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

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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

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

Lakes:
- Large CO$_2$/CH$_4$ source
- CH$_4$ estimates revising upwards due to ebullition

Lake/wetland carbon emissions are sensitive to climate

High latitudes experiencing pronounced climate change
Climate Factors

- **Water table depth not uniform across landscape - heterogeneous**
- **Relationships non-linear**

**Living Biomass**

- **Acrotelm**
  - Temperature (via evaporation)

- **Water Table**

- **Catotelm**

**Note:** currently not considering export of DOC from soils
Lakes and Wetlands

• Lake/wetland CH4/CO2 emissions depend on T, C, nutrients, oxidation state, etc
• Wetland CH4/CO2 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 CH4/CO2 fluxes to climate
• We can improve model estimates by taking dynamic behavior into account
Monitoring the Sources

• In situ measurements (water table, CH4 flux) are localized and sparse

• Large-scale observations (towers, satellites) are less direct
  – Extent of saturated/inundated wetlands (e.g. SAR, passive microwave)
  – Atmospheric CH4 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

DEM (e.g. GTOPO30 or SRTM)

Topographic Wetness Index $\kappa(x,y)$

Water Table Depth $Z_{wt}(t,x,y)$

Soil Storage Capacity CDF(mm) = $f(\kappa_i)$

Cumulative Area Fraction

Saturated At Surface

Water Table

Summarize for a Single 100 km Grid Cell

VIC Spatial Avg Soil Moisture ($t$)
## Recent Progress in Modeling (Bohn et al., GRL 2010)

### 3 Main approaches to modeling large-scale CH4 emissions:

<table>
<thead>
<tr>
<th>Depth</th>
<th>Water Table Position</th>
<th>Water Table</th>
<th>CH4 Emissions</th>
<th>Cumulative Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Surface</td>
<td>Saturated / Inundated</td>
<td>Wetter</td>
<td>“Dry”</td>
<td>Wetter</td>
</tr>
<tr>
<td>Water Table</td>
<td>“Wet”</td>
<td>“Dry”</td>
<td>Wetter</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed Inundated Fraction (PALSAR Classification)</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Simulated Inundated Fraction (at optimal Zwt)</strong></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Approx. 30 km</strong></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>
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”
Composite Bathymetry

• How much area is covered by water of depth $\geq$ 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

\[
\text{Cumulative area} = \text{Depth} \quad \text{Cumulative area}
\]
Lake Bathymetry/Topography

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

Lake depths from literature
- ILEC
- Arctic Thaw Lakes
- Bog Pools

Lake storage-area relationship

SRTM and ASTER DEMs for surrounding topography

LANDSAT courtesy of E. Podest and N. Pinto of NASA/JPL
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$^2$d (Repo et al, 2007)
    - 100-500 mg CH$_4$/m$^2$d (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

Wetness Index from SRTM and ASTER DEMs

Close correspondence between:
- wetness index distribution and
- observed inundation of wetlands from satellite observations

WSL Peatland Map (Sheng et al., 2004)
Comparison With Observed Discharge

Modeled snowmelt pulse is narrower than observed

Interannual variability is good (where record is long enough)
AMSR/QSCAT-Derived Inundation

Annual Max – Min Fractional Inundation

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

Max % - Min %

- > 15%
- < 3%

Courtesy R. Schroeder, NASA/JPL
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

1. **Areas**

   - Total Wetland = 18%
   - Lake + Inund + Saturated = 3 - 6%
   - Lake + Inund = 1 - 3%
   - Lake = 0.6%

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

   ![Graphs showing monthly emissions of CH4](image_url)

   - Unsaturated wetland is the largest contributor to CH4 in summer because of its large area
   - Fluxes per unit area of entire basin
Annual Averages - Syum

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

- 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 CH4 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

- Cumulative Area
- Depth
- Soil Surface
- Water Table (poorly constrained)
- Surface Water (observed by satellite)
- Soil Surface
- Depth

Water table position related to total soil moisture

CH$_4$

A$_s$

Wetter

Drier

Cumulative Area
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
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
- CH4 sources for the rest of the world taken from Matthews and Fung (1987)
- Tracks several species and reactions relevant to CH4 transport and oxidation
- Used successfully in inverse modeling of global CO2 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 CH4 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 CH4 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

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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