ESTIMATES OF LARGE-SCALE FLUXES IN HIGH LATITUDES FROM TERRESTRIAL BIOSPHERE MODELS AND AN INVERSION OF ATMOSPHERIC CO_2 MEASUREMENTS

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Abstract. It is important to improve estimates of large-scale carbon fluxes over the boreal forest because the responses of this biome to global change may influence the dynamics of atmospheric carbon dioxide in ways that may influence the magnitude of climate change. Two methods currently being used to estimate these fluxes are process-based modeling by terrestrial biosphere models (TBMs), and atmospheric inversions in which fluxes are derived from a set of observations on atmospheric CO_2 concentrations via an atmospheric transport model. Inversions do not reveal information about processes and therefore do not allow for predictions of future fluxes, while the process-based flux estimates are not necessarily consistent with atmospheric observations of CO_2. In this study we combine the two methods by using the fluxes from four TBMs as *a priori* fluxes for an atmospheric Bayesian Synthesis Inversion. By doing so we learn about both approaches. The results from the inversion indicate where the results of the TBMs disagree with the atmospheric observations of CO_2, and where the results of the inversion are poorly constrained by atmospheric data, the process-based estimates determine the flux results. The analysis indicates that the TBMs are modeling the spring uptake of CO_2 too early, and that the inversion shows large uncertainty and more dependence on the initial conditions over Europe and Boreal Asia than Boreal North America. This uncertainty is related to the scarcity of data over the continents, and as this problem is not likely to be solved in the near future, TBMs will need to be developed and improved, as they are likely the best option for understanding the impact of climate variability in these regions.

1. Introduction

It is vital to understand the impacts of climate change on the global carbon cycle in order to predict future concentrations of atmospheric carbon dioxide (CO_2), which has the potential to influence the magnitude and path of climate change. This is especially true in the northern high-latitudes where vast amounts of carbon currently reside in relatively inert forms in the soil. In the event of global warming, respiration may act to return that carbon to the atmosphere, possibly creating a runaway feedback effect. It is therefore important to understand the response of the

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high-latitude ecosystems to past climate variability such that the risk of potential future climate change can be assessed.

One reason why net annual fluxes are difficult to estimate is that the net flux is the residual of two large fluxes, the net primary production and the heterotrophic respiration. It is the differing phase of these two fluxes that largely causes the seasonal cycle in atmospheric CO_2 observations. Therefore, to use process-based models to estimate the annual net exchange it is important to accurately simulate the amplitude and phase of that seasonal cycle. Also, if we are to understand how the reservoirs may change in size in response to future climate change, it is important to be able to simulate the past inter-annual variability of the carbon fluxes. Therefore, in this study we are focusing our efforts on the seasonal cycle and inter-annual variability rather than the net exchange. Once we are confident that we are modeling all the relevant processes in a satisfactory manor we can address the issue of the net exchange.

Key tools in carbon cycle studies are terrestrial biosphere models (TBMs) and atmospheric inversions. TBMs are very useful as they represent processes and provide detailed information as to the workings of the terrestrial carbon system. However evaluation of the TBMs has been difficult due to the space and time scales involved. Because it is impractical to monitor fluxes at fine resolution in a spatially continuous fashion across the terrestrial biosphere, the models are calibrated and validated with data at a limited number of sites. This up-scaling can lead to substantial uncertainty in the estimates of fluxes at large spatial scales. An alternative method of evaluation is to take the fluxes and use them as surface sources for an atmospheric transport model, and compare the simulated atmospheric CO_2 concentrations with the observations at various points around the globe (e.g., Heimann et al., 1998; Nemry et al., 1999). It is the latter approach we take it the first part of this study. In the second part of this study, we use a Bayesian Synthesis Inversion to calculate the surface fluxes required to match the atmospheric concentrations. The Bayesian style requires an initial guess (an *a priori*) of the fluxes, and the *a priori* sources can influence the results, especially where the inversion is poorly constrained by the atmospheric data. An important difference between the inversions and the TBMs is that the fluxes derived by an inversion give no information as to the processes involved. An ideal way to estimate fluxes consistent with the atmospheric measurements, and to gain an understanding of the processes involved, is to combine the TBM and atmospheric inversions methods. We do this by initializing our inversion with the fluxes from four different TBMs. In this set-up the inversion is essentially evaluating the fluxes from the biosphere models to test if they are consistent with the observations. But unlike the simple forward transport simulations we run, the inversion also produces estimates of how the fluxes need to be adjusted to best reproduce the observations. If no adjustments are required, then we can say that the inversion has validated the TBM fluxes for the given observation network and inversion technique. However, if significant adjustments are required, then there may be errors in the estimates of the TBM, assuming that the errors in the transport model and inversion technique have minimal influence on the adjustments. By examining the adjustments required, we have the potential to learn where improvements are required in the TBM processes.

2. Models and Data Description

2.1. TERRESTRIAL BIOSPHERE MODELS

The four TBMs in this study are the High Resolution Biosphere Model (HRBM, Esser et al., 1994), the Integrated Biosphere Simulator (IBIS, Foley et al., 1996), the Lund-Potsdam-Jena Dynamic Vegetation model (LPJ, Sitch et al., 2000), and the Terrestrial Ecosystem Model (TEM, Tian et al., 1999). The description and application of these models is presented in McGuire et al. (2001). The key importance of this suite of simulations is that the model simulations were done in a transient mode, such that the fluxes simulate inter-annual variability. The models were run with three scenarios, but here we only consider the simulations from the third scenario in which the models were constrained with increasing CO_2, climate variability and land-use change (the land-use change data set considers only agricultural establishment and abandonment). Two of the models (LPJ and IBIS) include simple fire disturbance models, while none of the models take into account the role of insect disturbance, the impact of anthropogenic fire suppression, or the conversion of natural landscapes to pasture. The role of disturbance can act to increase the amplitude of the seasonal cycle as it decreases the average stand age, as forests that are still growing will have larger NPP than a forest in equilibrium. Only TEM models the nitrogen cycle that may explain why it tends to have less variability than the other models.

2.2. ATMOSPHERIC TRANSPORT MODEL

Our version of the Model of Atmospheric Transport and Chemistry (MATCH, Rasch et al., 1997; Mahowald et al., 1997) is a semi-Lagragian transport model run with 24 levels in the vertical on hybrid sigma-pressure coordinates. The horizontal resolution is 2.8° by 5.6° (latitude by longitude). The model was run in an ‘off-line’ mode with archived data from a control run of the Middle Atmosphere Community Climate Model II (MACCM2, Erickson et al., 1996). The model was run with a time-step of 1.5 hours. The sub-grid scale processes were parameterized using the Hack (1994) scheme for convection and Holtslag and Boville (1993) for diffusion. Because only one year of winds was used, inter-annual variability in the atmospheric CO_2 concentrations due to the transport is ignored. Dargaville et al. (2000) have shown that the impact of the variability in the transport is of second order importance, with a difference of only 0.3 ppmv in the inter-hemisphere gradient over the period 1985 to 1993 due to the transport. Although MATCH was not a participant in the first two phases of the transport model intercomparison

(TransCom: Law et al., 1996; Denning et al., 1999) the on-line version of the model (CCM2/NCAR model) did participate. The CCM2/NCAR model produced an inter-hemispheric difference (IHD) of 3.05 ppmv for the fossil source case. We have run the TransCom fossil source case for our version of MATCH and get a similar IHD of 2.91 ppmv. The results indicate that MATCH has comparable transport to the other transport models widely used such as GISS (IHD = 2.78 ppmv) and TM2 (IHD = 3.36).

2.3. ATMOSPHERIC CO_2 DATA

We have compared the model simulations of the atmospheric seasonal cycle with the observations at four high latitude stations: Mould Bay, Canada (76.3° N, 240.7° E), Point Barrow, U.S.A. (71.3° N, 203.4° E), Ocean Station ‘M’, Norway (66.0° N, 2.0° E) and Cold Bay, U.S.A. (55.2° N, 197.3° E) (see X’s on Figure 1). These are the four high-latitude GLOBALVIEW (GLOBALVIEW 1997) sites that have the best data coverage over the period 1980 to 1992. These data are published at approximately weekly resolution, and have been processed to interpolate missing data values. The method for interpolation takes into consideration the known signal at each station along with the inter-annual variability observed at marine boundary stations at similar latitudes (Masarie and Tans, 1995). We choose to use the data processed with the interpolation method as missing data could affect the shape and phase of the seasonal cycle, but only Mould Bay (92% complete) and Station M (87%) required any filling.

To allow comparison between the observations and simulations we have detrended the data by subtracting a spline fit (Enting, 1987) with a four-year attenuation to remove the long-term trend. From this detrended series the average seasonal cycle was calculated by simply averaging the values at each time point for each year.

For the Bayesian Synthesis Inversion, we have used a network of 38 NOAA/CMDL stations, including the four mentioned above. The additional stations that are located in the northern hemisphere are plotted in Figure 1 with the symbol ‘○’.

2.4. BAYESIAN SYNTHESIS INVERSION

Synthesis inversions have been used widely to estimate net regional sources of CO_2 (Tans et al., 1990; Enting et al., 1995; Fan et al., 1998; Fan et al., 1999; Rayner et al., 1999; Bousquet et al., 1999). As stated above, the Bayesian Synthesis Inversion takes an *a priori* source field and modifies it so that a forward transport model simulation will match the observations as closely as possible. This is done by dividing the globe into as many regions as we wish to resolve, and using our transport model, calculate the response of a unit pulse of CO_2 released from each region at each station for each month. The number of regions selected is made keeping in mind that the larger the number of regions, the greater the uncertainty in the fluxes calculated in each region. In this study we use 14 terrestrial and 12

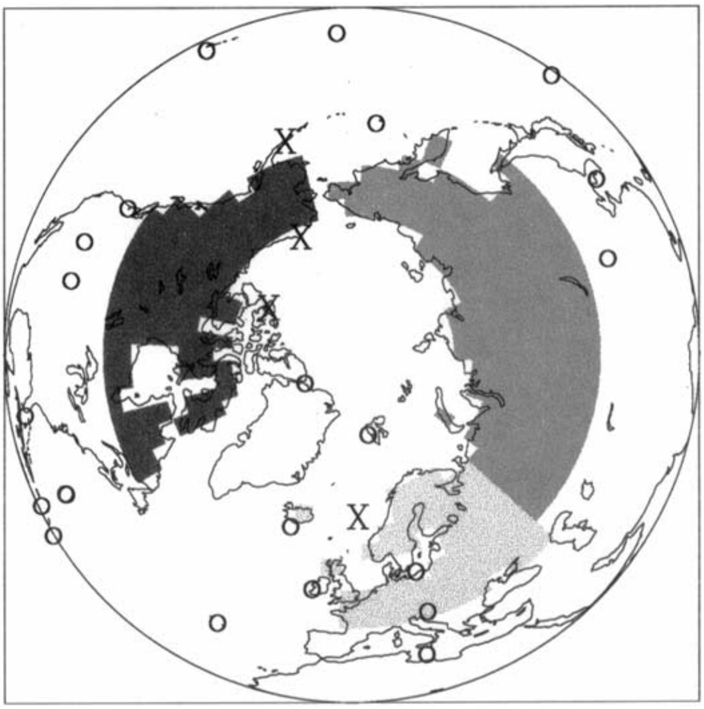

Figure 1. The three regions resolved by the Bayesian Synthesis Inversion that are presented in this study. The regions are denoted 'Europe' (light gray), 'Boreal Asia' (middle gray) and 'Boreal North America' (dark gray). 'X' marks the four stations where we have compared the forward simulations with the observations and '○' marks the additional stations that were used in the Bayesian Synthesis Inversion (only northern hemisphere sites shown).

ocean regions. Figure 1 shows the three regions we have focused on in this paper (Europe, Boreal Asia and Boreal North America). The inversion scales and sums the response functions so that a set of observations is matched as well as possible.

The method of Rayner et al. (1999) calculates fluxes for each month, and therefore produces an estimate of the seasonal cycle as well as the net fluxes required to reproduce the atmospheric patterns and trends. We have used a larger observational data set here, expanding the number of stations to 38 NOAA/CMDL monitoring sites (Rayner et al. used 12), and have not used the ^{13}C or O_2:N_2 records from Cape Grim which are subject to problems relating to global representativeness (Francey, pers. comm.). Rayner et al. (1999) describe the inversion technique in more detail. As well as the land flux, the inversion requires *a priori* estimates of the ocean and fossil fuel fluxes. The ocean fluxes are based on the partial pressure CO_2 in Takahashi et al. (1997) and the fossil fluxes are based on Marland et al. (1989). Each of the *a priori* fluxes is assigned an uncertainty range in which the inversion can adjust the flux to arrive at a final estimate. For the terrestrial biosphere this uncertainty is set at ±1 GtC yr^{-1}, which is a generous amount given that the predicted net flux in any region is no more than 0.3 GtC yr^{-1}.

In this experiment we have run the inversion 5 times. Once using each of the four TBMs as *a priori* source estimates, and once using an estimate of the fluxes based on remotely sensed NDVI data (Fung et al., 1987). This estimate does not have interannual variability. In the results, we show the fluxes calculated from the inversion as a range of the five inversions, giving an indication as to the uncertainty in the inversion based on the sensitivity to the *a priori* fluxes.

3. Results

Figure 2 shows the average seasonal cycles of the detrended atmospheric concentrations for both the observations and the four forward simulations using each of the TBMs and MATCH. In each plot a bold line represents the observations with error bars showing the plus and minus one standard deviation, which indicates how variable the phase and amplitude of the cycle at each station is. The thin lines represent each of the transport model simulations with the TBM fluxes. All the TBMs produce reasonable results, however there are some discrepancies. In the three northern most stations the TBMs tend to arrive at the minimum concentrations too early, and generally the amplitude is too small. Also, the pattern of the concentrations over the period January to April is generally not in agreement with the observations, suggesting that the TBMs are taking up too much carbon from the atmosphere in the early part of the year.

Figure 3 shows the average seasonal cycle of the fluxes for each of the three regions as modeled by the TBMs and the estimate from the NDVI method (thin lines), and the range of the five inversion calculations (shaded area). Note that negative values are uptake of carbon by the terrestrial ecosystems. These results identify the way the inversion has had to alter the initial conditions so that the best fit to the atmospheric observations was achieved. The plots for Europe and Boreal Asia show that the range of results from the inversion mostly covers the range of the *a priori* fluxes. This indicates that both the TBMs are producing fluxes that are consistent with the observational data set, and that the observations do not give much information about the fluxes in these regions and so the inversion returns fluxes similar to the initial conditions. The plot for Boreal North America shows the inversion has required significant changes to the TBM fluxes to achieve a fit to the observations, and the narrow range of results shows that the inversion is relatively insensitive to the *a priori* fluxes in this region. In three of the four cases the inversion has increased the summer uptake and moved the maximum uptake to later in the year. The figure shows that the fluxes from LPJ in this region are the most consistent with the observations, but the inversion suggest that the spring and fall out-gassing shown by LPJ and especially the NDVI fluxes are not consistent with the atmospheric CO_2 observations.

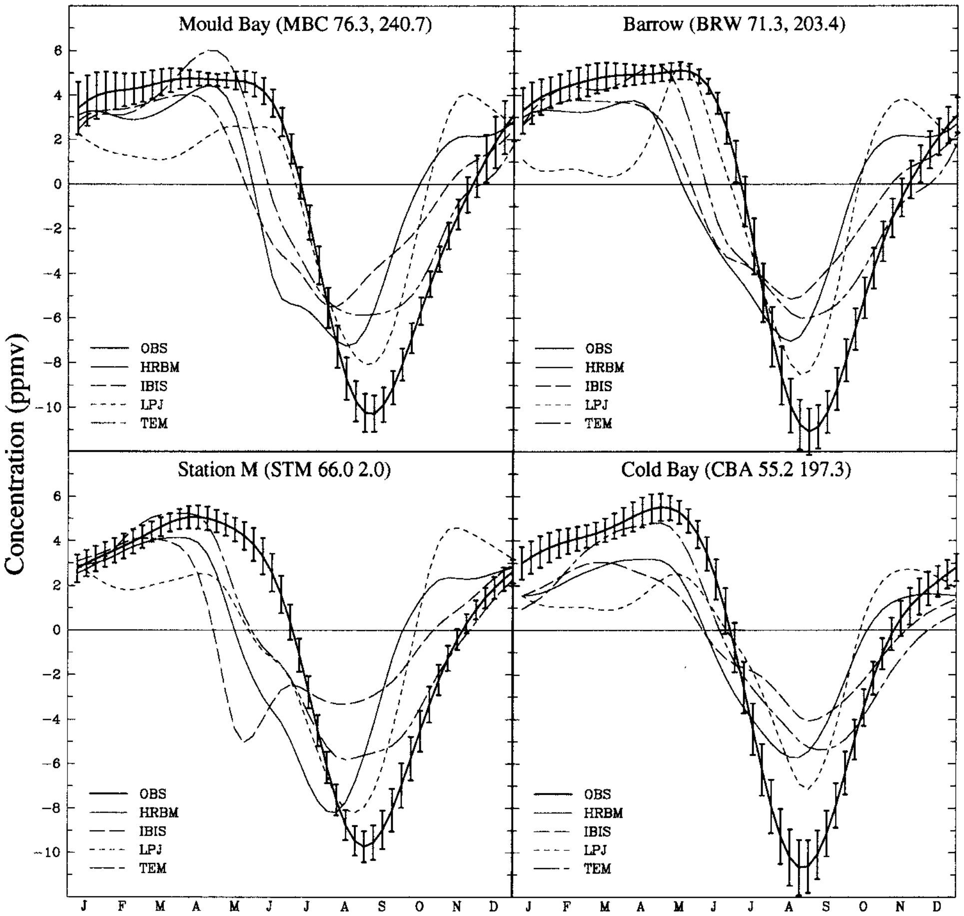

Figure 2. Average atmospheric seasonal cycles for the period 1980 to 1993 for the observations and forward model simulations. The observations are plotted as the solid line with error bars representing plus and minus one standard deviation. The thin lines are each of the atmospheric transport simulations at the stations using each of the TBMs as the surface fluxes. The headers on each plot are the station names, abbreviations and latitude and longitude.

The plots of flux anomalies (Figure 4) show results which are somewhat similar to the seasonal cycle plots, in that the *a priori* fluxes and those predicted by the inversion show times where the models and inversion agree, and times where the inversion shows that the TBMs are not consistent with the atmospheric observations. As in the seasonal cycle plots, it appears that the inversion is better constrained by the data in Boreal North America which shows the range of results is slightly narrower than for the other two regions. The magnitude of the interannual variability is larger in the inversion than predicted by the TBMs, possibly due to the fact that all the TBMs do not model all the processes that lead to interannual variability.

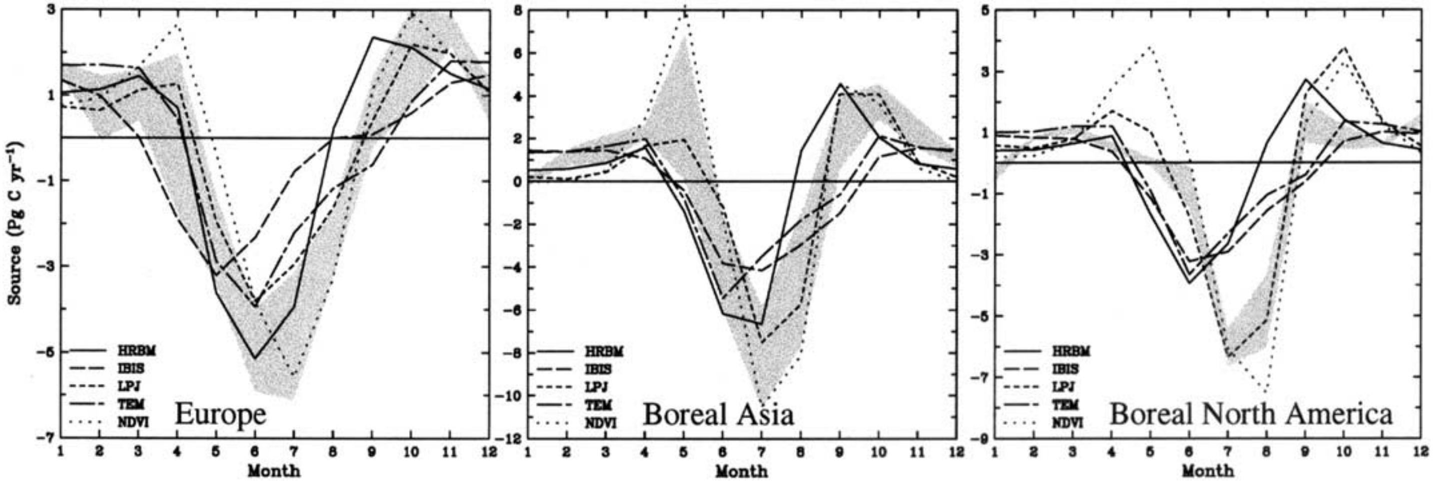

Figure 3. The average seasonal cycle aggregated over the regions shown in Figure 1 for the *a priori* TBM fluxes and inversion results. The lines represent each of the TBMs and the NDVI fluxes, and the shaded area is the range of results from each of the five inversions.

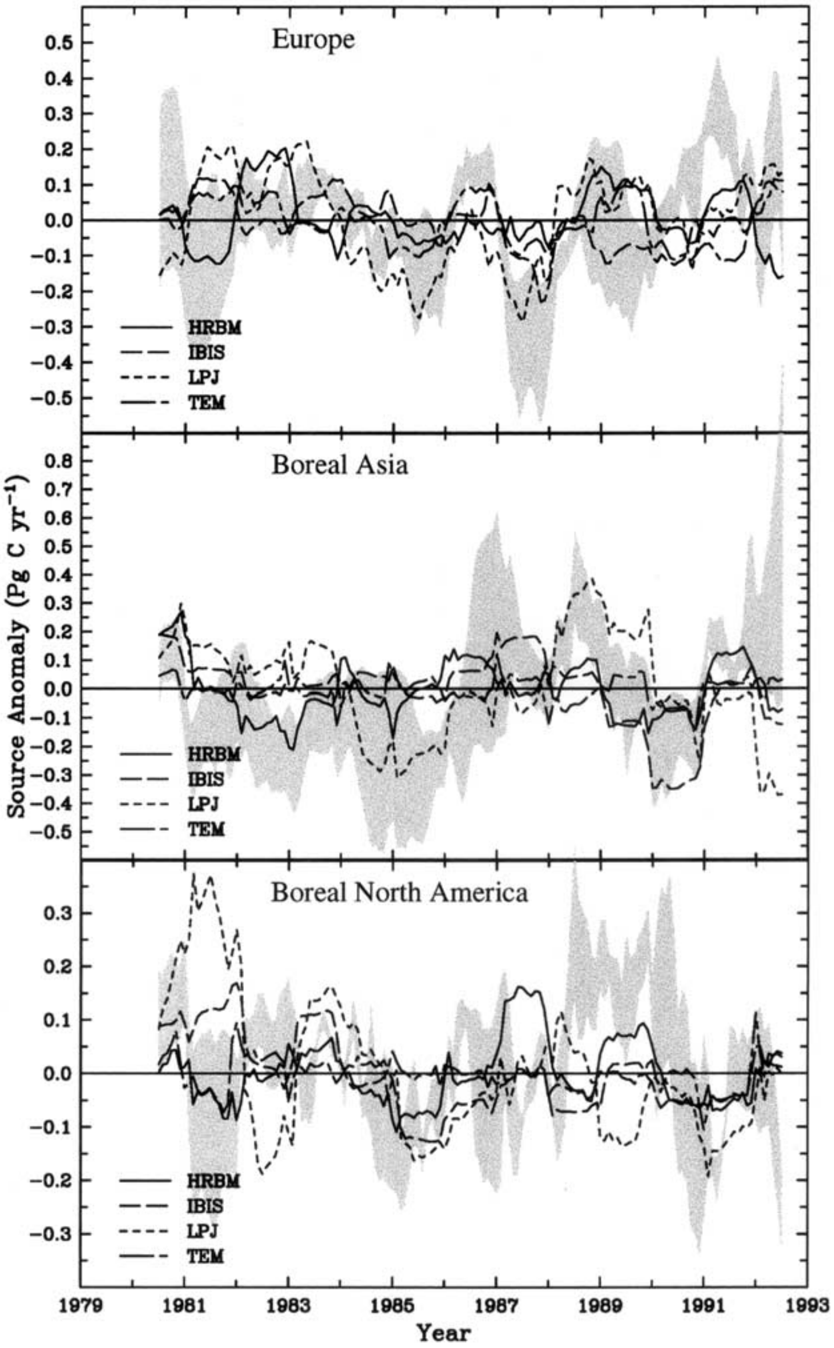

Figure 4. Similar to Figure 3, but for the flux anomalies. Anomalies were calculated by applying a 12 month running mean to the time series of fluxes for each region. Note that the *a priori* fluxes for the NDVI data have no interannual variability, but the variability the inversion calculates for the inversion are included in the range.

Two such processes are fire and insect disturbance, the omission of which could lead to an underestimation of interannual variability.

4. Discussion and Conclusions

We have presented CO_2 fluxes from four TBMs and used them as a surface fluxes for atmospheric transport model simulations, and compared simulated atmospheric concentrations with observations. We also used the TBM fluxes as *a priori* fluxes for a Bayesian Synthesis Inversion. The results indicate that the flux estimates from the TBMs show reasonable agreement with the atmospheric CO_2 observations but that some modifications to the TBMs are required to improve the flux estimates. This conclusion assumes that the errors in the transport model, inversion and the observations have not substantially influenced the results of our analysis. Especially in the case of the inversion, this may be a large assumption given the range of results coming from various regional inversion studies (Enting et al., 1995; Rayner et al., 1999; Fan et al., 1999). However, in this study we are examining the seasonal cycle and interannual variability in the fluxes rather than the net fluxes. These two feature of the carbon cycle have larger signal to noise ratios, and therefore the inversion can give more robust information. Firstly, both the forward simulations and the inversion results suggest that the TBMs generally underestimate the amplitude of the seasonal cycle. This is perhaps expected as all the TBMs do not model all the processes which potentially contribute to the seasonal cycle, such as fire and insect disturbance (Zimov et al., 1999), and the role of soil freeze and thaw (Goulden et al., 1998; McGuire et al., 2000). We may expect that if these important processes were included in the TBMs, then the amplitude and shape of the seasonal cycle could change. This highlights the need for caution when ‘tuning’ models to the observations when the models do not represent all the important processes.

The inversion has allowed us to explain what changes to the TBMs would improve the flux estimates. Except for one of the TBMs (LPJ), the key change seen is that a later and stronger summer uptake is required. In the case of LPJ a reduction in the autumn efflux is required. The later timing of the summer drawdown may be due to the models not taking into consideration the freezing of the soil over winter. One theory is that when the atmospheric temperatures reach a certain level the models begin photosynthesis, whereas in reality the frozen soil prevents the roots from drawing up the water and nutrients required. More realistic soil thermodynamics may be a necessary addition to improve the seasonal cycle phase. Improvements in TBMs by comparing to high latitude tower data may also help (e.g., Goulden et al., 1998).

The results from the inversion have shown that the results in the regions that are not as well represented by the observations are more sensitive to the *a priori* fluxes. We have focused on the land regions of the northern high latitudes here in this study, and results show that the inversion does give considerable information about the fluxes in these regions. While the observing network has been increasing in size, the number of stations sampling in remote areas is still small. Therefore, in many regions, it will be important to use methods other than inversions to improve our understanding of the CO_2 fluxes. This is especially true in the tropics, where the transport tends to mix the signal from the fluxes into the upper troposphere by convection, and therefore even with many surface observations, constraining this region is difficult in the inversion, and so flux estimates from the TBMs may be the best option for determining flux variability. It is therefore important to develop and improve the TBMs, and the combination of the 'top down' and 'bottom up' approaches appears to be a solid move forward.

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