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Magnitude and seasonality of wetland methane emissions from the Hudson Bay Lowlands (Canada)

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Abstract

The Hudson Bay Lowlands (HBL) is the second largest boreal wetland ecosystem in the world and an important natural source of global atmospheric methane. We quantify the HBL methane emissions by using the GEOS-Chem chemical transport model to simulate aircraft measurements over the HBL from the ARCTAS and pre-HIPPO campaigns in May–July 2008, together with continuous 2004–2008 surface observations at Fraserdale (southern edge of HBL) and Alert (Arctic background). The difference in methane concentrations between Fraserdale and Alert is shown to be a good indicator of HBL emissions, and implies a sharp seasonal onset of emissions in June (consistent with the aircraft data) and seasonal shut-off in September. The model, in which seasonal variation of emission is mainly driven by surface temperature, reproduces well the observations in summer but its seasonal shoulders are too broad. We suggest that this reflects the suppression of emissions by snow cover, and greatly improves the model simulation by accounting for this effect. Our resulting best estimate for HBL methane emissions is 2.3 Tg a^{-1}, several-fold higher than previous estimates.

1 Introduction

Methane is the second most important anthropogenic greenhouse gas after carbon dioxide (IPCC, 2007). Methane concentrations have increased from 700 ppbv in the pre-industrial atmosphere to 1700 ppbv by the early 1990s (Etheridge et al., 1998). This increase is presumably driven by direct emissions from industry and agriculture (IPCC, 2007), but could also reflect changes in the chemical sink (reaction with the OH radical) and the effects of climate change on natural emissions (Worthy et al., 2000). Wetlands are the largest natural source of methane and are highly sensitive to changes in climate (Kaplan et al., 2006), especially in the boreal zone (Zhuang et al., 2006; Sitch et al., 2007). Here we use aircraft observations over the Hudson Bay Lowlands in Northern Ontario as well as surface observations at Fraserdale and Alert to better quantify this boreal wetland source.

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Methane is produced in boreal wetlands by heterotrophic respiration of partially decomposed organic material under anoxic conditions. As it rises to the surface, it may encounter oxic conditions resulting in oxidation. The remaining methane escapes to the atmosphere (Walter et al., 2001). Production of methane primarily depends on soil temperature, and the distribution of anoxic and oxic zones depends primarily on the water table level (Pelletier et al., 2007; Moore et al., 1994). Compounding this complexity in boreal wetland emissions is the seasonal thaw that propagates from the surface to depth (Dunn et al., 2009; Wania et al., 2009).

The Hudson Bay Lowlands (HBL) is an ecologically significant and well-studied boreal wetlands region (e.g., Glooschenko et al., 1994). It is (after the West Siberian wetlands) the second largest semi-continuous wetland region in the world, covering an area of 320 000 km^2 or about 10% of the total area covered by boreal wetlands (Wang et al., 2008; Glooschenko et al., 1994). The ABLE-3B/NOWES airborne and ground campaign conducted in the summer of 1990 estimated an annual methane emission of $0.5 \pm 0.3\,Tg\,a^{-1}$ from the HBL (Roulet et al., 1994). Worthy et al. (2000), using inverse methods to interpret observations from the Alert and Fraserdale Canadian sites, obtained a similar estimate of $0.2–0.5\,Tg\,a^{-1}$. These estimates are low compared to most global inversion studies that infer total boreal wetland emissions of $27–38\,Tg\,a^{-1}$ (Hein et al., 1997; Wang et al., 2004; Bousquet et al., 2006), although Chen & Prinn (2006) obtained an estimate of $7\,Tg\,a^{-1}$. Typically, the HBL is assumed to contribute 10% to global boreal wetland emissions. Walter et al. (2001) used a hydrological model to estimate an even higher global source of $65\,Tg\,a^{-1}$ from boreal wetlands. Finally, in a recent study of the carbon balance in the Arctic, McGuire et al. (2010) estimates annual emissions from the HBL as $4.7\,Tg\,a^{-1}$ using processed-based modeling tools.

The above inconsistencies point to the need for a better understanding of methane emissions from the HBL as a window into the global boreal wetlands source. We exploit here methane concentration measurements from the ARCTAS and Pre-HIPPO aircraft campaigns in May–July 2008 (Fig. 1), together with long-term surface data from Environment Canada at Fraserdale (81.6° W, 49.9° N) and Alert (62.5° W, 82.5° N). We

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interpret these data using a global bottom-up scheme for wetland emissions implemented in the GEOS-Chem chemical transport model (CTM). The ARCTAS airborne campaign based in Cold Lake, Alberta (Jacob et al., 2010) conducted three flights over the HBL in early July, while the Pre-HIPPO campaign based in Boulder, Colorado (Pan et al., 2010) conducted two flights in the region in May–June.

2 Model description

We use the GEOS-Chem CTM originally described by Bey et al. (2001) in a methane simulation for 2004–2008 to interpret both aircraft and surface observations. GEOS-Chem is driven by GEOS-5 analyzed meteorological data from the NASA Global Modeling and Assimilation Office (GMAO). The GEOS-5 data have $1/2^{\circ}\times2/3^{\circ}$ horizontal resolution with 72 vertical levels and 6-h temporal resolution (3-h for surface variables and mixing depths). The horizontal resolution is degraded here to $2^{\circ}\times2.5^{\circ}$ for input to GEOS-Chem for computational reasons. The methane simulation in GEOS-Chem was originally described by Wang et al. (2004) and has been subsequently improved and updated by Drevet and Bey (2010). Major sources include anthropogenic emissions from EDGAR 4.0[1], natural emissions from wetlands as described below, GFED2 biomass burning emissions (Giglio et al., 2006) and termites. Chemical loss of methane is computed using a global 3-D archive of monthly average OH concentrations from a GEOS-Chem simulation of tropospheric chemistry. The mean OH concentration is 10.8×10^5 mol cm^{-3}, which can be compared to the mean value of $11.1\pm1.7\times10^5$ mol cm^{-3} from a global model inter-comparison reported by Shindell et al. (2006). The corresponding tropospheric lifetime of methyl-chloroform against oxidation by OH is 5.3 years, within the range constrained by the methylchloroform observations (Prinn et al., 2005). Additional minor sinks for methane in the model include

[1]Source: European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL). Emission Database for Global Atmospehric Research (EDGAR), release version 4.0. http://edgar.jrc.ec.europa.eu, 2009

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stratospheric oxidation prescribed as a constant decay (Wang et al., 2004) and soil absorption (from EDGAR 4.0).

The wetlands emission scheme in GEOS-Chem applies methane emission factors to respiration rates in tropical and boreal wetlands, following algorithms described by Kaplan et al. (2002), Sitch et al. (2003) and Bergamaschi et al. (2007). The emission flux E (molecules $CH_4\,m^{-2}\,s^{-1}$) for each model grid square is given by:

$$E = W\delta F\beta A e^{\frac{-E_0}{T-T_0}} \sum_{i=1}^{4} \frac{C_i}{\tau_i} \quad (1)$$

where respiration rates are defined by four gridded ($2^\circ \times 2.5^\circ$) carbon pools (C_i, mol C m^{-2}) with fixed residence times (τ_i) from Sitch et al. (2003). The Arrhenius factor with $A=1.0e^{+3}$, $E_0=309$ K and $T_0=-227$ K (Lloyd and Taylor, 1994) specifies the temperature dependence of respiration. The methane emission factor is $\beta=3\times10^{-2}$ mol CH_4/mol C respired (Christensen et al., 1996). An additional scaling factor F is used to match observed ecosystem fluxes of methane, separately for tropical (T) and boreal (B) wetlands:

$$F = \alpha \cdot F_T + (1-\alpha)\cdot F_B \quad (2)$$

where $\alpha = \min\left(\exp\left[\left(\bar{T}-T_1\right)/8\right], 1\right)$ and $\bar{T}$ (K) is the mean monthly soil temperature taken here as the GEOS-5 skin temperature and $T_1=303.15$ K. Scaling factors $F_T=0.14$ and $F_B=0.005$ were derived by J. Kaplan and J. Drevet (personal communication) to match published emission estimates for the Amazon (Melack et al., 2004) and boreal wetlands (Hein et al., 1997; Wang et al., 2004). Finally, W in Eq. (1) represents the maximum potential fraction of wetland coverage for the grid square, as obtained from various databases described by Kaplan et al. (2002) and Bergamaschi et al. (2007). Whether a wetland is actually present ($\delta=1$) or not ($\delta=0$) over that fraction W at any given time depends on the level of the water table, which we diagnose using GEOS-5 soil moisture as a proxy (Bergamaschi et al., 2007). Wetlands are present if the

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soil moisture exceeds a specified threshold of 0.1 for the ratio between the soil water content and the porosity of the soil (J. Kaplan, personal communication, 2009).

Annual emissions for the HBL (geographically defined as 50° N–60° N, 75° W–96° W) computed in the above manner in GEOS-Chem average 2.9 Tg a^{-1} for 2004–2008, with the spatial distribution shown in Fig. 1. This estimate is within the range of global studies but much larger than the previous HBL specific estimates of Roulet et al. (1994) and Worthy et al. (2000).

3 Constraints on HBL methane emissions

We now discuss the consistency of our simulation, and the 2.9 Tg a^{-1} annual emission estimate, with aircraft data from Pre-HIPPO and ARCTAS and surface data from Fraserdale and Alert. The DACOM tunable diode laser instrument used in ARCTAS (Sachse et al., 1987) has an estimated accuracy/precision of 1%/0.1%. The quantum cascade laser instrument used in Pre-HIPPO had an estimated accuracy and precision of 0.25%. The surface measurements at Fraserdale are obtained by gas chromatography on samples collected from a 40-m high tower and have an accuracy/precision of 1%/0.2% (Worthy et al., 2003). Similar specifications apply to the surface measurements at Alert.

Figure 2 shows the ensemble of aircraft vertical profiles over the HBL from 12 May (Pre-HIPPO) to 5 July (ARCTAS). We excluded stratospheric air as diagnosed by a molar O_3/CO ratio exceeding 1.25 (Hudman et al., 2007) and fire plumes as diagnosed by CO exceeding 200 ppbv. The latter filter is needed because ARCTAS targeted fire plumes, which are a minor source of methane; it effectively removes correlation between methane and CO so that the HBL methane enhancements shown in Fig. 2 can be reliably attributed to wetland emissions rather than biomass burning.

The ARCTAS observations on 4–5 July show strong boundary layer enhancements over the HBL. The Pre-HIPPO flight on 12 May shows no boundary layer enhancement while that on 23 June shows a moderate enhancement. Observers on the Pre-HIPPO

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aircraft reported snow cover over the HBL on 12 May but not on 23 June. For comparison with the aircraft we sample the model at the time and location of the flights. We find that the model provides a good simulation of the boundary layer structure for the different flights, the enhancement observed in ARCTAS, and the sharp springtime transition from May to July. However, model overestimation is evident for the 23 June profile.

To further investigate the magnitude and seasonal onset of HBL emissions we used 2004–2008 surface data at Fraserdale and Alert collected by Environment Canada, with Alert serving as an Arctic background site against which the HBL influence at the Fraserdale downwind site can be referenced (Worthy et al., 1998). We only use Fraserdale data associated with surface winds from the northern quadrants, corresponding to the HBL. Figure 3 shows the observed seasonal variations at the two sites for 2004–2008. The observations at Alert show a July minimum due to chemical loss in the Northern Hemisphere. The model minimum lags 1 month behind. The observations at Fraserdale follow the seasonal variation at Alert in winter-spring but deviate in late May toward an August maximum, ostensibly due to emissions from the HBL. The model shows the same seasonal deviation at Fraserdale relative to Alert but shifted one month early. A model sensitivity simulation with no HBL emissions (also shown in Fig. 3) confirms that the deviation is due primarily to HBL emissions. The model minimum lags 1 month behind, an offset that can be attributed to background error in the seasonal variation of sources, transport, or OH concentrations.

Although Fraserdale is at the southern end of the HBL and the data are collected at only 40 m altitude, they appear to be reasonably representative of the HBL. As a test, we partitioned the HBL into northern and southern halves and examined the model sensitivity of Fraserdale to emissions from each half. We found no significant difference. We also found no significant difference in methane concentrations when sampling the model at different altitudes over Fraserdale up to 500 m (five model layers).

Figure 4 shows the seasonal variation of the difference in concentrations between Fraserdale and Alert (ΔCH_4), illustrating more precisely the methane flux signature

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from the HBL. The observed onset of HBL methane emissions in late May is consistent with the aircraft observations discussed previously. From field studies in nearby James Bay peatlands, Pelletier et al. (2007) define a "growing season" conducive to methane emissions as beginning in mid-May.

The model difference between Fraserdale and Alert in Fig. 4 is consistent with observations in terms of the seasonal integral, supporting the model overall magnitude of HBL emissions. HBL influence in the model reaches a maximum in June–August, consistent with observations. We see that the apparent precession of the model maximum at Fraserdale relative to the observations (Fig. 3) is related more to model phase error in the background rather than HBL emissions timing. The model sensitivity simulation with no HBL emissions confirms the relevance of Alert as a background site, since the difference between Fraserdale and Alert in that simulation is relatively small except in September–November.

The main discrepancy between model and observations appears to be in the onset of HBL emissions in spring, which is about 1 month too early in the model (early April versus mid-May). This is not apparent in the model simulation of the Pre-HIPPO flight of 12 May (Fig. 2) because of delayed spring warming in 2008 and the more northerly location of the flight profile relative to the spatial maximum of emissions (Fig. 1). The premature onset in the model likely reflects the use of skin temperature as proxy for soil temperature. Seasonal increases in soil temperature at depth lag behind the land surface during the spring thaw, particularly because prolonged snow cover will insulate the underlying soil that has become frozen during the previous winter. Furthermore, poor drainage in flat lowlands results in a perched (elevated) water table following springtime snowmelt, with complicated implications for methane emissions (Dunn et al., 2009; Roulet et al., 1994).

We attempted to impose in the model a time lag for soil heating by using the standard heat transport parameterization of Campbell and Norman (1998) with thermal diffusivities from Sitch et al. (2003), but the resulting delay in the onset of emissions was insufficient. Instead we identified persistent snow cover in the GEOS-5 data well past

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the onset in model emissions. Consequently, we imposed a snow-cover based time-delay on the model emissions where emissions are only allowed in snow-free regions. Figure 4 shows that this corrects the model bias in the spring. The resulting annual reduction in emissions is 20% (2.3 Tg a^{-1} vs. 2.9 Tg a^{-1}), with contributions from both spring and autumn. In spring, lingering snow cover insulates the underlying soil from warming, inhibiting methanogenesis. Improved model consistency in the autumn indicates that snow cover is associated with the cessation of methane production or with the trapping of methane by the snow layer (Friborg et al., 1997).

The delayed onset does not affect the model comparison to the aircraft profiles in Fig. 2, since as shown in Fig. 4 the change in June–July is negligible. With this snow cover correction, the seasonal consistency of the model ΔCH_4 integral in Fig. 4 is improved, providing confidence in the 2.3 Tg a^{-1} model emission estimate for the HBL. The coincidence between the observed onset in emissions and the disappearance of snow cover implies little time lag following snowmelt for the thawing of the underlying peatlands before methanogenesis ensues. This delay in emissions following snowmelt has been observed in certain field studies (Dunn et al., 2009).

The model temporal variability of methane emissions in the snow-free season is driven largely by surface temperature (Eq. 1), and this appears adequate to match observations. Previous studies of boreal wetlands have pointed out the sensitivity in emissions to changes in the level of the water table (Moore et al., 1994; Pelletier et al., 2007). However, the flat topography of the HBL results in poor drainage and maintains persistent wetland coverage throughout the summer.

Figure 5 shows the seasonal variation of HBL model emissions for 2004–2008. The seasonal onset of emission can vary by a month from year to year, and this offset then persists until mid-summer. There is much less year-to-year variability in the fall shutdown of emissions. The annual emission is 2.3±0.3 Tg a^{-1}.

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4 Comparison to ABLE-3B/NOWES estimates

The ABLE-3B/NOWES surface and aircraft field study in July 1990 previously reported an annual emission estimate of 0.5±0.2 Tg a^{-1} for the HBL (Harris et al., 1994; Roulet et al., 1994). This is considerably less than our GEOS-Chem estimate of 2.3 Tg a^{-1}, and would be inconsistent with the Pre-HIPPO and ARCTAS data of Fig. 2 as well as the Fraserdale ΔCH_4 data of Fig. 4. The ABLE-3B/NOWES estimate was obtained by extrapolation of direct flux measurements at surface sites, using wetland coverage derived from satellite and aerial imagery. The surface sites and supporting aircraft eddy correlation flux measurements were located in two small study areas in the southern and northern edges of the HBL (Fig. 1). The aircraft estimates were ~5 g m^{-2} a^{-1} for July, similar between the two regions and consistent with chamber flux measurements from the southern region (Roulet et al., 1994). GEOS-Chem emissions are in fact consistent at 5–10 g m^{-2} a^{-1} for these two regions in July (Fig. 1). However, we see from Fig. 1 that the ABLE-3B/NOWES study regions are not in the areas of maximum model emissions, centered in the mid-section of the HBL. The boundary layer methane enhancements observed from the ABLE-3B aircraft (~30 ppbv) were also lower than the mean value of 60 ppbv observed on the ARCTAS flights (Fig. 2).

5 Conclusions

Aircraft observations over the Hudson Bay Lowlands (HBL) in May–July 2008 show a seasonal onset of methane emissions in June and 60 ppbv enhancements in the boundary layer in July. Surface observations at Fraserdale (just south of the HBL) for 2004–2008 show the same seasonal variation when referenced against a background Arctic site (Alert) to isolate the HBL contribution. The GEOS-Chem model including a standard emission scheme for boreal wetlands can successfully reproduce these observations except for a premature springtime onset. Seasonal variation of wetland emission in the model is mainly driven by surface temperature. We find that accounting

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in addition for suppression of emissions by snow cover corrects the seasonal onset in spring and also better simulates the seasonal shut-off in fall. Our resulting best estimate of HBL methane emissions is 2.3 Tg a^{-1}, much higher than previous estimates for the region. We argue that this reflects spatial gradients of methane emission within the HBL that were not previously accounted for.

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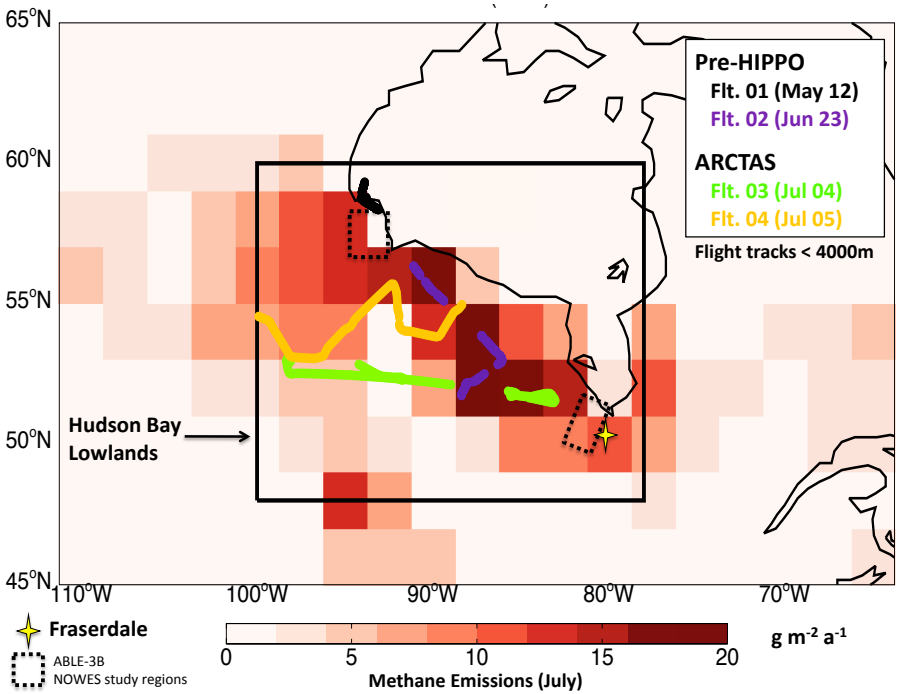

Fig. 1. ARCTAS and Pre-HIPPO flight tracks over the Hudson Bay Lowlands (HBL) below 4 km, superimposed on a map of GEOS-Chem methane emissions for July 2008. The locations of Fraserdale and of the ABLE-3B/NOWES study regions are also shown. The black rectangle encompasses the HBL region as defined in the present study.

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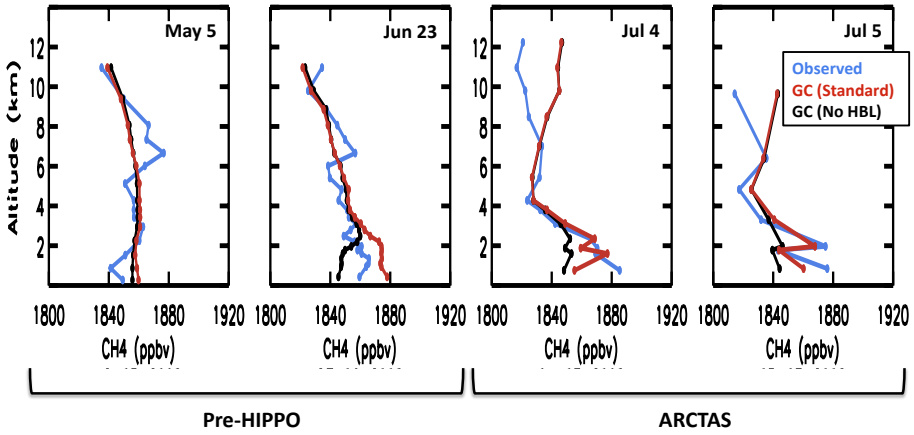

Fig. 2. Methane vertical profiles from Pre-HIPPO and ARCRAS over the HBL (May–July 2008). Observations (blue) are compared to GEOS-Chem (GC) model vertical profiles sampled along the flight tracks at the flight times. The standard simulation (red) and a sensitivity simulation with no HBL emissions (black) are presented.

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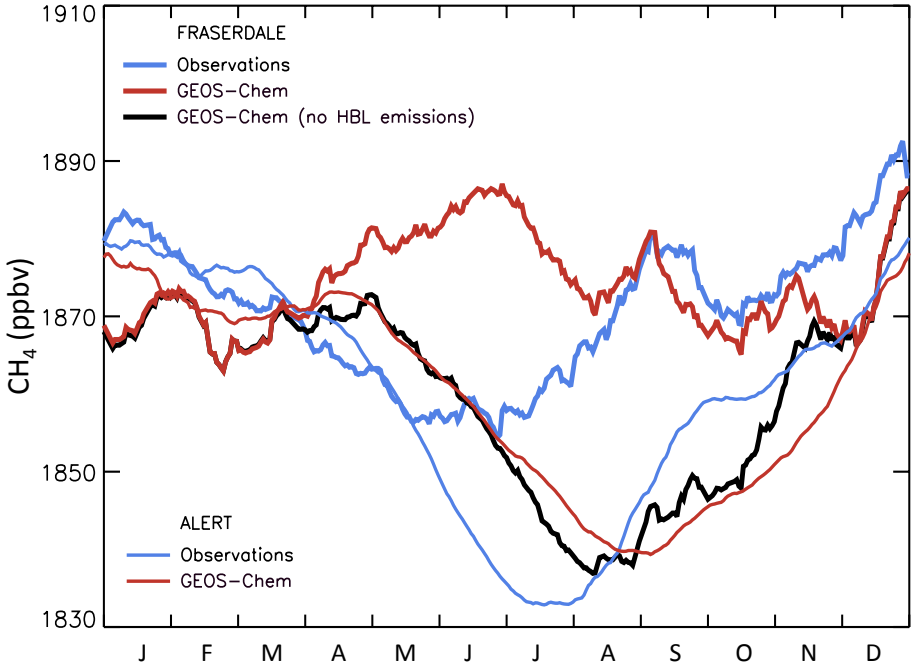

Fig. 3. Seasonal variation (2004–2008) of methane at Fraserdale and Alert. GEOS-Chem results are compared to observations. Also plotted is the model background concentration at Fraserdale as derived from a simulation with no HBL emissions. Data are daytime selected, smoothed with a 28-day moving average and then averaged over 5 years.

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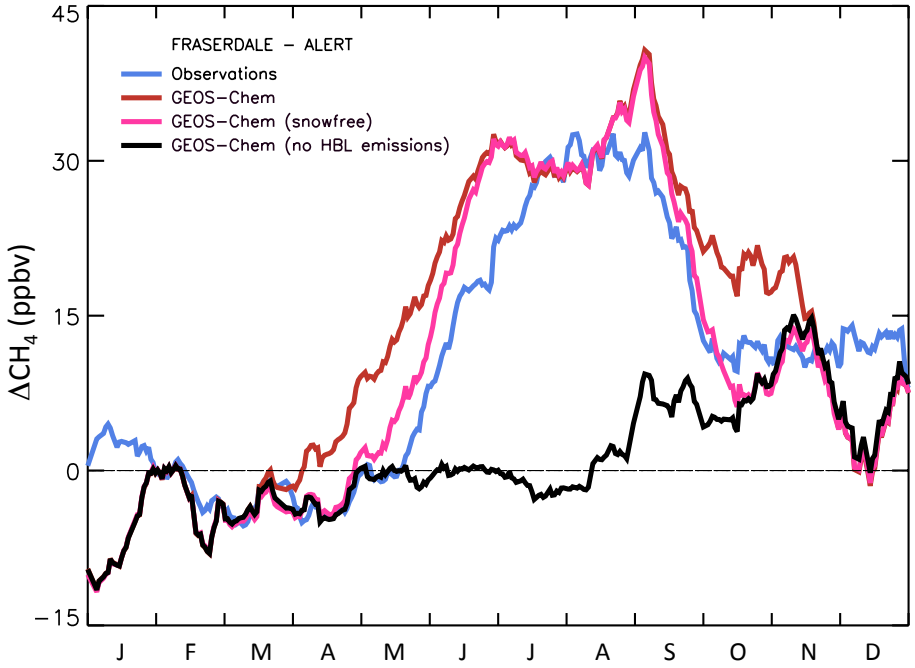

Fig. 4. Mean seasonal differences in CH_4 concentration between Fraserdale and Alert (ΔCH_4) for 2004–2008. Observations (blue) are compared to the standard GEOS-Chem simulation, a sensitivity simulation restricting emissions to snow-free ground, and a sensitivity simulation with no HBL emissions.

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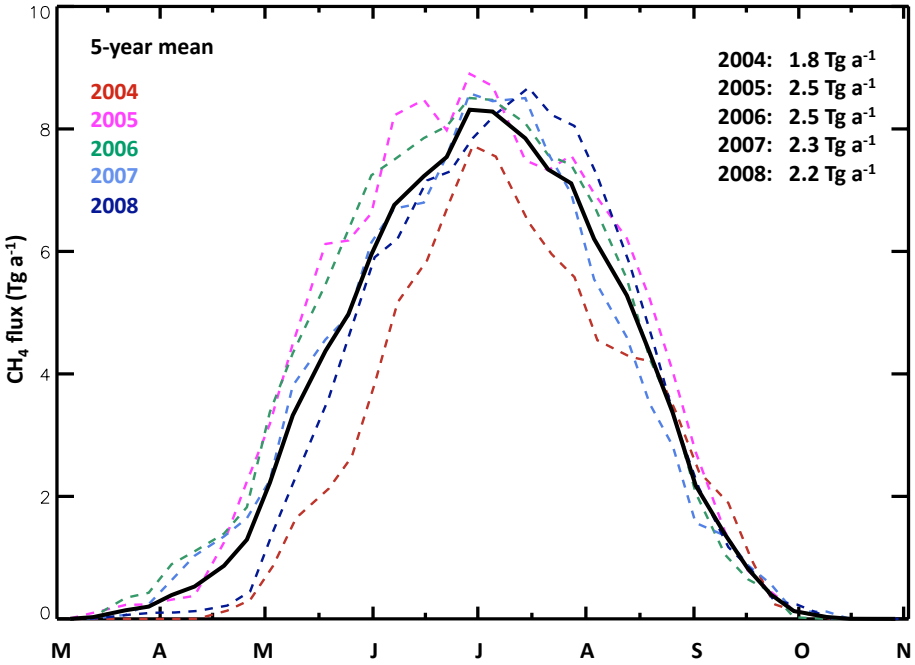

Fig. 5. Seasonal variation of HBL methane emissions simulated by the model for 2004–2008. Values are integrated spatially over the HBL domain (50° N–60° N, 75° W–96° W) and smoothed temporally with a 4-week moving average. Also tabulated are annual emission estimates for individual years.

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