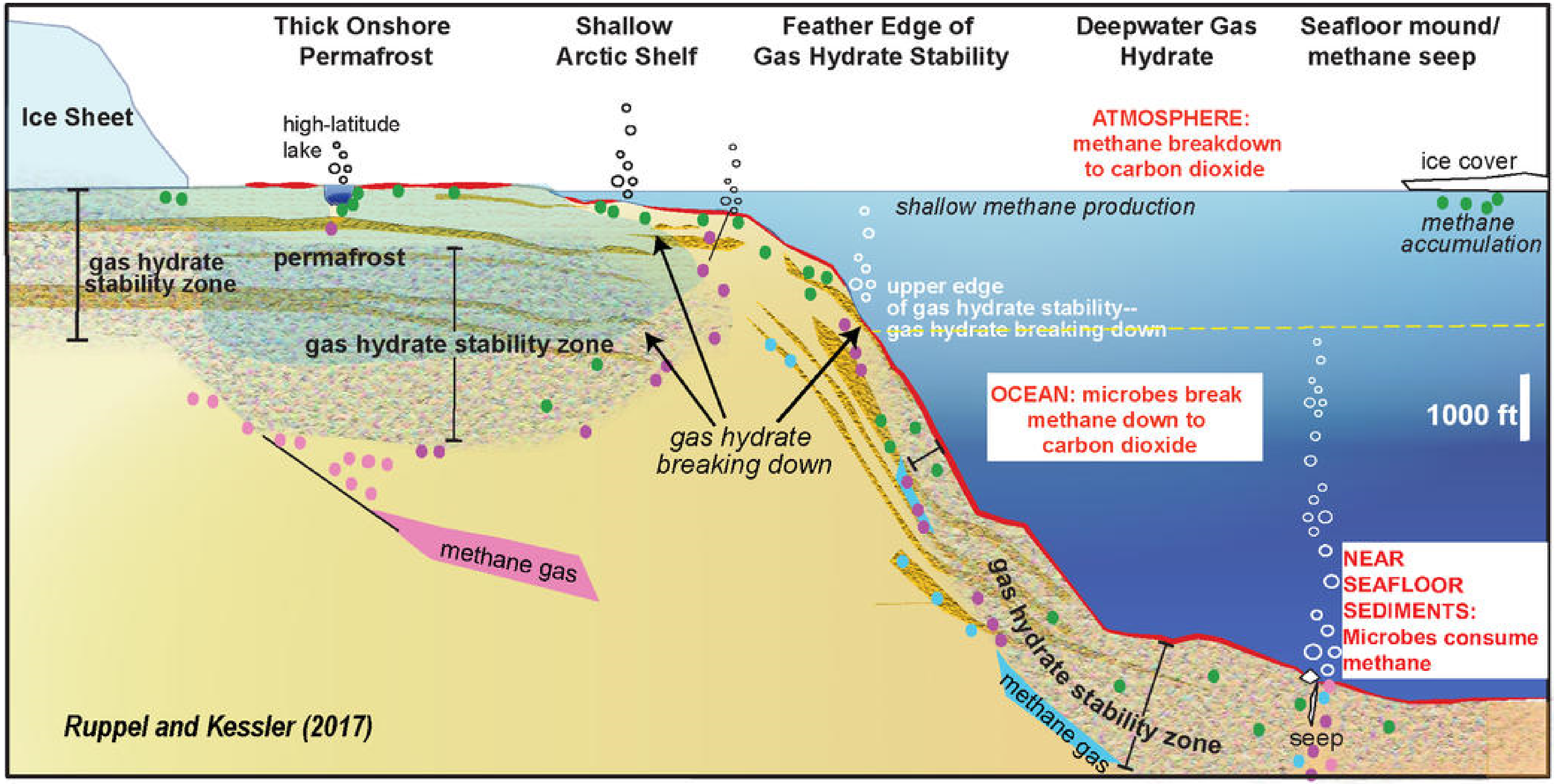
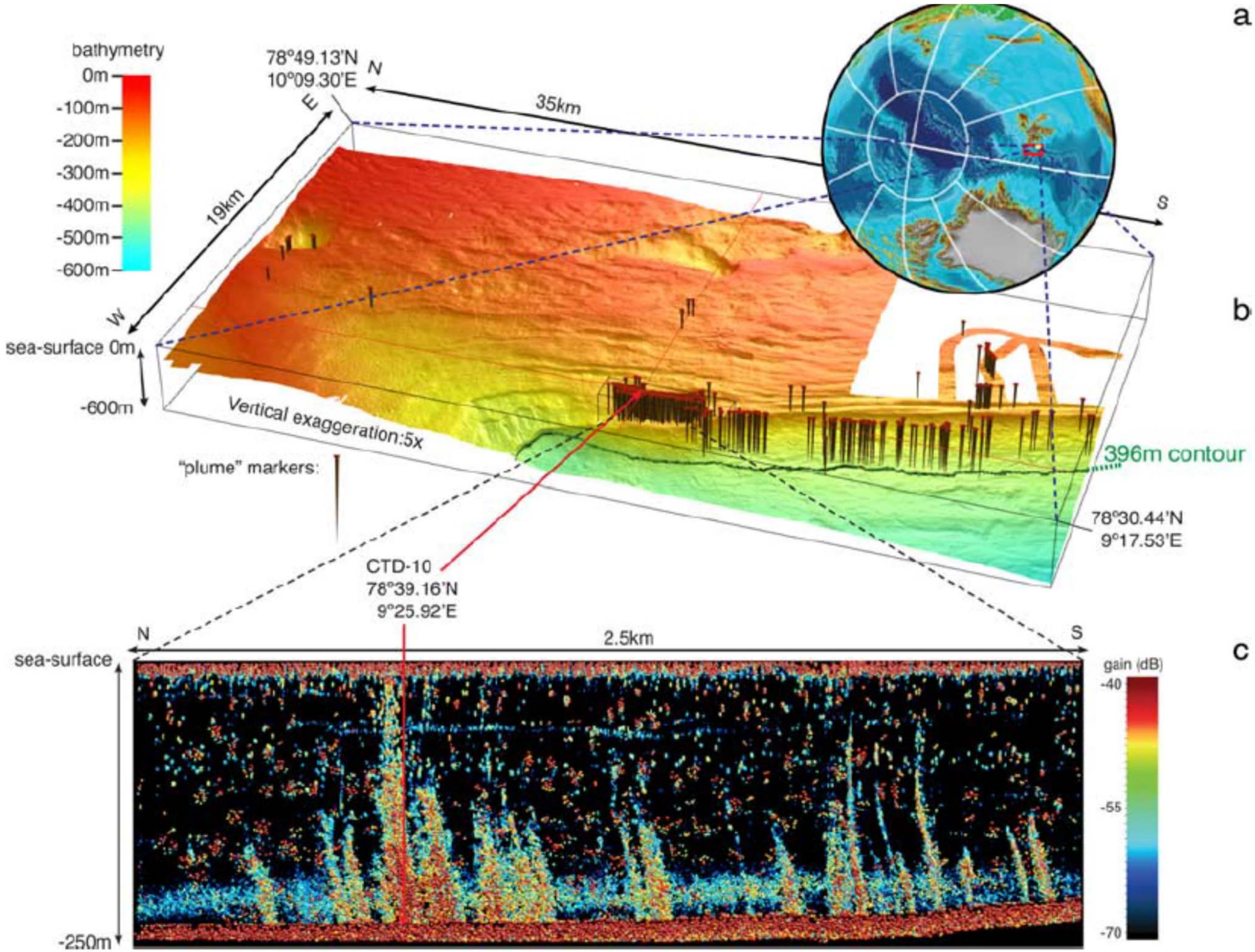


Thick Onshore Permafrost
Shallow Arctic Shelf
Feather Edge of Gas Hydrate Stability
Deepwater Gas Hydrate
Seafloor mound/ methane seep
Ice Sheet
high-latitude lake
ATMOSPHERE: methane breakdown to carbon dioxide
ice cover
shallow methane production
methane accumulation
gas hydrate stability zone
permafrost
gas hydrate stability zone
upper edge of gas hydrate stability-- gas hydrate breaking down
OCEAN: microbes break methane down to carbon dioxide
1000 ft
gas hydrate breaking down
methane gas
gas hydrate stability zone
methane gas
NEAR SEAFLOOR SEDIMENTS: Microbes consume methane
seep
Ruppel and Kessler (2017)



Westbrook et al. 2009

	Kirschke et al. (2013) bottom-up	Kirschke et al. (2013) top-down	Bottom-up			Top-down		
Period of time	2000–2009	2000–2009	2000–2009	2003–2012	2012	2000–2009	2003–2012	2012
Natural sources	347 [238–484]	218 [179–273]	382 [255–519]	384 [257–524]	386 [259–532]	234 [194–292]	231 [194–296]	221 [192–302]
Natural wetlands	217 [177–284]	175 [142–208]	183 [151–222]	185 [153–227]	187 [155–235]	166 [125–204]	167 [127–202]	172 [155–201]
Other natural sources	130 [45–232]	43 [37–65]		199 [104–297]		68 [21–130]	64 [21–132]	49 [22–137]
Other land sources	112 [43–192]			185 [99–272]				
Fresh waters	40 [8–73]			122 [60–180]				
Geological (onshore)	36 [15–57]			40 [30–56]				
Wild animals	15 [15–15]			10 [5–15]				
Termites	11 [2–22]			9 [3–15]				
Wildfires	3 [1–5]			3 [1–5]				
Permafrost soils (direct)	1 [0–1]			1 [0–1]				
Vegetation				[e]				
Oceanic sources	18 [2–40]			14 [5–25]				
Geological (offshore)	–			12 [5–20]				
Other (including hydrates)	–			2 [0–5]				
Anthropogenic sources	331 [304–368]	335 [273–409]	338 [329–342]	352 [340–360]	370 [351–385]	319 [255–357]	328 [259–370]	347 [262–384]
Agriculture and waste	200 [187–224]	209 [180–241]	190 [174–201]	195 [178–206]	197 [183–211]	183 [112–241]	188 [115–243]	200 [122–213]
Enteric fermentation & manure	101 [98–105][a]		103 [95–109][b]	106 [97–111][b]	107 [100–112][b]			
Landfills & waste	63 [56–79][a]		57 [51–61][b]	59 [52–63][b]	60 [54–66][b]			
Rice cultivation	36 [33–40]		29 [23–35][b]	30 [24–36][b]	29 [25–39][b]			
Fossil fuels	96 [85–105]	96 [77–123]	112 [107–126]	121 [114–133]	134 [123–141]	101 [77–126]	105 [77–133]	112 [90–137]
Coal mining	–	–	36 [24–43][b]	41 [26–50][b]	46 [29–62][b]			
Gas, oil & industry	–	–	76 [64–85][b]	79 [69–88][b]	88 [78–94][b]			
Biomass & biofuel burning	35 [32–39]	30 [24–45]	30 [26–34]	30 [27–35]	30 [25–36]	35 [16–53]	34 [15–53]	35 [28–51]
Biomass burning	–	–	18 [15–20]	18 [15–21]	17 [13–21]			
Biofuel burning	–	–	12 [9–14]	12 [10–14]	12 [10–14]			
Sinks								
Total chemical loss	604 [483–738]	518 [510–538]				514[d]	515[d]	518[d]
Tropospheric OH	528 [454–617]							
Stratospheric loss	51 [16–84]							
Tropospheric Cl	25 [13–37]							
Soil uptake	28 [9–47]	32 [26–42]				32 [27–38]	33 [28–38]	36 [30–42]
Sum of sources	678 [542–852]	553 [526–569]	719 [583–861]	736 [596–884]	756 [609–916]	552 [535–566]	558 [540–568]	568 [542–582]
Sum of sinks	632 [592–785]	550 [514–560]				546[c]	548[c]	555[c]
Imbalance		3 [−4–19]				6[c]	10[c]	14[c]
Atmospheric growth		6				6.0 [4.9–6.6]	10.0 [9.4–10.6]	14.0 []

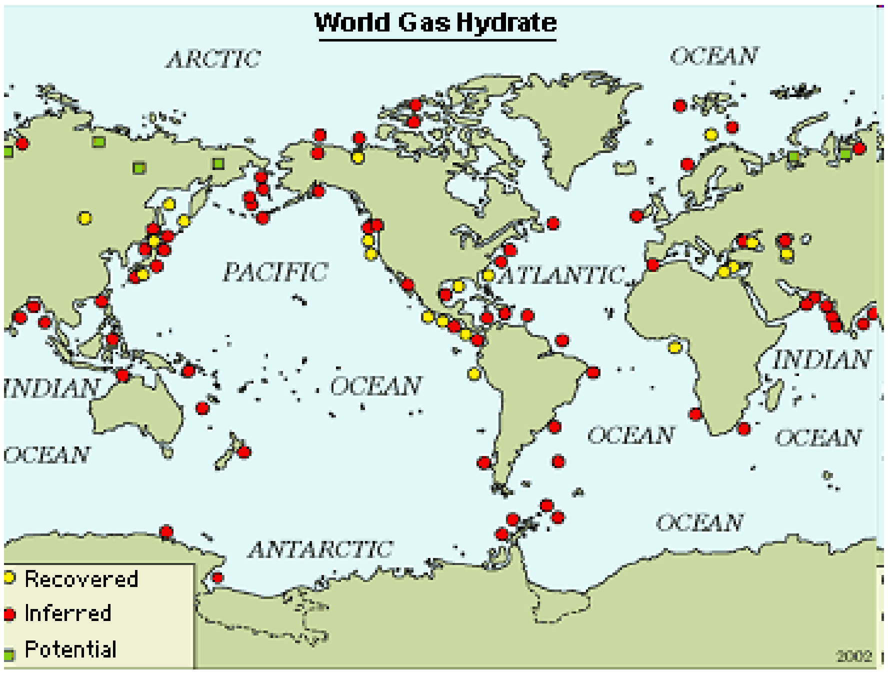
[a] Manure is now included in enteric fermentation & manure and not in waste category.

[b] For IIASA inventory the breakdown of agriculture and waste (rice, enteric fermentation & manure, landfills & waste) and fossil fuel (coal, oil, gas & industry) sources use the same ratios as the mean of EDGAR and USEPA inventories.

[c] Total sink is deduced from global mass balance and not directly computed.

[d] Computed as the difference of global sink and soil uptake

Saunois *et al.*, 2016



Locations of known and inferred gas hydrate occurrences in oceanic sediments of outer continental margins and permafrost regions. Only a limited number of gas hydrate deposits have been examined in any detail.

NATIONAL/REGIONAL ESTIMATES OF THE AMOUNT OF GAS WITHIN HYDRATES

(cubic feet)

UNITED STATES	
$317{,}700 \times 10^{12}$	Collett 1995
INDIA	
$4{,}307 \times 10^{12}$	ONGC 1997
BLAKE RIDGE, USA	
635×10^{12}	Dillon & others 1993
$2{,}471 \times 10^{12}$	Dickens & others 1997*
$2{,}824 \times 10^{12}$	Holbrook & others 1996*
$2{,}012 \times 10^{12}$	Collett 2000*
$1{,}331 \times 10^{12}$	Collett 2000
NANKAI TROUGH, JAPAN	
$1{,}765 \times 10^{12}$	MITI/JNOC 1998
ANDAMAN SEA, INDIA	
$4{,}307 \times 10^{12}$	ONGC 1997
NORTH SLOPE, ALASKA	
590×10^{12}	Collett 1997

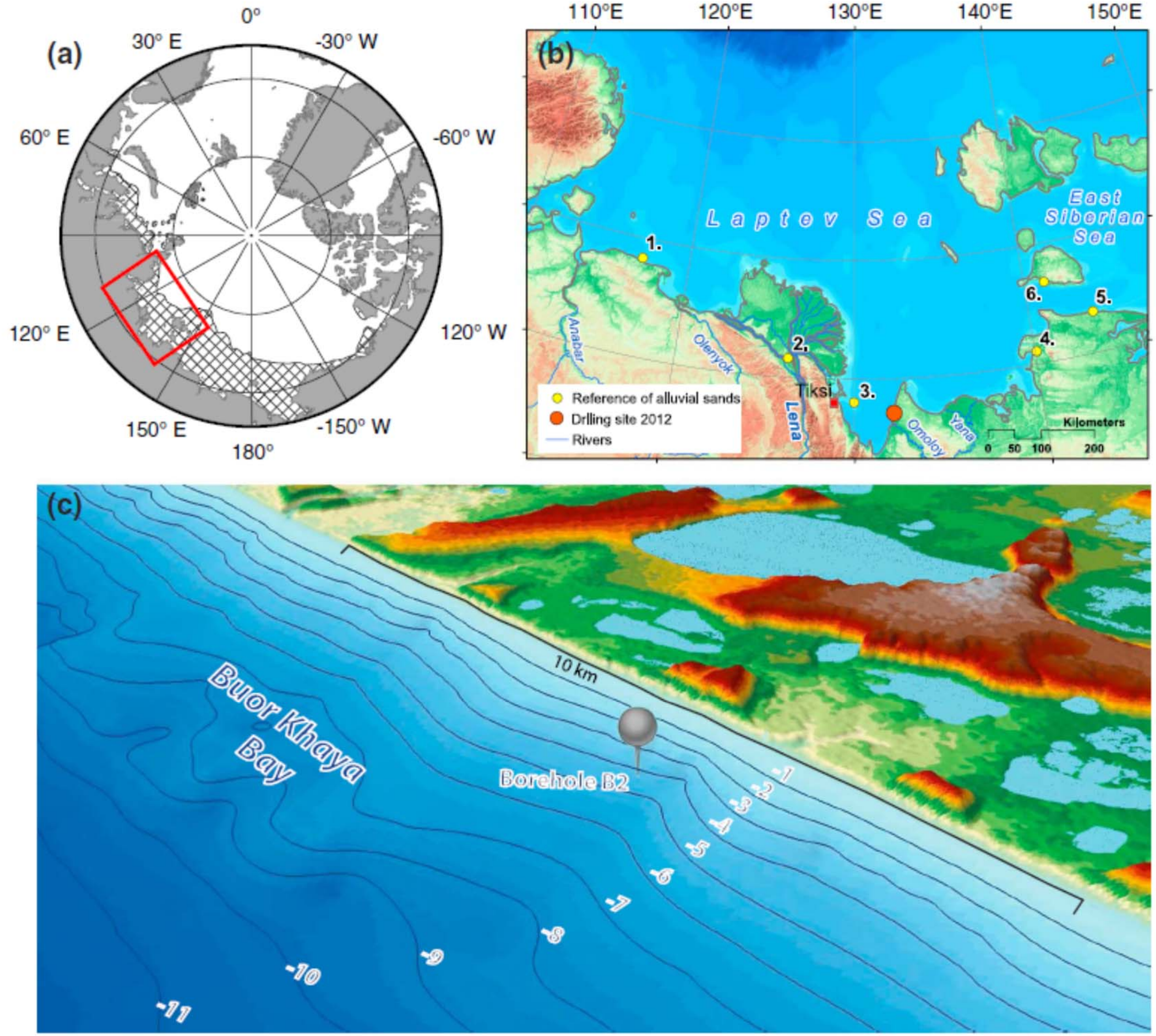
* Includes associated free-gas

Worldwide Estimates of Gas Hydrates:
Oceanic: 30,000 to 49,100,000 x 10^{12}
Continental: 5,000 to 12,000,000 x 10^{12}

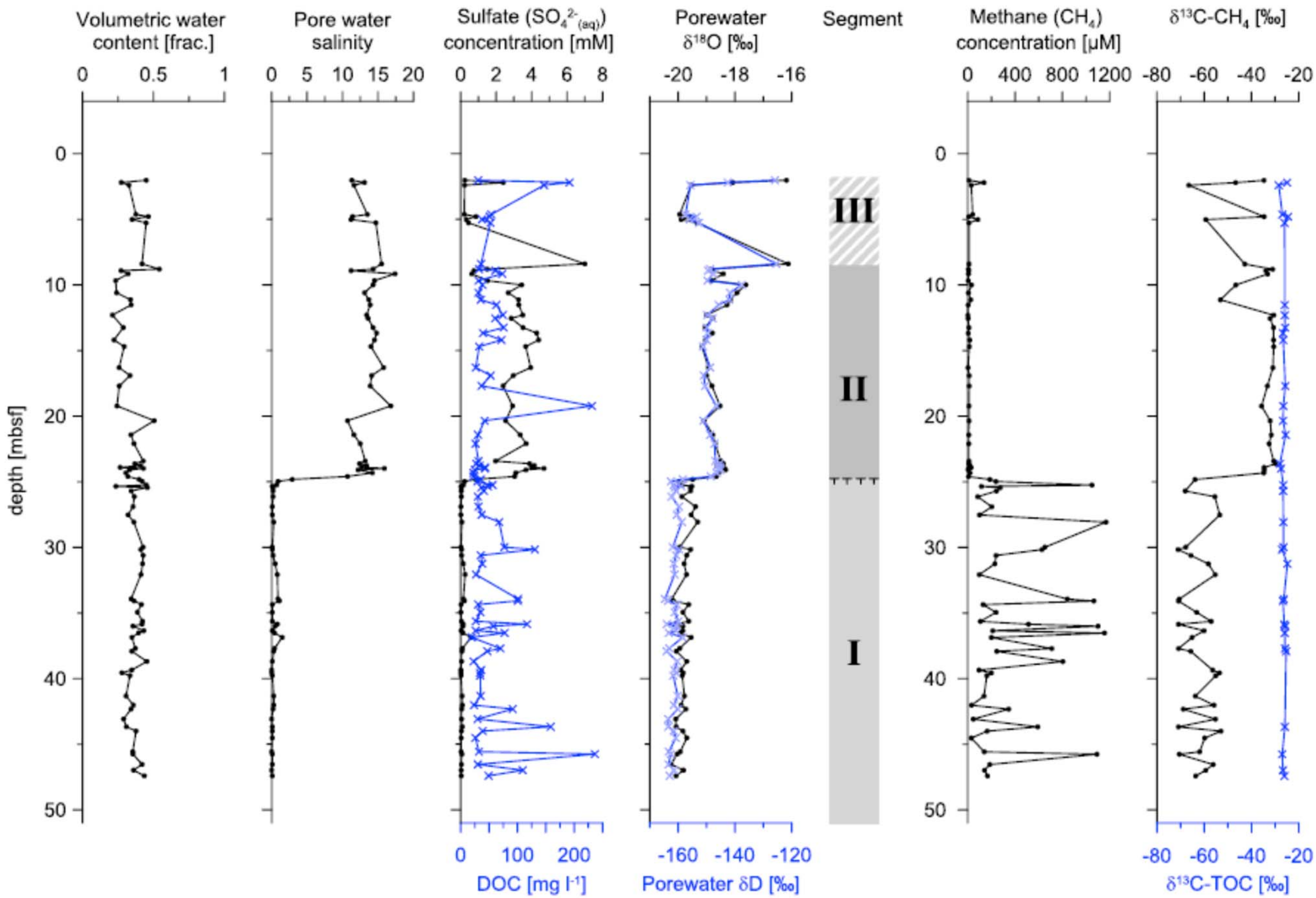
Conventional Gas Resources:
13,000 x 10^{12}

5000 ft^3= ca.81000 g (81 Pg);
12000000 ft^3 = 1.94x10^8 g (200,000 Pg)

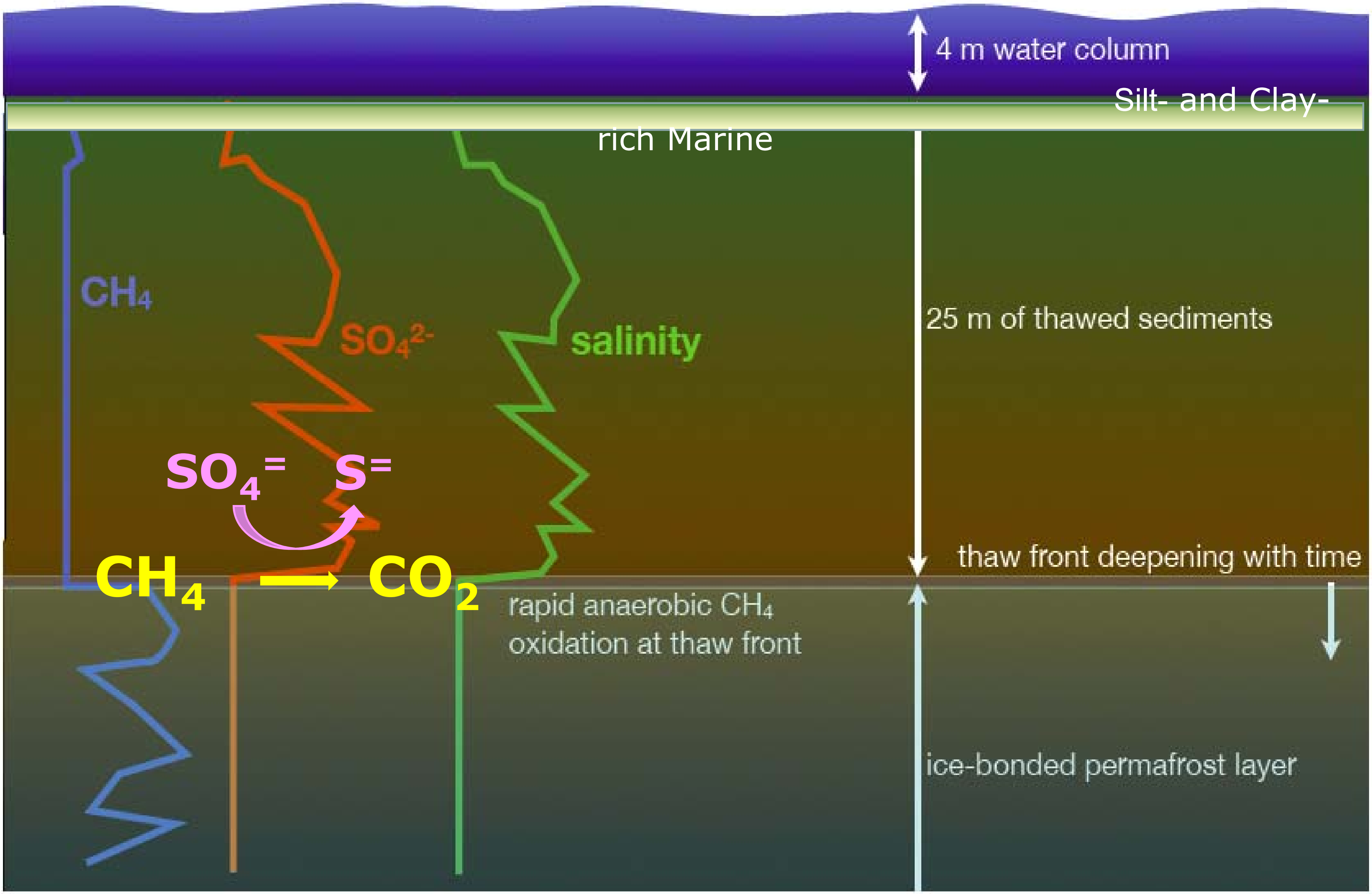
http://geology.usgs.gov/connections/mms/joint_projects/methane.htm



from Overduin *et al*., 2015



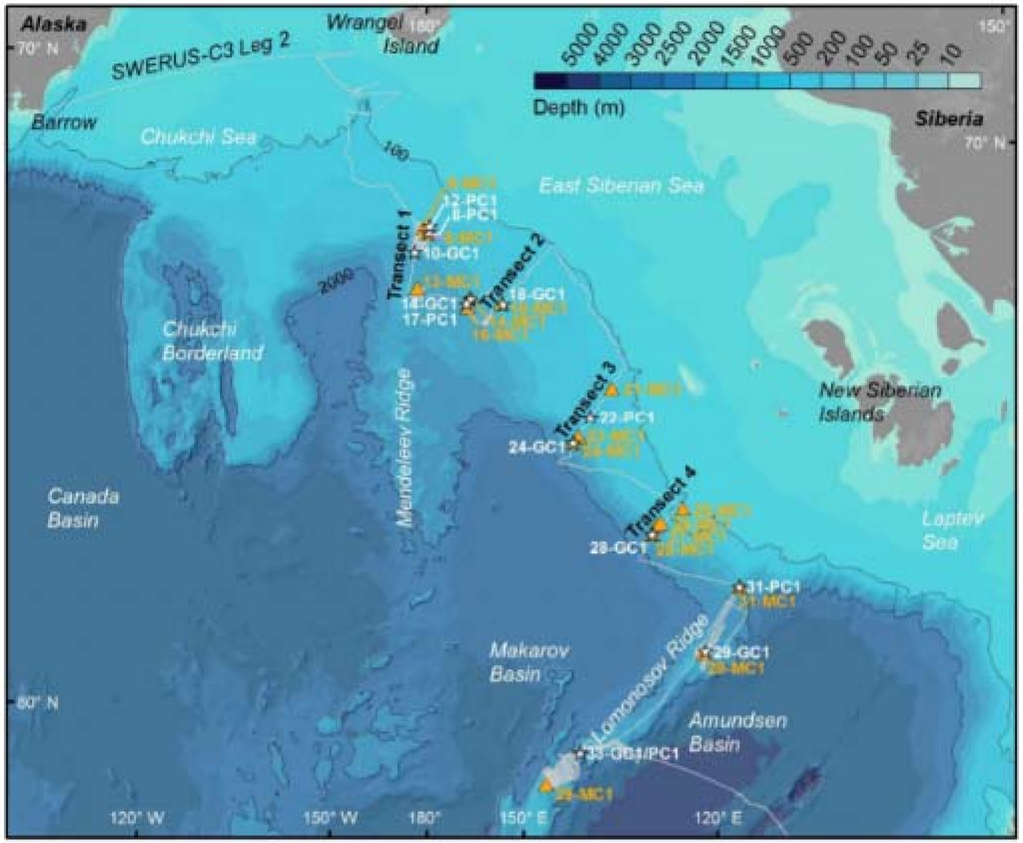
from Overduin *et al.*, 2015



Thornton and Crill, 2015

SWERUS articles published on gas hydrate stability in slope-sediments

Clint M. Miller, Gerald R. Dickens, Martin Jakobsson, Carina Johansson, Andrey Koshurnikov, Matt O'Regan, Francesco Muschitiello, Christian Stranne and Carl-Magnus Mörth, in revision, ***Pore water geochemistry along continental slopes north of the East Siberian Sea: Inference of low methane concentrations*** *: Biogeosciences*



Study based on pore water chemistry from 32 sediment cores taken during Leg 2 of the 2014 SWERUS-C3 expedition. The results suggest that abundant CH_4, including gas hydrates, do not characterize the East Siberian Sea slope or rise along the investigated depth transects.

Table S1| Data summary areas of the western Svalbard margin investigated in this study

Property	Unit	Shallow Shelf Seep Field (<250 m)			Nearshore Coastal Zone (<110 m)	Slope Seeps (~240 m)	Deep Water Gas Hydrate (> 2000 m)
		All	High Flux	Bkgrnd			
	Area (km^2)	150.5	17.6	132.9	38.7	11.5	112
	% of area		11.7%	88.3%			
CH_4 Flux	µmol m^{-2} d^{-1}	3.8 ± 5.5	17.3 ± 4.8	2.0 ± 1.9	5.5 ± 6.5	0.30 ± 0.26	1.05 ± 0.61
	kg $(100\ km)^{-2}$ d^{-1}	6.1	27.7	3.2	8.8	0.48	1.67
CO_2 Flux	µmol m^{-2} d^{-1}	-18,037 ± 8,464	-33,317 ± 7,927	-16,017 ± 6,152	-24,944 ± 17,818	-2,166 ± 1,117	-42,001 ± 24,528
	kg $(100\ km)^{-2}$ d^{-1}	-86,597	-159,878	-76,903	-119,670	-10,397	-202,160
C-isotopes	$\delta^{13}C$-CH_4	-49.3 ± 0.6	-50.1 ± 0.4	-49.3 ± 0.5	-49.2 ± 0.5	-41.9 ± 0.8	-43.7 ± 1.9
	$\delta^{13}C$-CO_2	-8.33 ± 0.6	-7.50 ± 0.3	-8.39 ± 0.6	-6.42 ± 1.8	-7.89 ± 0.7	-6.05 ± 2.2
Surface Water	Temperature (°C)	6.08 ± 0.37	5.43 ± 0.13	6.18 ± 0.28	5.70 ± 0.19	5.67 ± 0.21	4.29 ± 0.95
	Salinity	34.73 ± 0.004	34.73 ± 0.002	34.73 ± 0.004	34.72 ± 0.009	34.75 ± 0.055	34.28 ± 0.352
	Diss. Oxygen (mg L^{-1})	10.55 ± 0.26	11.02 ± 0.22	10.48 ± 0.19	11.77 ± 0.47	10.13 ± 0.11	10.92 ± 0.50
	pH	8.038 ± 0.012	8.053 ± 0.014	8.035 ± 0.010	8.12 ± 0.04	8.16 ± 0.010	8.09 ± 0.0471
	FDOM (QSE)	-1.14 ± 0.04	-1.15 ± 0.03	-1.14 ± 0.05	-1.12 ± 0.04	-1.36 ± 0.03	-1.32 ± 0.07

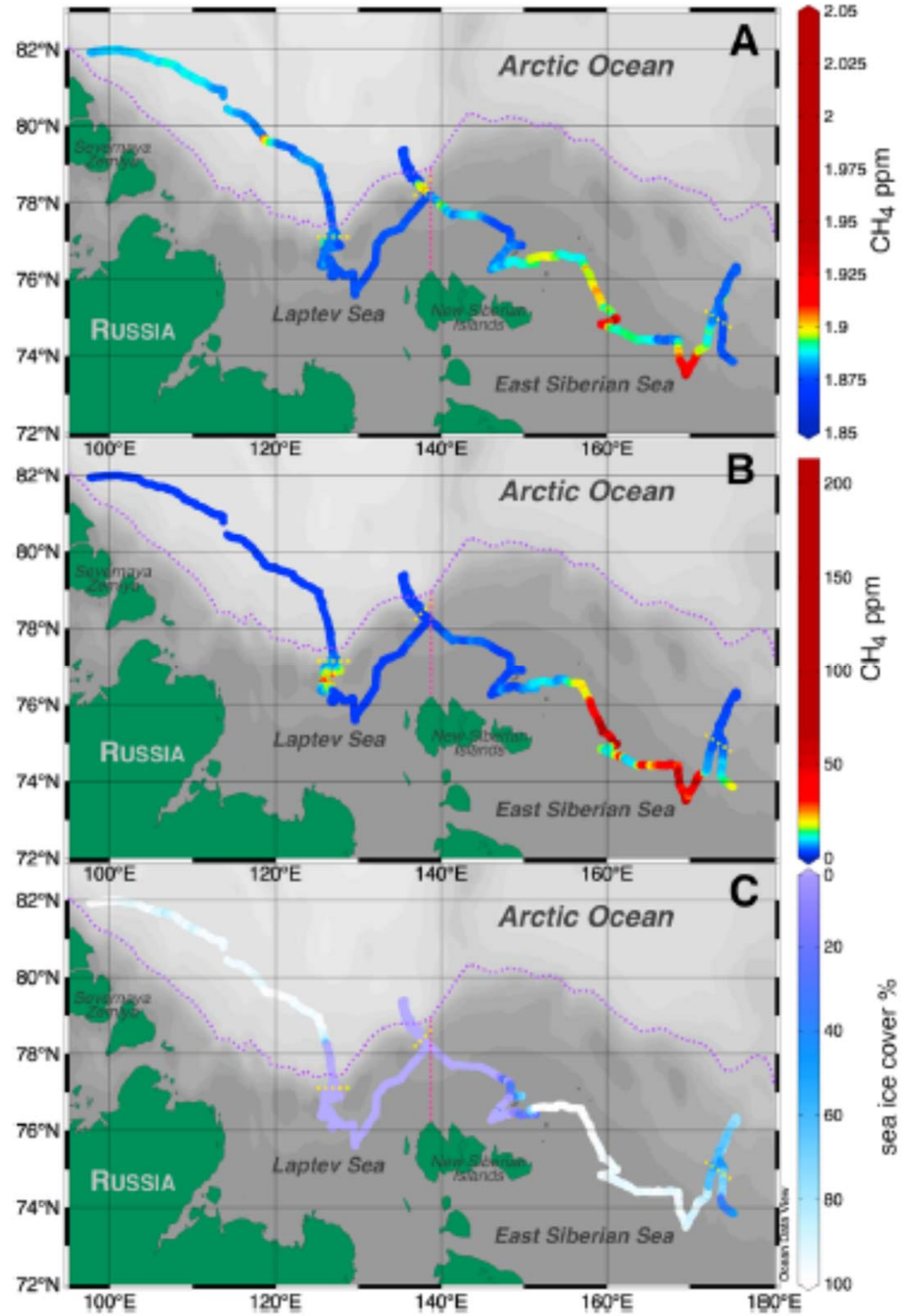
Pohlman *et al*. PNAS 2017

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

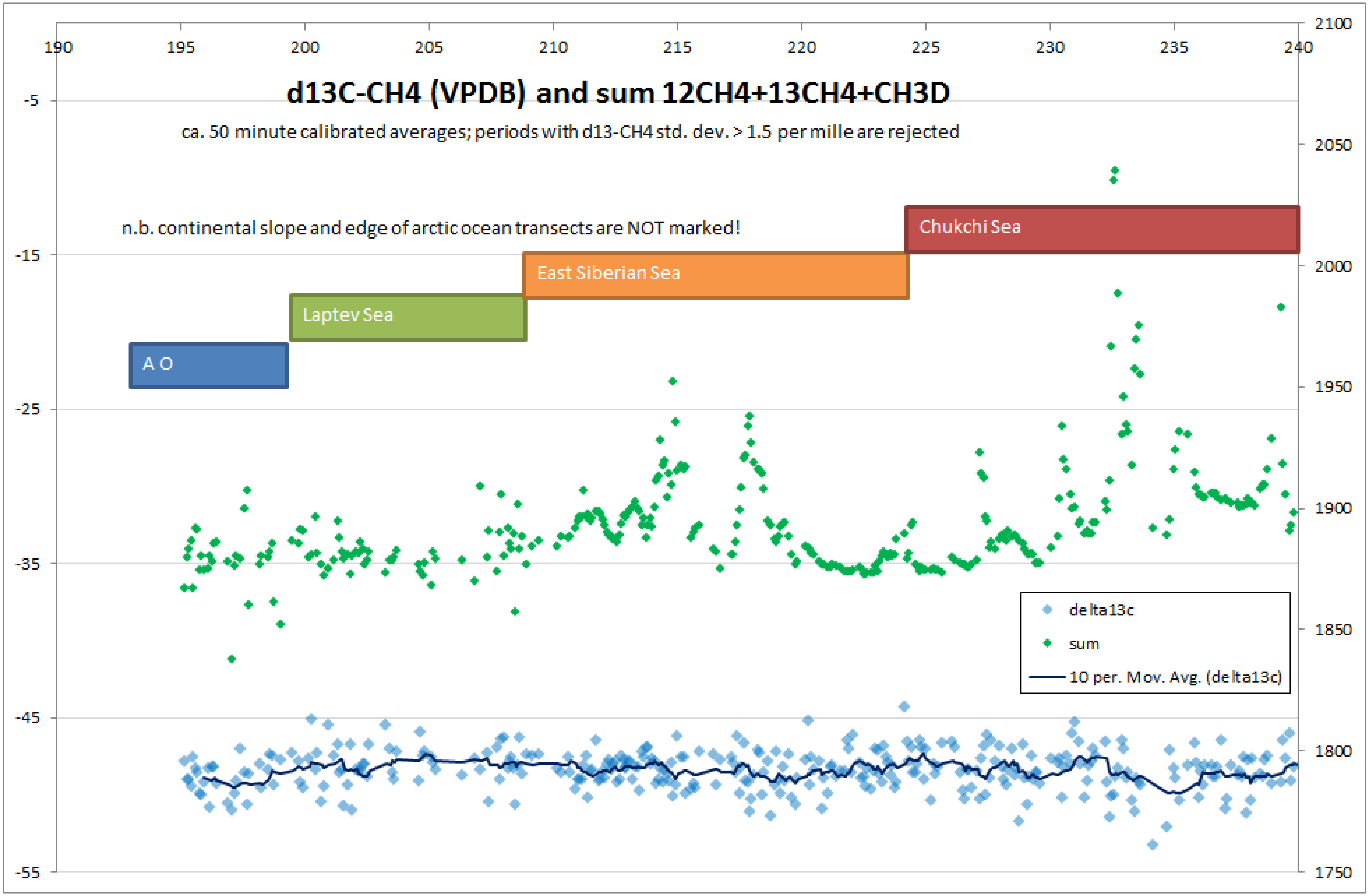
	$Tg\,y^{-1}$	Study
	Bottom-Up Estimates	
Lakes and ponds > 50°N	16.5 ± 9.2	*Wik et al.* [2016b]
Lakes and ponds > 60°N (bLake4Me model)	11.9	*Tan and Zhuang* [2015]
Rivers and streams > 54°N	0.3	*Bastviken et al.* [2011]
Rivers and streams > 54°N	7.5	*Stanley et al.* [2016]
Reservoirs > 54°N	1.2	*Bastviken 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.

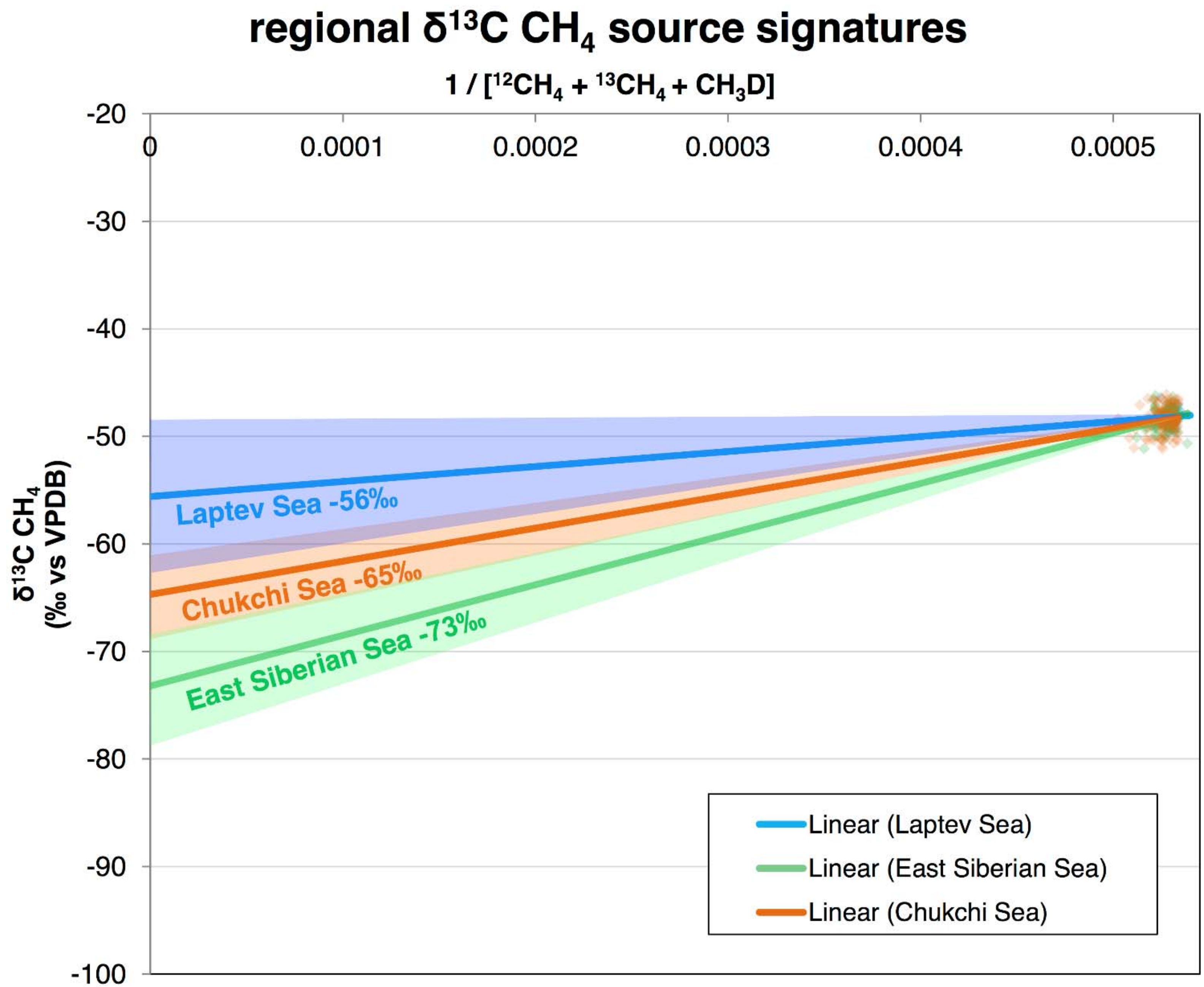
Thornton *et al*. GRL, 2016



Thornton *et al*. GRL, 2016

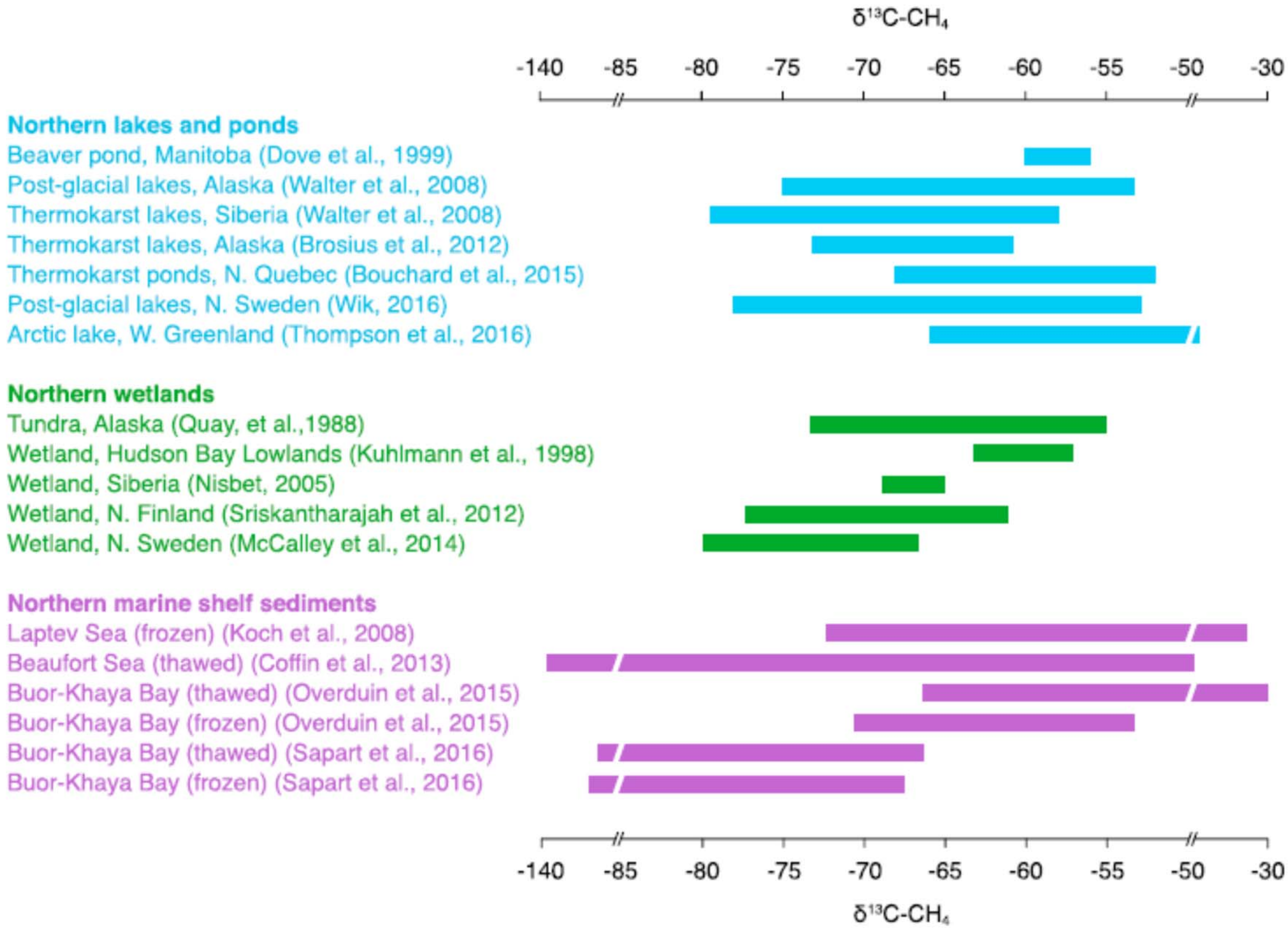


Thorton and Crill unpublished

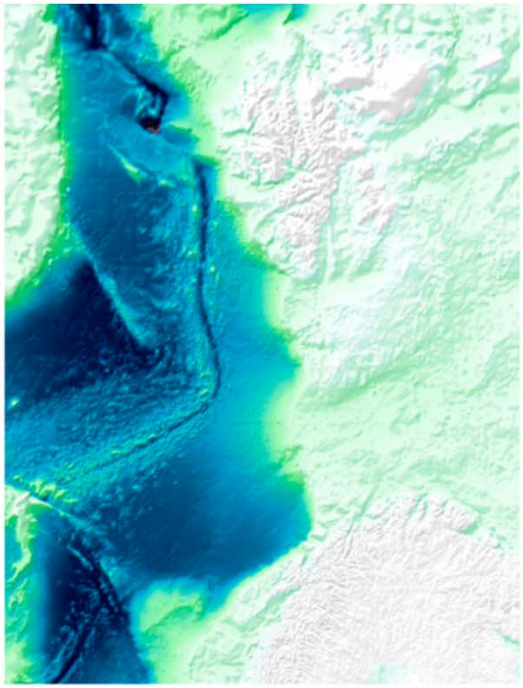


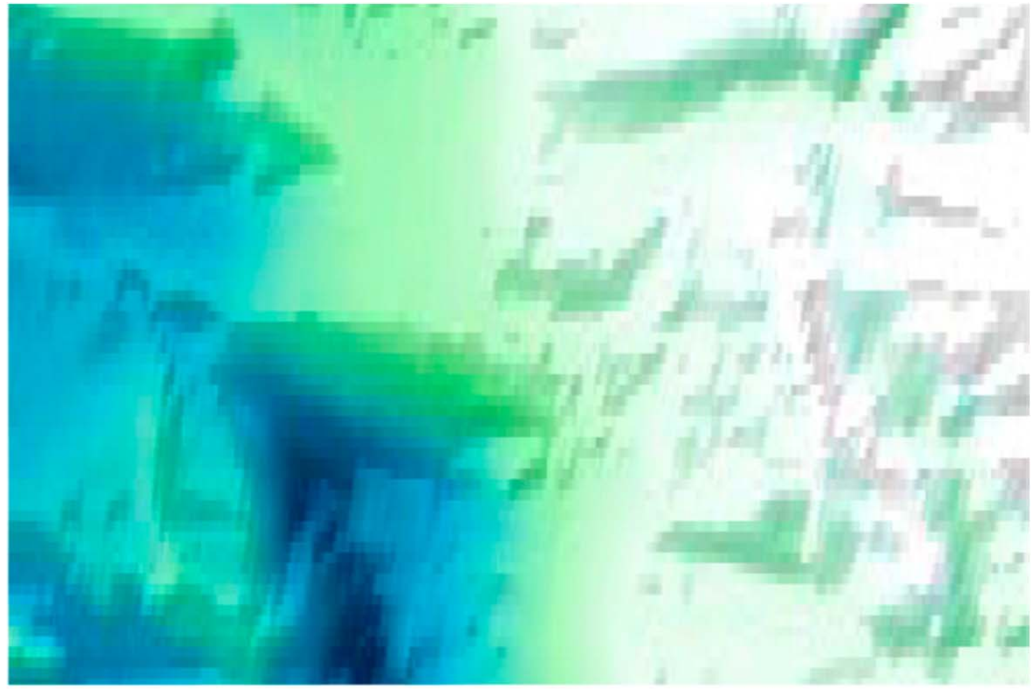
Thorton and Crill unpublished

Can $\delta^{13}C\text{-}CH_4$ help us?

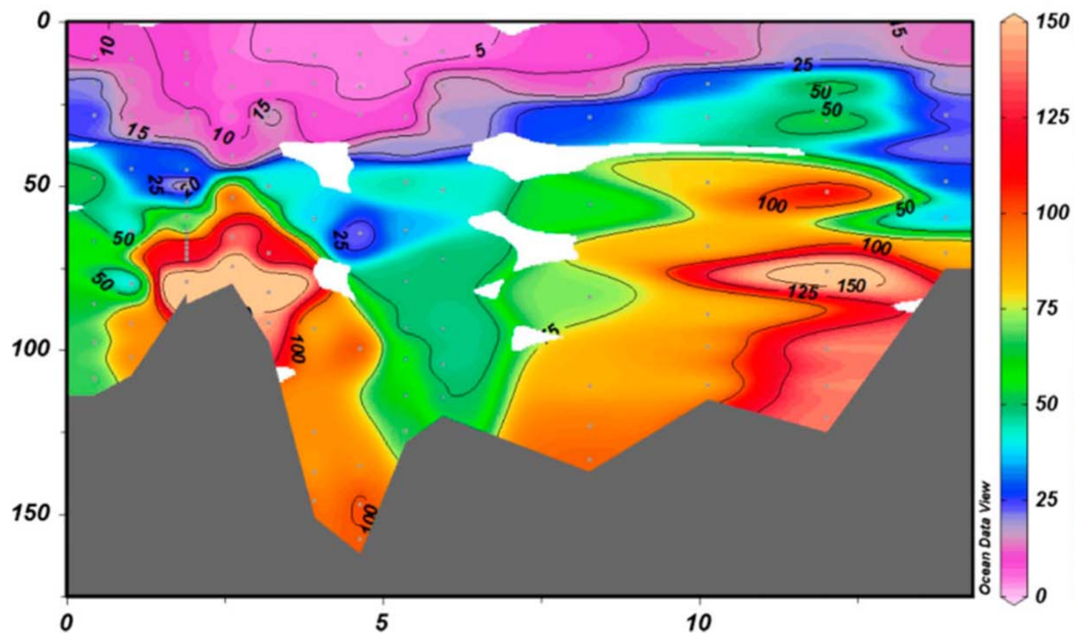


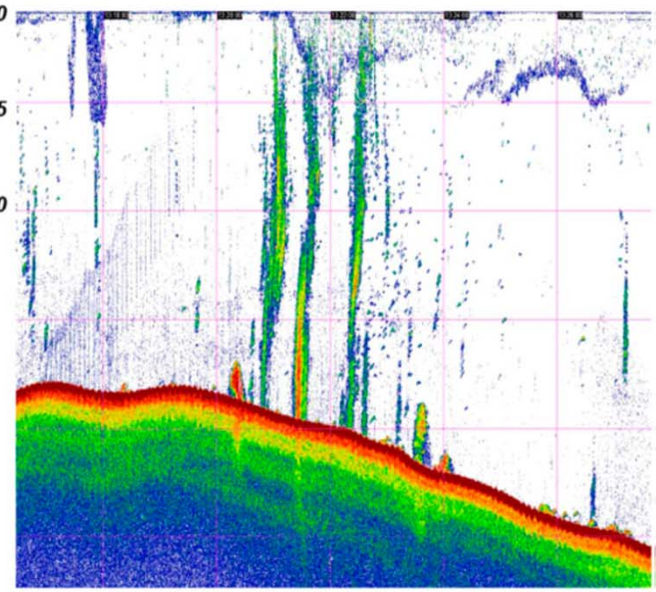
Thornton *et al*. GRL, 2016





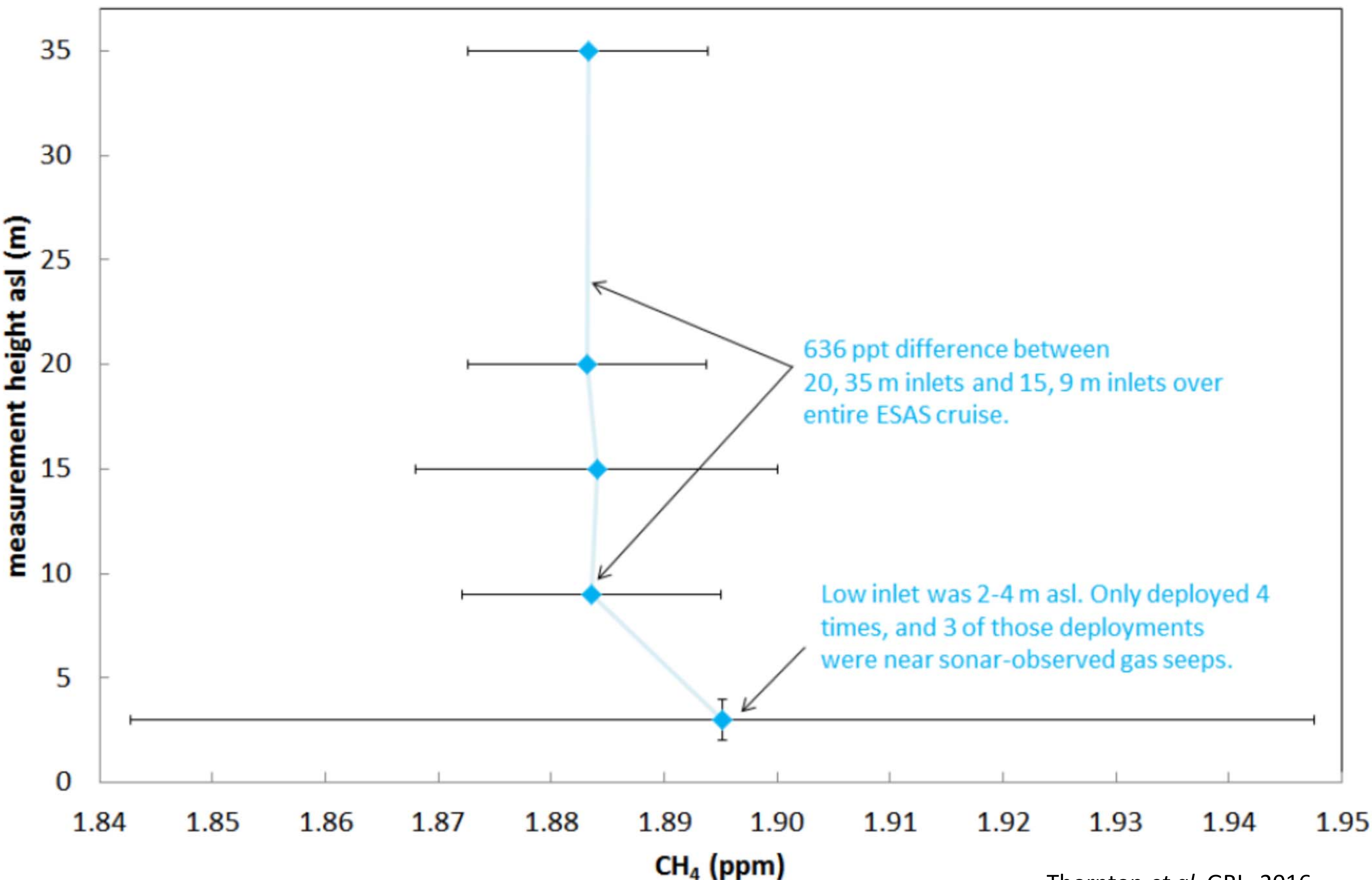
0.1 to 31.8 μmol m⁻² d⁻¹



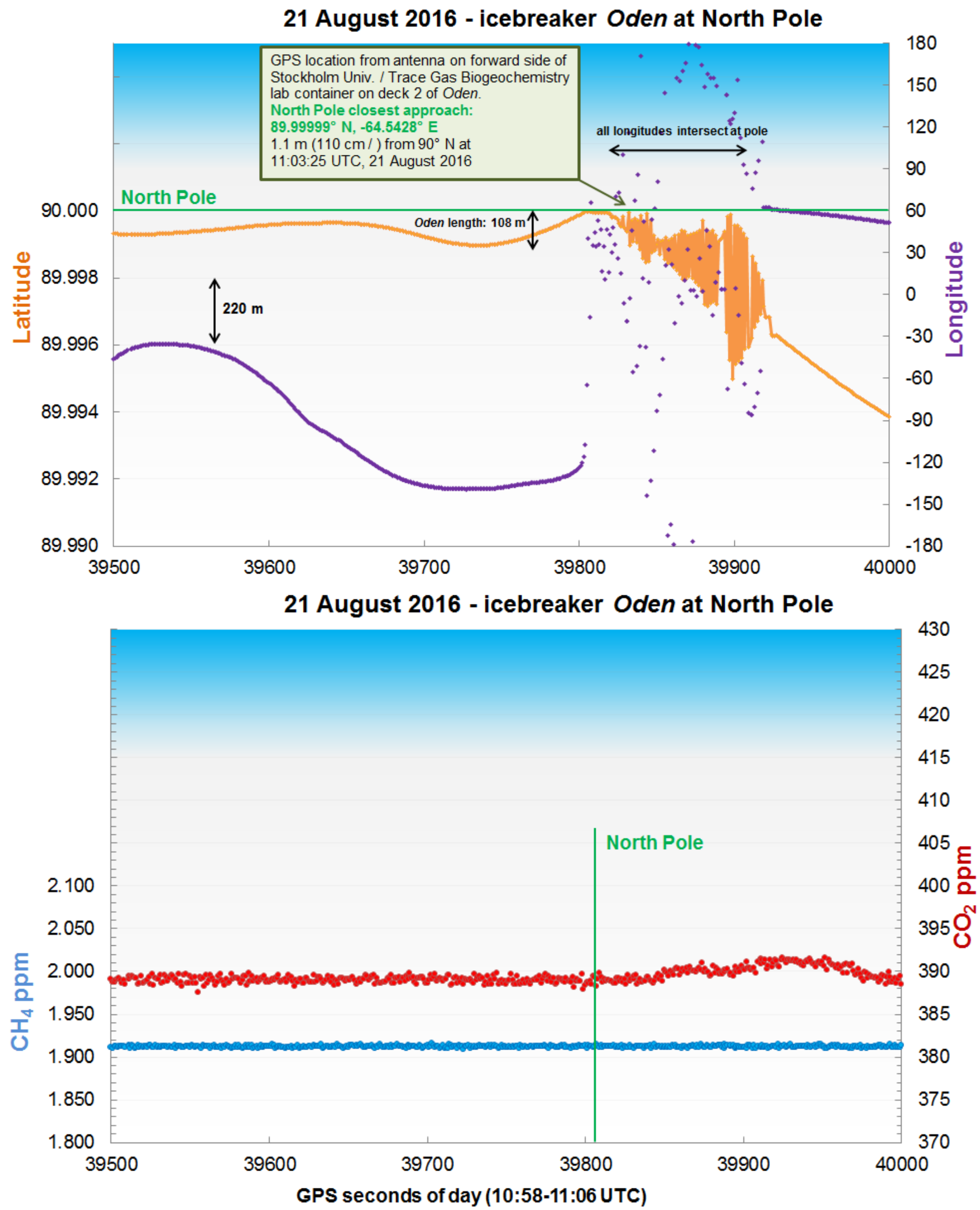


Pohlman *et al*. PNAS 2017

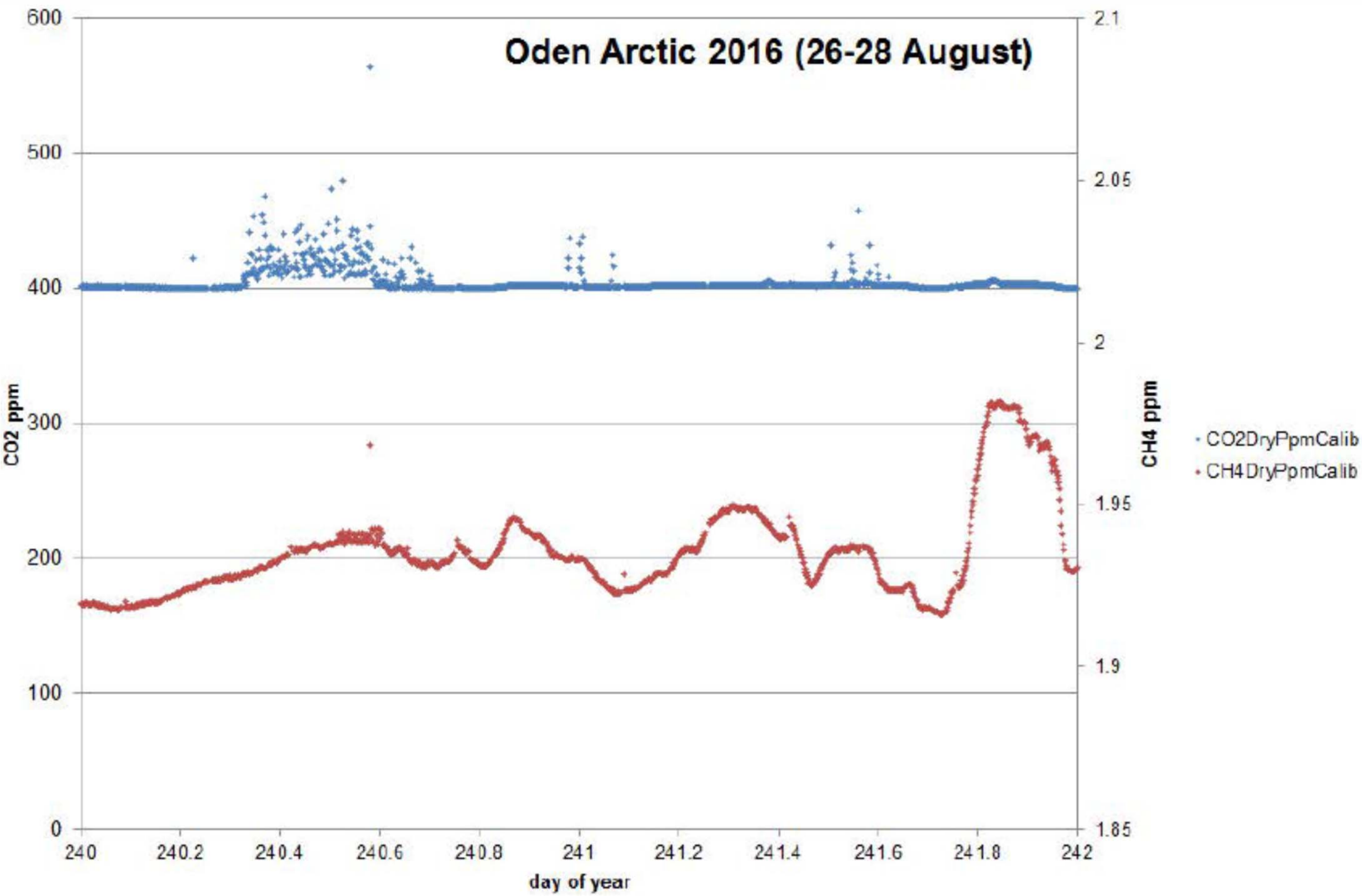
Figure S4: Observed vertical gradient of CH_4 in air over ESAS seas during SWERUS



Thornton *et al*. GRL, 2016



Thorton and Crill unpublished



Thorton and Crill unpublished

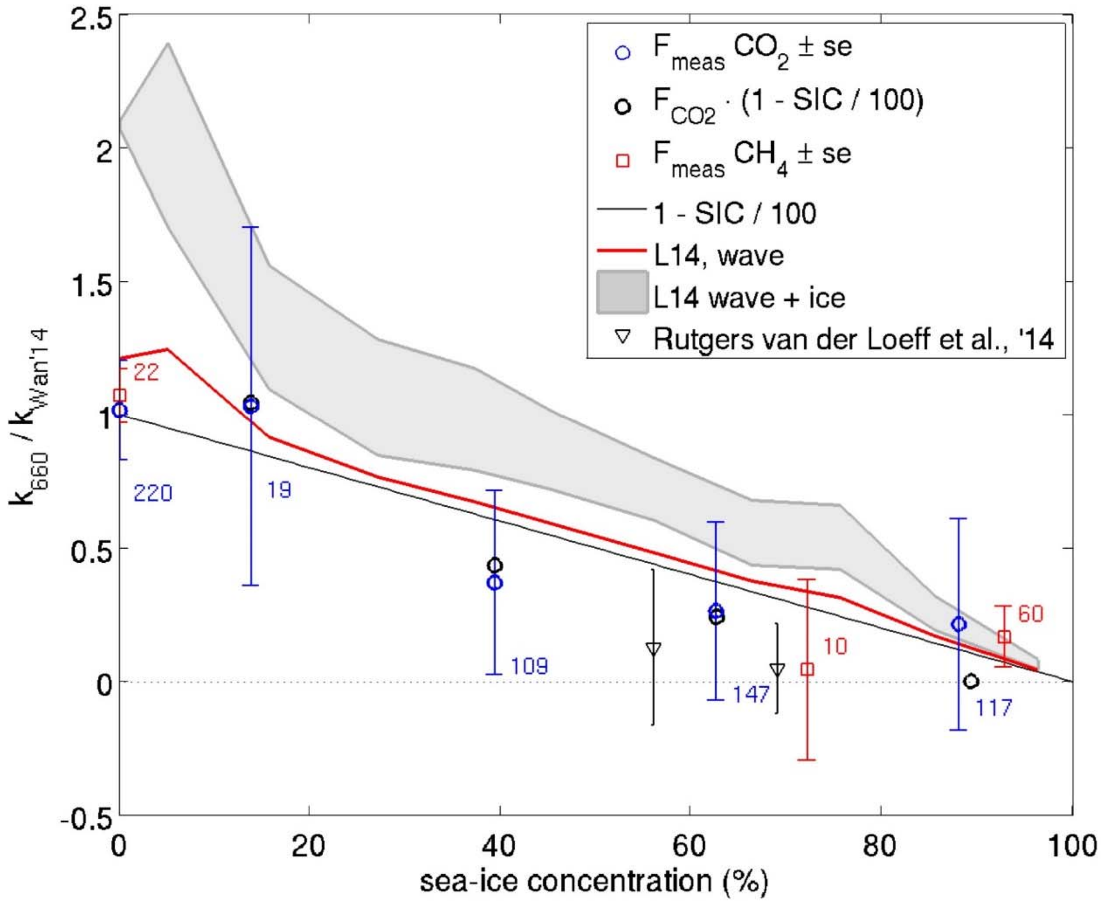
Thornton *et al*. GRL, 2016

Table 2. Calculated Mean Sea-Air CH_4 Fluxes by Region[a]

	Temporal (Cruise Track) Fluxes		Spatially Corrected Fluxes		Average Observed Wind Speed (Cruise Max 15.2 m s^{-1})
	(ng m^{-2} s^{-1})	(mg m^{-2} d^{-1})	(ng m^{-2} s^{-1})	(mg m^{-2} d^{-1})	m s^{-1} ± 1 SD
Arctic Ocean[b]	-	-	-	-	5.6 ± 1.3
Shelf breaks and upper continental slope	18.4	1.6	16	1.4	5.1 ± 1.8
Shelf seas (LS + ESS), ice-free regions	148	12.8	44	3.8	4.5 ± 3.3
LS (all)	190	16.5	45	3.9	2.9 ± 1.9
LS without seep areas	24.2	2.1	17	1.5	2.6 ± 1.8
ESS, ice-covered/melt regions[b]	287	24.8	190	16.4	5.1 ± 2.0
ESS, ice-free regions	41.2	3.6	43	3.7	8.5 ± 2.2

[a]Wind measurements were collected at 35 m above sea surface. The numbers presented are corrected down to a 10 m level.
[b]Includes ice-covered regions with sea ice where flux calculations represent theoretical fluxes for ice-free state and thus exceeding actual fluxes. No fluxes are calculated for Arctic Ocean region due to high sea ice coverage.

- EC trace gas fluxes used to determine air-sea *k* from an icebreaker in the Eastern Arctic
- Open water CO_2 results agree with bulk parameterizations
- *k* has a near-linear dependence on decreasing sea-ice concentration – in agreement with recent EC results from the Southern Ocean (Butterworth and Miller, 2016, GRL).



from Prytherch *et al*., 2017


Photo by Crill


Photo by Ian Brooks


Photo by Crill

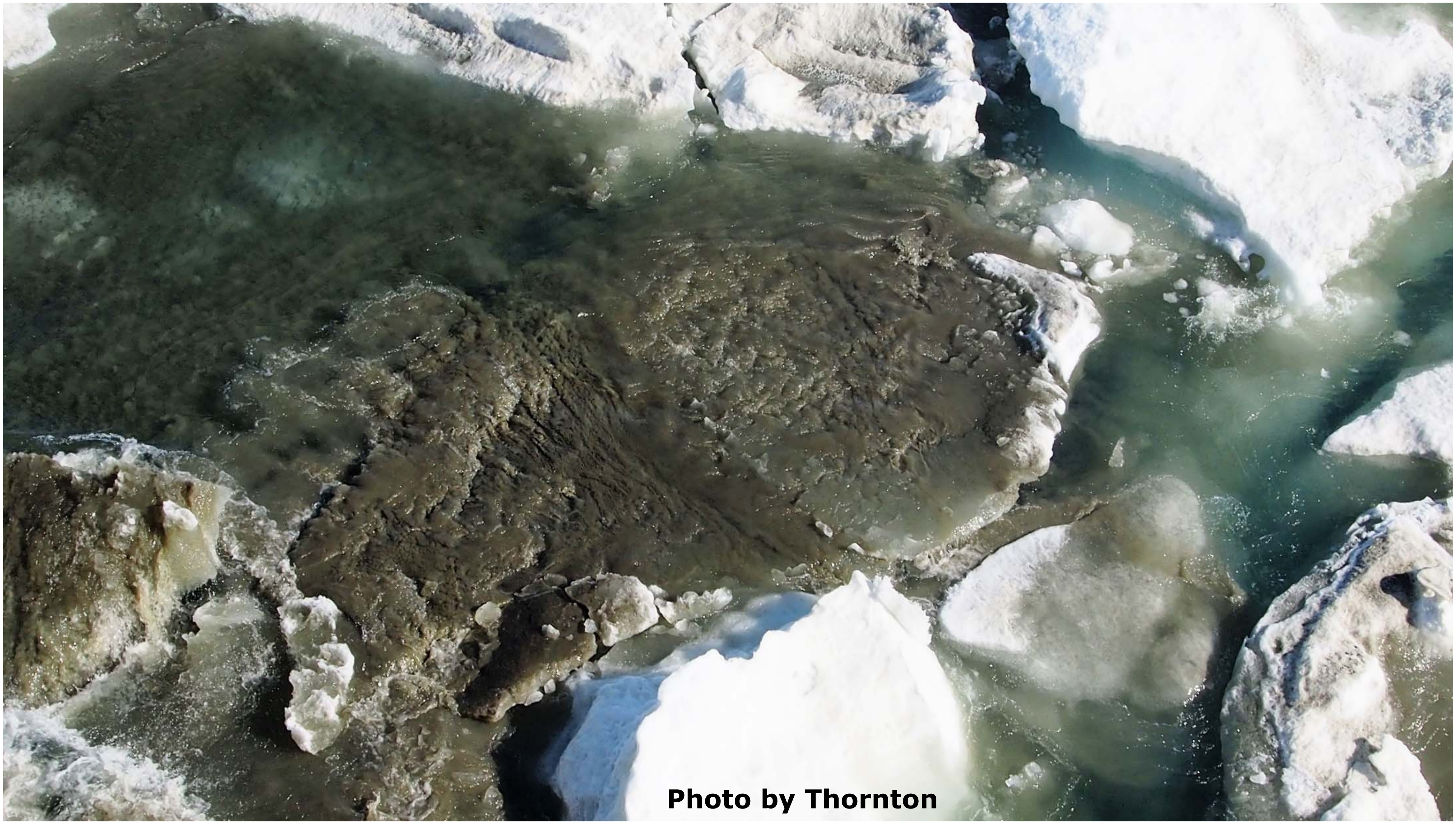
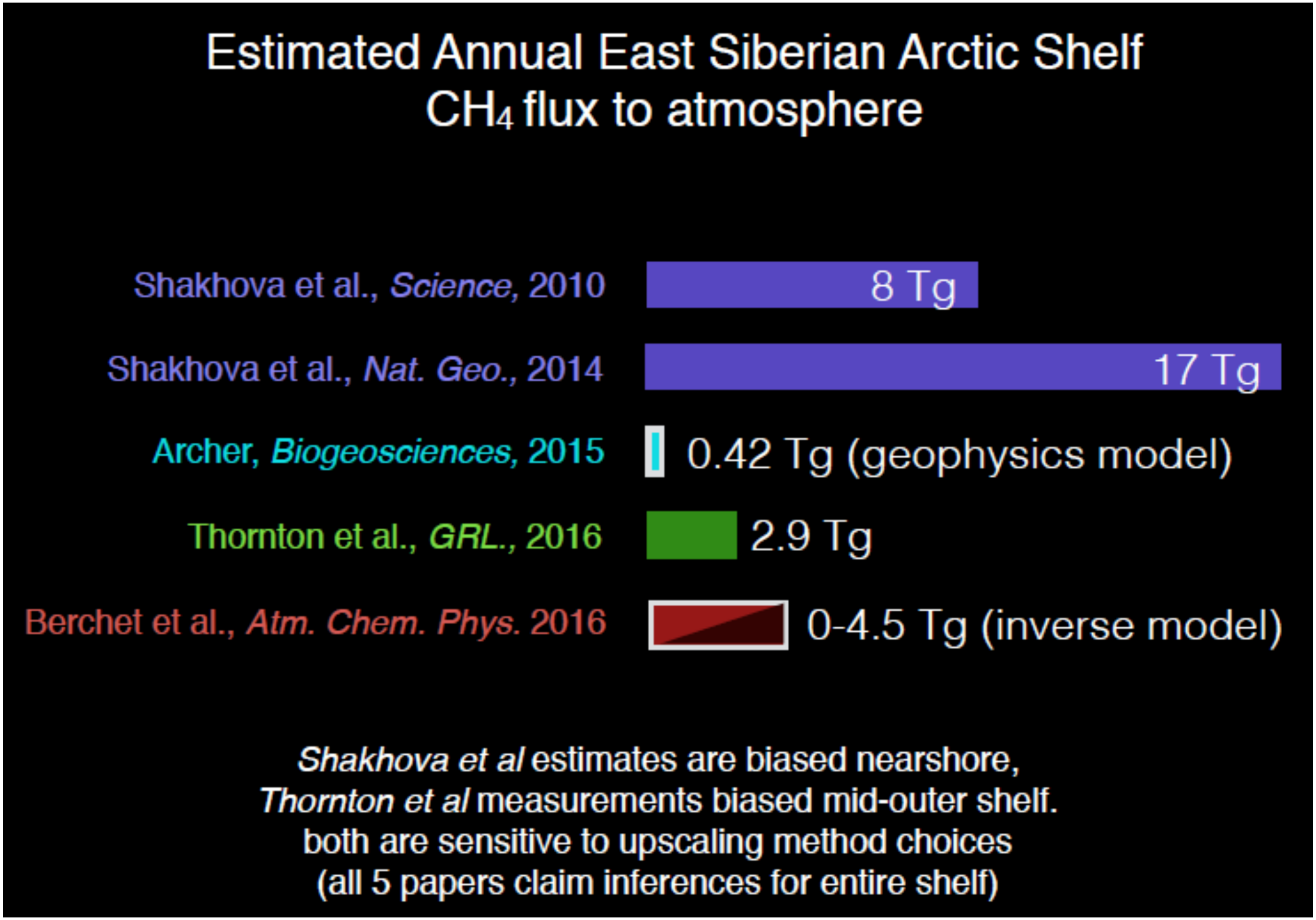


Photo by Thornton


Photo by Thornton


Estimated Annual East Siberian Arctic Shelf
CH_4 flux to atmosphere
Shakhova et al., *Science*, 2010
8 Tg
Shakhova et al., *Nat. Geo.*, 2014
17 Tg
Archer, *Biogeosciences*, 2015
0.42 Tg (geophysics model)
Thornton et al., *GRL.*, 2016
2.9 Tg
Berchet et al., *Atm. Chem. Phys.* 2016
0-4.5 Tg (inverse model)
Shakhova et al estimates are biased nearshore,
Thornton et al measurements biased mid-outer shelf.
both are sensitive to upscaling method choices
(all 5 papers claim inferences for entire shelf)

Thawing permafrost causes large blocks of tundra to slump into the Arctic Ocean.
USGS
http://www.windows.ucar.edu/tour/link=/earth/polar/images/slump_tundra_usgs_lg_jpg_image.html