$ is the standard level required for significance.

Added a comment on this to the new paragraph on statistics in section 2.3.

P9L13. How were these 40-50 and 55-65N bands chosen?
Figure 7 seems to suggest net release and net uptake for 40-55N and 55-75N, respectively. Also, please check P13L10 for consistency.

From comparing July and fall trends in Fig 7b. Changed 55-65 to 55-70N.

P9L25 In order to . . .

Fixed.

P10L27 “We found significantly strong positive correlations between July CO2 flux and April through August temperatures of the same year. . .” The next sentence is confusing because it suggests lower CO2 uptake (more release) in warm years, in contrast to the quoted sentence – please clarify that "positive correlation" means the July flux is weaker not stronger.

This is confusion about the sign convention of NEE. Added: *"It is also important to remember that NEE is negative when there is net CO_2 uptake from the atmosphere when interpreting the sign of correlations."*

P12L17-20 "Increased summer CO2 uptake cannot be explained by earlier spring leaf-out, but rather points to changes in mid-summer photosynthetic and respiration fluxes themselves." Where is this sentence supported in the Results?

We decided to cut this sentence because the point about increased summer uptake was already made. Relating that model prediction to spring leaf out was confusing.

P12L31-33 "This difference could reflect the importance of structural ecosystem changes due to warming on the long time scale increasing photosynthesis (Graven et al., 2013), but on the short time scale, respiration is the dominant control." This seems like a core conundrum of this study (together with the fact that no apparent increase in net CO2 uptake is occurring in the band where the CO2 amplitude is increasing). Both of these points might be worth discussing more.

Actually, the July CO_2 uptake is increasing in the boreal zone, as shown in Fig 5, it's just smaller when expressed as a % increase in the seasonal flux amplitude in Fig 4. Graven et al. (2013) showed that the summer boreal CO_2 uptake must be increasing as well from atmospheric constraints. Atmospheric transport can cause somewhat of a disconnect between observed amplitude changes and the region of fluxes. It has been shown that even far northern flask stations are somewhat influenced by more southerly fluxes.

I don't find the different drivers for long-term trends and short-term interannual variability to be contradictory. Added: "*This difference could reflect the importance of structural ecosystem changes due to warming on the long time scale increasing photosynthesis (Graven et al., 2013), but are also consistent with respiration as the dominant control of NEE on short time scales (Schaefer et al., 2002)."*

Response references:

Graven, H. D., Keeling, R. F., Piper, S. C., Patra, P. K., Stephens, B. B., Wofsy, S. C., Welp, L. R., Sweeney, C., Tans, P. P., Kelley, J. J., Daube, B. C., Kort, E. A., Santoni, G. W. and Bent, J. D.: Enhanced seasonal exchange of CO_2 by northern ecosystems since 1960, Science, 341(6150), 1085–1089, doi:10.1126/science.1239207, 2013.

Schaefer, K., Denning, A. S., Suits, N., Kaduk, J., Baker, I., Los, S. and Prihodko, L.: Effect of climate on interannual variability of terrestrial CO_2 fluxes, Global Biogeochemical Cycles, 16(4), 49–1–49–12, doi:10.1029/2002GB001928, 2002.

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.

Increasing summer net CO_2 uptake in high northern ecosystems inferred from atmospheric inversions and comparisons to remote sensing NDVI

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Abstract. Warmer temperatures and elevated atmospheric CO_2 concentrations over the last several decades have been credited with increasing vegetation activity and photosynthetic uptake of CO_2 from the atmosphere in the high northern latitude ecosystems: the boreal forest and Arctic tundra. At the same time, soils in the region have been warming, permafrost is melting, fire frequency and severity are increasing, and some regions of the boreal forest are showing signs of stress due to drought or insect disturbance. The recent trends in net carbon balance of these ecosystems, across heterogeneous disturbance patterns, and the future implications of these changes are unclear. Here, we examine CO_2 fluxes from northern boreal and tundra regions from 1985 to 2012, estimated from two inverse models (RIGC and Jena). Both used measured atmospheric CO_2 concentrations and wind-fields from interannually variable climate reanalysis. In the Arctic zone, the latitude region above 60°N excluding Europe (10°W – 63°E), neither model finds a significant long-term trend in annual CO_2 balance. The boreal zone, the latitude region from approximately 50°N to 60°N, again excluding Europe, showed a trend of 8–11 Tg C yr^{-2} over the common period of validiy from 1986 to 2006, resulting in an annual CO_2 sink in 2006 that was 170–230 Tg C yr^{-1} larger than in 1986. This trend appears to continue through 2012 in the Jena inversion as well. In both latitudinal zones, the seasonal amplitude of monthly CO_2 fluxes increased due to increased uptake in summer, and in the Arctic zone, also due to increased fall CO_2 release. These findings suggest that the boreal zone has been maintaining and likely increasing CO_2 sink strength over this period, despite browning trends in some regions, changes in fire frequency and land use. Meanwhile, the Arctic zone shows that increased summer CO_2 uptake, consistent with strong greening trends, is offset by increased fall CO_2 release, resulting in a net neutral trend in annual fluxes. The inversion fluxes from the Arctic and boreal zones covering the permafrost regions showed no indication of a large-scale positive climate-carbon feedback caused by warming temperatures on high northern latitude terrestrial CO_2 fluxes from 1985 to 2012.

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1 Introduction

The high northern latitudes, including the tundra and boreal forest regions, are particularly vulnerable to the effects of climate change as this region has been experiencing dramatic changes in recent climate. Warming in northern ecosystems results in many physical and ecological changes that have consequences for carbon cycling (Chapin, 2005; Hinzman et al., 2005; McGuire et al., 2009; Serreze et al., 2000; Smith and Dukes, 2012; Walther, 2010; Wu et al., 2012). Annual mean surface air temperatures over land increased by 0.64°C per decade north of 60°N from 1979 to 2008, roughly twice the rate of 0.33°C per decade for the northern hemisphere as a whole (ACIA, 2004; Bekryaev et al., 2010; Wolkovich et al., 2012). This northern polar amplification has been attributed to ice/snow-albedo feedbacks (Cess et al., 1991; Qu and Hall, 2007; Serreze and Barry, 2011). Minimum sea ice extent in the Arctic Ocean has declined rapidly (Comiso et al., 2008) with feedbacks and teleconnections on the continental areas as well (2016; Francis et al., 2009). Impacts in the northern regions are predicted to intensify, as climate scenario modeling projects further arctic temperature increases of 5–7 °C by the end of this century (ACIA, 2004; Ewers et al., 2005) and atmospheric CO$_2$ concentrations continue to rise at a rate approaching 2.0 ppm per year.

Tundra ecosystems and boreal forests hold large stores of carbon in soil organic matter buried in cold or frozen permafrost soils. It is estimated that 1,400 to 1,850 Pg C are stored in high northern latitude soils and another 60 to 70 Pg C in above and below-ground vegetation (Gedney et al., 2006; Keenan et al., 2013; McGuire et al., 2009). The natural turnover time of this carbon is very slow, but there is a risk that warmer temperatures will increase microbial respiration rates and expose previously frozen organic matter to decomposition by melting the permafrost (Cao et al., 2010; Johnstone et al., 2010; Schuur et al., 2008; Trahan and Schubert, 2015). Over the past several decades there has been a measureable trend to earlier spring snowmelt and surface soil thaw (Brown et al., 2013; McDonald et al., 2004; Smith, 2004) and increases in permafrost borehole temperatures (Romanovsky et al., 2010) demonstrating changes in the thermal stability of northern circumpolar soils. It has been speculated that warming could trigger a massive release of carbon from these soils, in the form of CO$_2$ and CH$_4$, leading to a positive climate-carbon feedback (Pastick et al., 2015; Schuur et al., 2008). This has been nicknamed the Arctic 'carbon bomb' in the popular media (Treat and Frolking, 2013).

However, warming and the associated lengthening of the growing season encourages plant growth in these otherwise temperature-limited areas, as does increased atmospheric CO$_2$ fertilization (Lloyd and Farquhar, 1996; Wickland et al., 2006; Yi et al., 2009) and increased nitrogen deposition (Baird et al., 2012; Barber et al., 2000; Bunn and Goetz, 2006; Goetz et al., 2005; Holland et al., 1997; Soja et al., 2007). The net carbon balance of increased plant growth and increased soil respiration is unclear, but has important consequences for predicting carbon-climate feedbacks (Abbott et al., 2016; Koven et al., 2015).

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Measurements of atmospheric CO_2 concentrations at Barrow, Alaska by Keeling et al. (1996) provided evidence for increased photosynthetic activity and net primary production (NPP) at northern latitudes from 1960 through 1994. The changes were attributed to increased CO_2 uptake by vegetation during spring and summer, leading to earlier drawdown and larger seasonal amplitudes of atmospheric CO_2 concentrations (Barichivich et al., 2014; Keeling et al., 1996; Randerson et al., 1999). This perspective is also supported by satellite observations of an increase in vegetation greenness at northern latitudes (Myneni et al., 1997) and global ecosystem process models suggesting that northern ecosystems have become more productive as a result of combined changes in temperature, CO_2 concentration and nitrogen availability (Kimball et al., 2007; McGuire et al., 2001; Wang et al., 2012). An updated perspective on the northern CO_2 cycles from Barrow data and from repeated airborne surveys of the mid troposphere showed 50% increase in the amplitude from 1960 to 2010, implying a significant increase in northern ecosystem growing season CO_2 uptake over the last several decades (Graven et al., 2013; Ueyama et al., 2014).

Since the late 1990s, however, some indicators of ecosystem function suggest that the terrestrial biosphere response to recent climate change in the high northern latitudes may be different from the previous few decades, and that terrestrial CO_2 uptake has since slowed down or even turned to a net source. Analysis of the changes in the seasonality of atmospheric CO_2 suggests that temperature-induced late summer drought may be increasing fall CO_2 release and offsetting enhanced spring CO_2 uptake (Angert et al., 2005; Piao et al., 2008; Rozendaal et al., 2009). Piao et al. (2008) estimated that current warming during autumn increases respiration in northern ecosystems enough to cancel 90% of the increased spring CO_2 uptake. While these studies provide important insights into changing ecosystem function, changes in CO_2 seasonal cycles in the atmosphere depend not just on surface fluxes but also variations in atmospheric circulation (Higuchi, 2002).

Vegetation productivity and distribution have also changed during this same period. The treeline has advanced northward and woody shrub colonies have expanded in the tundra zone displacing less productive species (Goetz et al., 2005; Lloyd et al., 2005; Pearson et al., 2013; Stoll and Ortega, 2013; Sturm, 2005; Tape et al., 2006). Within the boreal zone, satellite observations show large areas of the boreal forest not disturbed by fire have been 'browning' since 2000 as observed by Normalized Difference Vegetation Index (NDVI) measurements (Goetz et al., 2005; 2007; Verbyla, 2008; 2011; Zhang et al., 2008). These studies are mostly based on either trends in maximum or growing season integrated NDVI or NDVI-derived LAI. One statistical analysis suggests the browning trends in the Alaskan boreal forest have been ongoing for the last three decades (Forkel et al., 2013). These results have been consistent with ground observations which also report widespread tree mortality caused by insect outbreaks due to warmer winter temperatures (Kurz et al., 2008) and drought (Hogg et al., 2008; Peng et al., 2011). However, an updated NDVI processing algorithm in the NDVI3g product shows overall more areas greening than the older version, with the largest greening in western Eurasia (Xu et al., 2013; Zhu et al., 2016) but with browning still occurring in parts of North America (Xu et al., 2013). Park et al. (2016) estimates that the overall greening, or increase in

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growing season integrated NDVI, is equivalent to a 20.9% gain in productivity since 1982 and the smaller areas of browning are equivalent to a 1.2% loss of productivity. Furthermore, these trends in greening and productivity seem to be independent of shifts in the start and end of the growing season and growing season length (Park et al., 2016).

It is important to determine the net carbon balance of these large northern regions to see if they have been increasing or decreasing in CO$_2$ sink strength, or perhaps transitioning to a net CO$_2$ source. Approaches used to estimate the net CO$_2$ fluxes of large areas include forest inventories, atmospheric inversions, and process-based models. Each of these methods has its strengths and weaknesses. Atmospheric inversions can infer the global, continental and sometimes regional-scale fluxes of CO$_2$ between the atmosphere and the land biosphere and the oceans, by analyzing the temporal and spatial records of atmospheric CO$_2$ change (Enting, 2002). Inversions have the advantage of including the effects of disturbance and changing vegetation patterns, but are limited to the period of sufficient CO$_2$ concentration observations and are best suited to resolving continental-scale fluxes. Few inversion analyses have specifically focused on the high northern latitude terrestrial ecosystems. Zhang et al. (2013) aggregated the inversion fluxes from five different models into Eastern Canada and Western Canada plus Alaska. The inversions examined showed consistent increases CO$_2$ uptake in Eastern Canada and no long-term trend in Western Canada plus Alaska.

Atmospheric inversion CO$_2$ fluxes can provide useful validation metric for other methods of ecosystem monitoring because they resolve the net effect of above and below ground carbon fluxes. Repeat forest inventories are useful for identifying trends in forest productivity over time. However, they are limited to detecting trends in above-ground carbon only, not changes in below-ground carbon. Forest inventory studies have found drought-induced tree mortality and above ground carbon loss in Canada, with the western region most affected (Hogg et al., 2008; Ma et al., 2012; Michaelian et al., 2010; Peng et al., 2011).

Process-based modeling studies attempt to account for above and below-ground carbon changes while providing full spatial coverage, and are therefore capable of simulating net ecosystem fluxes that can be compared to atmospheric inversions. Several process-based modeling studies have concluded that the Arctic tundra and boreal forests have been decreasing sinks or increasing sources since the 1980s due to climate effects, namely warmer temperatures increasing soil organic matter decomposition, and increased fire and insect disturbance, offsetting increased CO$_2$ uptake driven by CO$_2$ fertilization (Bradshaw and Warkentin, 2015b; Hayes et al., 2011; McGuire et al., 2010), though McGuire et al., (2012) found that 6 our of 11 processes based models (global and regional) predicted a strengthening carbon sink (including CH4 contributions) in the 2000s compared to the 1990s. Processes including permafrost melt, hydrologic changes, nutrient dynamics, and fire emissions are critical to predicting any changes in the net CO$_2$ fluxes from the northern regions, but difficult to include in the models with much certainty (Abbott et al., 2016; Harden et al., 2012). Abbott et al. (2016) conducted a survey of experts in the field and found that the overwhelming opinion was that any increases in biomass are not going to be enough to offset carbon

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releases from permafrost melt by 2040 nor 2100. These models and expert predictions can be directly challenged with results from atmospheric inversions.

In this study, we examine large regional-scale temporal variability in terrestrial CO$_2$ fluxes from two atmospheric inversions using interannually variable atmospheric transport from 1985 to 2012. We focus on trends in the carbon uptake of the land biosphere north of approximately 50°N. The primary objective of this study is to evaluate temporal changes in the annual and seasonal land biosphere CO$_2$ fluxes. We determine in what months surface CO$_2$ fluxes have likely changed, i.e. increased summer uptake or winter release. We further examine NDVI, air temperature trends, and correlations with CO$_2$ fluxes to provide some spatial and process context for temporal changes in the inversion fluxes.

2 Methods and data analysis

2.1 Inversion models

We compared two different atmospheric inversions: the RIGC inversion and the Jena CO$_2$ inversion (s85v3.6). The RIGC inversion method was adapted from Rayner et al. (1999), and largely followed the TransCom-3 protocol (Gurney et al., 2003). The RIGC model uses a 64-region time-dependent inverse method to infer carbon source/sink estimates based on the method of Patra et al. (2005). The RIGC inverse calculation starts with *a priori* fossil-fuel emissions and terrestrial and oceanic fluxes which are then optimized to match observations. For the *a priori* fluxes, terrestrial exchanges were taken from the CASA monthly output (Randerson et al., 1997) and monthly-mean oceanic exchanges from Takahashi et al. (Takahashi et al., 2002) as in TransCom-3 protocol (Gurney et al., 2003). Total anthropogenic CO$_2$ emissions were derived from the Oak Ridge National Lab monthly fossil fuel estimates from CDIAC (Boden et al., 2009) plus bunker fuel and non-fuel oxidation estimates from the Emissions Database for Global Atmospheric Research (EDGAR) (Oliver and Berdowski, 2001). RIGC uses the NIES/FRCGC (National Institute for Environmental Studies/Frontier Research Center for Global Change) global forward transport model driven by interannually varying (IAV) meteorology from the NCEP reanalysis and the GLOBALVIEW-CO$_2$ product to derive residual *a posteriori* land and ocean surface fluxes for the 64 inversion regions.

In the RIGC inversion, the GLOBALVIEW-CO$_2$ input was limited to the 26 stations, which have nearly continuous CO$_2$ observation from 1985 to 2006 (Table 1). Among these are stations that document changes in high northern latitudes, including Barrow (71°N), Alert (82°N), Station M (66°N), Cold Bay Alaska (55°N), Shemya (52°N), and Cimone (44°N). A selected set of stations was used to avoid creating spurious trends in the inversion results from adding new stations mid-way through the inversion period. All selected stations had at least 71% of months sampled at least once and came online by 1989. Stations north of 39°N had 84% to 100% monthly coverage. The resulting fluxes from the RIGC inversion are valid from 1986 to 2006, after removing years at the beginning and end for 'edge effects' from the inversion setup.

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Compared to the RIGC model, the Jena inversion, version s85_v3.6 (Rodenbeck, 2005) uses a slightly different set of 19 stations selected to completely cover the 1985–2012 estimation period, but includes all of the same stations north of 50°N (Table 1). It uses individual measurements from various sampling networks, without smoothing or gap filling. Fluxes are estimated at the grid-scale resolution (approximately 4° latitude by 5° longitude), to reduce aggregation errors. However, to counteract that the estimation would be underdetermined, spatial and temporal a-priori correlations are imposed, smoothing the estimated flux field on scales smaller than about 1 week and about 1600 km (land, in longitude direction), 800 km (land, latitude), 1900 km (ocean, longitude), or 950 km (ocean, latitude), respectively. Land flux adjustments are spatially weighted with a productivity proxy, the long-term mean NPP from the LPJ terrestrial biospheric model (Sitch et al., 2003). Prior fluxes comprise anthropogenic CO_2 emissions from EDGAR v4.2 (EDGAR, 2011), a constant spatial flux pattern on land (time-mean NEE from the LPJ model), and an ocean-interior inversion by Mikaloff Fletcher et al. (2006) with a mean seasonal cycle of ocean fluxes from Takahashi et al. (2002). The Jena inversion uses the TM3 global atmospheric transport model driven by interannually varying meteorology from the NCEP reanalysis. The 4 x 5 degree gridded *a posteriori* land and ocean surface fluxes are aggregated to our larger analysis regions. Resulting fluxes are valid from 1985 to 2012.

2.2 Datasets

We compared CO_2 fluxes with satellite-based normalized difference vegetation index (NDVI) data over the same time period and with land temperature records. NDVI is a proxy for photosynthetically active above-ground biomass, calculated from the visible and near-infrared light reflected by vegetation. It has dimensionless units and varies from a value of 0 for no vegetation to a value of 1 for the highest density of green leaves. We used NDVI data produced by NASA's Global Inventory Modeling and Mapping Studies (GIMMS version 3g) from measurements of the Advanced Very High Resolution Radiometer satellite and supplied at the monthly, 1 x 1 degree resolution (Pinzon and Tucker, 2014). Winter NDVI data was excluded from this analysis because of the confounding influence of snow (Myneni et al., 1997). We defined growing season NDVI (Zhou et al., 2001) as the sum of monthly NDVI from April to October following the example of earlier work. 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.

We used monthly mean temperature anomalies from the NASA GISS 2 x 2 degree gridded dataset to compare to CO_2 fluxes and NDVI variability (Hansen et al., 1999). Temperature anomalies are computed by subtracting the 1951 to 1980 mean. Throughout this manuscript, we abbreviate seasonal means by 'MAM' (March, April, May), `JJA' (June, July, August), `SON' (September, October, November), and `DJF' (December, January, February).

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We examined estimates of fire CO_2 emissions from 1985 to 2000 from the RETRO compilation and from 1997 to 2012 from the GFEDv4 model (Giglio et al., 2013; Schultz et al., 2008).

2.3 Analysis approach

Our focus is primarily on the interannual variability in the CO_2 fluxes which is considered more robust across inversions than the absolute values of the mean fluxes (Baker et al., 2006). For that reason, we look at anomalies from the long-term mean values of each inversion model.

We focused our analysis on land carbon fluxes in two roughly zonal bands at high northern latitudes partly based on the TransCom regional boundaries defined by Gurney et al. (2003). Figure 1 shows the regions of Boreal Asia (BA) and Boreal North America (BNA) that we aggregated into what we refer to as the 'boreal zone' roughly between 50°N and 60°N and the 'Arctic zone' north of 60°N. Note here that while we refer to the boreal zone as roughly '50°N to 60°N', the southern boundary is not defined at the 50°N latitude, but follows the irregular southern boundary of boreal forest (stippled area in Fig. 1), nor does it include the entire boreal forest as the northern boundary extends well into the 'Arctic zone' north of 60°N. We decided to omit the European (EU) land region from our zonal analysis for two reasons. First, the TransCom protocol followed by the RIGC inversion does not separate northern Europe at 60°N like it does for BA and BNA, rather northern EU section is everything north of 50°N. Second, the EU region includes a relatively small fraction of the tundra and boreal forest ecosystems compared to BA and BNA, and the forest area is highly managed. Our focus is how the less intensively managed ecosystems of the north have been responding to climate change and examining the boreal zone and the arctic zone should maximize any potential signals of change. A similar approach of excluding EU was used in the Arctic analysis of McGuire et al. (2009).

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. For that reason, we check the EU and Northern Ocean (NO) regions for any trends that might be offsetting trends in what we define as the 'Boreal zone' and the 'Arctic zone' caused by spatial errors in the assignment of surface fluxes by the inversion analyses that could complicate our interpretations of the data. We performed the trend analysis for two periods: from 1986-2006 when we have inversion results for both models, and from 1985–2012 for just the Jena s85 inversion.

We examine trends in the monthly, seasonal, and annual net ecosystem exchange (NEE) fluxes from the inversion models. Amplitudes of the annual seasonal cycle in CO_2 fluxes were calculated from the maximum and minimum monthly mean fluxes within each calendar year as: flux amplitude = maximum

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NEE - minimum NEE. The flux amplitude is indirectly related to the amplitude in atmospheric CO_2 concentrations, as the atmospheric concentration is roughly the integral of the monthly fluxes. It is unnecessary to detrend the time series of fluxes from the models prior to calculating the flux amplitude, unlike the concentration amplitude which has a persistent long-term trend from anthropogenic CO_2 emissions. We also examine the latitudinal gradient of the trends in the seasonal fluxes in ~4° latitude bands from the gridded Jena inversion. This analysis was not possible with the RIGC inversion because of the larger basis regions. This approach attempted to answer the question of whether summer uptake is increasing or fall respiration (or both) and how that might change with latitude.

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Two methods were used to calculate the slopes of long-term trends and statistical significance of trends, linear least squares and Mann-Kendall tests. Trends were considered significant if they passed the 90% confidence level (p-values < 0.1). The Model I linear region analysis (LSQ) was done in Matlab using the function 'lsqfity' developed by Peltzer (2000) based on Bevington and Robinson (1992). The non-parametric monotonic Mann-Kendall trend test (M-K) with Sen's slope was also done in Matlab using the function 'ktaub' developed by Burkey (2006). Results of both tests are presented in Table 2. The independent tests generally agree on slope and significance of trends.

3 Results

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3.1 CO_2 flux trends

3.1.1 Arctic zone (>60°N)

The arctic zone containing the tundra region showed no significant trend in annual CO_2 uptake (Fig 2a, Table 2) from 1986–2006 in either inversion. The longer period, 1985–2012, in the Jena inversion did show a small but significant trend toward increased uptake of an extra 4 Tg C yr^{-1}. Anomalously strong annual CO_2 uptake occurred in years 1990 and 2004 in the RIGC inversion and strong CO_2 release in 1996. These large anomalous fluxes were not present in the Jena inversion.

The Jena and RIGC inversions differ in their mean seasonal cycle in the arctic zone, with the RIGC inversion yielding peak CO_2 uptake approximately twice that of the Jena inversion (Fig 3b). The seasonal amplitude and phase has previously been found to differ among inversion models (McGuire et al., 2012). 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. Trends in monthly net CO_2 flux, computed with the method of Randerson et al., (1997), reveal increasing uptake in July in both inversions and stronger releases in September, October, and November (Fig. 3d). These seasonal changes largely cancel in the annual net fluxes, but contribute to increasing CO_2 flux amplitudes, computed as the difference between the maximum and minimum monthly CO_2 fluxes, by ~1.0% $year^{-1}$ relative to the mean seasonal amplitude from 1986 to 2006 for both inversions (Fig 4, Table 2). Figure 5 shows the annual values of the July CO_2 flux in Pg C yr^{-1} over this record. This is directly related to July trend data in Figure

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3d. On a per area basis, this translates to an increase in July peak summer CO_2 uptake of 0.007–0.013 gC m^{-2} day^{-1} yr^{-1}, depending on the inversion used, averaged over the entire zone or a ~10% increase in peak summer CO_2 uptake over these 21 years. The trends over 1985–2012 are similar at 0.007 gC m^{-2} day^{-1} yr^{-1} for the Jena inversion (Table 2).

3.1.2 Boreal zone (50°N – 60°N)

The boreal zone shows a trend towards increasing annual net CO_2 uptake in both inversions (Fig 2b, Table 2). From 1986 to 2006, the trend in the RIGC inversion was 10 Tg C yr^{-1} with a p-value <0.1. The Jena inversion resulted in a similar trend of 8 Tg C yr^{-1}, but did not meet the criteria for significance, p>0.1 (Table 2). The most noticeable difference between the inversions is that the RIGC inversion predicted an anomalous release of CO_2 in 1994 that was not confirmed by the Jena inversion. Over the longer period from 1985–2012, the Jena inversion predicts the same trend toward greater CO_2 uptake with a slope of 7–8 Tg C yr^{-1} and a p-value <0.1 (Fig. 2b, Table 3).

The Jena and RIGC inversions resulted in similar mean seasonal cycles of the monthly net CO_2 fluxes, but the seasonal amplitude in the Jena inversion was slightly larger (Fig. 3a). The trends in the monthly fluxes show increasing CO_2 uptake in the growing season, and in the case of the Jena inversion, increasing CO_2 uptake in the spring and release in the fall (Fig. 3c). There was a corresponding increase in the seasonal amplitude of net CO_2 flux of 0.4% yr^{-1} (p=0.04) estimated by the Jena inversion, but not in the RIGC inversion (Fig. 4b and Table 2). Figure 5 shows the time series CO_2 flux in July (month of peak flux) over this period. Both models show an increase in July CO_2 uptake although they don’t agree on anomalies from year to year. In Figure 3cd, both models also show an increase in the fall CO_2 release in the northern land regions, but the Jena inversion attributes this mostly to the boreal zone, whereas the RIGC inversion attributes it mostly to the arctic zone.

3.2 Europe and Northern Ocean fluxes and fossil-fuel emissions

For completeness, we also show the time series of CO_2 flux trends, both net annual and seasonal amplitude from the 55°N to 80°N region of Europe (EU) and the northern ocean (NO) to be sure that fluxes in these regions are not compensating for fluxes in our analysis of the BA+BNA regions (Fig. 6). There were no offsetting positive trends in the annual net flux of CO_2 or negative trends in the seasonal amplitude in EU from 1986–2006 and none were statistically significant (Table 2). Likewise the NO flux trends are insignificant with the exception of the seasonal amplitude trend in the RIGC inversion of -2.4% yr^{-1}. This was statistically significant using the modified Mann-Kendall p-test, but the mean amplitude of the ocean flux (~0.1 Pg C yr^{-1}) is much too small to offset gains in the land flux amplitude in the BA+BNA regions (mean 4.6–9.9 Pg C yr^{-1} for north of 60°N and mean 11.4–13.9 Pg C yr^{-1} for 50°N–60°N). There is no indication that inversion-resolved trends in the EU and NO regions in the north of 50°N zone are forcing offsetting trends in the BA+BNA regions, however, we cannot rule out misallocation of fluxes among the inversion regions used in this study.

The RIGC and Jena inversions use different fossil-fuel emissions datasets to isolate the net land surface fluxes related to biology. Comparing fossil-fuel emissions for the EU and BA+BNA Arctic and Boreal zones used in each inversion (SI Fig. 1) shows that while the mean emissions were lower in the RIGC inversion, the IAV and trends in absolute fluxes were similar in each inversion. Differences in the fossil emissions are therefore unlikely to contribute significantly to trends in the biological land fluxes of the BA+BNA Arctic and Boreal zones.

3.3 Flux amplitude trends

We define the seasonal flux amplitude as the difference between the peak summer CO_2 uptake and the maximum CO_2 release in the fall, within a calendar year. We examined changes in the flux amplitude using several approaches. Figure 4 shows that the flux amplitude increase, in percent of the mean flux amplitude, is larger in the Arctic zone than the Boreal zone. This is also reflected in the monthly trends in Figure 3cd.

We also examined the change in the seasonal flux amplitude across latitudes from the Jena inversion to see if this observed increase in the seasonal flux amplitude was unique to the high northern latitudes, or if it is more widespread. Here we define the fall flux as the mean of SON, and the summer uptake is fixed as July. Figure 7 shows that significant increases in the annual flux amplitude have occurred between 40–70°N with a peak from 50–65°N. Looking at the fall and summer contributions separately shows that both increasing fall CO_2 release and peak summer uptake contribute to the annual amplitude increase, with increasing fall CO_2 release outpacing peak summer uptake in the 40–50°N band and increasing peak summer CO_2 uptake outpacing fall release in the 55–70°N band (Fig. 7b).

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3.4 Fire emissions

The net fluxes examined here are dominated by land biosphere fluxes, but they also include CO_2 emissions from forest fires, which occur mostly in summer (Fig. S3) (van der Werf et al., 2006). If fire activity were responsible for the trend in summer net carbon uptake, then fire frequency would need to be decreasing. We examined estimates of fire CO_2 emissions from 1985 to 2000 from the RETRO compilation and from 1997 to 2012 from the GFEDv4 model (Giglio et al., 2013; Schultz et al., 2008). While we cannot combine the two emissions estimates into a continuous time series because of the different methodologies used, we can examine trends over each record. Neither record shows evidence of decreasing fire emissions over their respective time periods (Fig. S4), therefore, biological activity clearly dominates the trends.

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3.5 Temperature and NDVI trends

In order to investigate possible drivers of the trends in CO_2 fluxes, we also examine trends in surface air temperature and NDVI. Seasonal temperature changes from 1986 through 2006 were not uniform across the far north (Fig. 8). In general, warming has been the greatest in the fall (SON) and winter (DJF), although these patterns vary regionally. Despite the general trend toward warming, cooling trends are seen over the 1986–2006 period for Siberia in winter (DJF) and western North America in spring (MAM). Nearly all of the land regions in the northern hemisphere have experienced warmer summers (JJA) and falls (SON).

Figure 9 shows linear trends from 1986–2006 in gridded NDVI averaged over the "growing season" (April through October) and for the month of July. Widespread greening trends are observed, with the exception of browning in the southern boreal forest of North America. Significant greening trends are found in tundra regions, especially in North America.

Figure 10a averages the growing season NDVI over the latitude bands, for each year, showing both the growing season average (top panel) and seasonal maximum (bottom panel). The period 1986-2006 showed no significant trend in the 50–60°N band in either growing season or maximum metrics (Fig. 9). In contrast, a significant increasing trend of 0.13% yr^{-1} (Table 2, p=0.01) is found in the >60°N band over this period, driven mostly by trends in tundra regions. Although not included in the trend analysis, growing season NDVI north of 60°N increased abruptly at the end of the record by ~5% from 2009 to 2010. Similarly large changes occurred in 1991–1992 and 1996–1997.

Figure 10b shows the trend in annual peak NDVI, the maximum monthly value for each year regardless of which month it is. This also shows a small but significant increase north of 60°N, 0.12% yr^{-1} (Table 2,p=0.0103) from 1986-2006 and no significant trend in the 50-60°N region. Compared to growing season NDVI, the peak NDVI increase from 2009 to 2010 was less extreme. Plant growth in 2010 was increased in the shoulder seasons in addition to the mid-season peak.

3.6 Controls of temperature and NDVI on CO_2 fluxes

Summer uptake and fall release of CO_2 play a large role in atmospheric CO_2 fluxes and concentration amplitude, so here we look at the correlations of CO_2 fluxes with temperature and NDVI as proxies for primary productivity and soil respiration variability to help assess mechanistic links. We performed lagged correlation analysis on monthly time series by calculating the temporal correlation for either the July net CO_2 fluxes or fall (SON) fluxes and 3 month running means of temperature or NDVI time series with 0 to 60 month (up to 5 year) lags. In this analysis, all data sets were de-trended using a stiff spline to remove long-term trends, thus emphasizing processes controlling interannual variability (IAV). It is also important to remember that NEE is negative when there is net CO_2 uptake from the atmosphere when interpreting the sign of correlations.

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Figure 11 shows the lagged correlations for the period 1986–2006 of both inversions for the Boreal zone. We found significantly strong positive correlations between July CO_2 NEE and April through August temperatures of the same year, but no evidence of correlation with NDVI. The temperature correlation suggests that warmer growing season temperatures increase soil respiration (or wildfires) and result in reduced peak CO_2 uptake (less negative NEE). The RIGC inversion shows significant correlation between warm winters and increased CO_2 uptake the following growing season (negative correlation), consistent with Russell and Wallace (2004), but this relation did not appear in the Jena correlation. The fall CO_2 fluxes were also positively correlated with growing season temperatures of the same year (not shown). This is consistent with increased growing season air temperatures stimulating soil respiration through the fall, either through increased carbon pools from enhanced summer productivity or warmer soil temperatures that persist into the fall.

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Our analysis found significant correlations out to 2 to 4 years prior, suggesting that temperature anomalies could have an impact on NEE after several years delay. While there have been studies suggesting that multi-year lags between climate and CO_2 fluxes are important (e.g. Bond-Lamberty et al., 2012), these correlations were not consistent between the inversion models, preventing us for speculating as to the cause.

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An analysis of the peak July NDVI correlations with lagged air temperatures showed that warmer temperatures in the 14 months prior to the peak NDVI were associated with higher NDVI in the boreal zone (Fig. 12). One possible interpretation of the correlation analyses presented here is that warmer temperatures in the boreal zone lead to increased plant productivity (indicated by positive NDVI and temperature correlation), but that the IAV of the net C balance in July and the fall was dominated by respiration (indicated by positive NEE and temperature correlation and by the lack of an NDVI and NEE correlation).

Lagged correlations for the arctic zone were generally less significant (Fig. S2). July CO_2 fluxes did not show a strong correlation with either temperature or NDVI. Fall CO_2 fluxes were not consistently correlated with temperatures in the same season in either inversion. Peak July NDVI was weakly correlated with May-June temperatures. Overall, we conclude that this northern region may be dominated by other controls, like soil thermal processes that would not show up clearly in the correlation analysis with air temperature and NDVI.

4 Discussion

The results of these two inversion estimates show that the northern high latitude regions of BNA+BA remain nearly constant or slightly increasing sinks of atmospheric CO_2. The Boreal zone, again excluding Europe, absorbed an extra 8–11 Tg C yr^{-2} over the period from 1986 to 2006, resulting in an annual CO_2 sink in 2006 that was 170–230 Tg C larger than in 1986. This trend towards increasing CO_2 uptake appears to continue through 2012 as indicated by the longer Jena s85 inversion. This result contradicts some modeling studies, which point to trend reversals in observed NDVI and modeled net CO_2 fluxes. Hayes et al. (2011) used the TEM ecosystem model to show that increased respiration and fires in this region had weakened the sink strength since 1997. Dynamic global vegetation models have also predicted a trend toward CO_2 release to the atmosphere across much of the northern land region from 1990–2009 (Sitch et al., 2015). In general, Carvalhais et al. (2014) found that models tend to over-predict the transfer of carbon from the soils to the atmosphere and overestimate the sensitivity of heterotrophic respiration to climate, although they didn't include the TEM model used by Hayes et al. (2011). The results of this inversion analysis suggest that respiration is over-predicted in models or that increased primary production not captured by these models is offsetting increases in soil respiration and/or forest fire emissions. Our results are also consistent with Forkel et al. (2016) which uses process modeling constrained by atmospheric observations to conclude that photosynthesis has responded more strongly to warming than carbon release processes.

Sensor drift and calibration errors may have resulted in false browning trends in the boreal forest, particularly in the needle-leaf evergreen forests. Recent analyses of NDVI trends in the updated GIMMS3g version find significantly more greening trends than in the previous GIMMSg version observed (Bi et al., 2013; Guay et al., 2014). On a pan-boreal basis, it seems plausible that the CO_2 sink strength has continued to increase despite previous reports of drought stress reducing CO_2 uptake of the boreal region. As a complication, however, any changes in net carbon fluxes in these ecosystems will depend not only on above ground vegetation changes that can be observed by remote sensing, but also on processes occurring below ground, where most of the carbon is stored (Iversen et al., 2015).

For the Arctic zone, we estimate that July CO_2 uptake increased from 1986 to 2006 by 0.15 to 0.27 g C m^{-2} day^{-1}, depending on the inversion and the trend detection algorithm. This estimate is based on multiplying the regression slopes (Table 2) by the 21-year time frame. In this zone, we found the strongest NDVI greening trends in the tundra regions, covering roughly 25% of the relevant land area. In light of evidence of rapid shrub expansion in these tundra ecosystems (Myers-Smith et al., 2011; Tape et al., 2006) (Elmendorf et al., 2012), a rapid increase in July CO_2 uptake by the tundra ecosystems is plausible.

Most of the previous studies investigating seasonal variability in the northern ecosystem carbon fluxes have relied on observations of atmospheric CO_2 concentrations (Angert et al., 2005; Buermann et al., 2013; Keeling et al., 1996; Piao et al., 2008; e.g. Randerson et al., 1999). The analysis presented here is unique in that it considers variability in atmospheric transport through the inversion model approach. Our results are

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generally consistent with the finding of Piao et al. (2008) that enhanced CO_2 losses from northern ecosystems in the fall partially cancel the enhanced CO_2 uptake earlier in the growing season, especially in the arctic zone. We also find evidence of uptake enhancement in the summer as well as the spring in both the arctic and boreal zones, consistent with Graven et al. (2013) and Forkel et al. (2016).

Our investigation of the controls on interannual variability of the CO_2 fluxes showed increased CO_2 uptake in cooler summers. There are many previous attempts to identify the short-term drivers of the net carbon balance of ecosystems from eddy covariance studies. Several studies have found that warm and dry summers lead to drought stress and reduced net CO_2 uptake in boreal forest ecosystems (Arain et al., 2002; McMillan et al., 2008; Welp et al., 2007). Net CO_2 flux reductions could be the result of decreased primary productivity, increased respiration, or both. Correlations between temperature and annual tree ring growth increments point to a switch from a positive correlation to a negative correlation (reduced growth during warm years) driven by increased drought stress in recent decades (Barber et al., 2000; Beck et al., 2011). Wunch et al. (2013) and Schneising et al. (2014) found that summertime total column CO_2 in the north was relatively higher during years with warm anomalies in the boreal region, suggesting that reduced net CO_2 uptake during warm summers may be driven by the temperature dependence of soil respiration. These correlations of interannual variability are contrary to the overall long-term association with warming and greater summer uptake (Keeling et al., 1996). This difference could reflect the importance of structural ecosystem changes due to warming on the long time scale increasing photosynthesis (Graven et al., 2013), but are also consistent with respiration as the dominant control of NEE on short time scales (Schaefer et al., 2002). The difference in the time scale of response is important to consider.

A full explanation of the trends in CO_2 fluxes of the arctic and boreal zones is still lacking, with possible causes including changes in temperature, which were explored here, but also soil moisture, nutrient status, or fire and insect disturbance. An important unresolved question is how the distribution of deciduous and evergreen plant functional types has changed at the pan-boreal scale over this period. A shift to younger forests, with increasing deciduous fraction, would increase the seasonal flux amplitude (Welp et al., 2006; Zimov, 1999), perhaps with little change in common NDVI metrics.

The latitude gradient of changes in land fluxes from the Jena inversion, now including results from Europe, shows that, from the 1985–1989 mean to the 2007–2011 mean, the surface flux amplitudes have increased the most from 40°N to 65°N (Fig. 7a). This is consistent with Graven et al. (2013), who argued that, over the longer period from 1960–2010, the increases in CO_2 flux amplitude were centered mostly on boreal regions. Our analysis of the Jena inversion by latitudinal bands shows that the increases in peak July uptake have been greater than the fall CO_2 releases north of 55°N, but from 40–50°N, fall release out-paced July uptake (Fig. 7b). The results presented here show that the increased seasonal amplitude in atmospheric CO_2 in the high northern latitudes isn't caused by flux trends in the summer or fall only, but rather both contribute (Fung, 2013; Graven et al., 2013). The trend in annual net CO_2 fluxes also includes

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changes in other months, with namely greater uptake in the spring (not shown in Fig. 7), which contributes to the annual sum. The advantage of this analysis is that it incorporates interannually varying atmospheric transport, so the temporal changes in the surface fluxes should be better resolved. It does not identify whether individual months have a disproportionately larger influence on the atmospheric CO_2 concentration amplitude.

Our attempt to distinguish changes by ~10° latitude arctic and boreal zones is pushing the limits of what is feasible from atmospheric inversions based on sparse atmospheric CO_2 observations. The limitation is illustrated by the tendency of the two inverse calculations to allocate the increase in fall CO_2 release mostly to different latitude bands and the shift to increasing earlier CO_2 uptake in the Jena model compared to the RIGC model in Figure 3c. Resolving fluxes with monthly resolution is also challenging (Broquet et al., 2013), but the long record examined here, by two independent inversions, gives us reasonable confidence in this aspect.

5 Conclusions

The two atmospheric inversions analyzed in this study show that the annual net CO_2 sink strength in the boreal zone has increased from 1985–2012. However, the annual net CO_2 fluxes in the Arctic zone showed no trend. Both regions show significant increases in mid-summer CO_2 uptake. But a trend towards greater CO_2 emissions in the fall has partly canceled the trend toward greater summer uptake, with the largest cancelation in the Arctic zone. These trends in summer and fall fluxes cause the seasonal amplitude of the fluxes to increase, and consequently, the seasonal amplitude of atmospheric CO_2 concentrations.

We also examined NDVI and CO_2 flux interannual correlations showing that while warmer summers were correlated with increasing NDVI in the long term, relatively cooler summers favor net CO_2 uptake in the boreal region in the short term. This suggests that increased respiration can outpace increases in productivity in the short term. Overall, there is evidence from these atmospheric inversions that increased CO_2 uptake from the northern region is offsetting carbon release in the pockets of browning in the boreal zone. In the Arctic zone, shrub expansion and dramatic greening in the tundra has not influenced the net annual CO_2 sink of the region. Our findings are consistent with the recent NDVI studies from the GIMMS3g product that find overall greening of the boreal and arctic regions (Park et al., 2016; Xu et al., 2013; Zhu et al., 2016). By itself, this would suggest the potential for continued or strengthening net CO_2 uptake. However, north of 60°N, our findings show that fall CO_2 release largely offsets increased summer uptake in the net annual budget. These results underscore the difficulty of resolving net fluxes from remote sensing indices alone, which can only 'see' the productivity and not the respiration fluxes.

Furthermore, our atmospheric inversions results show no evidence of an overall trend towards increasing CO_2 releases in either the boreal or Arctic zone over the 1985-2012 period. This is an important check for

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process-based biospheric models which tend to predict a shift from sink to source in the next century (Treat and Frolking, 2013). Our results are not consistent with studies that suggest carbon sinks have weakened in boreal and Arctic ecosystems over past decades (Bradshaw and Warkentin, 2015a; Hayes et al., 2011), but support some process models which do predict an strengthening CO_2 sink in the northern region (McGuire et al., 2012). To date, the increase in biomass productivity has appeared to be outpacing CO_2 losses from warming northern carbon-rich soils. Time will tell whether this trend continues, or whether it will reverse and become a net carbon source in a few decades as predicted by popular opinion among the community of experts (Abbott et al., 2016).

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Data Availability

The data used this in this analysis is publically available from the individuals authors responsible for creating the products. The Jena CO_2 inversion results are posted to the project website, http://www.bgc-jena.mpg.de/~christian.roedenbeck/download-CO_2/. Run ID s85 version 3.6 was used in this project. Associated files contain the atmospheric monitoring site locations and data used in the inversion and the fossil fuel emissions that were used to solve for the biological land CO_2 fluxes. The RIGC CO_2 inversion results are posted on the Global Carbon Atlas project website, http://www.globalcarbonatlas.org/?q=en/content/atmospheric-inversions. Likewise, associated files contain the atmospheric monitoring site locations and data used in the inversion and the fossil fuel emissions that were used to solve for the biological land CO_2 fluxes. The GIMMS NDVI3g data used is posted on the AVHRR website, https://nex.nasa.gov/nex/projects/1349/. After the final acceptance of this manuscript, the code used in the analysis will be posted on GitHub.

Acknowledgements

This project was supported by NASA under award NNX11AF36G, the U.S. Department of Energy under awards DE-SC0005090 and DE-SC0012167, NSF under award PLR-1304270 and UC Multiple Campus Award Number UCSCMCA-14-015. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NASA, NSF, DOE, or UC.

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Table 1. CO_2 observation stations included in each inversion model.

Station	Lat	Years	Coverage	RIGC	Jena	Lab
ALT	82.4	1985- 2012	95%	X	X	SIO/NOAA
BRW	71.3	1985 - 2012	100%	X	X	SIO/NOAA
STM	66.0	1985 - 2009	100%	X	X	NOAA
CBA	55.2	1985 - 2012	84%	X	X	NOAA
SHM	52.7	1985 - 2012	88%	X	X	NOAA
SCH	48.0	1985 - 2001	89%	X		UBA
CMN	44.1	1985 - 2012	100%	X	X	NOAA
NWR	40.0	1985 - 2012	100%	X	X	NOAA
RYO	39.0	1987 - 2012	90%	X		NOAA
LJO	32.9	1985 - 2012			X	SIO
BME	32.3	1989 - 2010	81%	X		NOAA
BMW	32.2	1989 - 2012	77%	X		NOAA
MID	28.2	1985 -2012	97%	X		NOAA
KEY	25.6	1985- 2012	95%	X	X	NOAA
MLO	19.5	1985 - 2012	100%	X	X	SIO/NOAA
KUM	19.5	1985 - 2012	100%	X	X	SIO/NOAA
GMI	13.4	1985 - 2012	97%	X		NOAA
RPB	13.1	1987 - 2012	84%	X		NOAA
CHR	1.7	1985 - 2012			X	SIO
SEY	-4.6	1985 - 2012	87%	X		NOAA
ASC	-7.9	1985 - 2012	98%	X	X	NOAA
SMO	-14.2	1985 - 2012	100%	X	X	NOAA
AMS	-37.9	1985 - 1990	89%	X		NOAA
KER	-29.0	1985 - 2012			X	SIO
CGO	-40.6	1985 - 2012	99%	X	X	NOAA
BHD	-41.4	1999 - 2012	71%	X	X	NOAA
PSA	-64.9	1985 - 2012	94%	X	X	NOAA
SYO	-69.0	1986 - 2012	78%	X		NOAA
SPO	-89.9	1985- 2012	97%	X	X	SIO/NOAA

Coverage refers to percent coverage of observation data from 1985 - 2006 used in the RIGC inversion. Most station records start before 1985 and continue beyond 2012 but that data was not used in this analysis.

Lab stations names and data links as following:

NOAA: NOAA ESRL/CMDL, http://www.esrl.noaa.gov/gmd/ccgg/globalview/co2/co2_observations.html

SIO: Scripps Institution of Oceanography, http://cdiac.ornl.gov/trends/co2/sio-keel-flask/

UBA: Umweltbundesamt and University of Heidelberg, Germany, http://cdiac.ornl.gov/trends/co2/uba/uba-sc.html

Table 2. Trend and significance statistics for time series of interest, from 1986 through 2006. 'Trend' is the slope from linear least squares (LSQ) and Mann-Kendall (M-K) sen slope, likewise, 'Sig (p-value)' is the p-value from LSQ and M-K tests. Arctic zone and boreal zone are for BNA+BA, EU = Europe, NO = northern ocean. Italic values indicate 90% significance level.

1986-2006			**Trend**		**Sig (p-value)**	
Time series	**zone**	**inversion**	**LSQ**	**M-K**	**LSQ**	**M-K**
CO_2 flux annual sum (Pg C yr^{-2})	arctic	RIGC	0.0350	0.0051	0.5719	0.2389
	arctic	JENA	-0.0028	-0.0021	0.3550	0.6077
	boreal	*RIGC*	*-0.0110*	*-0.0101*	*0.0724*	*0.0967*
	boreal	JENA	-0.0081	-0.0076	0.1438	0.1941
	EU	RIGC	0.0007	-0.0027	0.9295	0.7398
	EU	JENA	-0.0052	0.0020	0.5092	0.8326
	NO	*RIGC*	*-0.0032*	*-0.0037*	*0.0308*	*0.0320*
	NO	*JENA*	*-0.0014*	*-0.0015*	*0.0005*	*0.0060*
CO_2 flux amplitude (% yr^{-2})	*arctic*	*RIGC*	*0.93*	*0.85*	*0.0019*	*0.0201*
	arctic	*JENA*	*1.04*	*0.97*	*0.0002*	*0.0004*
	boreal	RIGC	0.15	0.22	0.3241	0.2639
	boreal	*JENA*	*0.44*	*0.39*	*0.0328*	*0.0372*
	EU	*RIGC*	*0.62*	*0.55*	*0.0769*	*0.1390*
	EU	JENA	0.18	0.16	0.2723	0.3812
	NO	*RIGC*	*-2.35*	*-2.20*	*0.0192*	*0.0372*
	NO	JENA	0.63	0.65	0.2894	0.2639
CO_2 flux July (g C m^{-2} day^{-1} yr^{-2})	*arctic*	*RIGC*	*-0.0128*	*-0.0120*	*0.0167*	*0.0655*
	arctic	*JENA*	*-0.0072*	*-0.0082*	*0.0004*	*0.0028*
	boreal	RIGC	-0.0058	-0.0034	0.1712	0.3492
	boreal	*JENA*	*-0.0097*	*-0.0085*	*0.0615*	*0.0571*
Fossil fuel emissions (Pg C yr^{-2})	*arctic*	*RIGC*	*-0.0206*	*-0.0011*	*0.0024*	*0.0320*
	arctic	JENA	-0.0159	0.0001	0.9664	0.9759
	EU	*RIGC*	*-0.0013*	*-0.0195*	*<0.0001*	*0.0002*
	EU	*JENA*	*-0.0000*	*-0.0135*	*<0.0001*	*0.0086*
NDVI gs (% yr^{-2})	*arctic*		*0.1500*	*0.1300*	*0.0112*	*0.0103*
	boreal		0.0587	0.0532	0.3170	0.4503
NDVI peak (% yr^{-2})	*arctic*		*0.1200*	*0.1200*	*0.0109*	*0.0103*
	boreal		0.0030	-0.0043	0.9419	0.9759

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Spring T	arctic	-0.0124	0.0439	0.8592	0.7858
(°C yr^{-2})	boreal	0.0063	0.0192	0.8961	0.6506
Summer T	*arctic*	*0.0848*	*0.0915*	*0.0011*	*0.0041*
(°C yr^{-2})	*boreal*	*0.0491*	*0.0527*	*0.0043*	*0.0072*
Fall T	*arctic*	*0.0500*	*0.0377*	*0.1559*	*0.0655*
(°C yr^{-2})	*boreal*	*0.0551*	*0.0503*	*0.0080*	*0.0072*
Winter T		1.1.1.1			
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(°C yr^{-2})	boreal	-0.0041	0.0122	0.9172	0.8326

Table 3: Same as Table 2, but for the period from 1985 through 2012.

1985-2012			**Trend**		**Sig (p-value)**	
Time series	**zone**	**inversion**	**LSQ**	**M-K**	**LSQ**	**M-K**
CO$_2$ flux net annual (Pg C yr^{-2})	*arctic*	*JENA*	*-0.0040*	*-0.0038*	*0.0411*	*0.0722*
	boreal	*JENA*	*-0.0072*	*-0.0078*	*0.0655*	*0.1095*
	EU	JENA	-0.0032	0.0005	0.5155	0.9842
	NO	JENA	-0.0010	-0.0010	0.0001	0.0037
CO$_2$ flux amplitude (% yr^{-2})	*arctic*	*JENA*	*0.81*	*0.85*	*<0.0001*	*0.0001*
	boreal	*JENA*	*0.35*	*0.31*	*0.0094*	*0.0187*
	EU	JENA	<0.01	<0.01	0.4365	0.4179
	NO	JENA	<0.01	<0.01	0.4299	0.3740
CO$_2$ flux July (g C m^{-2} day^{-1} yr^{-2})	*arctic*	*JENA*	*-0.0068*	*-0.0072*	*<0.0001*	*0.0001*
	boreal	*JENA*	*-0.0083*	*-0.0084*	*0.0345*	*0.0380*

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Figure captions

Figure 1: The major land and ocean basis regions used in the RIGC inversion based on the TransCom3 regions. The Jena inversion was done on a ~4x5 degree grid and aggregated to these regions. The northernmost land regions are shown in color. The two zones that we discuss in this analysis cover Boreal North America and Boreal Asia and are marked in shades of blue, with the arctic zone (>60°N) in light blue and the boreal zone (50°N to 60°N) in dark blue. The European basis region, in red, is not divided at 60°N in the RIGC inversion and therefore is not included in this analysis. Stippling indicates the boreal forest biome based on the GLDAS UMD modified IGBP land classification scheme (http://ldas.gsfc.nasa.gov/gldas/GLDASvegetation.php). The tundra biome is north of the stippling.

Figure 2: Annual CO_2 fluxes normalized by subtracting the 1986–2006 mean value for (a) arctic zone (>60°N) and (b) boreal zone (50°N to 60°N). Black shows the RIGC inversion results. Grey shows the Jena s85 inversion results. Dashed lines are linear trends from 1986 to 2006. Negative values represent uptake of CO_2 by the land biosphere, i.e. out of the atmosphere (Table 2).

Figure 3: Mean monthly CO_2 fluxes for (a) arctic zone (>60°N) and (b) boreal zone (50°N to 60°N). Black circles are the 1986–2006 means of the RIGC inversion. Grey squares are the Jena s85 inversion over that same period. Magenta is the Jena inversion average over a longer time period (1985–2012). Differences are likely due to differences in atmospheric transport, including vertical mixing, between the models. Linear monthly trends of (c) arctic zone and (b) boreal zone for the same inversions and time periods as in (a) and (b) (Table 2).

Figure 4: CO_2 flux amplitude for each year calculated as the maximum monthly flux (positive = CO_2 release to the atmosphere) minus the minimum monthly flux (negative = CO_2 uptake by the biosphere) for (a) arctic zone and (b) boreal zone. Black shows the RIGC inversion, grey shows the Jena s85 inversion. Dashed lines show the linear trends from 1986–2006, the common period between the inversions.

Figure 5: July CO_2 flux for each region and inversion normalized by subtracting the 1986–2006 mean value. This is the month of maximum CO_2 uptake in each case (see Figure 3). The dashed lines are the linear trends from 1986 to 2006, also plotted in Figure 3c and d.

Figure 6: Fluxes from the Northern Ocean and European basis regions. (a) Annual fluxes and (b) annual flux amplitude for the Northern Ocean. (c) Annual sum and annual flux amplitude for the European region. The trends in these fluxes are small, and in the case of Europe, in the same direction, compared to the trends resolved for the Boreal North America and Boreal Asia regions.

Figure 7: Latitudinal gradients in the land CO_2 fluxes from the Jena s85 inversion. (a) Green is the difference from the 2007–2011 mean from the 1983–1989 mean in the July CO_2 uptake with the sign reversed (here positive is uptake by the biosphere) and magenta is the difference in the mean of Sep–Nov fall CO_2 release with conventional sign (positive is release of CO_2 to the atmosphere). (b) The difference between the 2 curves in (a) showing the change in CO_2 seasonal flux amplitude in Pg C yr^{-1}. Positive values reflect an increase in the peak-to-trough flux amplitude.

Figure 8: Gridded temporal trends in surface air temperature from the GISS temperature record (data.giss.nasa.gov). Plots were made using software available on the data archive website.

Figure 9: Gridded temporal trends in GIMMS 3G NDVI (a) growing season (Apr–Oct) mean and (b) July only from 1986–2006. Trends are expressed as percent changes from the mean.

Figure 10: Time series of NDVI trends averaged for the analysis regions in this study. (a) growing season (Apr–Oct) mean and (b) annual maximum, usually in July. Black is the arctic zone and grey is for the boreal zone.

Figure 11: Correlation coefficients for July CO_2 fluxes in a given year (Year 0) from the boreal zone with lagged 3-month running mean temperature (area-weighted and NPP-weighted) and NDVI for the same region. (a) RIGC inversion and (b) Jena s85 inversion over the current and previous 4 years. Positive correlations mean that high temperature or NDVI leads to less CO_2 uptake. Filled circles indicate significance greater than the 95% level. Shaded bars indicate the summer months (May–August).

Figure 12: Correlation coefficients for maximum NDVI in given year (Year 0) with lagged 3-month running mean temperature (area-weighted and NPP-weighted). Positive correlations mean greater NDVI during (or following) warmer temperature. Filled circles indicate significance greater than the 95% level. Shaded bars indicate the summer months (May–August).