Integration of Inundation and Soil Moisture Estimates in an Ecosystem-Atmosphere Gas Exchange Model: Sensitivity and Error Analysis

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Objectives

- Characterize ecosystem model greenhouse gas (GHG, e.g., CH_4) flux sensitivity to soil moisture and seasonal inundation in diverse ecological zones
- Characterize future SMAP (Soil Moisture Active Passive Mission) inundation extent and duration measurement abilities
- Develop and test a SMAP-ecosystem model fusion system

Overview

- Inundation retrieval from SMAP SAR:

  We assess SMAP inundation mapping capabilities using a semi-empirical open water retrieval algorithm and scene simulations based on data from the Phased Array L-Band Synthetic Aperture Radar (PALSAR).
- Ecosystem model soil moisture sensitivity:

  We evaluate soil moisture and CH_4 emission results from Dynamic Land Ecosystem Model (DLEM) runs for North America with normal, low, and high precipitation forcing. We are using these results to understand how the model would respond to SMAP-derived soil moisture and inundation inputs and their errors.

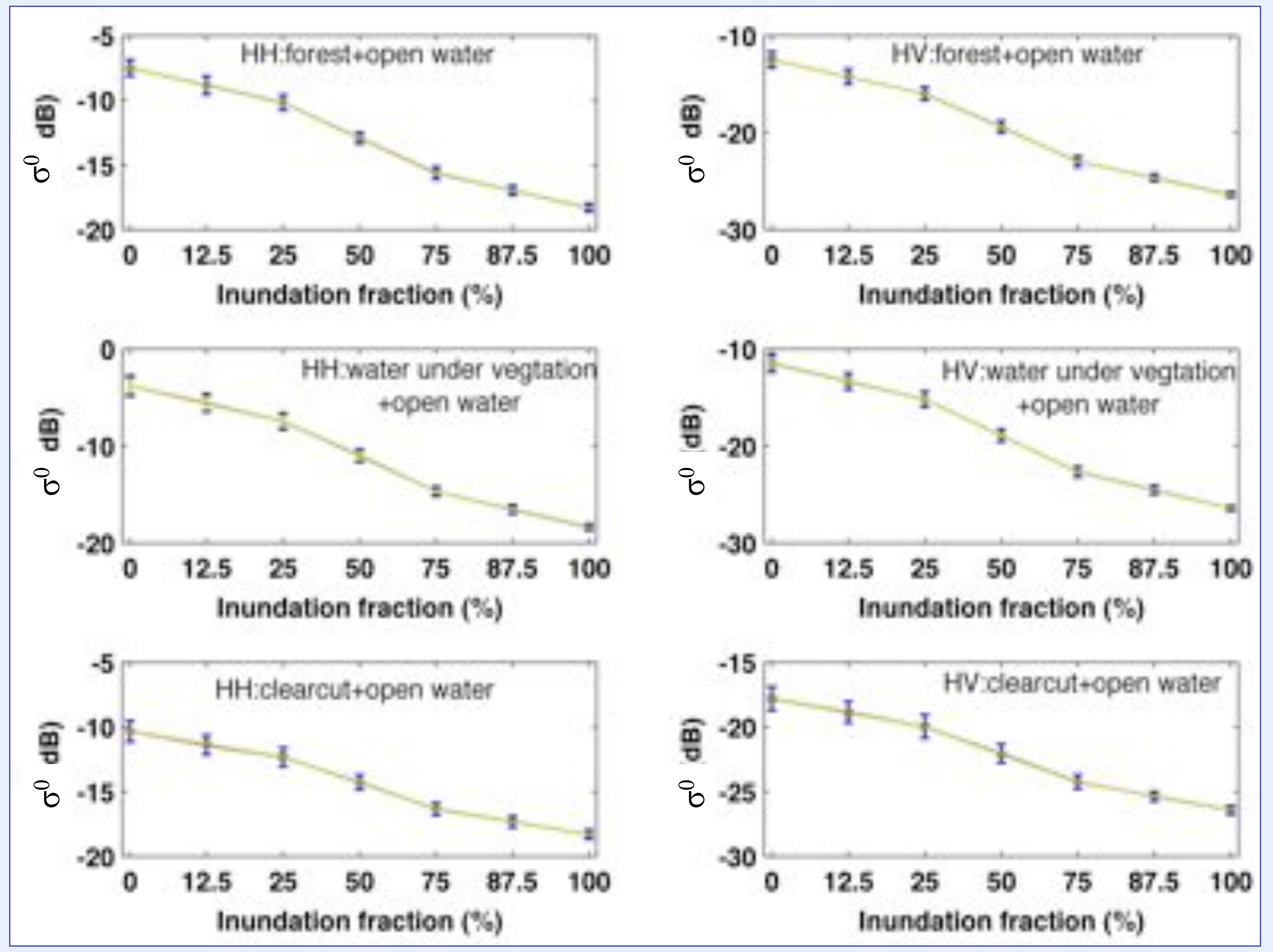
SMAP Overview

- Launch expected Nov. 2014 – May 2015
- Mission concept
  - 40 km L-band (~1.4 GHz) microwave radiometer
  - 1-3 km L-band synthetic aperture radar (SAR)
  - 2-3 day revisit period
  - L-band measurements enable vegetation and clouds penetration and deeper soil moisture sensitivity
- Primary mission products (9-40 km resolution)
  - Soil moisture
  - Freeze/thaw detection
  - Net ecosystem exchange (NEE)
- Potential inundation mapping features
  - Water detection or water fraction (f_w) retrieval
  - 1-9 km resolution
  - Under-canopy water detection

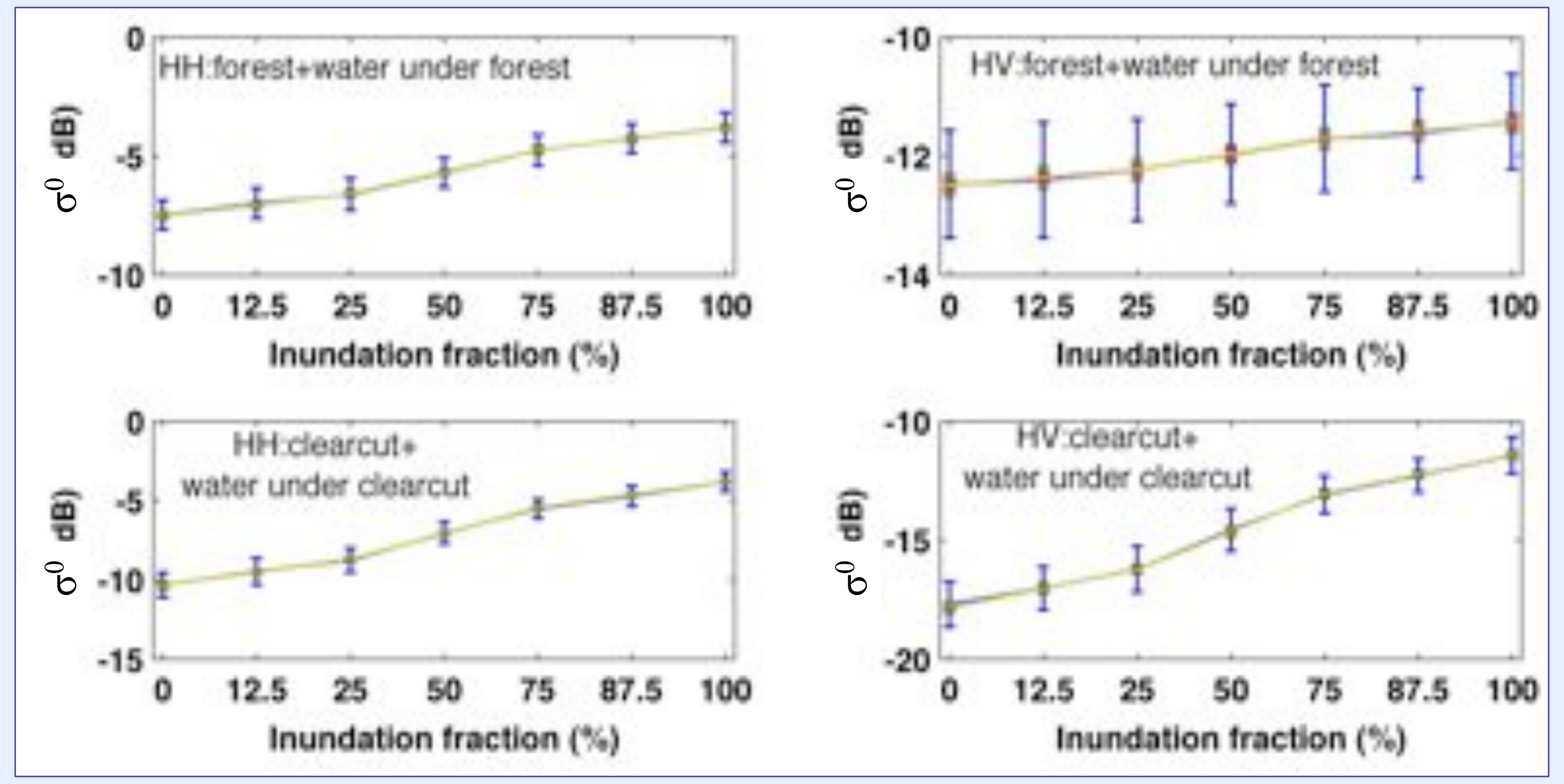
Radar Backscatter Data- and Model-Based Approach for Mapping Changes in Inundation Extent

- False color composites of PALSAR backscatter for three test regions
  - 12.5 m resolution
  - Red: HH, Green: HH-HV, Blue: HV
- Regions differ in the characteristic scales of inundated (i.e., open water, under-canopy water) and uninundated land cover types
- Proportions of land cover types in SMAP pixels (3-10 km resolution) will affect backscatter and retrieval skill

Backscatter vs. open water inundation



Backscatter vs. under-canopy inundation



- Standardized backscatter signatures simulated from test region SAR data (PALSAR, 12.5 m resolution) and semi-empirical models
  - Variability includes randomization of secondary model inputs (e.g., soil and vegetation properties) for 0.1 to 10 km resolution pixels
- Under-canopy water signal is weaker than open water signal
- Under-canopy water increases backscatter, countering open water fraction signal in mixed pixels

Open Water Inundation Retrieval Algorithm

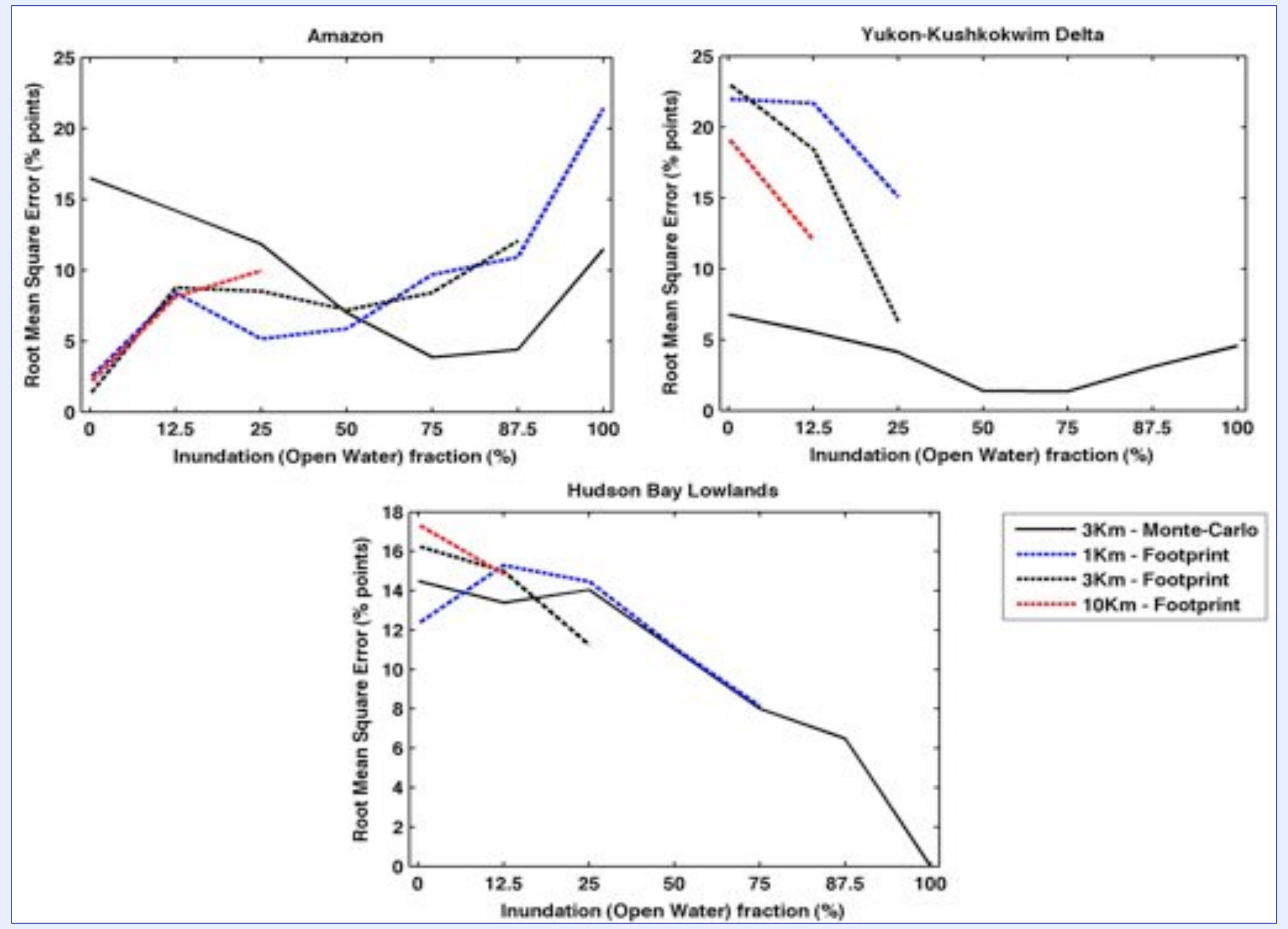
- Inputs: HH and HV backscatter and land cover
- Search look-up-tables (e.g., at left), test for consistency, and average HH and HV results
- Output: Open water inundation fraction (% of area)

Algorithm Performance Tests

- Source data: 12.5-m PALSAR scenes (divided 50/50 for algorithm training/testing)

1. Monte-Carlo type random sampling to simulate 3-km pixels: 1 dB speckle noise added
   - Maximum retrieval error about 15%
   - Retrieval error decreases with increasing water cover up to 75%
   - Retrieval error increases at high water cover (>75% in Amazon and YK Delta) due to larger variability in water backscatter (e.g., from wind and rapids)
2. Physical footprint sampling: 1/3/10 km pixels, 10% shift at 1km, 1dB speckle noise
   - Maximum retrieval error about 20-25%
   - Availability of pixels with higher water cover fractions decreases with footprint size
   - Retrieval error decreases with increasing water cover in YK Delta and Hudson Bay Lowlands and increases with increasing water cover in Amazon
     - ◆ Degree and type of pixel and scene heterogeneity strongly affects retrieval error

Open water inundation retrieval error



- Open water fraction (% of area) retrieval errors expressed as root mean square error (rmse, % of area) for Monte-Carlo (3 km) and physical footprint (1-10 km) sampling. For physical footprint simulations, only open water fraction bins with at least 5 points are included.

Ecosystem-Atmosphere Gas Exchange Model: Methane (CH4) Emission Sensitivity to Soil Moisture and Inundation

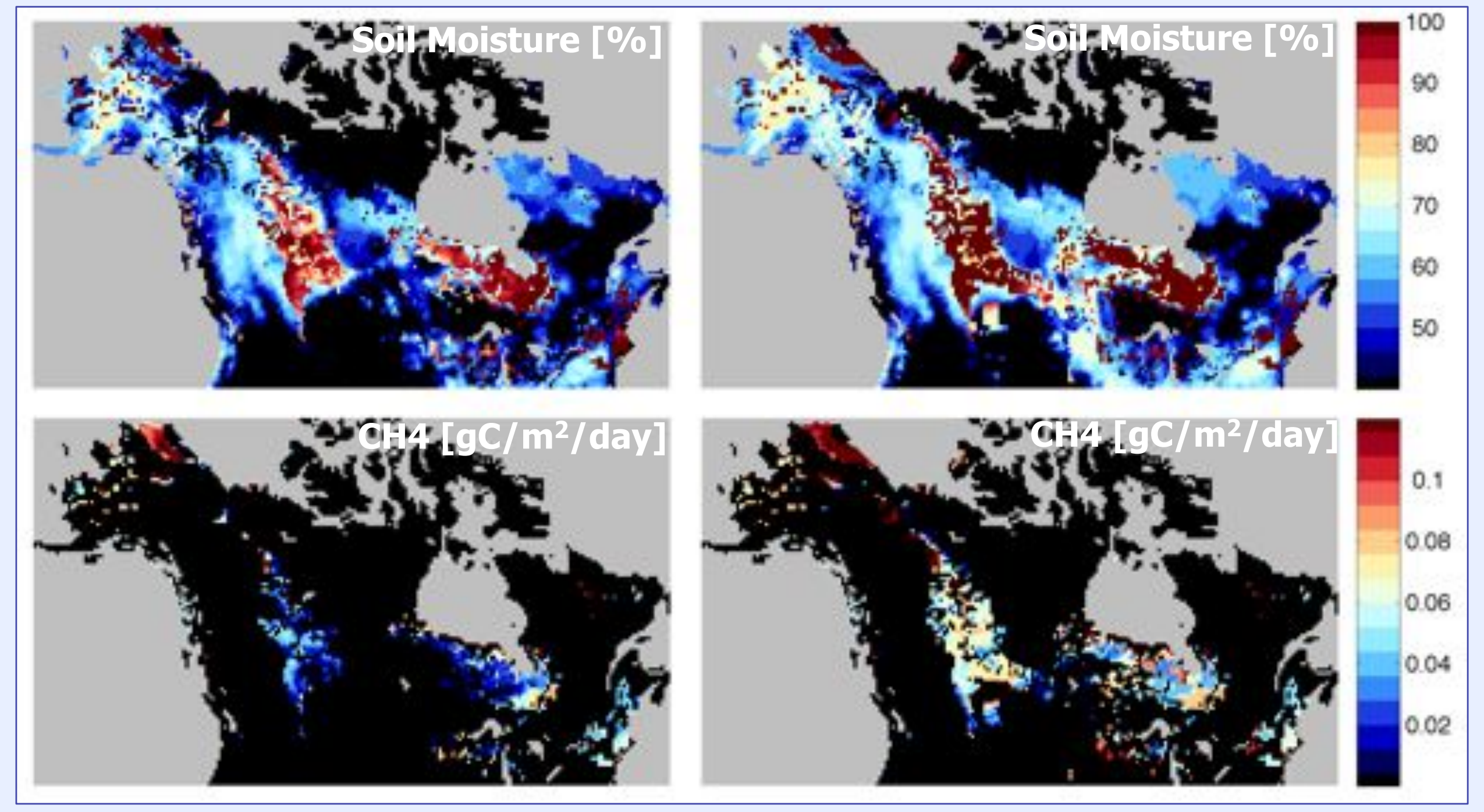
DLEM (Dynamic Land Ecosystem Model) Overview

- **Quantifies regional GHG fluxes (including CH4, CO2, N2O) daily given atmospheric forcing (including precipitation)**
- **Soil saturation is a prognostic variable**
- **Open water is not modeled and inundation is not explicitly modeled**
- **32x32 km resolution with one land cover type per cell**
- **Only wetlands land cover types allow soil saturation**

Model Runs with Perturbed Precipitation

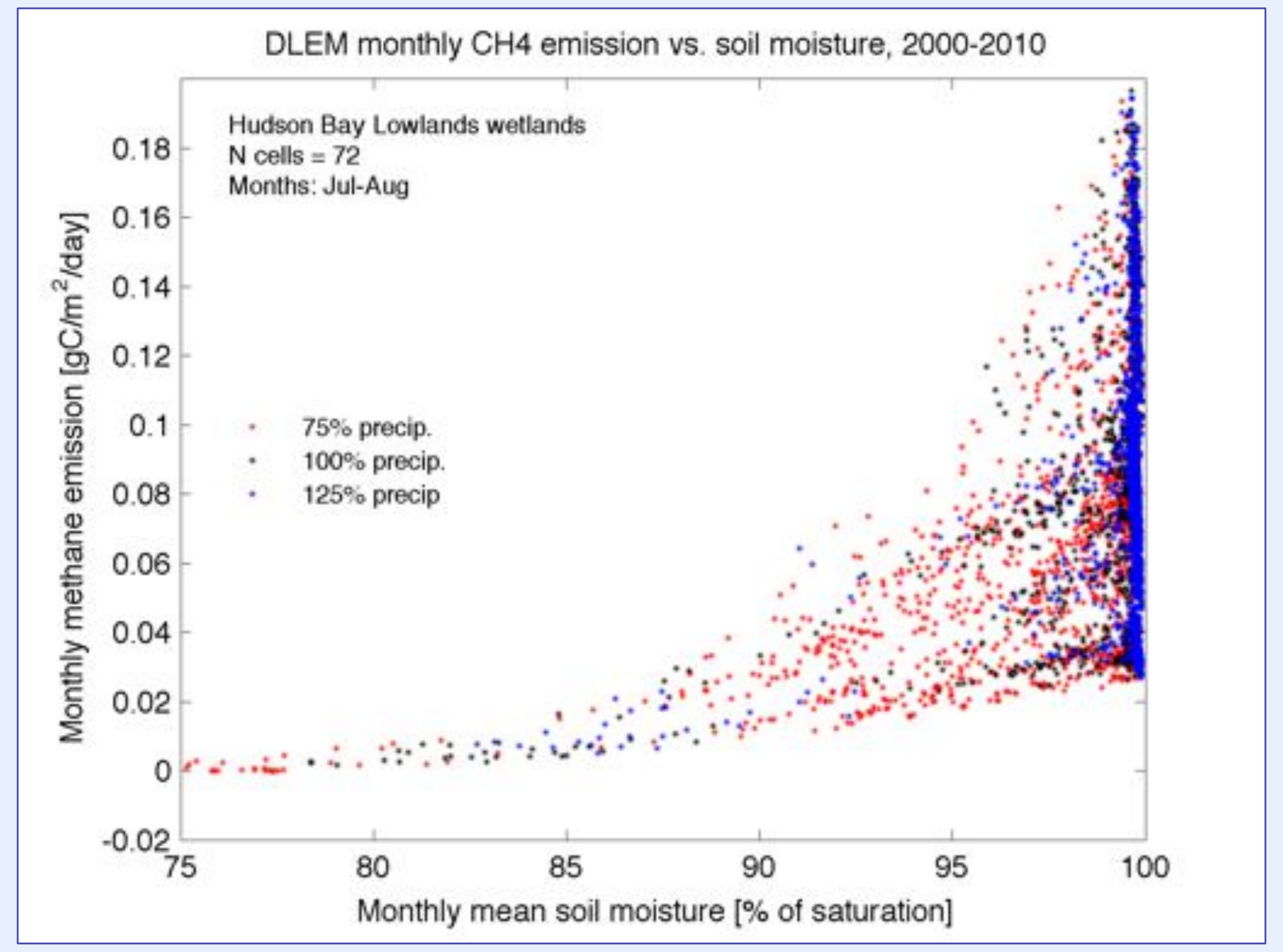
- **Three model runs for North America 2000-2010 are used to approximately isolate soil moisture and saturation effects:**
  - ➢ **Normal precipitation**
  - ➢ **75% of normal precipitation**
  - ➢ **125% of normal precipitation**
- **Simulates model response to external inundation and soil moisture forcing**
- **Diagnostic variables (monthly means):**
  - ➢ **Soil moisture (% of saturation)**
  - ➢ **CH4 emission ($gC/m^2/day$)**

Model CH4 response to perturbed precipitation forcing

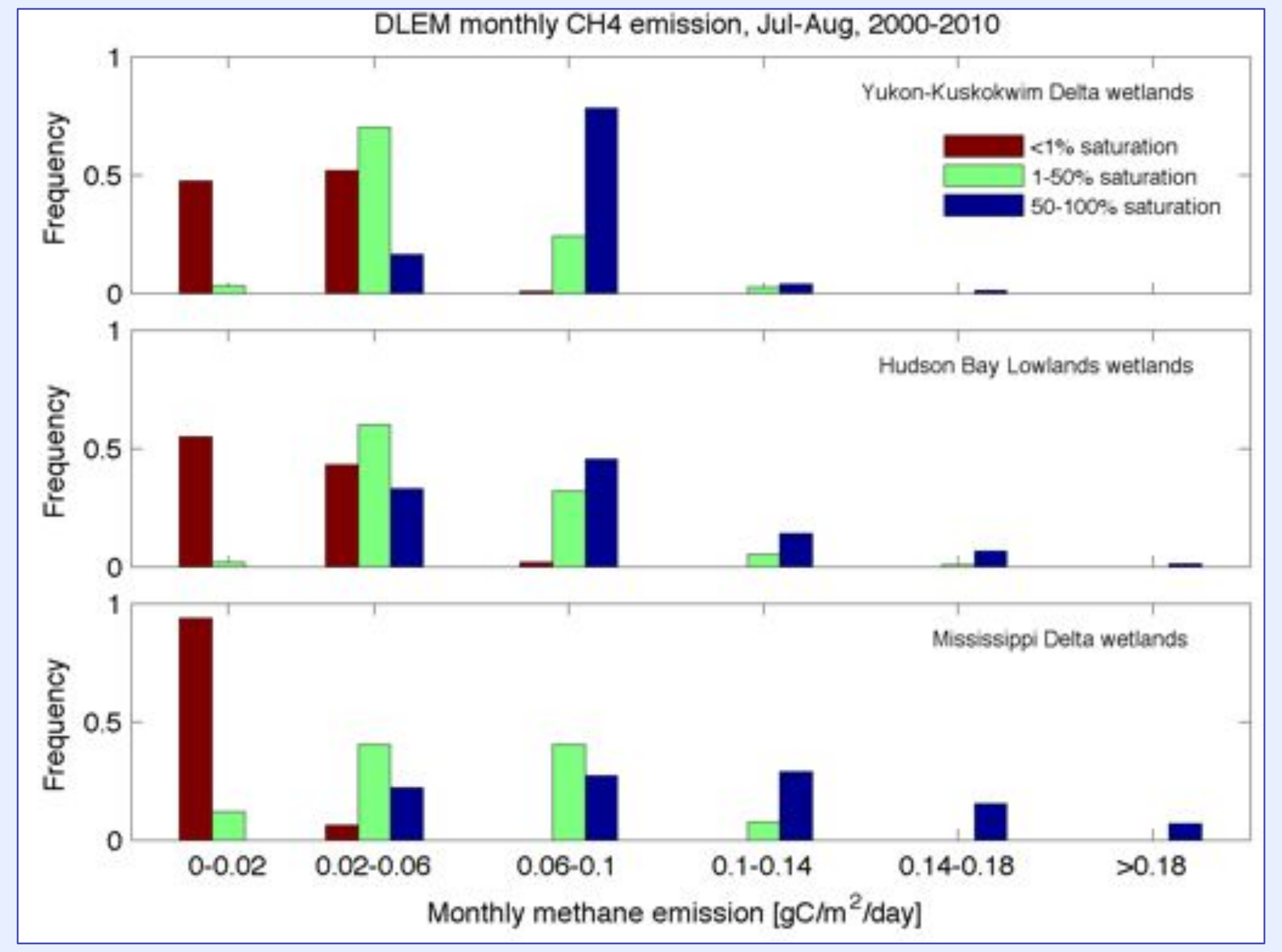


- **DLEM model soil moisture (% of saturation) and CH4 emission for July 2003**
- **Soil moisture with 125% precipitation:**
  - ➢ **Increases extent of saturated areas (i.e., saturated all or most of month)**
- **CH4 emission with 125% precipitation:**
  - ➢ **Increases extent of CH4-emitting areas**
  - ➢ **Increases CH4 emission rate in areas only partly saturated under 75% precipitation conditions**
- **Total CH4 emission increases with increases in extent and duration of soil saturation**

Model CH4 sensitivity to soil moisture and saturation rate



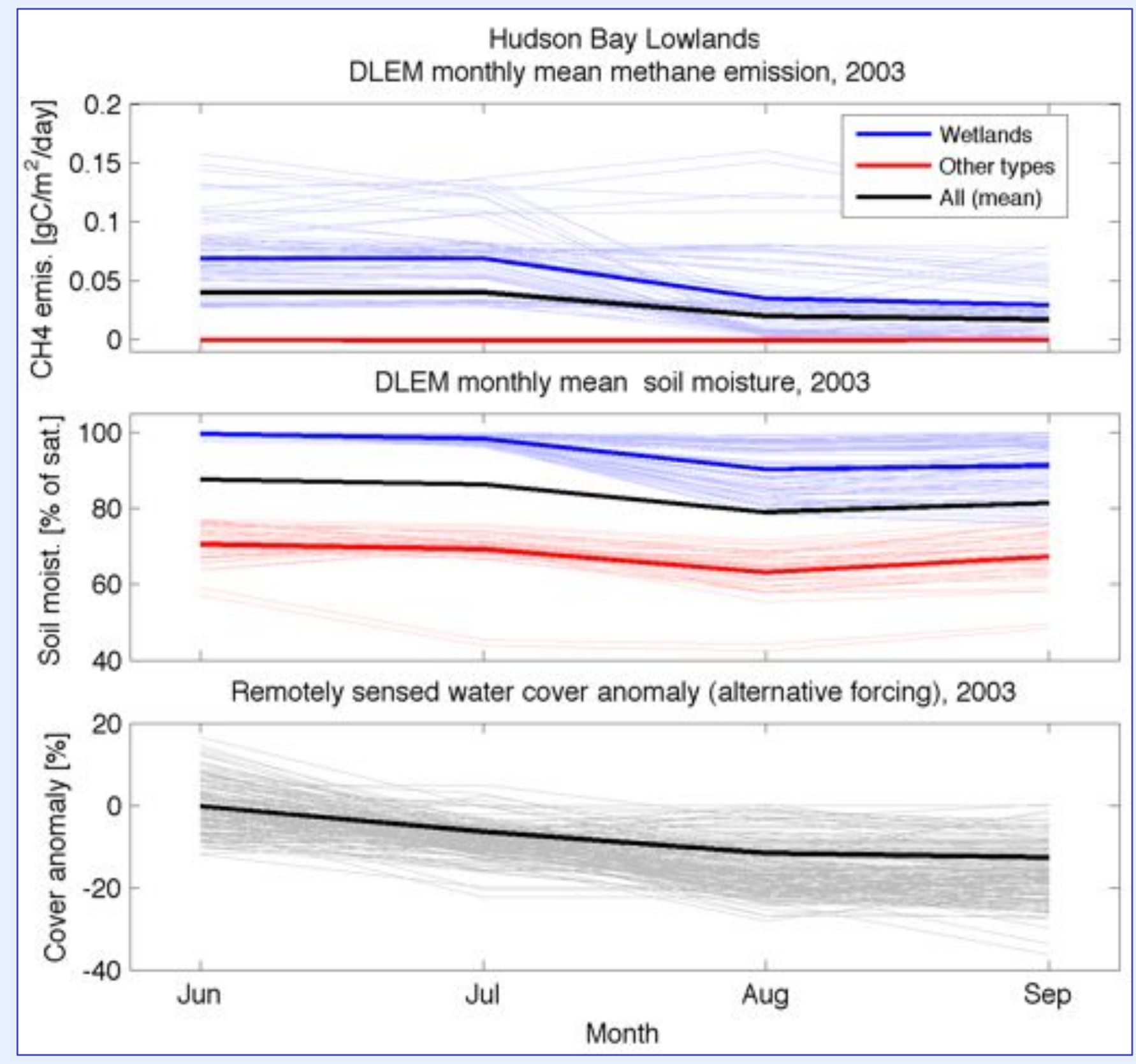
- **DLEM model CH4 emission vs. soil moisture for wetlands land cover types in the Hudson Bay Lowlands region, July-August, 2000-2010**
- **CH4 emission strongly depends on saturated or nearly-saturated soil**



- **Frequency of model CH4 emission across three categories of monthly soil saturation rate:**
  - ➢ **0% of days saturated per month**
  - ➢ **1-50% of days saturated**
  - ➢ **50-100% of days saturated**
- **Moderate soil saturation rates (1-50% of days) can result in significant monthly CH4 emission rates**

Model seasonal response and potential for external forcing from inundated-fraction retrievals

Hudson Bay Lowlands

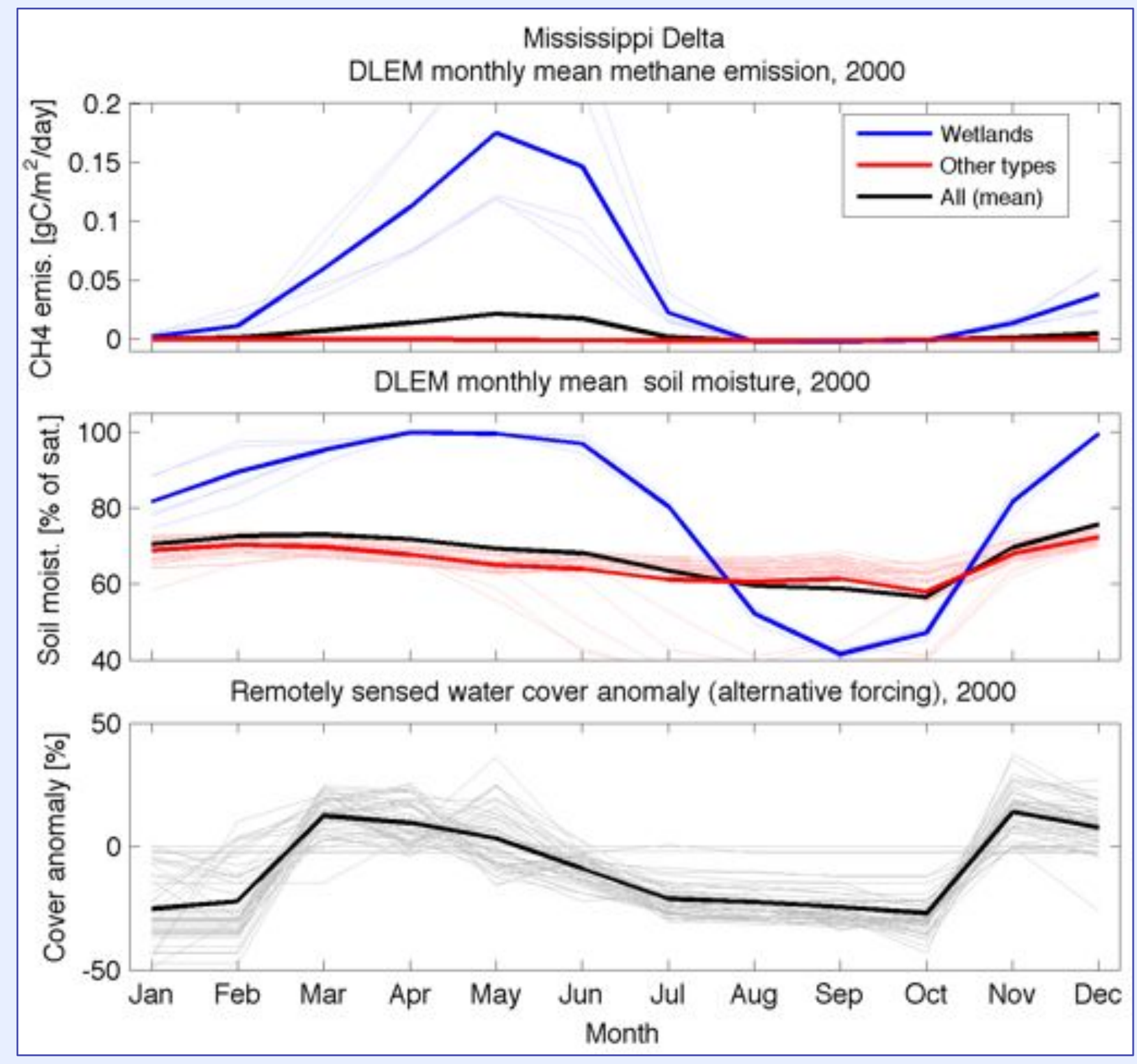


CH4 and soil moisture seasonal response

- **Top two panels: Warm-season CH4 emission and soil moisture**
  - ➢ **Blue: wetlands cells (ensemble and mean)**
  - ➢ **Red: other surface type cells (ensemble and mean)**
  - ➢ **Black: overall mean**

- **Hudson Bay Lowlands, 2003**
  - ➢ **Drier Aug-Sep conditions reduces wetlands saturation rate and CH4 emission**
  - ➢ **Overall CH4 emission falls due to large (near-equal) proportion of wetlands to non-wetlands**

Mississippi Delta



- **Mississippi Delta, 2000**
  - ➢ **Wetlands have large annual soil moisture and CH4 variation**
  - ➢ **Overall CH4 emission varies little due to dominance of non-wetlands land cover types**

- **Bottom panels: Remotely sensed water cover anomaly data [Prigent et al., 2001, 2007; Papa et al., 2010]**
  - ➢ **Regional water cover anomalies suggest potentially larger seasonal variation in saturated conditions than seen in model overall soil moisture**
  - ➢ **A model parameterization allowing for transitions between wetlands and non-wetlands types could use water cover data as an additional forcing**

Conclusions

- Inundation retrieval from SMAP SAR:
  - – Error metrics strongly depend on regionally varying factors (e.g., scale of heterogeneity, vegetation canopy density)
  - – Accurate land cover classification is required for 5-25% retrieval uncertainty
  - – Time-series analysis approaches are needed for further uncertainty reduction
  - – Detect-and-scale-up approach is needed where inundation fraction look-up-tables cannot be applied (e.g., multi-end-member pixels with under-canopy inundation)
- Ecosystem model soil moisture sensitivity:
  - – CH4 emission is highly sensitive to extent and duration of soil saturation in wetlands surface types
  - – Non-wetlands surface types have no CH4 emission
- Implications for SMAP-DLEM fusion:
  - – Inundation fraction products must adjust for permanent water consistent with DLEM surface type representations
  - – Fractional wetland cover (i.e., sub-grid) approach is needed to model seasonal inundation extent variation and small-scale or heterogeneous wetlands (under development)

References

- De Roo, R. D., Y. Du, and F. T. Ulaby (2001), A semi-empirical backscattering model at L-band and C-band for a soybean canopy with soil moisture inversion, *IEEE Trans. Geosci. Rem. Sens.*, 39(4), 864-872.
- Entekhabi, D., et al. (2010), The soil moisture active passive (SMAP) mission, *IEEE Int. Geosci. Rem. Sens. Sym.*, 98(5), 704-716.
- Hallikainen, M. T., F. T. Ulaby, M. C. Dobson, M. A. El-Rayes, and L-K. Wu (1985), Microwave dielectric behavior of wet soil-Part 1: empirical models and experimental observations, *IEEE Trans. Geosci. Rem. Sens.*, GE-23(1), 25-34.
- Oh, Y., K. Sarabandi, and F. T. Ulaby (1992), An empirical model and inversion technique for radar scattering from bare soil surfaces, *IEEE Trans. Geosci. Rem. Sens.*, 30, 370-381.
- Oh, Y., K. Sarabandi, and F. T. Ulaby (1994), An inversion algorithm for retrieving soil moisture and surface roughness from polarimetric radar observation, *IEEE Int. Geosci. Rem. Sens. Sym.*, 3, 1582-1584.
- Papa, F., C. Prigent, C. Jimenez, F. Aires, and W. B. Rossow (2010), Interannual variability of surface water extent at global scale, 1993-2004, *J. Geophys. Res.*, 115, D12111, doi:10.1029/2009JD012674.
- Prigent, C., E. Matthews, F. Aires, and W. B. Rossow (2001), Remote sensing of global wetland dynamics with multiple satellite data sets, *Geophys. Res. Let.*, 28 , 4631-4634.
- Prigent, C., F. Papa, F. Aires, W. B. Rossow, and E. Matthews (2007), Global inundation dynamics inferred from multiple satellite observations, 1993-2000, *J. Geophys. Res.*, 112, D12107, doi:10.1029/2006JD007847.
- Pulliainen, J. T., L. Kurnonen, and M. T. Hallikainen (1999), Multitemporal behavior of L- and C-band SAR observations of boreal forests, *IEEE Trans. Geosci. Rem. Sens.*, 37(2), 927-937.
- Tian, H., X. Xu, M. Liu, W. Ren, C. Zhang, G. Chen, and C. Lu (2010), Spatial and temporal patterns of CH4 and N2O fluxes in terrestrial ecosystems of North America during 1979–2008: application of a global biogeochemistry model, *Biogeosciences*, 7, 2673-2694, doi:10.5194/bg-7-2673-2010.

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