Challenges for Satellite Remote Sensing of Northern High Latitude CO2 & CH4

Charles Miller, Nick Parazoo, Junjie Liu, Chris O'Dell,
Niina Luus, Roisin Commane, Jakob Lindaas, Steve Wofsy

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Summary

NHL CO_2 and CH_4 observations are essential for accurate regional and global flux estimates

Northern high latitudes pose critical observing challenges

- **Minimal sunlight from Sep – March each year**
- **Snow, ice, fog, clouds, inundated land surfaces**
- **Short, but intense seasonal cycle → Large seasonal cycle amplitude**
- **Cold season signals dominated by transport from lower latitudes**

Few soundings pass baseline (lower latitude) OCO filters

- **NHL-specific filters required to optimize sounding yield**

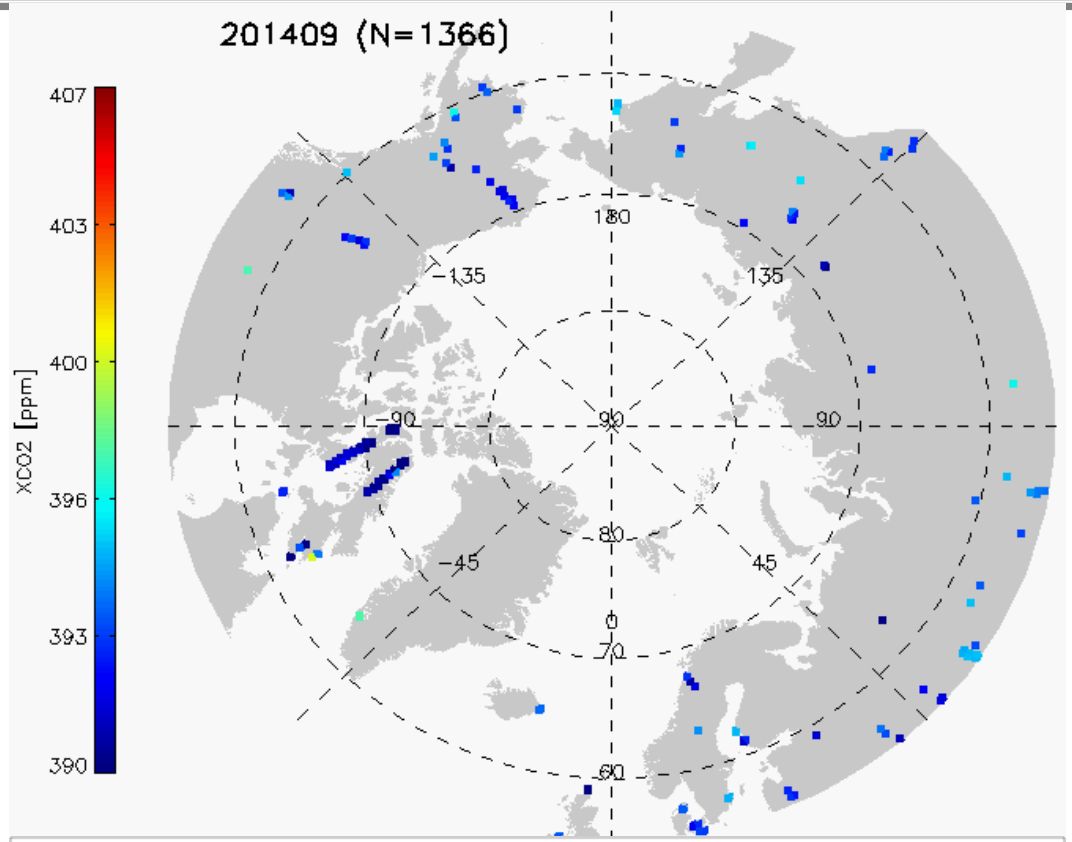
Opportunities to leverage

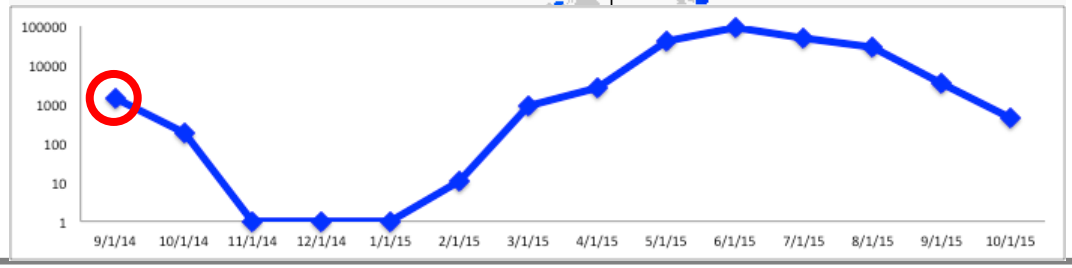
- **CARVE CO_2 profiles & flux estimates (2014, 2015)**
- **Upcoming ABoVE field & airborne activities (2016 -)**

OCO-2 XCO2 Observations > 55 N: Sep 2014

Minimal sounding yield (N = 1366) despite most of the month still in “summer”

Critical to capture early cold season respiration signals





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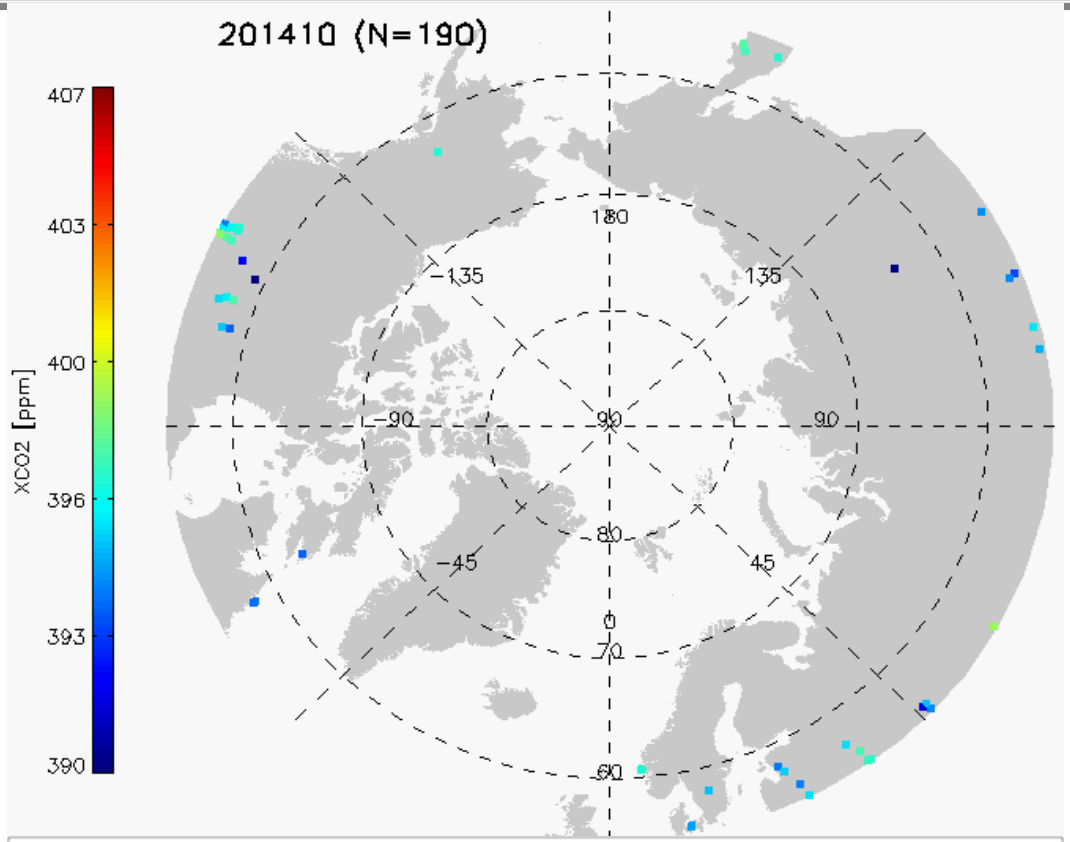
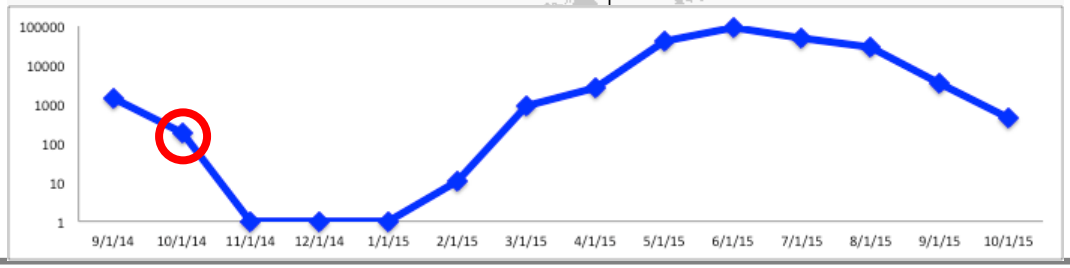
OCO-2 XCO2 Observations > 55 N: Oct 2014

Poor sounding yield (N = 190) and order of magnitude drop off from Sep (N = 1366)

Critical to capture early cold season respiration signals





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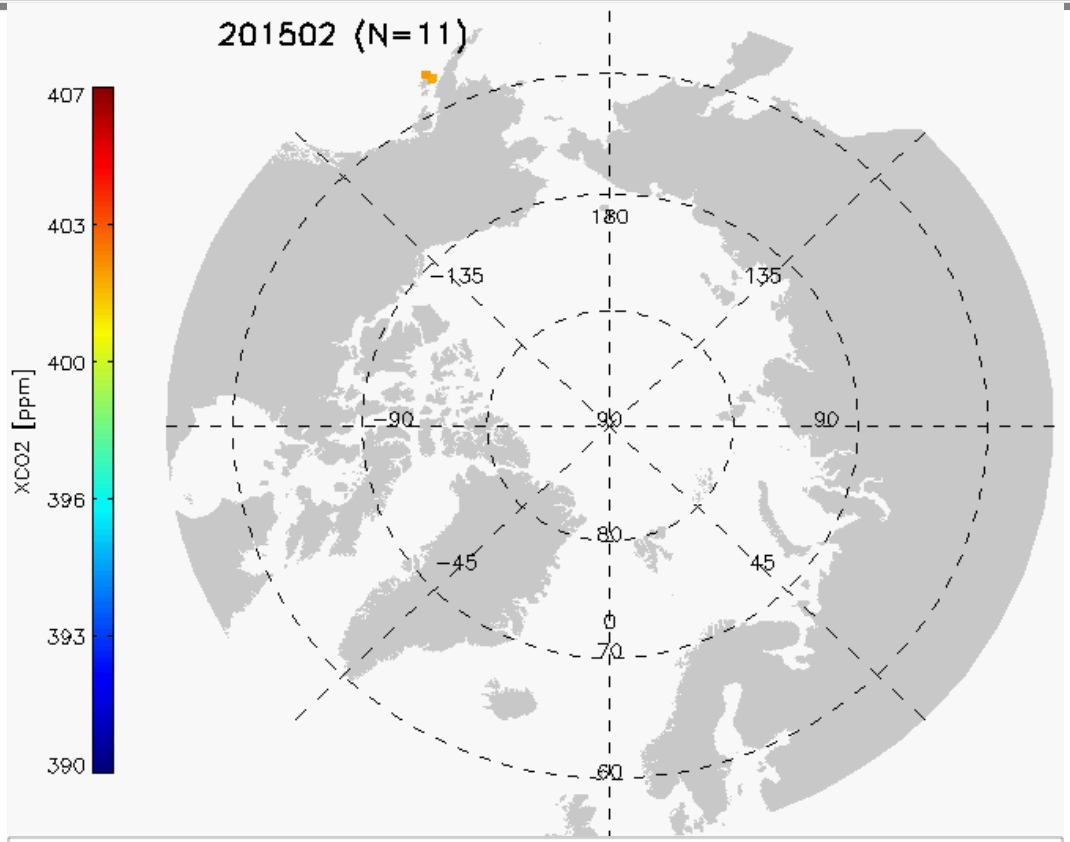
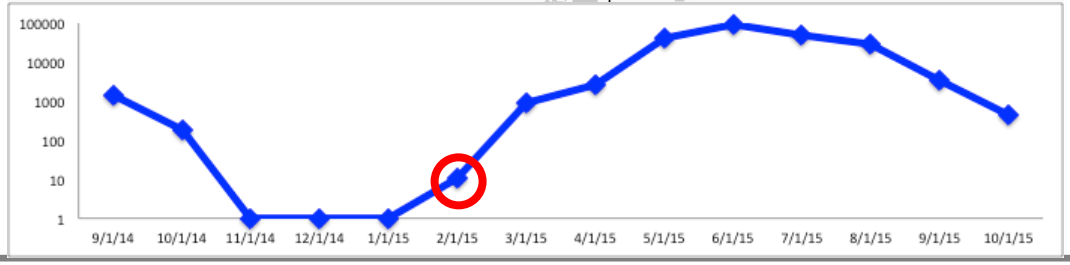
OCO-2 XCO2 Observations > 55 N: Feb 2015

Poor sounding yield (N = 11)

Cold season XCO2 are critical to constrain pan-Arctic respiration and transport from lower latitudes





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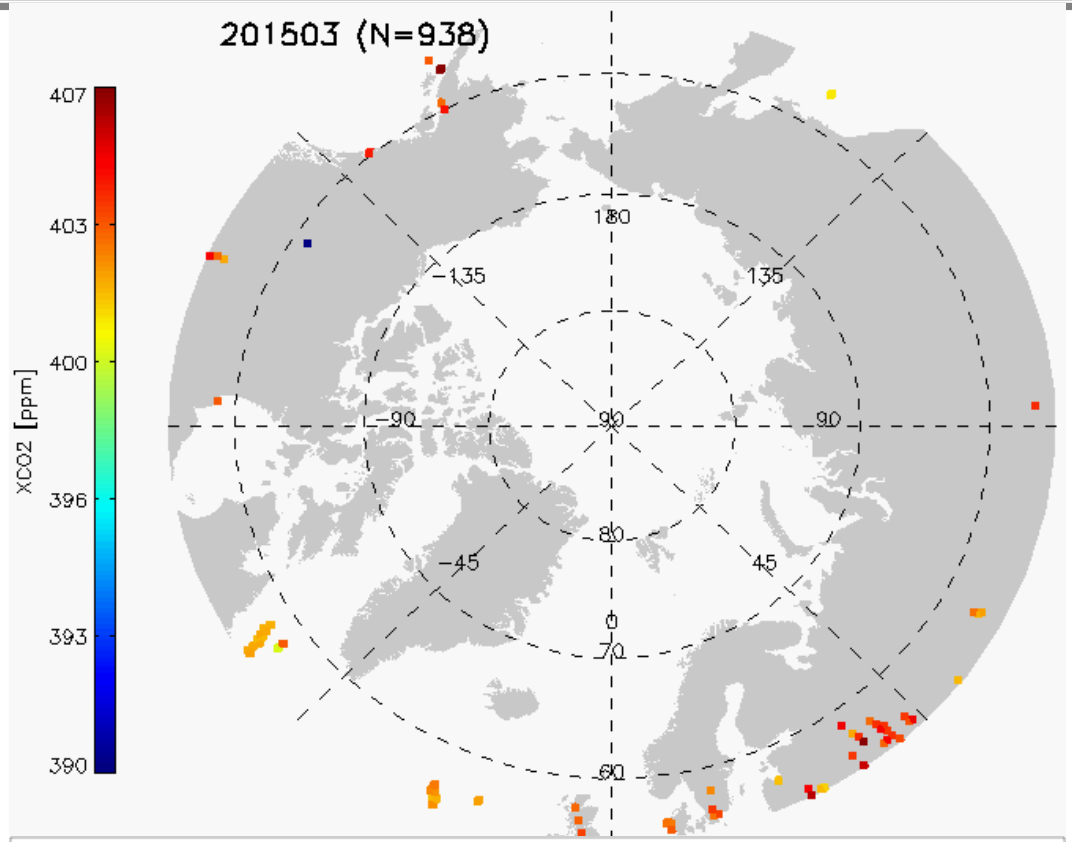
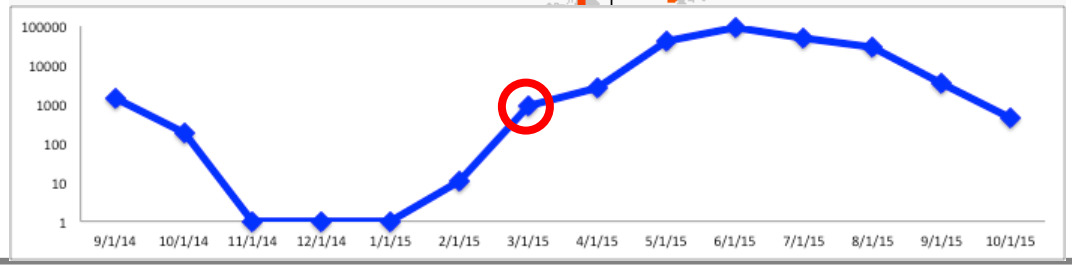
OCO-2 XCO2 Observations > 55 N: Mar 2015

Poor sounding yield (N = 938) with none above 60N despite equinox solar conditions

Cold season XCO2 are critical to constrain pan-Arctic respiration and transport from lower latitudes





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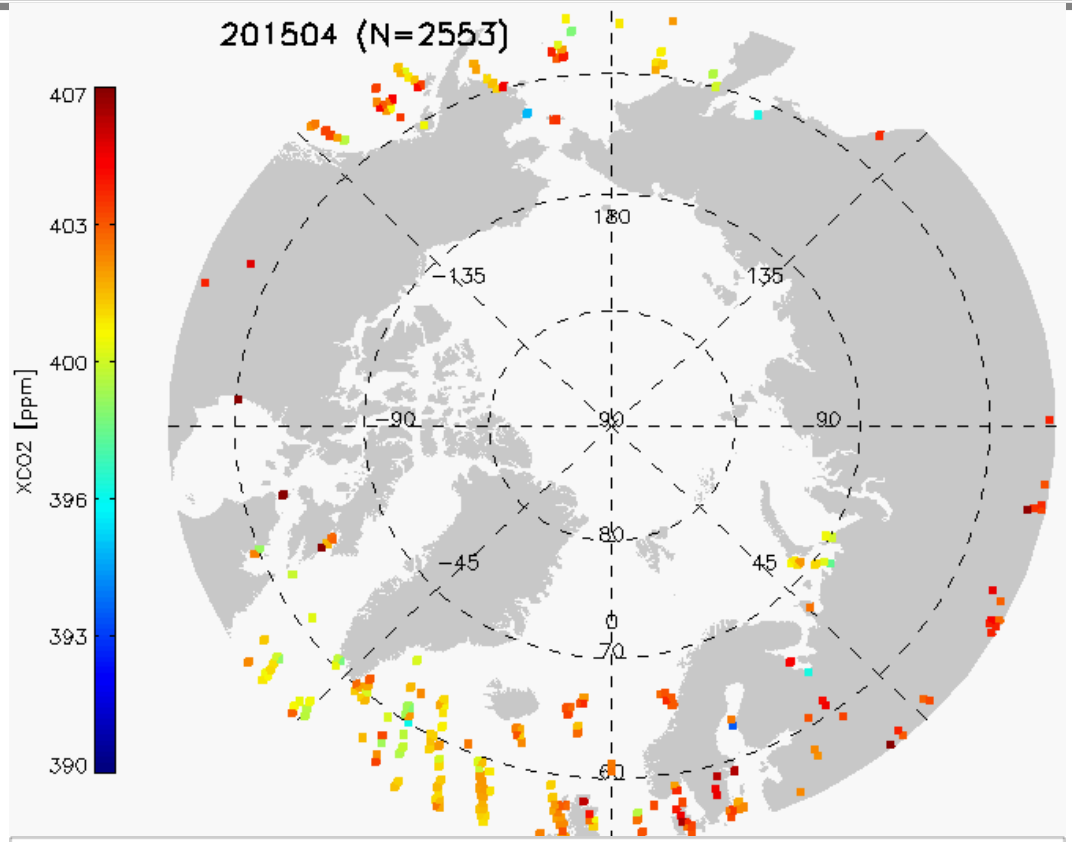
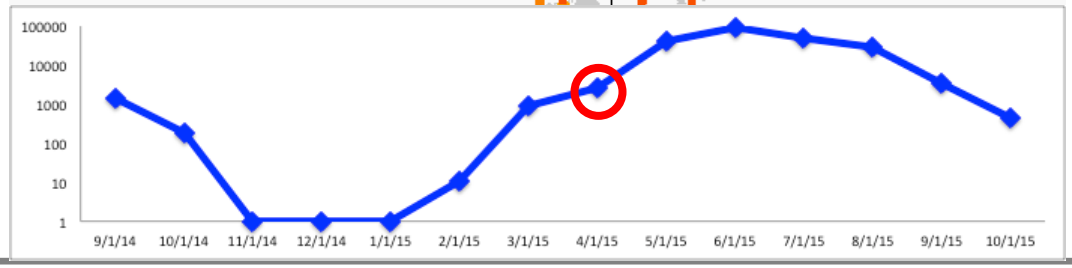
OCO-2 XCO2 Observations > 55 N: Apr 2015

Low sounding yield (N = 2553) with few above 60N and none above 70 N

Critical to capture boreal forest freeze/thaw transition and onset of growing season drawdown





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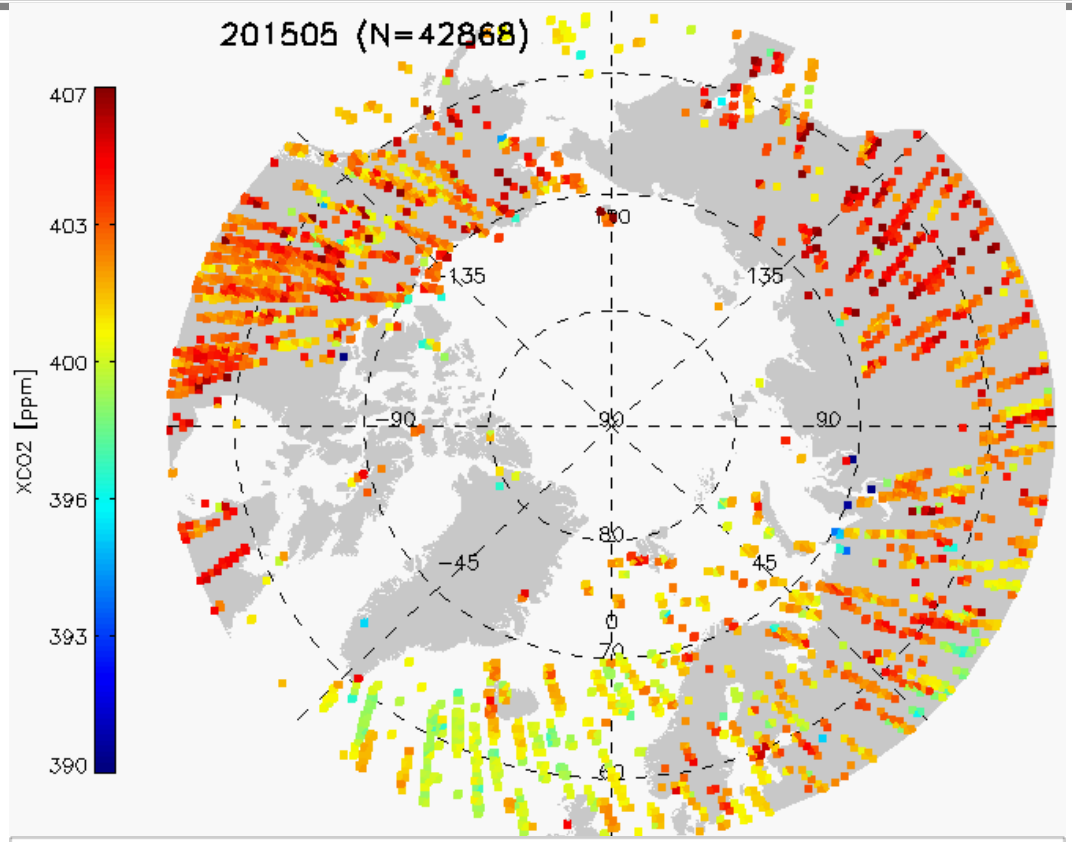
OCO-2 XCO2 Observations > 55 N: May 2015

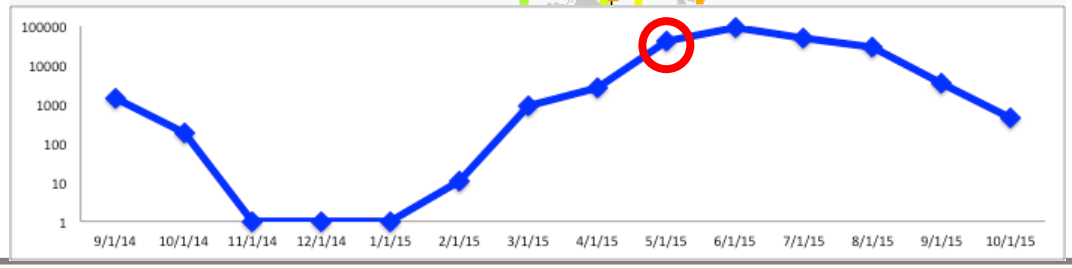
Improved sounding yield (N = 42868), an order of magnitude more soundings than Apr 2015

>20 hour days

Coverage extends through 70N, but still essentially zero yield over Greenland

Spring respiration signals dominate, but start of drawdown seen below 60N over Europe & western Siberia





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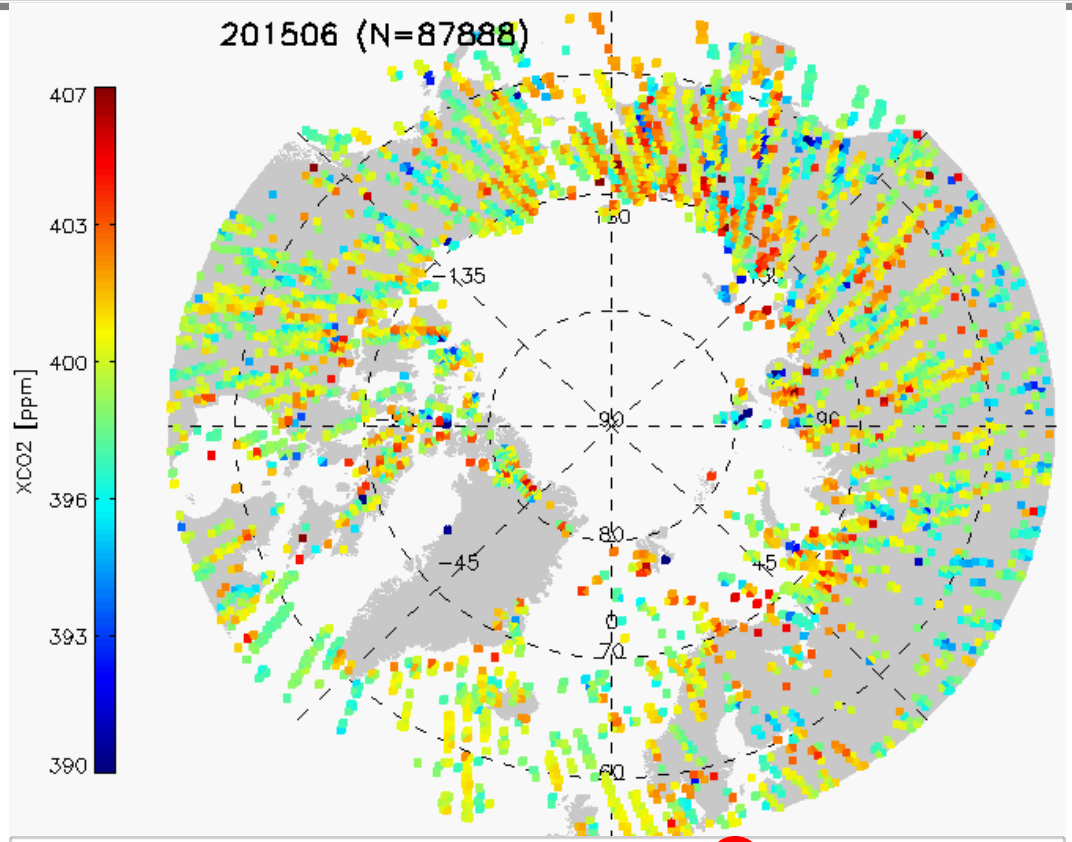
OCO-2 XCO2 Observations > 55 N: Jun 2015

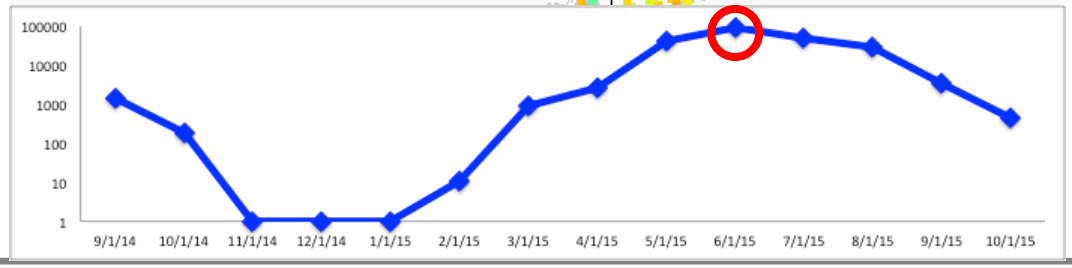
Mid-summer, max sounding yield

Sounding yield increases ~2x over May 2015

Coverage extends to 80N, but still essentially zero yield over Greenland

Mix of drawdown and Spring respiration signals observed





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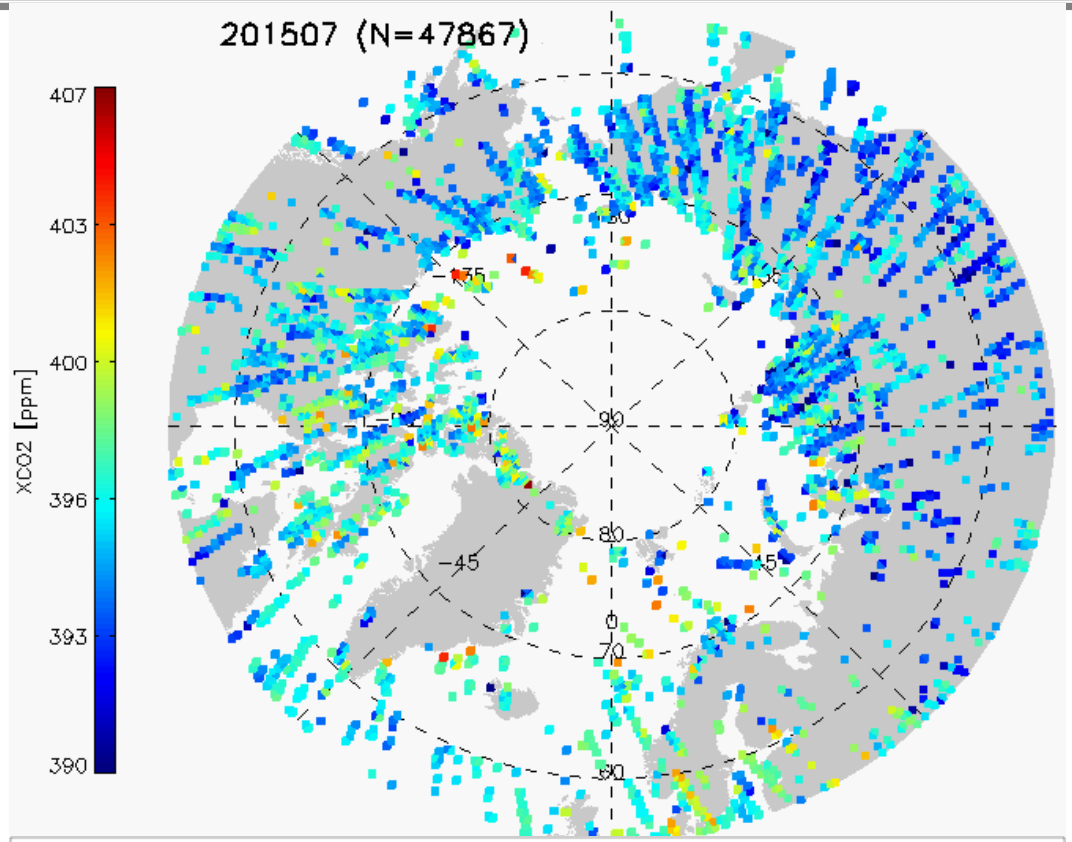
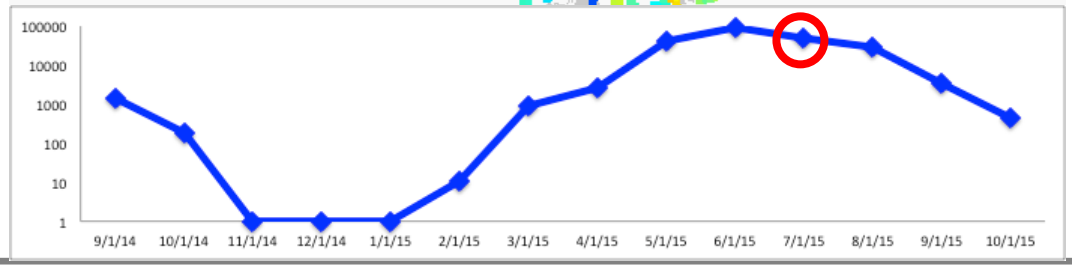
OCO-2 XCO2 Observations > 55 N: Jul 2015

Sounding yield decreases ~2x vs Jun 2015 despite > 20-hour days

Coverage extends to 80N, but still essentially zero yield over Greenland, poor yields over Europe, Scandinavia, and western North America

Peak drawdown signals





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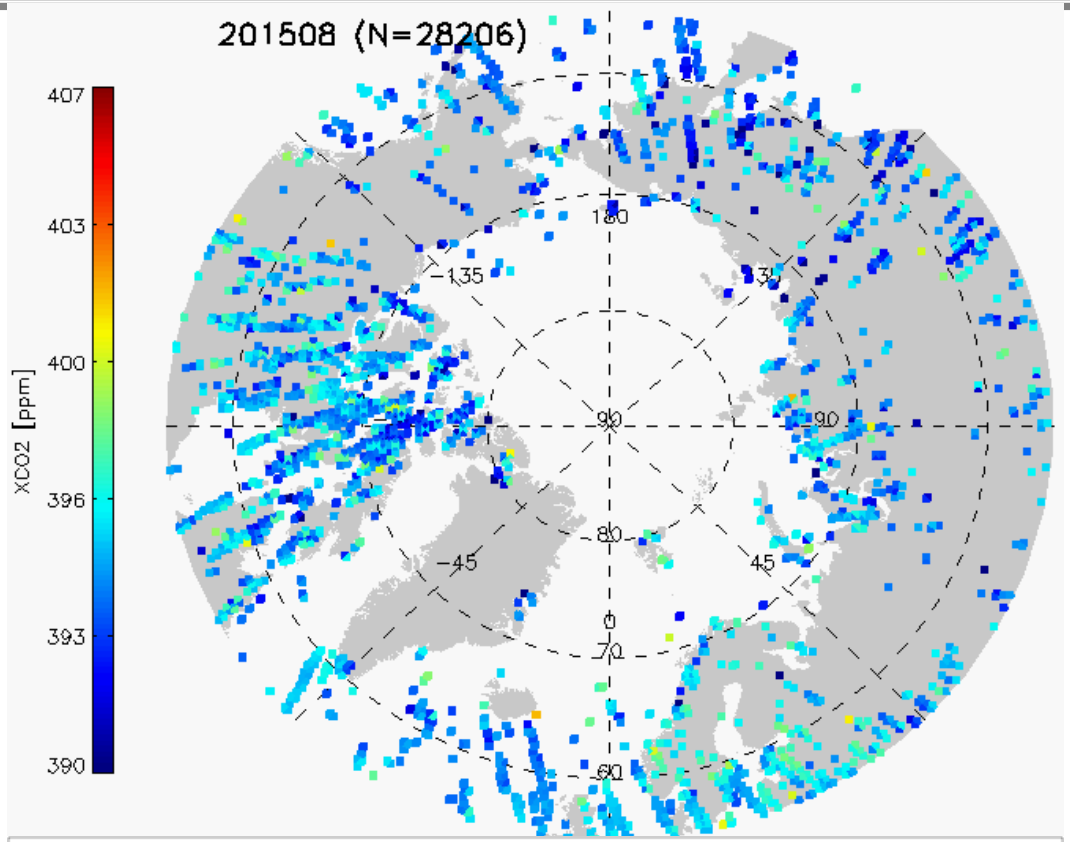
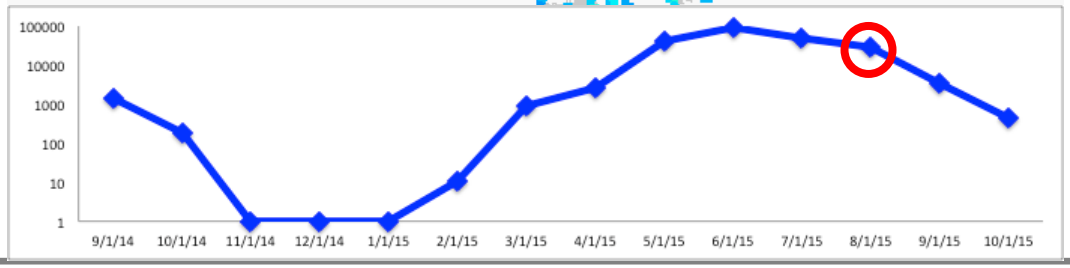
OCO-2 XCO2 Observations > 55 N: Aug 2015

Sounding yield decreases ~2x vs Jul 2015

Coverage extends to 80N, but still essentially zero yield over Greenland, poor yields over Europe, Scandinavia, Siberia and western North America

Drawdown signals still widespread





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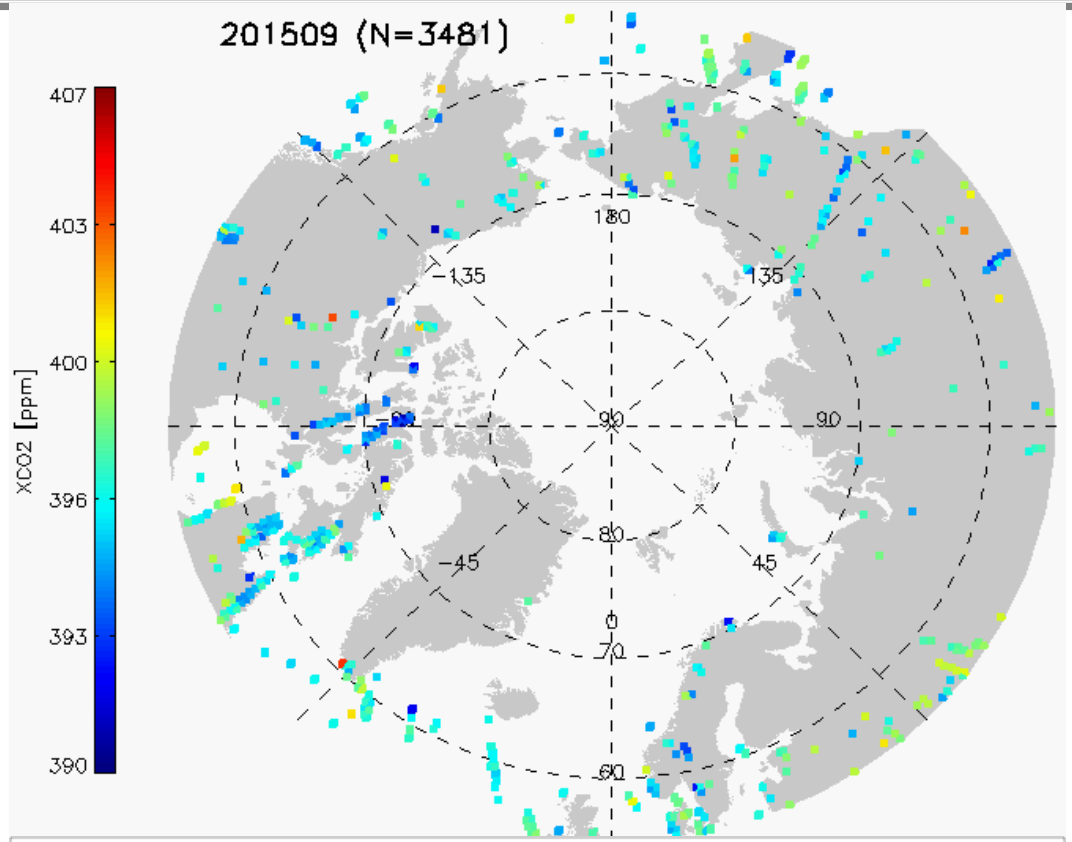
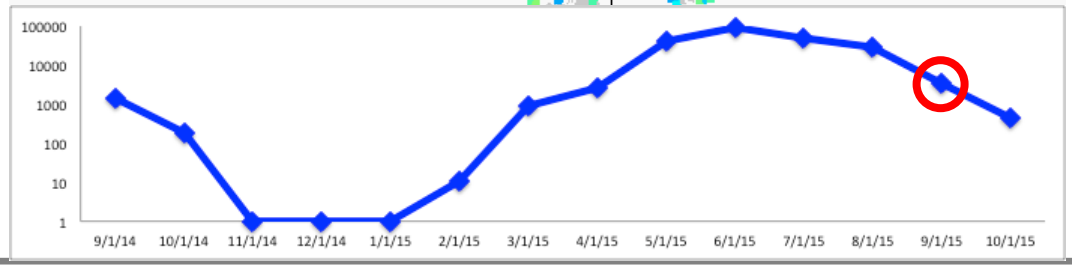
OCO-2 XCO2 Observations > 55 N: Sep 2015

Poor yield (N = 3481) decreases an order of magnitude vs Aug 2015 despite the equinox conditions

Sporadic coverage, mostly confined < 60 N

Critical to capture early cold season respiration signals





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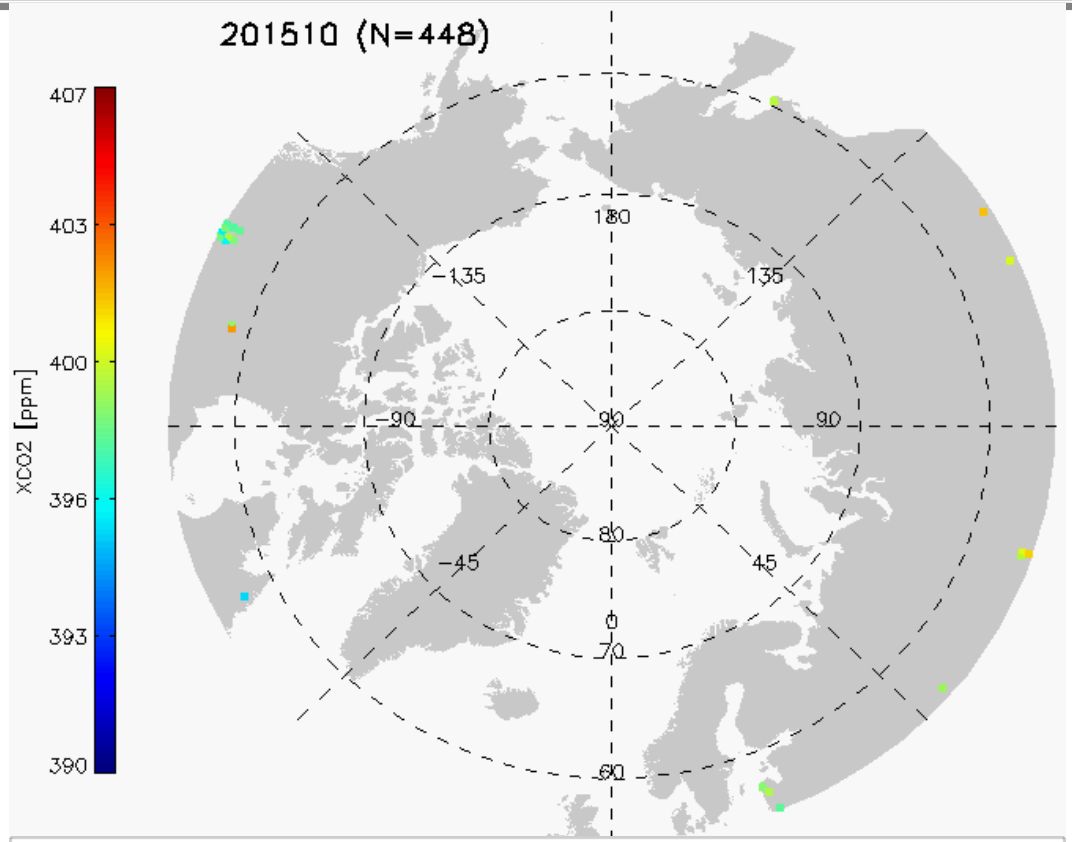
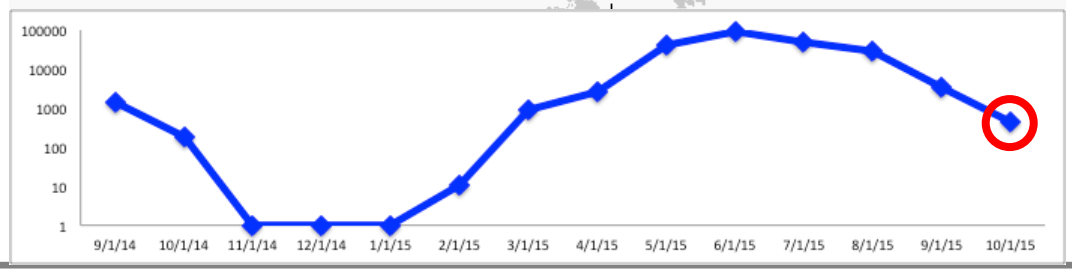
OCO-2 XCO2 Observations > 55 N: Oct 2015

Poor yield (N = 448) decreases an order of magnitude vs Sep 2015

Critical to capture early cold season respiration signals





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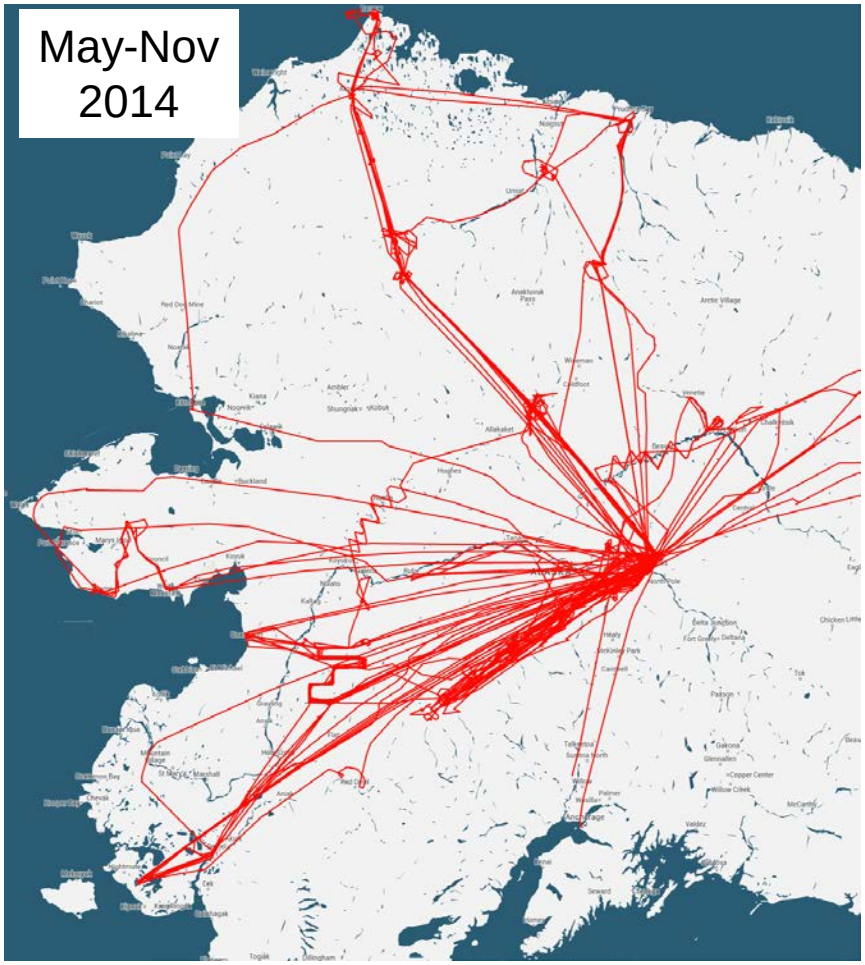
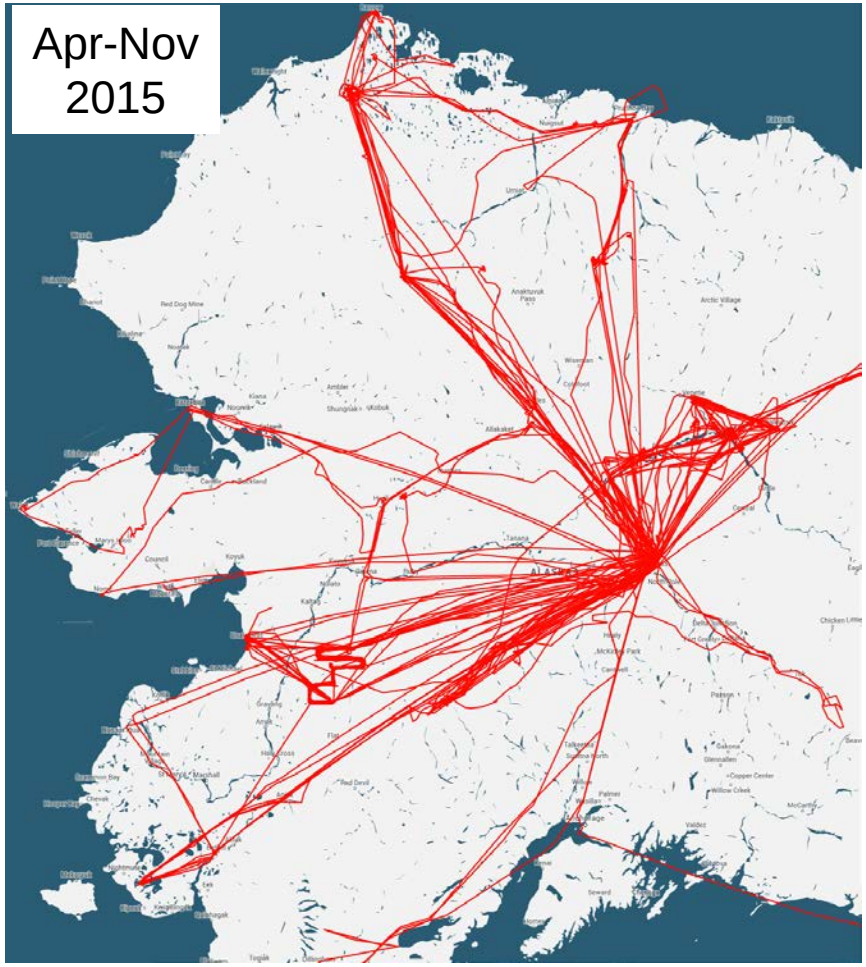
More than 1000 Science Flight Hours of CARVE Data 2012 - 2015



CARVE 2014 Flight Tracks



CARVE 2015 Flight Tracks

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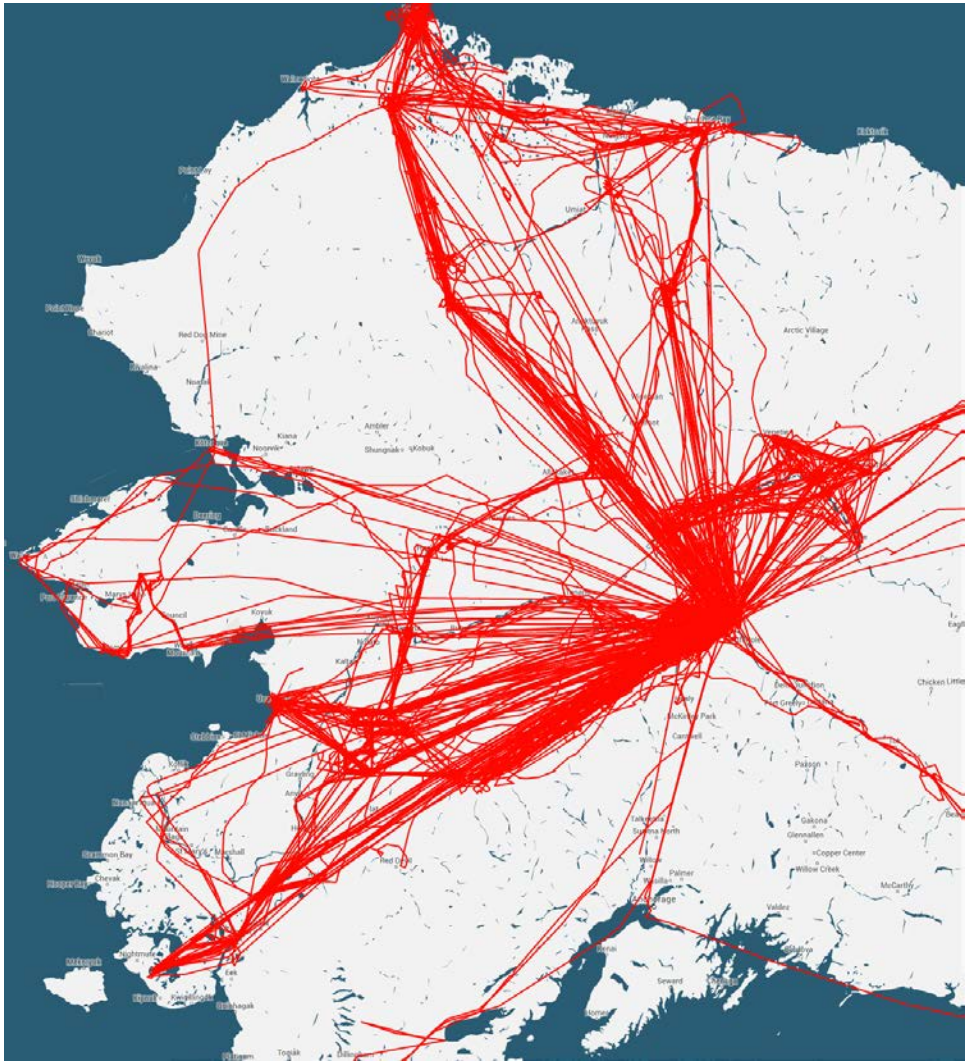
CARVE 2012 – 2015 Cumulative Flight Lines

CARVE By The Numbers

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



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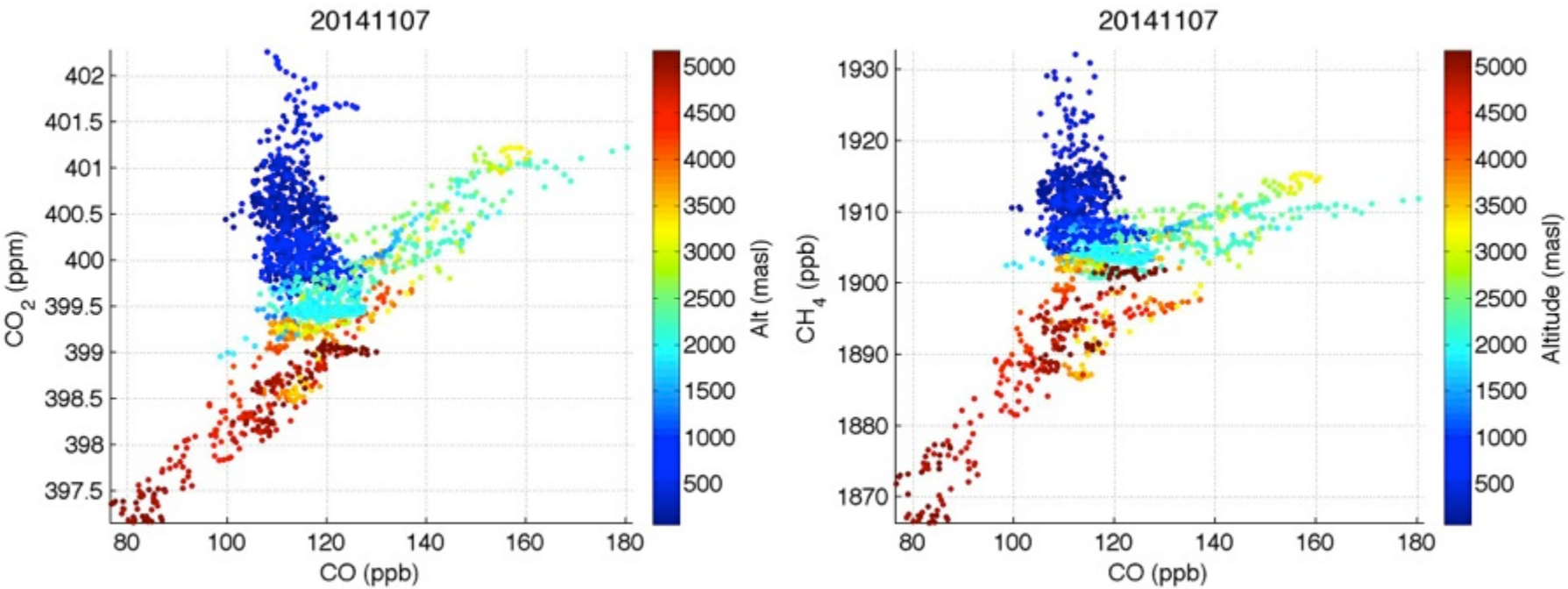
7 Nov 2014/DOY 311 CARVE Science Flight North Slope Emissions Still Evident



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

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

Jet Propulsion Laboratory
California Institute of Technology

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[k], Jordan P. Goodrich[k], Virginie Moreaux[k], Anna Liljedahl[l,j], Jennifer D. Watts[m], John S. Kimball[m], David A. Lipson[n], and Walter C. Oechel[a,n]

[a]Department of Biology, San Diego State University, San Diego, CA 92182; [b]Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, United Kingdom; [c]Institute of Biometeorology, National Research Council, Firenze, 50145, Italy; [d]School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138; [e]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099; [f]Department of Physics, University of Helsinki, FI-00014 Helsinki, Finland; [g]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80304; [h]Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO 80305; [i]Department of Physics and Atmospheric Science, Dalhousie University, Halifax, Nova Scotia, Canada B3H 4R2; [j]Atmospheric and Environmental Research, Inc., Lexington, MA 02421; [k]Water and Environmental Research Center, University of Alaska Fairbanks, Fairbanks, AK 99775-7340; [l]International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK 99775-7340; [m]Numerical Terradynamic Simulation Group, College of Forestry & Conservation, The University of Montana, Missoula, MT 59812; and [n]Department of Earth, Environment and Ecosystems, Open University, Milton Keynes, MK7 6AA, United Kingdom

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.

This article is a PNAS Direct Submission.

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).

[1]To whom correspondence should be addressed. Email: dzona@mail.sdsu.edu.

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

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1516017113/DCSupplemental.

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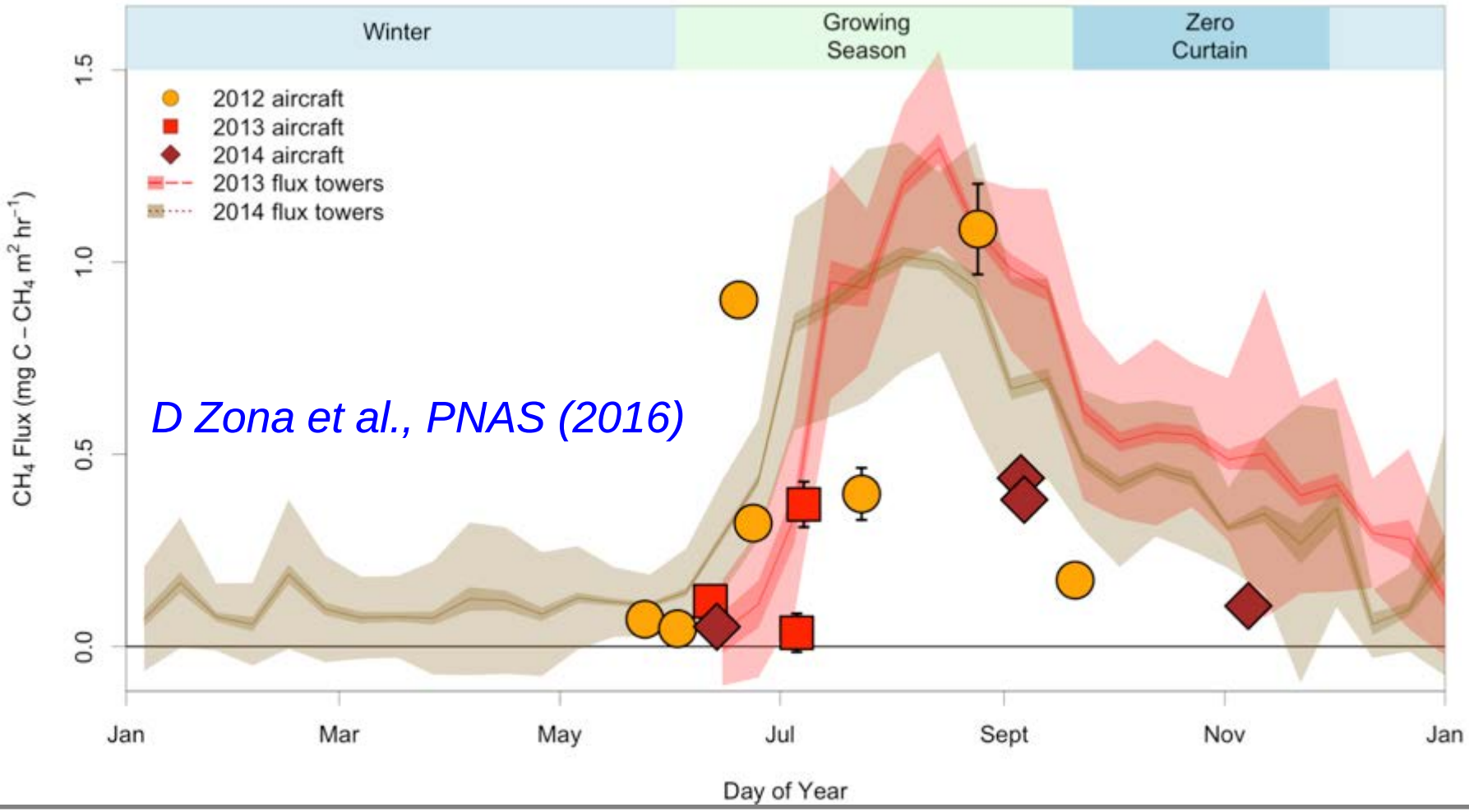
More than 50% of the North Slope CH4 Flux Occurs During the Cold Season

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



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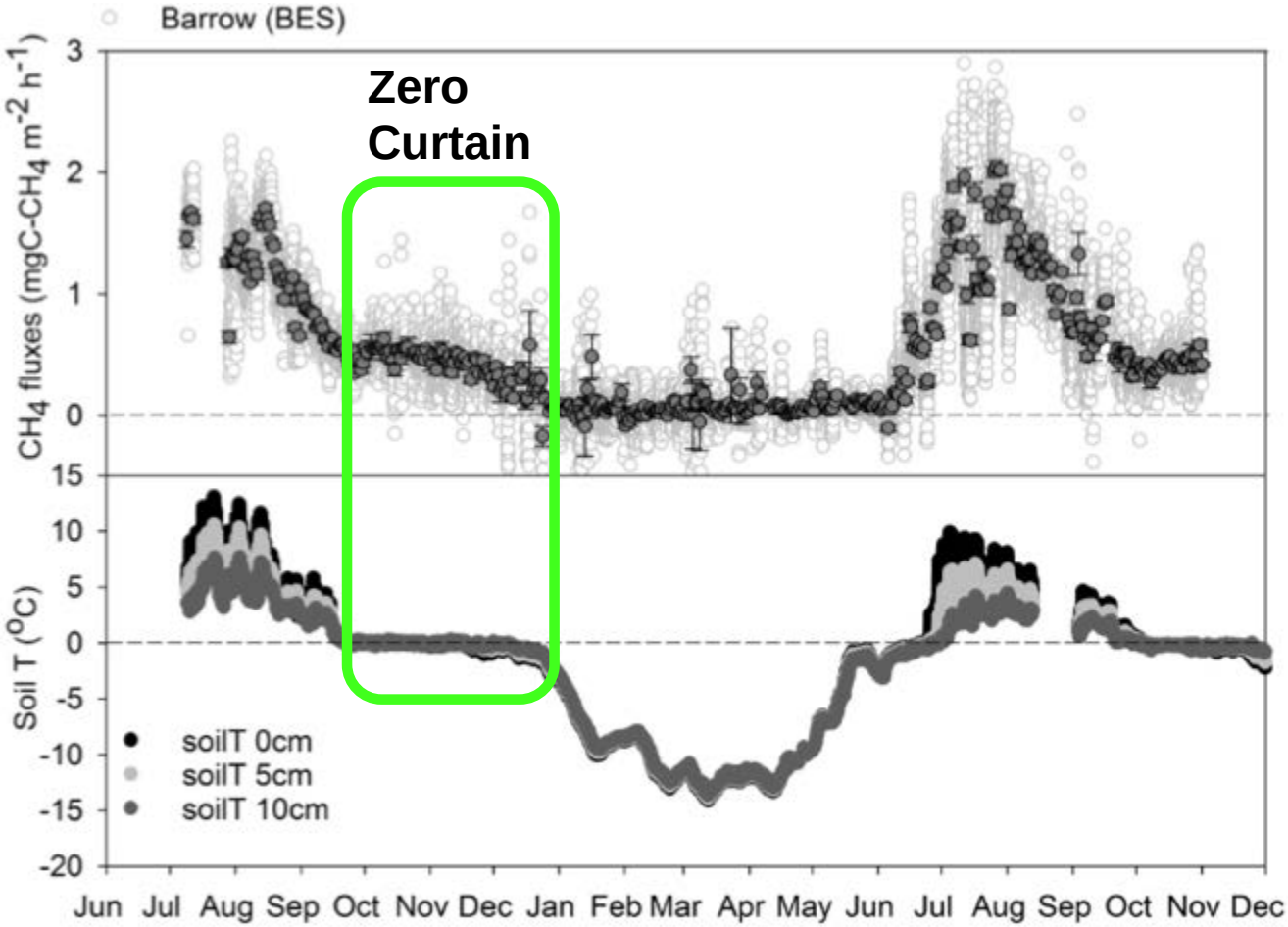
North Slope CH4 Emissions Persist Through the Zero Curtain Period

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



D Zona et al., PNAS (2016)

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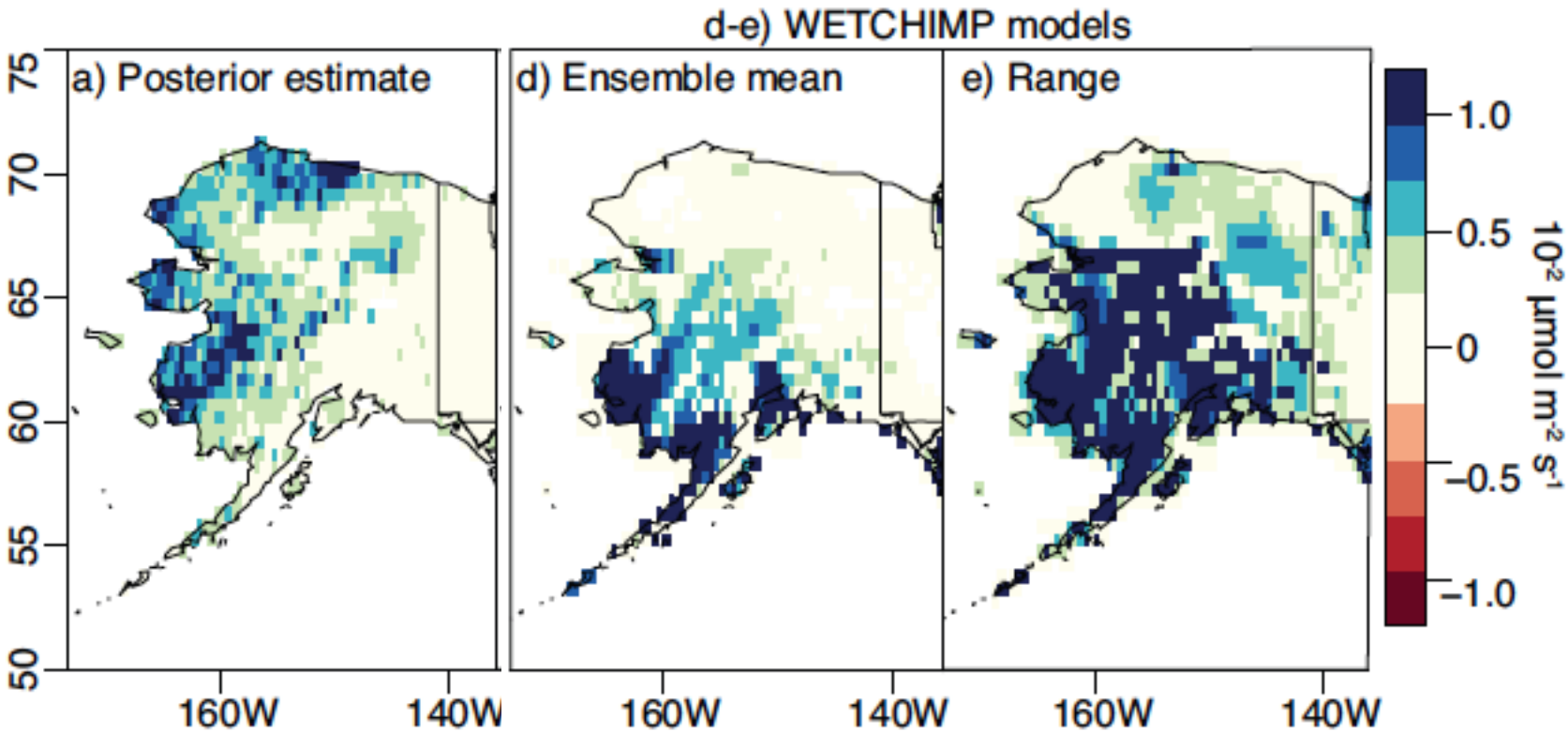
Alaska CH4 Fluxes Estimated from CARVE 2012-2014 Mean



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

S Miller, A Michalak et al., GBC (2016); Poster C.05

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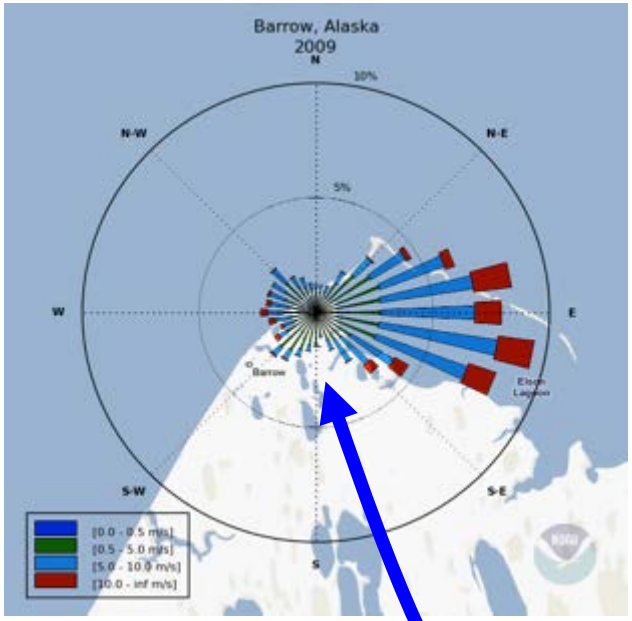
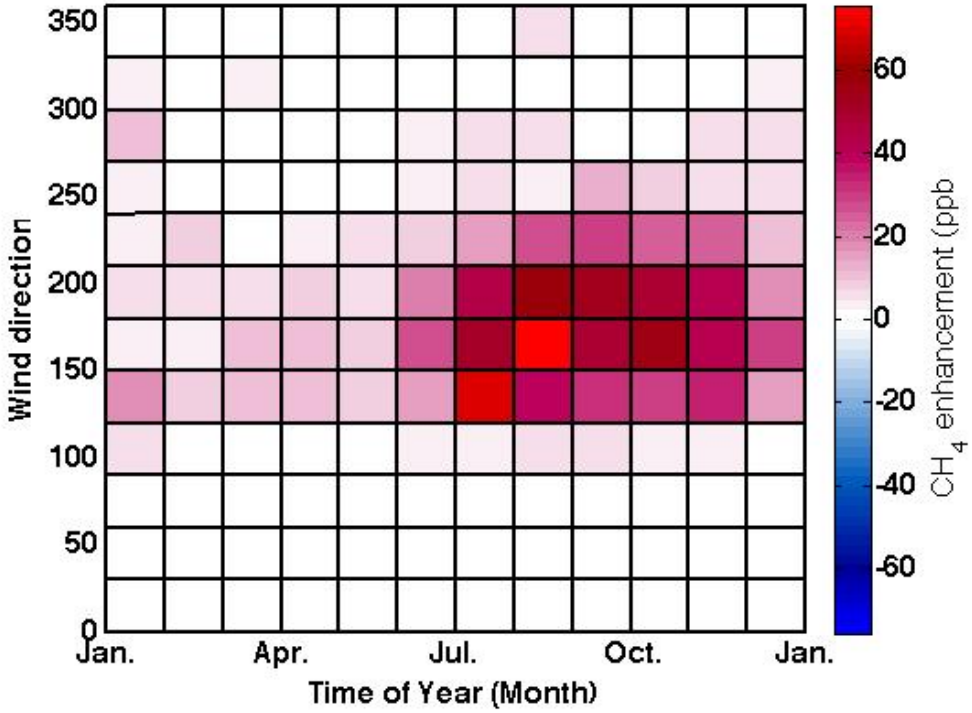
30-yr BRW Record Shows Persistent Early Cold Season CH4 Enhancement



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)

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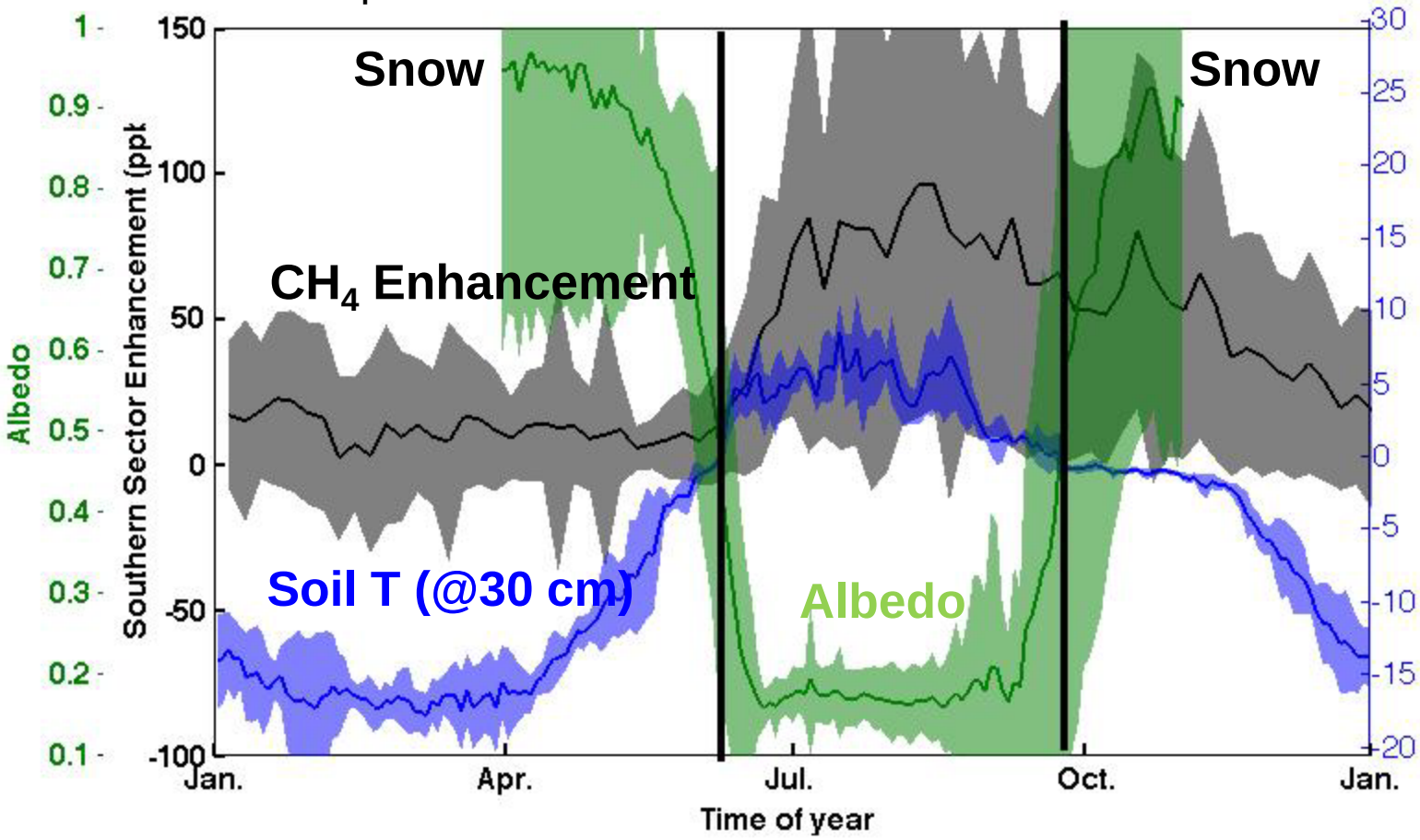
Atmospheric CH4 Measurements in the Context of the Barrow Seasonal Cycle

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



C Sweeney

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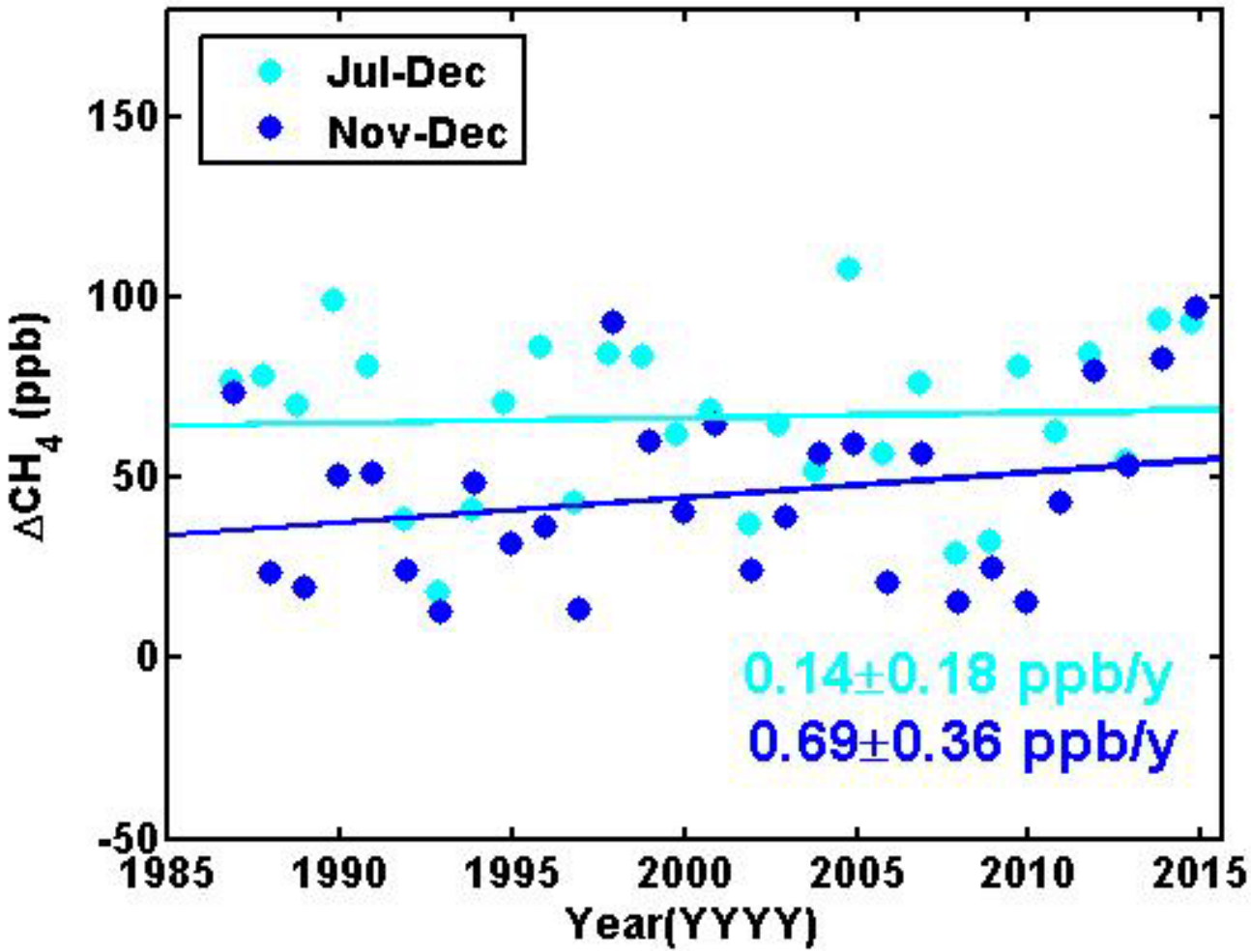
No Significant Increase in Long-Term CH4 Emissions from North Slope Alaska



C Sweeney *et al.*, GRL (2016)

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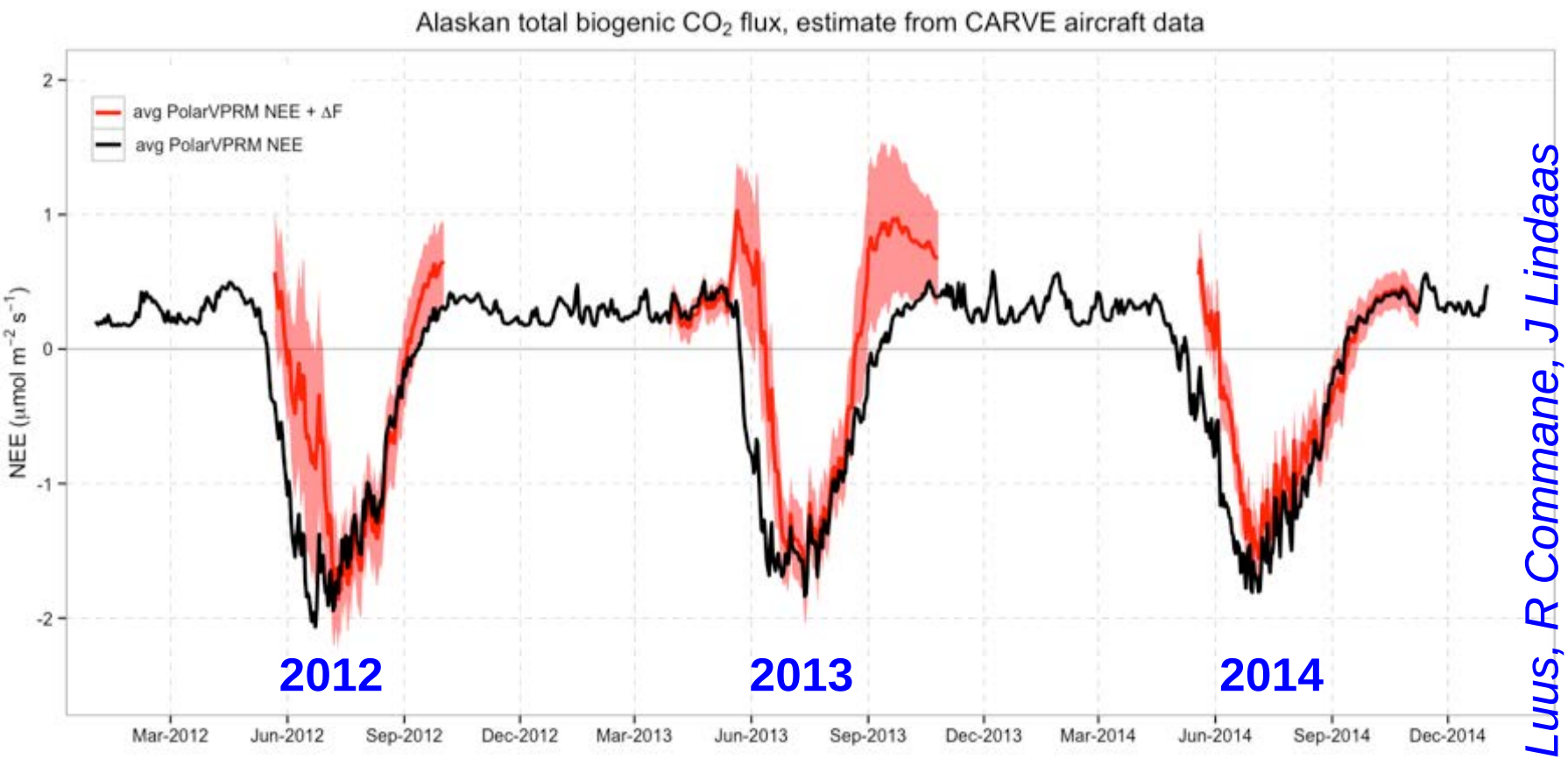
Optimized Biogenic CO2 Flux for AK PVPRM & CARVE



N Luus, R Commane, J Lindaas

- Spring drawdown 2-4 weeks later than PVPRM
- Observations: Earlier fall zero crossing and larger fall emissions

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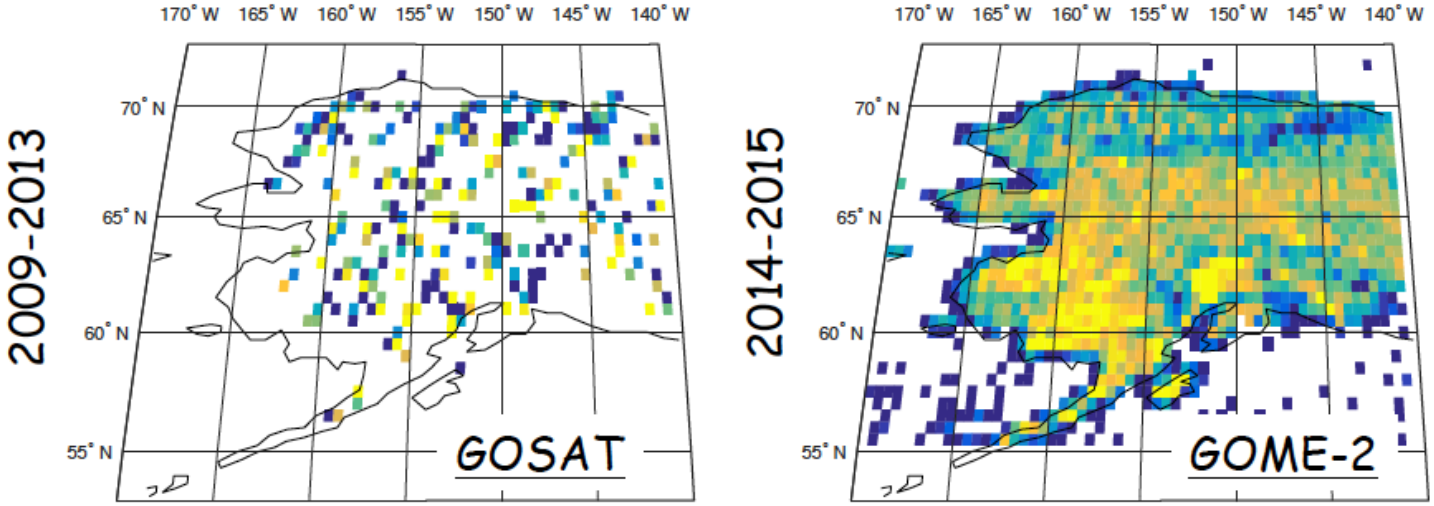
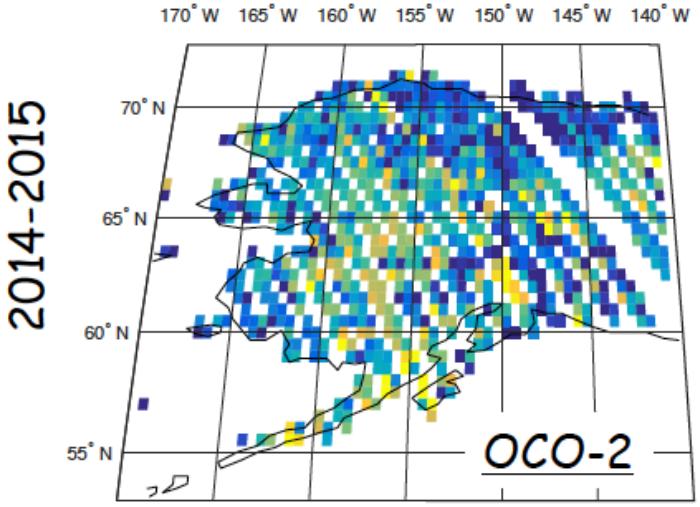
Using SIF to Correct Spring Drawdown Bias





GOME-2 and OCO-2 show spatially coherent patterns of ecosystem productivity

** What can this tell us about seasonal phenology in the Arctic? **

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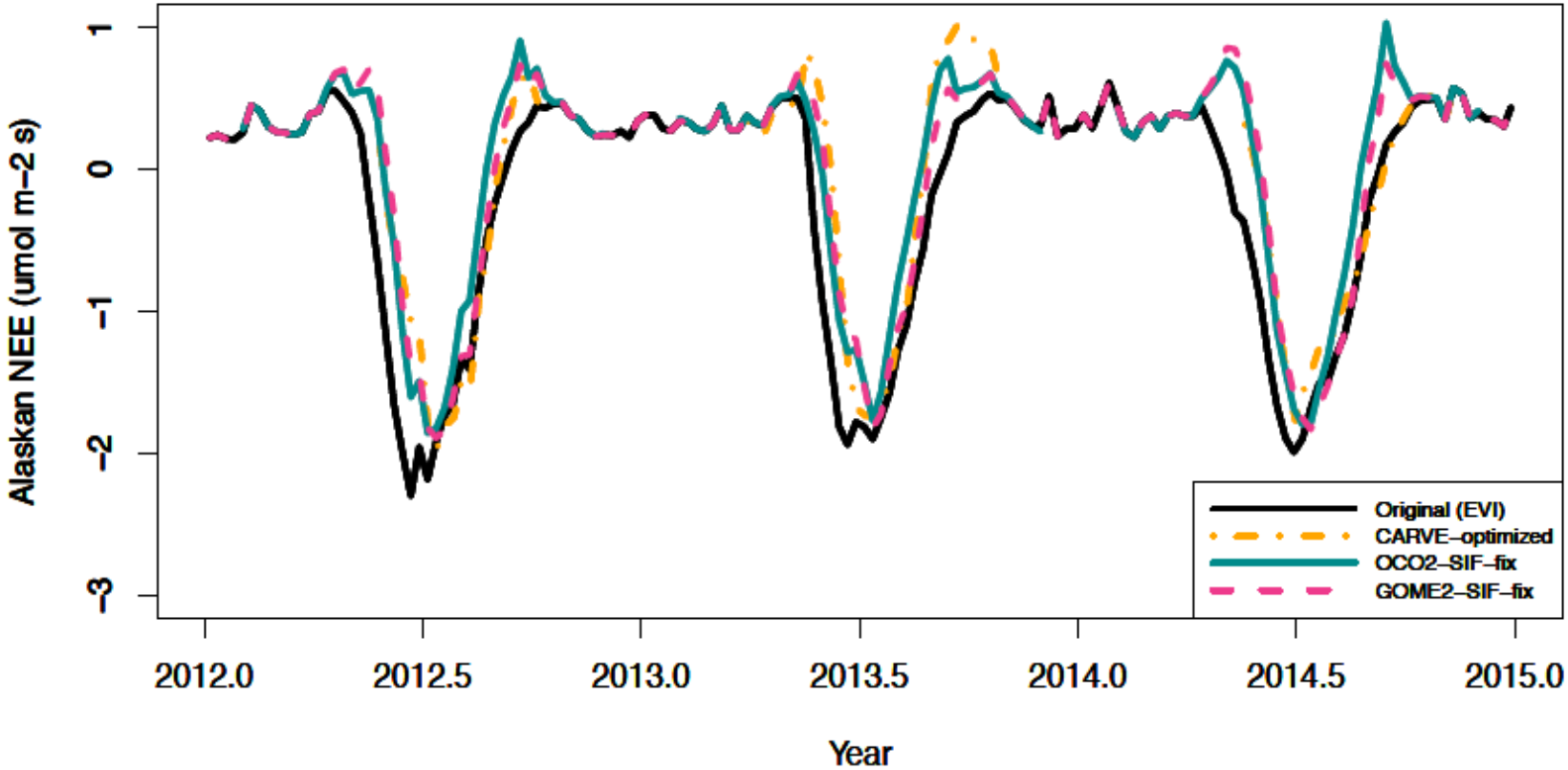
N Parazoo

SIF Corrects Spring Drawdown Bias



SIF offers a potential solution to the known spring bias in CMIP5 models

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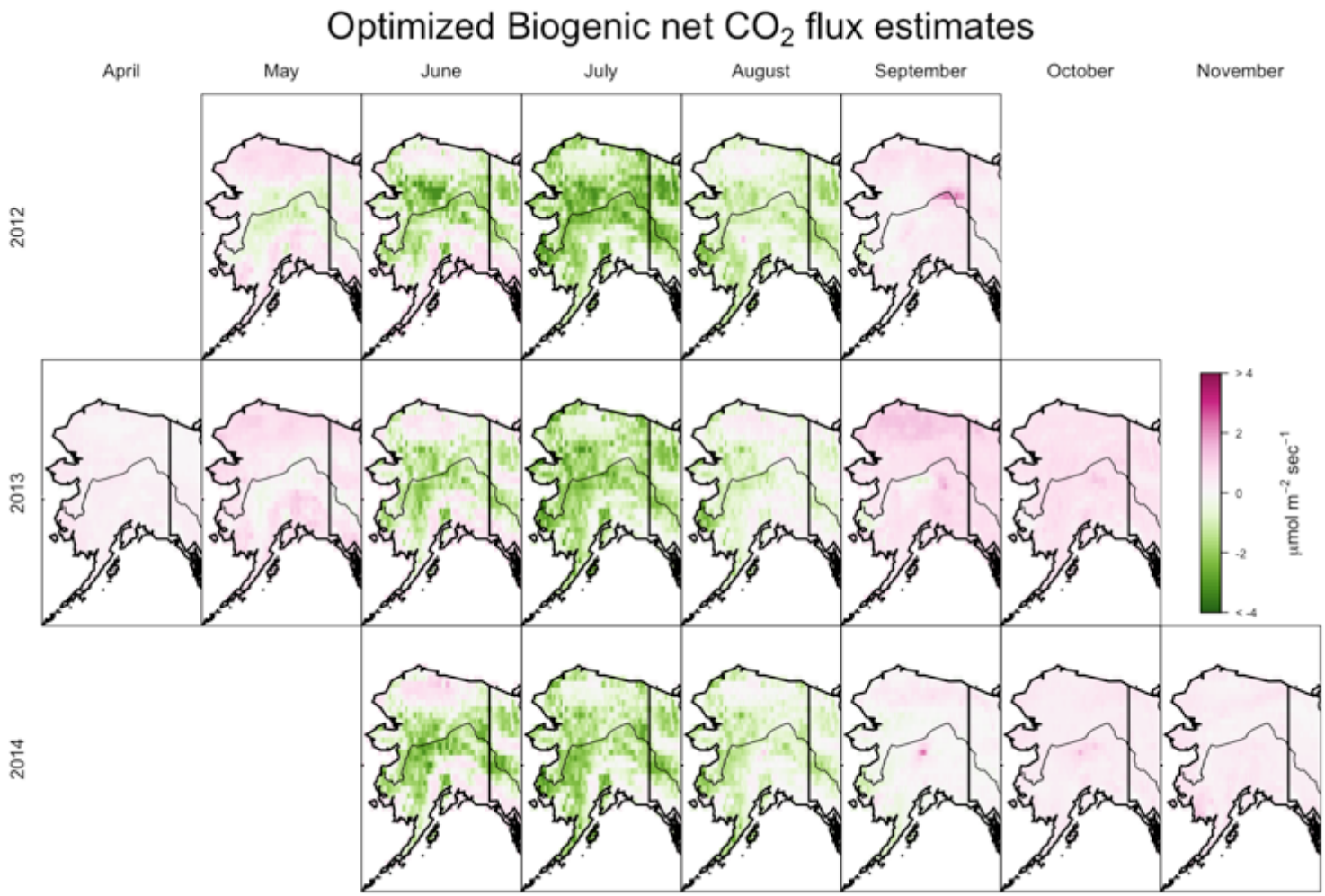
Monthly Optimized Biogenic NEE
PVPRM & CARVE



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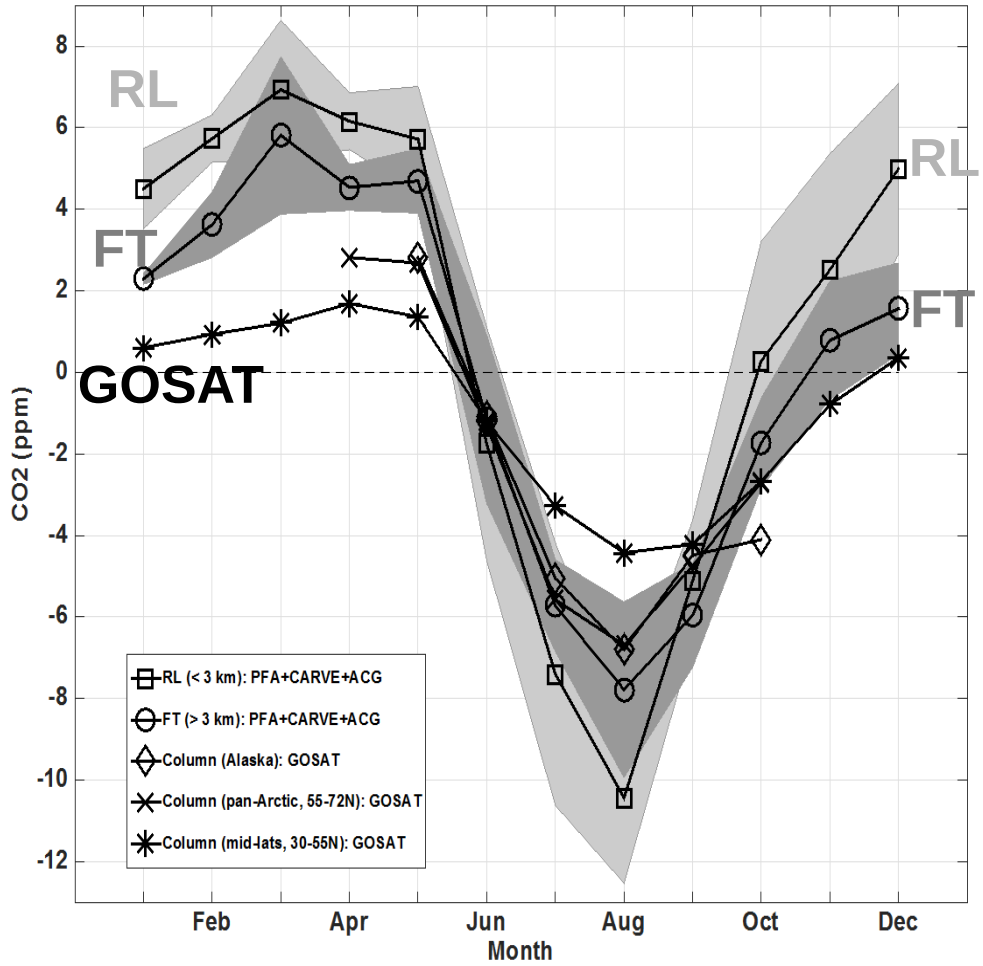
RL & FT CO2 Reveal Different Aspects of Alaska CO2 Seasonal Cycle

- Residual Layer (RL) data contain local Alaska information
- Free Troposphere (FT) data help quantify pan-Arctic and long-range transport contributions

2009 – 2014 average CO2 seasonal cycle amplitudes for
- Residual Layer (RL)
- Free Troposphere (FT)

CARVE, ACG, PFA aircraft data profiles
GOSAT column CO2



Parazoo et al., PNAS (2016); Poster C.05

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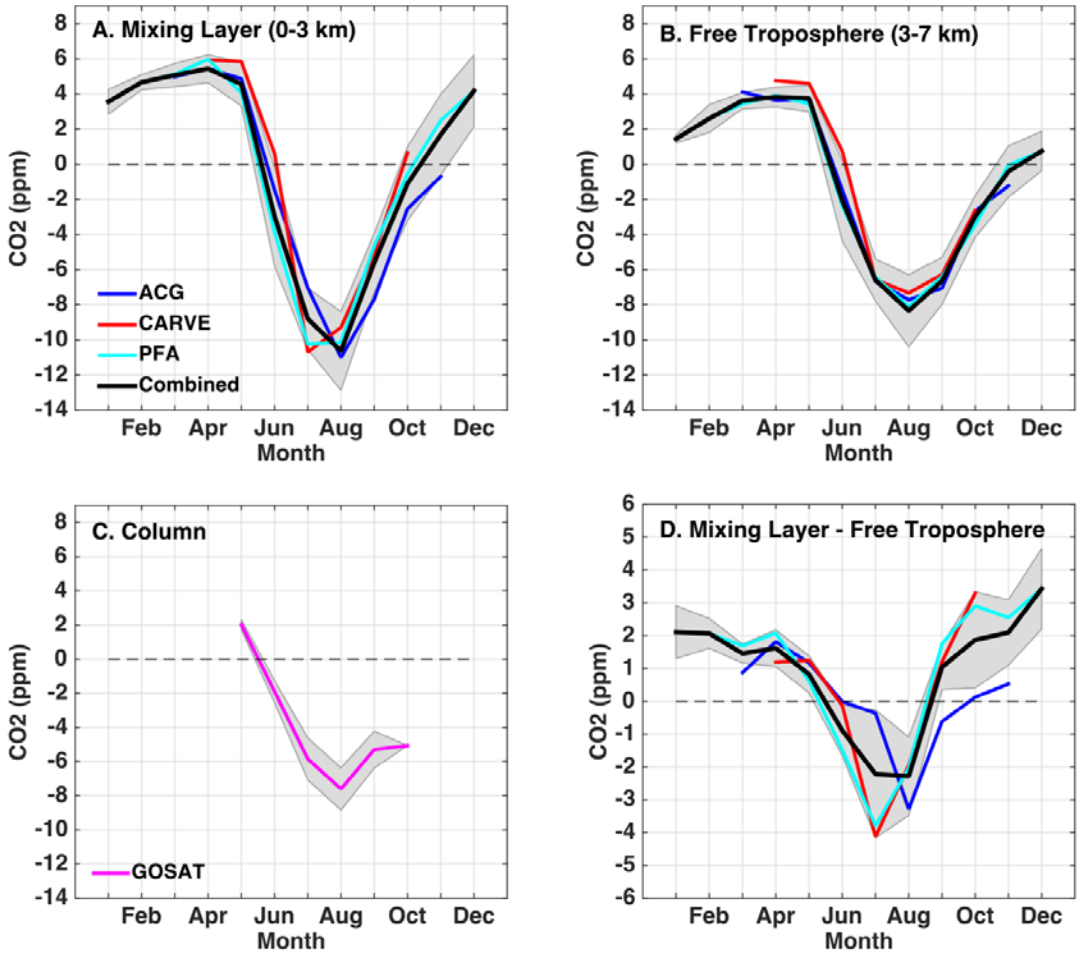
Current Measurement Strategies & Alaska CO2 Seasonal Cycle

None of the individual airborne sampling strategies available in the 2009-2014 period captured the full CO2 seasonal cycle as well as their composite

Vertical profile information in the ML – FT difference gives high sensitivity to changes in the Alaska CO2 seasonal cycle



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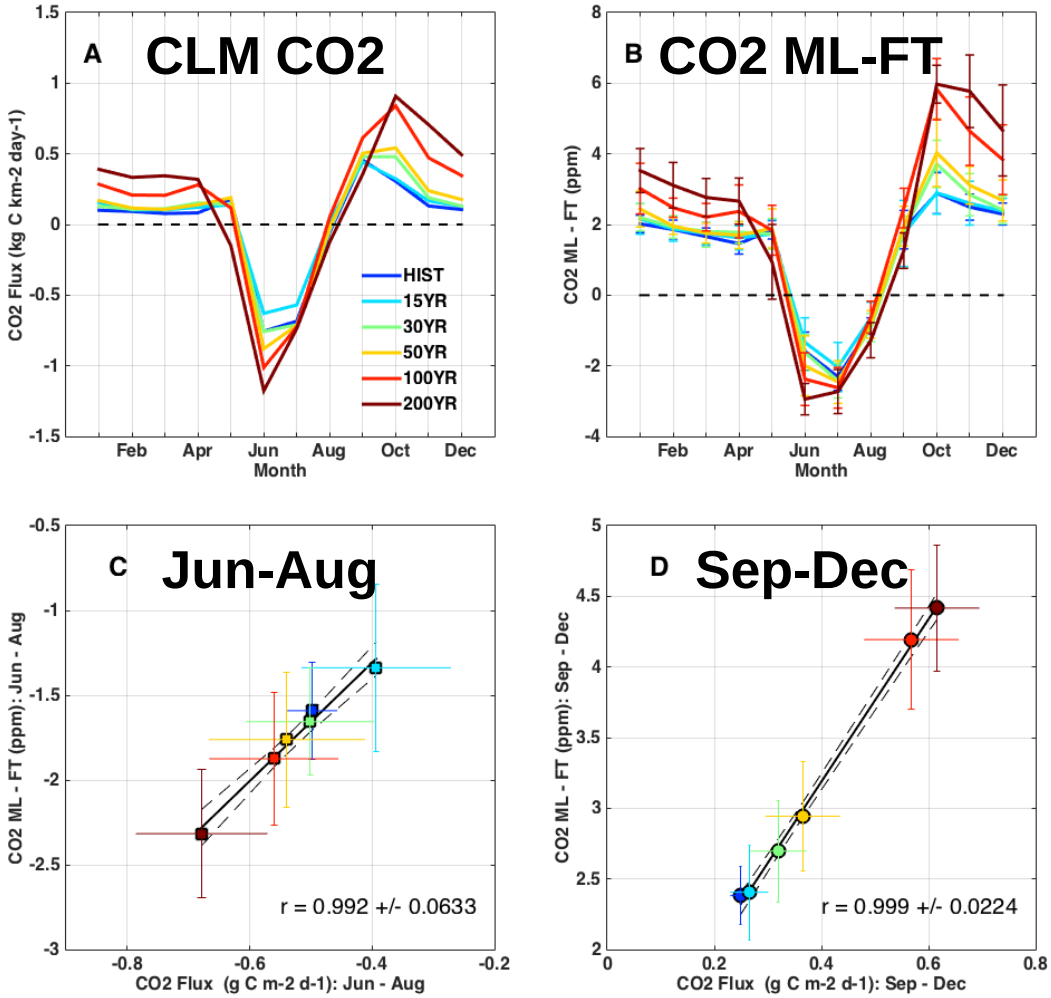
Modeled CO2 Sensitivity to Future Warming & Permafrost Thaw

A. CLM4.5BGC CO2 fluxes for projected Alaska warming scenarios

B. CO2 vertical gradients (ML-FT) for the fluxes in (A)

Regression fits to Jun-Aug CO2 minimum (C) and Sep-Dec CO2 maximum (D)



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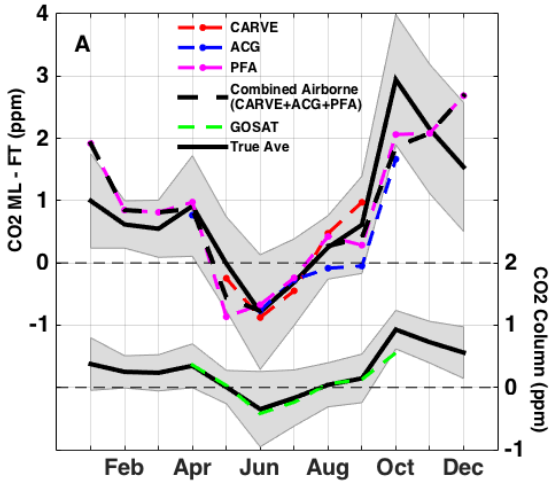
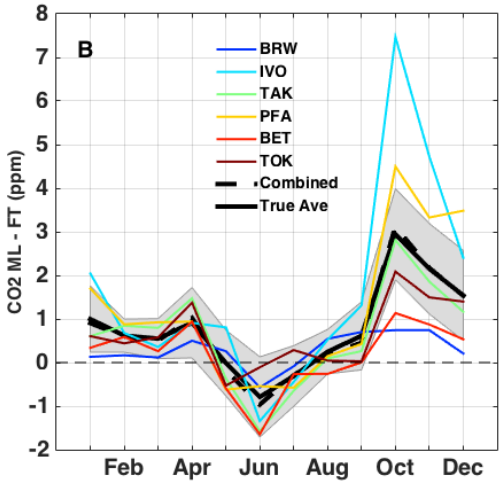
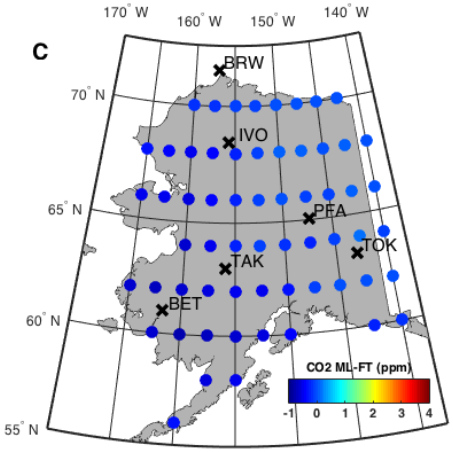
Airborne Strategy for Detecting the Permafrost Carbon Feedback

Monthly vertical profiles (0 – 7 km) at 6 sites across Alaska could capture the summer and cold season changes in CO2 emissions from the permafrost carbon feedback

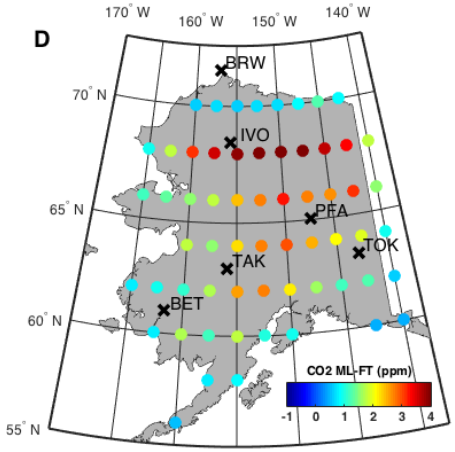
Current strategies lack the required combination of year-round sampling and geographic coverage







Jun-Aug



Sep-Dec

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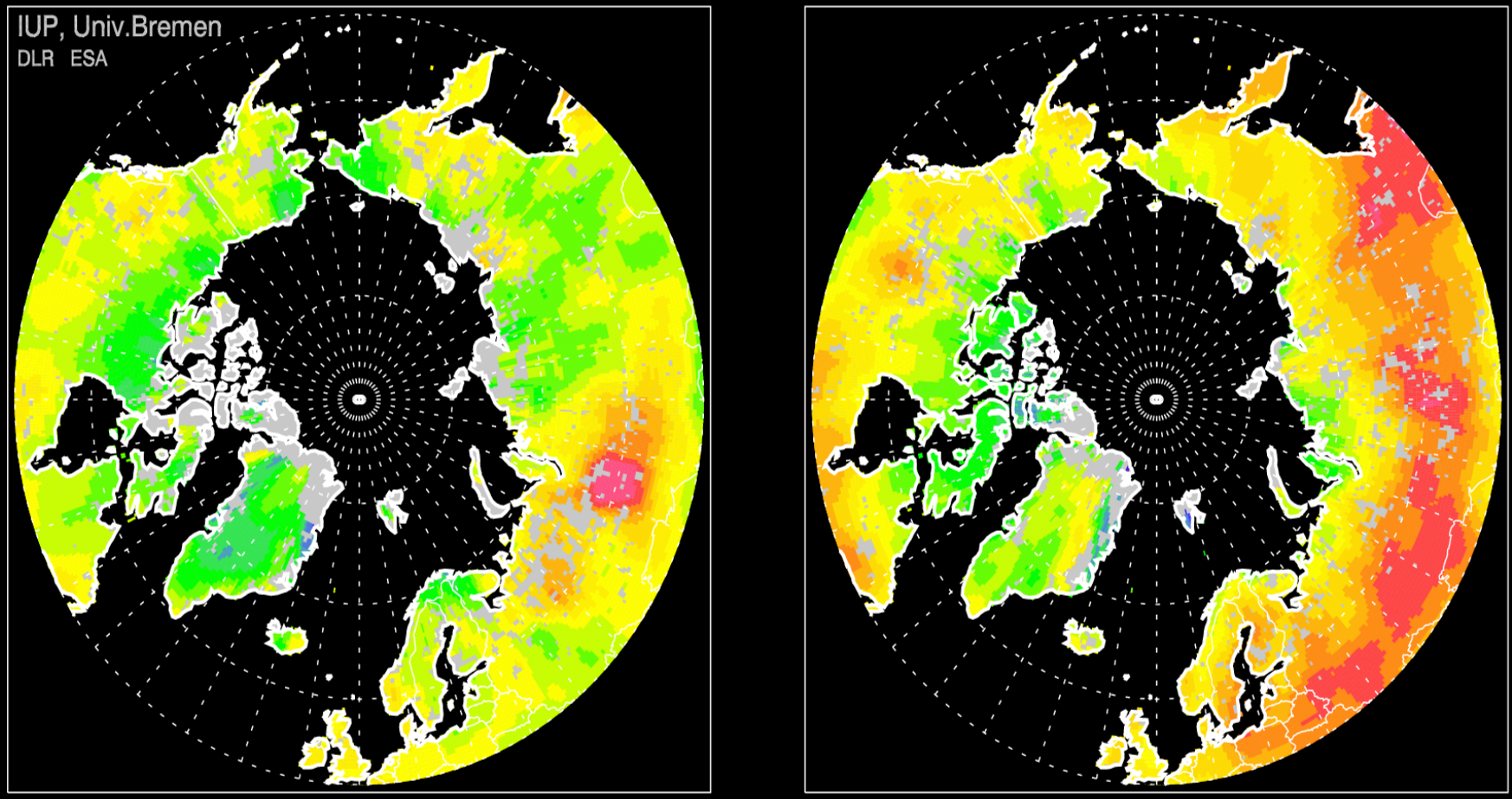
Methane SCIAMACHY/Envisat Northern Hemisphere

April-June 2003

July-September 2003



Number of methane molecules per billion air molecules

1700 1725 1750 1775 1800

TropOMI instrument on Sentinel-5P Mission
LRD: Late 2016
Global CH4

Summary

NHL XCO2 observations are essential for accurate regional and global flux estimates

Measurements during the cold season are particularly important for monitoring climate change and the permafrost carbon feedback

Northern high latitudes pose XCO2 observing challenges

- **Minimal sunlight from Sep – March each year**
- **Snow, ice, fog, clouds, inundated land surfaces**
- **Short, but intense seasonal cycle → Large seasonal cycle amplitude**
- **Cold season signals dominated by transport from lower latitudes**

Charles.E.Miller@jpl.nasa.gov