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An assessment of the carbon balance of arctic tundra: comparisons among observations, process models, and atmospheric inversions

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Abstract

Although arctic tundra has been estimated to cover only 8 % of the global land surface, the large and potentially labile carbon pools currently stored in tundra soils have the potential for large emissions of carbon (C) under a warming climate. These emissions as radiatively active greenhouse gases in the form of both CO_2 and CH_4 could amplify global warming. Given the potential sensitivity of these ecosystems to climate change and the expectation that the Arctic will experience appreciable warming over the next century, it is important to assess whether responses of C exchange in tundra regions are likely to enhance or mitigate warming. In this study we compared analyses of C exchange of Arctic tundra between 1990–1999 and 2000–2006 among observations, regional and global applications of process-based terrestrial biosphere models, and atmospheric inversion models. Syntheses of the compilation of flux observations and of inversion model results indicate that the annual exchange of CO_2 between arctic tundra and the atmosphere has large uncertainties that cannot be distinguished from neutral balance. The mean estimate from an ensemble of process-based model simulations suggests that arctic tundra acted as a sink for atmospheric CO_2 in recent decades, but based on the uncertainty estimates it cannot be determined with confidence whether these ecosystems represent a weak or a strong sink. Tundra was 0.6 °C warmer in the 2000s compared to the 1990s. The central estimates of the observations, process-based models, and inversion models each identify stronger sinks in the 2000s compared with the 1990s. Similarly, the observations and the applications of regional process-based models suggest that CH_4 emissions from arctic tundra have increased from the 1990s to 2000s. Based on our analyses of the estimates from observations, process-based models, and inversion models, we estimate that arctic tundra was a sink for atmospheric CO_2 of 110 $Tg\,C\,yr^{-1}$ (uncertainty between a sink of 291 $Tg\,C\,yr^{-1}$ and a source of 80 $Tg\,C\,yr^{-1}$) and a source of CH_4 to the atmosphere of 19 $Tg\,C\,yr^{-1}$ (uncertainty between sources of 8 and 29 $Tg\,C\,yr^{-1}$). The suite of analyses conducted in this study indicate that it is clearly important to reduce uncertainties in the

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observations, process-based models, and inversions in order to better understand the degree to which Arctic tundra is influencing atmospheric CO_2 and CH_4 concentrations. The reduction of uncertainties can be accomplished through (1) the strategic placement of more CO_2 and CH_4 monitoring stations to reduce uncertainties in inversions, (2) improved observation networks of ground-based measurements of CO_2 and CH_4 exchange to understand exchange in response to disturbance and across gradients of hydrological variability, and (3) the effective transfer of information from enhanced observation networks into process-based models to improve the simulation of CO_2 and CH_4 exchange from arctic tundra to the atmosphere.

1 Introduction

The distribution of the arctic tundra biome is generally north of the boreal forest treeline and covers approximately 8 % of the global land surface (McGuire et al., 1997). The exact location of the biome's southern border is subjective, with the transition between closed boreal forest and treeless tundra up to several hundred kilometers wide in regions of low topographic relief (Vlassova, 2002; Callaghan et al., 2005). Climate in the Arctic is harsh, characterized by cold winters and cool summers, with mean July temperatures below ~12 °C (Callaghan et al., 2005), and annual mean temperatures typically below −10 °C (New et al., 1999). Consequently, plant growth is restricted to a relatively short growing season on the order of three months or less during the boreal summer. The tundra biome is home to approximately 1800 species of vascular plants and has less species diversity than more temperate biomes (Callaghan et al., 2005). The stature of vascular plant species is limited by environmental conditions, with trees almost entirely absent and woody plant species restricted largely to shrubs and dwarf shrubs. In addition to vascular plant species, non-vascular mosses and lichens play a very important role in the structure and function of tundra ecosystems. Frozen soils are prevalent in northern high latitudes and there is a gradient of continuous to discontinuous permafrost from north to south. Most of the tundra biome is underlain

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by continuous permafrost. The spatial and temporal dynamics of permafrost and periodic disturbance are crucial in shaping the arctic landscape and its heterogeneity with important consequences for the areal extent of wetlands and the exchange of carbon dioxide (CO_2) and methane (CH_4).

Future climate warming is predicted to be very pronounced over the Arctic, especially during winter and spring. The arctic autumn-winter is expected to warm between 3 and 6 °C by 2080 (SWIPA Assessment Executive Summary, 2011), which is expected to lead longer growing seasons, thawing of permafrost, warming and deepening of the soil active layer, and large changes in hydrology. These changes are likely to substantially affect tundra ecosystem structure and function. In fact, there is increasing evidence that physical and ecological changes are already occurring throughout the tundra biome (Serreze et al., 2003; Hinzman et al., 2005; McDonald et al., 2004; Piao et al., 2008, 2011; Post et al., 2009; Rawlins et al., 2010; Rowland et al., 2010; Beck and Goetz, 2011; Kim et al., 2011).

The large and potentially labile carbon (C) pools currently stored in arctic soils (Ping et al., 2008; Tarnocai et al., 2009) have the potential to be emitted as radiatively active greenhouse gases in the form of both CO_2 and CH_4 under warmer conditions (Schuur et al., 2008, 2011; Chapin et al., 2008; McGuire et al., 2009; Schaefer et al., 2011; Koven et al., 2011). Whether the emissions of CO_2 from tundra soils tends to amplify or mitigate global warming depends on the degree to which C accumulation in tundra plants responds to warming (Sitch et al., 2007). This balance determines whether the tundra is a source or sink of CO_2. Changes in the emissions of CH_4 may also affect the degree to which tundra amplifies or mitigates global warming. While CH_4 has only a small role on the mass balance of C between the atmosphere and tundra, it is a highly potent greenhouse gas. Changes in CH_4 emissions are likely to be strongly linked to changes in hydrology. Current emissions of CH_4 are difficult to quantify because of substantial variability in time and space due to variations in the environment associated with topography, hydrology, and soil chemistry.

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Because of the substantial changes that are already affecting the structure and function of arctic tundra, it is important to assess how C exchange of arctic tundra has been changing in recent decades. The response of C dynamics of arctic tundra to environmental change can be evaluated through a synthesis of (1) observations of C exchange with the atmosphere, (2) the application of process-based models, and (3) the analysis of atmospheric inversions of C exchange with the atmosphere. Each of these scaling approaches has it strengths, weaknesses, and limitations in assessing the carbon dynamics of arctic tundra. In this paper we compare analyses of C dynamics of arctic tundra in the two most recent decades among the three scaling approaches to gain insight on how C exchange of arctic tundra may be responding to ongoing environmental changes. The analysis in this paper represents the arctic tundra contribution to the Global Carbon Project's REgional Carbon Cycle and Assessment Processes (RECCAP) synthesis (Canadell et al., 2011).

2 Methods

2.1 Estimates from flux observations

Methods for ground-based observation of the exchange of C between land and atmosphere face great challenges in arctic environments. The challenges include (1) comprehensive spatial coverage in the face of a heterogeneous landscape mosaic that is often characterized by "hot spots"; (2) continuous sampling to achieve full year-round estimates of carbon dynamics; (3) high temporal resolution to sample episodic exchanges of CO_2 and CH_4; and (4) collection of C exchange data without line power in remote conditions.

A single technique is not available that meets all of these challenges. Currently, manual chambers, automatic chambers, and eddy covariance towers are the primary techniques being used to measure C exchange between tundra with the atmosphere. For CO_2 flux measurements, these sampling techniques are linked to infra-red gas

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analyzers that measure CO_2 concentrations. For CH_4, the field technology is less developed, and has relied on gas sample collection in the field, with laboratory estimates of CH_4 concentrations using gas chromatographs. Measurement systems have recently been developed that allow direct CH_4 concentration estimates in the field. In Table 1 we compare the relative performance of these methods for a number of requirements and considerations. Because typical tundra areas are heterogeneous, it is often necessary to employ chamber methods of measurement to differentiate the C exchange for the individual components (e.g., soil, moss, and vascular plants) and to better understand the underlying processes of land-atmosphere C exchange. Chamber-based measurements complement tower-based measurements that more effectively integrate across a heterogeneous landscape. In Appendix A in the Supplement we have compiled approximately 250 estimates from 120 published papers of the mean exchange of CO_2 and CH_4 between Arctic tundra and the atmosphere at growing season, winter season, and annual time scales based on published observational studies. The exchange of CO_2 with the atmosphere is reported as net ecosystem exchange (NEE), i.e., net land-atmosphere CO_2 flux, in which a positive NEE represents a loss of CO_2 from tundra to the atmosphere. Similarly the exchange of CH_4 is reported as a positive flux when the net exchange is to the atmosphere and as a negative flux when the net exchange is into the ecosystem. Both CO_2 and CH_4 estimates are reported in units of C. In this study we used only estimates of CO_2 and CH_4 exchange from Appendix A in the Supplement for the time period between 1990 and 2009 unless stated otherwise.

2.2 Estimates from process-based models

The spatial domain of arctic tundra we considered in this study (Fig. 1) was defined by the Regional Carbon Cycle Assessment and Processes (RECCAP) Activity. It is important to note that the spatial domain of arctic tundra was defined from an atmospheric perspective as a region that could potentially be resolved by the applications of inversion models. The region does extend into boreal forest in some areas (for example in western North America). In this study we compare the carbon dynamics of Arctic tundra

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between 1990 and 2006 estimated by regional applications of three models that have focused on representing processes in ecosystems underlain by permafrost: LPJ-Guess WHyMe (Smith et al., 2001; Wania et al., 2009a, b, 2010; Hickler et al., 2012), Orchidee (Koven et al., 2009, 2011), and version 6 of the Terrestrial Ecosystem Model (TEM6; McGuire et al., 2010; Hayes et al., 2011). For evaluating the production estimates of the three regional process-based models, we have also included the Terrestrial Carbon Flux (TCF) model (Kimball et al., 2009) in the regional process-based model analysis. The general features of the models are compared in Table 2 (see Appendix B in the Supplement for more details).

The TCF is unique among the models in that it is partially driven by satellite-based vegetation gross primary production (GPP) estimates from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) for the period between 2000 and 2009 (Zhao and Running, 2010). The MODIS (MOD17) GPP estimates are used to derive vegetation net primary production (NPP), while heterotrophic respiration (RH) is determined from a simulated surface ($<$10 cm depth) soil organic carbon pool and dynamic soil moisture and temperature constraints to litter decomposition. The TCF does not account for other carbon emission sources, including fire disturbance, so NEE is derived as the residual difference between NPP and RH, and assumed equivalent to net ecosystem production (NEP). The TCF calculations assume dynamic steady-state conditions between NPP and RH so that estimated NEE/NEP has no trend over the decade from 2000 to 2009. The other three models were driven in a prognostic fashion by atmospheric CO_2 and climate data of their own choosing over the simulation period. Because of each models choice of climate data, both LPJ-Guess WHyMe and TEM6 produced estimates for only the 1990–2006 time period. Therefore, we only compare 2000–2006 among the models in the most recent decade. See Appendix B in the Supplement for more details on the application of the regional models in this study.

All models make estimates of GPP, NPP, RH, and NEP. Both LPJ-Guess and TEM6 make estimates of losses of carbon to the atmosphere associated with fire and biogenic CH_4 emissions. In addition, TEM6 also calculates ecosystem losses of carbon associated with the export of harvested products and dissolved organic carbon. For each of the models we also calculate the net ecosystem carbon balance (NCB) as the sum of NPP and the atmospheric and export losses. The sign conventions for NEP and NCB are positive for a net flux of carbon into the ecosystem. We also report net CO_2-C exchange with a sign convention of positive representing a source to the atmosphere and negative representing a sink into tundra ecosystems. In this study, we compare the mean C budget estimated from 1990–1999 and 2000–2006 among simulations of LPJ-Guess WHyMe, Orchidee, and TEM6. We also report net CO_2-C exchange for each of the models as previously defined. We also provide mean GPP and NPP estimates simulated by TCF for 2000–2006. To explore issues involving the mean seasonal cycle of CO_2 exchange, we compare the mean monthly flux estimates for GPP, NPP, RH, and NEP for 1990–2006 simulated by LPJ-Guess, Orchidee, and TEM6, and for 2000–2009 simulated by TCF. We also compare interannual variability for estimates of GPP, NPP, RH, NEP, other atmospheric losses, export losses, and NCB among the models. To explore the importance of changing climate on the regional applications of the process-based models, we conducted additional simulations that were driven by constant climate keeping all other drivers unchanged. The constant climate for the three models was based on the 1901–1930 climate used to drive their transient simulations. We estimate the effect of a changing climate on NPP, RH, and NEP between 1990 and 2006 by subtracting the estimates of the constant climate simulation of each model from that of the corresponding transient climate simulation.

The RECCAP activity is also comparing the mean C budgets for the 1990s and 2000s estimated by a suite of global applications of dynamic global vegetation models (DGVMs). These DGVM applications were conducted as part of the Trendy project (http://dgvm.ceh.ac.uk) to examine trends in the net land C exchange over the period 1980–2009. In this study we compare the mean C budget of these global applications for the Arctic tundra region of this study for the time periods 1990–1999 and 2000–2006. The DGVM applications compared in this study include contributions from CLM4C (Lawrence et al., 2010), CLM4CN (Thornton et al., 2007, 2009; Bonan and

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Levis, 2010; Lawrence et al., 2010), Hyland (Levy et al., 2004), LPJ (Sitch et al., 2003), LPJ-Guess (Smith et al., 2001), O-CN (v0.74; Zaehle and Friend, 2010), SDGVM (Woodward et al., 1995; Woodward and Lomas, 2004), and TRIFFID (Cox, 2001). The models used a common protocol (http://dgvm.ceh.ac.uk) applying CRU-NCEP climatology over the period 1901–2009. Note that the global application of LPJ-Guess is quite different from the regional application of LPJ-Guess WHyMe, which represents processes relevant to arctic tundra function and structure including (1) soil water freezing; (2) arctic shrub and open ground plant functional types (e.g., *Sphagnum* mosses and tundra graminoids; (3) peatland hydrology, decomposition, and plant functional types; (4) a methane module for peatlands; and (5) root exudates (see Appendix B in the Supplement for details).

2.3 Estimates from inversion-based models

We also analyzed the mean land-atmosphere CO_2-C exchange for the arctic tundra domain from a set of ten inversion models that were applied in support of RECCAP analyses (Gurney et al., 2012). The inversion models include C13_CCAM_law, C13_MATCH_rayner, CTRACKER_EU, CTRACKER_US, JENA_s96_v3.3, JMA_2010, LSCE_an_v2.1, LSCE_var_v1.0, NICAM_niwa_woaia, and rigc_patra. Among these inversion models, the applications span the time period from 1985–2009. However, the period of application is highly variable among the models. We report the mean NEE estimate for arctic tundra from 1990–1999 and 2000–2006 for eight of the applications of these inversion models; we do not report the results from CTRACKER_EU or CTRACKER_US as these models did not start making estimates until 2001. We report the mean season cycle of CO_2-C exchange estimates based on the time period of application of each of the ten models. Similarly, we report the interannual variability of NEE anomalies across the time period of application of each of the ten models.

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3 Results

3.1 Estimates based on flux observations

3.1.1 CO_2 exchange

Most direct observational studies of the exchange of CO_2 between tundra and the atmosphere have been conducted during the summer growing season. These studies generally indicate that arctic tundra has been a sink for atmospheric CO_2 during the summer in all subregions of the Arctic (i.e., NEE is largely negative; Fig. 2) and that there has not been a substantial change in the sink strength between the 1990s and 2000s (Table 3). While it appears from Table 3 that the summer sink strength in Eurasia has more than doubled since 2000, the mean estimates are not significantly different as the confidence limits since 2000 completely overlap the confidence limits for the 1990s. The existing observations suggest that wet (lowland) tundra is strong sink for CO_2 during the growing season, while dry/mesic (upland) tundra tends to be a growing season source of CO_2 to the atmosphere with a confidence interval that overlaps neutral balance (Table 4).

Only a handful of studies have estimated the exchange of CO_2 in winter, as there are considerable challenges in maintaining accurate flux measurements outside the growing season. The available estimates indicate that tundra ecosystems are sources of CO_2 to the atmosphere (Fig. 2, Table 3). Given that few studies have been conducted, it does not appear that the strength of sources differs among subregions (Table 3). Also, the scarcity of winter exchange data does not allow us to evaluate if there are differences in source strength between the 1990s and 2000s. The existing observations suggest that there is little difference in the source strength of CO_2 during the winter between wet and dry/mesic tundra (Table 4).

There are a growing number of observationally based studies that are attempting to estimate annual CO_2 exchange between tundra and the atmosphere. In general, the range of variability among estimates is scattered around neutral annual CO_2 exchange

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in all subregions (Fig. 2). In North America, the data suggest that tundra ecosystems tended to be annual sources of CO_2 to the atmosphere prior to 2000, but have been approximately neutral or weak sinks since 2000 (Table 3). The existing observations suggest that wet tundra is a strong sink for CO_2 annually, while dry/mesic tundra tends to be an annual source of CO_2 to the atmosphere with a confidence interval the overlaps neutral balance (Table 4).

Based on the mean and range of NEE observations reported in Table 3 for the different geographical regions of the Arctic, we developed first order estimates of NEE and ranges in uncertainty in those estimates for Arctic tundra between 1990 and 2009 (see Appendix C in the Supplement for details). This analysis suggests that tundra was source of 138 $Tg\,C\,yr^{-1}$ as CO_2 to the atmosphere in the 1990s with a range of uncertainty between a 102 $Tg\,C\,yr^{-1}$ sink and a 378 $Tg\,C\,yr^{-1}$ source. In contrast, the analysis suggests that tundra was a 202 $Tg\,C\,yr^{-1}$ sink in the 2000s with an uncertainty range between a 628 $Tg\,C\,yr^{-1}$ sink and 224 $Tg\,C\,yr^{-1}$ source. Across the two decades, we estimate that tundra was a sink of 103 $Tg\,C\,yr^{-1}$ with an uncertainty between a 297 $Tg\,C\,yr^{-1}$ sink and 89 $Tg\,C\,yr^{-1}$ source.

3.1.2 CH_4 exchange

Similar to data on CO_2 exchange, most of the studies of the exchange of CH_4 between tundra and the atmosphere have been conducted during the summer growing season. These studies generally indicate that arctic tundra is a substantial source of CH_4 to the atmosphere during the summer (Fig. 2) and that there has not been a substantial change in the strength of the source between the 1990s and 2000s (Table 3). However, the existing observations suggest that there are differences among different tundra types as mean summer emissions of CH_4 for wet tundra are 9.2 $g\,C\,m^{-2}$ compared with 0.8 $g\,C\,m^{-2}$ for dry/mesic tundra with no overlap in the confidence intervals (Table 4). There are only two studies that have estimated the exchange of CH_4 in winter, and these studies indicate that tundra ecosystems are a weak source of around

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3.0 (range 0.1 to 6.0) g CH_4-C m^{-2} $winter^{-1}$ to the atmosphere. The inference from the studies in North America during the 2000s suggest that there are substantial emissions of CH_4 during the winter, but the studies in northern Europe in the 2000s suggest that CH_4 emissions in winter are negligible. The inconsistency is likely to due to bias associated with different representations of wet and dry/mesic tundra in the summer vs. annual estimates, as the summer and annual fluxes are consistent with each other when broken down by landscape position/wetness (Table 4).

Based on the mean and range of CH_4 observations reported in Table 3 for the different geographical regions of the Arctic, we developed estimates of CH_4 emissions and ranges in uncertainty in those estimates for Arctic tundra before and since 2000 (see Appendix C in the Supplement for details). This analysis suggests that tundra emitted 10 Tg C yr^{-1} as CH_4 to the atmosphere in the 1990s with a range of uncertainty between −1 and 22 Tg C yr^{-1}. The analysis suggests that tundra was stronger emitter of CH_4 during the 2000s (20 Tg C yr^{-1}), but the uncertainties since 2000 are much larger than in the 1990s (between a sink of 11 and a source of 51 Tg C yr^{-1}). Across the two decades, our analysis indicates that tundra emitted 11 Tg C yr^{-1} as CH_4 with a range from 0 to 22 Tg C yr^{-1}.

3.2 Process-based model estimates

3.2.1 Mean C budgets for 1990–1999 and 2000–2006

GPP estimated by the regional applications of process-based models over the arctic tundra region from 1990 through 1999 varies from 1755 Tg C yr^{-1} (191 g C m^{-2} yr^{-1}) for LPJ-Guess WHyMe to 5295 Tg C yr^{-1} (577 g C m^{-2} yr^{-1}) for Orchidee (Table 5). NPP is estimated to be approximately 65 %, 61 %, and 40 % of GPP by LPJ-Guess WHyMe, Orchidee, and TEM6, respectively. TEM6 estimates a higher proportion of GPP allocated to autotrophic respiration because the temperature sensitivity of autotrophic respiration in the model increases with decreasing mean annual temperature

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(McGuire et al., 1992). RH estimates vary from 875 Tg C yr^{-1} (95 g C m^{-2} yr^{-1}) for TEM6 to 2954 Tg C yr^{-1} (322 g C m^{-2} yr^{-1}) for Orchidee, and RH is estimated to be less than NPP by each model. NEP estimates vary from 85 Tg C yr^{-1} (10 g C m^{-2} yr^{-1}) for TEM6 to 255 Tg C yr^{-1} (28 g C m^{-2} yr^{-1}) for Orchidee. TEM estimates 30 Tg C yr^{-1} in fire emissions, which is 20 Tg C yr^{-1} more than is estimated by LPJ-Guess WHyMe. After accounting for fire emissions of CO_2, the estimates of the net exchange of CO_2 vary from 55 Tg C yr^{-1} taken up from the atmosphere by TEM6 to 255 Tg C yr^{-1} taken up by Orchidee, which is a higher range of uptake than is estimated by the global applications of process models (from null balance estimated by Hyland to an uptake of 188 Tg C yr^{-1} by LPJ-Guess). Most of the NEP estimated by TEM6 is lost to fire emissions, biogenic CH_4 emissions, and the export of harvested products and DOC. Approximately 20 % of NEP estimated by LPJ-Guess WHyMe is lost to fire and CH_4 emissions. Thus, NCB estimated by the models varies from approximately 20 Tg C yr^{-1} (TEM6) to 255 Tg C yr^{-1} (Orchidee).

In comparison to the 1990s, GPP estimated by the regional applications of process-based models over the Arctic tundra region from 2000 through 2006 is higher (from an increase of 9 g C m^{-2} yr^{-1} by TEM to an increase of 38 g C m^{-2} yr^{-1} by Orchidee; compare Table 6 to Table 5). The satellite-based estimate of GPP by TCF from 2000–2006 is 307 g C m^{-2} yr^{-1}, which is 47 % and 14 % higher than the estimates by LPJ-Guess WHyMe and TEM6, respectively, and 50 % of the estimate by Orchidee. Similar to GPP, both NPP and RH estimates of the regional applications are higher in the 2000s compared to the 1990s. Although NEP estimates increase by 1 to 6 g C m^{-2} yr^{-1} between the two decades across the models, the increase from 1990 to 2006 is significant only for the LPJ-Guess WHyMe simulation (0.57 g C m^{-2} yr^{-1}; $P = 0.001$). The TEM6 simulation estimates that fire emissions doubled in the 2000s compared to the 1990s. Estimates of the net uptake of CO_2 increase (lower or more negative net CO_2-C exchange) for both LPJ-Guess WHyMe and Orchidee in the 2000s compared to the 1990s, but decrease for TEM6. Between 1990 and 2006 both Orchidee and LPJ-Guess WHyMe estimate substantially greater net uptake of CO_2 (31 and 4 g C m^{-2} yr^{-1}, respectively;

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Table 7) than TEM6 ($4\,g\,C\,m^{-2}\,yr^{-1}$). Among the global models, only LPJ and SDGVM estimate less net uptake of CO_2 (less negative net CO_2-C exchange) in the 2000s (Table 6) compared to the 1990s (Table 5). The greatest uptake between 1990 and 2006 among the global models is simulated by LPJ-Guess ($23\,g\,C\,m^{-2}\,yr^{-1}$), which is similar to the uptake estimated by LPJ-Guess WHyMe (Table 7).

To explore the importance of changing climate on the regional applications of the process-based models, we conducted additional simulations that were driven by constant climate. We estimated the effect of a changing climate on NPP, RH, and NEP between 1990 and 2006 by subtracting the estimates of the constant climate simulation of each model from that of the corresponding transient climate simulation. This analysis indicated that climate change between 1990 and 2006 caused NPP and RH of all three models to increase (Table 8). In comparison to TEM6, NPP was 69 % and 106 % more sensitive in the LPJ-Guess WHyMe and Orchidee simulations, respectively. In contrast, the RH sensitivity of LPJ-Guess WHyMe was similar to that of TEM6, while the RH sensitivity of Orchidee was 146 % more sensitive than TEM6. The different sensitivities of NPP and RH caused quite different sensitivities in NEP. Climate change between 1990 and 2006 caused LPJ-Guess WHyMe NEP to increase by $8\,g\,C\,m^{-2}\,yr^{-1}$, TEM6 NEP to increase by $1\,g\,C\,m^{-2}\,yr^{-1}$, and Orchidee NEP to decrease by $4\,g\,C\,m^{-2}\,yr^{-1}$.

3.2.2 Seasonal cycle and changes in the seasonal cycle

The shape of the seasonal cycle of NPP, RH, and NEP is similar among the regional applications of the process-based models (Fig. 3). In general, all models indicate that the growing season lasts from June through September with three of the models indicating that NPP starts to increase above winter values in May (LPJ-Guess WHyMe, Orchidee, TCF) and one of the models indicating a similar level of May production in October (Orchidee). In contrast to the other models, TCF is the only model that predicts positive, albeit very small, fluxes of NPP throughout the winter. All models estimate that the month of maximum production is July, followed closely by August. RH is generally

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estimated to be small from November through April, to increase in magnitude from May through July/August, and to decrease in magnitude during September and October. All the models estimate that the month of maximum RH is July, except for LPJ-Guess WHyMe, for which August is characterized by the greatest RH. All models indicate that the maximum NEP occurs in July, but the number of months with positive NEP varies among the models between two (TCF) and four (LPJ-Guess WHyMe and Orchidee).

Both LPJ-Guess WHyMe and Orchidee have the same pattern of differences in monthly NEP between the 2000s and 1990s (Fig. 4), with the largest increases in July. LPJ-Guess WHyMe has relatively larger increases in May, while Orchidee has relatively larger increases in August. The summer increases of LPJ-Guess WHyMe and Orchidee are driven by increases in NPP that are greater than increases in RH. In contrast, TEM6 has the largest increases in September, followed by August as NPP increases in August and September are greater than increases in RH; in June and July there are similar increases in both NPP and RH. All three models indicate substantially lower NEP in October because of increases in RH when NPP is close to zero in both decades.

3.2.3 Interannual variability

Among the regional applications of the process-based models, Orchidee stands out as having the highest range of interannual variability in GPP, NPP, RH, and NEP (Fig. 5). Correlations are high among the models for interannual variability in the anomalies of GPP ($R = 0.73$ to 0.88; Fig. 5a) and RH ($R = 0.81$ to 0.97; Fig. 5c). The correlations for NPP anomalies (Fig. 5b) are slightly lower ($R = 0.66$ to 0.80), except for a low correlation between TCF and TEM6 ($R = 0.23$). In contrast, correlations among the anomalies of NEP (Fig. 5d) are poor and range from negative correlations ($R = -0.64$ between Orchidee and TCF) to low positive correlations ($R = 0.30$ between Orchidee and TEM6).

TEM6 estimates of fire emissions are characterized by substantial interannual variability in comparison to LPJ-Guess WHyMe, which has little interannual variability

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(Fig. 6a); the variability is uncorrelated between the models ($R = 0.07$). LPJ-Guess estimates of biogenic CH_4 emissions are correlated with those of TEM6 ($R = 0.69$; Fig. 6b), but are characterized by more interannual variability than those of TEM6. The other flux anomalies estimated by TEM6 have less interannual variability (~0.25 $g\,C\,m^{-2}$; Fig. 6c) than fire emissions (~16 $g\,C\,m^{-2}$; Fig. 6a) and bioigenic CH_4 emissions (~0.5 $g\,C\,m^{-2}$; Fig. 6b). In general, the correlations among the models for interannual variability in NCB (Fig. 6d) are similar to those for NEP (Fig. 6d), except that all of the correlations are weaker between TEM6 and the other models. This suggests that fire emissions, biogenic CH_4 emissions, and other export fluxes are important to consider in evaluating interannual variability in carbon storage of Arctic tundra.

3.3 Atmospheric inversion estimates

We analyzed the net exchange of CO_2 (i.e., NEE) between arctic tundra and the atmosphere estimated by inversions for 1990–1999 and 2000–2006 (Table 9). Among the three models that made estimates between 1990 and 1999, the mean annual exchange ranged from a source of 140 $Tg\,C\,yr^{-1}$ (15 $g\,C\,m^{-2}\,yr^{-1}$) to a sink of 321 $Tg\,C\,yr^{-1}$ (35 $g\,C\,m^{-2}\,yr^{-1}$). In comparison to the 1990–1999 time period, the range among the eight models that made estimates for 2000–2006 is wider and ranges from a source of 206 $Tg\,C\,yr^{-1}$ (22 $g\,C\,m^{-2}\,yr^{-1}$) to a sink of 439 $Tg\,C\,yr^{-1}$ (48 $g\,C\,m^{-2}\,yr^{-1}$).

The shape of the mean seasonal cycle of NEE between 2000 and 2006 is generally similar among the inversions (Fig. 7). All models indicate that the maximum NEE occurs in July, but the number of months with negative NEE varies among the models between two (C13_MATCH_rayner) and four (LSCE_an_v2.1). Among the inversion models, the NEE estimates of individual months are generally within 10 $g\,C\,m^{-2}$ except for LSCE_an_v2.1, which estimates higher releases of CO_2 to the atmosphere than the other models in April and May and higher uptake of CO_2 in July, August, and September.

Among the inversion models, interannual variability is smallest for LSCE_an_v2.1 (standard deviation of NEE anomalies = 2.1 $g\,C\,m^{-2}\,yr^{-1}$) and largest for rigc_patra

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(standard deviation = 13.1 g C m^{-2} yr^{-1}) (Fig. 8). Similar to the correlations of interannual variability in NEP anomalies among the process-based models, the correlations of interannual variability in NEE anomalies among the inversion models is poor with a mean correlation of 0.03; correlations range between -0.38 (between CTRACKER_EU and C13_CCAM_law) to +0.99 (between CTRACKER_US and LSCE_an_v2.1).

4 Discussion

The changing C balance of Arctic tundra has been an issue of concern for several decades (Billings et al., 1983; Oechel et al., 1993; McGuire et al., 2000, 2009, 2010; Chapin et al., 2000; Sitch et al., 2007; Hayes et al., 2011). It has been hypothesized that tundra will become a source of C to the atmosphere because of C emissions associated with the warming of soil organic matter in the active layer as well as the exposure of previously frozen C to decomposition as the active layer deepens. Some recent model applications that consider soil C stocks at depth in high latitudes and the exposure of those stocks to decomposition upon permafrost thaw indicate that northern terrestrial ecosystems will release soil C to the atmosphere (Koven et al., 2011; Schaefer et al., 2011; Schneider von Deimling et al., 2012). It has also been hypothesized that tundra could become a sink for atmospheric CO_2 if N-limited plants in tundra regions take up a substantial proportion of N that is released by enhanced decomposition (Shaver et al., 1992). Some coupled climate-carbon model simulations predict that the northern high latitudes will serve as a substantial land carbon sink during the 21st century because both climate warming and elevated global [CO_2] favor increased productivity and CO_2 uptake in the region (Friedlingstein et al., 2006; Qian et al., 2010; Sitch et al., 2008). Whether tundra becomes a source or a sink of atmospheric CO_2 in response to warming is an important scientific issue to resolve, as substantial source activity could compromise efforts to mitigate the increase of greenhouse gases in the atmosphere. Changes in CH_4 emissions are also important, because of the high global warming potential of CH_4. In terms of climate forcing, increasing CH_4 emissions could

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offset the effects of a CO_2 sink, or enhance the effects of a CO_2 source. In this study, we attempt to shed some light on these issues by analyzing the C balance of Arctic tundra through a synthetic comparison among estimates of CO_2 and CH_4 fluxes based on observations, regional and global applications of process-based models, and inversion models. We focused our comparison on the mean CO_2 and CH_4 budgets for the time periods 1990–1999 and 2000–2006, on aspects of the seasonal cycle of CO_2 exchange, and on interannual variability of CO_2 exchange.

4.1 Mean C budgets for the 1990s and 2000s

Table 10 compares the mean net exchanges of CO_2-C and CH_4-C from Arctic tundra to the atmosphere among observations, process-based models, and inversion models (see Appendix C in the Supplement for documentation of the estimates reported in Table 10). Syntheses of the compilation of flux observations and of inversion model results for Arctic tundra indicate that the annual exchange of CO_2 between Arctic tundra and the atmosphere has large uncertainties that cannot be distinguished from neutral balance. The synthesis of process-based model simulations indicate that Arctic has been acting as a sink for atmospheric CO_2, but based on the uncertainty estimates it is not clear if Arctic tundra acted as a weak or a strong sink. In comparison to the global process-based models, the regional process-based models indicate that Arctic tundra acted as a stronger sink.

Analysis of the CRU-NCEP data sets indicates that the region was 0.6 °C warmer in the 2000s compared to the 1990s. Most of the warming was in the autumn and winter (1.1 °C warmer) followed by summer (0.3 °C warmer), and little difference in the spring. The pattern of warmer autumns, winters, and summers in the 2000s occurred in all of the subregions except North America in which the mean summer temperature was not different between the two decades. It is notable that the central estimates of the observations, process-based models, and inversion models each identify stronger CO_2 sinks in the warmer 2000s compared with the 1990s. A stronger sink in the 2000s compared to the 1990s suggests that the efficiency of the tundra CO_2 sink is not currently

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weakening; a common response of process-based models to warming in this region is that NPP increases faster in response to warming than RH (Sitch et al., 2007).

The largest changes in central estimates between the 1990s and 2000s are for those of the observations and the inversion models, and there is more convergence among the central estimates in the 2000s than in the 1990s. The large changes between decades for the observations and inversion models might reflect biases in the 1990s since the diversity of flux observations, and the number of CO_2 concentration measuring stations and inversion model applications were fewer than in the 2000s. The only mean source activity is that suggested by the observations in the 1990s. In particular, the source strength of the observations in North America in the 1990s is driving the overall source estimate for Arctic tundra in the 1990s. It is possible that tundra in North America was responding differently than tundra in other regions of the Arctic as northwestern North America warmed more strongly than other regions of the Arctic at the end of the last century (Serreze et al., 2000). It is also possible that sampling of observations in the 1990s was biased toward dry tundra, which tends to act as a source for C in the observations in both the 1990s and 2000s.

In general, the regional process-based model applications predict stronger sinks than the global applications. This is primarily due to the response of Orchidee, which has the highest NPP and NEE among the 11 models. It is notable that NPP and the sink strength of O-CN is much less than that of Orchidee, which might reflect the role of N in limiting productivity in O-CN. Although the sink strength of the central estimates of both regional and global process-based model applications increase from the 1990s and 2000s, 5 of the 11 process-based models show either no change or a weaker sink between decades (TEM6, CLM4CN, Hyland, LPJ, and SDGVM). Detailed analysis of one of the model applications (TEM6) suggests that tundra became a weaker sink from the 1970s through the 2000s because of the effects of climate on net ecosystem carbon balance (McGuire et al., 2010). The constant climate experiments we conducted with the regional model applications suggests that warming increases both NPP and RH in all three models, but that the relative responses of NPP and RH to warming

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are different among the models. This analysis indicates that the relative responses of NPP and RH to climate change are major sources of uncertainty in the application of process-based models to assess whether Arctic tundra will act as a positive or negative feedback to climate change.

Our analysis of CH_4 responses between decades is limited to comparison between the observations and the regional model applications (Table 10). There is substantial uncertainty in the 2000s CH_4 flux observation-based estimate. Because of big differences in estimates of CH_4 fluxes between wet and dry/mesic tundra (Table 4), uncertainties could be reduced by adequately sampling CH_4 exchange between these two types of tundra within each of the subregions that we considered in scaling the CH_4 observations. The synthesis of observations produces central estimates in the 1990s (10 Tg CH_4-C yr^{-1}) and 2000s (20 Tg CH_4-C yr^{-1}) that are consistent with the range of uncertainty (23 to 75 Tg CH_4-C yr^{-1}) among observation-based and process-model estimates (McGuire et al., 2009) for northern high latitude terrestrial regions that include boreal forest in addition to tundra. The central estimates in Table 10 are also consistent with the range of uncertainty (11 to 38 Tg CH_4-C yr^{-1}) among CH_4 inversion models for northern high latitudes (McGuire et al., 2009). Similarly, the range of uncertainty of CH_4 exchange estimated by LPJ-Guess WHyMe and TEM6 are within the ranges of uncertainty for both the bottom-up (based on observations and process-based models) and top-down (based on inversion models) reported by McGuire et al. (2009). The central estimates of the observations suggest that CH_4 emissions have increased more than 100 % from the 1990s to the 2000s, while the applications of LPJ-Guess WHyMe and TEM6 suggest that CH_4 emissions have only increased ~10–20 % from the 1990s to the 2000s. Previous analyses with TEM6 suggest that increasing temperature plays an important role in this response (Zhuang et al., 2007; McGuire et al., 2010).

4.2 Seasonal cycle and changes in the seasonal cycle

The sink strength of Arctic tundra for CO_2 could increase between decades because of more net CO_2 uptake during the middle of the growing season or because of greater

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net uptake of CO_2 at either the start or end of the growing season. In general, the pattern of mean seasonal cycle NEP of the regional model applications is consistent with the pattern of mean seasonal cycle NEE of the inversion models. All applications identify that the greatest CO_2 uptake occurs in July, but there are differences among both the regional model applications and inversions about the length of the net uptake period. Our analysis of the seasonal response of the regional model applications indicates that NPP of LPJ-Guess WHyMe, Orchidee, and TEM6 increased during the growing season in the 2000s compared to the 1990s. This is consistent with a number of remote sensing studies that have concluded that the Arctic tundra has become more productive during the last several decades (Nemani et al., 2003; Zhang et al., 2008; Beck and Goetz, 2011; Goetz et al., 2011) in association with warmer summers (Piao et al., 2011). However, the models show different patterns in the response of NEP between decades. Both LPJ-Guess and Orchidee show stronger patterns of early and mid-growing season NEP increases than TEM6, which has stronger NEP increases late in the growing season. A number of studies have concluded that the growing season in northern high latitude regions has increased in recent decades (McDonald et al., 2004; Euskirchen et al., 2006; Parmesan, 2007; Karlsen et al., 2009; Piao et al., 2011), although the increase varies both spatially and temporally. The TEM6 late season NEP response is consistent with a recent analysis for boreal Eurasia that suggests that the springtime extension of the growing season has stalled from 1997–2006 while the fall season has continued to lengthen and warm (Piao et al., 2011). The pattern of lower October NEP between decades among all three models is consistent with the analysis of Piao et al. (2008), which concludes that warmer and longer falls lead to greater CO_2 release in northern terrestrial ecosystems.

4.3 Interannual variability

Our analysis of inter-annual NEP anomalies among the regional model applications and of inter-annual NEE anomalies among the inversion models indicates that there is little agreement among the models on the pattern of inter-annual exchanges of CO_2

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between Arctic tundra and the atmosphere. Although different inversions generally agree on the pattern inter-annual variability of regional NEE (Gurney et al., 2008), this is not the case for the Arctic tundra region and suggests that the inversions are not well constrained in this region. The regional applications of the process-models generally agree on patterns of inter-annual variability for GPP, NPP, and RH. The interannual patterns of GPP for LPJ-Guess WhyMe, Orchidee, and TEM6 are consistent with the satellite-based inter-annual variability of TCF, but the inter-annual variability of TEM6 NPP is not well correlated with that of TCF. Clearly, differences between GPP/NPP and RH need to be better constrained for the models to improve estimates of inter-annual variability.

4.4 Best estimates of carbon balance from 1990–2009

For the arctic tundra region, the use of observations, process-based models, and inversion models each have shortcomings with respect to estimating the net exchanges of CO_2 and CH_4 with the atmosphere in the 1990s and 2000s. Problems with observations include small sample size in comparison to the area being considered, biases in tundra types sampled in both space and time, different sampling technologies among the samples, and changes in sampling technology through time. Process-models have uncertainties with respect to conceptualization, formulation, and parameterization issues. Inversion models are not well constrained for the tundra regions. Given the shortcomings of these approaches, we decided to weight them equally in making estimates of net CO_2 and CH_4 exchange with the atmosphere for the time period from 1990–2009. For estimating CO_2 exchange, we first averaged the regional and global process-based model central estimates and high and low estimates of uncertainty for the 1990–2006 period in Table 10 and then average those estimates with the corresponding estimates for the observations and inversion models. This procedure results in an estimate of the net CO_2-C exchange of CO_2 between the atmosphere and tundra ecosystems of a 110 $Tg\,C\,yr^{-1}$ sink with an uncertainty range between a sink of 291 $Tg\,C\,yr^{-1}$ and a source of 80 $Tg\,C\,yr^{-1}$. For estimating CH_4 exchange, we averaged the central and

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the high and low estimates of uncertainty for the 1990–2006 period in Table 10 between the observations and the regional process-based models. This procedure results in an estimate of net CH_4-C exchange between the atmosphere and tundra ecosystems of a source of 19 Tg C yr^{-1} with an uncertainty range between sources of 8 and 29 Tg C yr^{-1}.

5 Conclusions

The syntheses of the compilation of flux observations and of inversion model results for Arctic tundra in this study indicate that the annual exchange of CO_2 between Arctic tundra and the atmosphere has large uncertainties that cannot be distinguished from neutral balance in the 1990s and 2000s. In contrast, the synthesis of process-based model simulations indicate that Arctic tundra acted as a sink for atmospheric CO_2 in recent decades, but based on the uncertainty estimates it is not clear if Arctic tundra acted as a weak or a strong sink. Our analyses do suggest that both the CO_2 sink strength and the CH_4 emissions of Arctic tundra are increasing in recent decades. However, the analyses we conducted in this study indicate that responses of the seasonal exchange of CO_2 between decades and the interannual variability in CO_2 exchange of process-based models are not consistent. Although the regional models generally agree on patterns of inter-annual variability in production and decomposition, the constant climate experiments we conducted with the regional models indicates that the relative sensitivity of production and decomposition to climate change are different among the models. Thus, it is clearly important to reduce uncertainties in the observations, process-based models, and inversions in order to better understand the degree to which Arctic tundra is influencing atmospheric CO_2 and CH_4 concentrations. As inversion models are currently poorly constrained for making estimates of CO_2 exchange for Arctic tundra, there is a need to identify and place additional atmospheric CO_2 monitoring stations in a strategic fashion for better constraining inversion models. The availability and technology of ground-based observations in Arctic tundra are

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improving, particularly through the implementation of the Arctic Observing Network that has been ongoing since the beginning of the International Polar Year in 2007 (Sorlin and Danell, 2008). However, it is important to improve the network so that observations can be effectively stratified into those for dry/mesic tundra vs. wet tundra so that regional estimates based on ground-based observations can be improved and uncertainties reduced. More importantly, observation networks need to be designed so that the observations can ultimately be synthesized to understand how and why the net annual and seasonal exchanges of CO_2 and CH_4 are changing in response to climate variability and change in different tundra types that span hydrological variability. Also, the effects of disturbances such as fire and thermokarst on the exchange of CO_2 and CH_4 are not well represented in observation networks. Information from enhanced observation networks needs to be effectively transferred into process-based models to improve the simulation of CO_2 and CH_4 exchange so that process-based models can more reliably assess whether Arctic tundra will act as to amplify or mitigate global climate change.

Supplementary material related to this article is available online at: http://www.biogeosciences-discuss.net/9/4543/2012/ bgd-9-4543-2012-supplement.pdf.

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Table 1. A summary of technical performance in various categories of different flux measurement techniques. Modified from Drösler et al. (unpublished data).

	Eddy covariance	Automatic chambers	Manual chambers
Steady state, undisturbed measurement	++	±	−
Integration over spatial variability	++	− (quantity of chambers vs. mosaic)	−(quantity of chambers vs. mosaic)
Direct measurement of small scale spatial variability	−	+	++
Tracking temporal variability	++	++	− (campaigns as basis for modelling)
Costs	−	−	++
Workload	++	+	−
Performance under all climate conditions	±	±	++

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Table 2. Description of process-based models compared in this study. See Appendix B in the Supplement for additional details.

	Model Description Recent Arctic Applications	LPJ-Guess WHyMe Smith et al. (2001) Wania et al. (2009a) Wania et al. (2009b) Wania et al. (2010)	Orchidee Koven et al. (2009) Koven et al. (2011)	TCF Kimball et al. (2009)	TEM6 Hayes et al. (2011) McGuire et al. (2010)
Scale					
Temporal	Resolution Application	Daily Daily to Century	30 min Diurnal to multi-seasonal (Century application)	Daily Daily to Decadal	Month Seasonal to Century
Spatial	Resolution Application	0.5° Plot – Globe	2° Plot – Globe	25 km Plot – Region	0.5° Plot – Globe
Structure					
Vegetation		Dynamic	Prescribed	Prescribed	Prescribed
Litter/Soil Pools		1/3	4/3	3	2
Microbial Pools		No	No	No	No
Processes					
General	Photosynthesis	Farquhar et al. (1980) modified by Haxeltine and Prentice (1996)	Farquhar et al. 1980	MODIS MOD17 production efficiency model (Running et al., 2004)	GPP based on multiple limiting factors (see McGuire et al., 1997)
	Heterotrophic Respiration (RH)	Dependent on soil carbon, soil temperature and moisture (Smith et al., 2001). Follows Wania et al. (2009a, b) for peatlands.	Q_{10} of 2 with respect to each soil layer temperature for unfrozen soil layers; linear drop off to 0 RH between 0 and −2 °C	Dependent on surface (<10 cm) soil organic carbon, surface soil temperature and moisture (Kimball et al., 2009)	Dependent on soil organic carbon, soil moisture, soil temperature (see Zhuang et al., 2003)
	Fire	Yes. On upland soils only, not in peatlands.	No	No	Yes
	C:N dynamics	Optimal N allocation to canopy assumed (Haxeltine and Prentice, 1996)	No	No	Yes
Especially Relevant to Arctic Tundra Ecosystems	Non-Vascular Plants (Mosses/Lichens)	Yes, but mosses only represented in peatlands	No	No	Yes in soil thermal dynamics, no in biogeochemical dynamics
	Permafrost	Freeze-thaw processes as described in Wania et al. (2009a, b)	Freeze/thaw processes described in Poutou et al. (2004); permafrost carbon pools described in Koven et al. (2009)	No	Yes, see Zhuang et al. (2001, 2003) and Hayes et al. (2011)
	Lateral Hydrology	No	No	No	No
	Methane	Yes, as described in Wania et al. (2010)	No	No	Yes, see Zhuang et al. (2004, 2007)

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Table 3. Summary of Observationally Based Estimates of Mean Net CO_2-C and CH_4-C Exchange from Arctic Tundra to the Atmosphere ($g\,C\,m^{-2}\,season^{-1}$) for Different Subregions.

Time Period	North America	North Atlantic	Northern Europe	Eurasia
		CO_2 Exchange		
Summer				
1990–1999	−7 (52[1]; −22 to 7[2])	−32 (9; −58 to −5)	−98 (4; −127 to −68)	−25 (18; −50 to −1)
2000–2009	−18 (28; −39 to 3)	−53 (12; −90 to −16)	−92 (5; −220 to 36)	−73 (12; −141 to −4)
1990–2009	−11 (80; −23 to 1)	−44 (21; −66 to −21)	−94 (9; −151 to −38)	−44 (30; −74 to −14)
Winter				
1990–2009	31 (9;15 to 47)	–	41 (3; 11 to 71)	29 (2; −13 to 73)
Annual				
1990–1999	29 (9; 2 to 57)	–	−25 (6; −63 to −14)	–
2000–2009	−3 (14; −28 to 21)	–	−19 (33; −30 to −8)	–
1990–2009	10 (23; −10 to 28)	−68 (4; −213 to 78)	−20 (39; −30 to −10)	−82 (6; −134 to −30)
		CH_4 Exchange		
Summer				
1990–1999	2.4 (10; 0.7 to 4.2)	–	7.8 (13; 1.4 to 14.2)	3.0 (15; −0.4 to 6.5)
2000–2009	1.4 (9; −0.2 to 2.9)	–	12.5 (10; 1.9 to 23.0)	5.1 (29; 1.6 to 8.6)
1990–2009	1.9 (19; 0.8 to 3.0)	3.1 (3; 2.3 to 3.8)	9.9 (23; 4.5 to 15.2)	4.4 (44; 1.9 to 6.9)
Annual				
1990–1999	4.4 (24; 1.4 to 7.4)	–	15.0 (3; −18.3 to 48.3)	–
2000–2009	16.9 (2; −12.0 to 45.7)	–	11.3 (27; 6.6 to 16.0)	8.2 (7, −1.8 to 18.1)
1990–2009	5.4 (26; 1.9 to 8.9)	–	11.7 (30; 7.2 to 16.1)	8.2 (7; −1.8 to 18.1)

[1] Number of site-year estimates, [2] 95 % confidence interval

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Table 4. Summary of Observationally Based Estimates of Mean Net CO_2-C and CH_4-C Exchange from Arctic Tundra to the Atmosphere ($g\,C\,m^{-2}\,season^{-1}$) for Different Tundra Types.

Time Period	Wet Tundra	Dry/Mesic Tundra
CO_2 Exchange		
Summer	−43 (45[1]; −27 to −59[2])	5 (46; −11 to 21)
Winter	31 (3; 1 to 61)	31 (7; 11 to 51)
Annual	−26 (27; −15 to −37)	10 (12; −27 to 47)
CH_4 Exchange		
Summer	9.2 (38; 5.4 to 13.0)	0.8 (25; 0.3 to 1.4)
Annual	14.6 (22; 8.5 to 20.2)	2.3 (24; 0.3 to 4.3)

[1] Number of site-year estimates, [2] 95 % confidence interval

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Table 5. Mean C Budget of Arctic Tundra Simulated by Process Models for 1990–1999.

Model	GPP	NPP	RH	NEP	FIREC	CO2*	BIOCH4	OTHER	NCB
$g\,C\,m^{-2}\,yr^{-1}$									
Regional Apps.									
LPJ-G WHyMe	191	124	102	22	1	−21	4	–	17
Orchidee	577	350	322	28	–	−28	–	–	28
TEM6	261	105	95	10	4	−6	2	2	2
Global Apps.									
CLM4C	101	31	30	1	1	0	–	–	0
CLM4CN	–	–	–	1	–	−1	–	–	1
Hyland	23	11	11	0	–	0	–	–	0
LPJ	464	291	253	38	18	−20	–	–	20
LPJ-Guess	490	306	265	41	20	−21	–	–	21
O-CN	64	28	27	1	–	−1	–	–	1
SDGVM	–	–	–	23	5	−18	–	–	18
TRIFFID	332	208	200	8	–	−8	–	–	−8
$Tg\,C\,yr^{-1}$									
Regional Apps.									
LPJ-G WHyMe	1755	1133	934	199	10	−189	34	–	155
Orchidee	5295	3209	2954	255	–	−255	–	–	255
TEM6	2391	960	875	85	30	−55	15	20	20
Global Apps.									
CLM4C	929	289	275	14	8	−6	–	–	6
CLM4CN	–	–	–	5	–	−5	–	–	5
Hyland	210	105	105	0	–	0	–	–	0
LPJ	4255	2671	2323	348	169	−179	–	–	179
LPJ-Guess	4497	2804	2433	371	183	−188	–	–	188
O-CN	585	256	252	4	–	−4	–	–	4
SDGVM	–	–	–	212	44	−168	–	–	168
TRIFFID	3053	1907	1837	70	–	−70	–	–	70

* Net CO_2-C Exchange, positive sign indicates source to the atmosphere and negative sign indicates tundra sink.

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Table 6. Mean C Budget of Arctic Tundra Simulated by Process Models for 2000–2006.

Model	GPP	NPP	RH	NEP	FIREC	CO2[1]	BIOCH4	OTHER	NCB
$g\,C\,m^{-2}\,yr^{-1}$									
Regional Apps.									
LPJ-G WHyMe	209	135	110	25	1	−24	4	–	20
Orchidee	615	371	337	34	–	−34	–	–	34
TEM6	270	109	98	11	8	−3	2	2	−1
TCF	307	181	183	2	–	–	–	–	–
Global Apps.									
CLM4C	108	34	32	0[2]	1	−1	–	–	1
CLM4CN	–	–	–	1	–	−1	–	–	1
Hyland	27	14	14	0	–	0	–	–	0
LPJ	502	315	274	22[2]	19	−3	–	–	3
LPJ-Guess	562	349	305	44	20	−24	–	–	24
O-CN	74	32	31	3[2]	–	−3	–	–	3
SDGVM	–	–	–	21	5	−16	–	–	16
TRIFFID	361	227	210	17	–	−17	–	–	17
$Tg\,C\,yr^{-1}$									
Regional Apps.									
LPJ-G WHyMe	1918	1239	1009	230	9	−221	37	–	184
Orchidee	5643	3404	3092	312	–	−312	–	–	312
TEM6	2476	1000	899	101	73	−28	18	18	−8
TCF	2817	1661	–	–	–	–	–	–	–
Global Apps.									
CLM4C	994	314	296	18	9	−9	–	–	9
CLM4CN	–	–	–	8	–	−8	–	–	8
Hyland	248	124	123	1	–	−1	–	–	1
LPJ	4608	2887	2518	369	171	−198	–	–	198
LPJ-Guess	5160	3204	2797	407	185	−222	–	–	222
O-CN	682	298	287	11	–	−11	–	–	11
SDGVM	–	–	–	193	47	−146	–	–	146
TRIFFID	3310	2079	1927	152	–	−152	–	–	152

[1] Net CO_2-C Exchange, positive sign indicates source to the atmosphere and negative sign indicates tundra sink.
[2] Reported NEP does not equal reported NPP – reported RH.

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Table 7. Mean C Budget of Arctic Tundra Simulated by Process Models for 1990–2006.

Model	GPP	NPP	RH	NEP	FIREC	CO2[1]	BIOCH4	OTHER	NCB
$g\,C\,m^{-2}\,yr^{-1}$									
Regional Apps.									
LPJ-G WHyMe	200	130	106	24	1	−23	4	–	19
Orchidee	596	361	330	31	–	−31	–	–	31
TEM6	266	107	97	10	6	−4	2	2	0
Global Apps.									
CLM4C	105	32	31	1	1	0	–	–	0
CLM4CN	–	–	–	1	–	−1	–	–	1
Hyland	25	13	13	0	–	0	–	–	0
LPJ	483	303	264	30[2]	19	−11	–	–	11
LPJ-Guess	526	328	285	43	20	−23	–	–	23
O-CN	69	30	29	2[2]	–	−2	–	–	2
SDGVM	–	–	–	22	5	−17	–	–	17
TRIFFID	347	218	205	13	–	−13	–	–	13
$Tg\,C\,yr^{-1}$									
Regional Apps.									
LPJ-G WHyMe	1837	1186	972	214	9	−205	35	–	170
Orchidee	5469	3307	3023	284	–	−284	–	–	284
TEM6	2434	980	887	93	52	−41	16	19	6
Global Apps.									
CLM4C	962	302	286	16	9	−7	–	–	7
CLM4CN	–	–	–	8	–	−8	–	–	8
Hyland	229	115	114	1	–	−1	–	–	1
LPJ	4432	2779	2421	359	170	−189	–	–	189
LPJ-Guess	4829	3004	2615	389	184	−205	–	–	205
O-CN	634	277	270	7	–	−7	–	–	7
SDGVM	–	–	–	203	46	−157	–	–	157
TRIFFID	3182	1993	1882	111	–	−111	–	–	111

[1] Net CO_2-C Exchange, positive sign indicates source to the atmosphere and negative sign indicates tundra sink.
[2] Reported NEP does not equal reported NPP – reported RH.

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Table 8. Inferred climate effect of NPP, RH, and NEP for 1990–2006 as the difference between simulations of the regional applications of process models driven by transient climate and constant climate.

Model	Transient Climate	Constant Climate	Inferred Climate Effect
NPP ($g\,C\,m^{-2}\,yr^{-1}$)			
LPJ-Guess WHyMe	128	101	27
Orchidee	359	326	33
TEM6	106	90	16
RH ($g\,C\,m^{-2}\,yr^{-1}$)			
LPJ-Guess WHyMe	105	86	19
Orchidee	328	291	37
TEM6	96	81	15
NEP ($g\,C\,m^{-2}\,yr^{-1}$)			
LPJ-Guess WHyMe	23	15	8
Orchidee	31	35	–4
TEM6	10	9	1

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Table 9. Mean Annual Net CO_2-C Exchange Estimates of Inversion Models of Arctic Tundra for the time periods 1990–1999 and 2000–2006.

Model	1990–1999 $Tg\,C\,yr^{-1}$	2000–2006 $Tg\,C\,yr^{-1}$	1990–2006 $Tg\,C\,yr^{-1}$	1990–1999 $gC\,m^{-2}\,yr^{-1}$	2000–2006 $g\,C\,m^{-2}\,yr^{-1}$	1990–2006 $g\,C\,m^{-2}\,yr^{-1}$
C13_CCAM_law	–	243		–	26	
C13_MATCH_rayner	–	−283		–	−31	
JENA_s96_v3.3	–	−117		–	−13	
JMA_2010	−321	−341	−331	−35	−37	−36
LSCE_an_v2.1	–	−124		–	−14	
LSCE_var_v1.0	140	206	173	15	22	19
NICAM_niwa_woaia	−178	−80	−129	−19	−9	
rigc_Patra	–	−439		–	−48	−14

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Table 10. Comparison of Estimates of Mean Net CO_2-C and CH_4-C Exchange from Arctic Tundra to the Atmosphere (Tg C yr^{-1}) among Observations, Process-Based Models, and Inversion Models.

Time Period	Observations	Regional Process-Based Models	Global Process-Based Models	Inversion Models
		CO_2 Exchange		
1990–1999				
Central Estimate	138	−166	−78	−13
Uncertainty	−102 to 378	−255 to −55	−188 to 0	−321 to 140
2000-2006*				
Central Estimate	−202	−187	−93	−117
Uncertainty	−628 to 224	−312 to −28	−222 to −1	−439 to 243
1990–2006*				
Central Estimate	−103	−177	−86	−96
Uncertainty	−297 to 89	−284 to −41	−205 to −1	−331 to 173
		CH_4 Exchange		
1990–1999				
Central Estimate	10	25	–	–
Uncertainty	−1 to 22	15 to 34	–	–
2000–2006*				
Central Estimate	20	28	–	–
Uncertainty	−11 to 51	18 to 37	–	–
1990–2006*				
Central Estimate	11	26	–	–
Uncertainty	0 to 22	16 to 35	–	–

* The estimates for the observations reported for the 2000–2006 and the 1990–2006 periods may include information after 2006.

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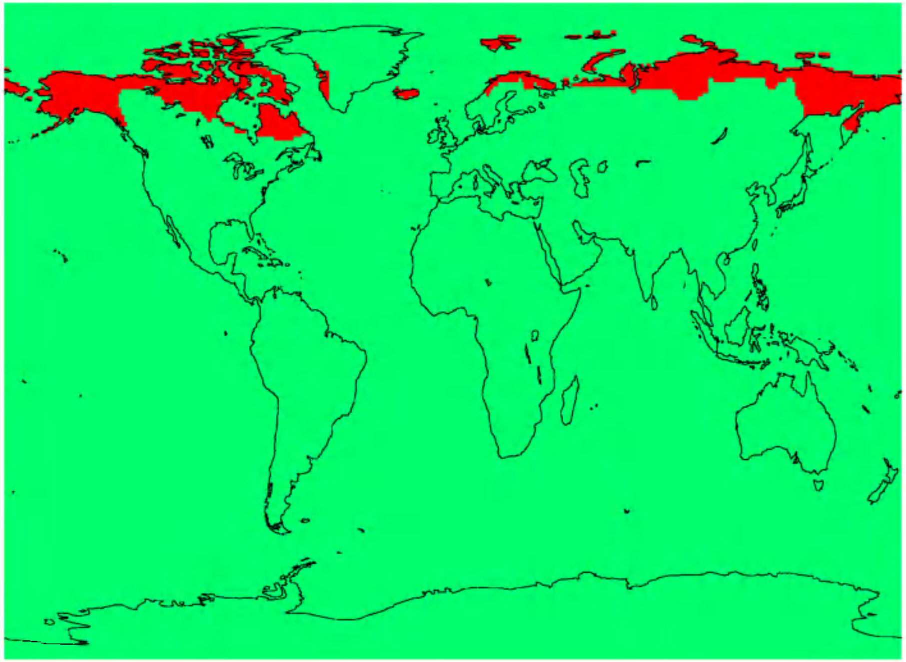

Fig. 1. The Arctic Tundra RECCAP Region.

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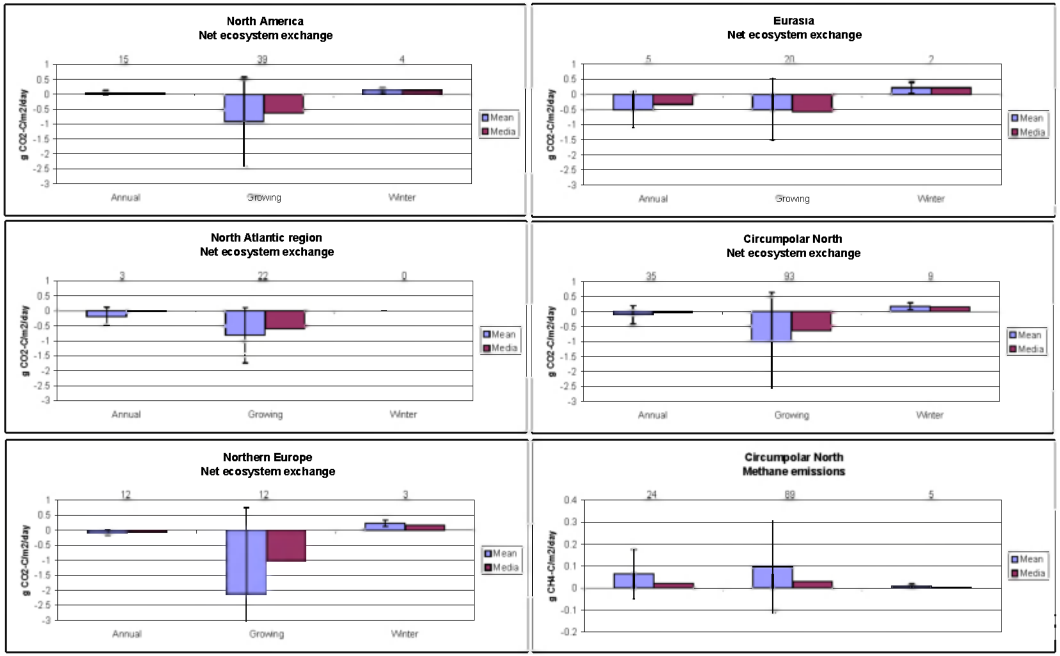

Fig. 2. A summary of the data presented in Appendix A in the Supplement; the summary includes observations prior to 1990. The synthesis of observed NEE for different geographical regions is shown in the first five panels. The mean ($g\,C\,m^{-2}\,day^{-1}$) ± standard deviation and the median are shown for summer, winter, and annual analyses. The number of studies used from Appendix A in the Supplement to estimate each mean/median is shown above the bars. Methane emissions for the circumpolar North are shown in the sixth panel in a similar fashion.

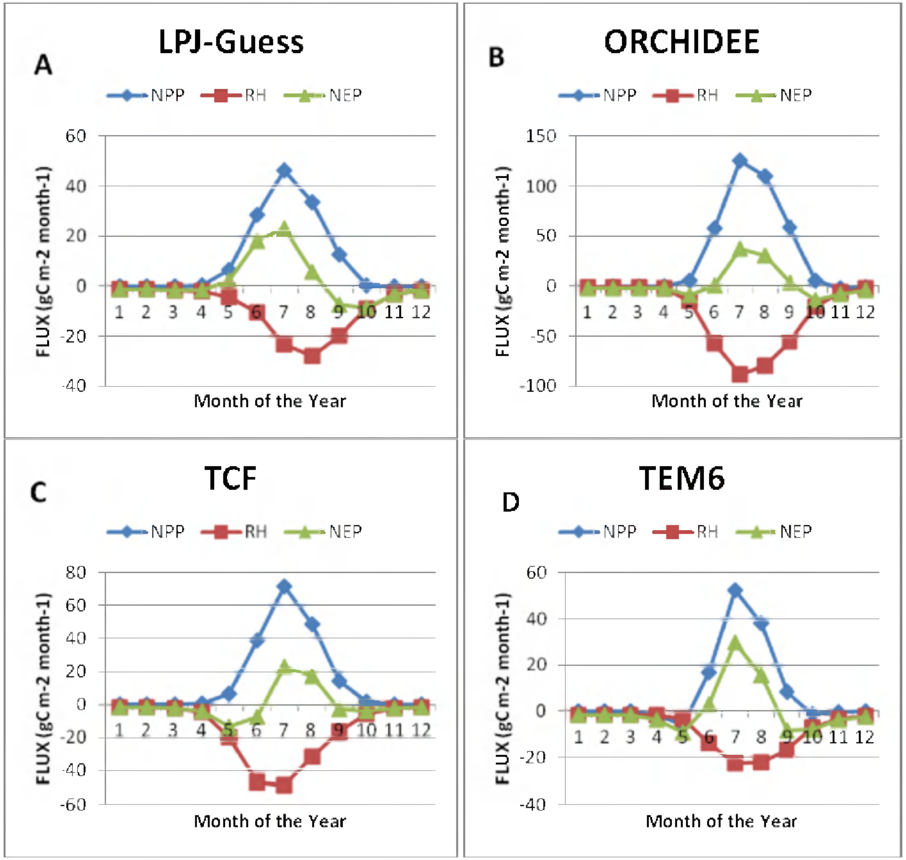

Fig. 3. Mean monthly fluxes of gross primary production (GPP), net primary production (NPP), heterotrophic respiration (RH), and net ecosystem production (NEP) simulated by LPJ-Guess WHyMe (panel **A**), Orchidee (panel **B**), and TEM6 (panel **D**) between 1990 and 2006 and by TCF (panel **C**) between 2000 and 2009.

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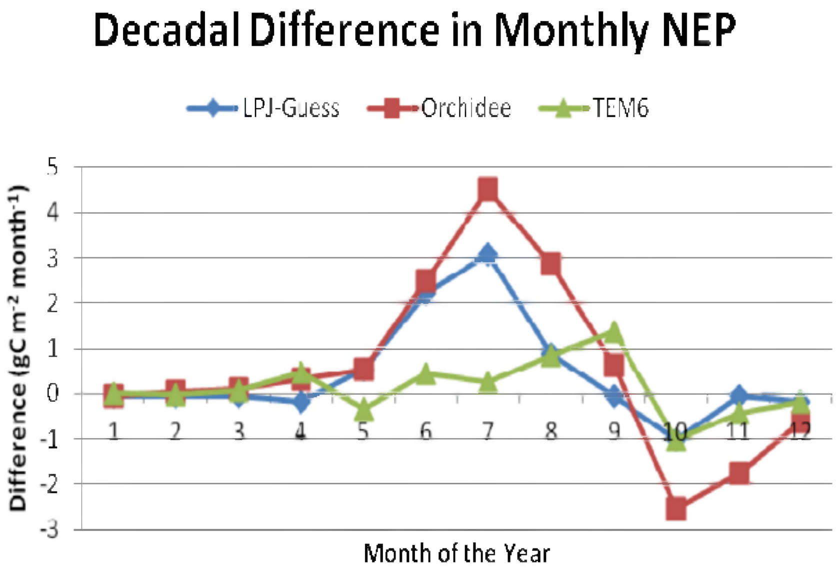

Fig. 4. Difference in mean monthly NEP between the 2000s (2000–2006) and the 1990s (1990–1999) for LPJ-Guess WHyMe, Orchidee, and TEM6.

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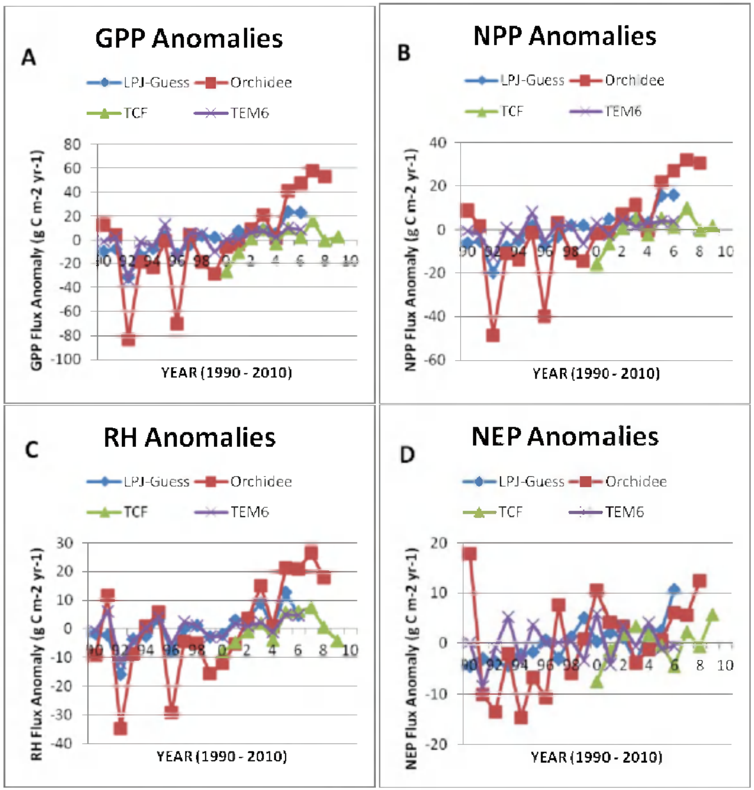

Fig. 5. Comparisons among LPJ-Guess WHyMe, Orchidee, TCF, and TEM of inter-annual variability between 1990 and 2010 for anomalies of gross primary production (GPP, panel **A**), net primary production (NPP, panel **B**), heterotrophic respiration (NPP, panel **C**), and net ecosystem production (NEP, panel **D**).

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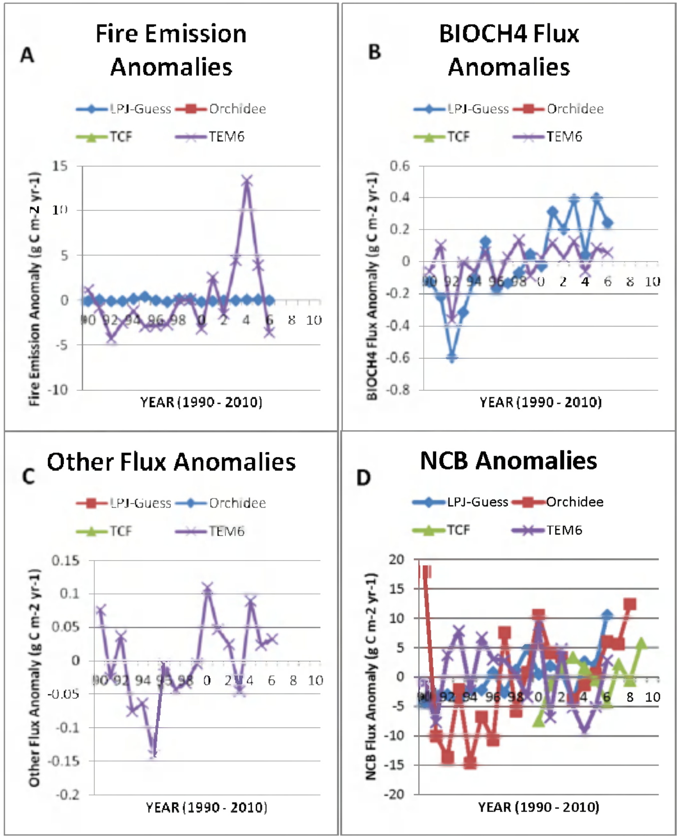

Fig. 6. Comparisons among LPJ-Guess WHyMe, Orchidee, TCF, and TEM of inter-annual variability between 1990 and 2010 for anomalies of fire emissions (panel **A**), biogenic CH_4 emissions (panel **B**), Other fluxes (harvest and DOC exports, panel **C**), and net carbon balance (NCB, panel **D**).

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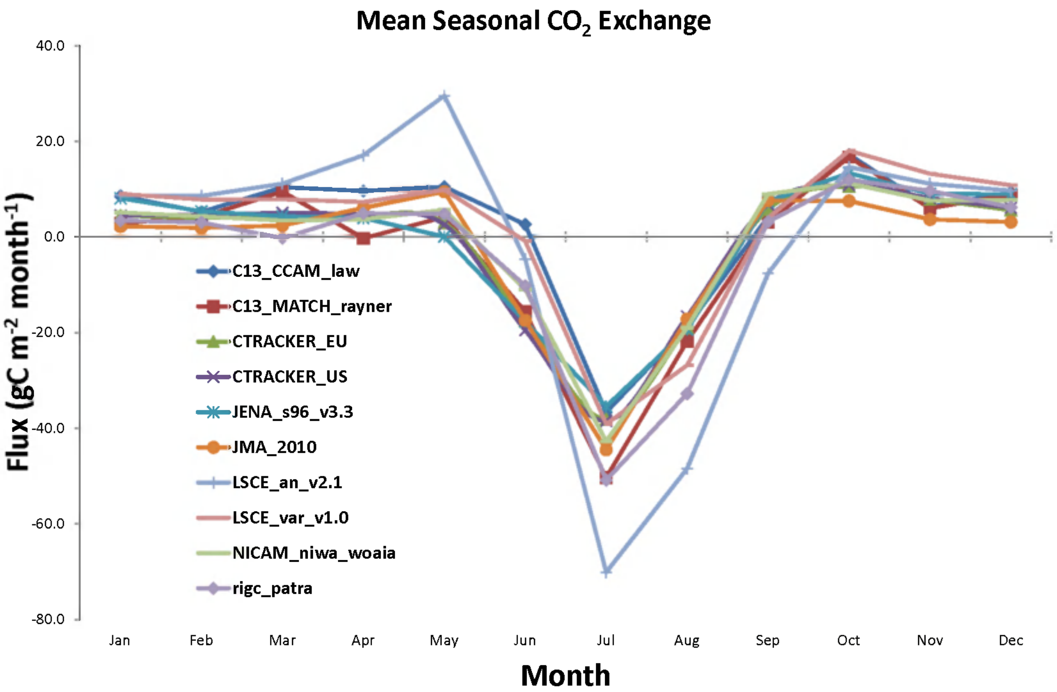

Fig. 7. Comparison among inversion model estimates of the mean net monthly exchange of CO_2 between arctic tundra and the atmosphere.

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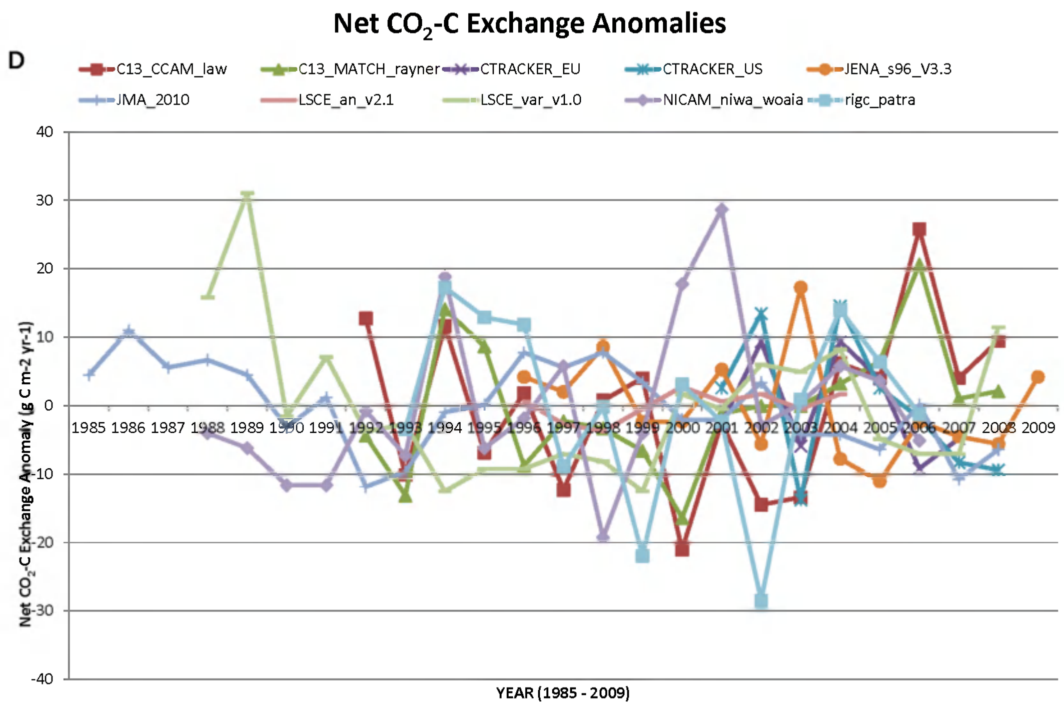

Fig. 8. Comparison among inversion model estimates of the interannual variability between 1985 and 2009 for anomalies of the net annual exchange of CO_2 between arctic tundra and the atmosphere.

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