Estimates of the Arctic Methane Budget

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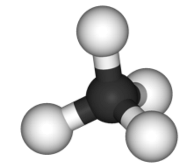
PCF Methane Is Highly Uncertain
Schuur et al., Nature (2015)



- Current best estimates are that there are 1035 ± 150 PgC in the top 300 cm of permafrost
  - Vulnerable C pool
- Expert judgment: 5-15% vulnerable to rapid mobilization by 2100
- Estimated CH4 release is 2-3%
- We do not know with confidence where, when, how much, or identity of potential PCF

REVIEW

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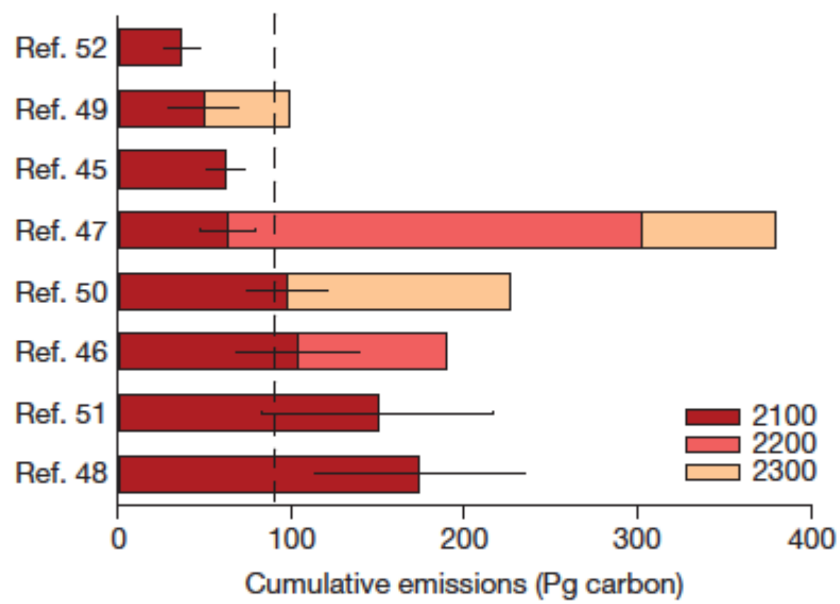
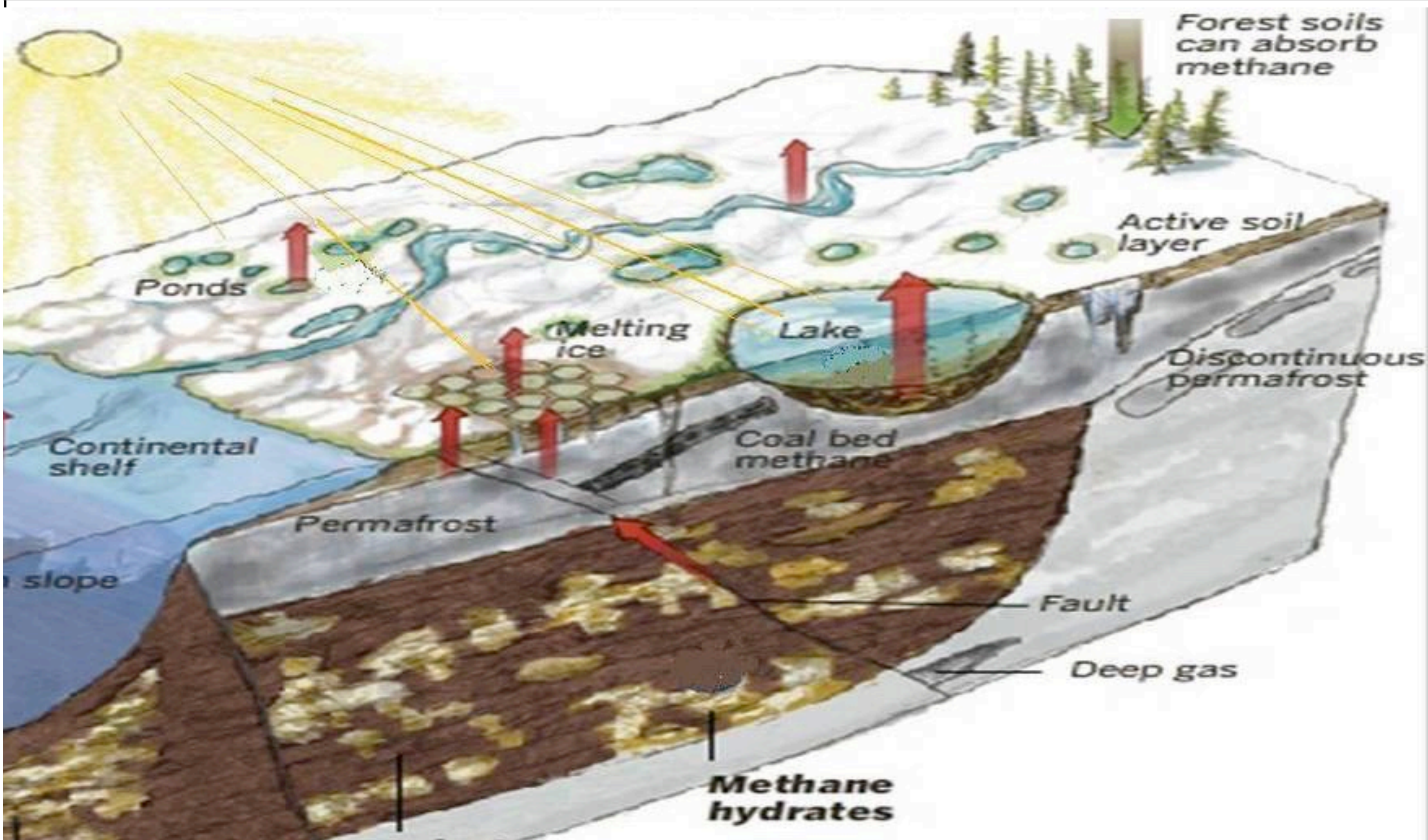
Climate change and the permafrost carbon feedback

E. A. G. Schuur[1,2], A. D. McGuire[3], C. Schädel[1,2], G. Grosse[4], J. W. Harden[5], D. J. Hayes[6], G. Hugelius[7], C. D. Koven[8], P. Kuhry[7], D. M. Lawrence[9], S. M. Natali[10], D. Olefeldt[11,12], V. E. Romanovsky[13,14], K. Schaefer[15], M. R. Turetsky[11], C. C. Treat[16] & J. E. Vonk[17]



Permafrost Carbon Feedback Threatens Large Arctic Methane Emissions



Estimates of the Northern Methane Budget

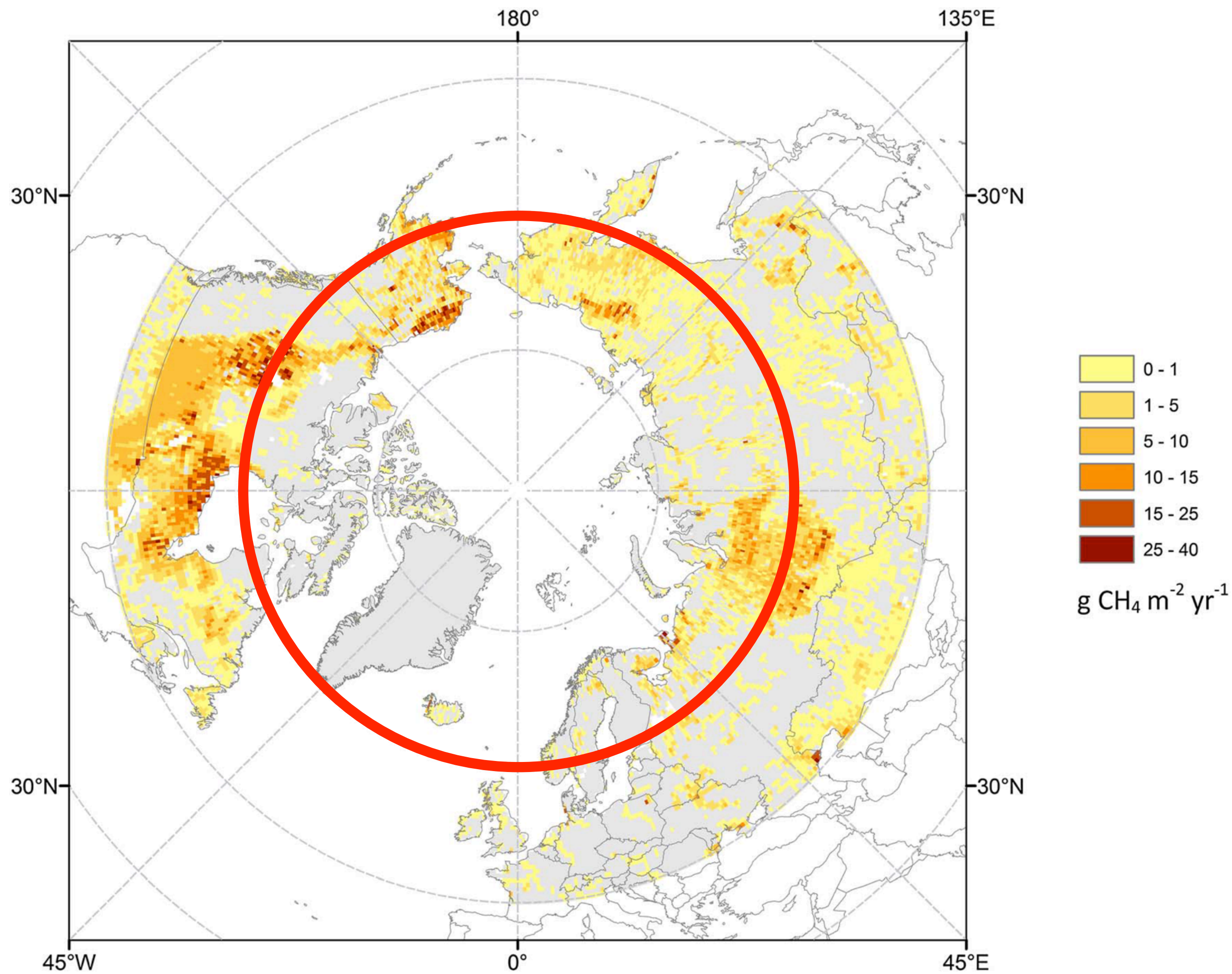
Tg CH4 yr-1	Period	Domain	Ref.
• 21 [15-24]	2003-2012	60 – 90 N	Saunois [2016]
• 83	2005-2013	50 – 90 N	Thompson [2016]
• ~27	2005-2013	60 – 90 N	Thompson [2016]*
• 31.1	1997-2006	Arctic Basin	McGuire [2010]
• 67.8 ± 6.2	1993 – 2004	45 – 90 N	Zhuang [2015]
• 48.7 [44-54]	1990 – 2009	45 – 90 N	Zhu [2013]

Notes:

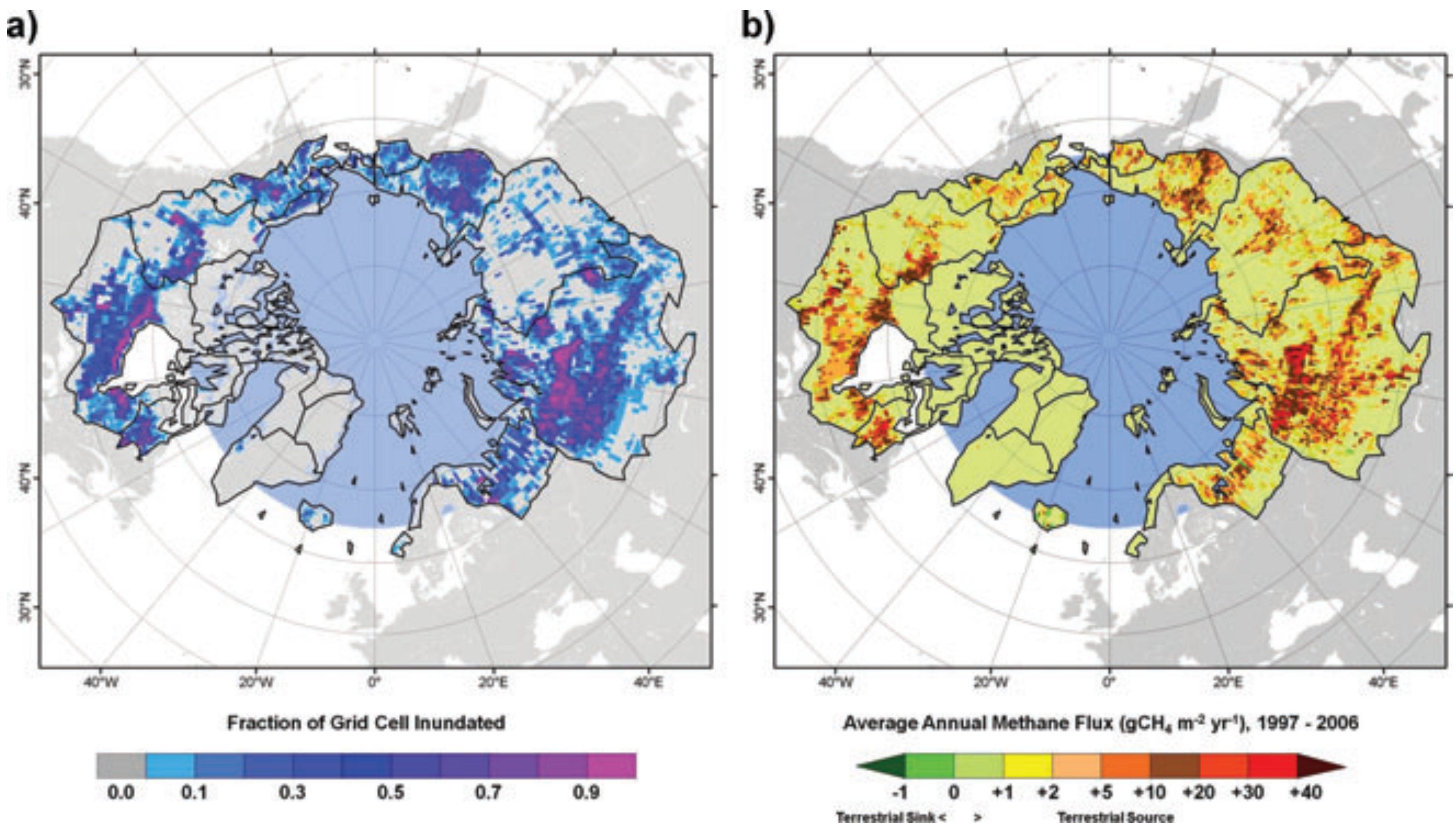
Thompson: 60% anthropogenic, 40% wetlands; uses JR-STATION sites

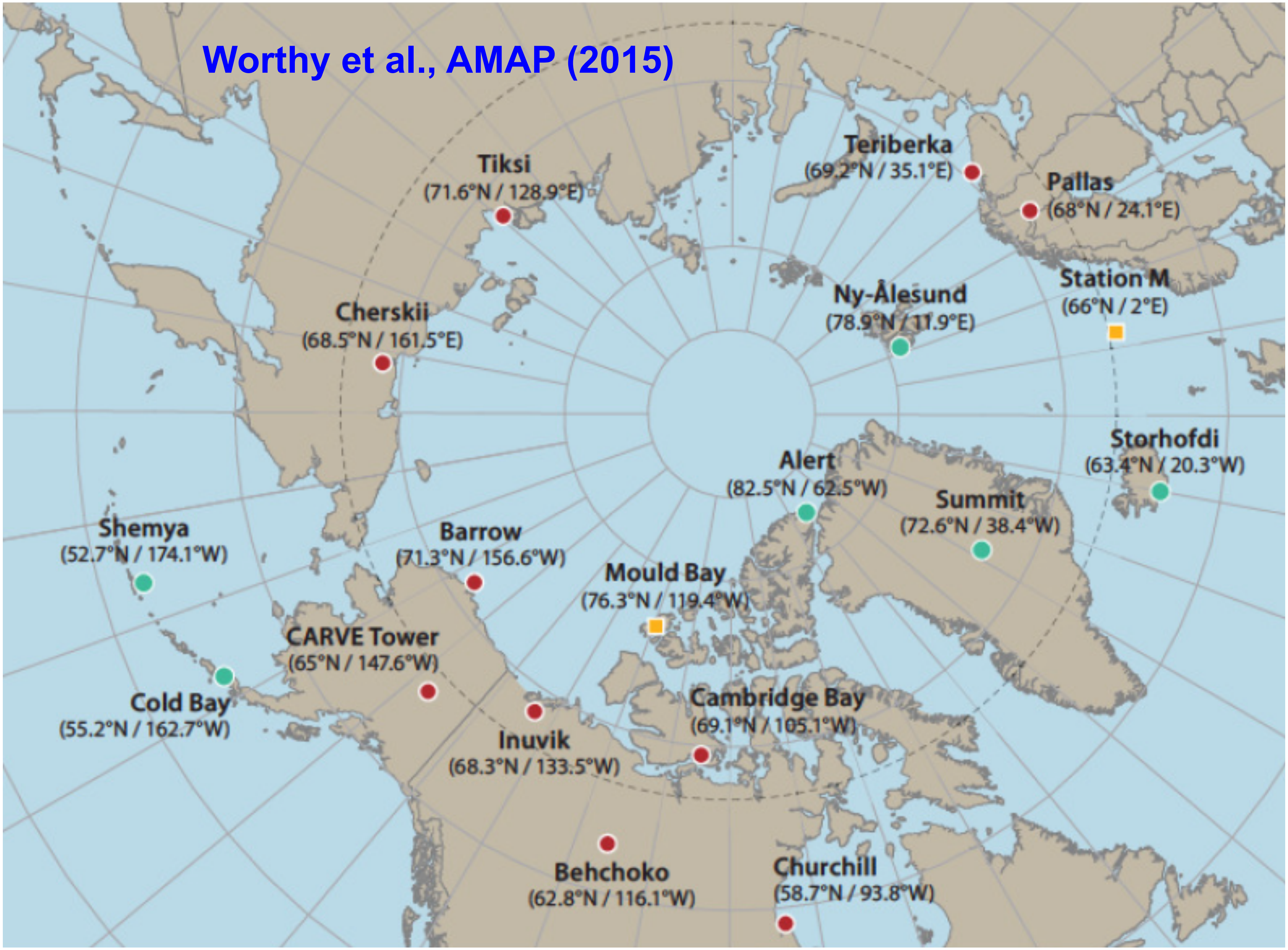
Zhuang: Uses dynamic inundation model

Estimated Methane Fluxes > 45 N
Zhu et al., GBC (2013)

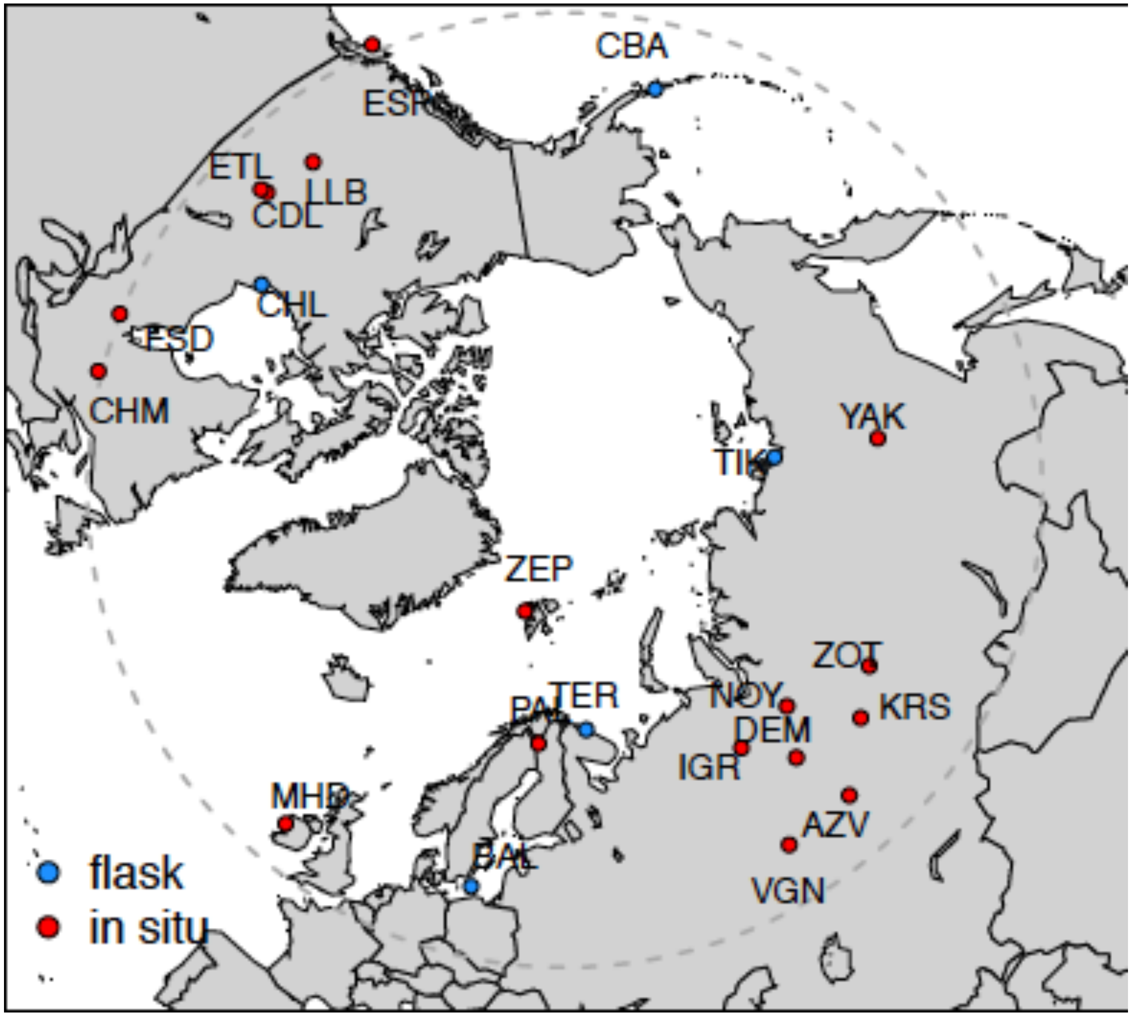


The Arctic Basin [McGuire (2010)]



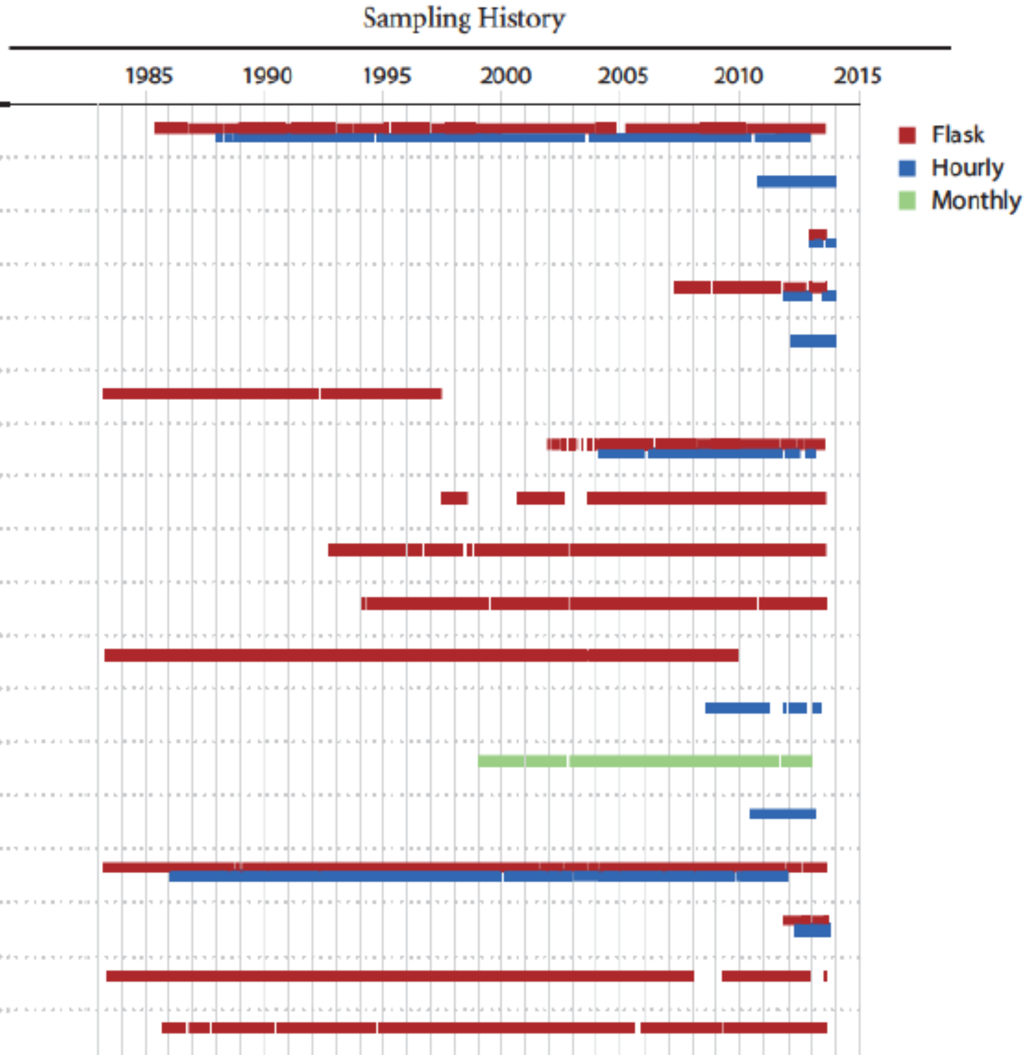

Worthy et al., AMAP (2015)
Tiksi
(71.6°N / 128.9°E)
Teriberka
(69.2°N / 35.1°E)
Pallas
(68°N / 24.1°E)
Station M
(66°N / 2°E)
Ny-Ålesund
(78.9°N / 11.9°E)
Cherskii
(68.5°N / 161.5°E)
Storhofdi
(63.4°N / 20.3°W)
Alert
(82.5°N / 62.5°W)
Summit
(72.6°N / 38.4°W)
Shemya
(52.7°N / 174.1°W)
Barrow
(71.3°N / 156.6°W)
Mould Bay
(76.3°N / 119.4°W)
CARVE Tower
(65°N / 147.6°W)
Cold Bay
(55.2°N / 162.7°W)
Inuvik
(68.3°N / 133.5°W)
Cambridge Bay
(69.1°N / 105.1°W)
Behchoko
(62.8°N / 116.1°W)
Churchill
(58.7°N / 93.8°W)

Arctic Methane Observations
Thompson et al., ACPD (2017)



Available Arctic Methane Observations
Worthy et al., AMAP (2015)

Station name (Country)	Latitude / Longitude	Height, m above sea level
Alert (Canada)	82.5°N / 62.5°W	210
Behchoko (Canada)	62.8°N / 116.1°W	179
Cambridge Bay (Canada)	69.1°N / 105.1°W	38
Churchill (Canada)	58.7°N / 93.8°W	29
Inuvik (Canada)	68.3°N / 133.5°W	100
Mould Bay (Canada)	76.3°N / 119.4°W	30
Pallas (Finland)	68°N / 24.1°E	560
Summit (Greenland)	72.6°N / 38.4°W	3238
Storhofdi (Iceland)	63.4°N / 20.3°W	118
Ny-Ålesund (Norway)	78.9°N / 11.9°E	474
Station M (Norway)	66°N / 2°E	0
Cherskii (Russia)	68.5°N / 161.5°E	30
Teriberka (Russia)	69.2°N / 35.1°E	40
Tiksi (Russia)	71.6°N / 128.9°E	8
Barrow (USA)	71.3°N / 156.6°W	11
CARVE Tower (USA)	65°N / 147.6°W	611
Cold Bay (USA)	55.2°N / 162.7°W	21
Shemya (USA)	52.7°N / 174.1°W	40

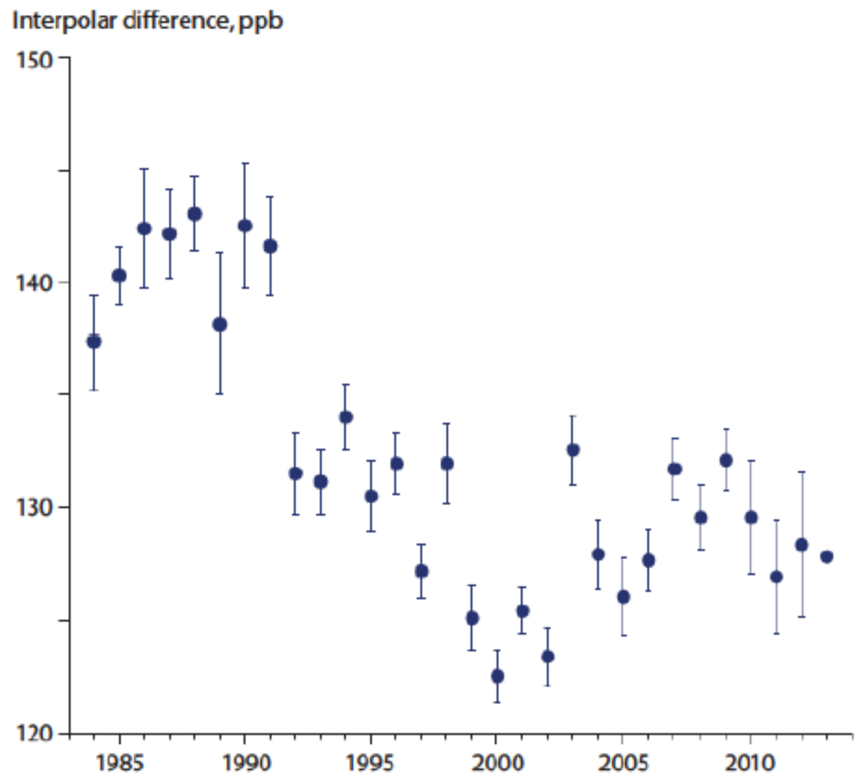


Other Observations Help Constrain Arctic Methane Emissions Estimates

Isotopes

Source	$\delta^{13}C_{CH4}$ ‰
Coal and industry, Europe	-35 ± 10
Natural gas, UK North Sea	-35 ± 5
Natural gas, Siberia (exported to EU)	-50 ± 5
Natural gas, Alberta/BC	-55 ± 10
Ruminants, C4 diet	-50 ± 5
Ruminants, C3 diet	-70 ± 5
Arctic wetlands, Finland	-70 ± 5
Boreal wetlands, Canada	-65 ± 5
Biomass burning, boreal vegetation	-28 ± 2
Landfills, Europe	-57 ± 4
Thermokarst lakes	-58 to -83
Hydrates, Arctic	-55 ± 10

Interpolar Difference

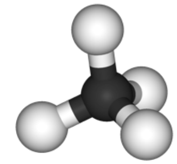


Worthy et al., AMAP (2015)

East Siberian Arctic Shelf (ESAS) Source

- Shakhova (2010) suggest up to 8 TgCH4 yr-1 source in ESAS
- Shakhova (2015) increase this estimate to up to 17 TgCH4 yr-1
- Berchet (2016) revise ESAS source estimate to 0.0 – 4.5 TgCH4 yr-1 for 2008/9 based on year round atmospheric methane measurements
- Thornton (2016) also suggest fluxes in the ~2 TgCH4 yr-1 range with a short season (Jul – Sep) for intense methane emissions

Summary, Part 1



- Current atmospheric observing network constrains estimates of the Arctic methane budget to ± 5 TgCH4 yr-1

- The current network is inadequate to characterize specific regional sources accurately

- Current inversion estimates use inconsistent domains and incomplete inclusion of existing ground-based and airborne observations

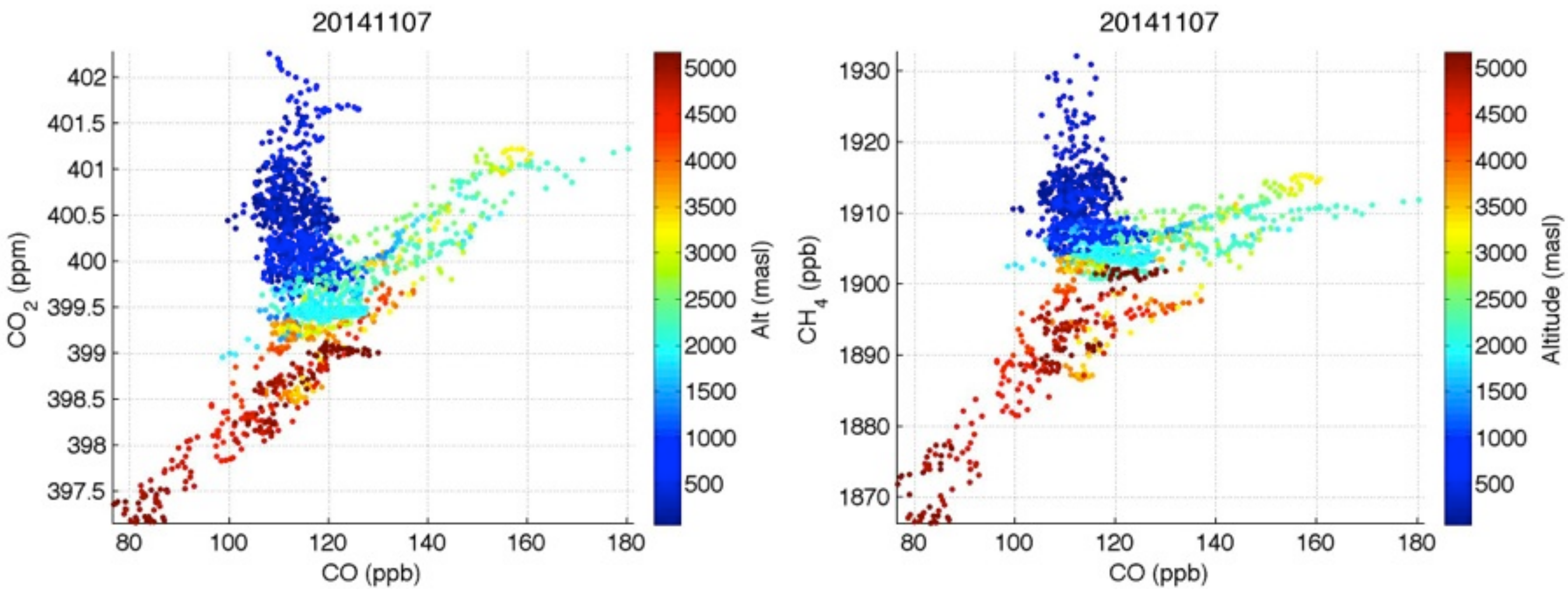
- Recent evidence suggests the ESAS source is 0.0 – 4.5 TgCH4 yr-1, not 8 – 17 TgCH4 yr-1

CARVE 2012–2015 Cumulative Flight Lines

CARVE By The Numbers

- 27 Campaigns
- 192 Flight Days
- 1080 Flight Hours
- >150,000 naut miles

7 Nov 2014/DOY 311 CARVE Science Flight
North Slope Emissions Still Evident

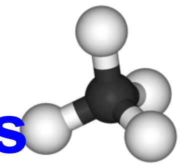


CO2 v CO and CH4 v CO correlations clearly show that the near surface regimes differ distinctly from the correlations observed aloft

Small but significant emissions still observed despite DOY 311, deep snow cover and surface ice

A. Karion, C Sweeney

Merging Airborne & EC Flux Tower Data to Quantify Year-round North Slope CH_4 Fluxes



CrossMark

Cold season emissions dominate the Arctic tundra methane budget

Donatella Zona[a,b,1,2], Beniamino Gioli[c,2], Róisín Commane[d], Jakob Lindaas[d], Steven C. Wofsy[d], Charles E. Miller[e], Steven J. Dinardo[e], Sigrid Dengel[f], Colm Sweeney[g,h], Anna Karion[g], Rachel Y.-W. Chang[d,i], John M. Henderson[j], Patrick C. Murphy[a], Jordan P. Goodrich[a], Virginie Moreaux[a], Anna Liljedahl[k,l], Jennifer D. Watts[m], John S. Kimball[m], David A. Lipson[a], and Walter C. Oechel[a,n]

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Edited by Mark H. Thiemens, University of California at San Diego, La Jolla, CA, and approved November 17, 2015 (received for review August 12, 2015)

Arctic terrestrial ecosystems are major global sources of methane (CH_4); hence, it is important to understand the seasonal and climatic controls on CH_4 emissions from these systems. Here, we report year-round CH_4 emissions from Alaskan Arctic tundra eddy flux sites and regional fluxes derived from aircraft data. We find that emissions during the cold season (September to May) account for ≥50% of the annual CH_4 flux, with the highest emissions from noninundated upland tundra. A major fraction of cold season emissions occur during the "zero curtain" period, when subsurface soil temperatures are poised near 0 °C. The zero curtain may persist longer than the growing season, and CH_4 emissions are enhanced when the duration is extended by a deep thawed layer as can occur with thick snow cover. Regional scale fluxes of CH_4 derived from aircraft data demonstrate the large spatial extent of late season CH_4 emissions. Scaled to the circumpolar Arctic, cold season fluxes from tundra total 12 ± 5 (95% confidence interval) Tg CH_4 y^{-1}, ~25% of global emissions from extratropical wetlands, or ~6% of total global wetland methane emissions. The dominance of late-season emissions, sensitivity to soil environmental conditions, and importance of dry tundra are not currently simulated in most global climate models. Because Arctic warming disproportionally impacts the cold season, our results suggest that higher cold-season CH_4 emissions will result from observed and predicted increases in snow thickness, active layer depth, and soil temperature, representing important positive feedbacks on climate warming.

permafrost | aircraft | fall | winter | warming

Emissions of methane (CH_4) from Arctic terrestrial ecosystems could increase dramatically in response to climate change (1–3), a potentially significant positive feedback on climate warming. High latitudes have warmed at a rate almost two times faster than the Northern Hemisphere mean over the past century, with the most intense warming in the colder seasons (4) [up to 4 °C in winter in 30 y (5)]. Poor understanding of controls on CH_4 emissions outside of the summer season (6–10) represents a large source of uncertainty for the Arctic CH_4 budget. Warmer air temperatures and increased snowfall can potentially increase soil temperatures and deepen the seasonal thawed layer, stimulating CH_4 and CO_2 emissions from the vast stores of labile organic matter in the Arctic (11). The overwhelming majority of prior studies of CH_4 fluxes in the Arctic have been carried out during the summer months (12–15). However, the fall, winter, and spring months represent 70–80% of the year in the Arctic and have been shown to have significant emissions of CO_2 (16–18). The few measurements of CH_4 fluxes in the Arctic that extend into the fall (6, 7, 9, 10) show complex patterns of CH_4 emissions, with a number indicating high fluxes (7, 10). Winter and early spring data appear to be absent in Arctic tundra over continuous permafrost.

Beginning usually in late August or early September, the seasonally thawed active layer (i.e., ~30–50 cm, near-surface soil layer over the permafrost that thaws during the summer growing season) in the Arctic starts freezing both from the top and the bottom, moving downward from the frozen, often snow-covered soil surface and upward from the permafrost layer (Fig. 1). A significant portion of the active layer can stay unfrozen for months, with temperatures poised near 0 °C because of the large thermal mass and latent heat of fusion of water in wet soils, and for the insulating effects of snow cover and low density surface

Significance

Arctic ecosystems are major global sources of methane. We report that emissions during the cold season (September to May) contribute ≥50% of annual sources of methane from Alaskan tundra, based on fluxes obtained from eddy covariance sites and from regional fluxes calculated from aircraft data. The largest emissions were observed at the driest site (<5% inundation). Emissions of methane in the cold season are linked to the extended "zero curtain" period, where soil temperatures are poised near 0 °C, indicating that total emissions are very sensitive to soil climate and related factors, such as snow depth. The dominance of late season emissions, sensitivity to soil conditions, and importance of dry tundra are not currently simulated in most global climate models.

Author contributions: D.Z., D.A.L., and W.C.O. designed research; D.Z., D.A.L., and W.C.O. performed research; R.C., J.L., S.C.W., C.E.M., S.J.D., C.S., A.K., R.Y.-W.C., and J.M.H. supported the collection and preparation of the Carbon in Arctic Reservoirs Vulnerability Experiment data; J.D.W. and J.S.K. contributed new reagents/analytic tools; D.Z., B.G., P.C.M., J.P.G., V.M., A.L., J.D.W., J.S.K., and W.C.O. analyzed data; R.C., J.L., and S.C.W. analyzed the aircraft data; and D.Z., B.G., R.C., S.C.W., C.E.M., S.J.D., S.D., C.S., A.K., R.Y.-W.C., J.M.H., P.C.M., A.L., J.D.W., J.S.K., D.A.L., and W.C.O. wrote the paper.

The authors declare no conflict of interest.

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Freely available online through the PNAS open access option.

Data deposition: The data reported in this paper have been deposited in the Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge data repository (dx.doi.org/10.3334/ORNLDAAC/1300 and dx.doi.org/10.3334/CDIAC/hippo_010).

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[2]D.Z. and B.G. contributed equally to this work.

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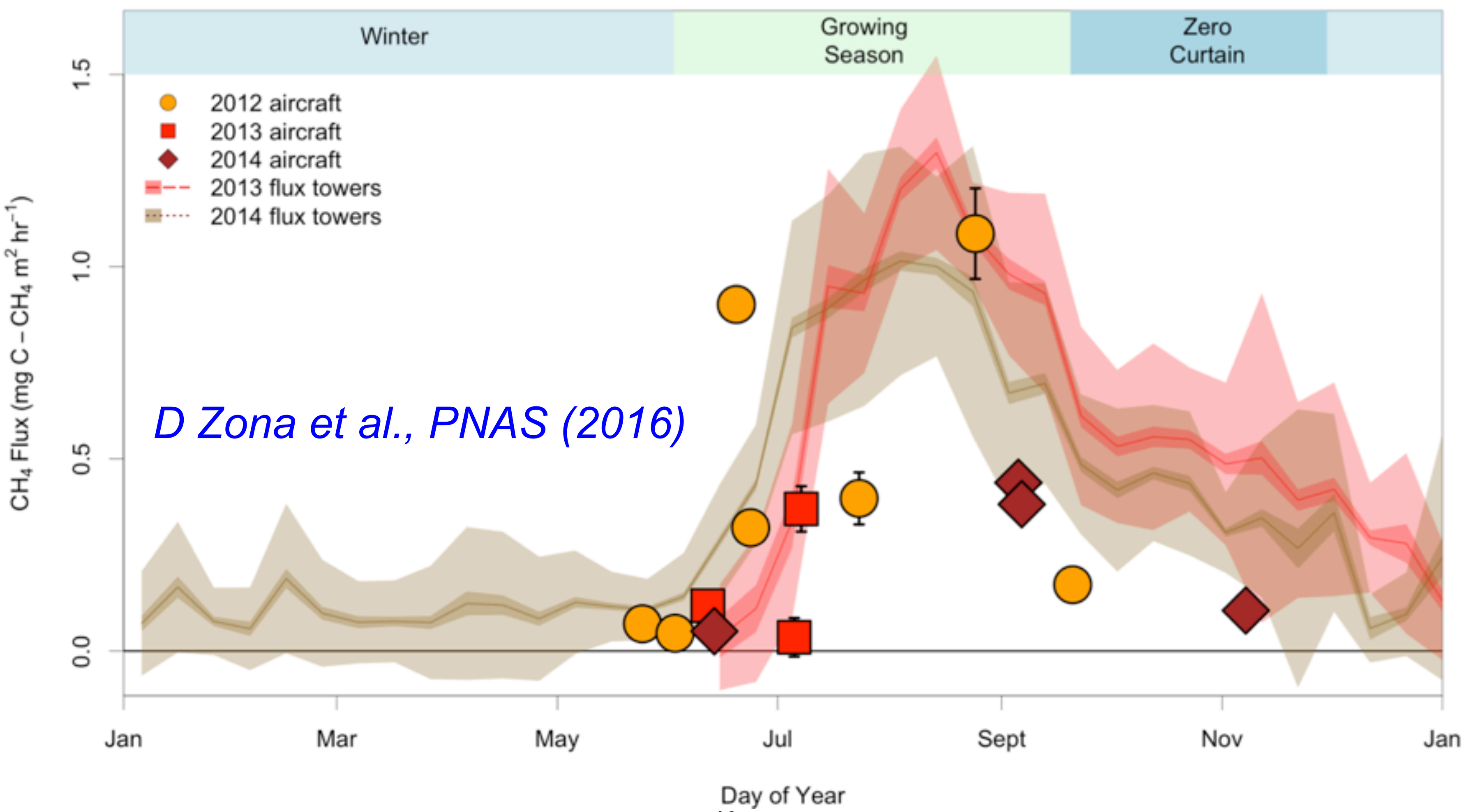
www.pnas.org/cgi/doi/10.1073/pnas.1516017113

5

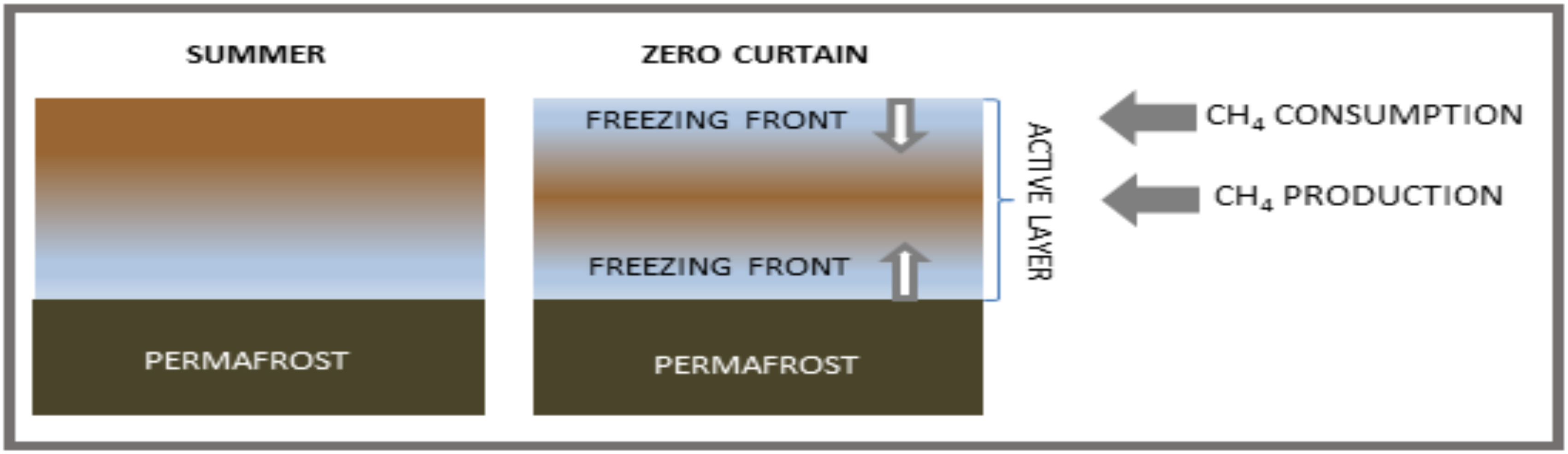
oal I

More than 50% of the North Slope CH4 Flux Occurs During the Cold Season

*** Year-round CH4 flux tower + CARVE North Slope flights***



Zero Curtain Period is Longer than Summer Growing Season

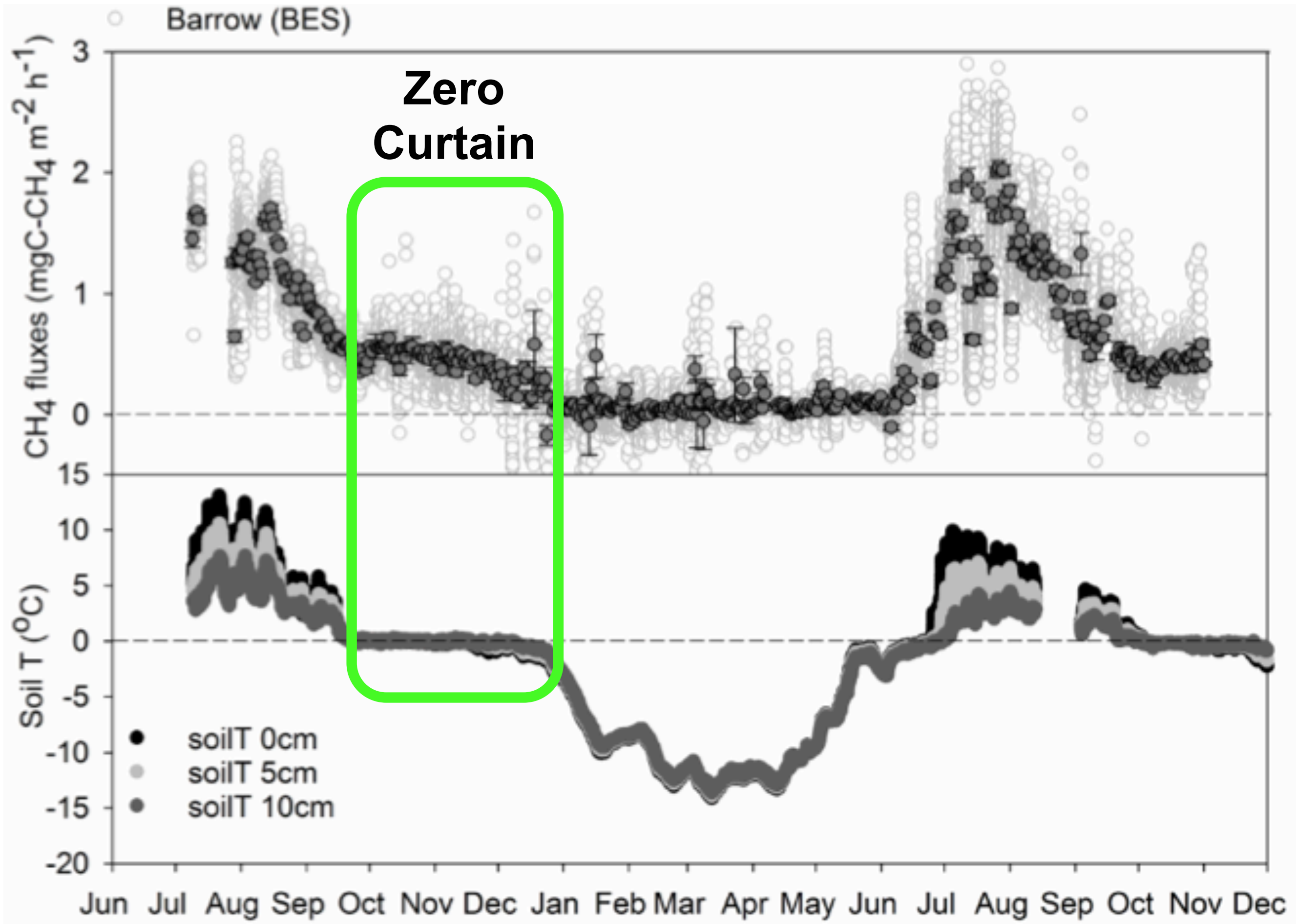


- Methanogenesis and methanotrophy continue into the cold season – "zero curtain period" – as long as liquid water is available
- Soil temperature is the driving environmental control

D Zona et al., PNAS (2016)

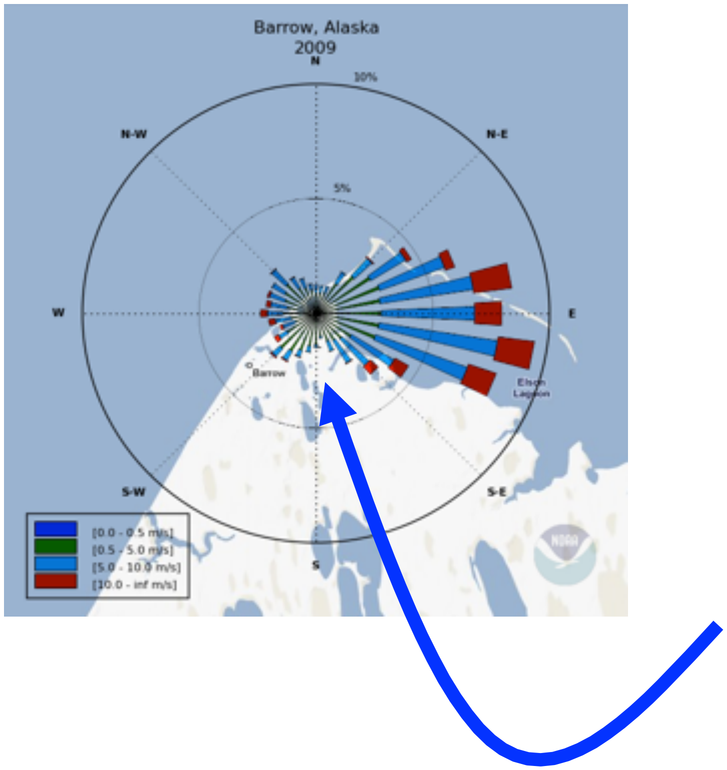
North Slope CH4 Emissions Persist Through the Zero Curtain Period

*** Year-round CH4 flux tower data ***

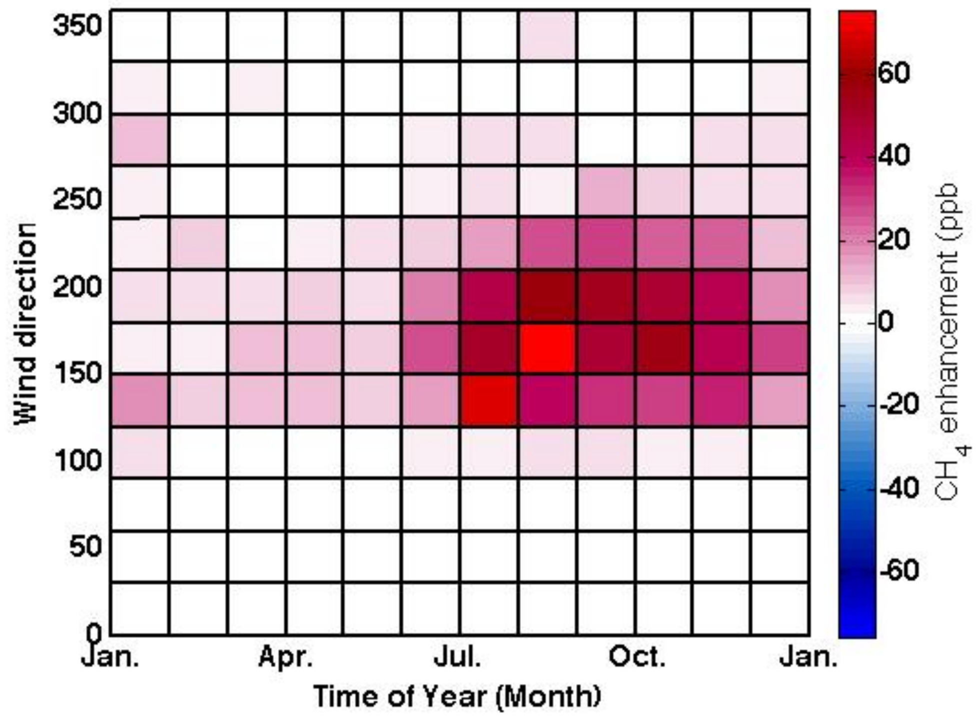


D Zona et al., PNAS (2016)

30-yr BRW Record Shows Persistent Early Cold Season CH4 Enhancement



Average enhancements of >70 ppb from southern 'Land' sector July – September (1990 – 2012 averages) consistent with CARVE observations

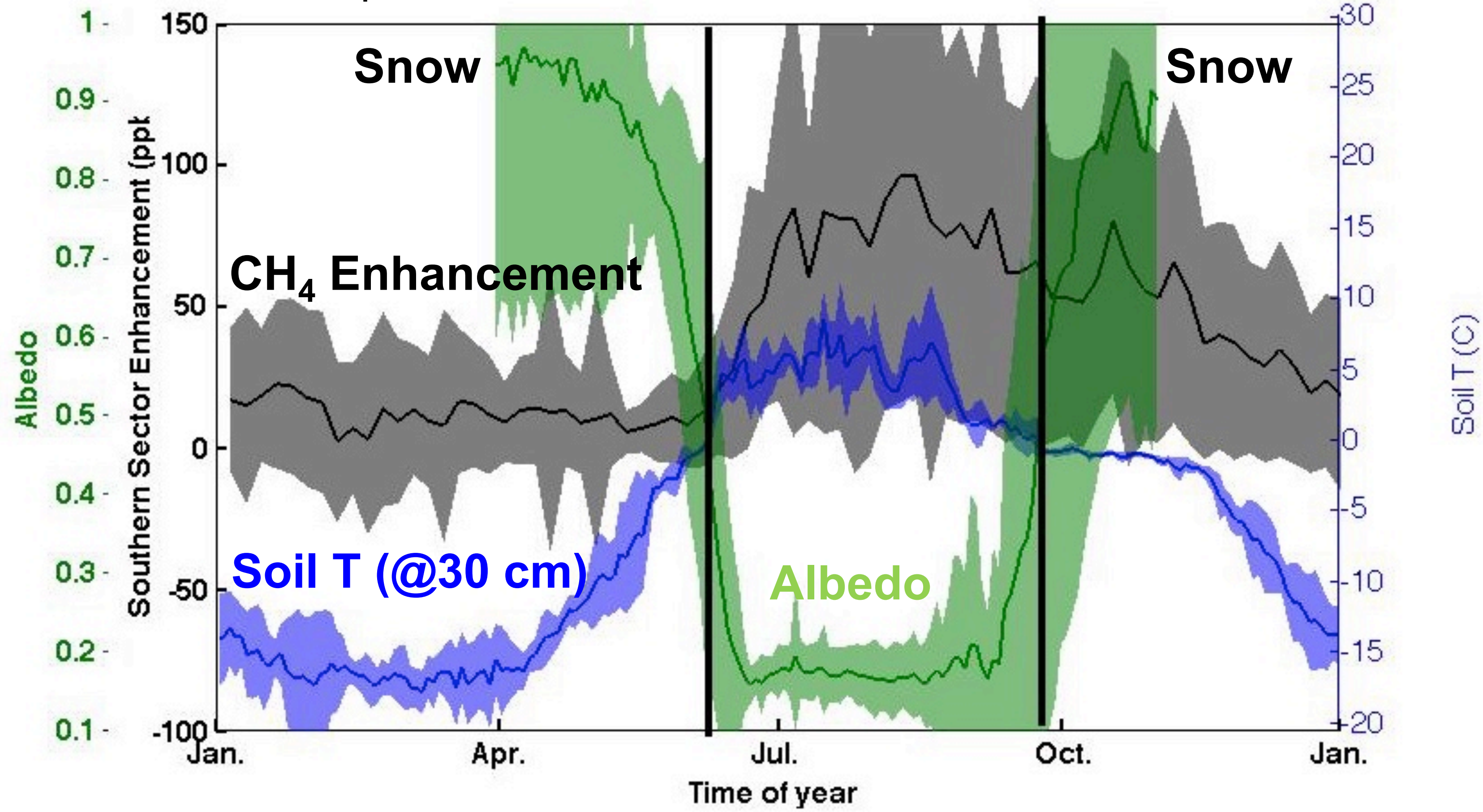


Background ~ 300 – 60
'Land' ~ 130 - 250

C Sweeney et al., GRL (2016)

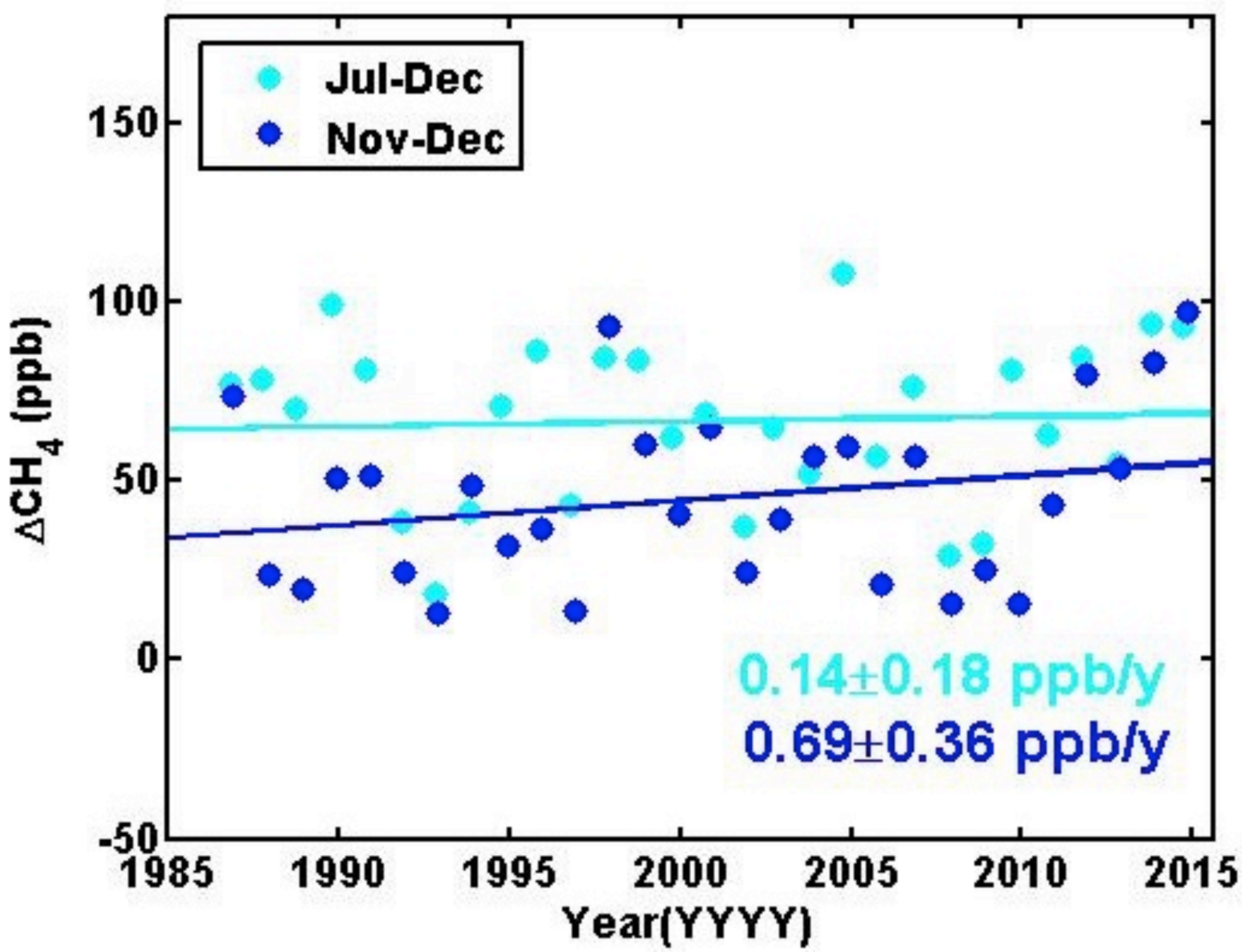
Atmospheric CH4 Measurements in the Context of the Barrow Seasonal Cycle

30-year BRW CH4 record mirrors the seasonal dependence of the Zona et al. CH4 fluxes



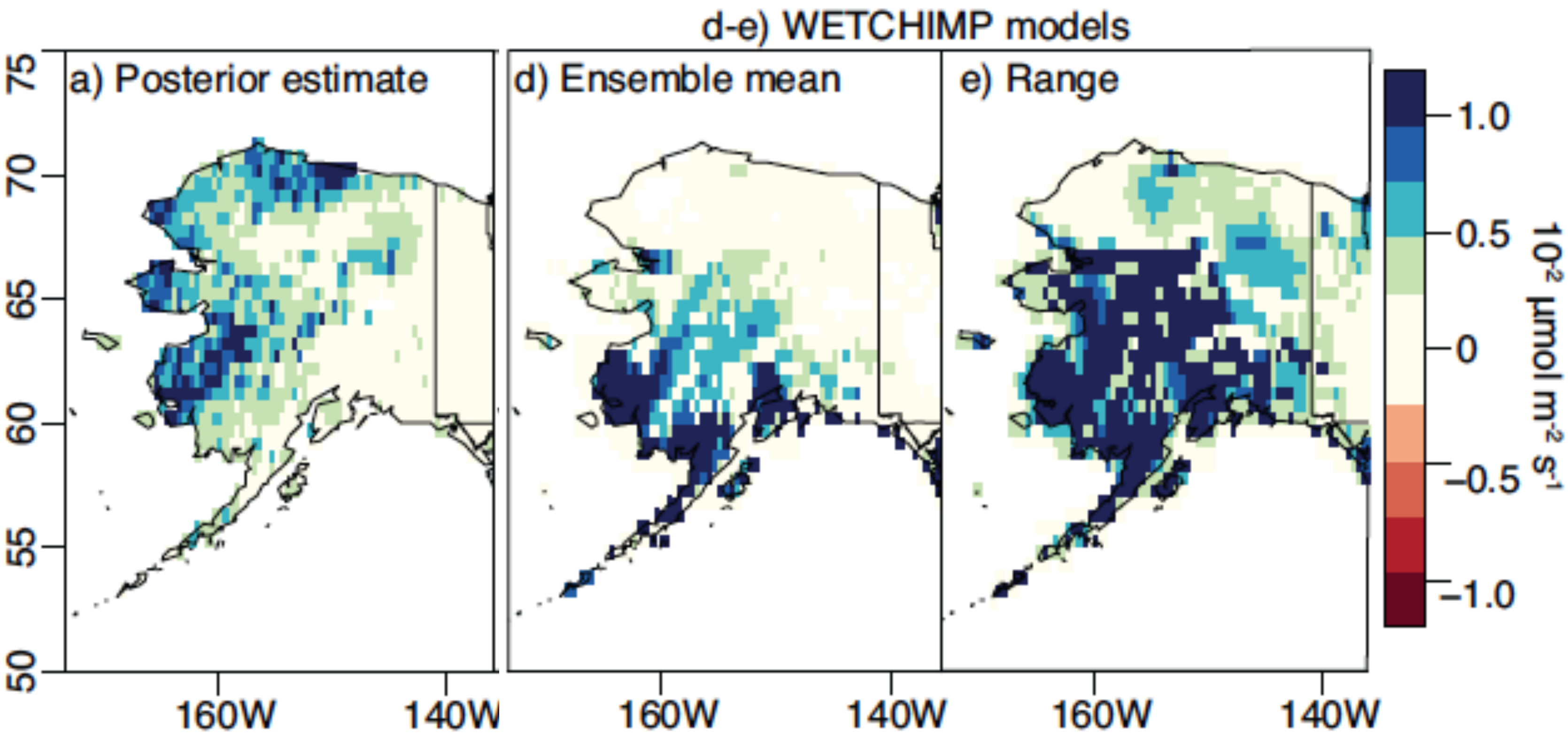
C Sweeney et al., GRL (2016)

No Significant Increase in Long-Term CH4 Emissions from North Slope Alaska



C Sweeney et al., GRL (2016)

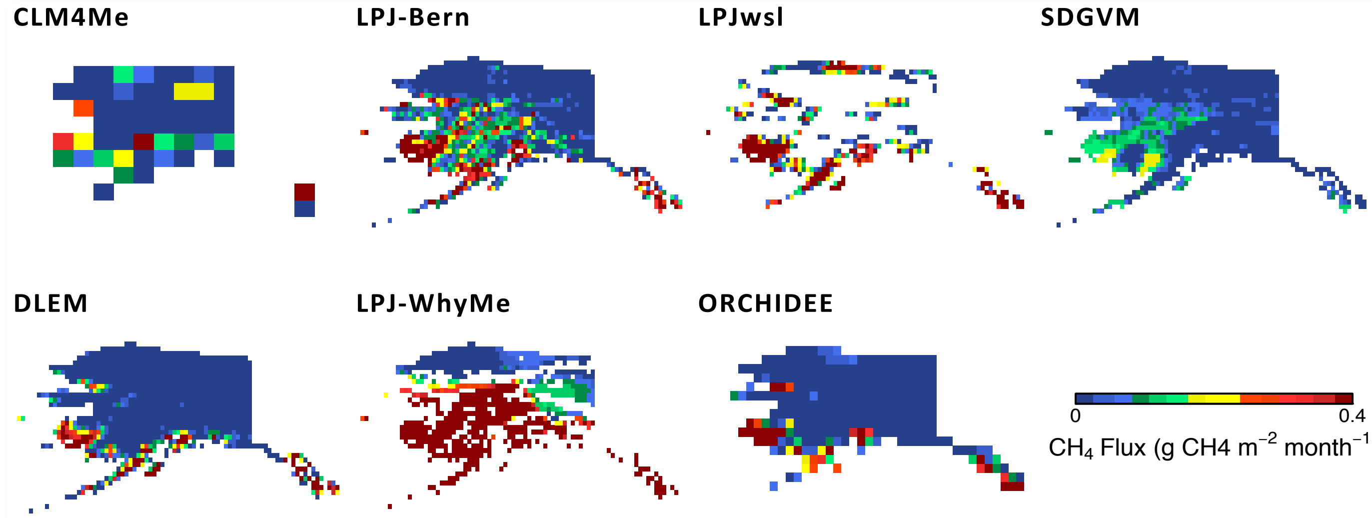
Alaska CH4 Fluxes Estimated from CARVE 2012-2014 Mean

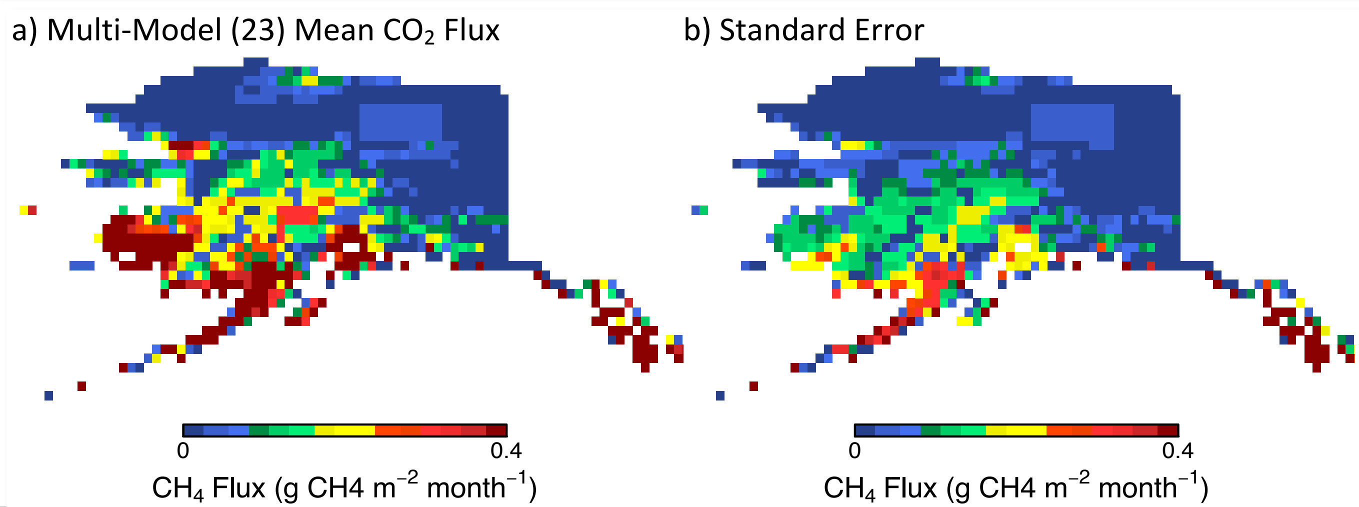


S Miller, A Michalak et al., GBC (2016)

- GIM Controls: wetland extent, sub-surface soil temperature
- 2012 – 2014 Budgets: 1.6 – 1.8 ± 0.6 Tg CH4/yr

Next Steps: Reconcile Models & CARVE
CH_4 Fluxes from 7 WETCHIMP Models





J Fisher et al., Biogeosciences (2014)

Summary, Part 2

- There appears to be no increase in North Slope Alaska methane emissions over the last 30 years despite a nearly +2 C change in surface temperatures
- Evidence that early cold season/zero curtain period emissions are increasing
- Year-round observations are urgently needed

- **Open Questions**:
  – How do the trends and behavior for Siberia and Scandinavia compare to those from Alaska & North America?
  – Why do models fail to reproduce atmospheric observations even qualitatively?
  – What is the magnitude of soil oxidation in uplands and High Arctic mineral soils?

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