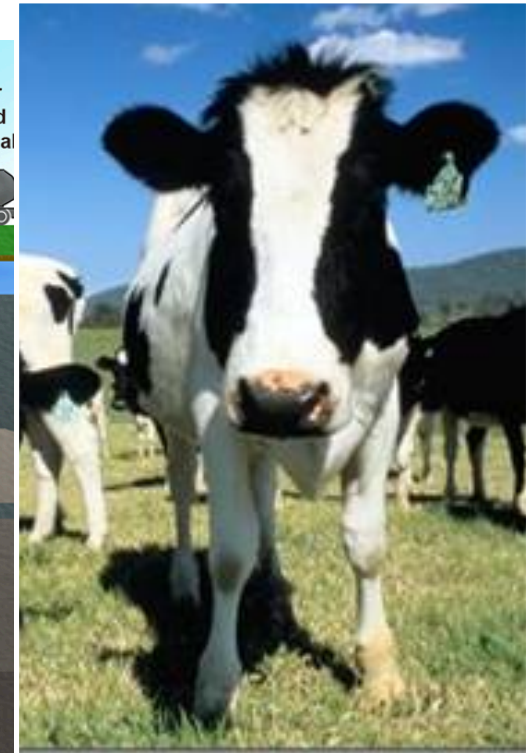
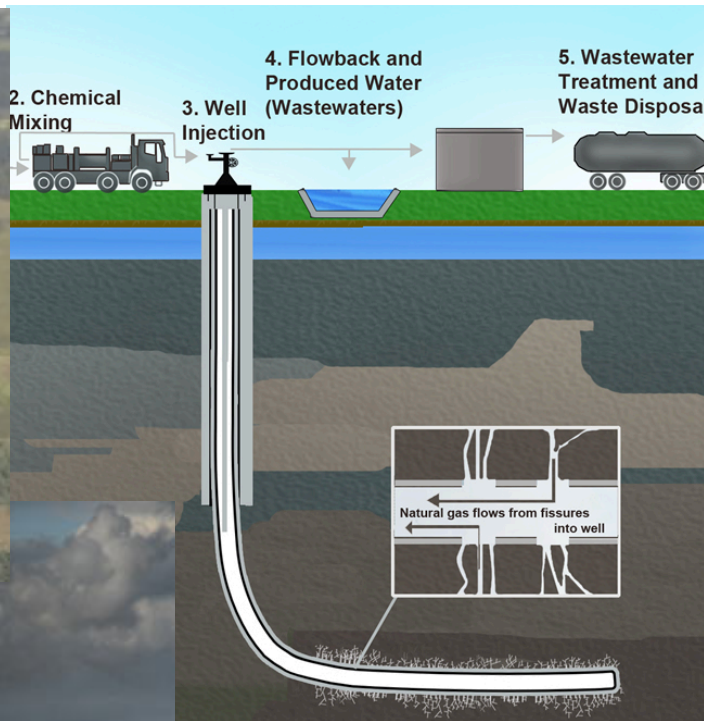


Atmospheric Greenhouse Gases: emission processes, trends, and the emerging dominance of human-related sources

Steven C. Wofsy
Harvard University
(and many others...!)

CO_2 and CH_4





How we learn about emissions of greenhouse gases and pollutants *using* atmospheric measurements

Studies of GHG emissions using regional scale approaches...widely applicable to air pollution ...

Beijing, 01 Aug 2017

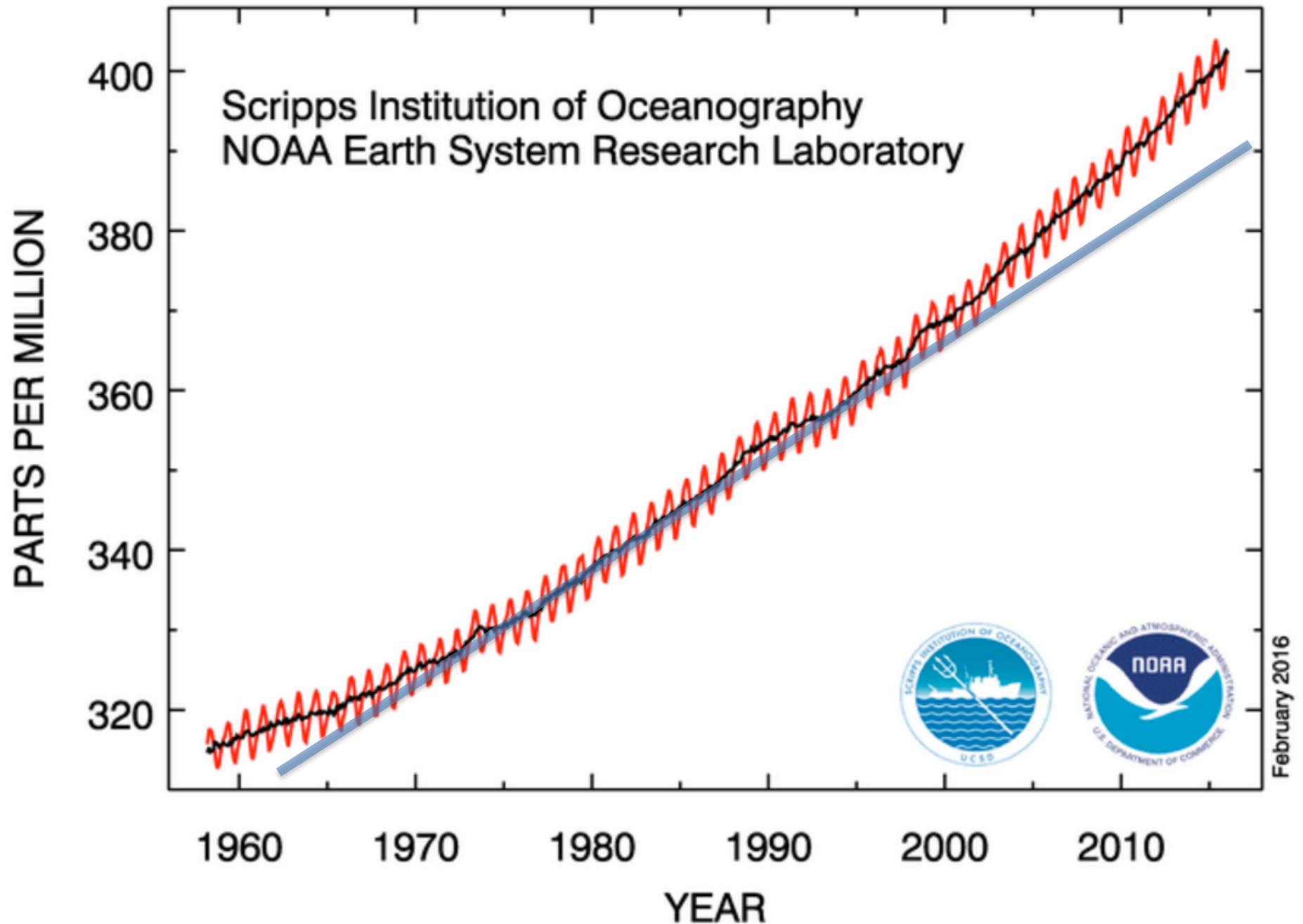
Carbon Dioxide (CO₂) –

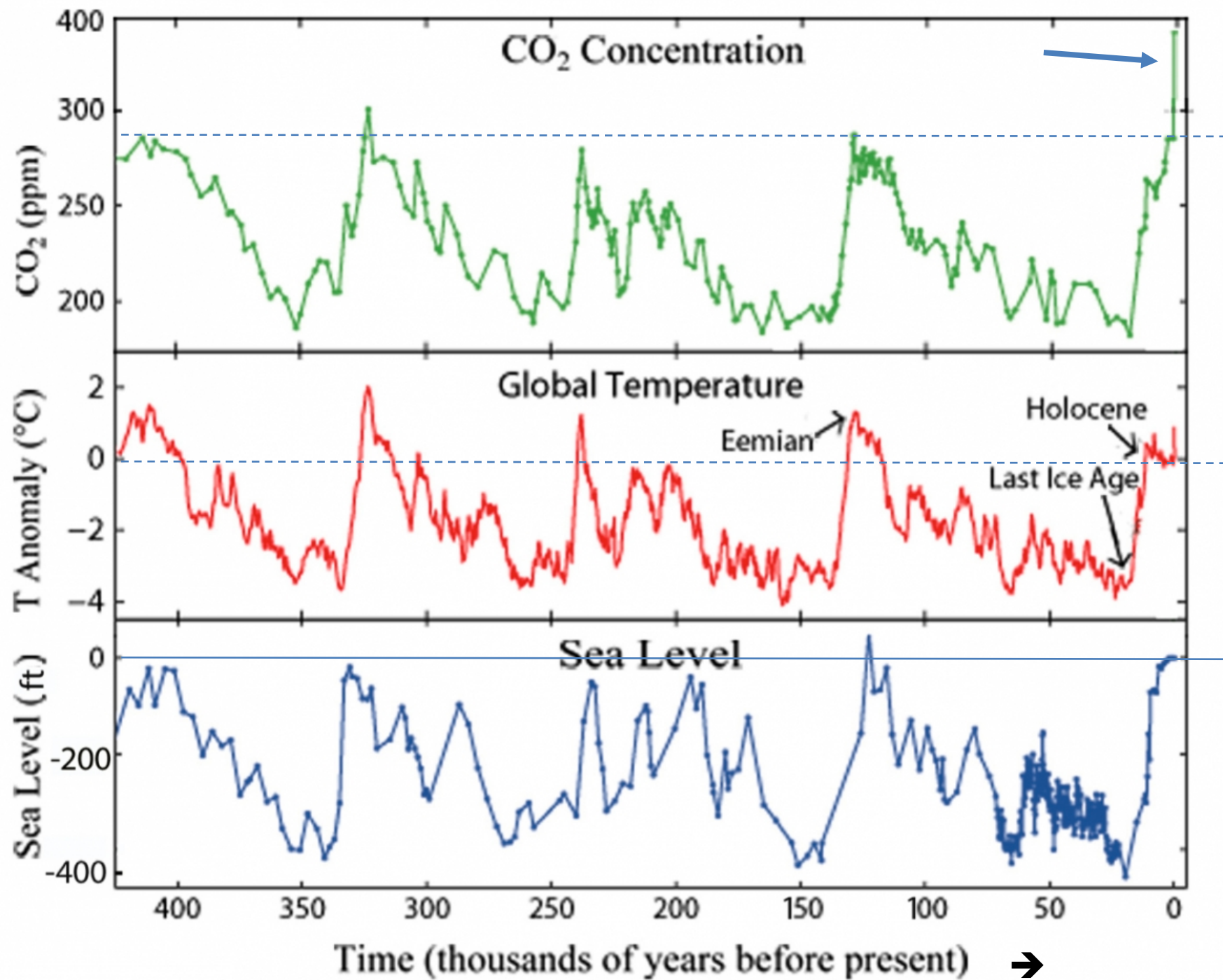
- **Greenhouse Gas**
- **Ocean acidification**

Methane (CH₄) –

- **Greenhouse Gas**
- **Controls Background Ozone**
- **Primer for pollutant production**
- **Stratospheric H₂O source**
- **Stratospheric Cl-radical sink**

Atmospheric CO₂ at Mauna Loa Observatory



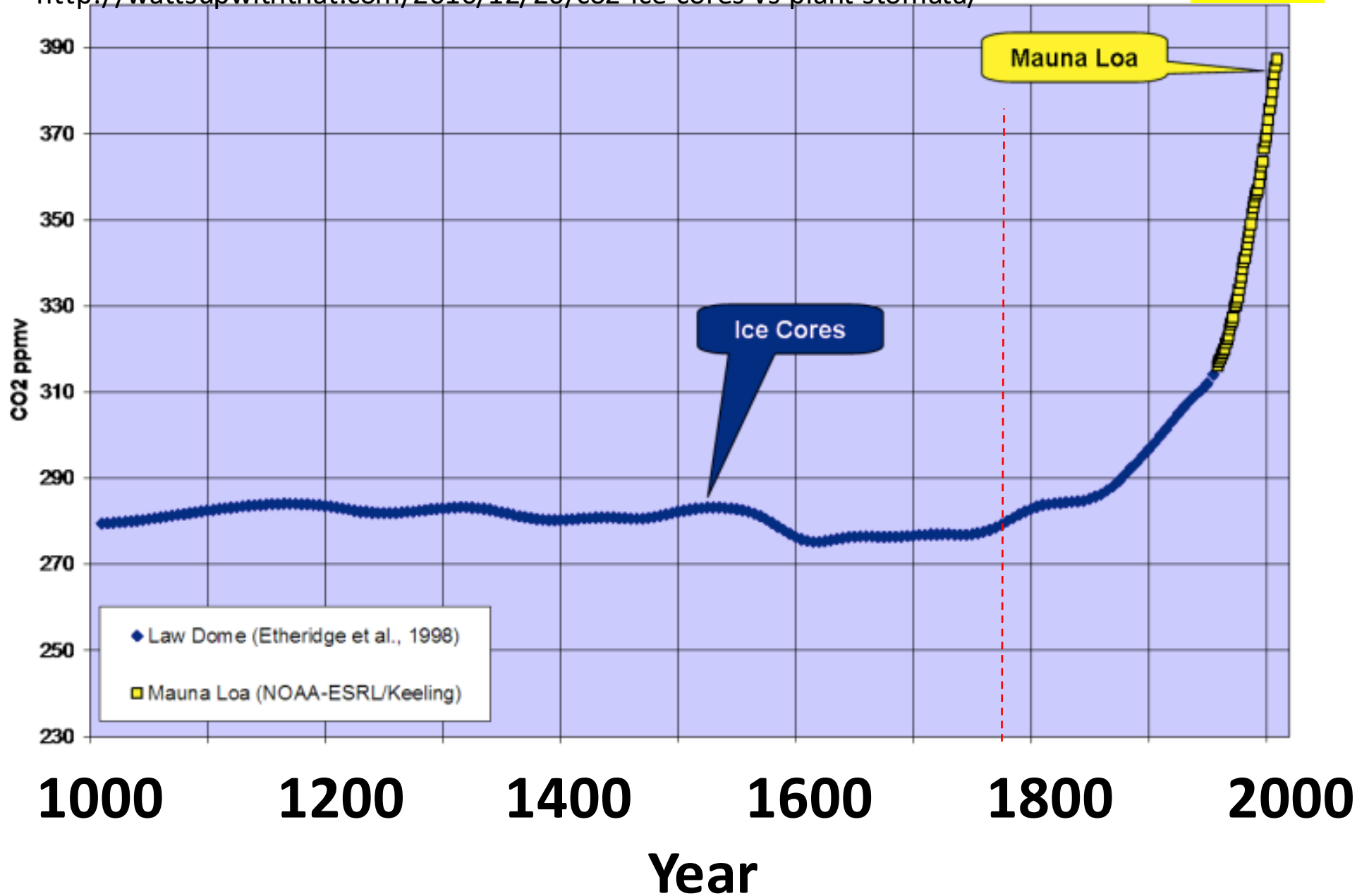


Atmospheric CO₂ 1000 – 2010 AD

+40%

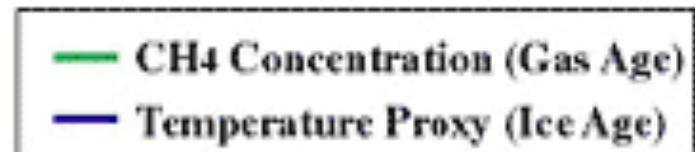
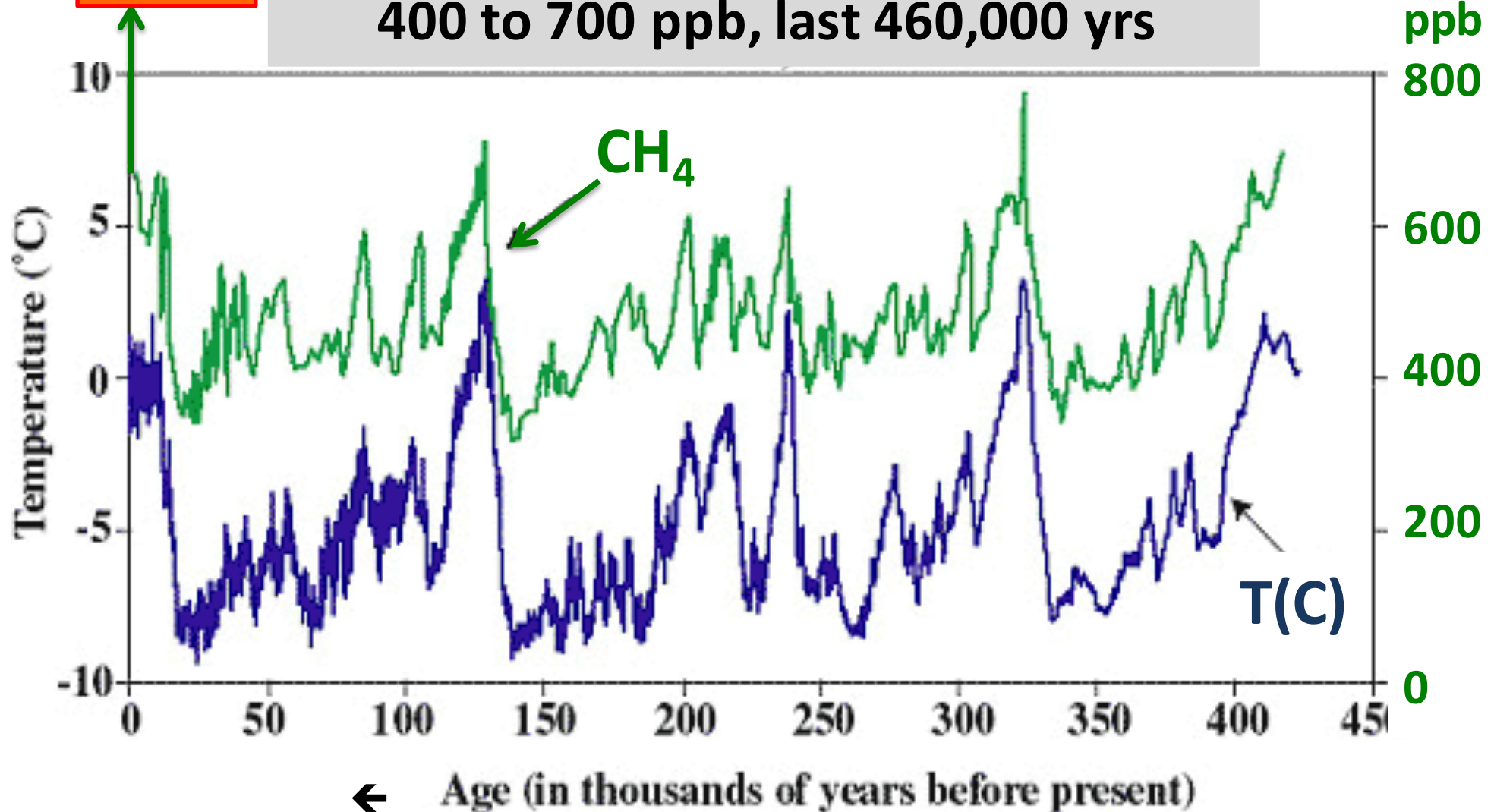
2015 *

<http://wattsupwiththat.com/2010/12/26/co2-ice-cores-vs-plant-stomata/>

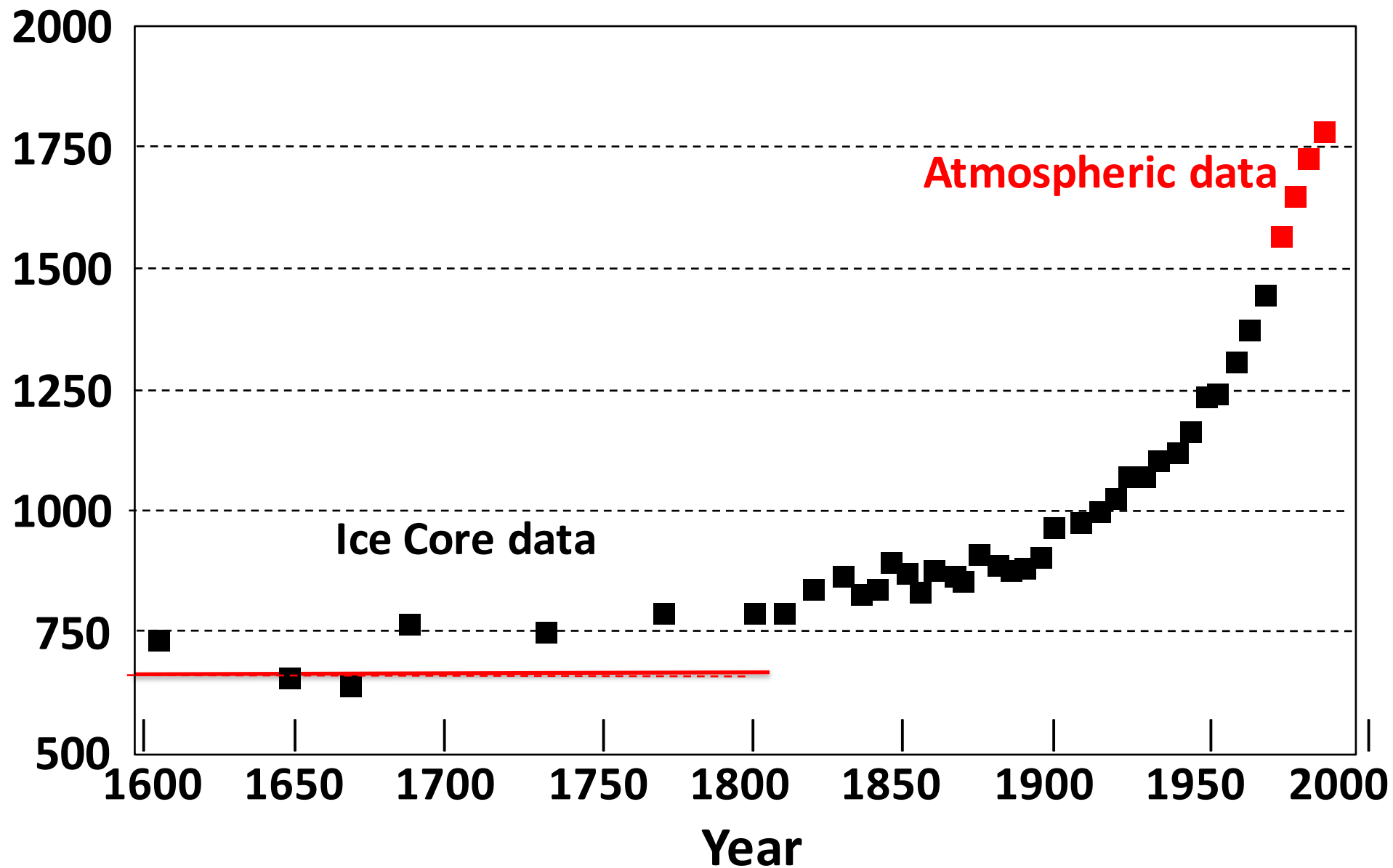


1800

Vostok Ice Core: CH₄ sync'd to climate
400 to 700 ppb, last 460,000 yrs

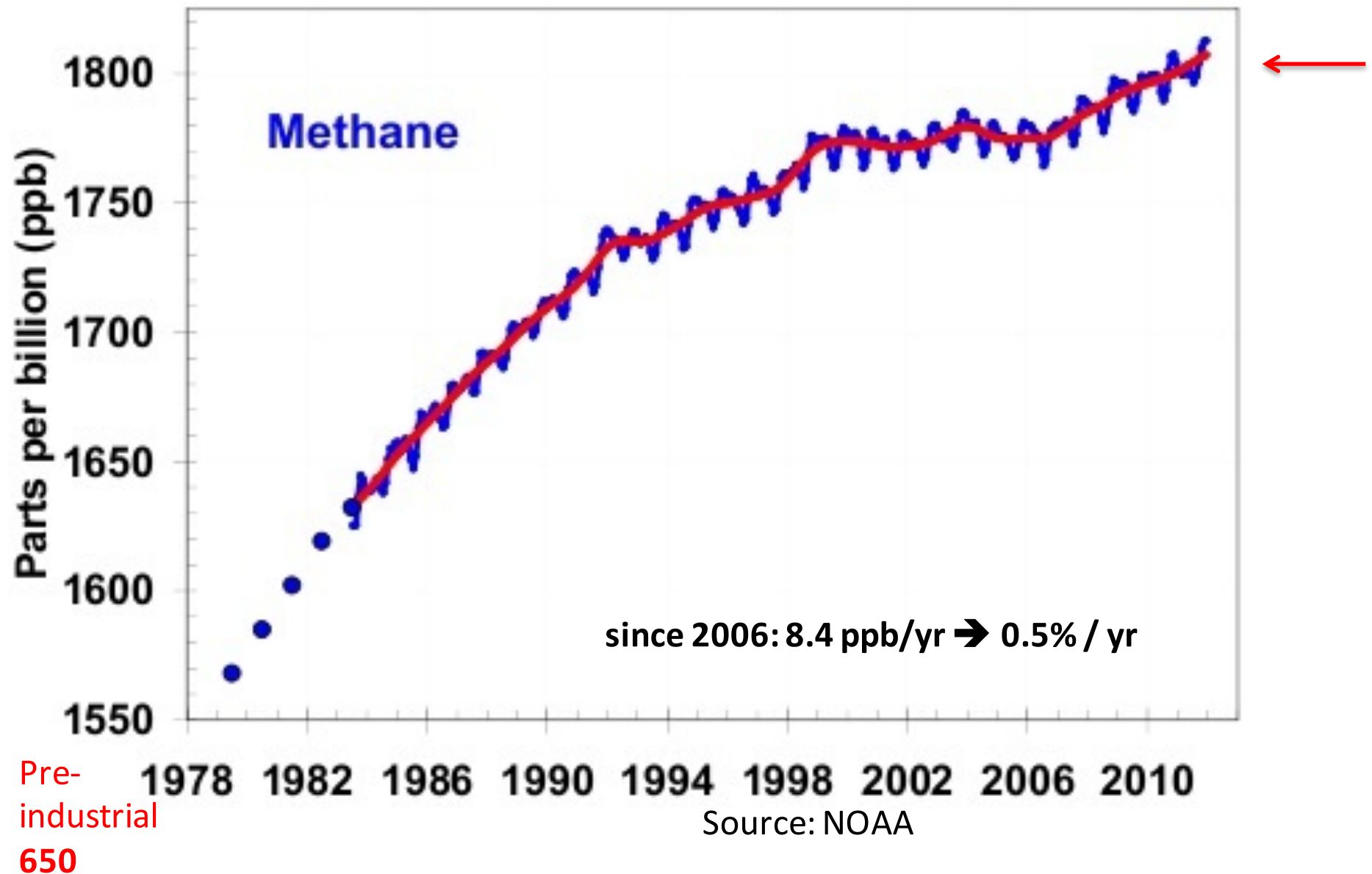


CH₄ concentrations (ppb) since 1600

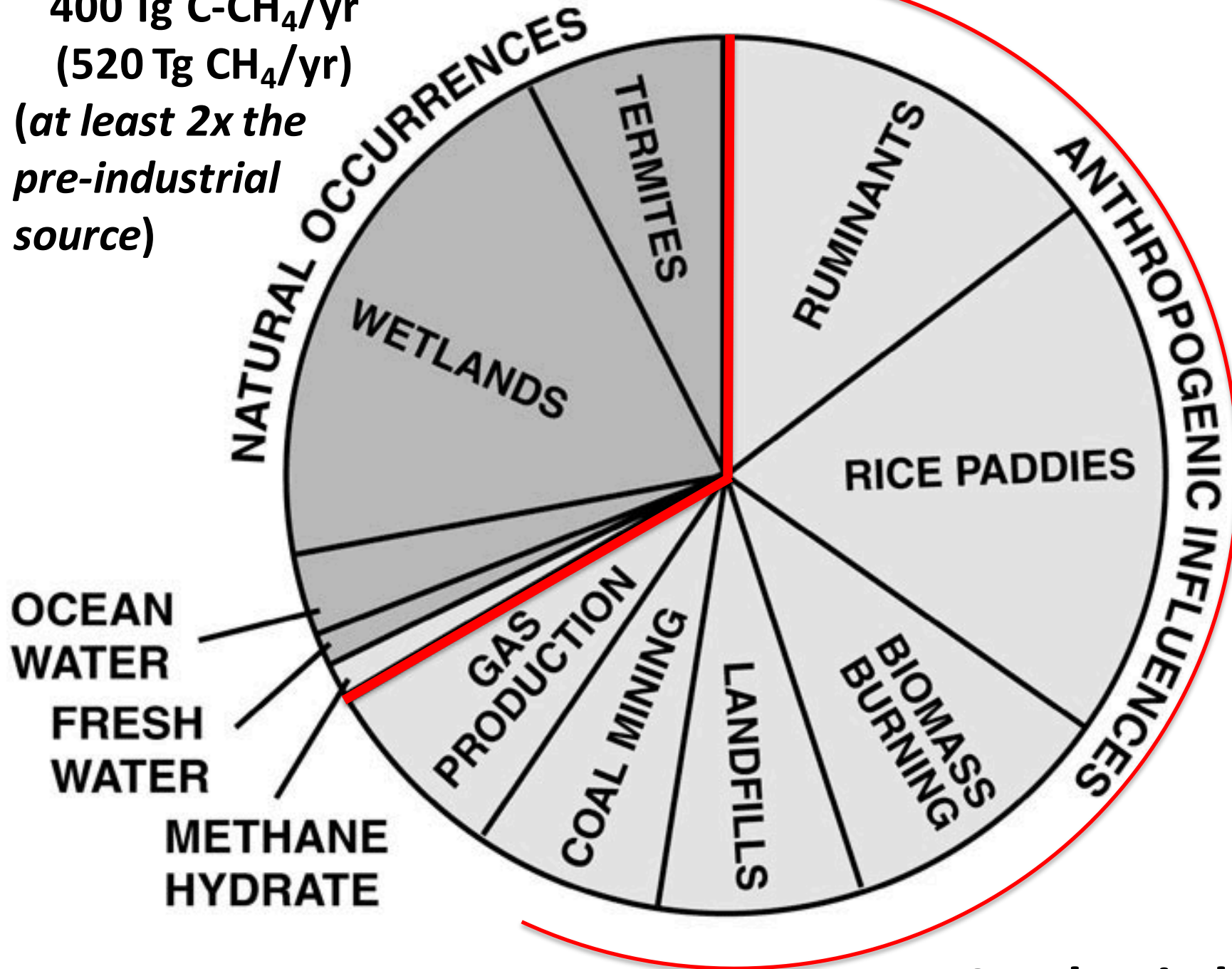


Etheridge et al., 1996

CH₄ concentrations rose rapidly for ~200 years, leveled off in the 1990s...and then resumed increasing rapidly



**400 Tg C-CH₄/yr
(520 Tg CH₄/yr)
(at least 2x the
pre-industrial
source)**



Elements of an exemplary “top-down” Study: CH₄ emissions in North America (*Scot Miller*)

1. DATA

**Measurements
of atmospheric
methane** at the

surface and in
aircraft profiles

(NOAA: A. Andrews,
C. Sweeney, E.
Dlugokencky);
Environment Canada:
D. Worthy)

**2007-8: 14000
*observations***

2. “Model”

**Computer
Simulation of
the data:**

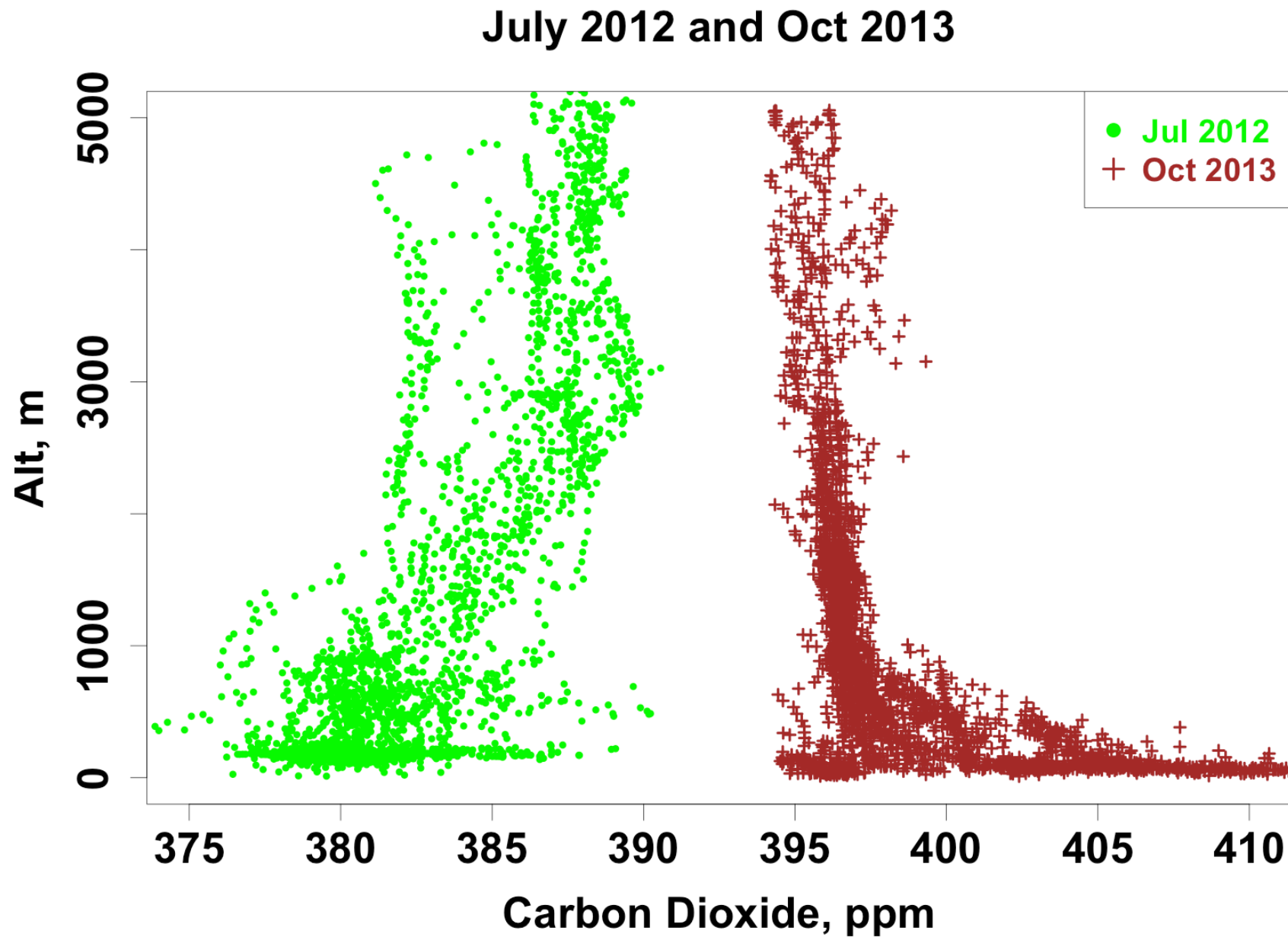
**Prior emissions
WRF/STILT**

(John Lin, Christoph
Gerbig, AER
collaborators,
Eluszkiewicz,
Nehrkorn))

3. ANALYSIS

Find the map of
emissions of CH₄
that best explain
(“fit”) the data
using geostatistics
(S. Miller, A.
Michalak)

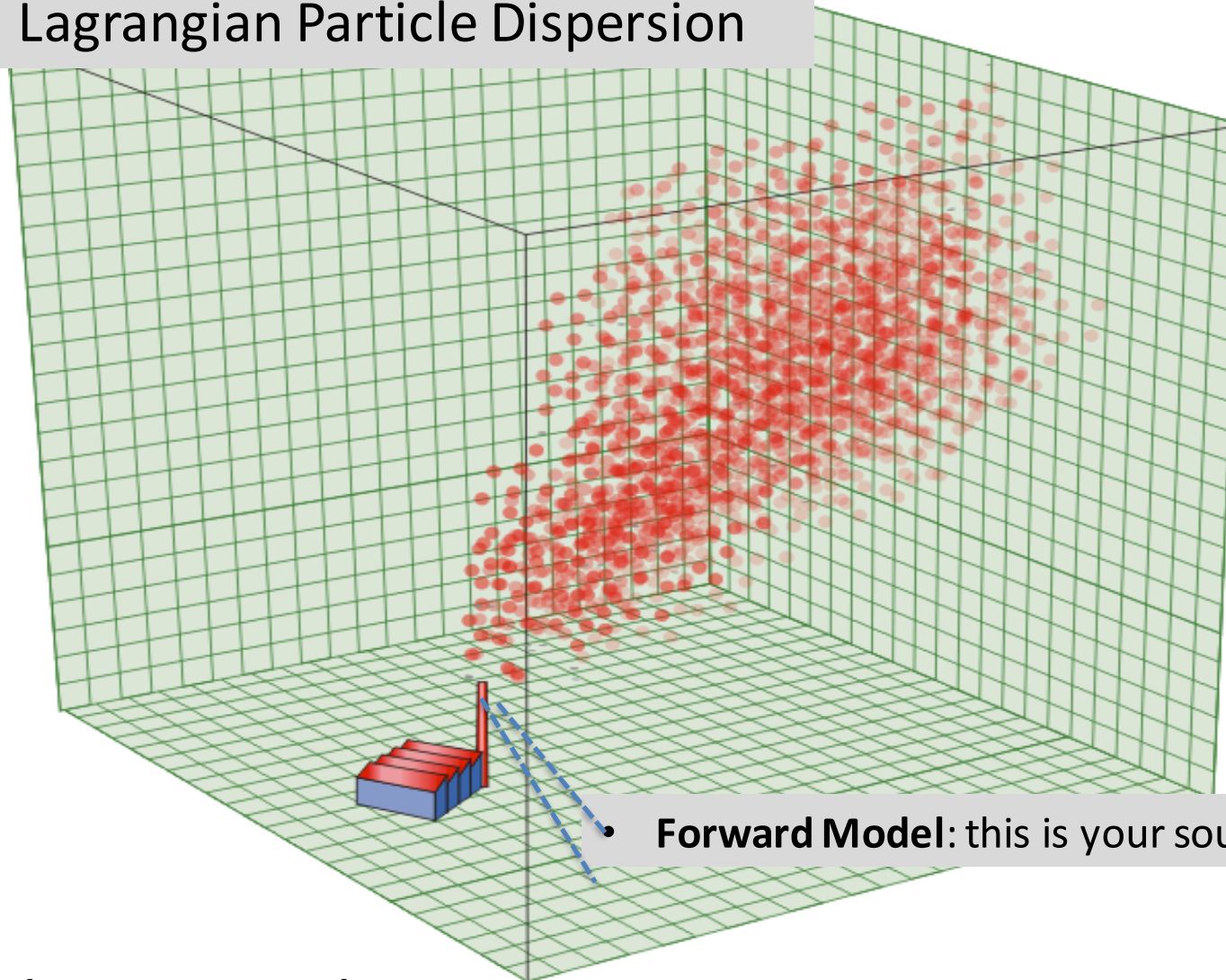
1. DATA (example)



2. Model of the observations

Lagrangian particle dispersion *adjoint* in a WRF framework – “WRF-STILT” (John Lin, Christoph Gerbig)

Lagrangian Particle Dispersion

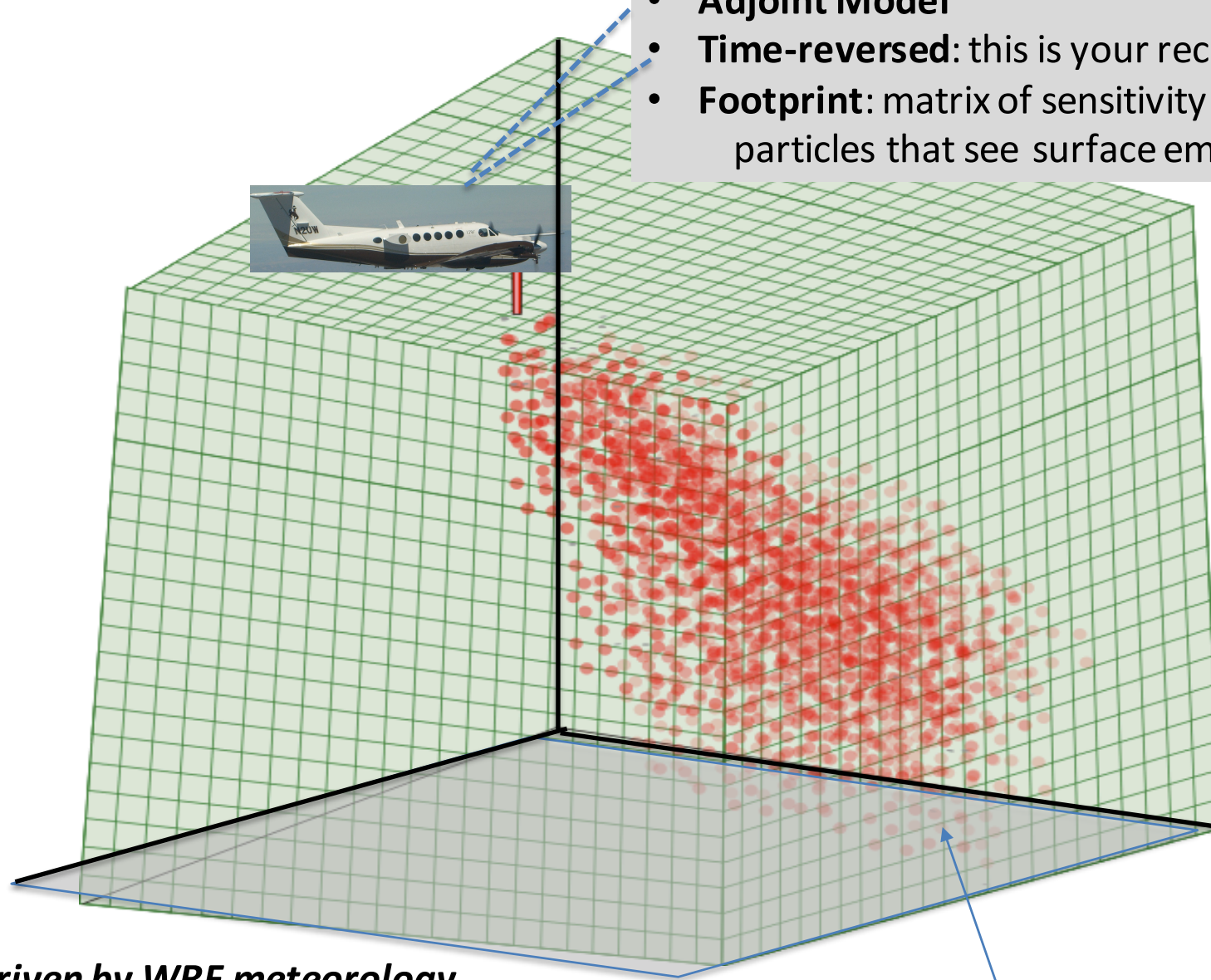


- **Forward Model:** this is your source

Driven by WRF meteorology

2. Model of the observations

- **Adjoint Model**
- **Time-reversed**: this is your receptor
- **Footprint**: matrix of sensitivity to the particles that see surface emissions

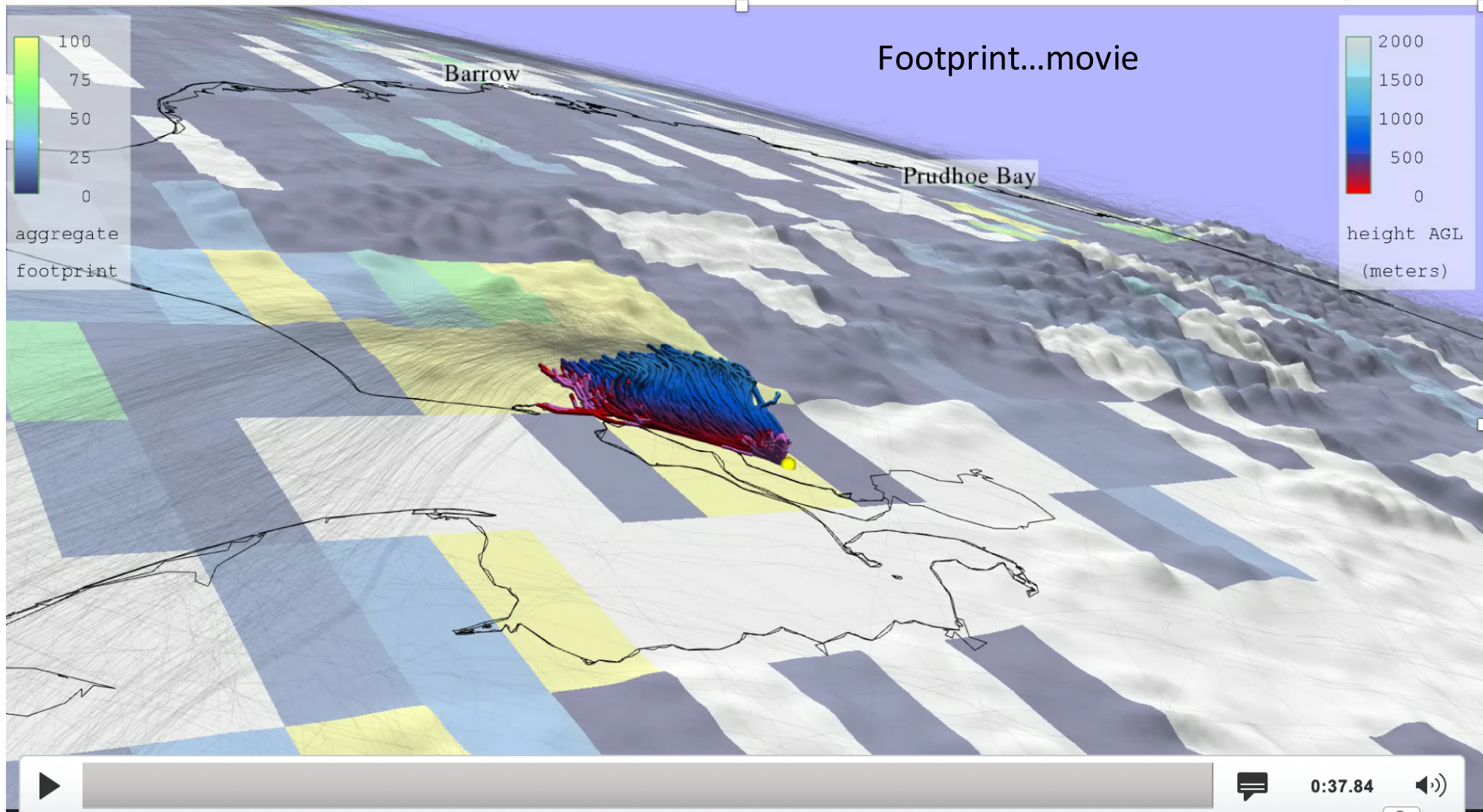


Driven by WRF meteorology

2. Model of the observations

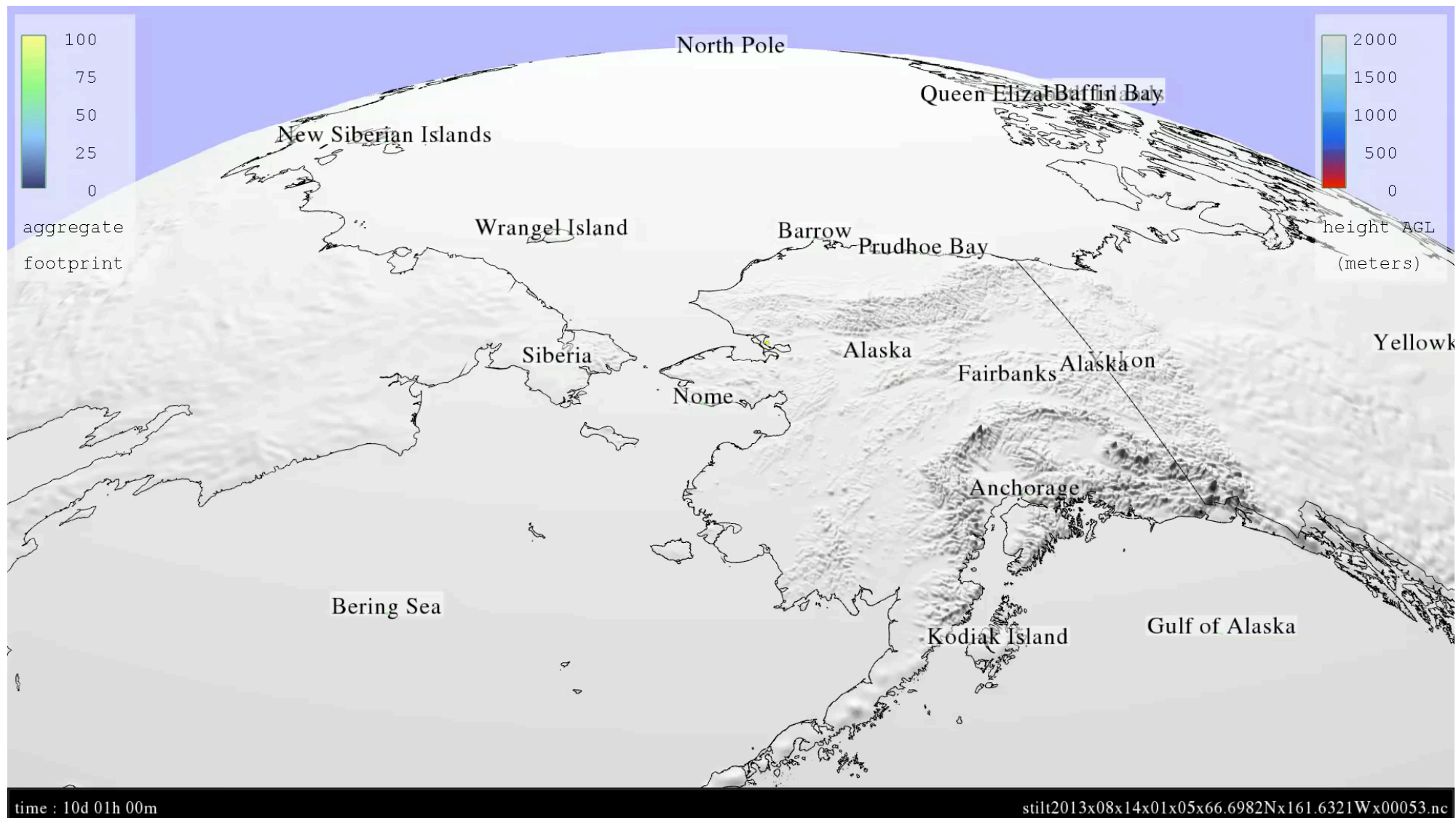
WRF -- STILT : visualization of particles contributing to the footprint for one receptor

John Henderson, AER

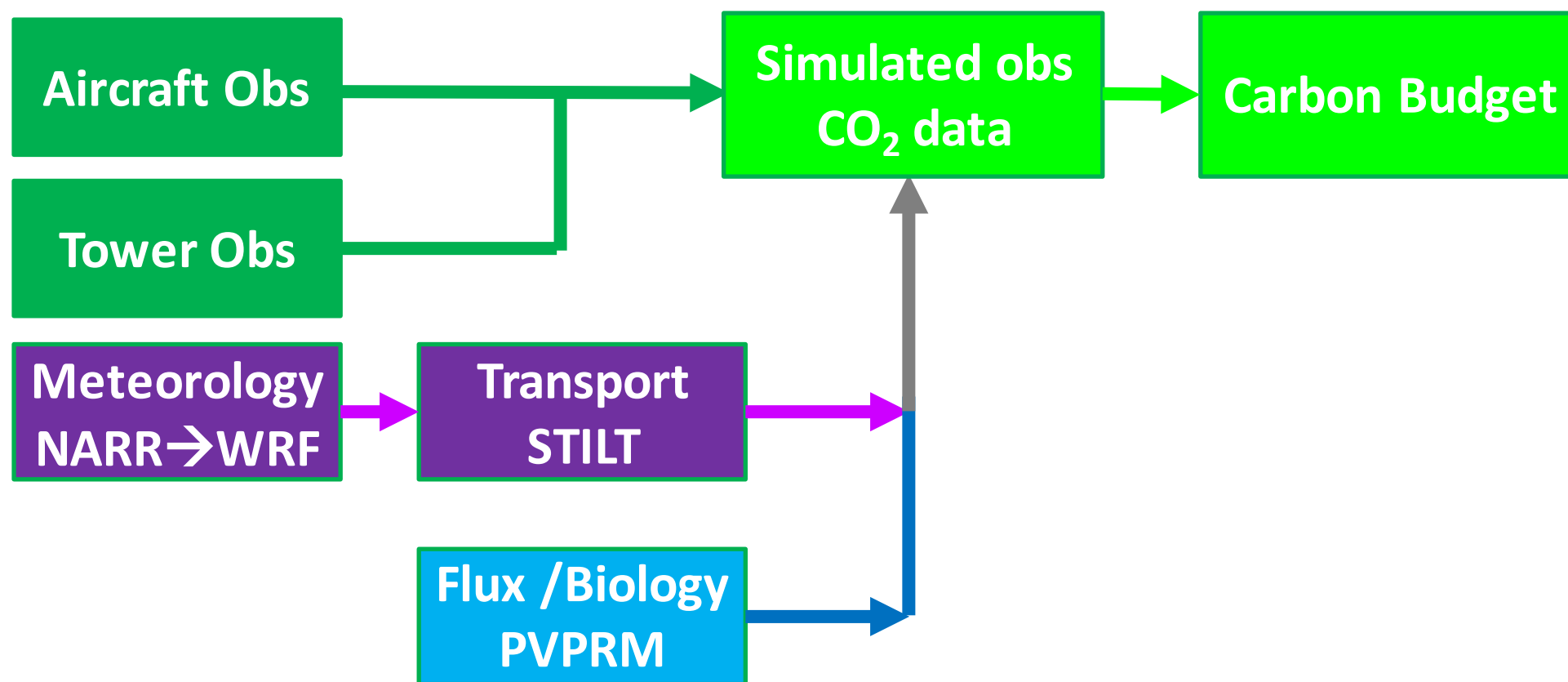


WRF -- STILT : visualization of particles contributing to the footprint for one receptor

John Henderson, AER



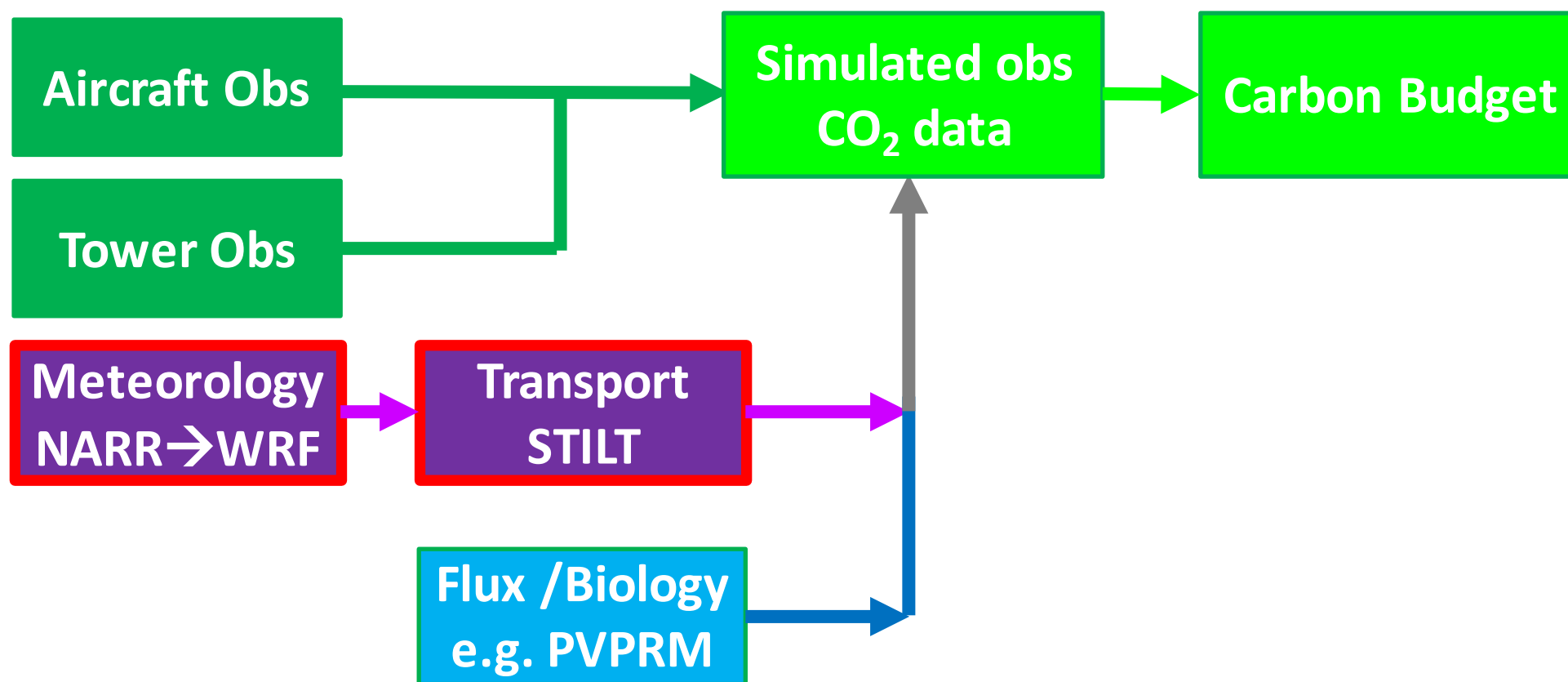
3. Elements of a model-data synthesis



“Weather Research and Forecast Model (WRF)” – high resolution mesoscale model driven by operations reanalysis meteorological fields

Prior emissions model, e.g. spatially explicit, functional model of biological fluxes of CO₂

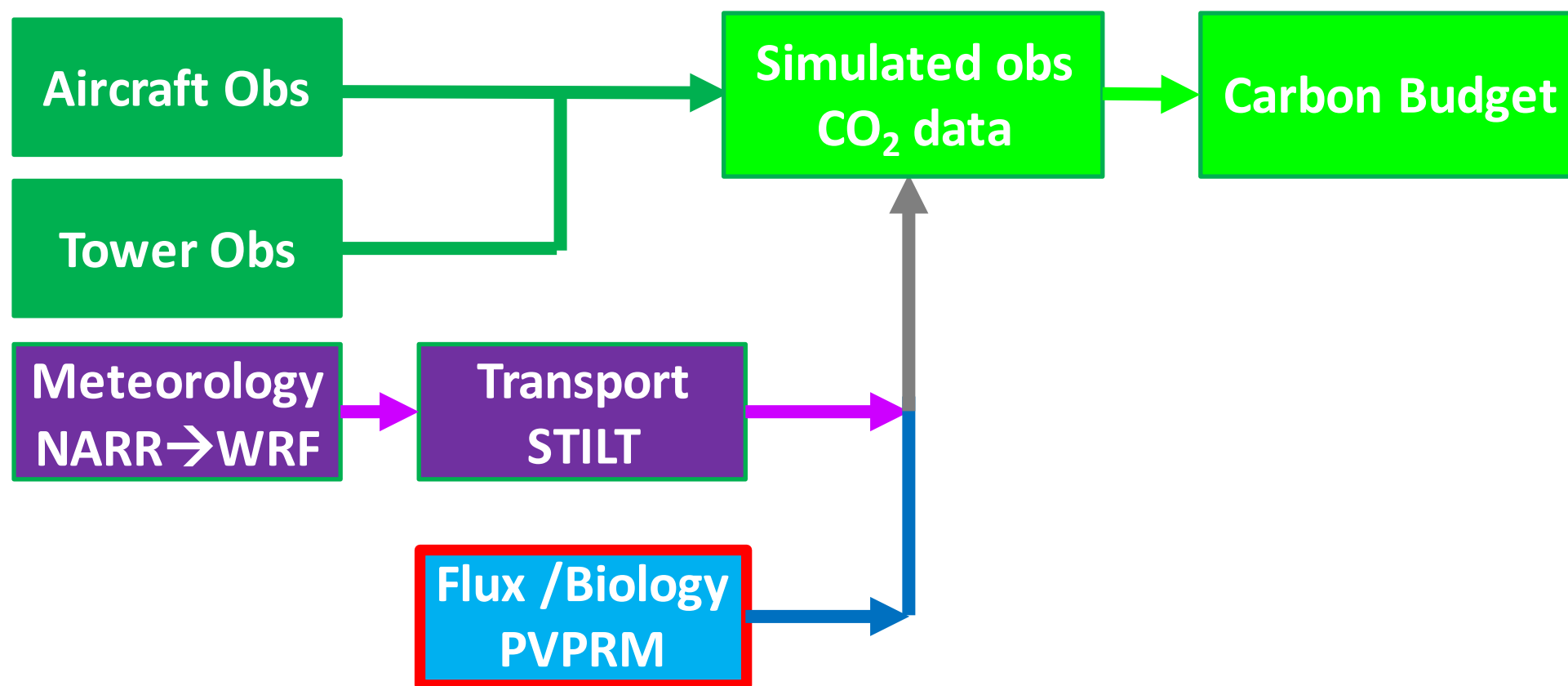
Elements of a model-data synthesis



“Weather Research and Forecast Model (WRF)” – high resolution mesocale model driven by operations reanalysis meteorological fields

Prior emissions model, e.g. spatially explicit, functional model of biological CO₂ fluxes

Elements of a model-data synthesis



“Weather Research and Forecast Model (WRF)” – high resolution mesoscale model driven by operations reanalysis meteorological fields

Prior Emissions Model, e.g. spatially explicit functional model of biological CO₂ fluxes

First Case Study :

Does US production of natural gas explain why global CH₄ rising again?

Related questions:

- 1. Are CH₄ releases significant from the USA fossil fuel industry? From agriculture?*
- 2. Are urban and end-user sources important?*

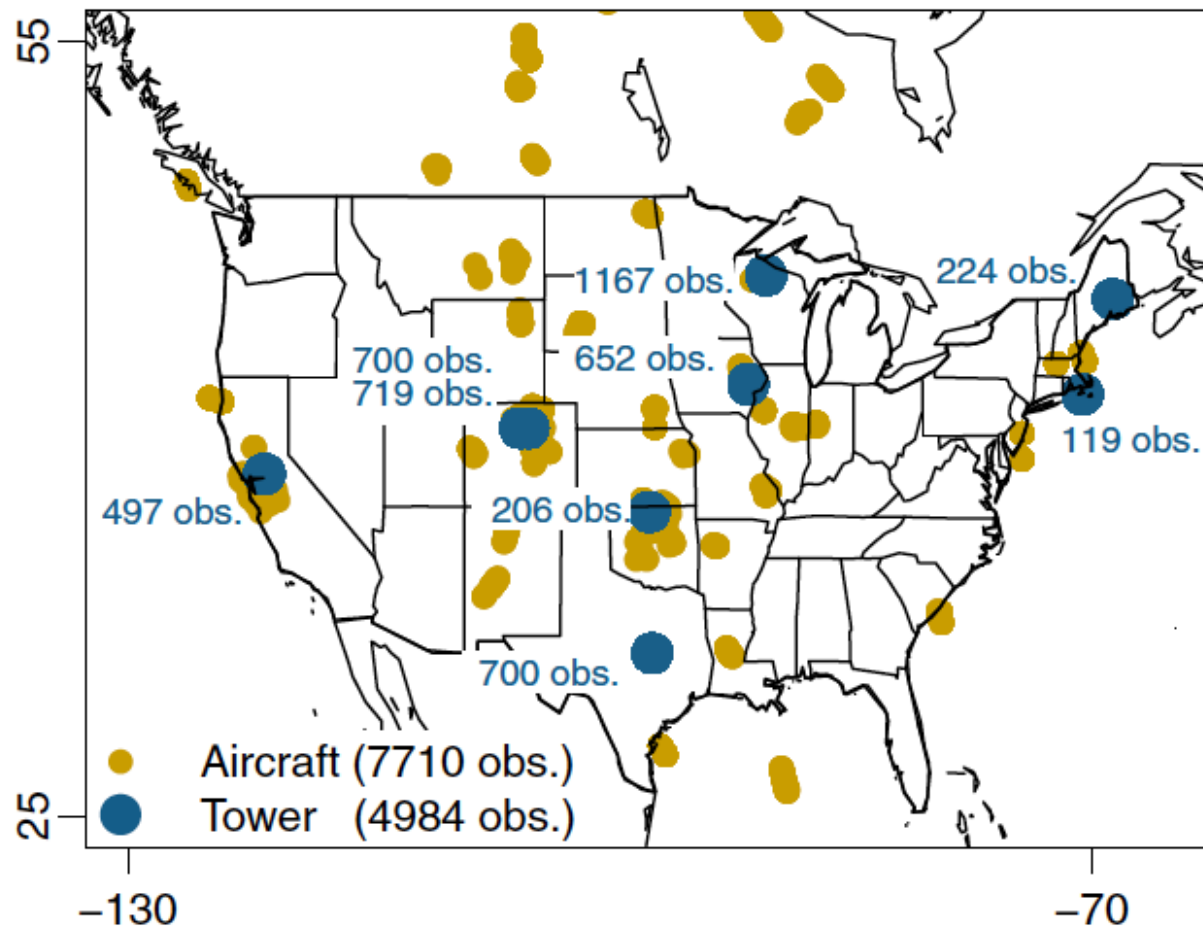


Anthropogenic emissions of methane in the United States

Scot M. Miller^{a,1}, Steven C. Wofsy^a, Anna M. Michalak^b, Eric A. Kort^c, Arlyn E. Andrews^d, Sebastien C. Biraud^e, Edward J. Dlugokencky^d, Janusz Eluszkiewicz^f, Marc L. Fischer^g, Greet Janssens-Maenhout^h, Ben R. Millerⁱ, John B. Miller^j, Stephen A. Montzka^d, Thomas Nehrkorn^f, and Colm Sweeney^j

^aDepartment of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138; ^bDepartment of Global Ecology, Carnegie Institution for Science, Stanford, CA 94305; ^cDepartment of Atmospheric, Ocean, and Space Sciences, University of Michigan, Ann Arbor, MI 48109; ^dGlobal Monitoring Division, Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO 80305; ^eEarth Sciences Division, and ^gEnvironmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720; ^fAtmospheric and Environmental Research, Lexington, MA 02421; ^hInstitute for Environment and Sustainability, European Commission Joint Research Centre, 21027 Ispra, Italy; and ⁱCooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO 80309

DATA – Atmospheric CH₄ time series

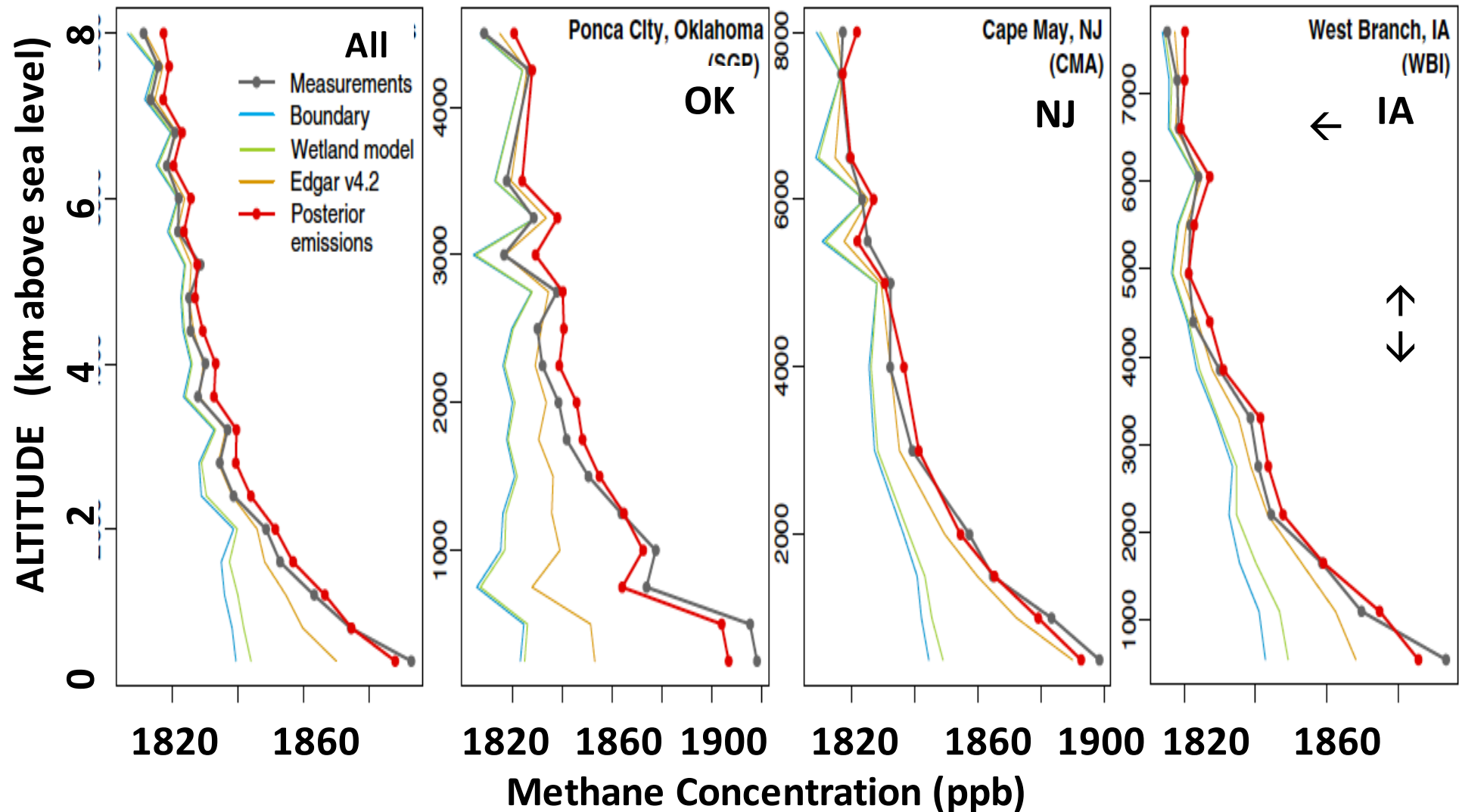


NOAA Flask
Samples, tall
tower %
aircraft
Arlyn Andrews
Colm Sweeney

**~14,000
Observations
for North
America,
2007--2008**

Fig. 2. CH₄ concentration measurements from 2007 and 2008 and the number of observations associated with each measurement type. Blue text lists the number of observations associated with each stationary tower measurement site.

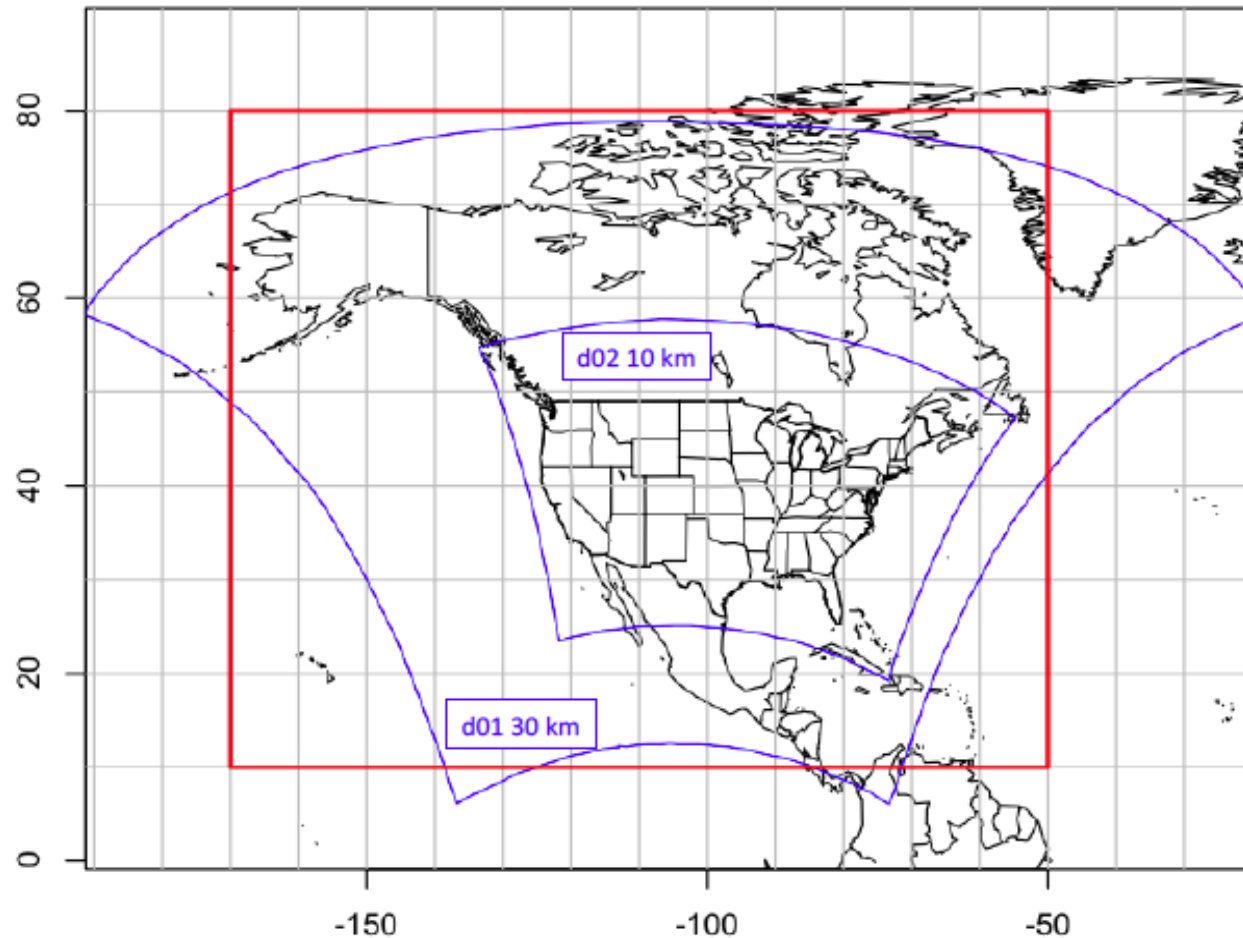
DATA – Atmospheric CH₄ profiles Regional ΔCH_4 : 30 – 80 ppb



Vertical column information $\Leftrightarrow$ mass loading $\rightarrow$
essential distinguish distant-stronger from close-weaker

Weather Research and Forecast **Model** (WRF)

AER WRF Simulations



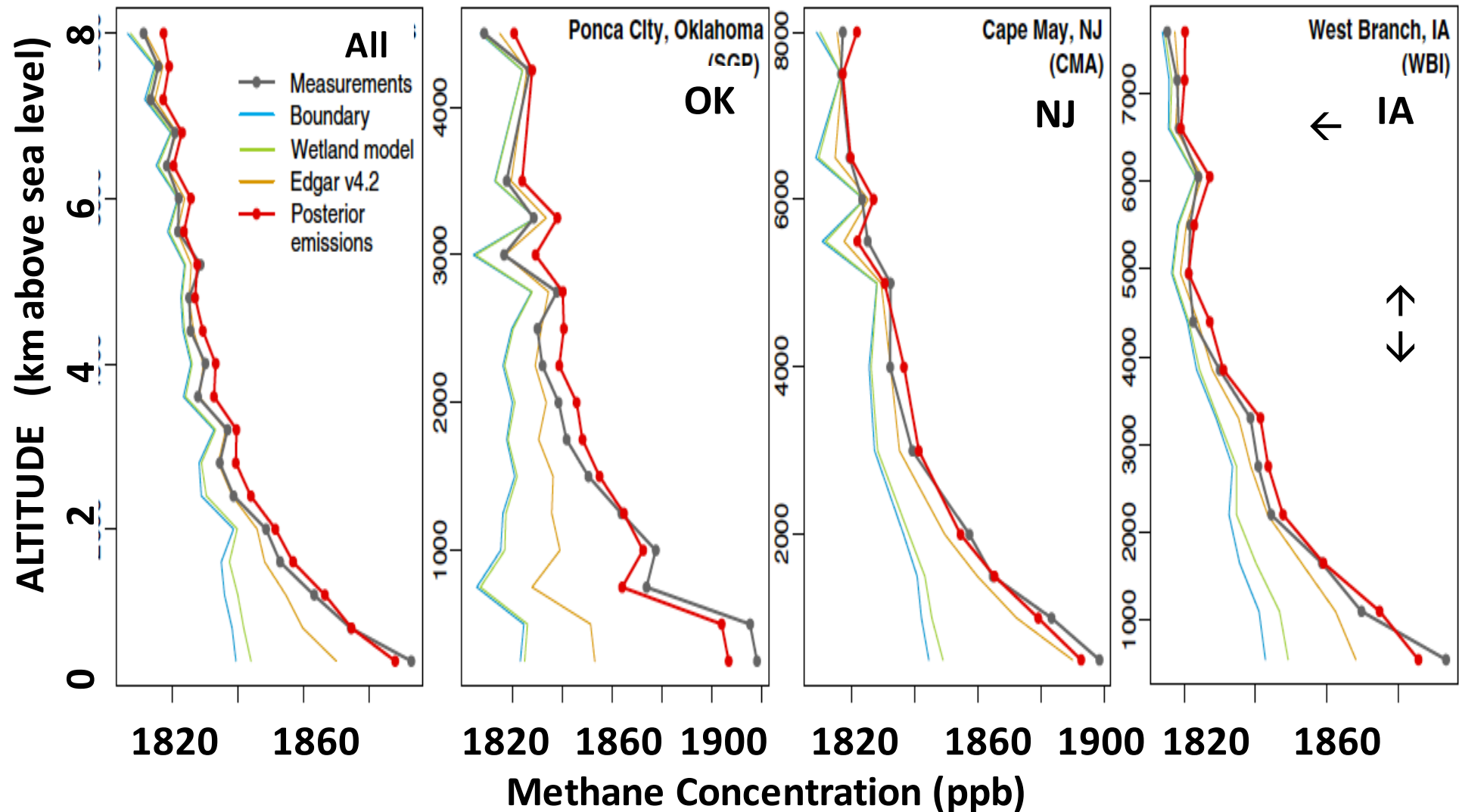
- CT-Lagrange North America 2008-2010 WRF domains (blue) with 1° footprint domain in red.
- WRF simulations are allowed to evolve (version updates, increased vertical levels, domain changes etc.)

Slide: Arlyn Andrews

WRF: Janusz Eluskiewicz, Thomas Nehrkorn, John Henderson

DATA and Model Simulations

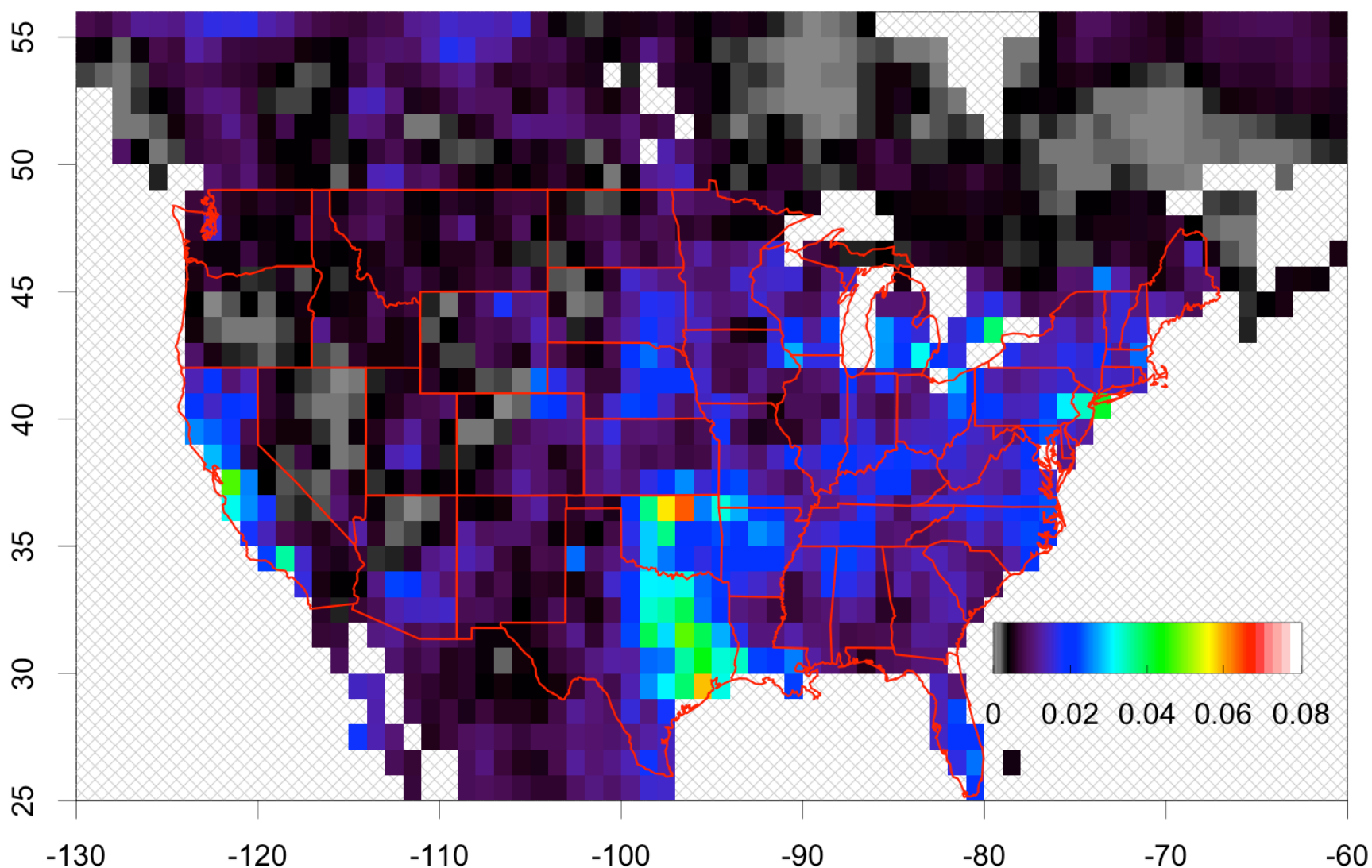
Regional ΔCH_4 : 30 – 80 ppb



Vertical column information $\Leftrightarrow$ mass loading $\rightarrow$
essential distinguish distant-stronger from close-weaker

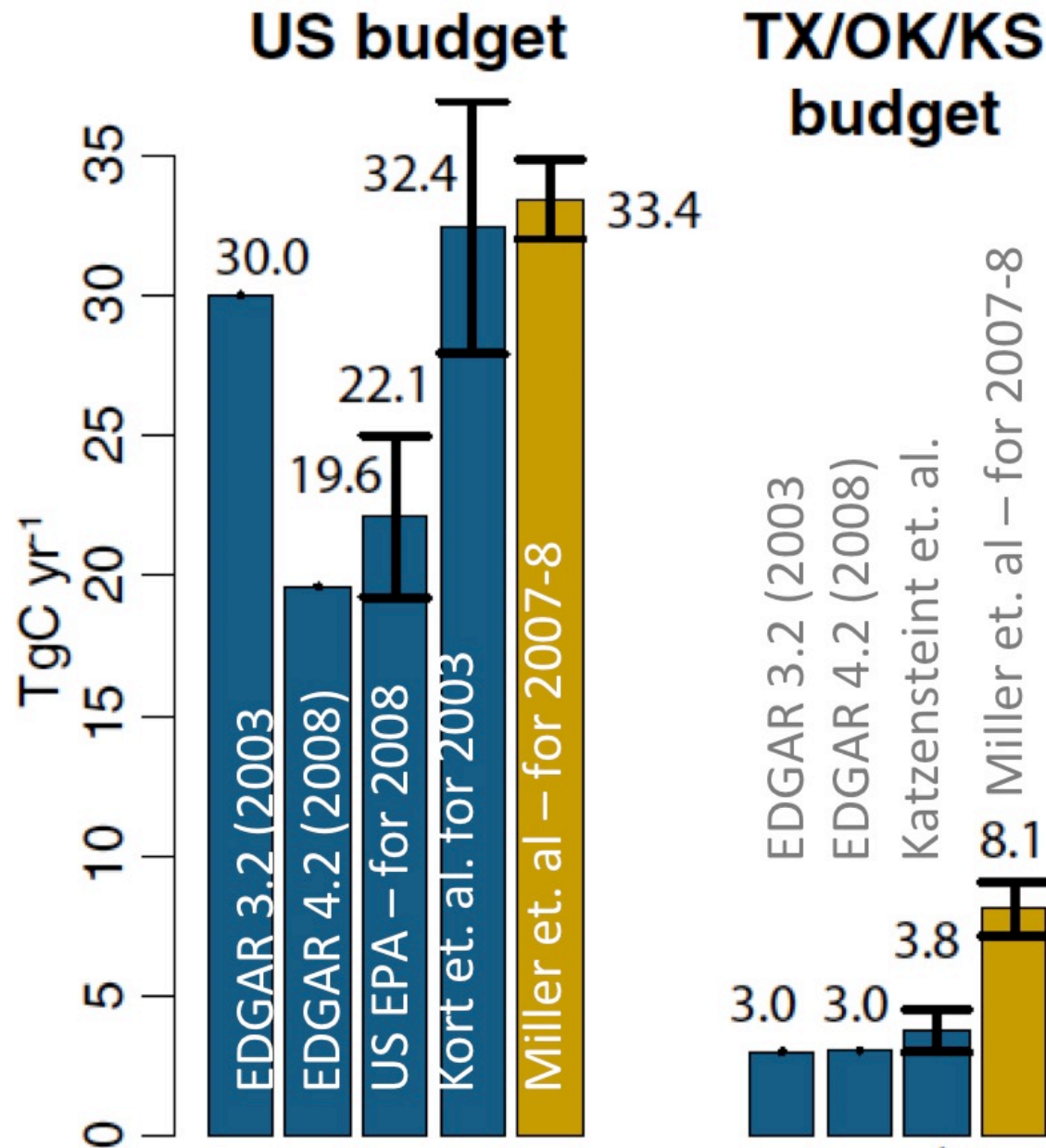
Analysis: Optimized North American Inversion using WRF/STILT and NOAA aircraft and tower data [Miller et al., PNAS, 2013]

CH₄ Fluxes 2007-8 $\mu\text{mole m}^{-2} \text{s}^{-1}$



US anthropogenic methane budgets.

(Cf. Total Global Emissions ~ 400 Tg C as CH_4 /yr.)



**~2% of
production
lost**

**biogenic $\cong$
natural gas
(fossil)**

*(Lyons; EDF
Barnett
Studies)*

Q2: Is arctic warming contributing to rising CO₂ and CH₄ in the atmosphere: positive feedback?

CO₂:

Arctic soils contain
1300+/-200 PgC,

500 non-permafrost

700 at the top (<1 m depth)

Pre-industrial atmosphere
600 PgC,
Today 840 PgC.

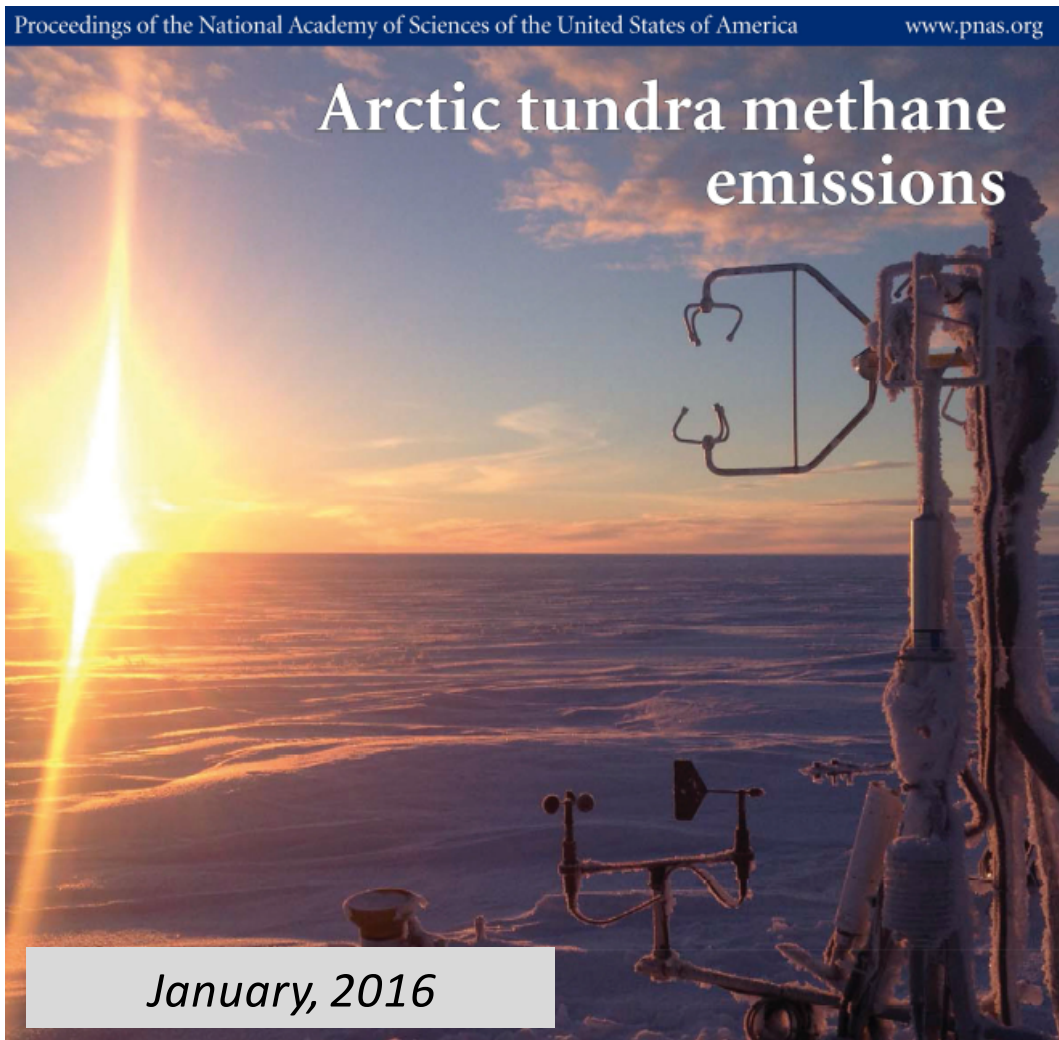


<http://northslope.org/>

Permafrost degradation on the North Slope.

Methane (CH₄)

by Rachel Y.-W. Chang *et al.* 2015
Donatella Zona et al., 2016



***Magnitude,
Seasonality
of biogenic
emissions of
CH₄ in the
Arctic***

CARVE –Alaska CO₂ and CH₄ Source Studies

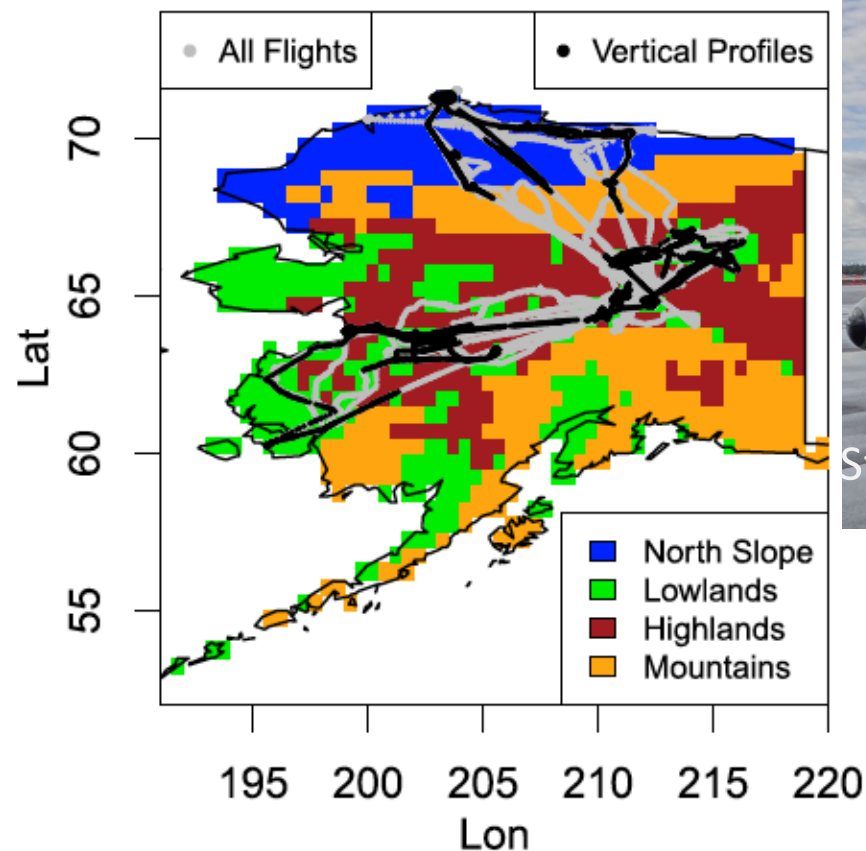
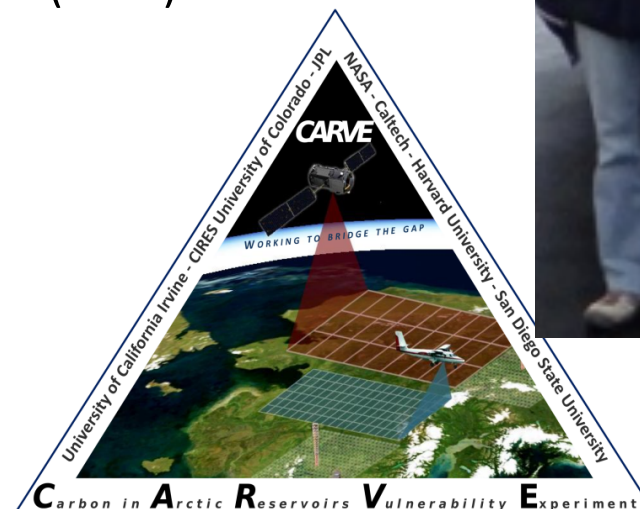


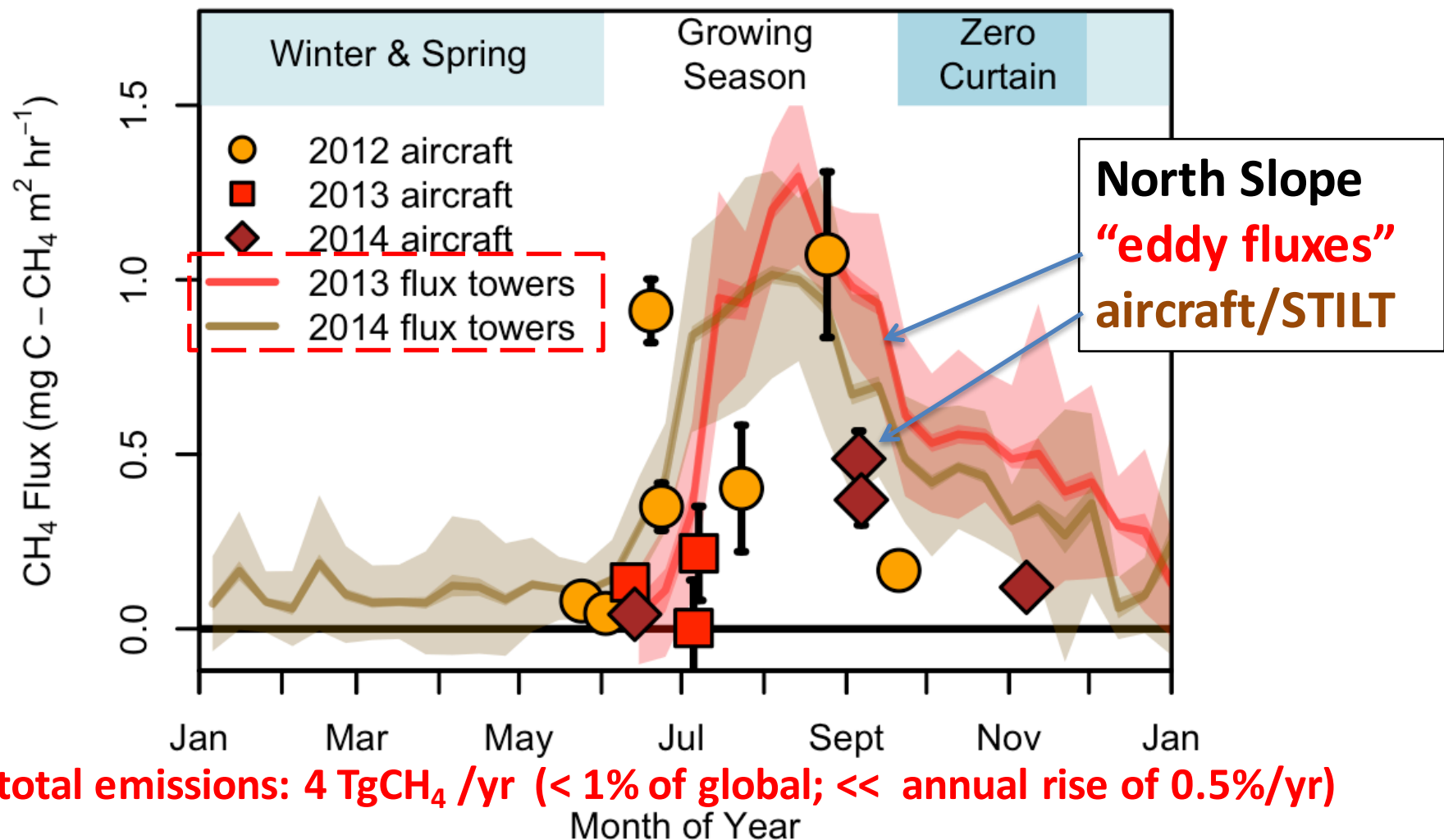
Fig. 1. Location of flight tracks (gray) and vertical profiles (black) during CARVE 2012. Background colors are elevation categories based on US EPA level III ecoregions (31).



Prof. Rachel Chang
(Prof.) Róisín Commene



CH₄ emissions in the Arctic are shifted into a long shoulder season, possibly providing a mechanism for strong amplification (in the “zero curtain”) due to climate warming.



Source from CARVE data: eddy flux: Zona, Oechel (SDSU); aircraft+WRF+STILT: Commane, Lindaas, Chang (HU), Sweeney, Karion (NOAA GMDL), Miller (JPL)

CH₄ sources in Alaska consistent with global – and with past data → baseline for assessing future changes.

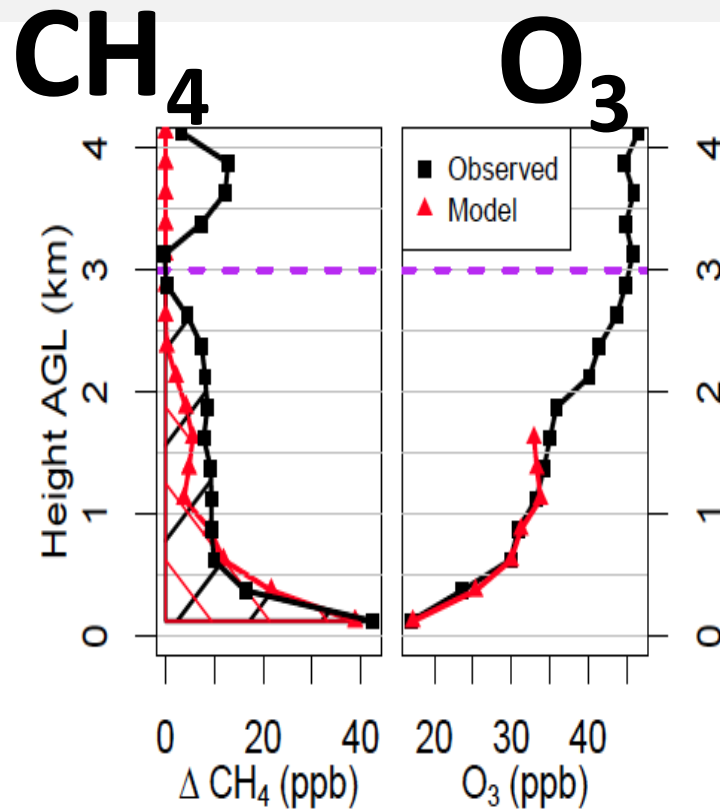


Fig. 2. Sample CH₄ vertical profile (A) used for column analysis and corresponding O₃ profile (B) from September 22, 2012. The dashed purple line represents the identified top of the residual layer, and the hatched area is used to determine the column enhancement.

1.7-2.6 Tg CH₄ / 5 months

Hundreds of profiles like the ones above

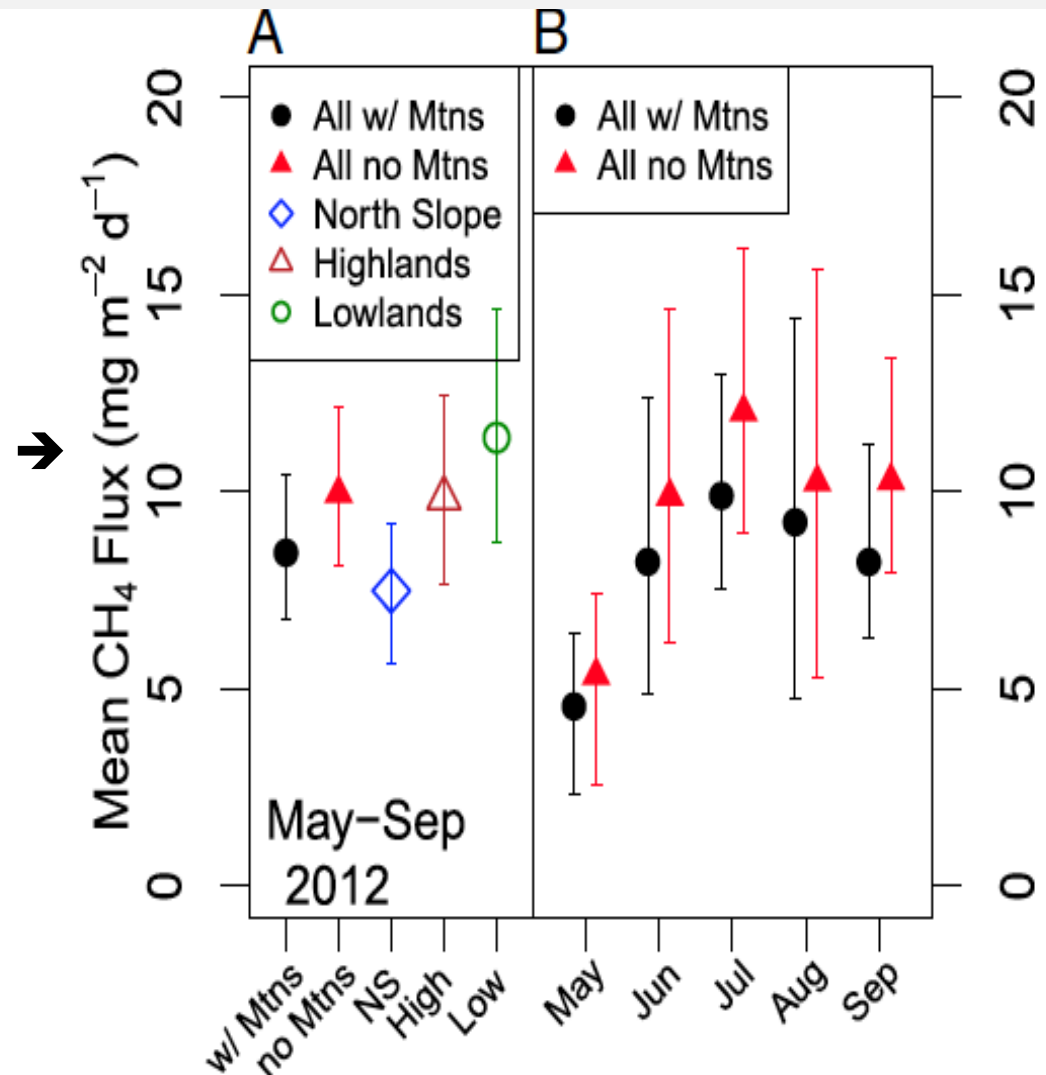
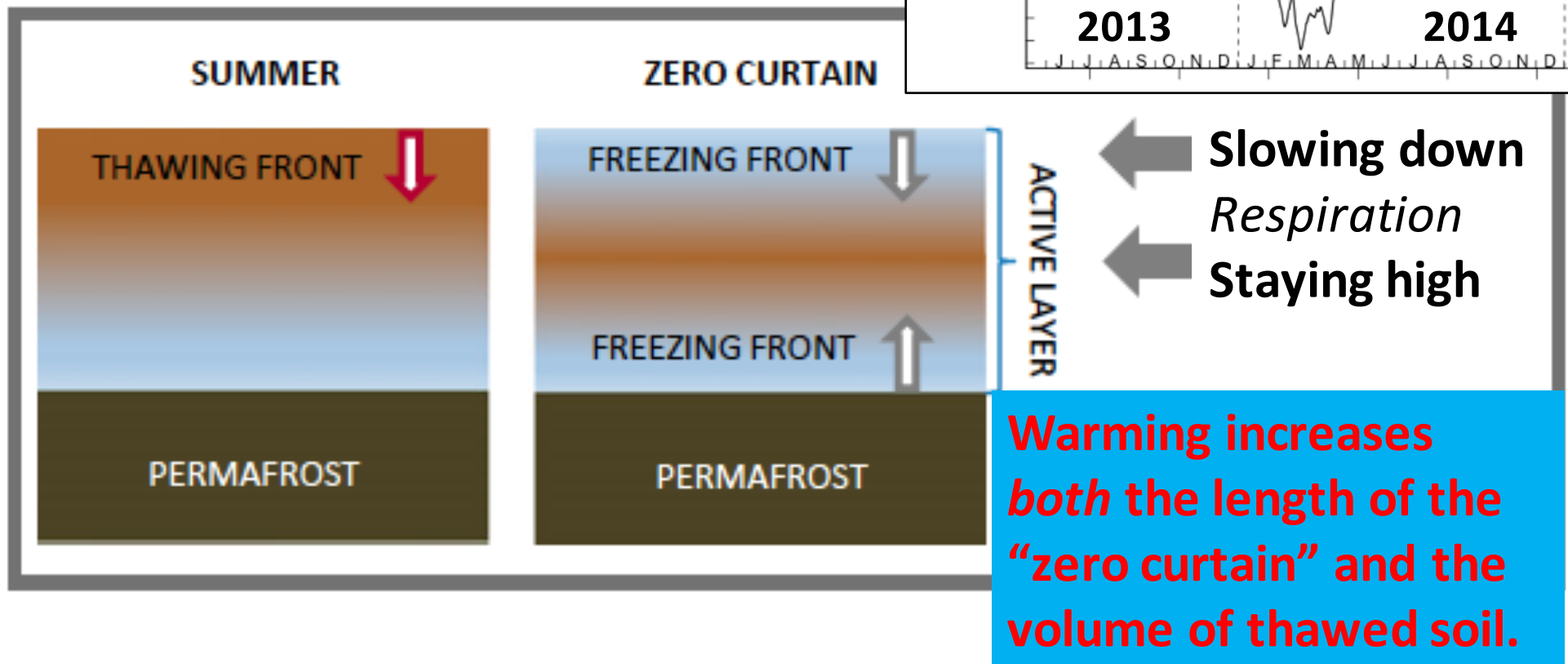
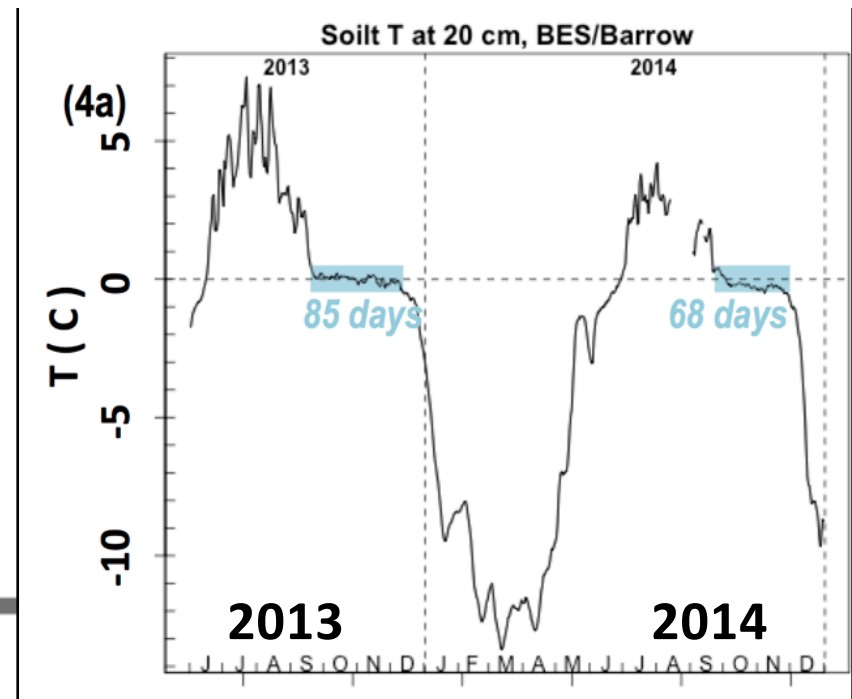


Fig. 3. Estimated mean CH₄ fluxes from the column analysis for (A) the entire study period (May to September 2012) and (B) by month. Error bars are the 95th percentile determined from the bootstrapping analysis described in the text.

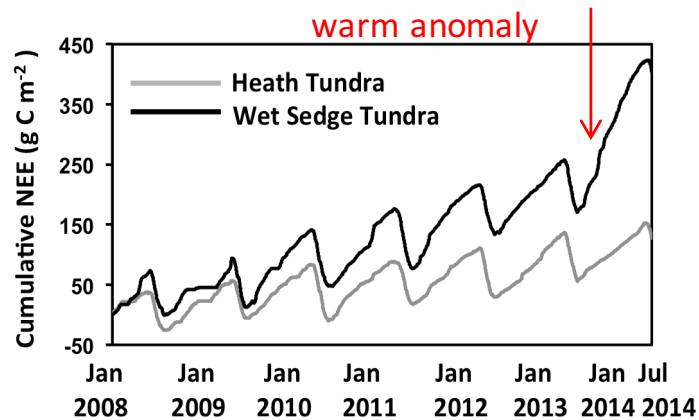
The fall—winter transition period produces the most biogenic CO₂ release to the atmosphere...due to the “zero curtain” where soil T is poised near zero (2-3 months).

Zona et al. 2016

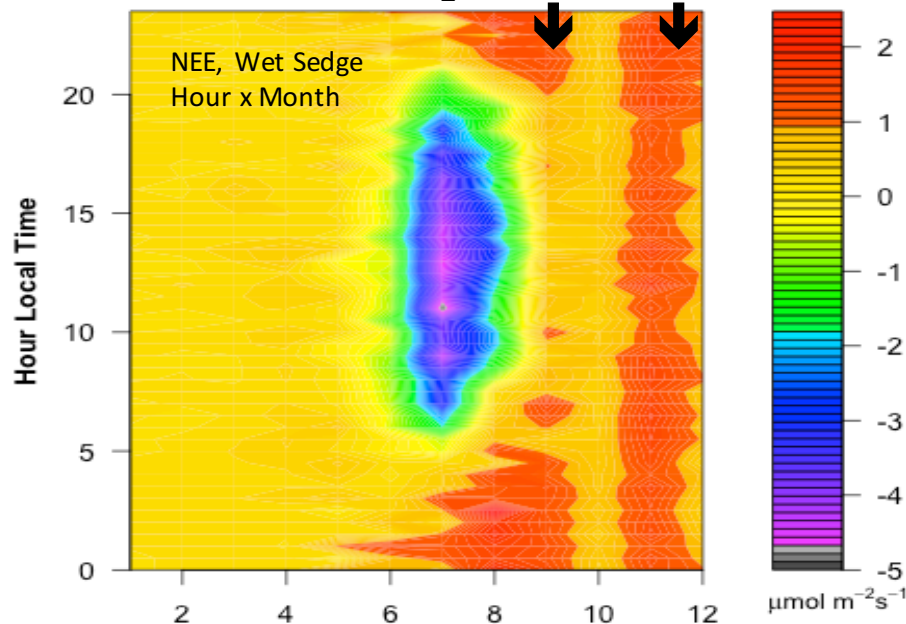


Adapted from a figure by D. Zona and W. Oeschel

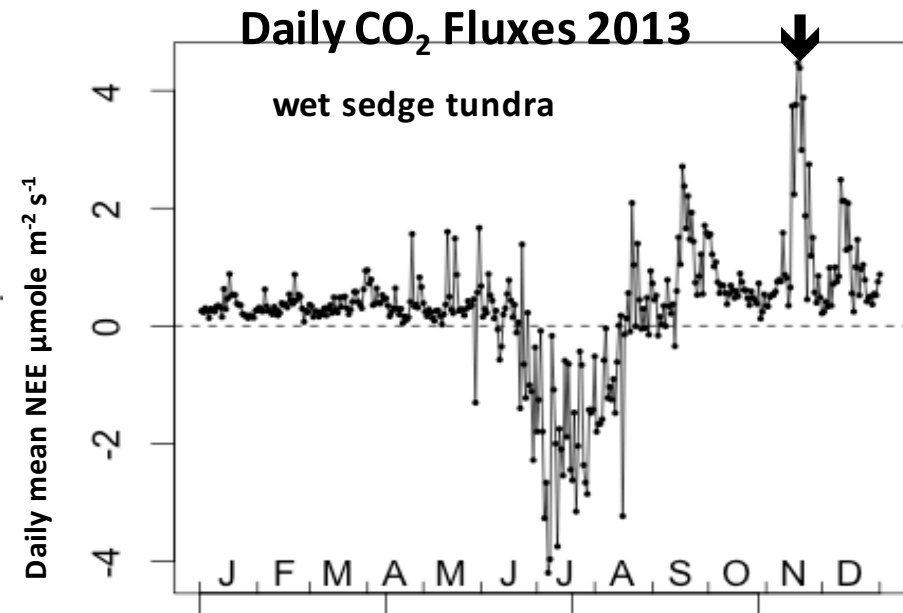
Arctic CO₂ : also a huge “shoulder season” for emissions



Toolik Hourly CO₂ Fluxes 2013



Month of 2013



Arctic—permafrost/boreal peat
carbon feedbacks: how important ?

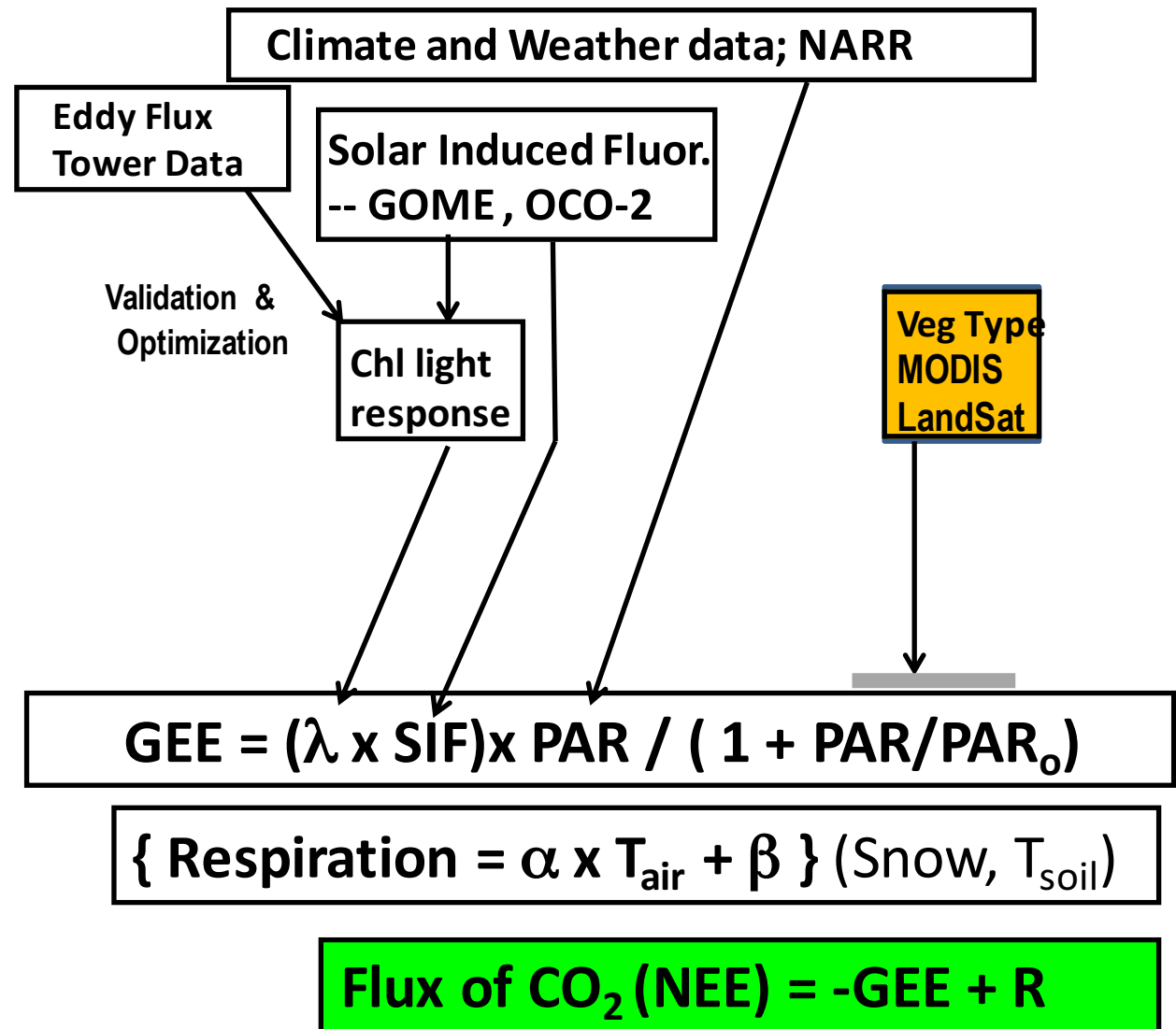
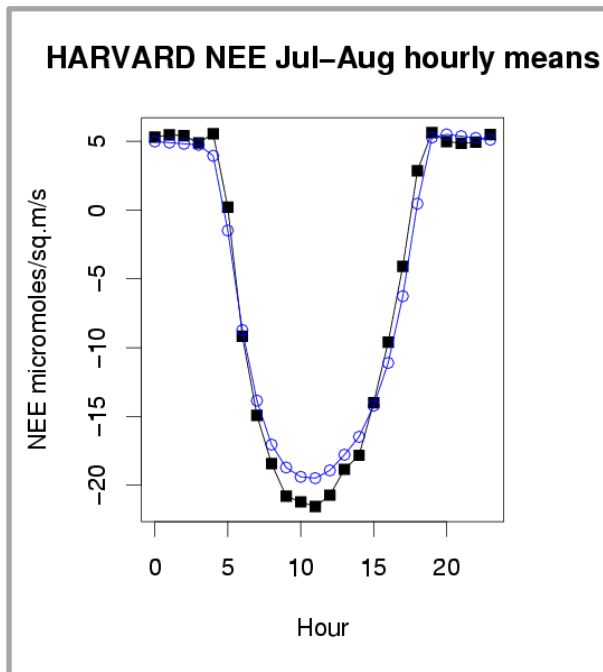
warming →

melt permafrost, deepen active layers →

increase CO₂ and CH₄ emissions →

more warming

P-VPRM: prior flux model, provides time/space explicit CO₂ emission field (prior) based on eddy flux + remote sensing in a functional form *Mahadevan (2008); Luus/Lin 2013-15*



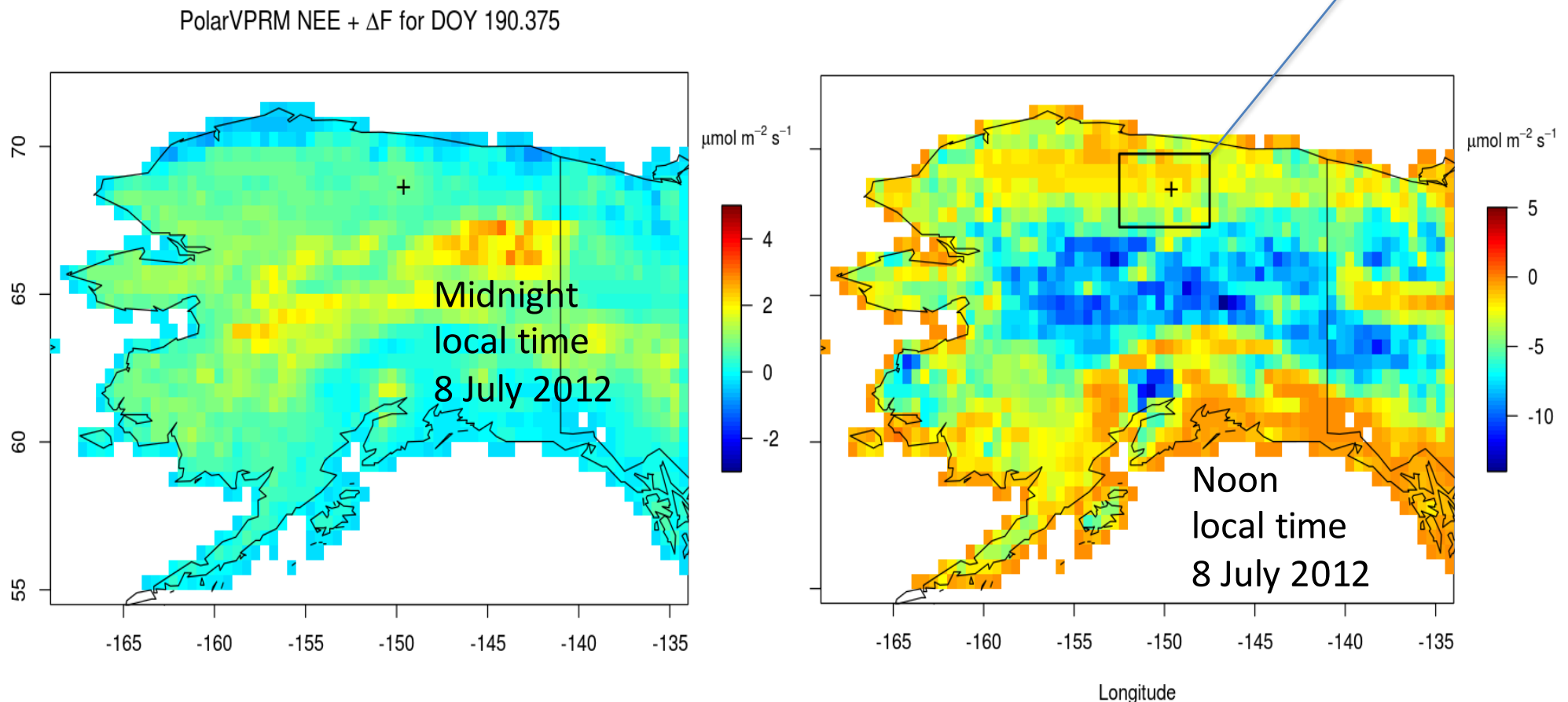
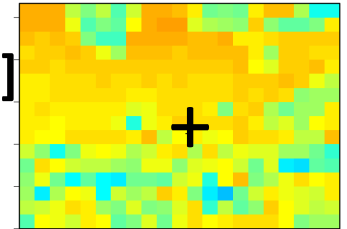
Very large amounts of disparate data go into a compact result in the P-VPRM

Heterogeneity of CO₂ emissions is captured by a very simple model tied to remote sensing and *NARR* radiation and subsurface data:

Polar Vegetation Photosynthesis and Respiration Model

[Mahadevan et al., 2008 <MODIS>; Luus et al., 2013, 2015 <+ NARR>]

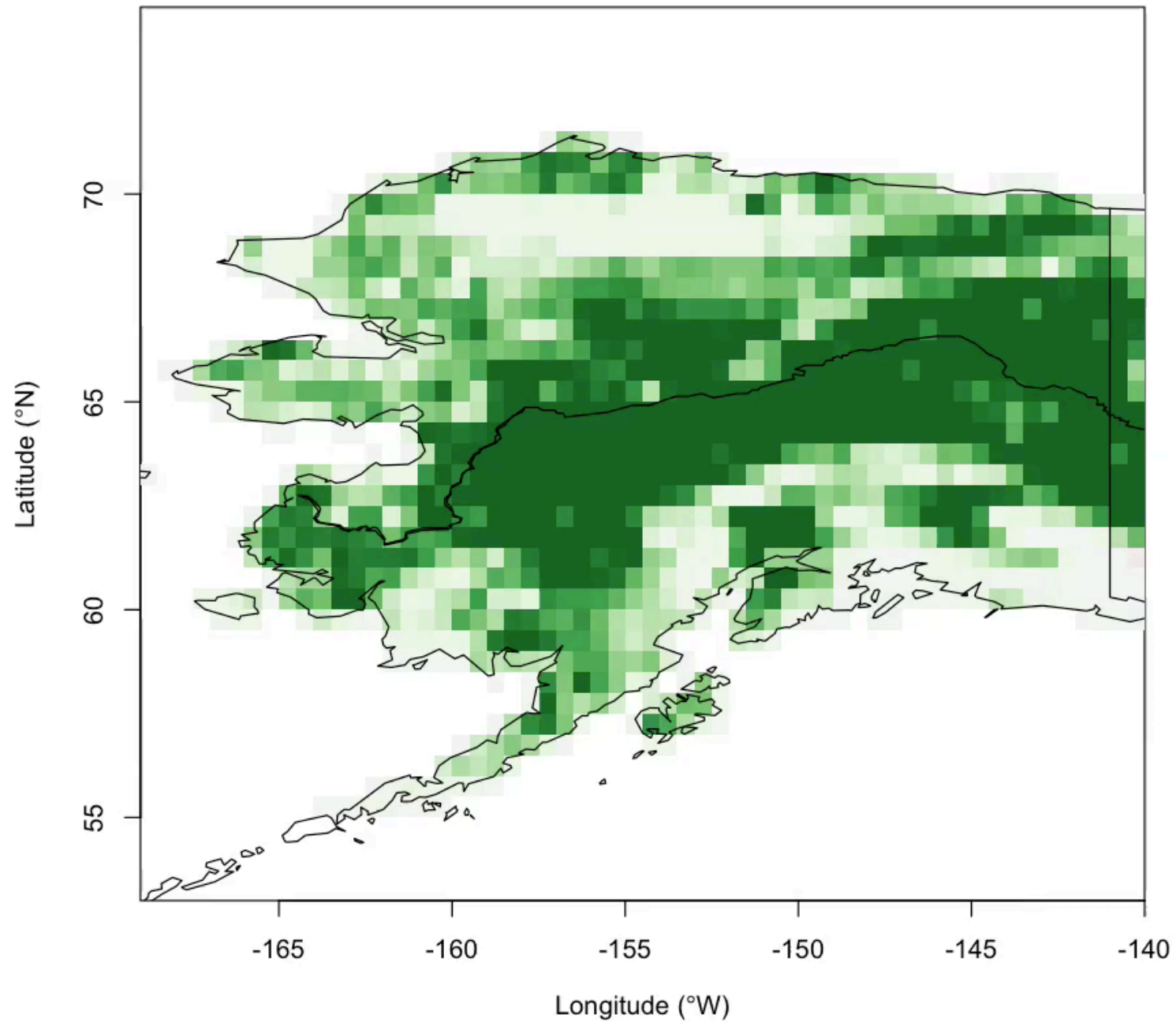
Coefficients estimated using eddy flux site data; MODIS land cover.



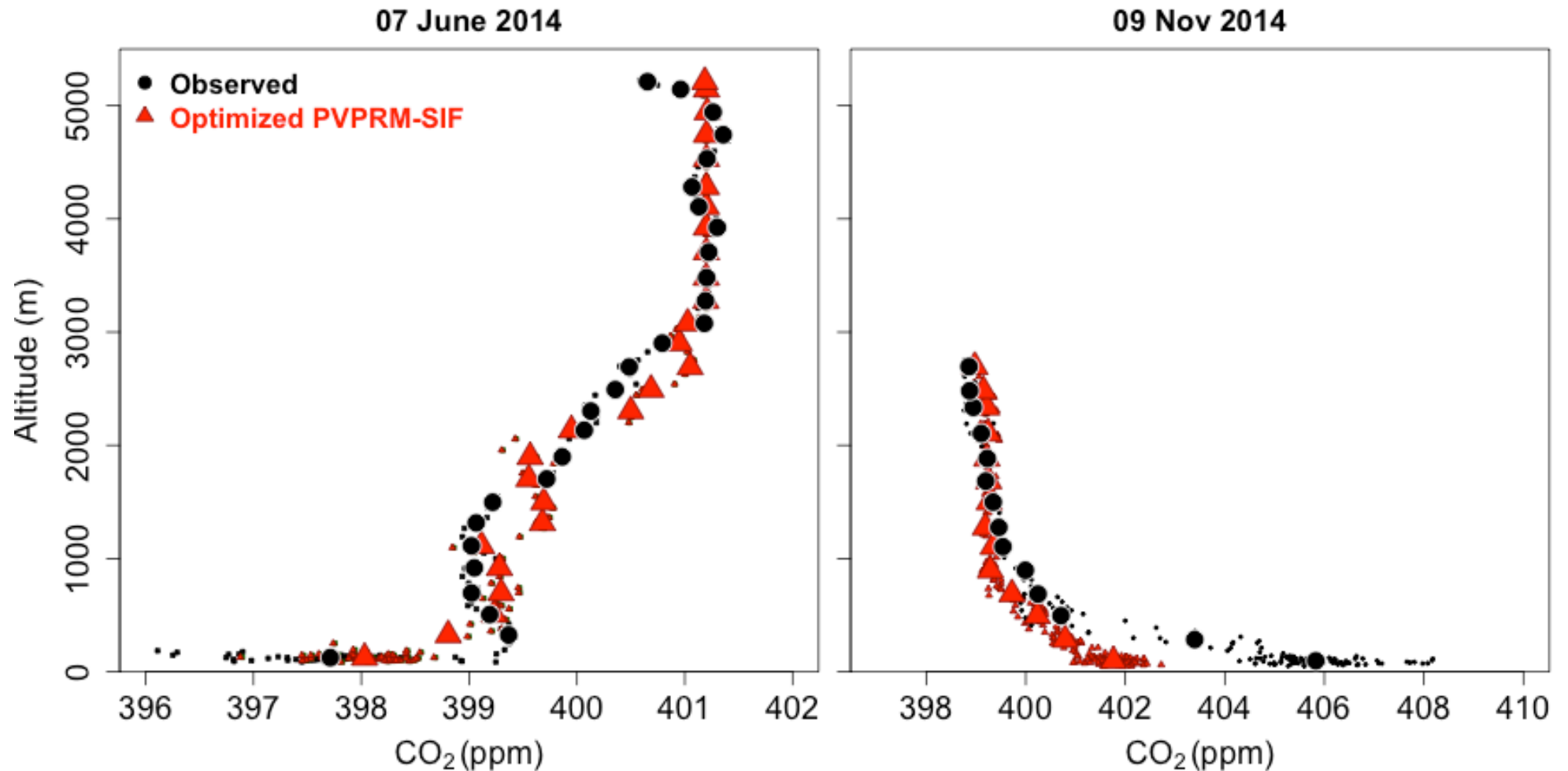
08 Jul 2012 Polar VPRM; Niina Luus

DOY: 180.92

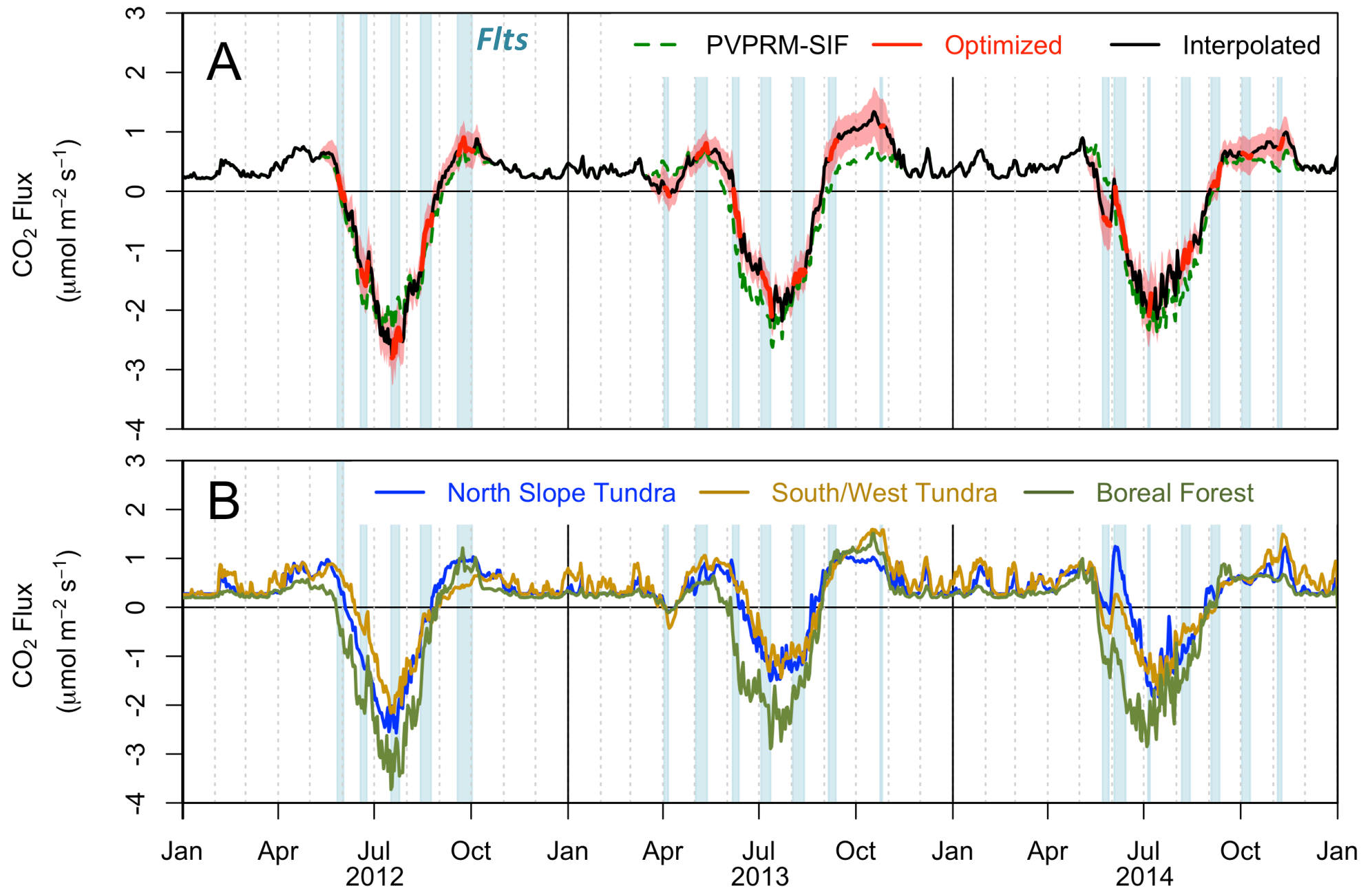
*K. Luus, Dublin;
R. Commene, Harvard*



Simulations of the aircraft data using the Model-Data Synthesis are excellent... the P-VPRM needs little adjustment

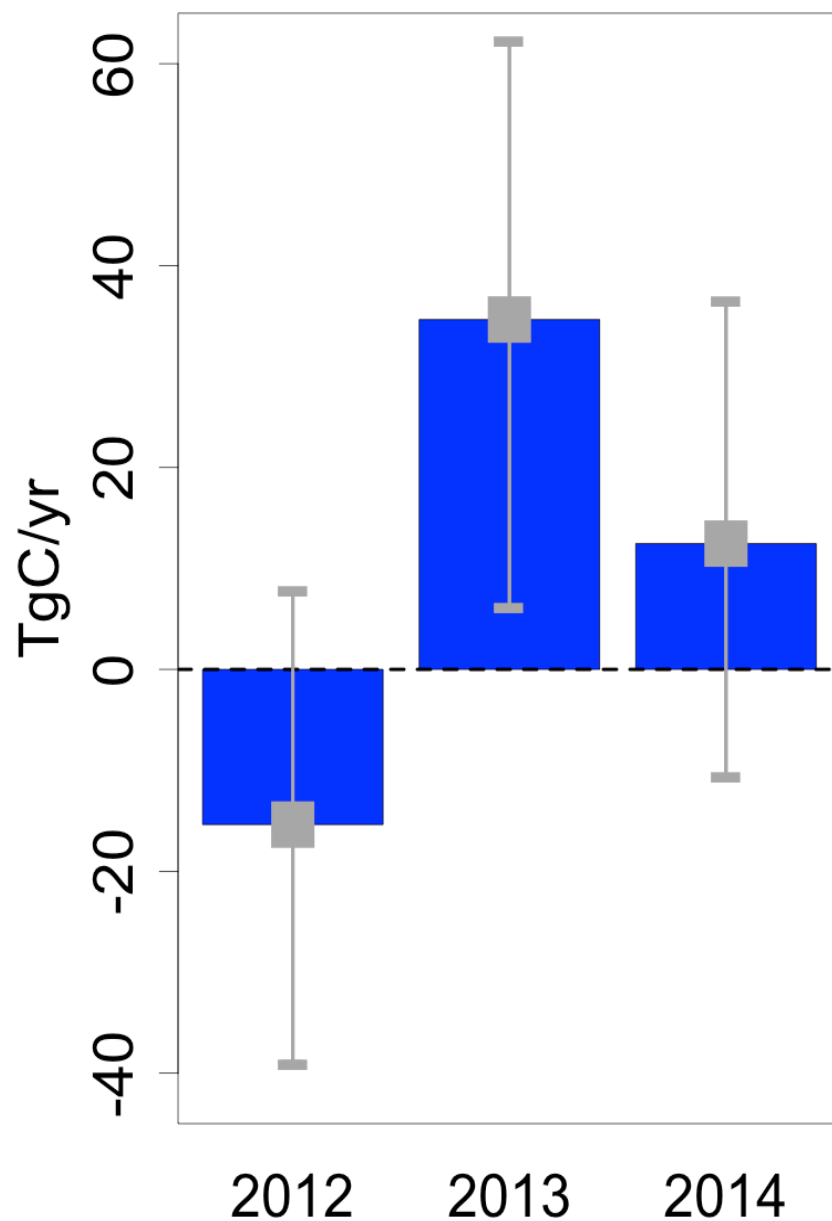


Alaska net biogenic CO₂ flux, from CARVE data with PVPRM+ spatial ΔF

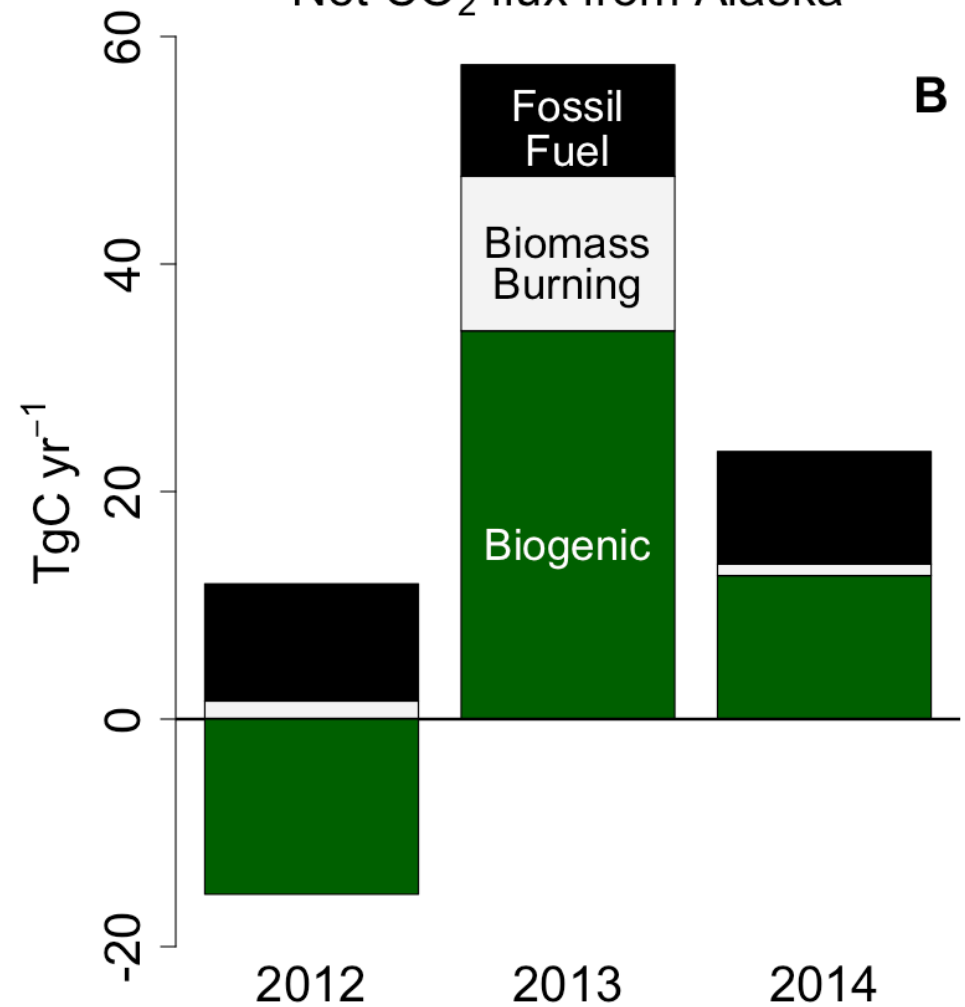


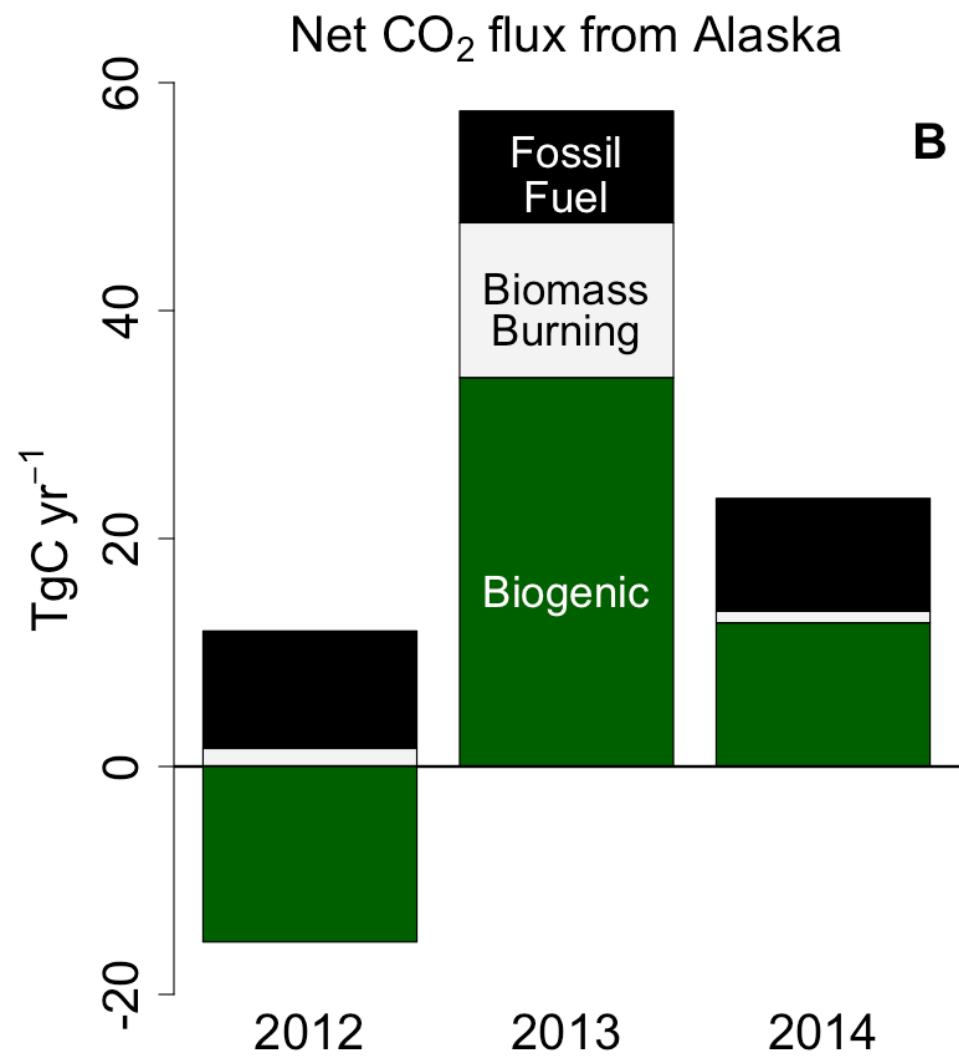
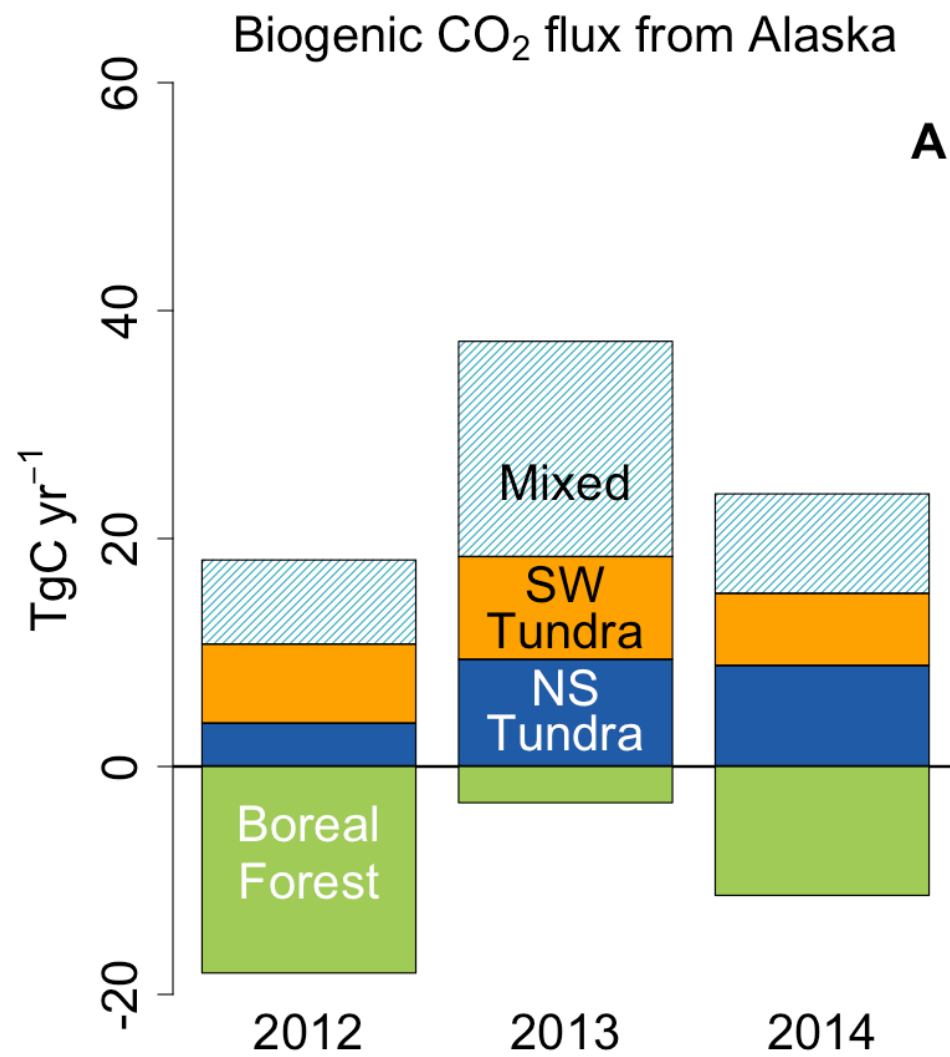
Alaska net biogenic and total CO₂ fluxes

Biogenic CO₂ flux from Alaska



Net CO₂ flux from Alaska



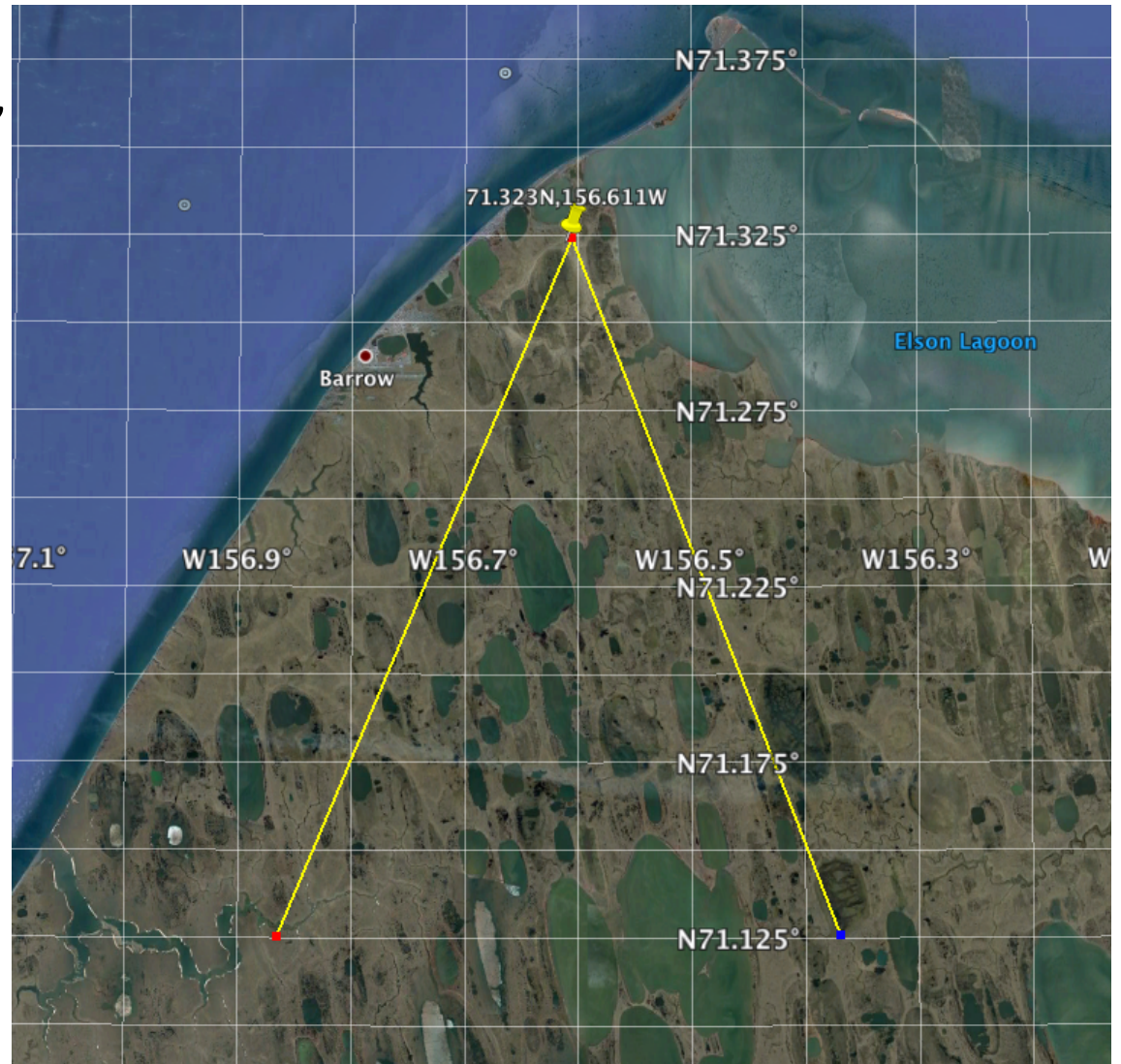


Have there been increases in CO₂ emissions in response to Arctic warming?

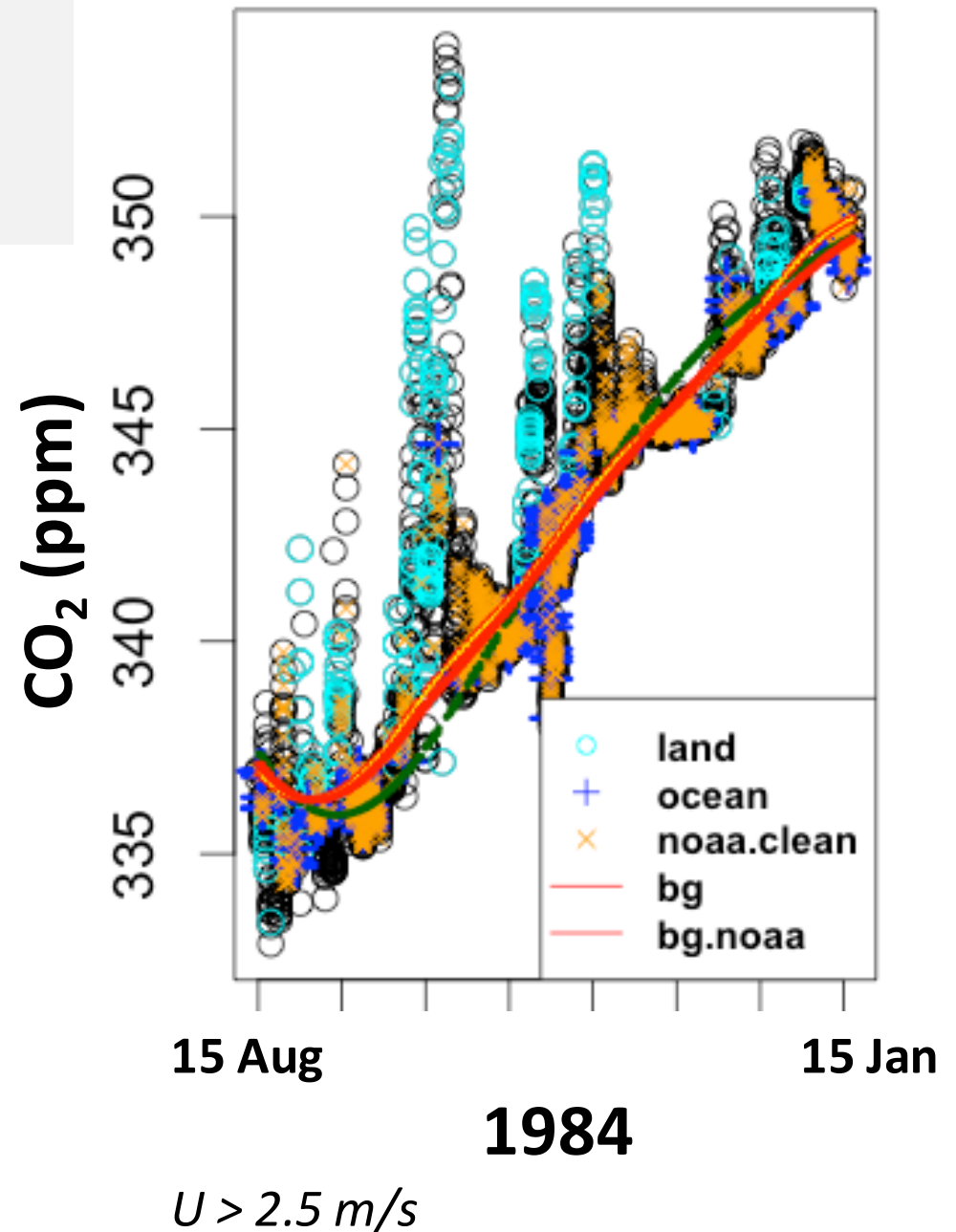
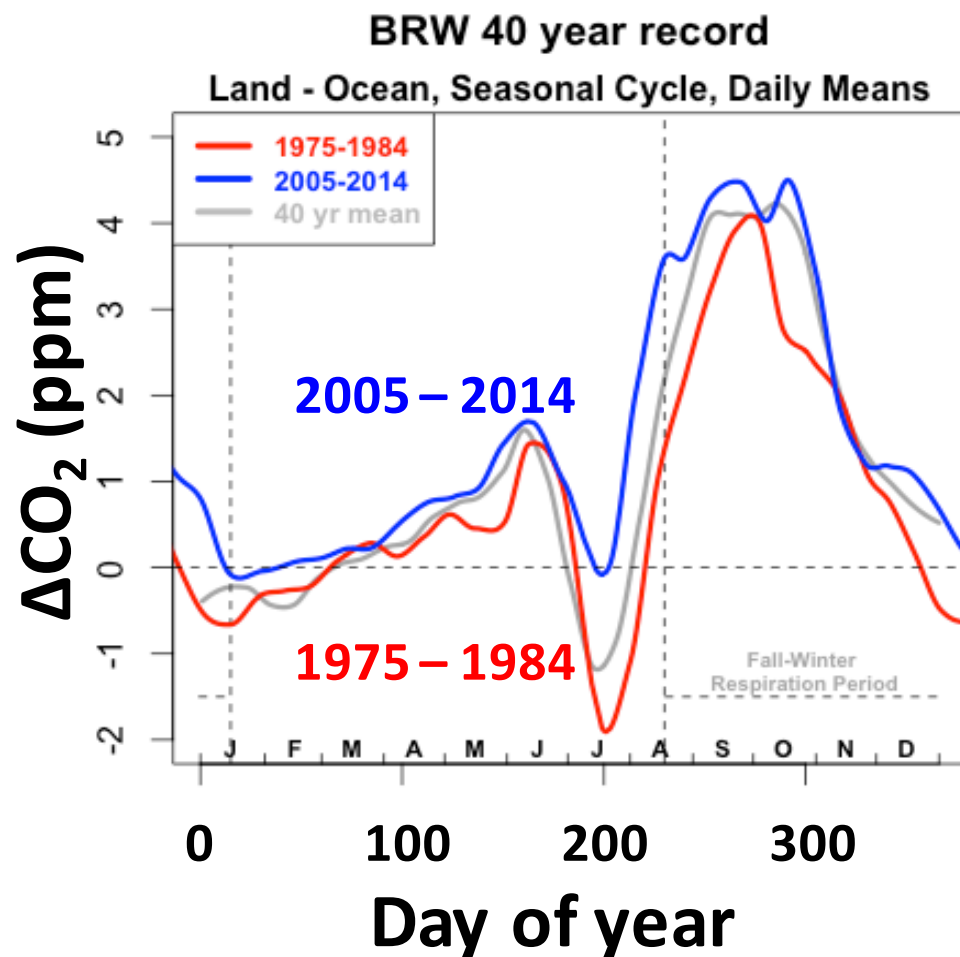
40 years of land sector CO₂ data at Point Barrow, AK

➔ Long term change ←

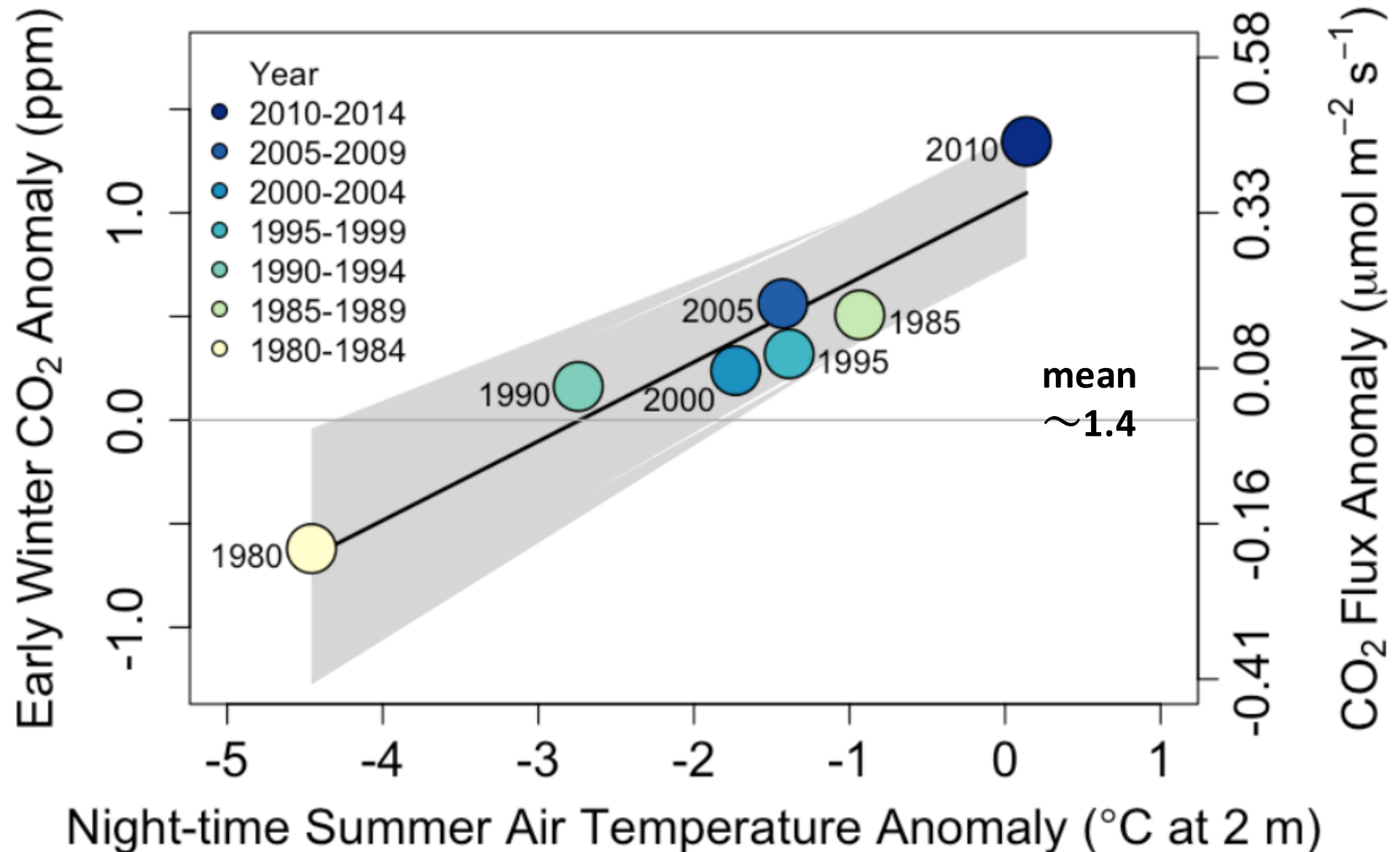
*Pieter Tans, Colm Sweeney,
NOAA ESRL/GMD*



Barrow data show distinct differences between land and ocean sectors, and revealing seasonal patterns



Warming summer temperatures over the last 35 year have stimulated release of CO₂ from organic matter in frozen soils of the North Slope—almost doubled in the autumn



Science results:

- We find that Alaska was a net source of CO₂ to the atmosphere, about half from the biosphere and another half from biomass burning.
- Regional scale studies can answer fundamental questions about the carbon cycle and climate.
- To interpret regional scale studies, a very diverse set of data must be synthesized in a framework with parallels to “big data”...and a long way to go to reach maturity.
- The dearth of long term measurements implies that we may find it very difficult to determine how feedbacks actually operate in the carbon—climate system.

Emission of carbon dioxide from tundra and boreal ecosystems in Alaska

Authors: Roisin Commane^{1*}, Jakob Lindaas^{1‡}, Joshua Benmergui¹, Kristina A. Luus², Rachel Y.-W. Chang³, Bruce C. Daube¹, Steven Dinardo⁴, Eugénie S. Euskirchen⁵, John M. Henderson⁶, Anna Karion^{7†}, John B. Miller⁸, Scot M. Miller⁹, Nicholas C. Parazoo^{4,10}, James T. Randerson¹¹, Colm Sweeney^{7,8}, Kirk Thoning⁸, Sander Veraverbeke^{11,12}, Charles E. Miller⁴, Steven C. Wofsy¹

Our questions for CH₄ sources

1. *Are CH₄ releases significant from the USA fossil fuel industry? **Yes**. From agriculture?*
2. *Are emissions from the Arctic rising rapidly, as some have predicted? **No (at least not yet). Need to watch the so-called “dormant season”.***

Our question about arctic CO₂

- 1. Are CO₂ releases significant from arctic tundra? **Yes.** Have emissions increased due to climate warming? **Yes, at least on the North Slope.***
- 2. Are emissions from the whole Arctic (tundra and forests) rising rapidly? **Not known. Need to watch the so-called “dormant season”, forest fires, etc.***

Questions ?



