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

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15th Annual LCLUC Science Team Meeting
University of Maryland University College
Adelphi, MD, 2011-Mar-29

Collaborators

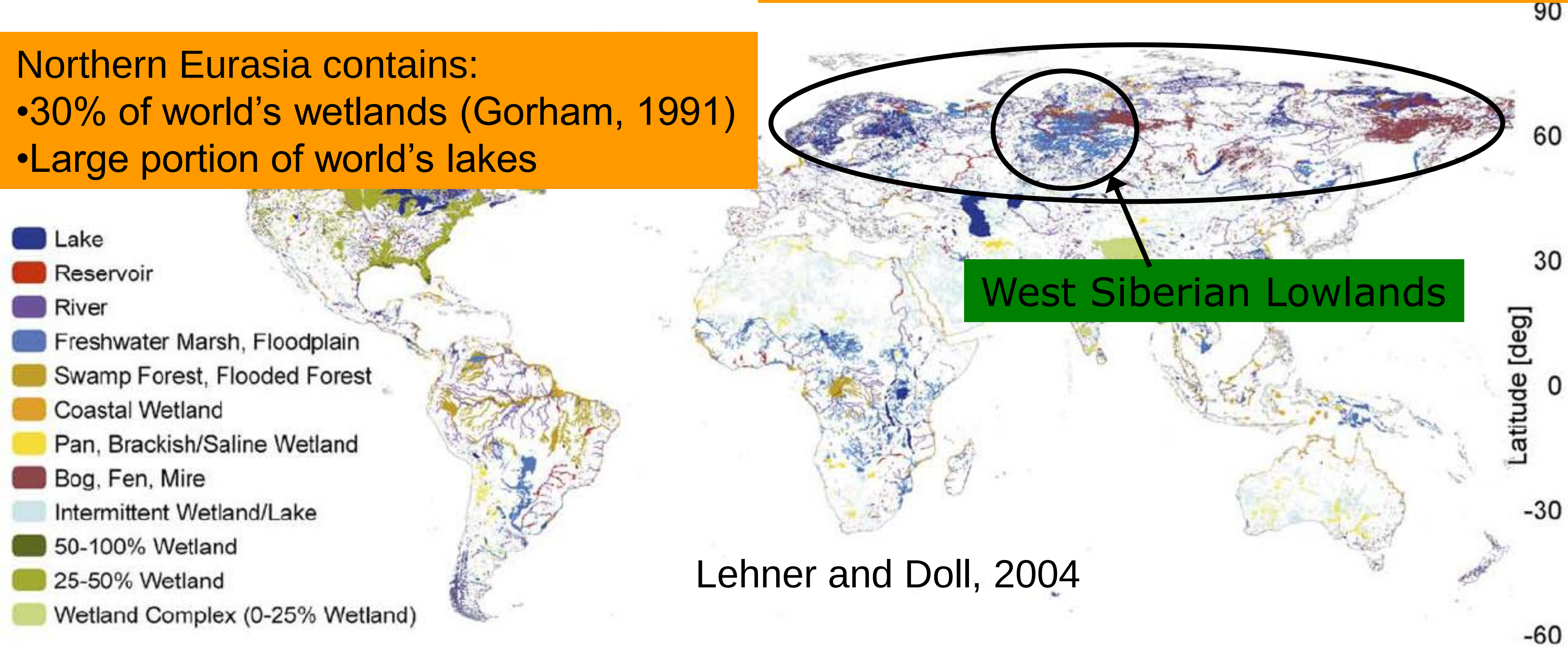
- Dennis Lettenmaier (PI) and Ted Bohn, University of Washington
- Kyle McDonald (co-PI), Erika Podest, and Ronny Schroeder, JPL/NASA
- Shamil Maksyutov and T. Machida, National Institute for Environmental Studies (NIES), Japan
- Mikhail Glagolev, Moscow State University, Russia

Importance of Lakes and Wetlands

Wetlands:
- Largest natural global source of CH_4
- Large C sink

Lakes:
- Large CO2/CH4 source
- CH_4 estimates revising upwards due to ebullition

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

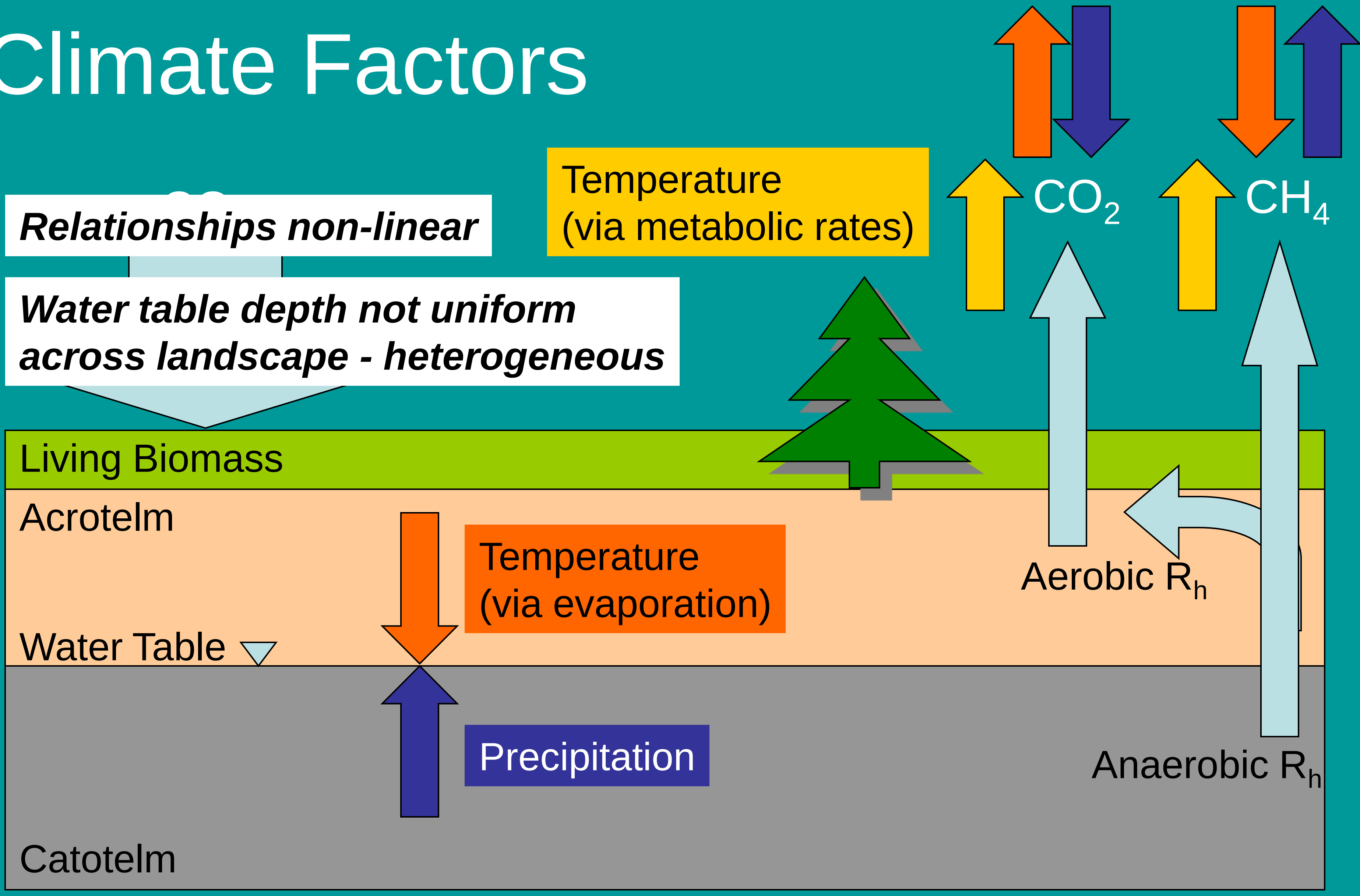


Lehner and Doll, 2004

Lake/wetland carbon emissions are sensitive to climate

High latitudes experiencing pronounced climate change

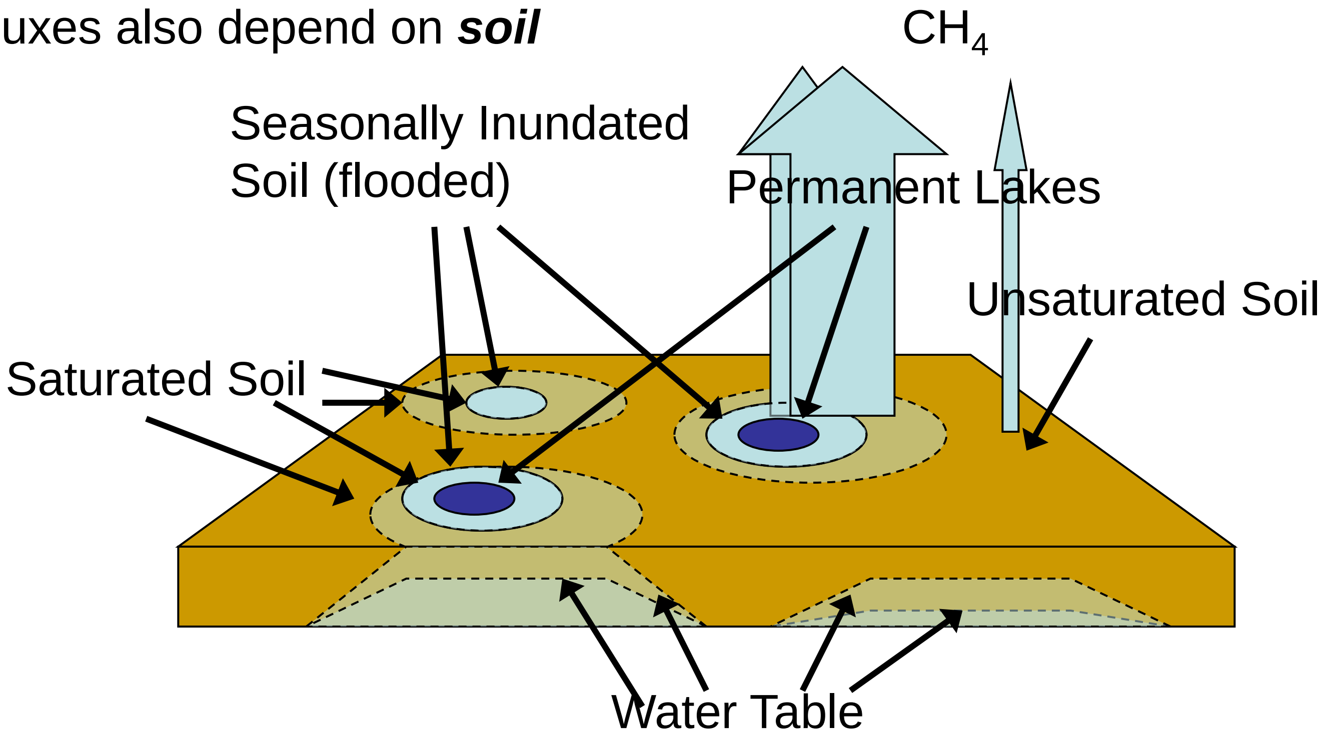
Climate Factors



Note: currently not considering export of DOC from soils

Lakes and Wetlands

- Lake/wetland CH_4/CO_2 emissions depend on T, C, nutrients, oxidation state, etc
- Wetland CH_4/CO_2 fluxes also depend on ***soil moisture***



- ***Areal extent of wet zones can vary substantially in time***
- ***Temporal variations in area play important role in response of CH_4/CO_2 fluxes to climate***
- ***We can improve model estimates by taking dynamic behavior into account***

Monitoring the Sources

- In situ measurements (water table, CH_4 flux) are localized and sparse
- Large-scale observations (towers, satellites) are less direct
  - Extent of saturated/inundated wetlands (e.g. SAR, passive microwave)
  - Atmospheric CH_4 concentrations (e.g. towers, GOSAT)
  - Large-scale runoff (stream gauges)
- Large-scale biogeochemical models can bridge the gap between indirect observations and the processes we want to monitor
  - Sub-surface soil moisture, temperature, methanogenesis
  - Simultaneous large-scale observations of multiple variables can constrain model parameters

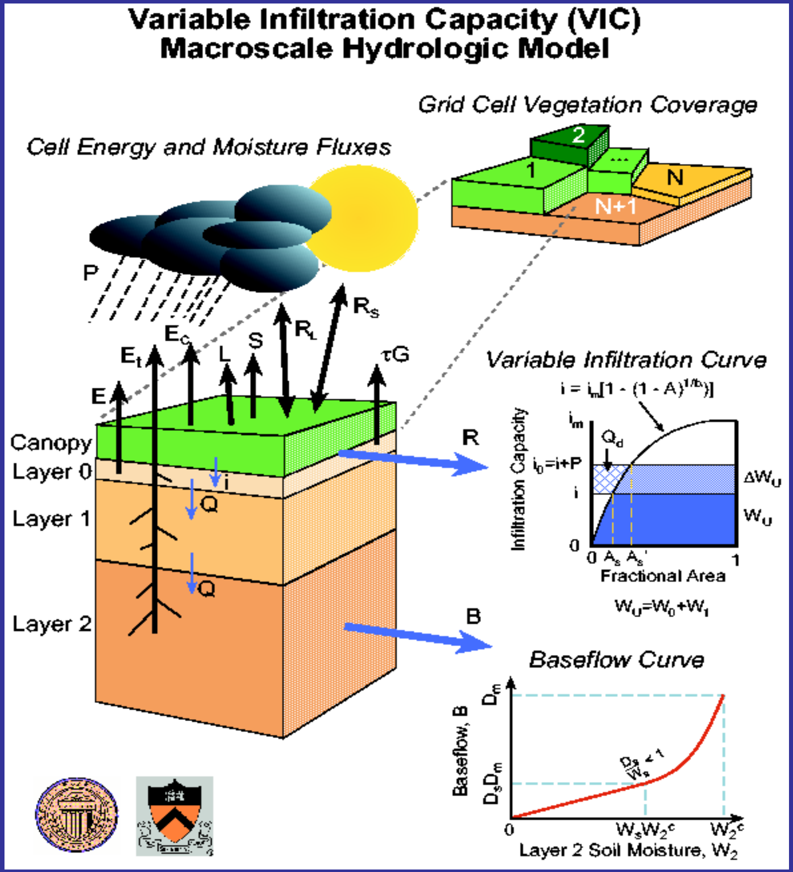
Science Questions

How do wetland methane emissions in W. Siberia respond to environmental conditions over a range of temporal and spatial scales?

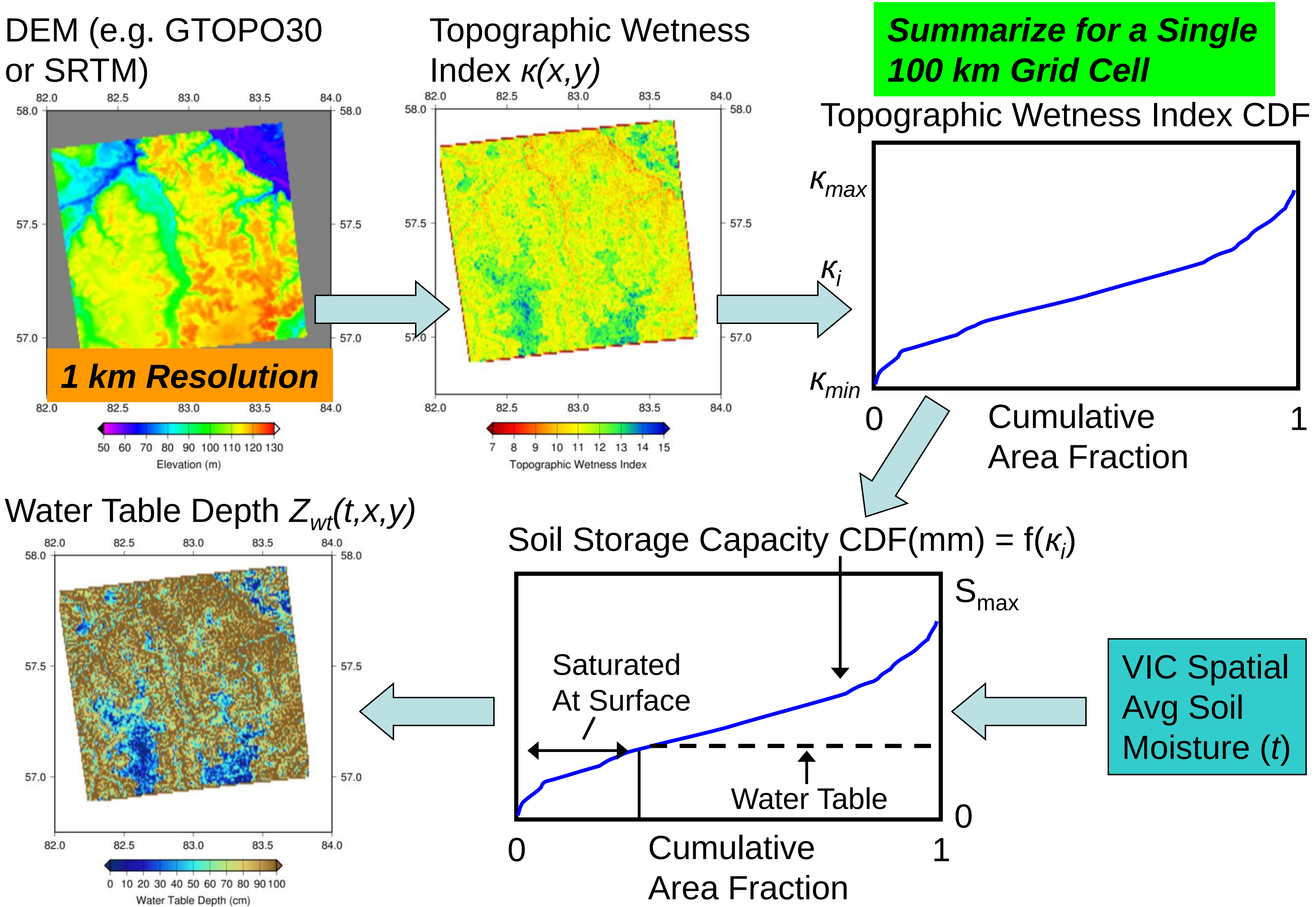
- Can wetland methane emissions in western Siberia be effectively monitored by a combination of models, towers, and remote sensing observations?
- Can tower and/or satellite observations be used to constrain errors in or identify areas for improvements in the models (e.g. poor representations of physical processes, state uncertainties, parameter uncertainties)?
- How much do SAR-based surface water products improve the match between simulated and observed methane concentrations?
- Can integration of satellite-based and tower-based (near-surface) atmospheric methane concentrations via data assimilation methods lead to better understanding of the space-time distribution of methane emissions over northern Eurasia?

Modeling Framework

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

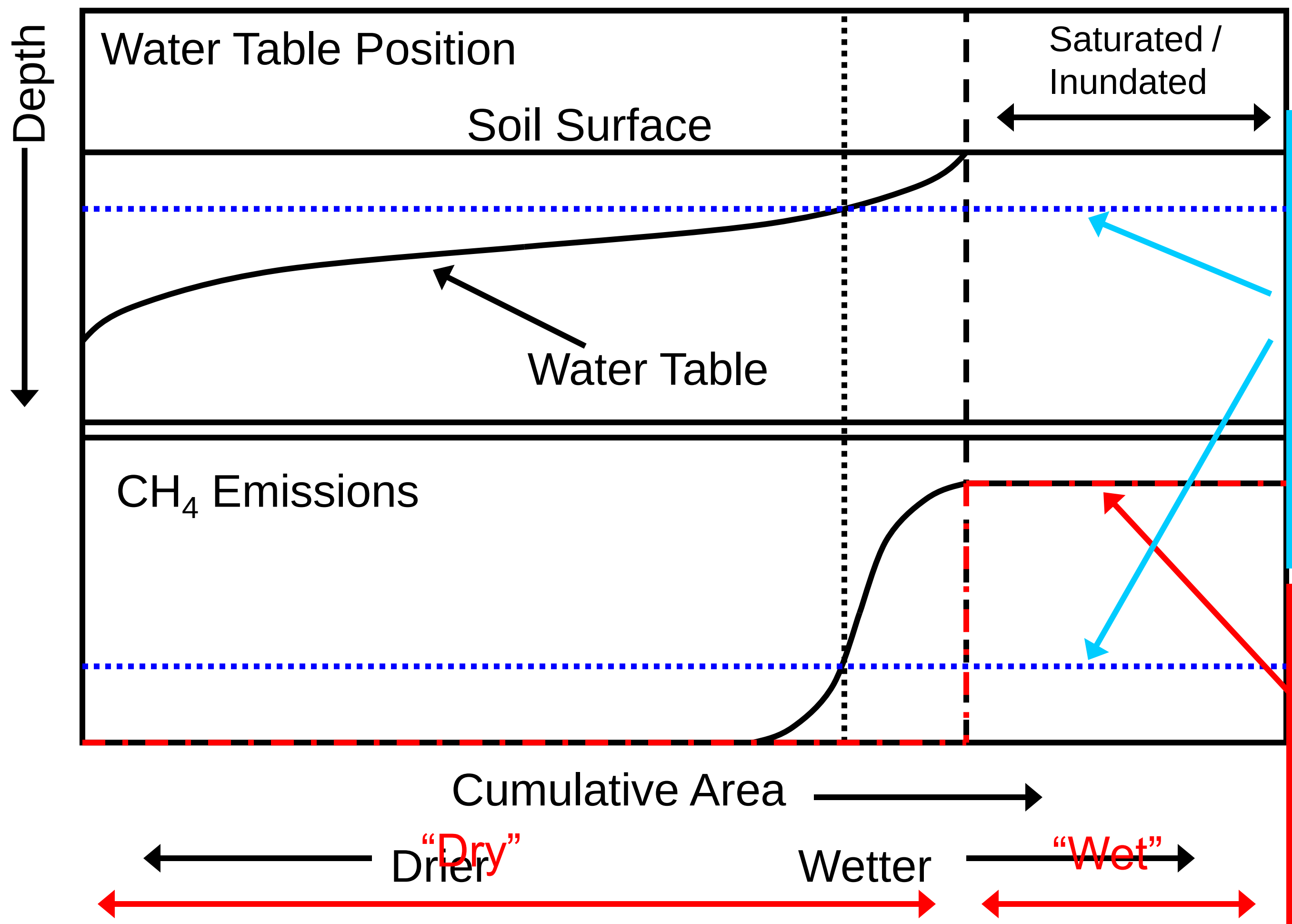


Distributed Water Table



Recent Progress in Modeling (Bohn et al., GRL 2010)

3 Main approaches to modeling large-scale CH4 emissions:



1. "Distributed" scheme:

- Heterogeneous water table and CH4
- Used by UW

2. "Uniform" scheme:

- Water table and CH4 emissions vary in time but uniform across grid cell
- Oversensitive to climate
- Biased +/- 30%

3. "Wet-Dry" scheme:

- Simulates time-varying saturated area
- Ignores water table and emissions from unsaturated zone
- Biased up to 30% too low

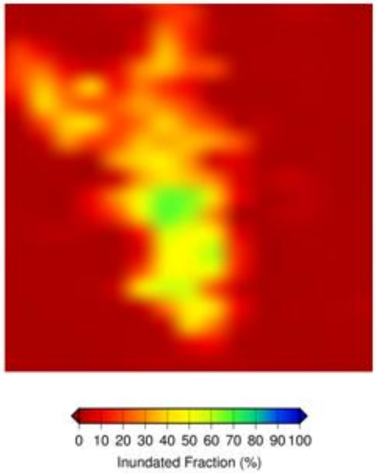
Comparison with PALSAR

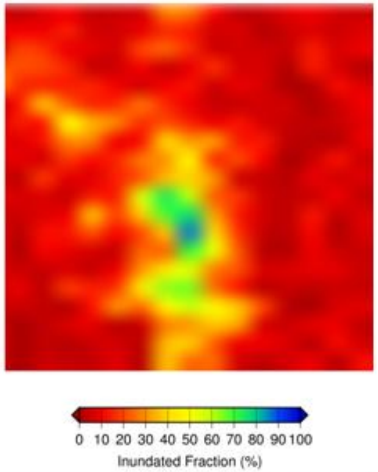
- Spatial distribution of inundation compares favorably with remote sensing
- This offers a method to calibrate model soil parameters

Observed Inundated Fraction (PALSAR Classification)

Simulated Inundated Fraction (at optimal Zwt)

ROI 1
2006-06-09

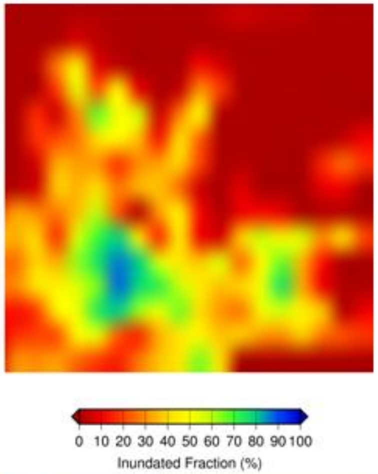


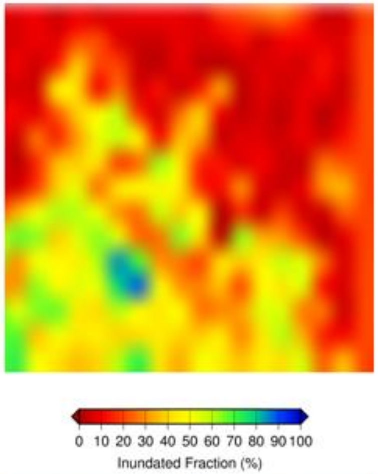


Observed Inundated Fraction (PALSAR Classification)

Simulated Inundated Fraction (at optimal Zwt)

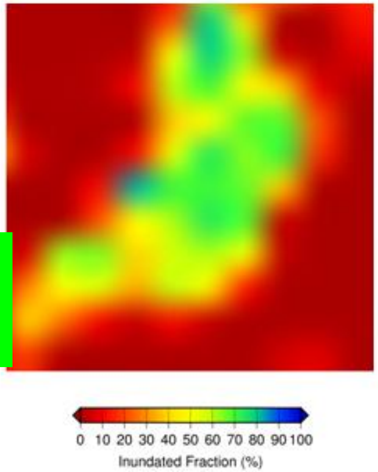
ROI 3
2006-05-28

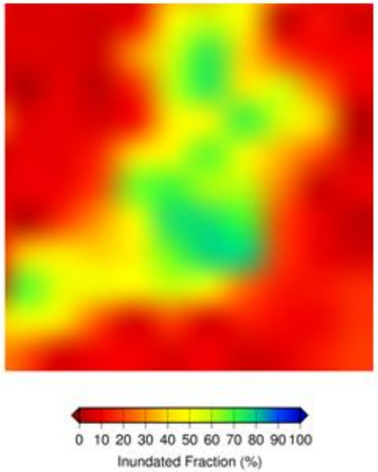




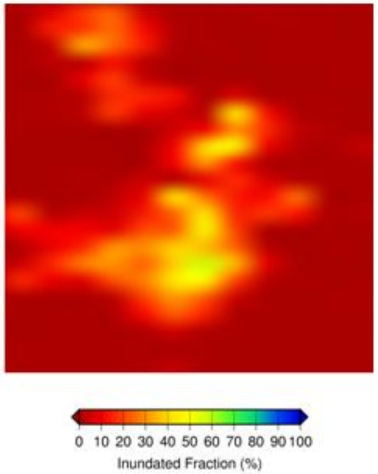
ROI 2
2007-07-06

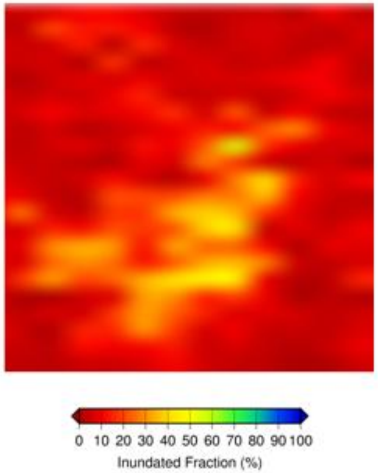
Approx.
30 km



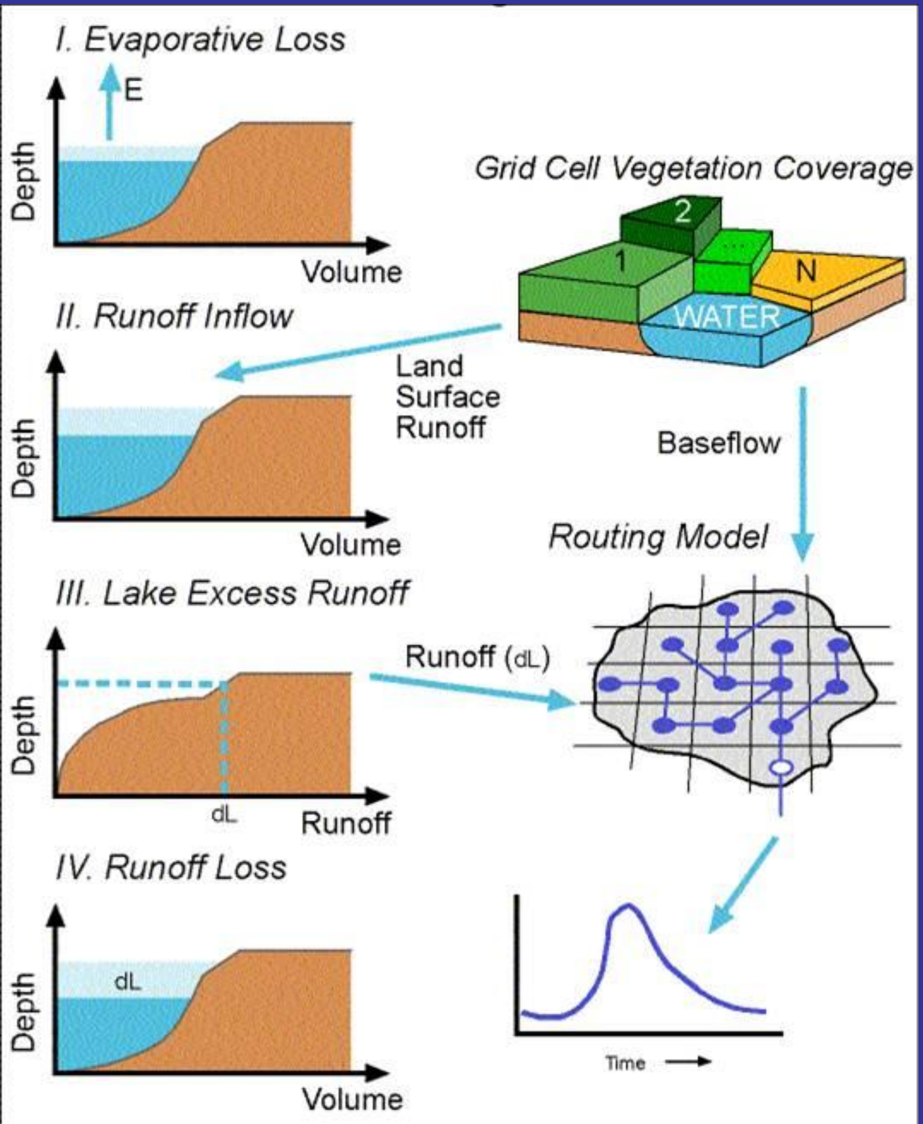


ROI 4
2007-07-18





VIC Dynamic Lake/Wetland Model



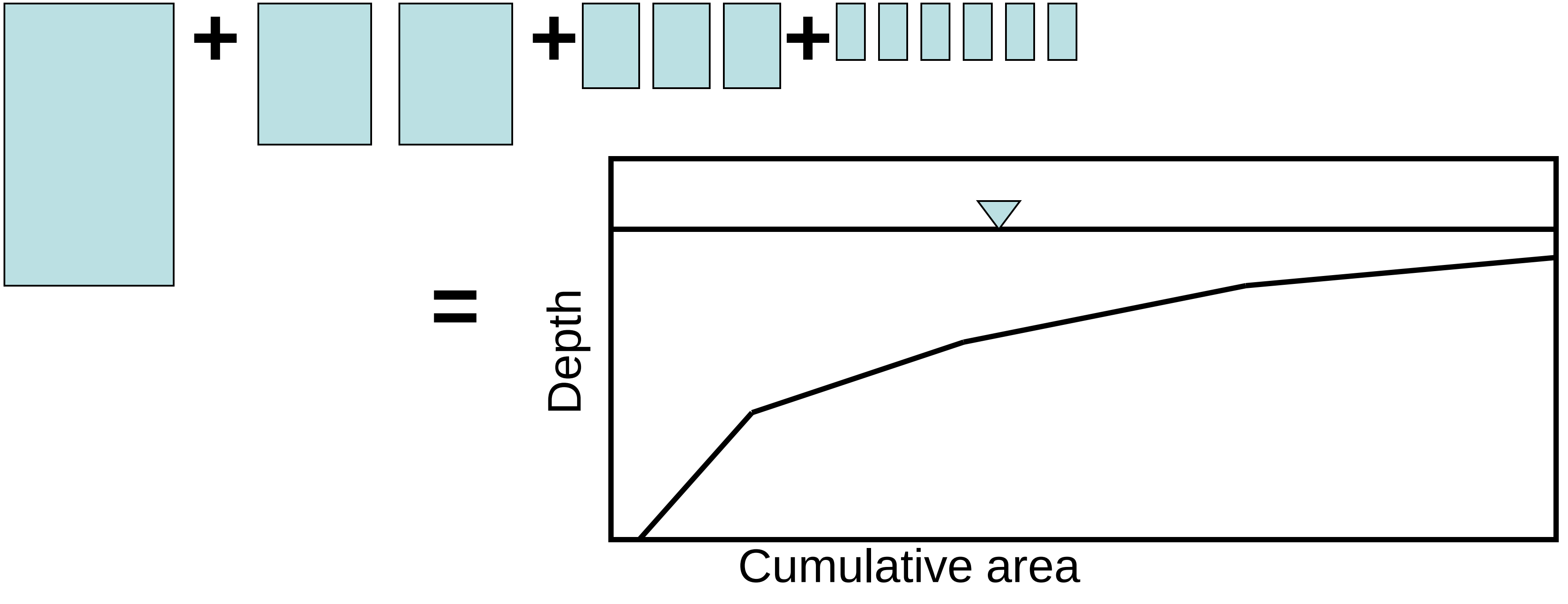
- Water & energy balance model
- Includes mixing, ice cover
- Dynamic area based on bathymetry
- Can flood surrounding wetlands based on topography

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

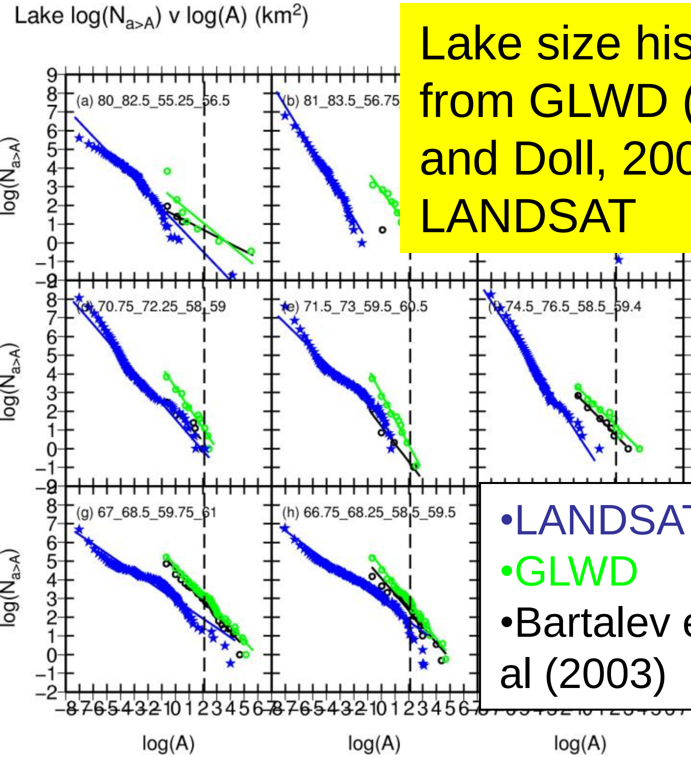
Bowling and Lettenmaier, 2010

Composite Bathymetry

- How much area is covered by water of depth >= a given threshold?
- Sum the areas of all lakes having depth > threshold
- Given a volume of surface water, we know how much area it will cover



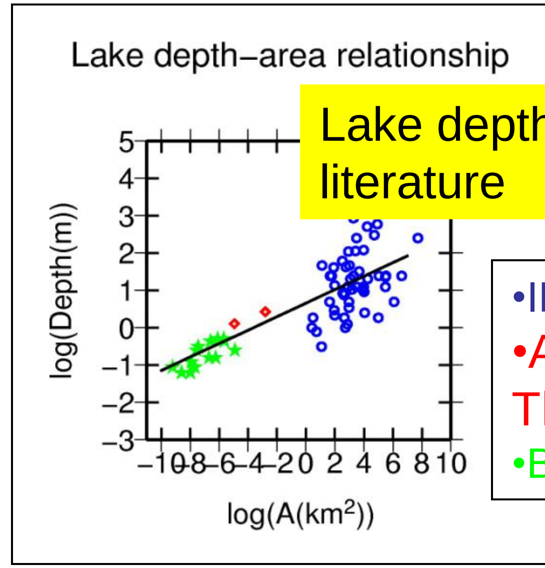
Lake Bathymetry/Topography



Lake size histograms from GLWD (Lehner and Doll, 2004) and LANDSAT

- LANDSAT
- GLWD
- Bartalev et al (2003)

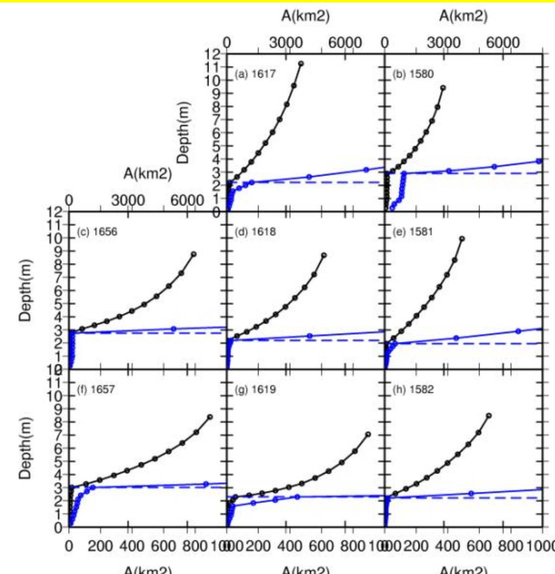
LANDSAT courtesy of E. Podest and N. Pinto of NASA/JPL



Lake depths from literature

- ILEC
- Arctic Thaw Lakes
- Bog Pools

Lake storage-area relationship

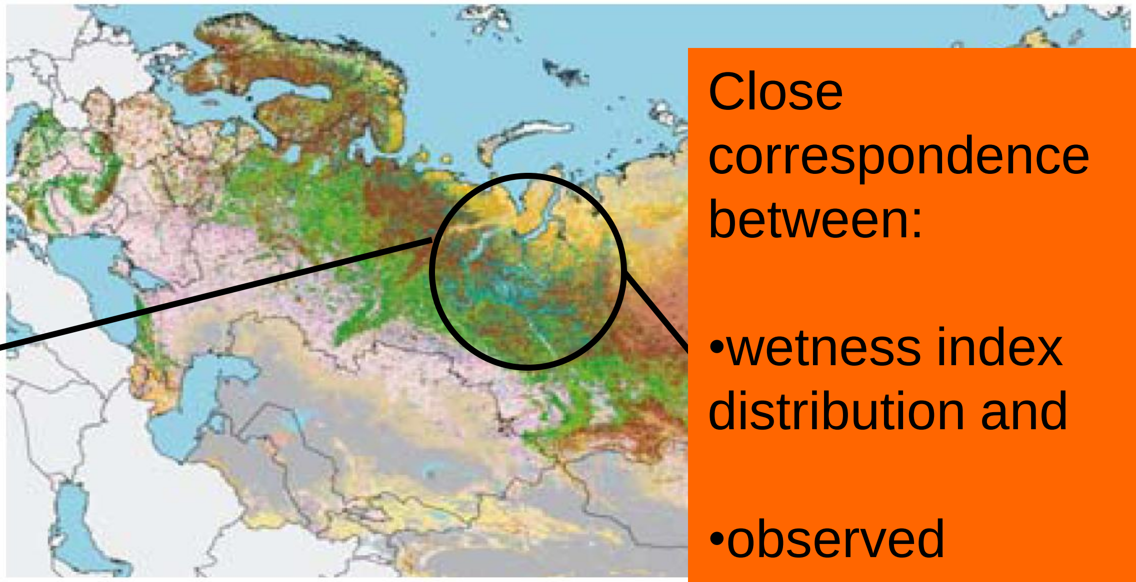


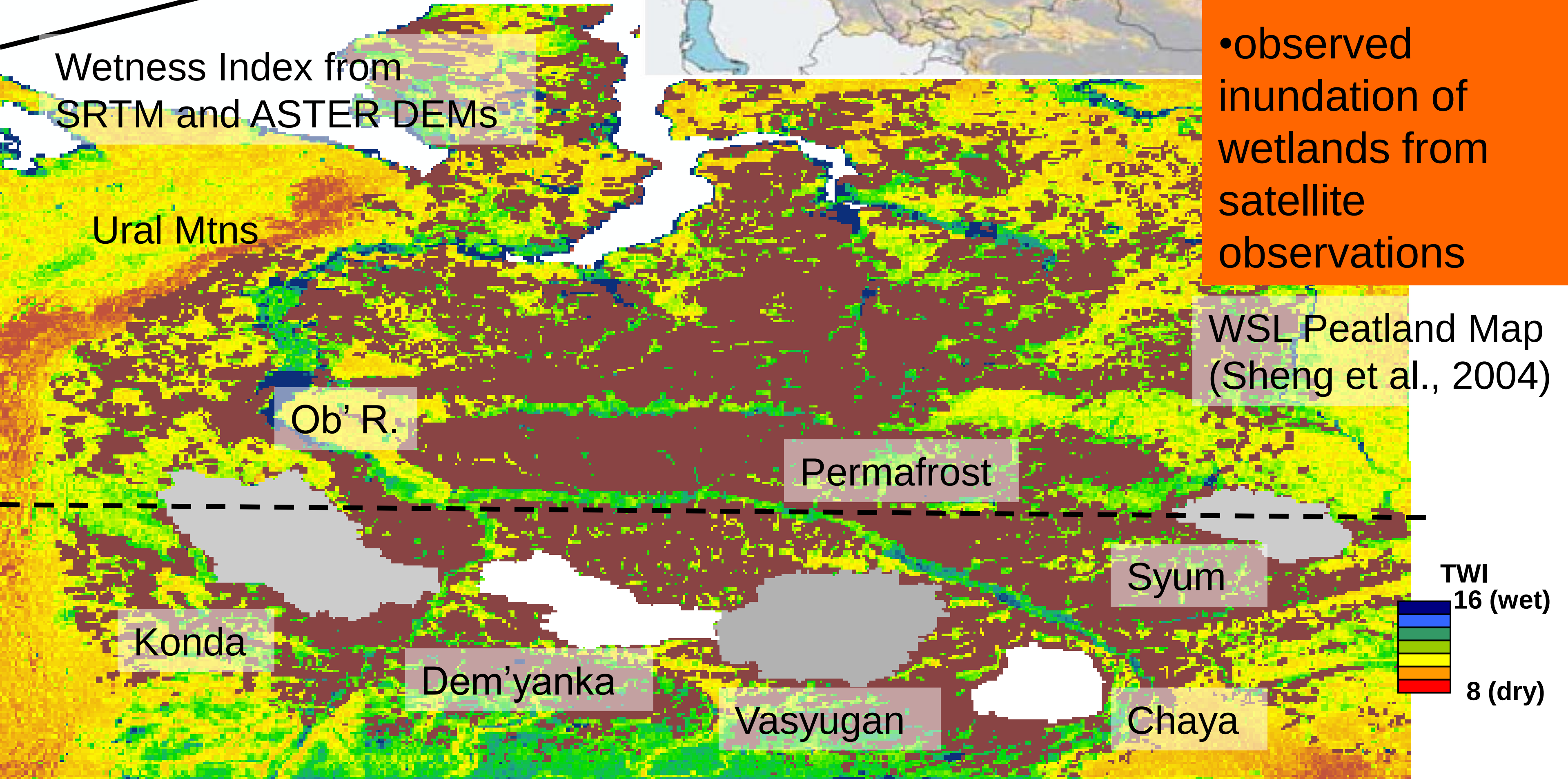
SRTM and ASTER DEMs for surrounding topography

First Phase: Historical Reconstruction

- Select test basins in West Siberian Lowlands
- Simultaneous calibration to both streamflow and inundated area
  - Streamflow gauge records from R-Arcticnet (UNH)
  - Inundated area derived from AMSR/QSCAT (NASA/JPL)
- Hydrologic calibration parameters
  - Soil layer thickness
  - Infiltration distribution
  - Maximum baseflow rate
  - Effective lake outlet width
- Parameters – CH4
  - Calibrated against observations at Bakchar Bog (Friborg et al, 2003)
  - For lakes, use range of observed CH4 rates from literature:
    - 10-50 mg CH_4/m^2d (Repo et al, 2007)
    - 100-500 mg CH_4/m^2d (Walter Anthony et al, 2010)
- Ultimate goal: estimate of responses of lakes and wetlands across West Siberia to end-of-century climate
- For now: what are the sizes and seasonal behaviors of the various CH4 sources?

Study Domain: W. Siberia

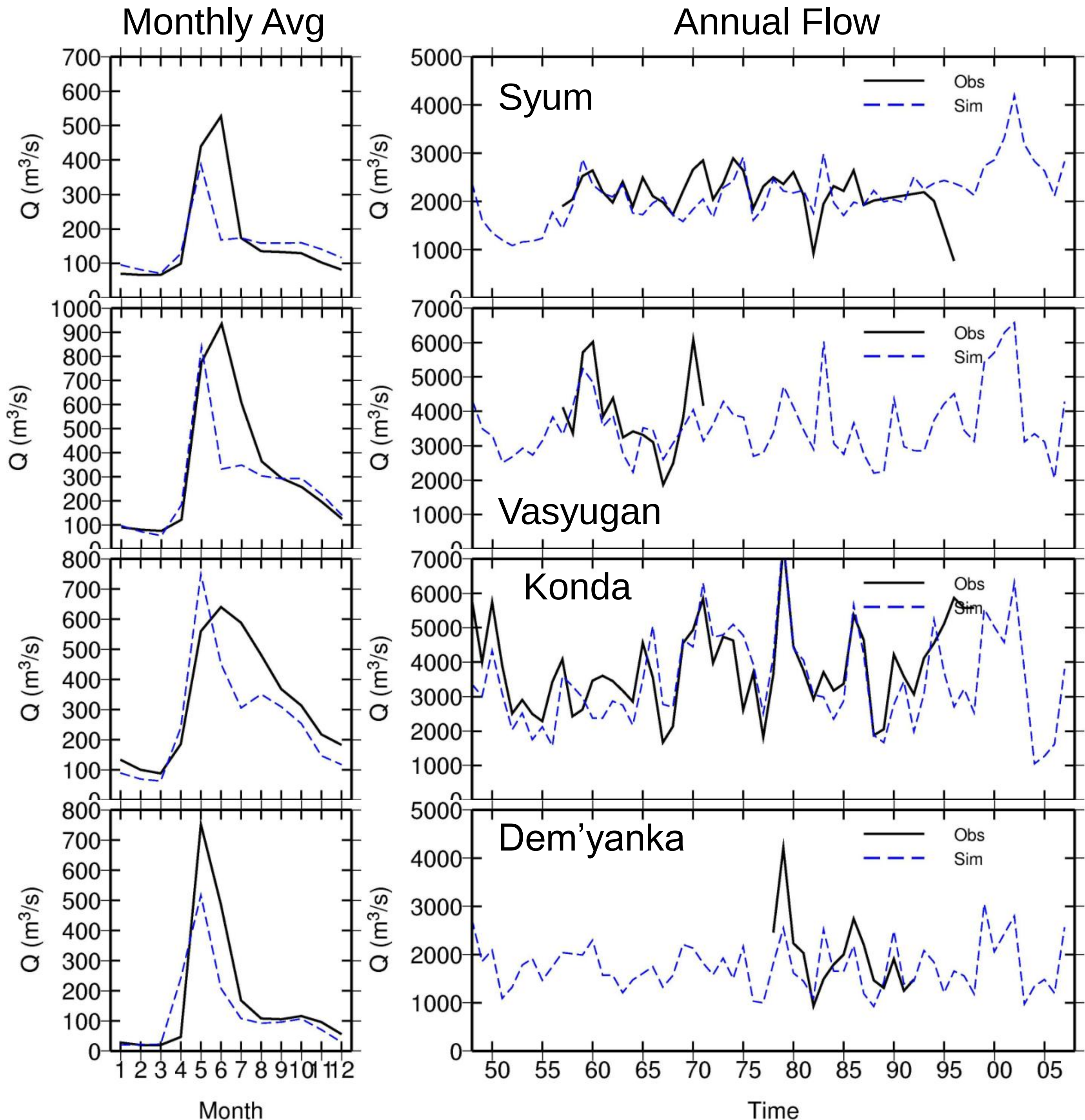




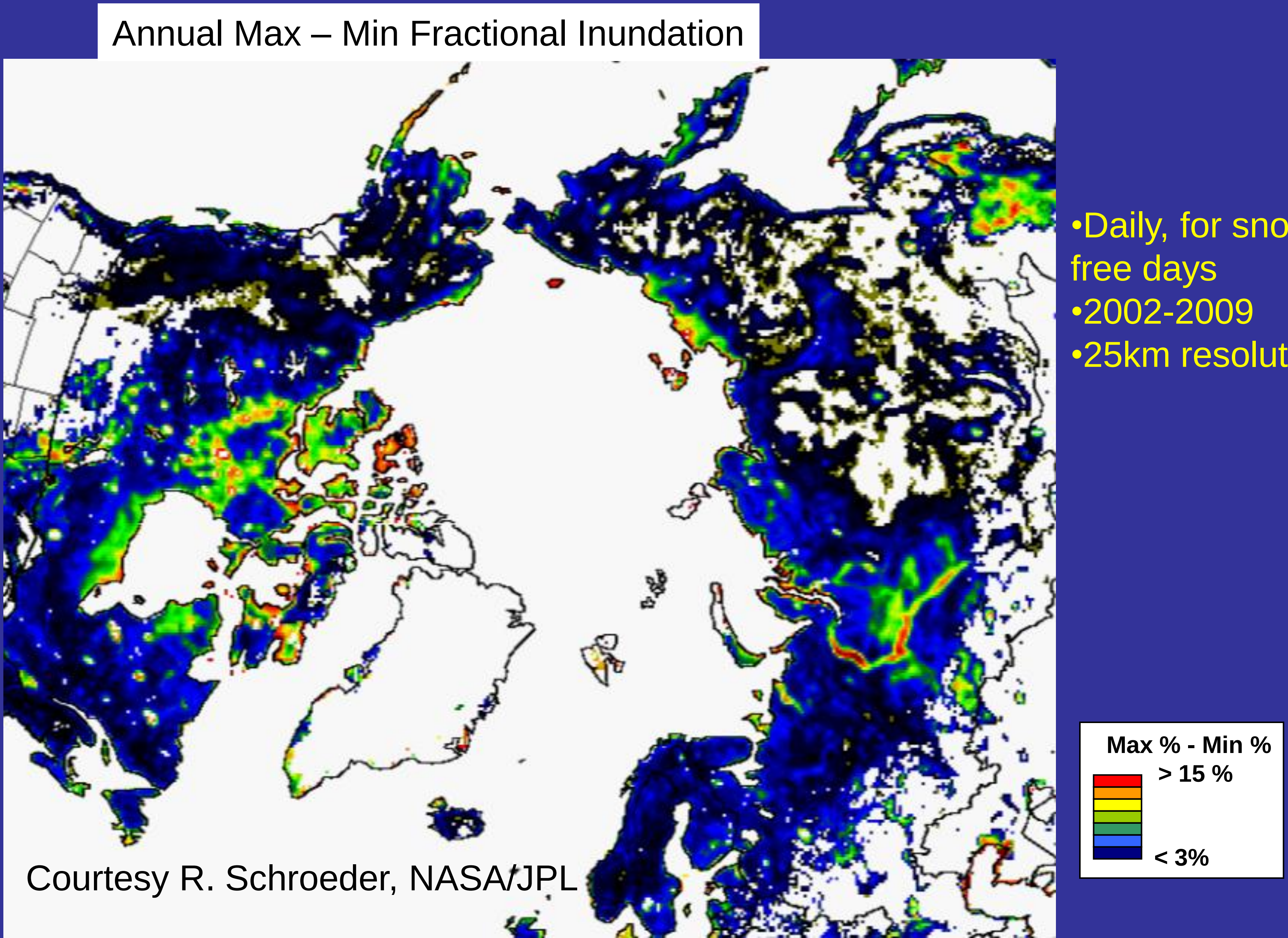
Comparison With Observed Discharge

Modeled snowmelt pulse is narrower than observed

Interannual variability is good (where record is long enough)



AMSR/QSCAT-Derived Inundation



- Daily, for snow-free days
- 2002-2009
- 25km resolution

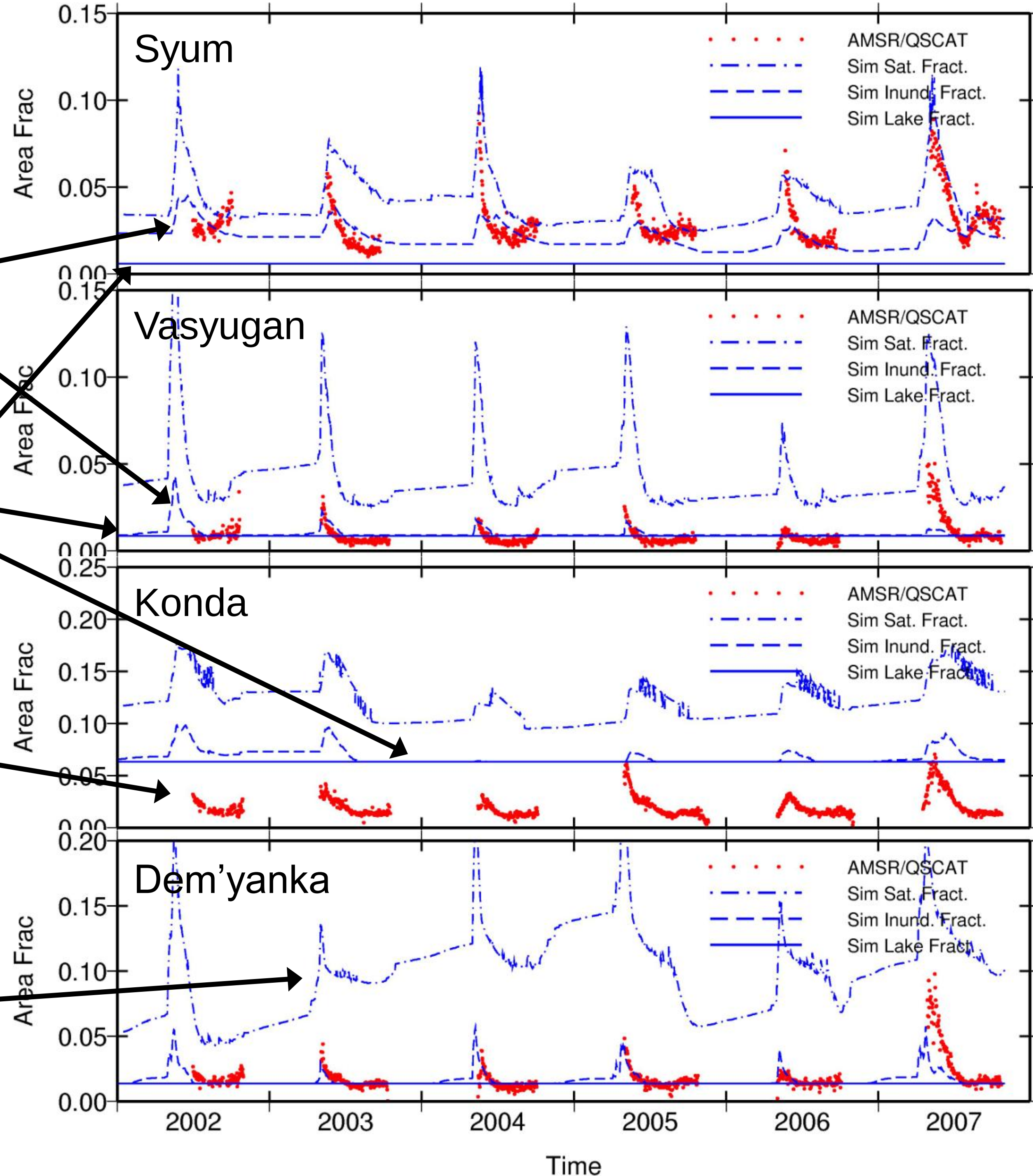
Comparison With Observed Inundation

Seasonal inundation can more than double lake area

Canonical lake area

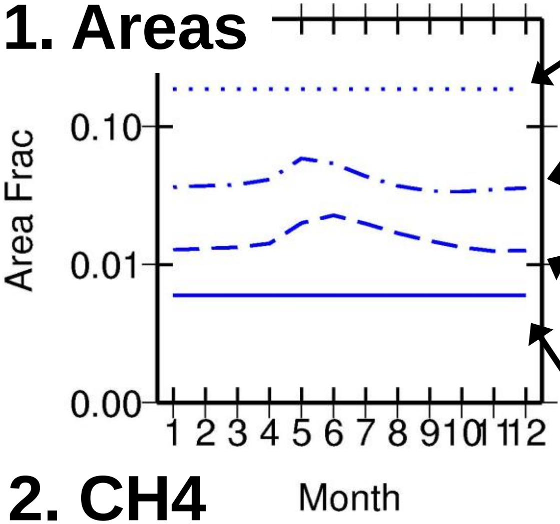
Poor match because AMSR/QSCAT is lower than canonical lake area

Large saturated area



Monthly Averages, 1948-2007, Syum Basin

1. Areas



Total Wetland = 18%

Lake + Inund + Saturated = 3 - 6%

Lake + Inund = 1 - 3%

Lake = 0.6%

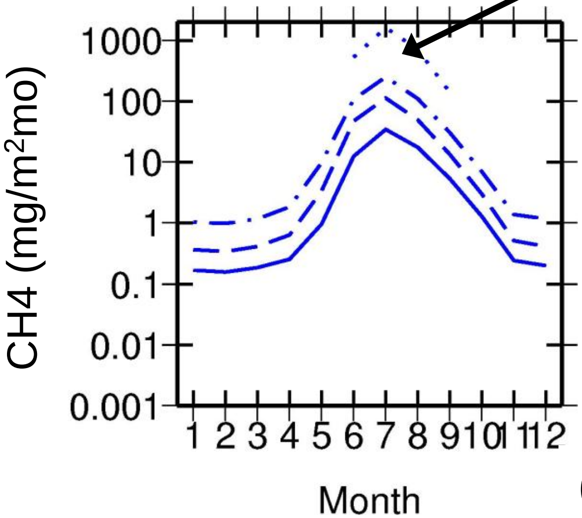
Unsaturated wetland is the largest contributor to CH4 in summer because of its large area

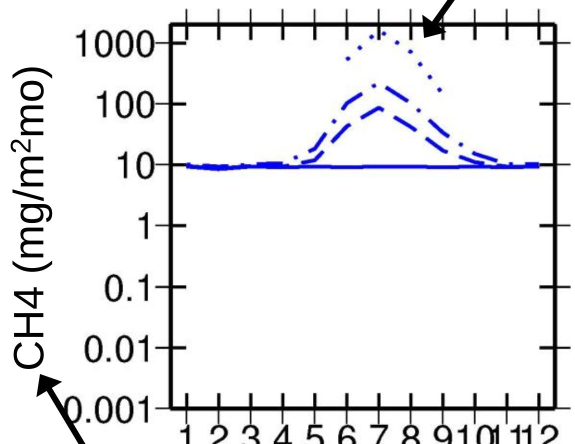
2. CH4

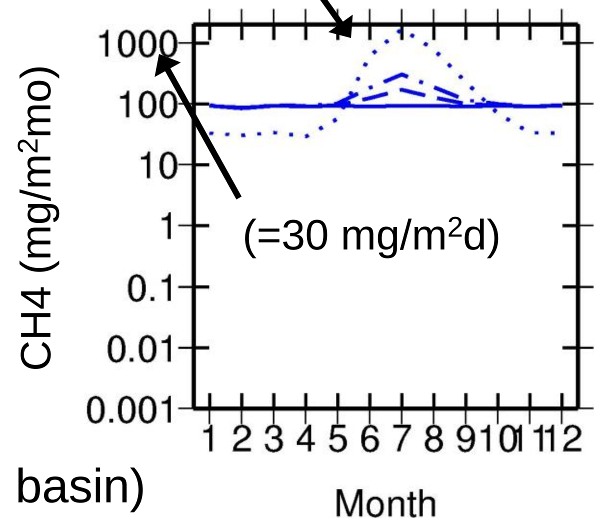
1. Lake emits at same rate as saturated wetland

2. Lake emits at rate of 50 mg CH4/m2d

3. Lake emits at rate of 500 mg CH4/m2d







(=30 mg/m^{2}d)

(Fluxes per unit area of entire basin)

Annual Averages - Syum

Source	Scenario				
	Lake=Wetland	Lake=10	Lake=50	Lake=100	Lake=500
Total Over Basin (mgCH4/m2y)	2580	2448	2532	2660	3528
Lake (%)	6	1	4	9	32
Inund (%)	5	5	5	5	3
Sat (%)	70	74	71	68	51
Unsat (%)	19	20	20	18	14

- Lakes have highest emission rate per unit area
  - If we assume high lake CH4 emission rates (100-500 mg/m2d) constant throughout year, lakes reach 9-32% of basin emissions
- But total lake contribution small
- Saturated wetland is largest component
- Unsaturated wetland is second largest, due to its large area
- Relative contributions of saturated and unsaturated zones vary in time with soil moisture
- This depends on wetland CH4 parameter set, and assumption that it applies everywhere in the wetland

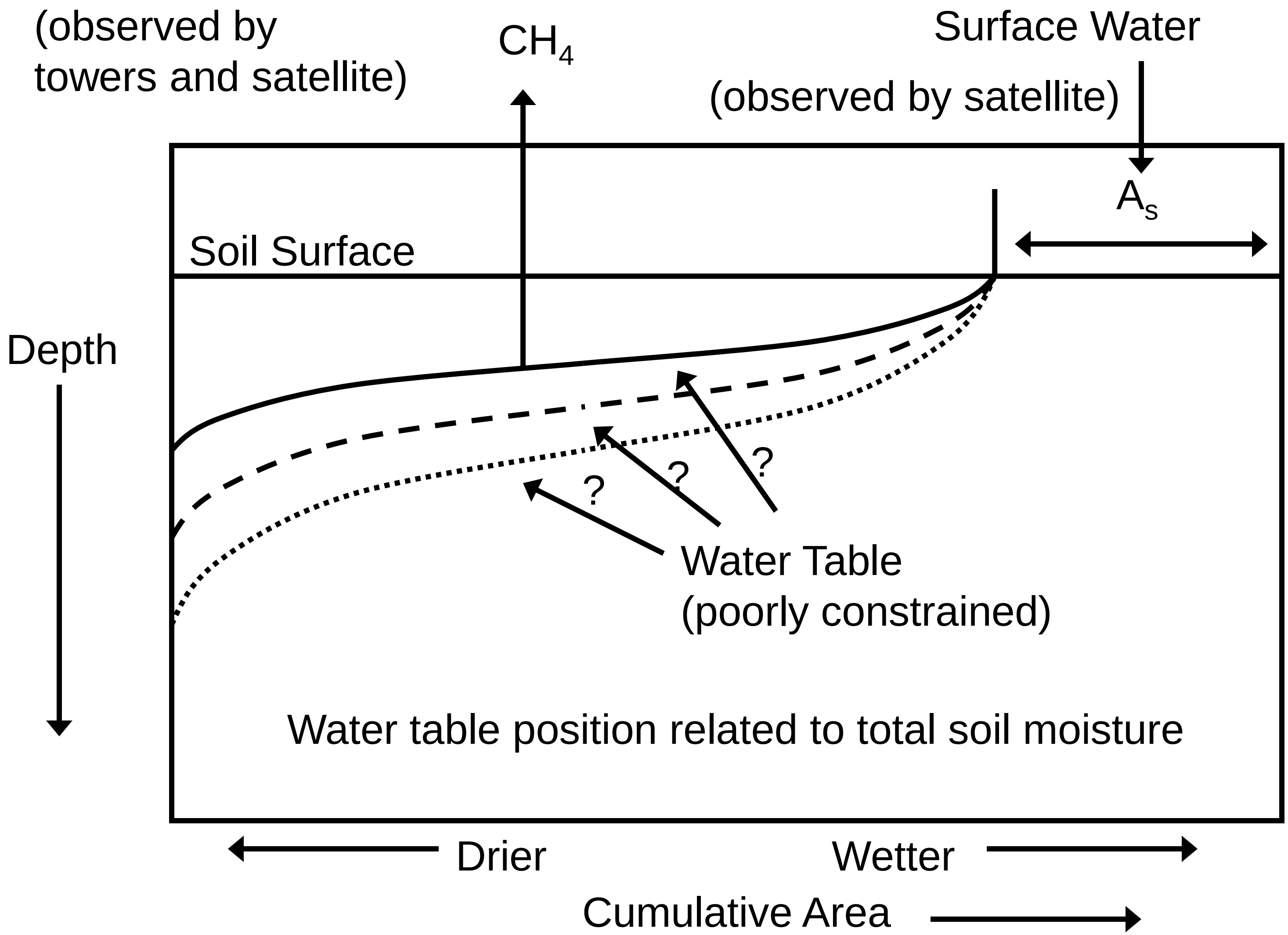
Current Status

- Refining the CH_4 model parameters with extensive in situ (flask) observations from M. Glagolev (Moscow State U) and S. Maksyutov (NIES)
- Simulation of methane fluxes from W. Siberia, 1948-2007, currently under way

Data Assimilation

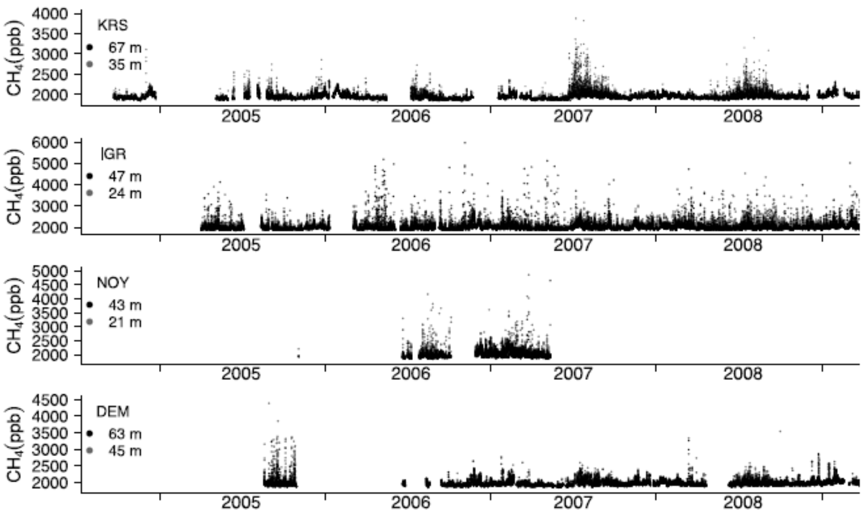
- Link VIC model to NIES atmospheric transport model (NIES-TM)
- State variables
  - Soil moisture
  - Surface inundation (linked to soil moisture)
  - Atmospheric CH4 concentration
- Observations
  - AMSR/QSCAT inundation
  - Tower [CH4] (initially)
  - Possible addition of GOSAT ***Total Column*** [CH4]

State Variables and Observations



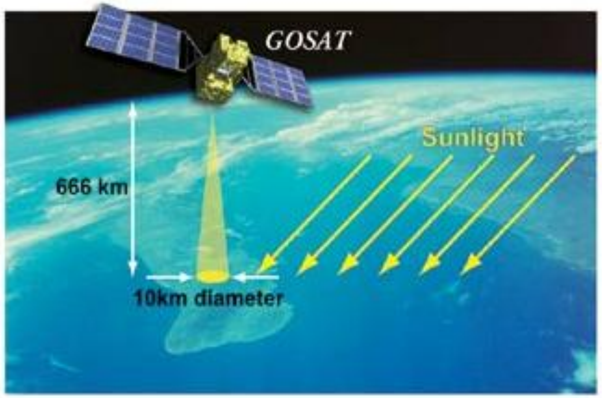
NIES Tower Network

- 60-100m towers
- Hourly measurements of CH4, CO2
- 2 sampling heights at each tower: 10-40m, 40-80m

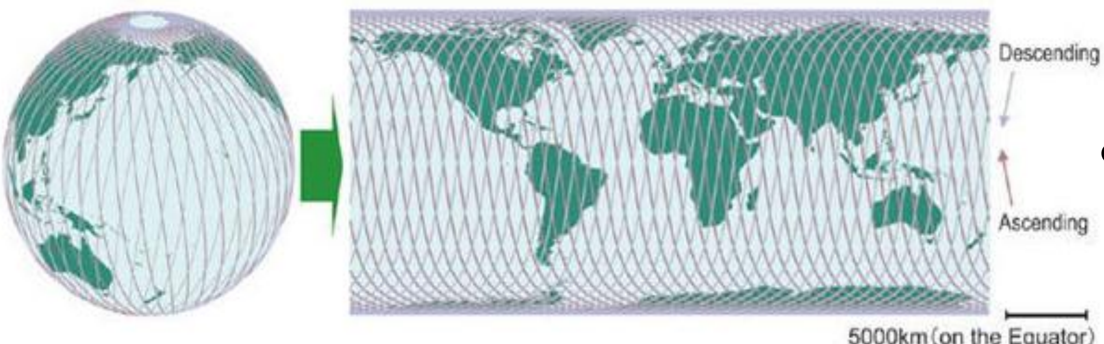


(Courtesy S. Maksyutov, NIES)

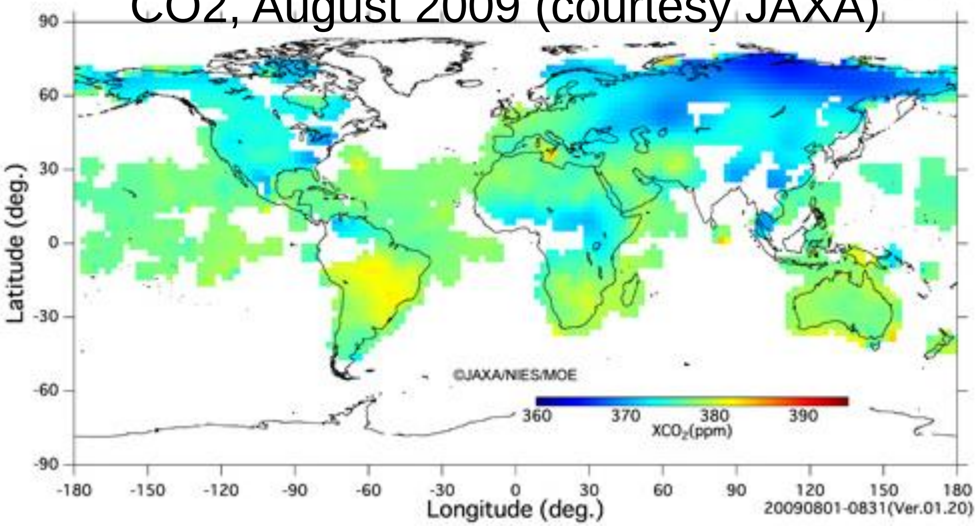
JAXA GOSAT



- Launched 2009
- Total column CH4 and CO2
- 10 km spatial resolution
- 1000 km swath width
- 3 days/44 orbit repeat cycle



CO2, August 2009 (courtesy JAXA)



NIES Atmospheric Transport Model (NIES-TM)

- Tracer transport/diffusion model
- Driven by NCEP/NCAR fields
- 2.5 x 2.5 degree resolution (resolution of drivers)
- 14 Vertical layers (1000 mbar, 850, … up to 10 mbar)
- 10 min temporal resolution
- West Siberian simulation embedded within global simulation
- CH_4 sources for the rest of the world taken from Matthews and Fung (1987)
- Tracks several species and reactions relevant to CH_4 transport and oxidation
- Used successfully in inverse modeling of global CO_2 sources in TRANSCOM experiment (Law et al., 2008)

Data Assimilation: Updates

- Daily (AMSR/QSCAT only) or Weekly
- Ensembles formed from perturbed initial soil moisture states
  - (or multiple NCEP/NCAR realizations, a la ESP)
- Ensemble Kalman Filter
  - Update state variables in place, i.e. at same time/location as observation
  - Can't use atm CH_4 to update soil moisture due to time lag between source and observation
- Ensemble Kalman Smoother (van Leeuwen and Evensen, 1996)
  - Takes account of all observations and model states at all times between updates
  - Can update state variables backwards in time, along particle trajectories between sources and observations

Conclusions

- Lakes have large per-area emissions but in many cases small total area
- The saturated and unsaturated areas of the wetland are large contributors of CH_4 as a result of their large extent
- Total fluxes from these areas can be constrained to some extent via calibration vs. streamflow and satellite observed inundation
- Further constraint with ground observations is needed
- Assimilating tower- and satellite-based observations should provide valuable constraints on simulated methane emissions

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.

This work was funded by NASA ROSES grant NNX08AH97G.

Recent Progress in Modeling

- Emissions from unsaturated zone can be substantial (Bohn and Lettenmaier, 2010)

•Common simplifications to wetland water table neglect unsaturated zone

•Can result in biases of +/- 30% in end-of-century CH4 emissions

•Here we consider a distributed water table