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Double-counting challenges the accuracy of high-latitude methane inventories

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Key Points:
- Top-down and bottom-up estimates of the Arctic CH_4 natural sources do not match; we suggest that double-counting of emissions in bottom-up accounting is a major cause of this discrepancy
- Double-counting can occur due to overlap of wetland and lake or fluvial areas in models or inventories using low-resolution maps
- Double-counting can occur due to overlap of the $\delta^{13}C$-CH_4 property between many Arctic CH_4 sources

Supporting Information:
- Supporting Information SI

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Abstract Quantification of the present and future contribution to atmospheric methane (CH_4) from lakes, wetlands, fluvial systems, and, potentially, coastal waters remains an important unfinished task for balancing the global CH_4 budget. Discriminating between these sources is crucial, especially across climate-sensitive Arctic and subarctic landscapes and waters. Yet basic underlying uncertainties remain, in such areas as total wetland area and definitions of wetlands, which can lead to conflation of wetlands and small ponds in regional studies. We discuss how in situ sampling choices, remote sensing limitations, and isotopic signature overlaps can lead to unintentional double-counting of CH_4 emissions and propose that this double-counting can explain a pan-Arctic bottom-up estimate from published sources, 59.7 Tg yr^{-1} (range 36.9–89.4 Tg yr^{-1}) greatly exceeding the most recent top-down inverse modeled estimate of the pan-Arctic CH_4 budget (23 ± 5 Tg yr^{-1}).

1. Introduction

At first glance, balancing the CH_4 budget should be simple. Decades long records of atmospheric CH_4 exist, and with a lifetime of less than 10 years in the atmosphere [*Prather et al.*, 2012], we should be able to construct a box model where known CH_4 sources minus known CH_4 sinks equals the current atmospheric burden. Though the atmospheric burden is well known, detailed accounting of both sources and sinks remains a tremendous challenge [*Kirschke et al.*, 2013], somewhat due to potentially large CH_4 sources newly noted in the past 10 years. Many of these potential new sources are regional, and many lie in the Arctic where warming temperatures may be more favorable for production and release of CH_4 from long-stored permafrost carbon (C), potentially contributing to a permafrost C warming feedback [*Schuur et al.*, 2015; *Vonk et al.*, 2013]. It remains a goal to reconcile the top-down Arctic CH_4 budget (e.g., calculating backward from the amount of CH_4 observed in the atmosphere to sources), with bottom-up budgets (e.g., summing the CH_4 sources and sinks to determine the atmospheric burden). We provide here an updated, but rough, bottom-up inventory, based on published estimates of various categories of natural Arctic CH_4 sources, in Table 1. Although we concentrate on the bottom-up budget in our discussion here, the top-down budget is not without issues. Top-down inverse modeling estimates for the Arctic are limited by relatively few atmospheric measurements in the Arctic [*Bruhwiler et al.*, 2014], tropospheric modeling capabilities [*Houweling et al.*, 1999], and uncertainty surrounding the hydroxyl radical, the primary atmospheric sink for CH_4 [*Montzka et al.*, 2011]. But top-down budgets are mass balanced by design, which is not the case for the bottom-up sums of independent studies.

2. Wetlands and Small Ponds

The past decade has seen increasing recognition of the importance of lakes and ponds as CH_4 sources in the Arctic and subarctic [*Bastviken et al.*, 2011; *Walter et al.*, 2006; *Wik et al.*, 2016b] and that those lakes and ponds' emissions are climate sensitive [*Arp et al.*, 2016; *Tan and Zhuang*, 2015; *Thornton et al.*, 2015]. Lakes and ponds are now seen as a distinct CH_4 source, apart from wetlands. The underlying methanogenic processes leading to CH_4 release from lakes and wetlands are similar, but not identical. For instance, the CH_4 flux from wetlands depends, in complex ways, on the water table [*Brown et al.*, 2014; *Turetsky et al.*, 2014], whereas more constant water in even small lakes eliminates this variable; further, lakes of various sizes can be active CH_4 producers throughout both their ice-free season and during winter [*Walter et al.*, 2008; *Wik et al.*, 2011], whereas wetlands may or may not be depending on seasonal weather. Many high-latitude lakes, for instance, have been found to release a substantial fraction of their annual CH_4 following ice-out in spring [*Jammet et al.*, 2015; *Wik et al.*, 2016b].

Table 1. Arctic CH_4 Budget; Bottom-Up Versus Top-Down[a]

	$Tg\,y^{-1}$	Study
Bottom-Up Estimates		
Lakes and ponds > 50°N	16.5 ± 9.2	*Wik et al.* [2016b]
Lakes and ponds > 60°N (bLake4Me model)	11.9	*Tan and Zhuang* [2015]
Rivers and streams > 54°N	0.3	*Bastviken et al.* [2011]
Rivers and streams > 54°N	7.5	*Stanley et al.* [2016]
Reservoirs > 54°N	1.2	*Bastviken et al.* [2011]
Arctic Ocean + Beaufort and Chukchi Seas (<82°N)	2	*Kort et al.* [2012]
ESAS	2.9	*Thornton et al.* [2016]
ESAS	17	*Shakhova et al.* [2014]
Wetlands > 60°N	23.2	*Zhang et al.* [2004]
Wetlands > 53.1°N (CarbonTracker prior model, based on *Bergamaschi et al.* [2005])	31	*Bruhwiler et al.* [2014]
Wetlands > 50°N (ORCHIDEE model)	31 ± 5	*Bousquet et al.* [2011]
Sources sum (minimum–maximum)	59.7 (36.9–89.4)	
Top-Down Inverse Model Estimates		
>60°N, all natural sources	23 ± 5	*Bruhwiler et al.* [2014] *Saunois et al.* [2016]
ESAS	0–4.5	*Berchet et al.* [2016]

[a]Recent bottom-up estimates for various Arctic CH_4 source flux strengths are sorted into categories of lakes and ponds, rivers and streams, reservoirs, Arctic Ocean, ESAS, and wetlands. Estimates are based on extrapolations of measurements, except for the three process models noted. Note that the latitude bands differ, which partly account for the ultimate bottom-up uncertainty seen here. Arctic Ocean flux is from the reported $2\,mg\,m^{-2}\,d^{-1}$ extrapolated over $10 \times 10^6\,km^2$ of seasonally ice-free Arctic Ocean regions for 100 ice-free days [*Kort et al.*, 2012]. Rivers and streams high estimate is based on the *Stanley et al.* [2016] global fluvial flux database distributed into fluvial surface areas reported by *Bastviken et al.* [2011]. Sum uses averages of the all estimates per category. Minimum uses category low values and lower bound of the *Wik et al.* [2016b] lake estimates; maximum uses category high values and upper bounds of ORCHIDEE wetland model and the *Wik et al.* [2016b] lake estimates. Including subarctic and boreal wetlands from 45°N to 60°N would add $34\,Tg\,yr^{-1}$ to the *Zhang et al.* [2004] wetland estimate.

Surprisingly, even uncertainties of total wetland area remain—not only in the Arctic [*Bridgham et al.*, 2013]. Some of this uncertainty may arise from a conflation of wetlands with small ponds. The definition of wetlands may contribute to a double-counting problem. Widely used descriptions of wetlands (standing water ≤ 2–2.5 m deep) [*Cowardin et al.*, 1979; *Tiner et al.*, 2015] overlap with a vast array of high-latitude lakes and ponds, which tend to be small and can be less than 1 m deep—especially lakes and ponds in permafrost peatlands and thermokarst lakes [*West and Plug*, 2008]. Some wetland studies explicitly include shallow ponds [*Melton et al.*, 2013]. Many shallow high-latitude lakes and ponds are persistent landscape features [*Smith et al.*, 2007], unlike other seasonally inundated wetland areas (e.g., ecosystems adapted to flooded conditions) [*Smith et al.*, 2007].

The error induced by double-counting of lake area emissions again as wetland area emissions is somewhat mollified by the fact that small lakes may have a greater annual emission potential than some small wetlands. However, productive fens can closely resemble small, shallow ponds' CH_4 emission magnitude [*Bubier et al.*, 1993; *McEnroe et al.*, 2009; *Pelletier et al.*, 2007]. It is precisely near the hazily defined wetland-or-lake boundary that the greatest CH_4 emissions per area are expected. The small water bodies which are most likely to be lumped into wetland areas cover an impressive expanse—lakes and ponds smaller than $0.1\,km^2$ cover in total about $1 \times 10^6\,km^2$ (equal to more than half the area of Alaska; Figure 1) [*Verpoorter et al.*, 2014] —10% or more of the—uncertain—global wetland area [*Melton et al.*, 2013].

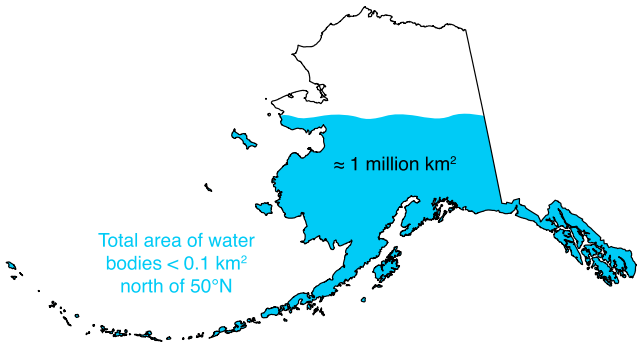

Figure 1. Visualization of total area of small ponds which are most likely to be counted as wetlands in assessments. *Verpoorter et al.* [2014] estimate that such sized water bodies cover roughly $1 \times 10^6\,km^2$. In perspective this is more than half the area of the largest U.S. state, Alaska.

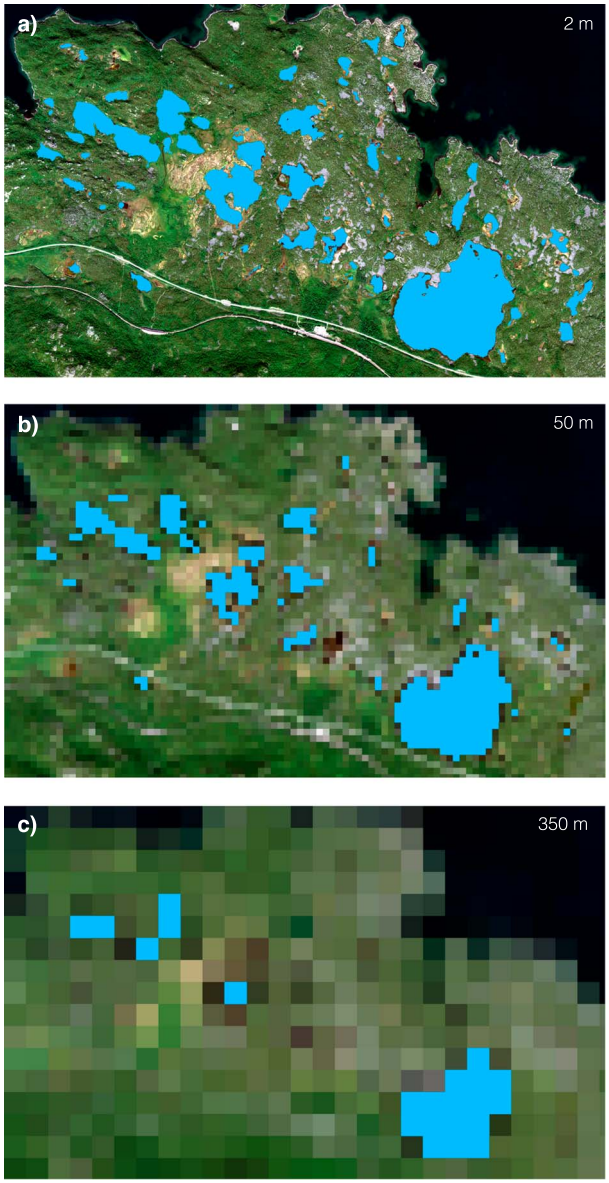

Figure 2. (a) Stordalen Mire, northern Sweden, 68°21′N, 19°02′E, at 2 m resolution. Worldview image (source: Digital Globe). Open lake waters are highlighted in blue (the large lake Torneträsk at the top of image is not highlighted). (b) Stordalen Mire at 50 m resolution, similar to resolution of lake database in [*Verpoorter et al.*, 2014], pixelated Figure 2a with lake pixel brightness tolerance of 10% from underlying open water pixel color. (c) Stordalen Mire at 350 m resolution, similar to resolution of lake database in *Lehner and Döll* [2004], lake pixels calculated as in Figure 2b.

Models of regional and global CH_4 emissions utilizing lake databases with pixel sizes larger than extant lake sizes implicitly exclude these small water bodies. Due to previous limitations in remote sensing techniques, many wetland estimates have been based on lower resolution imagery [*Lehner and Döll*, 2004] and only exclude lakes $< 0.1\ km^2$, such a lake is ~350 m in diameter. So far, only a very recent inventory, presented in the Global Water Bodies database (GLOWABO), accounts for smaller lakes, now as small as $0.002\ km^2$ [*Verpoorter et al.*, 2014]. Ironically, $0.002\ km^2$ is 40 times smaller than a common wetland/lake definition cutoff size, $0.08\ km^2$ [*Tiner et al.*, 2015], so the smallest lakes may, even if detected, sometimes be counted as wetlands. Figure 2 shows the effect of various pixel sizes on lake detection in a lake dense area in northern Sweden—a 49% loss of estimated water body area due to pixel size in this particular example; even GLOWABO misses many of the smallest ponds. Upscaling lake CH_4 emission estimates without including these small lakes not only excludes a large areal source but also excludes the strongest lake CH_4 source on a per unit area basis, as small water bodies are known to be hotspots of CH_4 production [*Laurion et al.*, 2010]. Conversely, a small wetland is not expected to be, per unit area, a larger CH_4 emitter than a large wetland. Additionally, it was recently shown that spatial and temporal sampling biases of CH_4 lake emissions are common and are likely to lead to underestimates of total lake emissions [*Wik et al.*, 2016a]. In the top-down total Arctic CH_4 budget, any such overlooked lake emissions due to sampling biases may have been counted as wetland emissions, but increasingly accurate lake emission estimates suggest the need to include lake distributions, distinct from wetland distributions, as a specific input prior in top-down emission estimates. Specifically, in scaling bottom-up emission estimates, lake or wetland emissions are multiplied by lake or wetland area. If some amount of area is counted in both categories—from low-resolution maps or fuzzy definitions—double-counting of CH_4 emissions will exist in bottom-up estimates. Generally, models that attempt to avoid the double-counting problem are necessarily limited by the resolution of lake databases used for masking out lakes embedded in wetlands [*Melton et al.*, 2013].

Although wetlands are now reported separately from freshwater systems [*Cole et al*., 2007] in global bottom-up and top-down accountings of CH_4 [*Kirschke et al*., 2013], the separation currently appears be more wishful than realistic. A recent bottom-up estimate that accounts for water bodies as small as 0.002 km^2 noted that lakes and ponds alone may account for as much as 70% of the inverse-modeling (top-down) 23 ± 5 Tg yr^{-1} predicted CH_4 emissions [*Bruhwiler et al*., 2014] from all northern natural sources—sources which have been historically thought to be dominated by wetlands [*Wik et al*., 2016b]. Wetlands are expected to dominate because nearly 50% of the world's wetlands lie between 50° and 70°N [*Tiner et al*., 2015]. In our view, the reason for this discrepancy is a double-counting of the contribution of small lakes within wetlands to total CH_4 emissions—these small water bodies may be included in both lake and wetland bottom-up estimates. Similar double-counting problems also arise with streams and rivers embedded in wetland landscapes, as discussed below. Double-counting wetlands as lakes and vice-versa would always increase the bottom-up estimates of the natural sources in the CH_4 budget. In fact, the bottom-up estimate of natural sources is significantly higher than the top-down estimate [*Kirschke et al*., 2013]. Improved resolution (smaller pixels) in remote sensing data of high-latitude landscape types [*Drusch et al*., 2012; *Jawak and Luis*, 2013] may improve bottom-up estimates. Higher resolution will allow the discrimination of more small lakes embedded in wetlands, though regional calibration and ground truth studies will be required.

3. Sea Challenges

One of the surprises in CH_4 studies has been reports of substantial emissions to the atmosphere from shallow shelf seas. The ocean has long been regarded as only a small contributor to global CH_4 [*Rhee et al*., 2009], but shallow seas are a different matter. Seafloor CH_4 sources—including bubble plumes—have a far better chance of reaching the atmosphere if the water is shallow, due to less time for the bubbles to dissolve, or for CH_4 to oxidize during upward advective transport [*McGinnis et al*., 2006]. Small sea-air CH_4 fluxes were first suggested in the 1990s in the Beaufort Sea [*Kvenvolden et al*., 1993], as well as moderate fluxes from the Beaufort and Chukchi Seas and Arctic Ocean [*Kort et al*., 2012].

The largest shallow shelf sea in the world is the combined Laptev, East Siberian, and Chukchi Sea shelf (collectively, East Siberian Arctic Shelf, or ESAS), about 2.1×10^6 km^2 with an average depth of 62 m [*Jakobsson*, 2002]. Understanding the scale of sea-air CH_4 fluxes from the ESAS has proven to be a challenge. Early reports of high fluxes from the Laptev and East Siberian Seas based on gas transfer models [*Shakhova et al*., 2010] have been followed by even higher estimates based on counting bubbles from seabed gas plumes using sonar [*Shakhova et al*., 2014]. CH_4 in shallow seas has been reported in other high-latitude locations [*Kodovska et al*., 2016; *Myhre et al*., 2016; *Schmale et al*., 2010], though seawater CH_4 does not necessarily presage substantial increases in atmospheric CH_4 [*Myhre et al*., 2016]. There are a wide variety of potential sources of CH_4 in the waters of the ESAS. As the ESAS was above sea level at the last glaciation, it contains substantial subsea permafrost and organic material originally formed and frozen subaerially [*Dmitrenko et al*., 2011]. Additionally, the Laptev and East Siberian Seas are strongly influenced by terrestrial organic carbon input from rivers, providing a modern source of C to the seas [*Charkin et al*., 2011; *Semiletov et al*., 2005]. Complicating matters further, the age of the carbon in the present day terrestrial organic matter source may be old or young, C released from thawing permafrost—or C in organic material produced in the annual cycle of plant growth. Coastal erosion of thawing permafrost shorelines provides yet another carbon input into the Arctic system [*Lantuit et al*., 2013]. All of these marine and shore processes might contribute C to the Arctic CH_4 cycle.

To date, atmospheric observations cannot account for extremely high fluxes of CH_4 from the Laptev and East Siberian Seas (Table 1) [*Berchet et al*., 2016], and recent reports have shown that not even all nearshore areas can be substantial sources [*Overduin et al*., 2015] due to CH_4 oxidation in the sediment, and offshore seep sites can be limited in spatial extent [*Thornton et al*., 2016]. Such heterogeneity is typical for all CH_4 sources, which complicates extrapolating regional total emissions from local measurements.

4. Isotopic Solutions

Lake, wetland, and sea emissions should be accounted for separately in CH_4 budgets, yet how can this be accomplished? Although variations in δ^{13}C-CH_4 can help separate thermogenic and biogenic CH_4, and δ^{13}C-CH_4 has been linked to methanogenic community changes along a thaw gradient in wetlands and

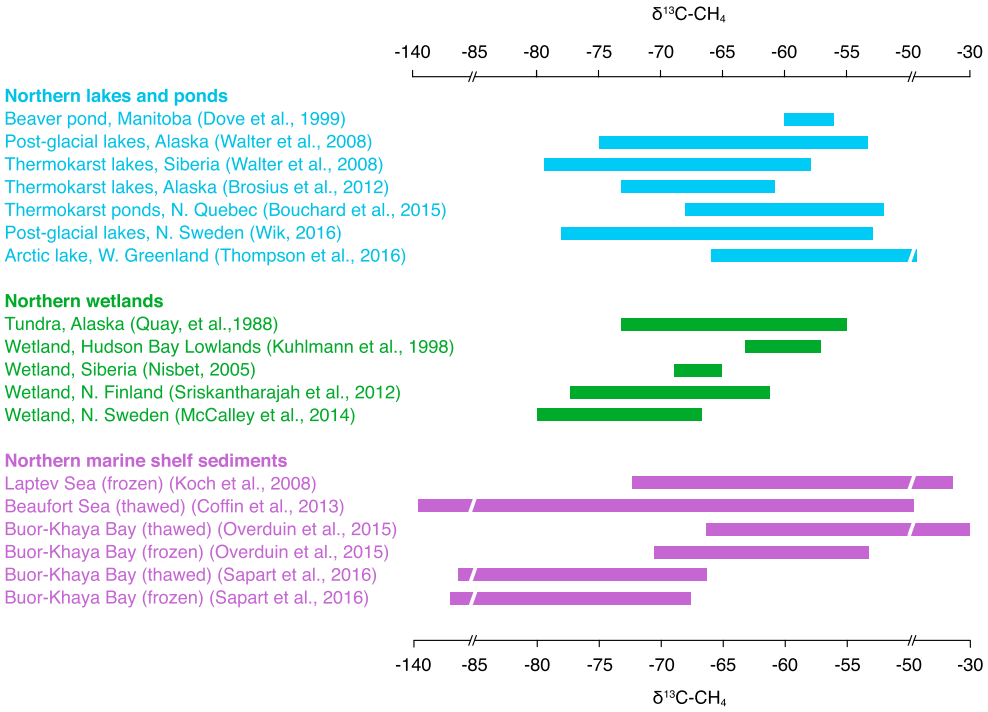

Figure 3. Ranges in site-specific mean δ^{13}C-CH_4 reported from Arctic and subarctic lakes, wetlands, and shallow marine sediment from multiple data sources [*Bouchard et al.*, 2015; *Brosius et al.*, 2012; *Coffin et al.*, 2013; *Dove et al.*, 1999; *Koch et al.*, 2009; *Kuhlmann et al.*, 1998; *McCalley et al.*, 2014; *Nisbet*, 2005; *Overduin et al.*, 2015; *Quay et al.*, 1988; *Sapart et al.*, 2016; *Sriskantharajah et al.*, 2012; *Thompson et al.*, 2016; *Walter et al.*, 2008; *Wik*, 2016]. Figure data are collected in the supporting information.

may thus shift global atmospheric δ^{13}C-CH_4 in a warmer climate [*McCalley et al.*, 2014], using this most common CH_4 isotope system for separating lakes, wetland, and shallow sea emissions is futile (Figure 3).

Recent work using a single isotope system suggests that the resumption of atmospheric CH_4 growth from 2007 onward is not due to new Arctic sources [*Nisbet et al.*, 2016]. However, the stable isotopic signature of CH_4 long stored in subsea reservoirs, or produced from recently mobilized Pleistocene age C (from coastal erosion or terrestrial permafrost), may deceptively appear to match modern CH_4 biologically produced in wetlands if looking at only δ^{13}C-CH_4 [*Sapart et al.*, 2016].

Additional isotope systems, including Δ^{14}C-CH_4 and δD-CH_4 may help in certain situations [*Walter Anthony et al.*, 2012], but such measurements remain relatively uncommon in the literature, and the aforementioned remobilization of radiocarbon-depleted sources may inhibit the usefulness of Δ^{14}C-CH_4 if old C is entering the modern carbon cycle. Regional assessments using multiple CH_4 isotopologues in the midlatitudes, however, have begun to appear [*Townsend-Small et al.*, 2016]. Other techniques which are only now becoming available, such as monitoring exotic CH_4 isotopologues, e.g., $^{13}CH_3D$ and $^{12}CH_2D_2$ [*Douglas et al.*, 2016], are promising for providing additional information, including the formation temperature of the CH_4, and source and sink strengths [*Whitehill et al.*, 2017], but presently are rarely applied due to methodological difficulty and cost. Ethane (C_2H_6) has been used to trace abiogenic CH_4 sources [*Simpson et al.*, 2012] and has been occasionally used in characterizing high-latitude thermogenic CH_4 sources [*Walter Anthony et al.*, 2012].

5. Rivers, Streams, and Reservoirs

Rivers are an additional CH_4 source in the Arctic [*Kling et al.*, 1992; *Striegl et al.*, 2012], and recognition that small rivers and streams may represent an additional uncounted CH_4 source has been growing in recent years [*Crawford et al.*, 2014; *McGinnis et al.*, 2016]. Five years ago, a data-limited synthesis estimated global CH_4 emissions from rivers at 1.5 Tg yr^{-1} [*Bastviken et al.*, 2011]; a more recent synthesis reports 26.8 Tg yr^{-1} [*Stanley et al.*, 2016]. The former report estimated fluvial CH_4 emissions from 54 to 66°N at 0.2 Tg yr^{-1} and

>66°N at 0.1 Tg yr^{-1}. The latter report included dozens of river and stream sites across the pan-Arctic, though a latitude-specific emission was not reported; we report in Table 1 an estimate based on fluvial area > 54°N and the new synthesis data from [*Stanley et al*., 2016]. As with lakes, double-counting issues with resolution can occur; for example, care must be taken when counting rivers in wetlands regions. We are not aware of published isotopic studies of CH_4 emissions from streams and rivers at high latitudes; however, for reasons discussed above, we expect that one-dimensional isotopic studies will not yield meaningful discrimination of the relative importance of small rivers and streams to the CH_4 budget. Finally, reservoirs are sometimes collected separately from lakes, though their total influence at high latitudes is thought to be small [*Bastviken et al*., 2011].

6. Conclusions

The picture or, rather, our appreciation of high-latitude CH_4 emissions from terrestrial aquatic sources seems to have grown much more complex. The Arctic CH_4 top-down inventory (23 ± 5 Tg yr^{-1}) [*Bruhwiler et al*., 2014; *Saunois et al*., 2016] and our rough bottom-up CH_4 inventory (59.7 (range 36.9–89.4) Tg yr^{-1}) do not match (Table 1). Although our inventory in Table 1 is hampered by variability in definitions of the pan-Arctic used in various studies, the mismatch remains. We do encourage future studies, as much as possible, to provide model and inventory outputs for a common set of latitude ranges (we suggest 50°N, >60°N, and above the Arctic Circle) to simplify intercomparisons.

Even 3 years ago, natural terrestrial CH_4 emission estimates were largely regarded as primarily wetlands [*Kirschke et al*., 2013], with a global ratio of 217:40 for wetlands:inland waters, based on bottom-up estimates. A more recent synthesis changes that ratio to 185:122 [*Saunois et al*., 2016], a dramatic change due to new knowledge of lake and pond, and river and streams emissions, but without concomitant changes of wetland total areas. In the last 3 years, estimates of global oceanic sources have actually been revised down, from 18 Tg yr^{-1} to 14 Tg yr^{-1}, reflecting reduced uncertainty about the magnitude of shallow sea sources, though these sea sources certainly exist. High-latitude postglacial lakes that are permanent will likely increase CH_4 fluxes to the atmosphere in a warmer climate, independently of permafrost thaw [*Thornton et al*., 2015]. Alongside that, large changes in the distribution and abundance of high-latitude thermokarst lakes are widely anticipated in the future [*Andresen and Lougheed*, 2015]. The challenges in interpreting the importance of CH_4 fluxes from any newly discovered or better-quantified sources were concisely stated in 2010 by Petrenko et al: "A newly discovered CH_4 source is not necessarily a changing source, much less a source that is changing in response to Arctic warming." [*Petrenko et al*., 2010]. For top-down estimates, which provide a mass-balanced analysis of atmospheric observations, any newly discovered source may displace a portion of known sources in the budget—such as freshwater sources somewhat did recently for wetlands—or new sinks must be found.

Given the high prevalence of wetlands in boreal and Arctic zones, we vitally need ways to reliably discriminate CH_4 emissions from lakes, wetlands, reservoirs, streams and rivers, and shallow seas. δ^{13}C-CH_4 studies alone are likely inadequate for this purpose, without a much greater understanding of what controls δ^{13}C-CH_4 variability, beyond simply site type (Figure 3). There is evidence that studies of other CH_4 isotopologues may provide tools for such CH_4 source discrimination, but at this time, available data sets remain limited. Still, such tools are likely to benefit both top-down modeling and bottom-up in situ and model-based inventories of Arctic CH_4. It seems presumptuous to predict the effects of postulated future landscape changes (subaerial or subsea) on CH_4 fluxes to the atmosphere when we do not yet adequately separate wetlands from lakes and seas in the present and likely double-count sources in assessments. Improved landscape remote sensing at high latitudes (and ground truthing of that data in key regions), along with consistently applied definitions of wetlands that clearly distinguish wetland areas from lakes and ponds, are vital keys to reliable bottom-up CH_4 inventories at high latitudes.

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