Assimilation of Tower and Satellite-Based Methane Observations for Improved Estimation of Methane Fluxes over Northern Eurasia

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MPI-BGC Jena

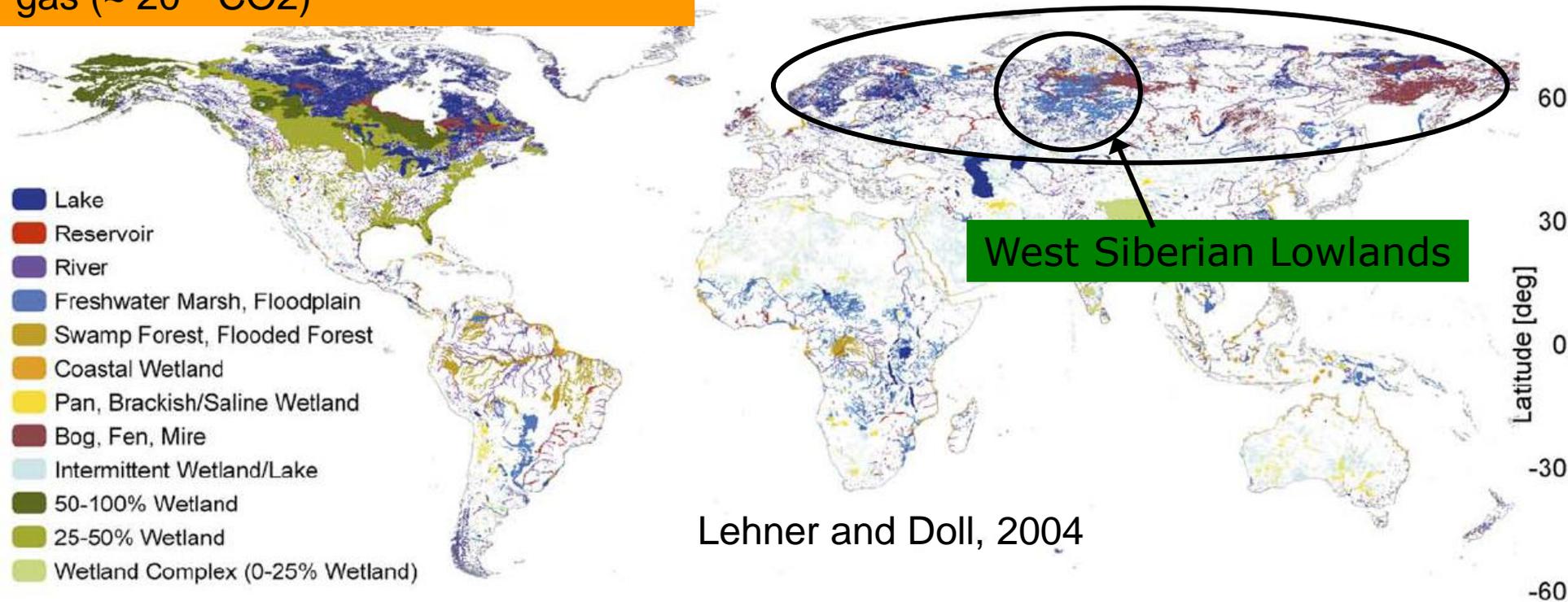NASA Jet Propulsion Laboratory
California Institute of Technology

Methane and Northern Eurasia

Lakes and wetlands are the world's largest natural source of methane
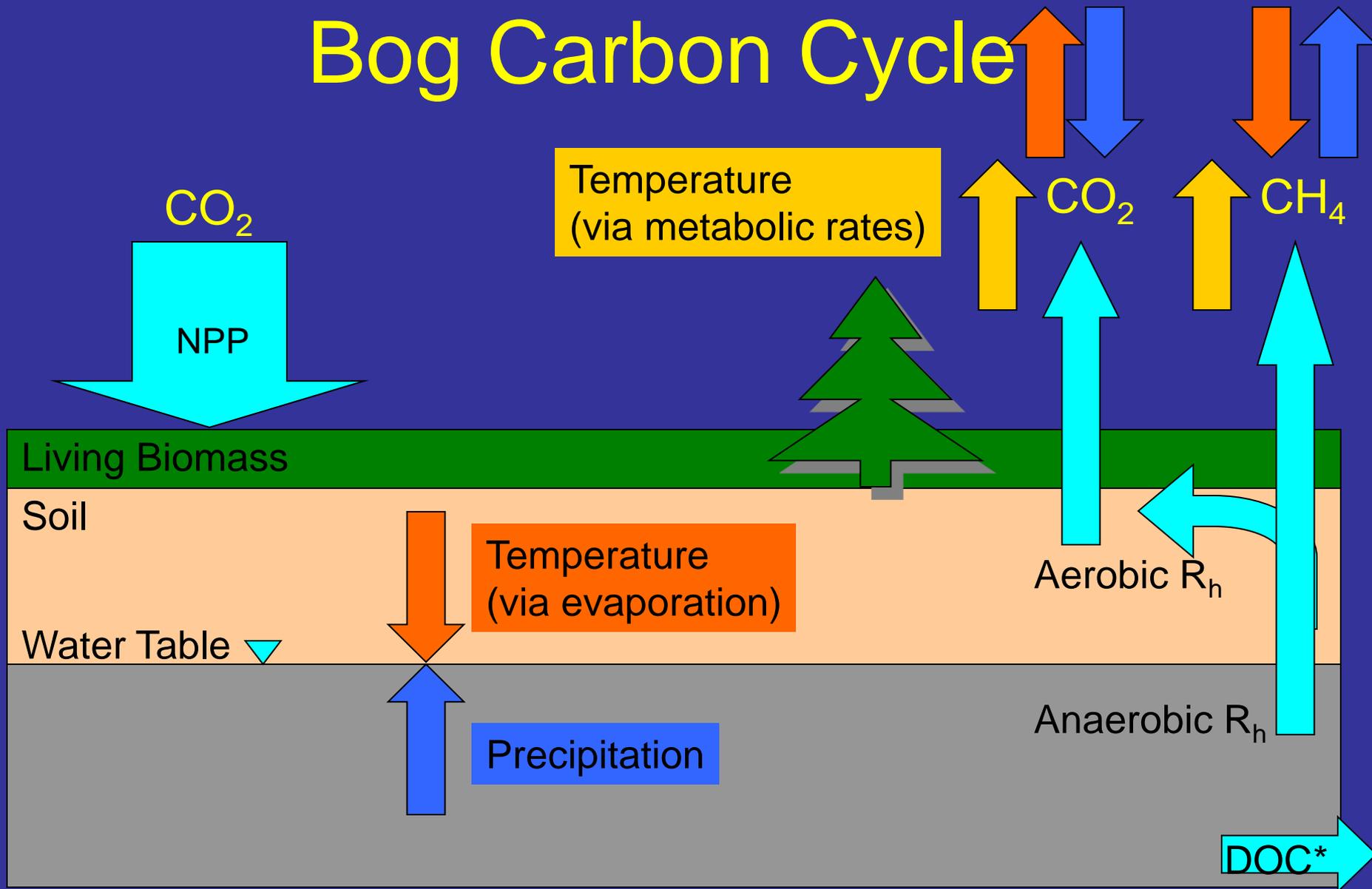
Methane is very powerful greenhouse gas (~ 20 * CO_2)

Northern Eurasia contains:
- 30% of world's wetlands (Gorham, 1991)
- Large portion of world's lakes
- Vast C pool in soil

West Siberian Lowlands

Lehner and Doll, 2004

Lake
Reservoir
River
Freshwater Marsh, Floodplain
Swamp Forest, Flooded Forest
Coastal Wetland
Pan, Brackish/Saline Wetland
Bog, Fen, Mire
Intermittent Wetland/Lake
50-100% Wetland
25-50% Wetland
Wetland Complex (0-25% Wetland)

Latitude [deg]

High latitudes experiencing pronounced climate change: potential climate feedback

Bog Carbon Cycle

CO$_2$

NPP

Temperature (via metabolic rates)

CO$_2$ CH$_4$

Living Biomass

Soil

Temperature (via evaporation)

Water Table ▽

Aerobic R$_h$
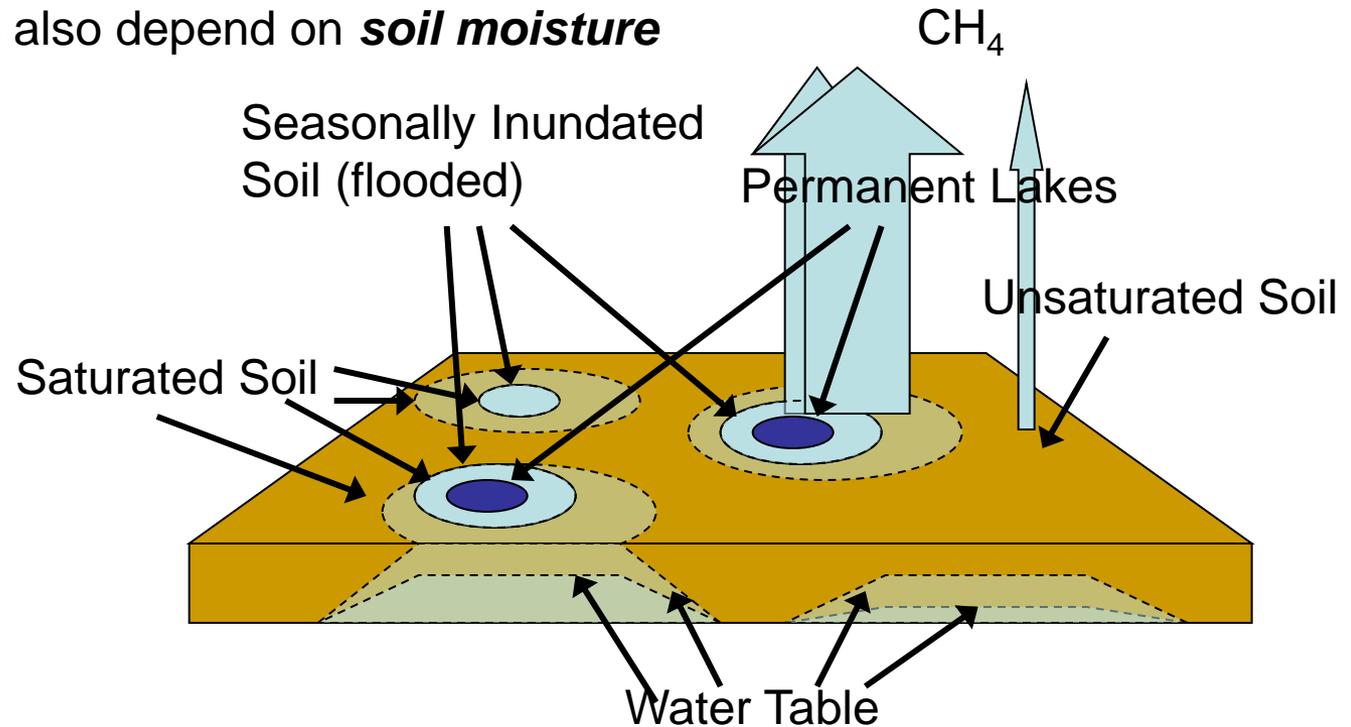
Precipitation

Anaerobic R$_h$

DOC*

C fluxes also depend on soil C profile, pH, redox

*Note: currently not considering export of DOC from soils

Lakes, Wetlands, and Methane

• Lake/wetland CH4 emissions depend on T, C, nutrients, oxidation state, etc
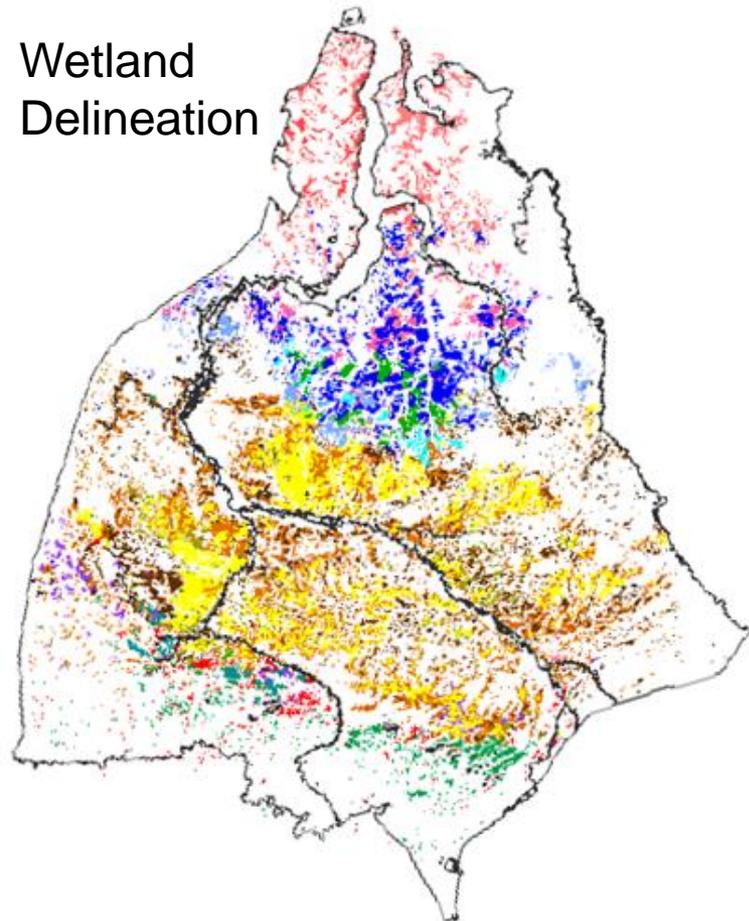
• Wetland CH4 fluxes also depend on *soil moisture*

CH$_4$

Seasonally Inundated Soil (flooded)

Permanent Lakes

Unsaturated Soil

Saturated Soil

Water Table

• *Areal extent of wet zones can vary substantially in time*
• *Areal extents are poorly-constrained*
• *CH4 emissions rates are poorly-constrained*

Emissions components & Uncertainties

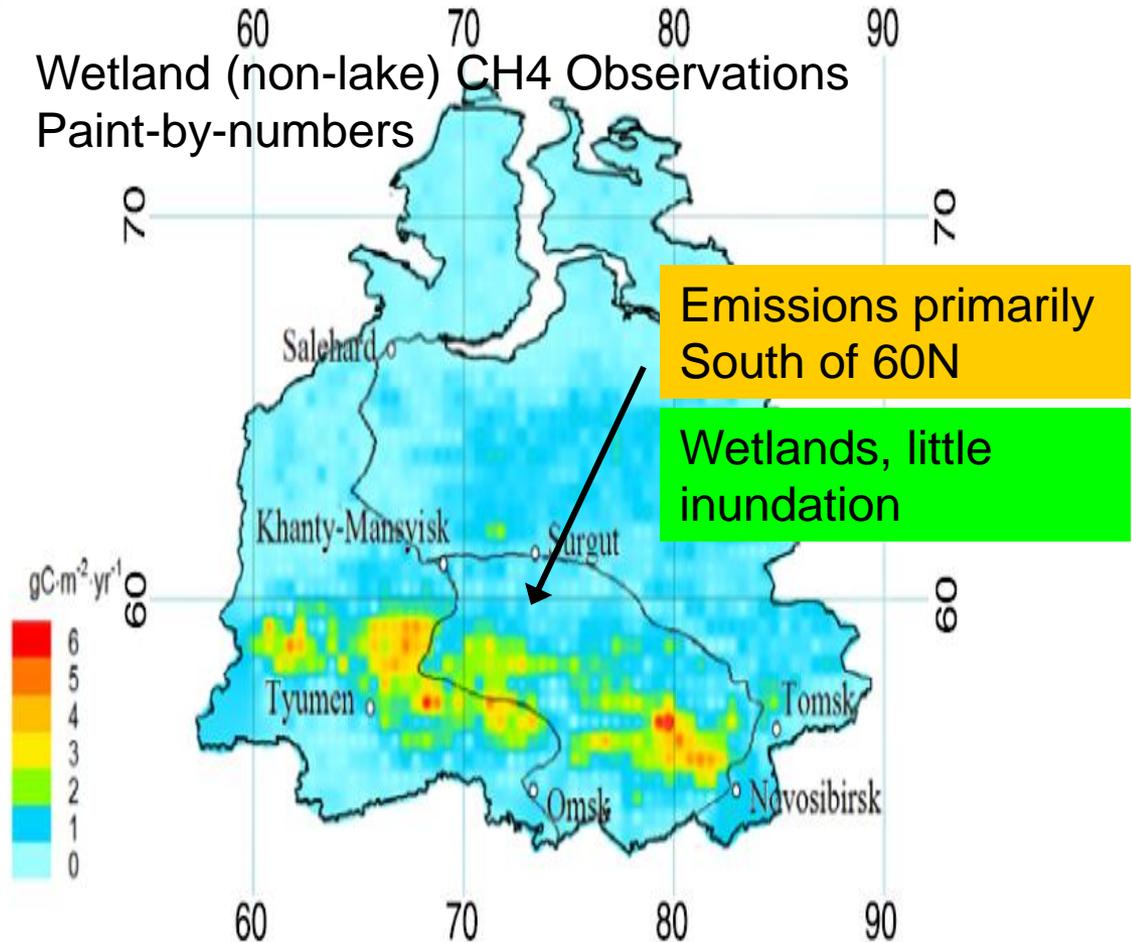| Component	Area	Emission Rate
Lakes	Underestimated by GLWD – factor of 2?	Poorly Constrained – 2 orders of magnitude
Saturated / Inundated Wetlands	Poorly-Constrained	+/-10% in W. Siberia
Unsaturated Wetlands	Water table distribution poorly constrained	+/- 10% in W. Siberia

Bottom-Up

Recent intensive field campaigns sampled
Areas, CH4, Zwt, T of microforms across W.
Siberia

Wetland
Delineation

Wetland (non-lake) CH4 Observations
Paint-by-numbers

Emissions primarily
South of 60N

Wetlands, little
inundation

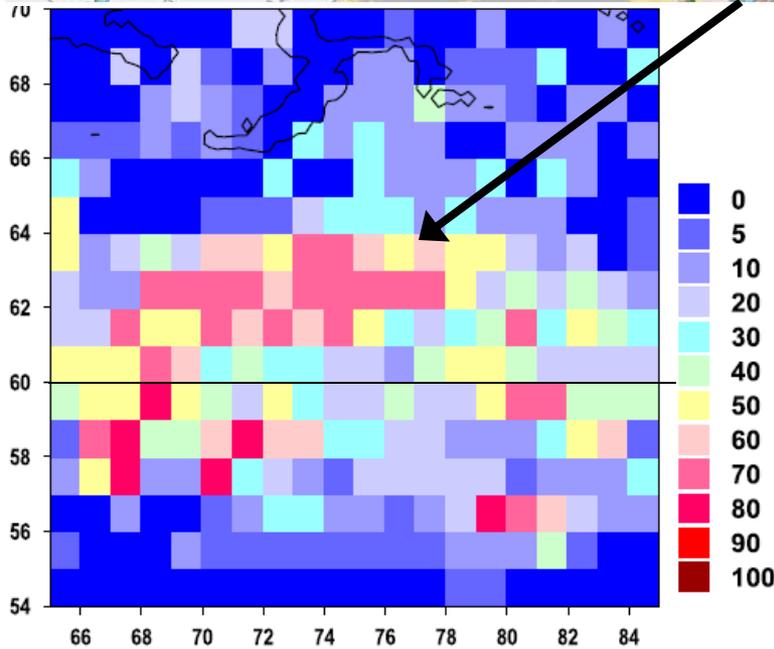$gC \cdot m^{-2} \cdot yr^{-1}$

Peregon et al., 2009

Glagolev et al., 2011

3.96 +/- 1.3 Tg CH4/y

Top-Down
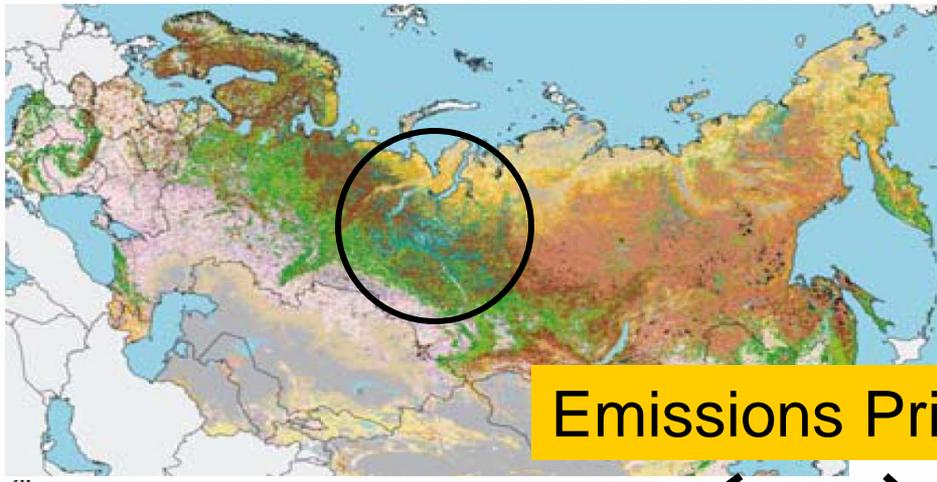
Emissions Primarily North of 60N

Primarily Lakes and Inundated Wetlands
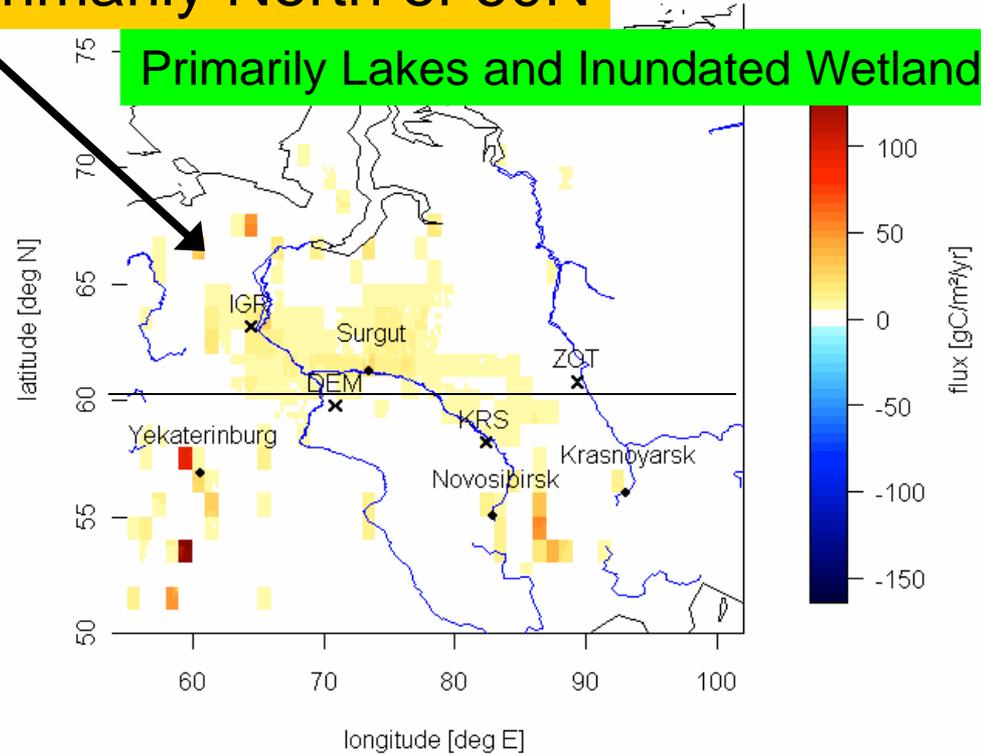
Matthews and Fung, 1987
(reprinted from Kim et al., 2011)
6.3 Tg CH4/year

Inverse modeling from tower network:
11.2 +/- 1.4 TgCH4/year
(Winderlich PhD Thesis, 2012)
(Spatial pattern inferred from forest cover)

Can We Reconcile Top-Down and Bottom-Up Estimates?

- Use combination of:
  - Land surface model (with carbon)
  - Atmospheric Transport model
  - In Situ observations
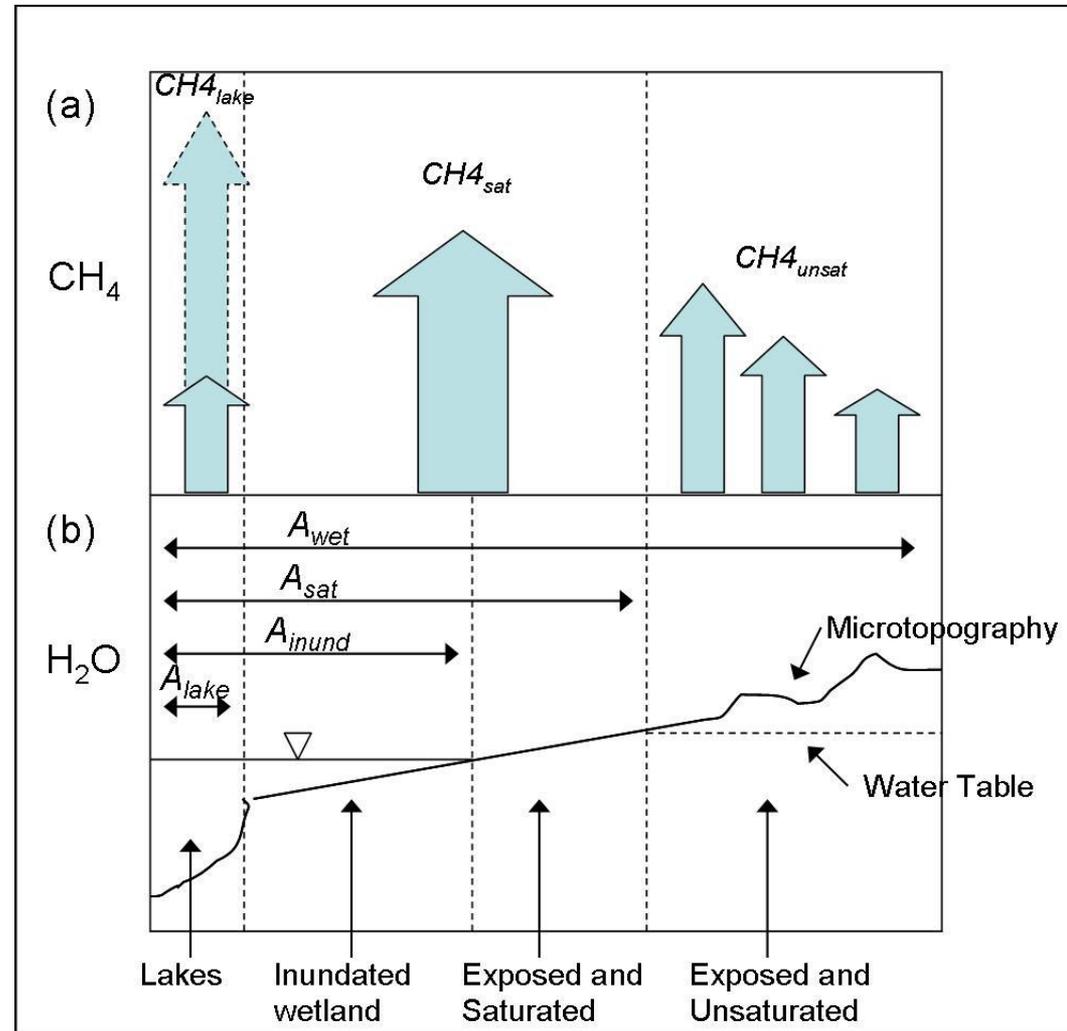 - Satellite Observations
- Take Bayesian approach

Modeling Framework

- VIC hydrology model
  - Large, "flat" grid cells (e.g. 100x100 km)
  - Mosaic of land cover tiles
  - On hourly time step, simulate:
    - Soil T profile (and permafrost)
    - Water table depth Z_{WT}
    - NPP
    - Soil Respiration
    - Other hydrologic variables…
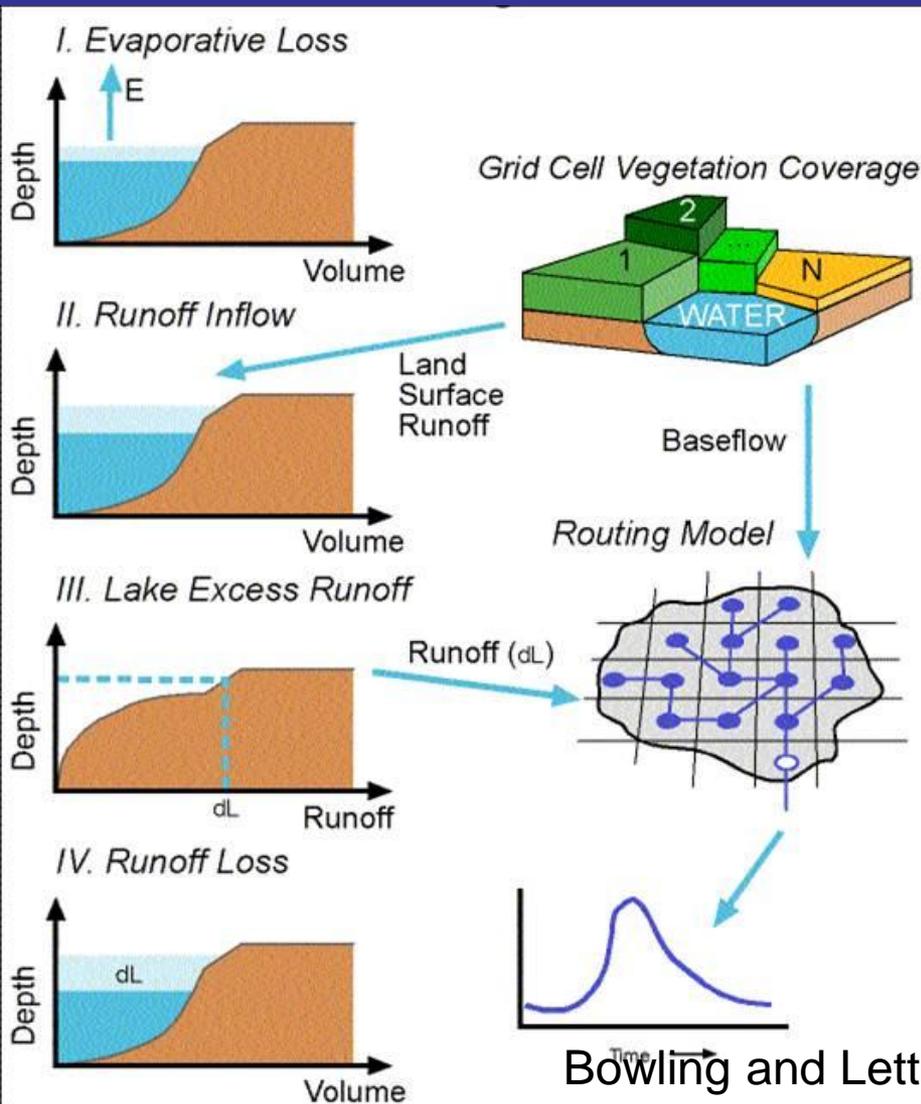- Link to CH4 emissions model (Walter & Heimann 2000)

Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model
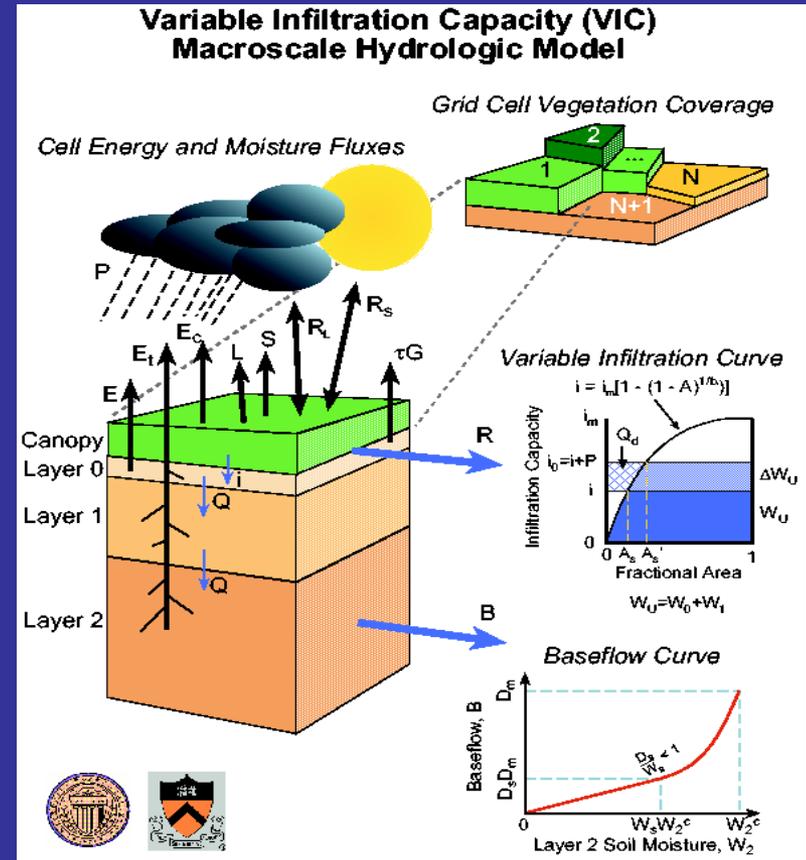
VIC's Lake-Wetland Continuum

- Dynamic Lake Model
- Seasonal Flooding of Wetlands
- Distributed water table depth in wetlands
  - Saturated zone extends beyond inundation
  - Unsaturated zone's water table depth is a function of microtopography
- Each zone has separate methane emissions

(a)

$CH4_{lake}$

$CH4_{sat}$

$CH4_{unsat}$

CH_4

(b)

A_{wet}

A_{sat}

A_{inund}

A_{lake}

H_2O

Microtopography

Water Table

Lakes | Inundated wetland | Exposed and Saturated | Exposed and Unsaturated

VIC Dynamic Lake/Wetland Model

- Water & energy balance model
- Includes mixing, ice cover
- Dynamic area based on bathymetry
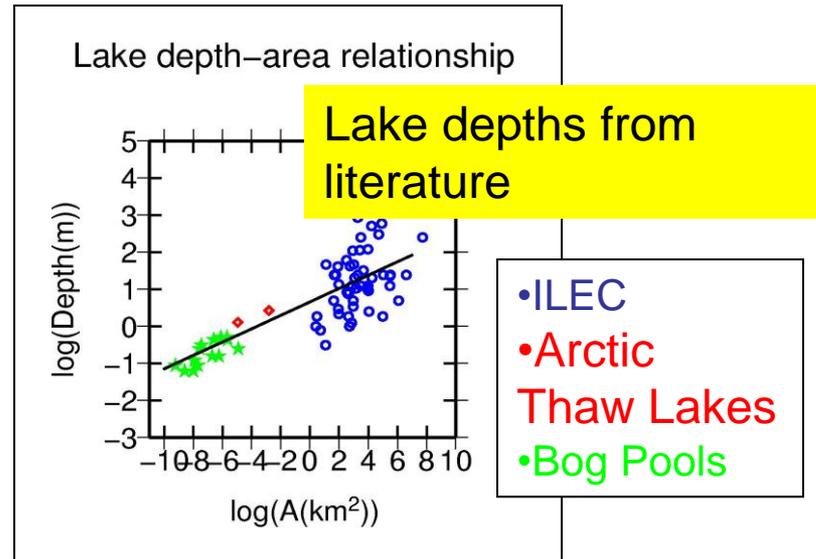- Can flood surrounding wetlands based on topography

Special application: treat all lakes, ponds, and inundated wetland area as a single "lake"

Bowling and Lettenmaier, 2010

Lake Bathymetry/Topography

Lake log($N_{a>A}$) v log(A) (km²)
55.5–56.5 N, 70.75–73.25 E
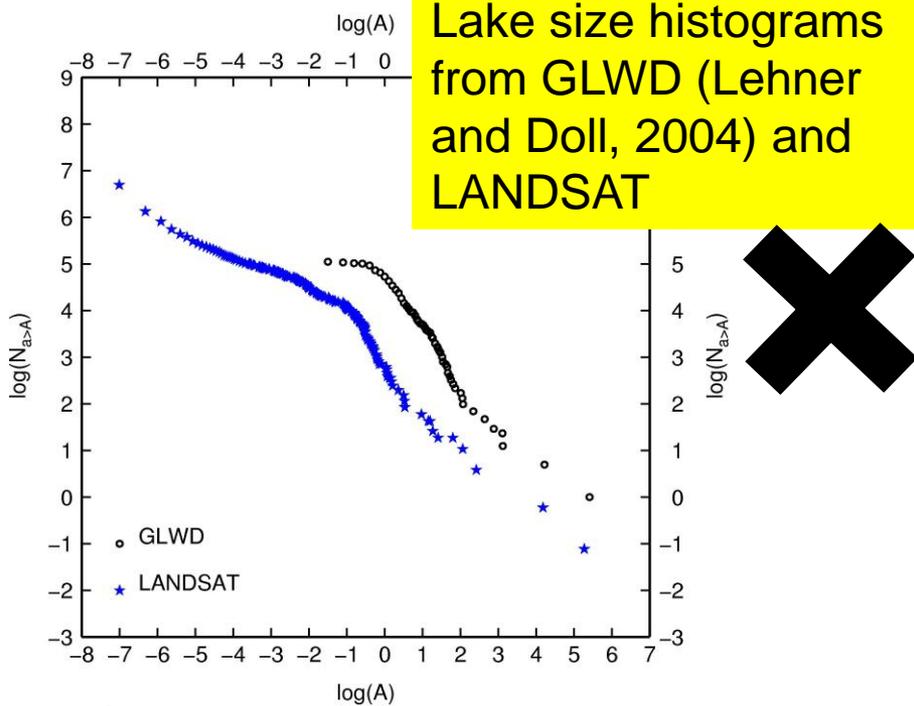
Lake size histograms from GLWD (Lehner and Doll, 2004) and LANDSAT

Lake depth–area relationship

Lake depths from literature

- •ILEC
- •Arctic Thaw Lakes
- •Bog Pools

LANDSAT courtesy of E. Podest and N. Pinto of NASA/JPL

Lake storage-area relationship

SRTM and ASTER DEMs for surrounding topography

Distributed Water Table

- Exposed wetland is composed of a mix of ridges and hollows
- Ridges have water table depth up to 50 cm deeper than hollows
- Mix of hollows and ridges is calibratable
- Bayesian calibration against observations indicates ridge fraction of landscape is 25%-60%, median approx 50%
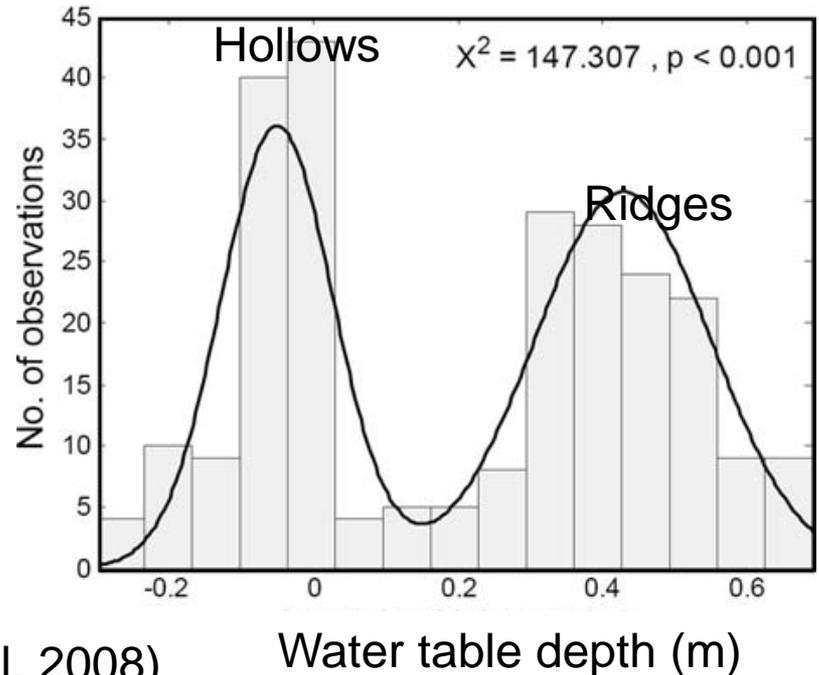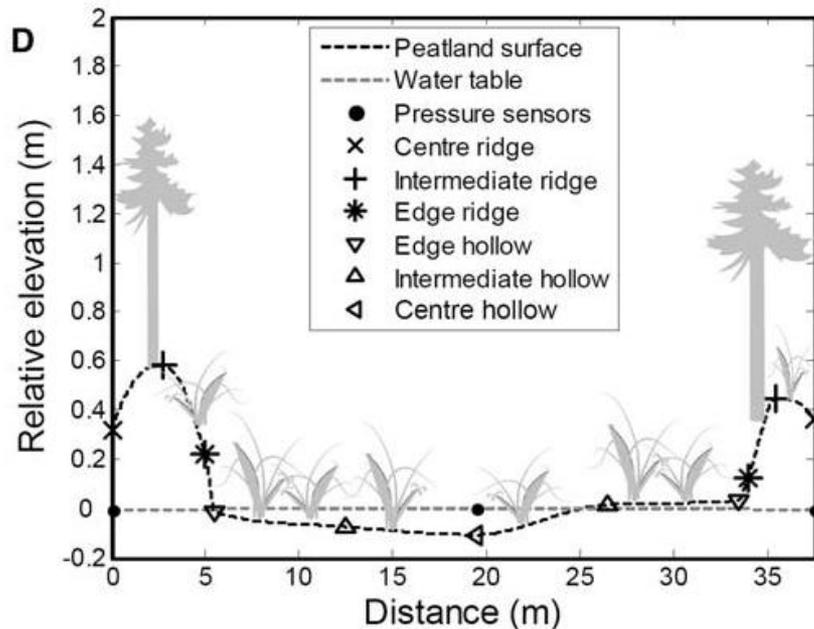
(Eppinga et al, 2008)

Water table depth (m)

CH4 Emissions

Based on Walter-Heimann (2000) wetland methane emissions model

Function of (supplied by VIC):

- Water Table Depth

- Soil Temperature

- Net Primary Productivity

- Soil Carbon Pool size

Converting Emissions into Concentrations

- Link VIC emissions estimates to the NIES Atmospheric Chemistry and Transport Model (ACTM)
- ACTM is driven by NCEP-DOE Reanalysis 2 fields
- Global simulations at 2.5 degree resolution (15 atmospheric levels)
- Global emissions taken from Matthews and Fung 1987 but with coefficients from inversion of Patra et al 2009
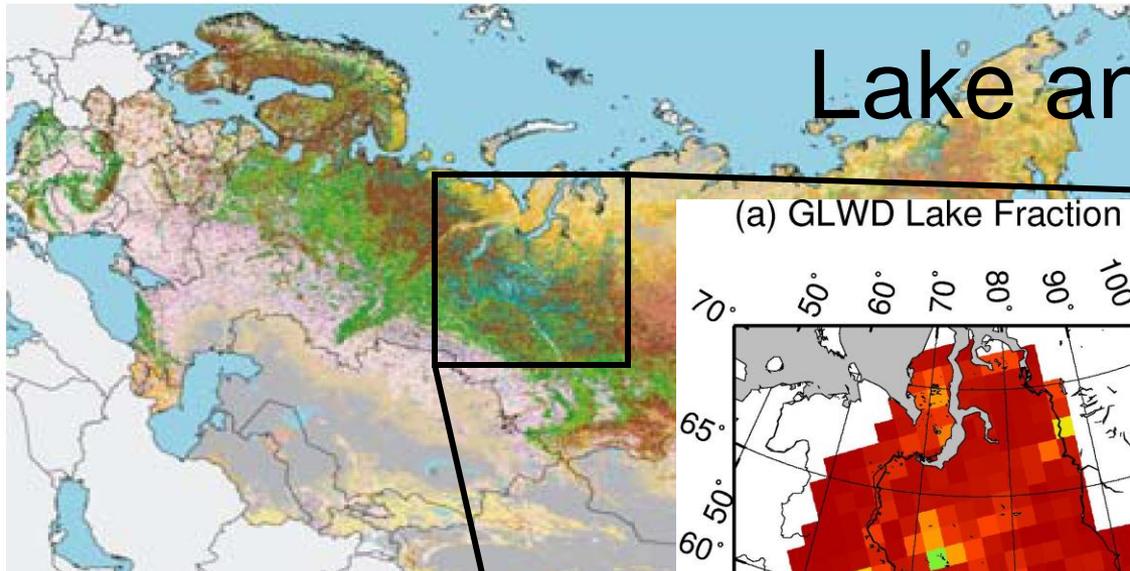- In West Siberia, use VIC emissions instead

AMSR/QSCAT-Derived Inundation

Maximum Annual Open Water Extent
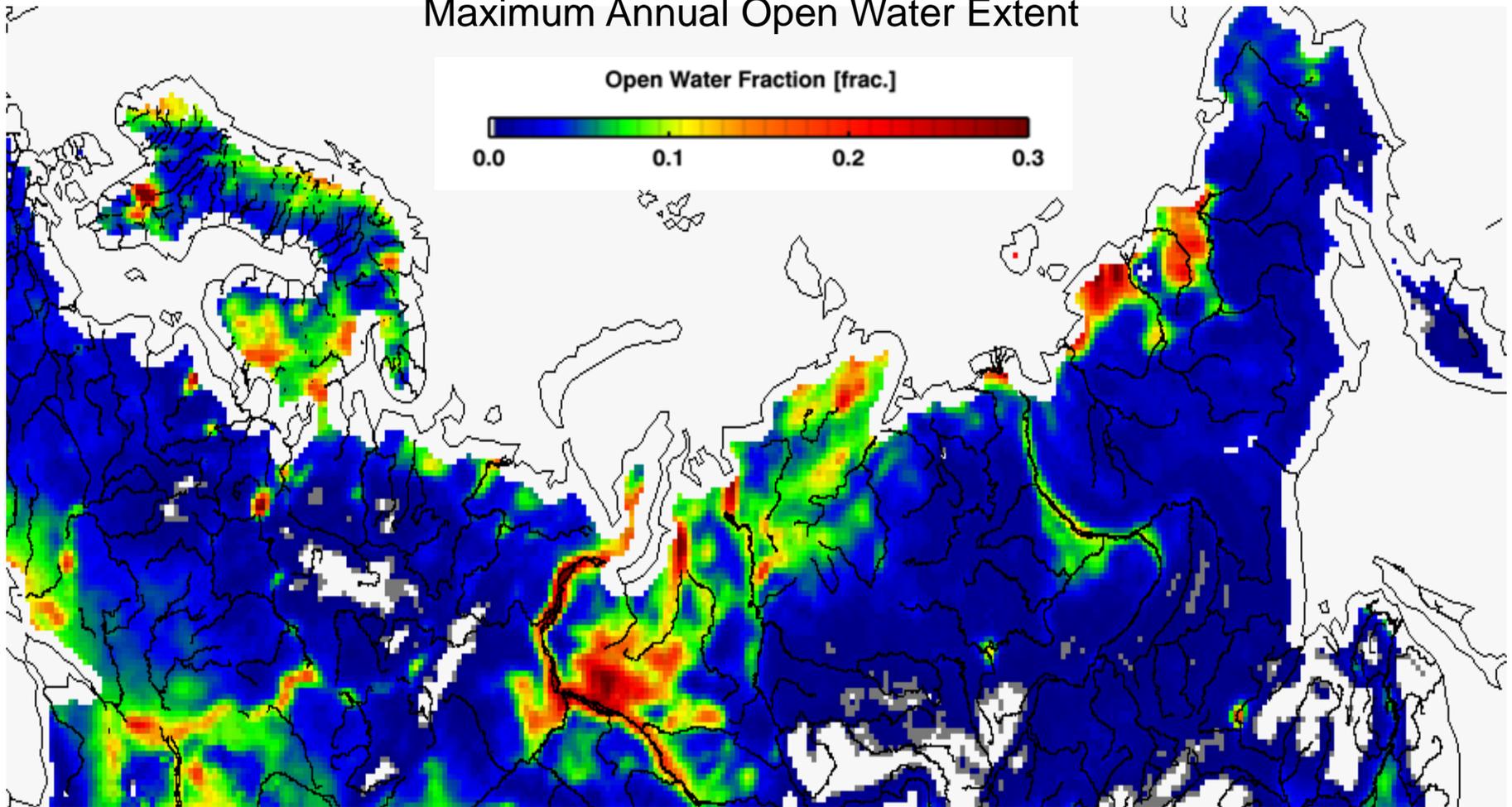
- Daily, for snow-free days
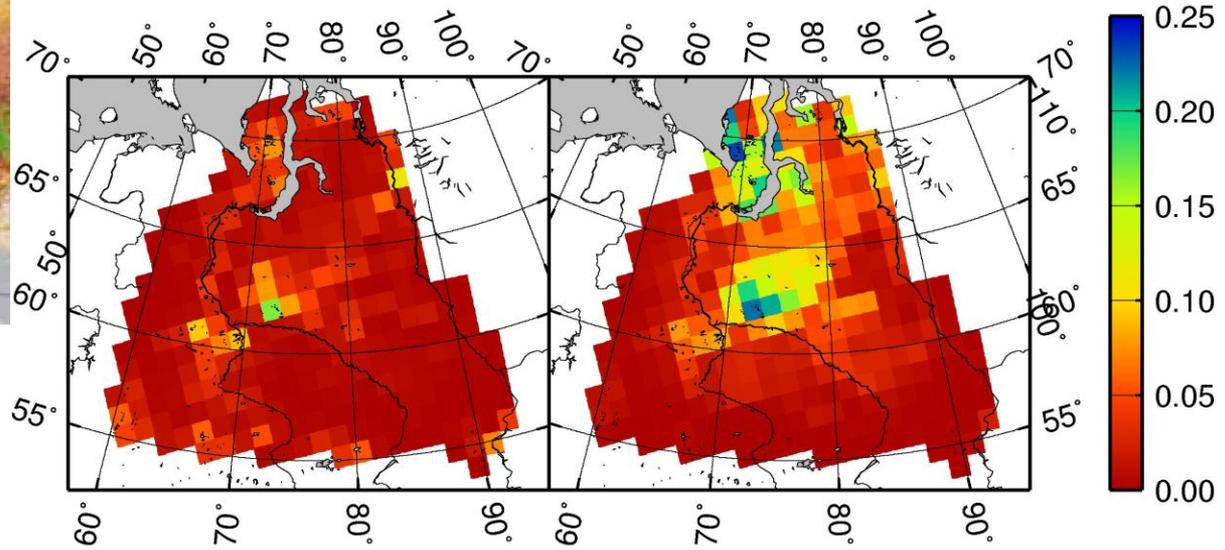- 2002-present
- 25km resolution

Courtesy R. Schroeder, NASA/JPL
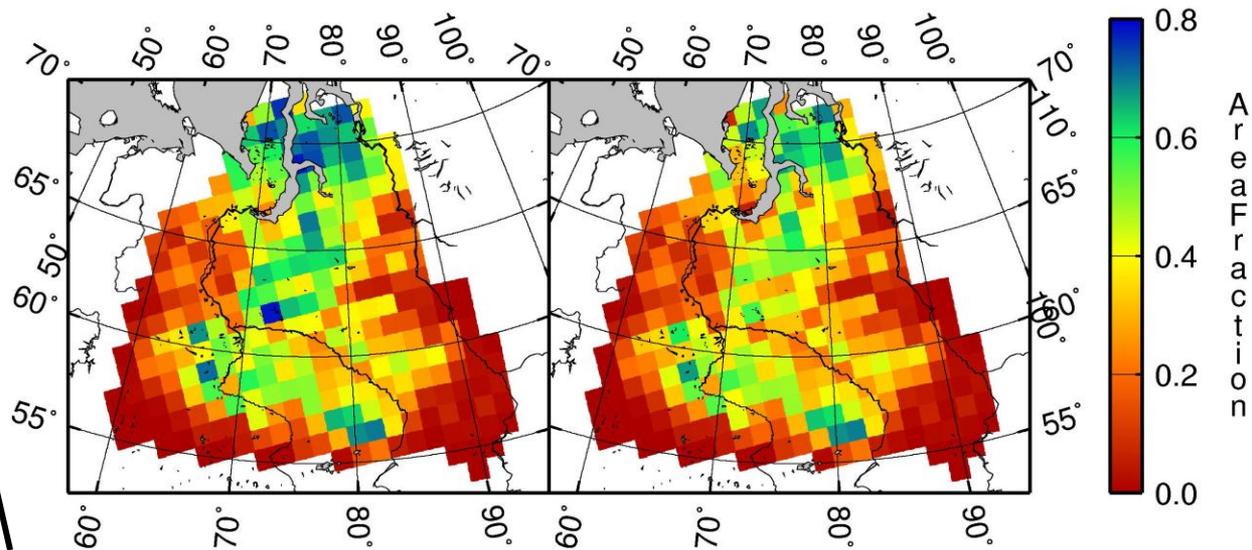
Lake and Wetland Areas

AMSR-based lake areas:
"Permanent" lake extent =
Minimum monthly average
surface water extent from
AMSR time series

GLWD (a) and AMSR (b)
lake areas have different
spatial distributions.

Wetland distribution (d) is
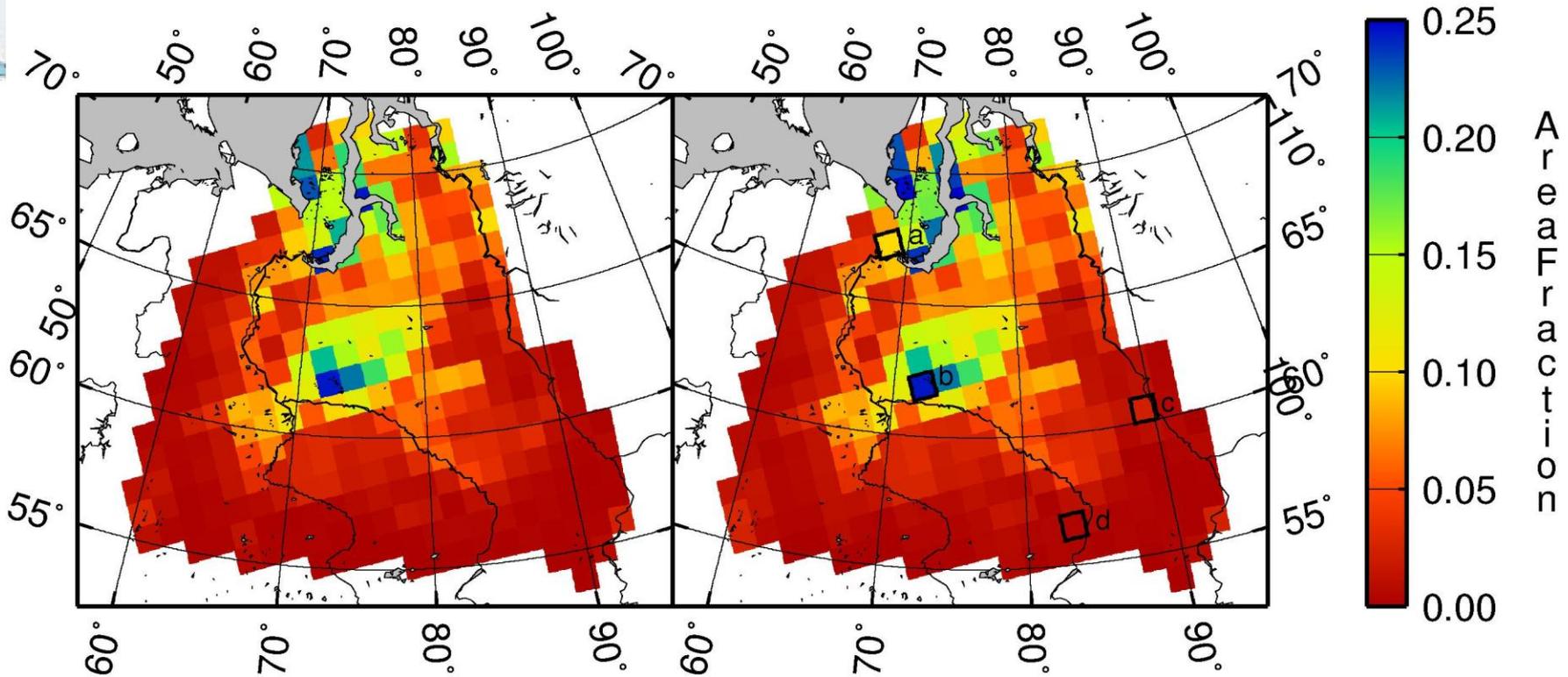different from either lake
distribution.

(a) GLWD Lake Fraction   (b) AMSR Lake Fraction

(c) Total Lake&Wet Frac   (d) (Total – AMSR Lake)
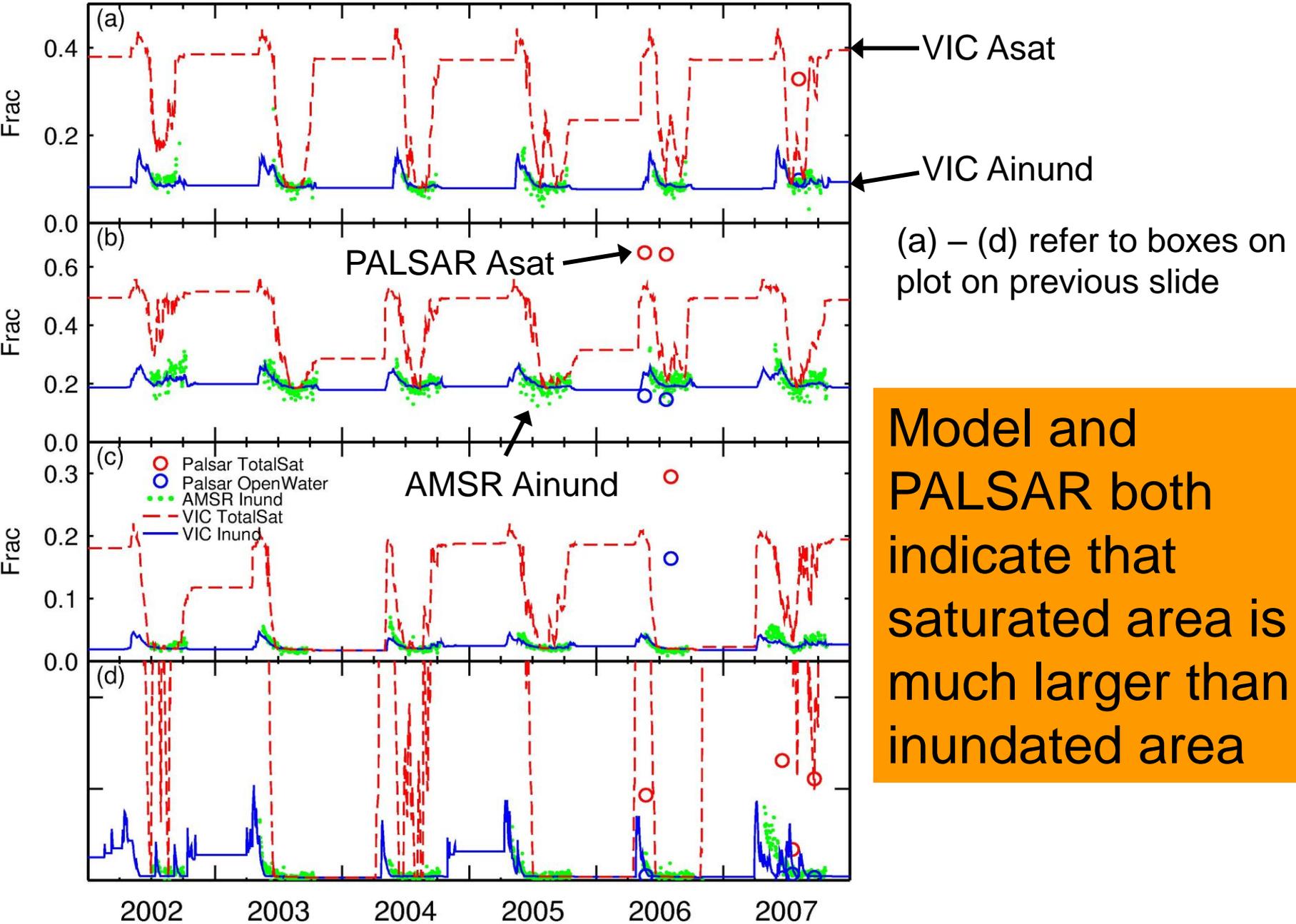
Inundated Area – Obs and Sim

1st to 99th percentiles of Ainund are +/- 10% of median

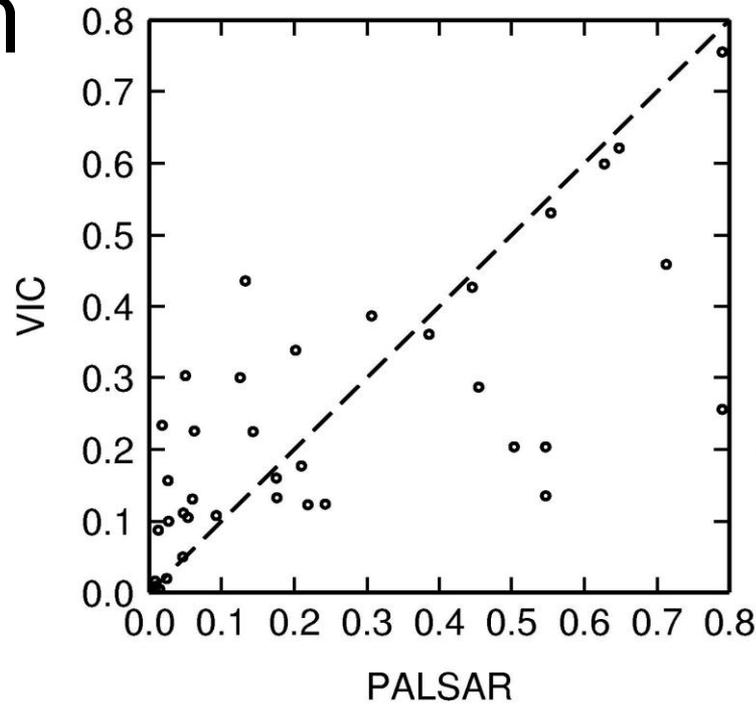(a) AMSR JJA Inund. Fraction   (b) VIC JJA Inund. Fraction
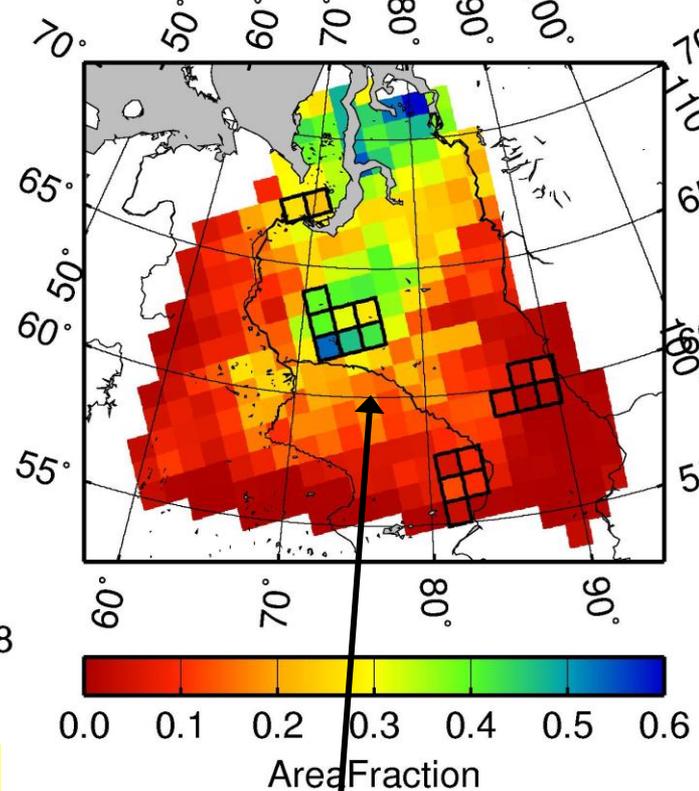
Timeseries of Ainund and Asat

VIC Asat

VIC Ainund

(a) – (d) refer to boxes on plot on previous slide

PALSAR Asat

AMSR Ainund

Palsar TotalSat
Palsar OpenWater
AMSR Inund
VIC TotalSat
VIC Inund

Model and PALSAR both indicate that saturated area is much larger than inundated area

Asat: Sim v. Obs

(a) VIC Asat v. PALSAR Asat

(b) VIC Asat (bias-corrected)

Simulated saturated area appears to be biased low by about 6%

But LARGE scatter

Large saturated area North of 60N

Assume:

- Median Asat = VIC Asat*1.06
- 1st pctl Asat = Ainund
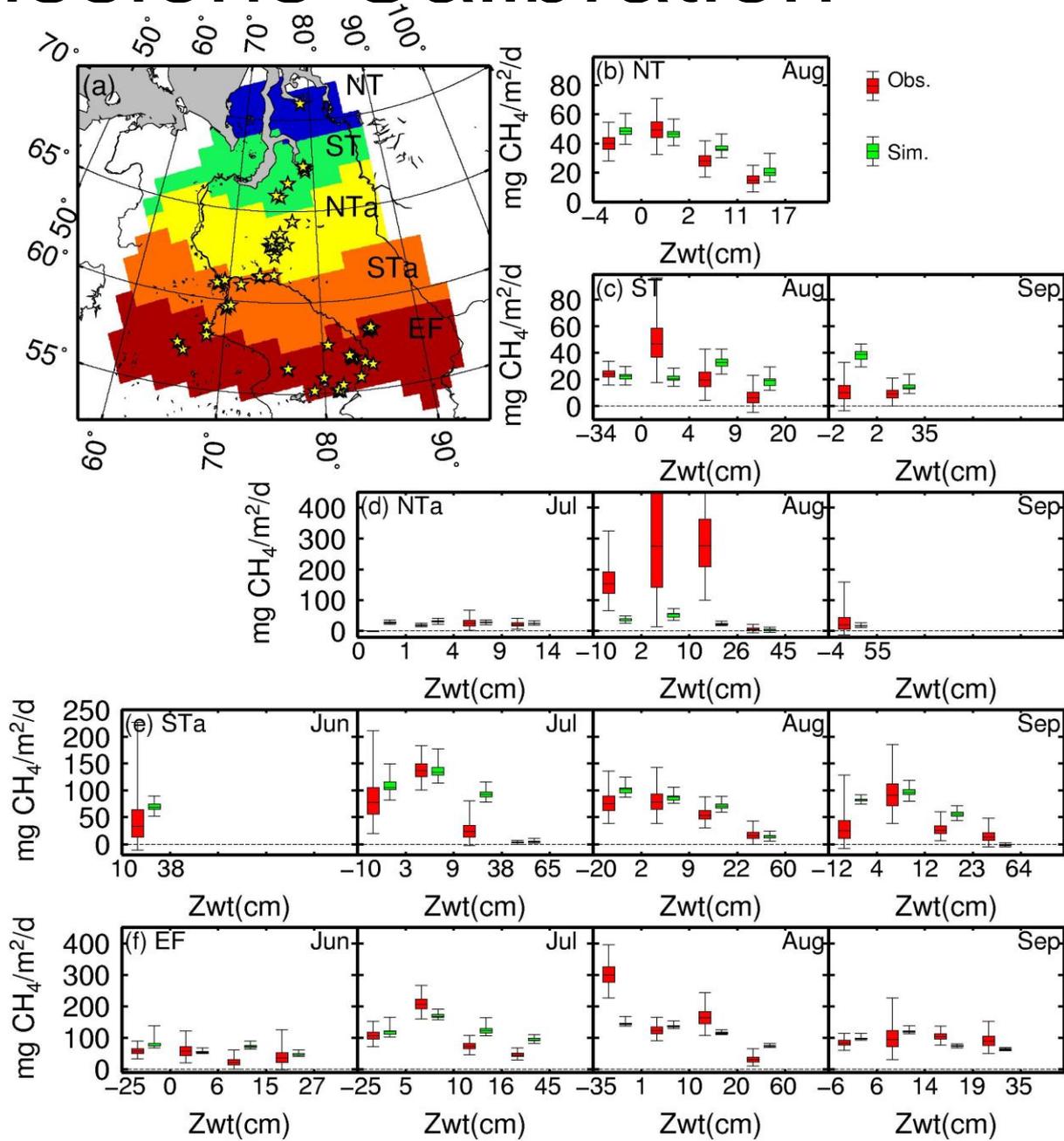- 99th pctl Asat = Awetland

CH4 Emissions Calibration

Calibrated to match observations of Glagolev et al 2011

Large scatter & mismatch in NTa (region d) in August is due to very high observed emissions at a single site
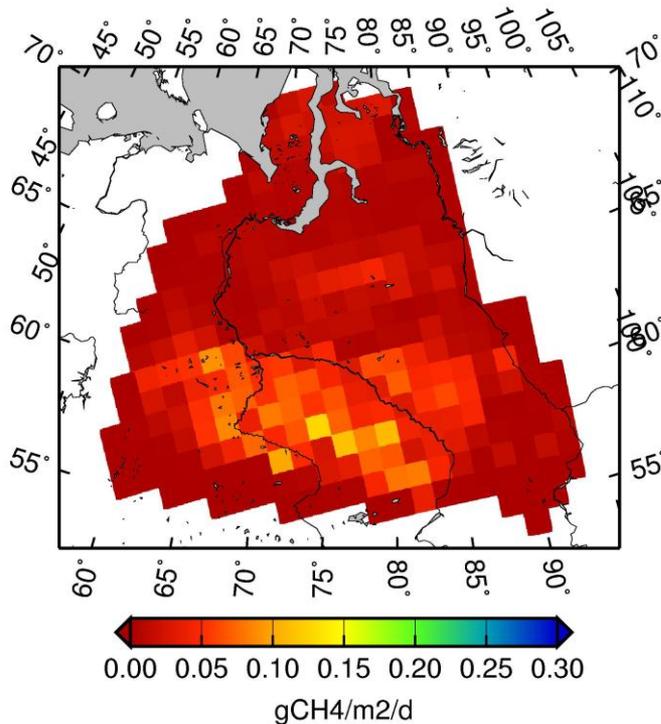
Wetland methane emissions decrease from South to North
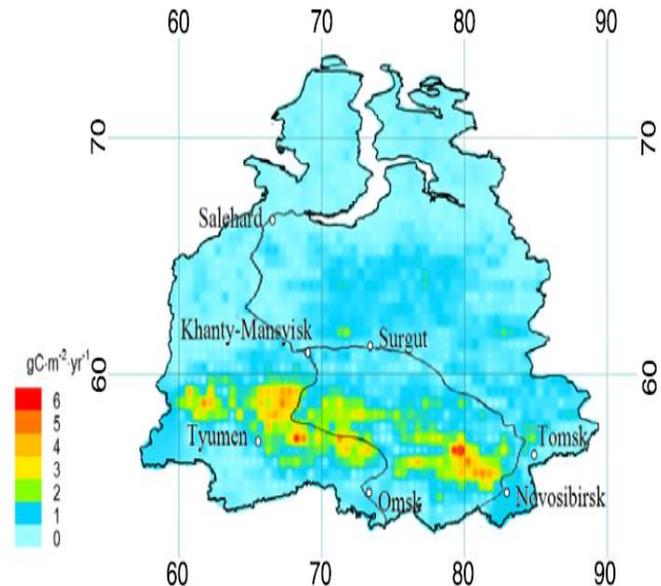
Wetland Emissions

- Spatial pattern looks similar to Glagolev et al 2011 paint-by-numbers
- Implies that our use of distributed water table is distributing emissions similarly to actual distribution of microtopography

Jul Avg Emissions

gCH4/m2/d

Median emissions: 4.17 Tg CH4/year

Min, Max
3.42 Tg CH4/year
6.92 Tg CH4/year

Glagolev et al (2011)
3.96 +/- 1.4 Tg CH4/year

What about lake areas and emissions?

Consider the 2 lake area sources (GLWD, AMSR) as upper and lower bounds

Consider range of constant emission rates per unit area, spanning range reported in literature
- 10 mg CH4/m2/day
- 125 …
- 250 …
- 375 …
- 500 …
- These nominal rates apply during ice-free season

Construct representative combinations of lake areas and emissions, wetland areas and emissions, and compare each "scenario" with AIRS satellite retrievals
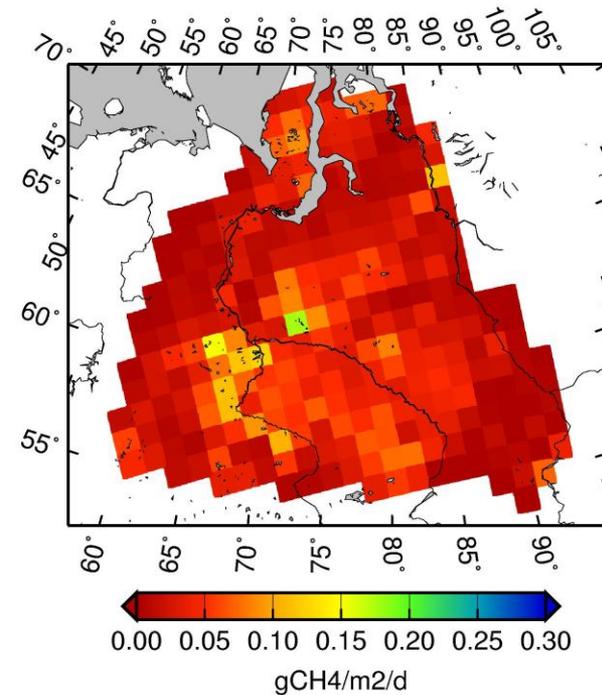
Emissions "Scenarios"

The various "scenarios" amount to linear combinations of 3 main end-members:

1. High Lake Emissions (500 mg/m2/day), GLWD Lake Area, 1st pctl wetland CH4

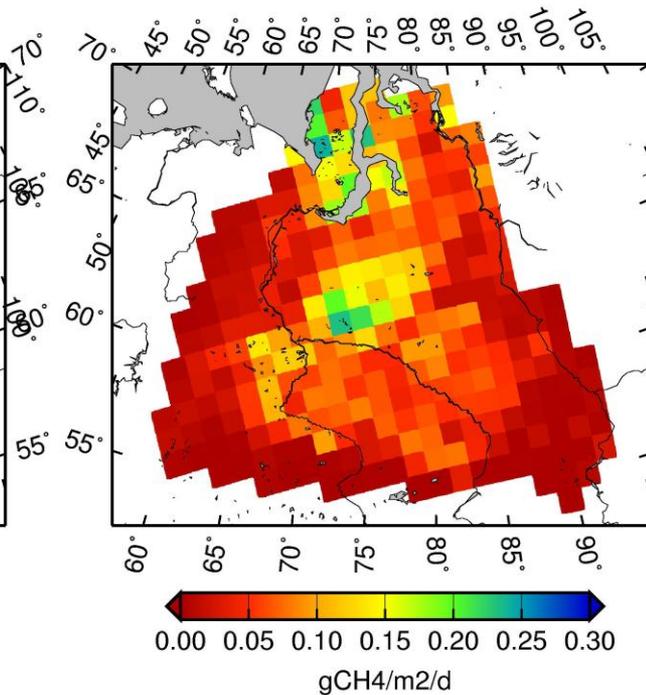2. High Lake Emissions (500 mg/m2/day), AMSR Lake Area, 1st pctl wetland CH4

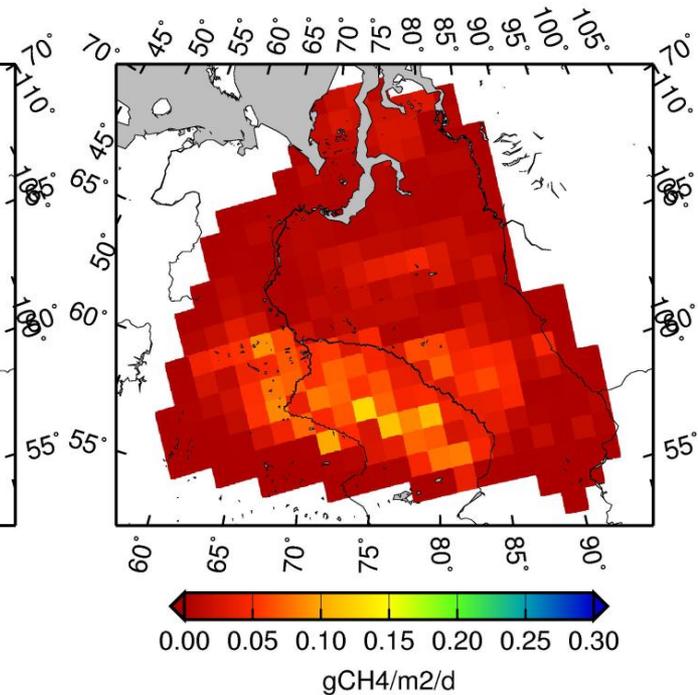3. Low Lake Emissions (10 mg/m2/day), Median Wetland Emissions

Annual emissions ~ 4.6 Tg CH4/year

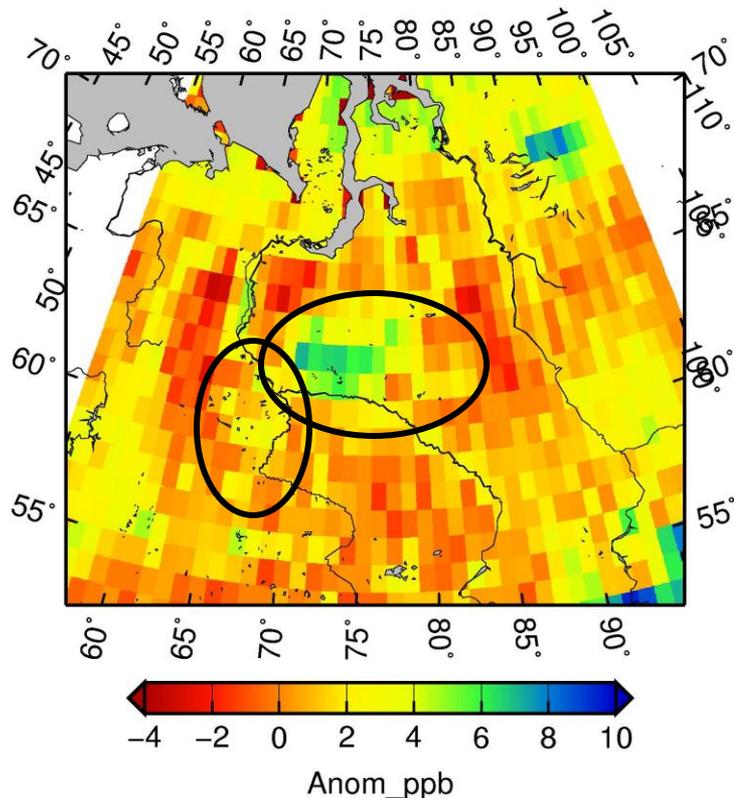Annual emissions ~ 14.1 Tg CH4/year

Annual emissions ~ 4.3 Tg CH4/year
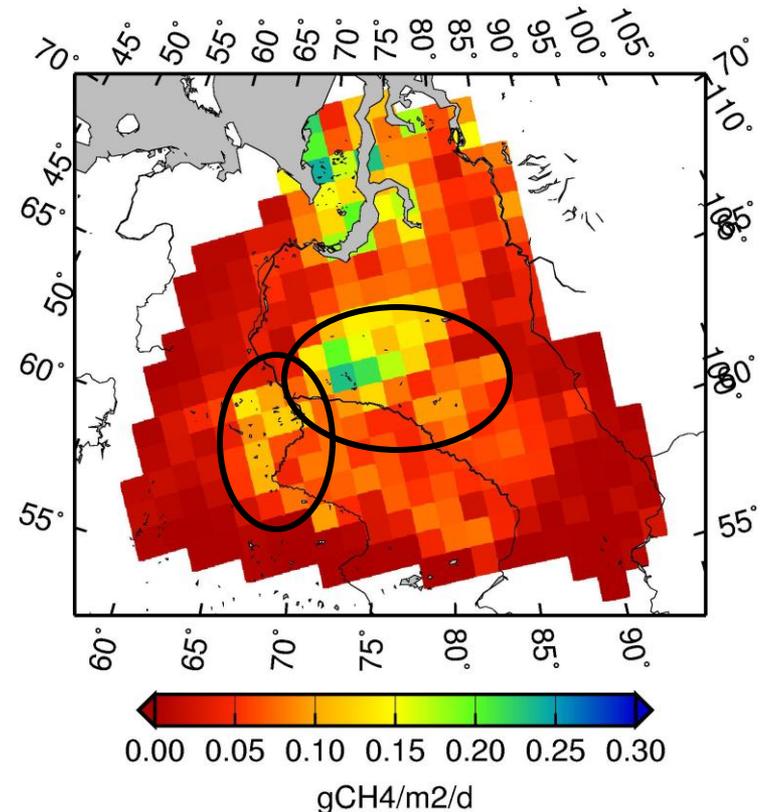
Comparison to Satellite CH4

Routing through atmospheric transport model and comparison with AIRS is underway

But if we compare the spatial patterns of emissions with AIRS [CH4] zonal anomalies:

AIRS CH4 Zonal Anomalies, JJA 2003–2010

Jul Avg Emissions

- Scenarios with AMSR lake area and high lake emissions rates (e.g., similar to end-member #2) give most plausible spatial distribution of emissions
- This implies lake emissions around 250-500 mgCH4/m2/day
- Interpret with caution, since [CH4] affected by advection and oxidation in atmosphere

Posterior Probabilities

- AMSR lake areas seem more likely than GLWD lake areas

- Lake emissions range from 250-500 mg/m^2/day, median = 375 mg/m^2/day

- This similar to thermokarst lake emission rates

Total Emissions Estimates

|	Min	Median	Max
Wetland	1st pctl Asat 1st pctl CH4 3.4 Tg CH4/year	Median Asat Median CH4 4.2 Tg CH4/year	99th pctl Asat 99th pctl CH4 6.4 Tg CH4/year
Lake	AMSR area 250 mg/m^2/day 5.4 Tg CH4/year	AMSR area 375 mg/m^2/day 8.1 Tg CH4/year	AMSR area 500 mg/m^2/day 10.7 Tg CH4/year
Total	8.8 Tg CH4/year	12.3 Tg CH4/year	17.1 Tg CH4/year

Other possible sources of CH4?

- ***Natural seeps*** have been observed in at least one location in W. Siberia; globally associated with oil and gas fields

- Oil and gas fields have similar distribution to lakes in W. Siberia

However:

- Natural gas fields (red) are primarily North of area of maximum [CH4]; fields in the area of maximum [CH4] are primarily oil (green)

- Oil fields also occur South of the Ob, where we do not see similarly large [CH4]

- High [CH4] concentrations over central W. Siberia appear to be seasonal; would natural seeps emit seasonally?

But we can't rule them out

Gas Fields

Oil Fields

From "Oil and Gas Resources of the West Siberian Basin, Russia", DOE, 1997
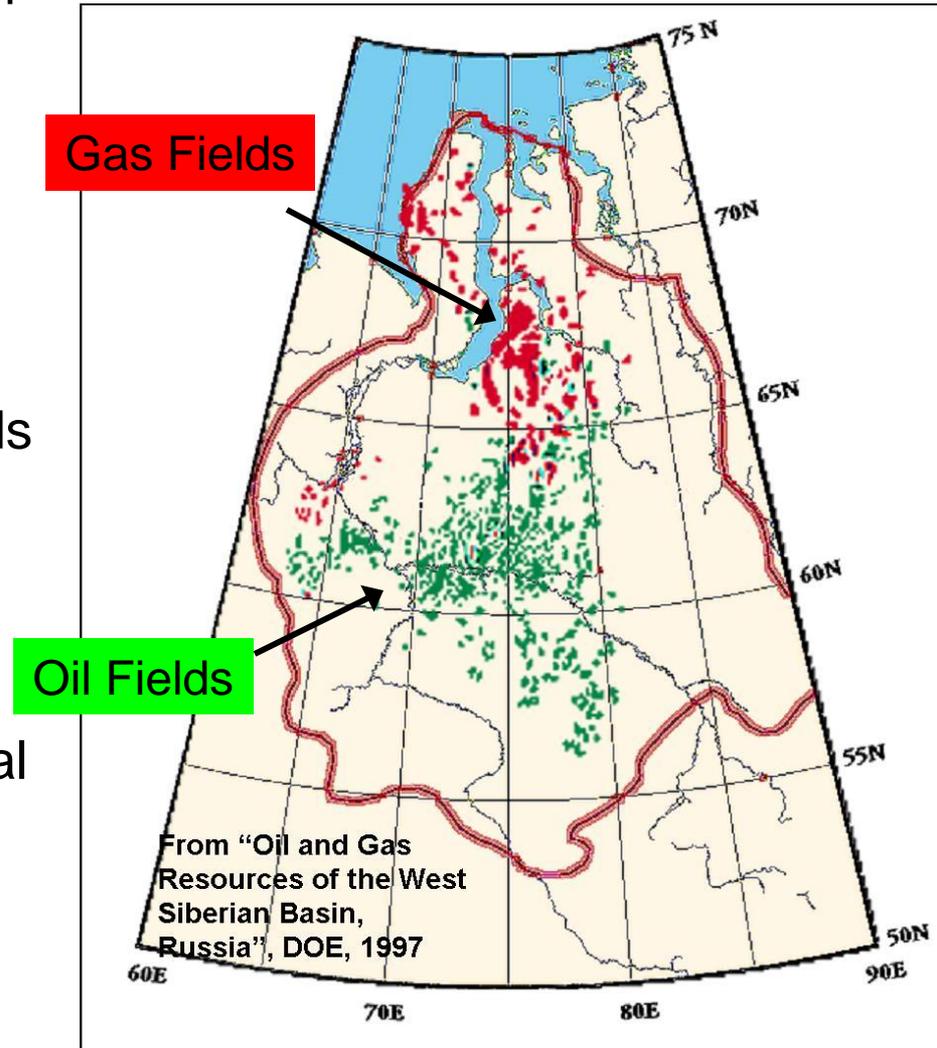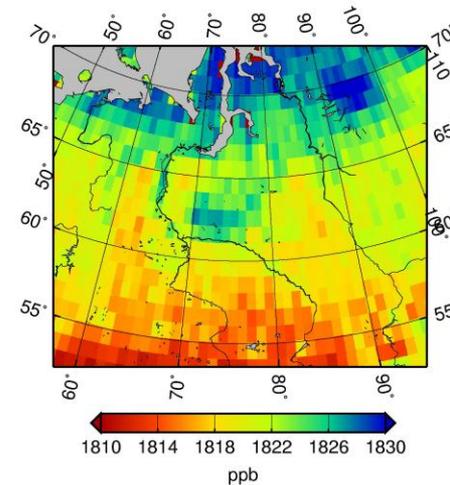
Assimilation Scheme

1. Start with ensemble of VIC-ACTM runs, chosen from percentiles of prior joint distribution of surface water and soil carbon → 2. Run until observation available
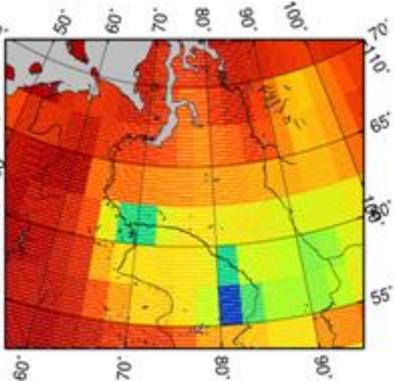

25th

50th

75th

3. Comparison with AIRS Satellite CH4 Observation
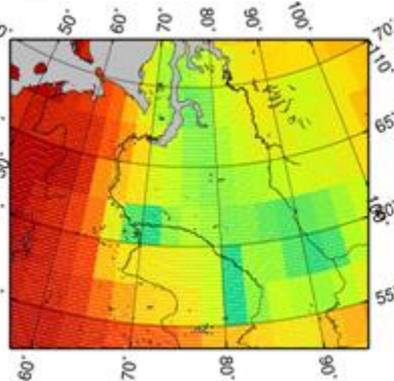

1810 1814 1818 1822 1826 1830
ppb

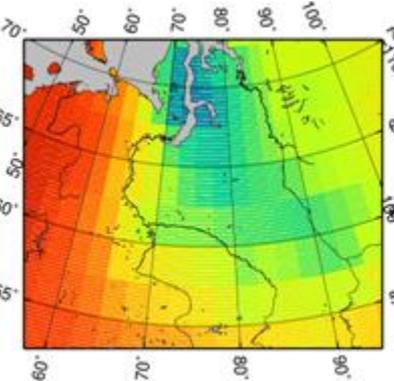4. Revised likelihoods = posterior distribution

5th

20th

50th

. . .

5. Run until next observation

Conclusions

- Wetland saturated area is substantially larger than inundated area
  - Important source of CH4 emissions
  - Still poorly constrained
- Lake areas in W. Siberia likely larger than Global Lake and Wetland Database implies
  - Passive microwave may give better estimates
- Lakes (plus seeps?) in W. Siberia likely emit at rates of 250-500 mg CH4/m2/day
- W. Siberian lakes (plus seeps?) and wetlands emit between 8.8 and 17.1 Tg CH4/year
- Assimilation of AIRS CH4 retrievals into VIC-ACTM is underway

Thank You

This work was carried out at the University of Washington and the Jet Propulsion Laboratory under contract from the National Aeronautics and Space Administration.