Large methane emission upon spring thaw from natural wetlands in the northern permafrost region

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Abstract

The permafrost carbon–climate feedback is one of the major mechanisms in controlling the climate–ecosystem interactions in northern high latitudes. Of this feedback, methane (CH4) emission from natural wetlands is critically important due to its high warming potential. The freeze–thaw transition has been confirmed to play an important role in annual CH4 budget, yet the magnitude of this effect is uncertain. An intensive field campaign was carried out in the Sanjiang Plain, Northeast China to estimate the CH4 emission in the spring freeze–thaw transition period. The observation concluded that a large CH4 source was caused by spring thaw; the maximum hourly emission rate was 48.6 g C m⁻² h⁻¹, more than three orders of the regularly observed CH4 emission rate in the growing season. In some sporadically observed ‘hot spots’, the spring thawing effect contributed to a large CH4 source of 31.3 ± 10.1 g C m⁻², which is approximately 80% of the previously calculated annual CH4 emission in the same study area. If our results are typical for natural wetlands in the Northern Hemisphere permafrost region, we estimate a global CH4 source strength of 0.5–1.0 Tg C (1 Tg = 10¹² g) caused by spring thaw in the Northern Hemisphere permafrost region in the year 2011. Combining with available satellite and flask data, a regional extrapolation reaches a temporal pattern of CH4 emission during 2003–2009 which is consistent with recently observed changes in atmospheric CH4 concentration in the high latitudes. This suggests that the CH4 emission upon spring thaw in the high latitudes might be enhanced by the projected climate warming. These findings indicate that the spring thawing effect is an important mechanism in the permafrost carbon–climate feedback and needs to be incorporated in Earth system models.

Keywords: carbon-climate feedback, methane, natural wetland, permafrost

Online supplementary data available from stacks.iop.org/ERL/7/034009/mmedia

1. Introduction

As one of the potent greenhouse gases, methane (CH4) plays an important role in terrestrial ecosystem–climate interaction (Bousquet et al 2006, Keppler et al 2006, Mastepanov et al...
2008), especially under the changing global environment (Isaksen et al 2011, Walter et al 2006, Xu and Tian 2012, Xu et al 2010). The recently observed increase in atmospheric CH$_4$ concentration has drawn a large amount of attention to CH$_4$ emission from natural wetlands in northern high latitudes (Dlugokencky et al 2009). The northern permafrost region is essential in global CH$_4$ cycling, especially over the trajectory of global warming (Christensen et al 2004), because the dense carbon storage in permafrost soils is a potential source of atmospheric CH$_4$ (Christensen et al 2004, Koven et al 2011, Schuur et al 2009), and is predicted to release more and more CH$_4$ to the atmosphere by 2100 (Anisimov 2007, Koven et al 2011), even though the winter season had been previously thought to be a period with a weak CH$_4$ emission before a number of field studies confirmed that the biological processes in winter directly make relatively large contributions to the annual CH$_4$ budget (Campbell et al 2005, Hao et al 2006).

Given the isolation of the frozen surface in the permafrost region, a large portion of the produced CH$_4$ cannot be released to the atmosphere immediately (Tokida et al 2007). During the thawing season in the following year, the release of CH$_4$ is expected to occur in a very short period, forming an emission outburst (Christensen et al 2004). This effect is defined as the spring thawing effect, which might partially contribute to the recently observed increase in atmospheric CH$_4$ concentration (Dlugokencky et al 2009, Tokida et al 2007). Although the spring thawing effect on atmospheric CH$_4$ has been recognized for a long time (Friborg et al 1997), the magnitude of the spring thawing effect on CH$_4$ emission remains far from certain (Friborg et al 1997, Tokida et al 2007). This study was conducted to estimate the effects of the spring thaw on CH$_4$ release from natural wetlands in the permafrost region in the Northern Hemisphere by using a combination of field observations, satellite data and flask data.

2. Data and methods

A combination of field observations, NOAA (National Oceanic and Atmospheric Administration) flask data (GLOBALVIEW-CH$_4$), and a satellite-derived CH$_4$ concentration dataset (SCIAMACHY: Scanning Imaging Absorption Spectrometer for Atmospheric Chartography) were used in this study.

2.1. Field observations

We conducted an intensive field campaign in the Sanjiang Plain, Northeast China to monitor seasonal variations in CH$_4$ emission from natural wetlands and estimate the CH$_4$ emission rate caused by spring thaw at site level (figures 1, 2 and S3 available at stacks.iop.org/ERL/7/034009/mmedia). The Sanjiang Plain is in the largest freshwater wetland area
in China; there are approximately 10,400 km$^2$ of natural wetlands in this region (Song et al. 2009). The study sites are located at the Sanjiang Experimental Station of Wetland Ecology, Chinese Academy of Sciences (47°35′N, 133°31′E) at an altitude representative of the natural freshwater wetland in the Sanjiang Plain (56 m a.s.l.). This region is located at the southern boundary of Northern Hemisphere permafrost (Qiu et al. 2002). Since the CH$_4$ emission pulses usually occur in a very short time period (Tokida et al. 2007), our previous observations had not captured this event. In the year 2011, we increased the observational frequency and broadened the monitoring area. Fortunately, the CH$_4$ emission pulses were captured (figures 1 and 2, table 1). The observed CH$_4$ emission pulse can be viewed in our online supporting video clip (video S1 available at stacks.iop.org/ERL/7/034009/mmedia).

Across our sampling area, twenty sites with high CH$_4$ emission pulses were identified (figure 1), of which thirteen were measured at least once by using a static chamber method (Song et al. 2009). We used 5–7 persons walking through the area to identify the potential bubbling spots; after each bubbling spot was identified, we measured the flux rate if labor resources allowed. Measurements for several spots were missed due to shortage of labor; we recorded the locations of these spots. Twenty-three measurements were conducted for CH$_4$ emission pulses (table 1). There are fourteen high emission plots in a 30 m × 30 m study area; the measurements define CH$_4$ emission from a 0.5 m × 0.5 m plot (figure 1 and table 1). So we estimated that approximately 0.39% of the area had high CH$_4$ pulses. This fractional coverage of high CH$_4$ emission was then used to estimate the spring thawing effects on CH$_4$ emission at regional scale.

The gas flux measurements were conducted by using static dark chamber and gas chromatography techniques (Song et al. 2009). The 0.5 m × 0.5 m × 0.5 m chamber was put on the ground which was covered by 5–10 cm surface water as sealer. A fan was installed in the sampling chamber to keep the air mixed during the gas sampling. Since the emission rate was quite large, the gas sampling process was carried out four times with a 5 min interval, rather than with a 10 min interval as in previous studies (Song et al. 2009, Xu et al. 2005). The gas samples were stored in syringes for less than 12 h before being measured. Gas chromatography was used to measure the gas concentrations. The gradient of gas concentration during sampling was used to calculate the gas flux between the ecosystem and the atmosphere. Positive values mean flux from the ecosystem to the atmosphere, and negative values mean flux from the atmosphere to the ecosystem (Song et al. 2009). The mixing ratios of CH$_4$ were analyzed with a modified gas chromatograph (Agilent 4890D) equipped with a flame ionization detector (FID). N$_2$ was used as the carrier gas with a flow rate of 30 ml min$^{-1}$. The CH$_4$ was separated with a 2 m stainless-steel 13 XMS column (60/80 mesh) with an inner diameter of 2 mm. CH$_4$ was directly measured by FID with an operation temperature of 200°C. The temperature for gas separation was 55°C. Fluxes were determined from the slope of the mixing ratio changes in four samples taken at 0, 5, 10 and 15 min after chamber closure. Sample sets were rejected unless they yielded a linear regression value of $r^2$ greater than 0.9.

The gas flux was calculated according to the following equation from Song et al. (2009):

\[ F = \frac{d c}{d t} \frac{M}{V_0} \frac{P_0}{T} \frac{H_c}{T} \]  

(1)

Here, $F$ is the CH$_4$ flux (mg C m$^{-2}$ h$^{-1}$). $d c/dt$ is the slope of the linear regression for the gas concentration gradient with time (mol mol$^{-1}$ h$^{-1}$). $M$ is the molecular mass of each gas (mg mol$^{-1}$). $P$ is the atmospheric pressure (Pa). $T$ is the absolute temperature during sampling (K). $V_0$, $T_0$, and $P_0$ are

| Date   | Site | Observed flux (mg CH$_4$−C m$^{-2}$ h$^{-1}$) | Duration (h) | Observed flux (mg CH$_4$−C m$^{-2}$ h$^{-1}$) | Duration (h) | Observed flux (mg CH$_4$−C m$^{-2}$ h$^{-1}$) | Duration (h) | Observed flux (mg CH$_4$−C m$^{-2}$ h$^{-1}$) | Duration (h) | Observed flux (mg CH$_4$−C m$^{-2}$ h$^{-1}$) | Duration (h) |
|--------|-----|---------------------------------------------|-------------|---------------------------------------------|-------------|---------------------------------------------|-------------|---------------------------------------------|-------------|---------------------------------------------|-------------|
| 4/6/2011 | H1-1 | 193.7                                       | 2           | H1-2                                        | 2           | H2                                          | 2           | H3                                          | 2           | H4                                          | 2           |
|        |     |                                             |             |                                             |             |                                             |             |                                             |             |                                             |             |
| 4/7/2011 | H9   | 345.0                                       | 1.5         | H10-1                                       | 1.5         | H10-2                                       | 1.5         | H10-3                                       | 1.5         | H12                                         | 1.5         |
|        |     |                                             |             |                                             |             |                                             |             |                                             |             |                                             |             |
| 4/8/2011 | H9-2 | 42.2                                        | 24          | H16-1                                       | 24          | H16-2                                       | 24          | H16-3                                       | 24          | H17                                         | 24          |
|        |     |                                             |             |                                             |             |                                             |             |                                             |             |                                             |             |
| 4/9/2011 | H19-1| 96.8                                        | 1           | H19-2                                       | 1           |                                             |             |                                             |             |                                             |             |
|        |     |                                             |             |                                             |             |                                             |             |                                             |             |                                             |             |
| 4/10/2011 | H19-3| 133.7                                       | 1           | H19-4                                       | 1           |                                             |             |                                             |             |                                             |             |
|        |     |                                             |             |                                             |             |                                             |             |                                             |             |                                             |             |
| 4/11/2011 | H19-5| 32.2                                        | 1           |                                             |             |                                             |             |                                             |             |                                             |             |
the gas mole volume (m³ mol⁻¹), absolute air temperature (K), and atmospheric pressure under standard conditions (Pa), respectively. \( H_e \) is the height of the chamber during sampling (m).

2.2. Satellite and flask data

The satellite data (available at [http://www.sciamachy.org/](http://www.sciamachy.org/)) were used to estimate the potential area with high CH₄ emission caused by spring thawing effects. Combining the estimate of high CH₄ emission area with the CH₄ emission rate derived from field observational data, we provided a large-scale estimation of the spring thawing effects on CH₄ emission from natural wetlands in the northern permafrost region. Flask data provided by NOAA were used to verify the increase in atmospheric CH₄ concentration over the study area and to compare with the regional estimate of the CH₄ emission from natural wetlands in the northern permafrost region. The GLOBALVIEW-CH₄ Cooperative Atmospheric Data Integration Project methane, available at [ftp://ftp.cmdl.noaa.gov/ccg/ch4/GLOBALVIEW/](ftp://ftp.cmdl.noaa.gov/ccg/ch4/GLOBALVIEW/), was used in this study with the last access on 16 June 2011. GLOBALVIEW-CH₄ is a product of the Cooperative Atmospheric Data Integration Project. While the project is coordinated and maintained by the Carbon Cycle Greenhouse Gases Group of the National Oceanic and Atmospheric Administration, Earth System Research Laboratory (NOAA ESRL), it is a cooperative effort among the many organizations and institutions making high-quality atmospheric CH₄ measurements. In this study, three sites located in the northern permafrost region were selected (table S1 available at [stacks.iop.org/ERL/7/034009/mmedia](http://stacks.iop.org/ERL/7/034009/mmedia)); the annual CH₄ concentrations measured at the three sites are shown in figure S4 (available at [stacks.iop.org/ERL/7/034009/mmedia](http://stacks.iop.org/ERL/7/034009/mmedia)).

2.3. Auxiliary data

The regional permafrost data were from the National Snow and Ice Data Center at [http://nsidc.org/data/ggd318.html](http://nsidc.org/data/ggd318.html). The circumpolar permafrost and ground ice data depict the distribution and properties of permafrost and ground ice in the Northern Hemisphere (20°N–90°N). The data set classifies permafrost into four categories: continuous, discontinuous, sporadic, and isolated. The fractions of permafrost in each category are 90–100%, 50–90%, 10–50%, <10%. The relative abundance of ground ice in the upper 20 m is estimated in per cent volume (>20%, 10–20%, <10% and 0%) (Brown et al 1998). The data set also contains the location of subsea and relict permafrost. The fractional distribution of natural wetlands was retrieved from and improved on the basis of the data from Aselmann and Crutzen (1989). Finally, we generated the natural wetlands distribution in the northern permafrost region by overlaying them in the same spatial domain (figures S1 and S2 available at [stacks.iop.org/ERL/7/034009/mmedia](http://stacks.iop.org/ERL/7/034009/mmedia)).

2.4. Spatial extrapolation of spring thaw-induced CH₄ emission

We processed the SCIAMACHY (satellite-derived methane concentration in air volume) data to define the grids which have potential high CH₄ emission (Bergamaschi et al 2009, Frankenberg et al 2011, Schneising et al 2011) (figure S6 available at [stacks.iop.org/ERL/7/034009/mmedia](http://stacks.iop.org/ERL/7/034009/mmedia)). Due to technical problems, there are a lot of spatial gaps in the CH₄ concentration derived from the SCIAMACHY data (figure S6 available at [stacks.iop.org/ERL/7/034009/mmedia](http://stacks.iop.org/ERL/7/034009/mmedia)), especially in the period of 2005–9 (Bergamaschi et al 2007, 2009, Frankenberg et al 2011, Schneising et al 2011). The percentage of the area with high CH₄ emission was calculated (figure S8 available at [stacks.iop.org/ERL/7/034009/mmedia](http://stacks.iop.org/ERL/7/034009/mmedia)). Then we combined the estimated percentage area of the ‘hot spots’ of CH₄ emission with the spatial distribution of the natural wetlands across the northern permafrost region to estimate the spring thawing effect on atmospheric CH₄ concentration. The criteria we used to identify potential high CH₄ pulses based on satellite were: (1) the CH₄ concentration in April is 10 ppb higher than that in May; (2) the estimated CH₄ concentration in April is higher than those in any other months (non-April) at the significance level of \( P = 0.05\). The value of 100 ppb was used because the uncertainties of the CH₄ concentration retrieved from the SCIAMACHY data were approximately 50 ppb (Frankenberg et al 2011, Schneising et al 2011), so the threshold of sufficient difference should be approximately 100 ppb on the basis of normal distribution. Based on the delineation of the spatial coverage of the area with potential high CH₄ emission, we further calculated the contribution of the spring thawing effect to the variations of atmospheric CH₄ concentration (table S2 available at [stacks.iop.org/ERL/7/034009/mmedia](http://stacks.iop.org/ERL/7/034009/mmedia)).

2.5. Satellite data in capturing spring thaw-induced CH₄ emission

To evaluate the satellite data in capturing the spring thaw effects on CH₄ emission, we analyzed the basin-level CH₄ concentration derived from satellite data (figure S5 available at [stacks.iop.org/ERL/7/034009/mmedia](http://stacks.iop.org/ERL/7/034009/mmedia)). The higher April CH₄ concentration was observed for a few years in Ob River basin, Lena River basin, Amur River basin and Mackenzie River basin (figure S7 available at [stacks.iop.org/ERL/7/034009/mmedia](http://stacks.iop.org/ERL/7/034009/mmedia)). We used the \( \Delta \text{CH}_4 \) (CH₄ concentration in April minus that in May) to quantify the magnitude of spring thaw effects on CH₄ emission. After 2006, a strong impact is shown as the \( \Delta \text{CH}_4 \) became larger and larger in Ob River basin, Amur River basin and Mackenzie River basin (figure S7 available at [stacks.iop.org/ERL/7/034009/mmedia](http://stacks.iop.org/ERL/7/034009/mmedia)).

3. Results and discussion

3.1. Observed high CH₄ emission pulses

The field observations showed that the CH₄ emission pulses occurred sporadically in some ‘hot spots’; the hourly emission
the spring thaw along the soil profile. This mechanism for
emission pulses are expected. To estimate the spring thawing effect on
CH4 emission, we used the following calculation to quantify
the spring thawing effect on CH4 emission:

\[ F_g = (1 - \text{Oxid}_g)q_0H_gQ_{10}T_g^{10} \]

\[ F_w = (1 - \text{Oxid}_w)q_0H_{ow}Q_{10}T_w^{10} \]

\[ F_{og} = \frac{F_g}{D_g} \]

\[ F_{ow} = \frac{F_w}{D_w} \]

\[ F_{STe} = \frac{F_{ow}}{F_{og}} \]

where \( F_g \) is the total CH4 emission in the growing season, and Oxid is the fraction of produced CH4 being oxidized in the growing season, \( q_0 \) is the potential CH4 production rate at 0°C, \( H \) is the depth of the soil profile for CH4 production, \( Q_{10} \) is the temperature sensitivity of CH4 production, \( T_g \) is the average temperature in the soil profile during the growing season, \( F_w \) is the total CH4 emission in the winter season, and Oxid is the fraction of produced CH4 being oxidized in the winter season, \( L_w \) is the duration of CH4 production in the winter season, \( H_{ow} \) is the observed CH4 emission rate and duration of the CH4 release in the growing season, \( F_{ow} \) and \( D_w \) are the observed CH4 emission rate and duration of the CH4 release in the winter season, and \( F_{STe} \), dimensionless, is the magnitude of spring effects on CH4 emission. The values for all parameter are provided in table 2.

3.2. Quantification of the spring thawing effect on CH4 emission

For the reasons mentioned in section 3.1, high CH4 emission pulses are expected. To estimate the spring thawing effect on CH4 emission, we used the following calculation to quantify the spring thawing effect on CH4 emission:

\[ F_g = (1 - \text{Oxid}_g)q_0H_gQ_{10}T_g^{10} \]

\[ F_w = (1 - \text{Oxid}_w)q_0H_{ow}Q_{10}T_w^{10} \]

\[ F_{og} = \frac{F_g}{D_g} \]

\[ F_{ow} = \frac{F_w}{D_w} \]

\[ F_{STe} = \frac{F_{ow}}{F_{og}} \]

where \( F_g \) is the total CH4 emission in the growing season, and Oxid is the fraction of produced CH4 being oxidized in the growing season, \( q_0 \) is the potential CH4 production rate at 0°C, \( H \) is the depth of the soil profile for CH4 production, \( Q_{10} \) is the temperature sensitivity of CH4 production, \( T_g \) is the average temperature in the soil profile during the growing season, \( F_w \) is the total CH4 emission in the winter season, and Oxid is the fraction of produced CH4 being oxidized in the winter season, \( L_w \) is the duration of CH4 production in the winter season, \( H_{ow} \) is the observed CH4 emission rate and duration of the CH4 release in the growing season, \( F_{ow} \) and \( D_w \) are the observed CH4 emission rate and duration of the CH4 release in the winter season, and \( F_{STe} \), dimensionless, is the magnitude of spring effects on CH4 emission. The values for all parameter are provided in table 2.
It is reported that oxidation could consume up to 90% of produced CH\(_4\) in the soil before releasing it to the atmosphere (Oremland and Culbertson 1992). A field study in a continuously flooded rice paddy system concluded on a 70% oxidation of produced CH\(_4\) (Mer and Roger 2001), and a study on wetland found a 72% oxidation of produced CH\(_4\) (Freeman et al 2002). Thus, we used 70% as the fraction of CH\(_4\) oxidation in soils in the growing season. It is reported that the oxidation of produced CH\(_4\) in soil is highly dependent on oxygen (King 1990). Meanwhile, a field study reported winter oxidation as approximately 5%–15% of that which occurs in summer (Chanton and Liptay 2000), therefore we used 10% as the fraction of CH\(_4\) oxidation in soil/water in the winter season (table 2), and two hours as the normal duration of CH\(_4\) emission during the thawing period (table 1). The temperature sensitivity dependence of CH\(_4\) production was set as \(Q_{10} = 2.5\) as reported in our previous study (Song et al 2009). The growing season at the Sanjiang Plain lasts from 1 May to 30 September, and the winter season, the frozen season referred in this study, lasts from 1 December to 31 March the following year. Thus the length of the winter season is 121 days. \(F_{STE}\) represents the relative magnitude of hourly CH\(_4\) emission rate during the spring thaw compared to that in the growing season. The calculation suggests the spring thawing effect could be as high as 167–1002 times. The CH\(_4\) emission rate during spring thawing could be more than three orders of the growing season CH\(_4\) emission at its peak. This is consistent with our field observations (table 1).

### 3.3. Spatial extrapolation of spring thaw-induced CH\(_4\) emission

Combining these site observations with other data, we further estimated the spring thawing effects on CH\(_4\) emission from the natural wetlands across the entire northern permafrost region by using two methods (figures S1 and S2 available at stacks.iop.org/ERL/7/034009/mmedia). Firstly, based on the areal representativeness of each observed CH\(_4\) pulse in the field campaign, we estimate that approximately 0.39% of the natural wetland served as outlets for the stored CH\(_4\) in spring across the monitoring area (figure 1, section 2.1). If the measurements and the areal percentages are representative, we estimate that the spring thawing effect was 0.5–97 Tg C of CH\(_4\) from natural wetlands across the northern permafrost region in the year 2011 (table S2 available at stacks.iop.org/ERL/7/034009/mmedia).

Meanwhile, we combined the time-series column CH\(_4\) concentration derived from SCIAMACHY data with field observations to estimate the temporal variation of spring thaw-induced CH\(_4\) emission in the northern permafrost region (figure 4). The SCIAMACHY data were partially verified in capturing CH\(_4\) concentration variations induced by spring thaw (section 2.5). The results showed that spring thaw-induced CH\(_4\) emission increased from 2003 through 2008 and slightly decreased in 2009, which is consistent with temporal changes in CH\(_4\) concentration derived from NOAA flask data except for the year 2003 (figure 4). The increase in CH\(_4\) concentration in the year 2003 could be attributed to biomass burning in boreal regions of Asia and North America (Dlugokencky et al 2009, van der Werf et al 2006). We acknowledge that the spring thaw-induced CH\(_4\) emission has

### Table 2. Parameters used in the calculation of the potential CH\(_4\) emission in the spring thaw and their ecological meanings. (All parameters are for the Sanjiang Plain, Northeast China.)

| Parameter | Value (unit) | Ecological meaning | Reference |
|-----------|--------------|---------------------|-----------|
| \(T_w\)   | 0.27 (°C)    | Mean temperature of the soil profile (0–50 cm) in the winter season | This study |
| \(T_g\)   | 16.16 (°C)   | Mean temperature of the soil profile (0–50 cm) in the growing season | This study |
| \(Q_{10}\) | 2.5          | Temperature sensitivity of methane production in the study site | Song et al (2009) |
| Oxid\(_w\) | 0.1          | Fraction of produced CH\(_4\) in the soil porosity oxidized in the winter season | Mer and Roger (2001), Roslev and King (1996) |
| Oxid\(_g\) | 0.7          | Fraction of produced CH\(_4\) in the soil porosity oxidized in the growing season | Conrad (1996), Mer and Roger (2001) |
| \(D_w\)   | 2–12 (h)     | Duration of the CH\(_4\) outburst during the spring thawing period | This study |
| \(L_w\)   | 2904 (h)     | Length of the winter season | This study |
| \(L_g = D_g\) | 3672 (h)   | Length and duration of CH\(_4\) production and emission over the growing season | This study |

![Figure 4. Temporal variation of year-to-year change in observed CH\(_4\) concentration and calculated CH\(_4\) emission from the spring thawing effect (CH\(_4\) change is defined as changes in atmospheric CH\(_4\) concentration at yearly time steps derived from NOAA flask data; STE: spring thawing effect).](image-url)
3.4. Uncertainty and research needs

We acknowledge that there are some uncertainties that need to be addressed in our further research effort. The extrapolation might cause large uncertainties in the regional estimate since we assume constant CH₄ emission over entire north permafrost region. To improve spatial extrapolation of CH₄ emission, it is clearly necessary to develop accurate spatial data on the distribution of the hot spots of CH₄ emission from natural wetlands in the northern permafrost region. Furthermore, all the field observations were conducted during the daytime and nighttime CH₄ emission pulses were not covered. Thus the current estimate might underestimate the CH₄ emission resulting from spring thawing effects. Yet we argue that this study captures the primary CH₄ outburst because nighttime usually has lower temperature and thaw events should not occur as often as in daytime. Meanwhile, high-frequency observations are needed to accurately estimate the CH₄ emission pulses. The comparison between satellite data and flask data shows partial verification of SCIAMACHY’s capacity in capturing variations in atmospheric CH₄ concentration driven by spring thaw effect-induced increase in CH₄ concentration (figure 4). In addition, integration with an atmospheric transport chemistry model would be an improvement for evaluating the spring thawing effect on atmospheric CH₄ concentration.

4. Concluding remarks

This study shows the dramatic contribution of the spring thawing effect to atmospheric CH₄ variations caused by recent Arctic warming. The extremely high CH₄ emission observed in this study confirmed that natural wetland might also emit a large amount of CH₄ via bubbling in the spring season, in addition to the observed CH₄ emission from thaw lakes (Walter et al. 2006). This high CH₄ emission enhances the positive feedback through greenhouse gases in the Arctic region (Chapin et al. 2005). Thus Earth system models should take this spring thawing effect into consideration to make more accurate examinations of permafrost carbon–climate feedback. We anticipate that the estimated contribution of the spring thawing effect to atmospheric CH₄ will stimulate further research into the large-scale feedback from terrestrial ecosystems to the climate system. Given the projected change in the climate system in the 21st century, the spring thawing effect might get stronger and stronger, serving as one of the most important mechanisms for permafrost carbon–climate feedback. To better understand this feedback, therefore, more efforts are needed to investigate the processes or factors responsible for the spring thawing effect on CH₄ emission.

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Author contributions

CS, XX and HT initiated the effort; XS, LS, YM, XW and YG conducted the field observations; XX performed the overall analysis of field, flask and satellite data. All authors contributed to interpreting the results and writing the paper.

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