Monitoring Surface Water Changes across the North American Arctic-Boreal Zone and Associated Impacts on Regional Carbon Fluxes

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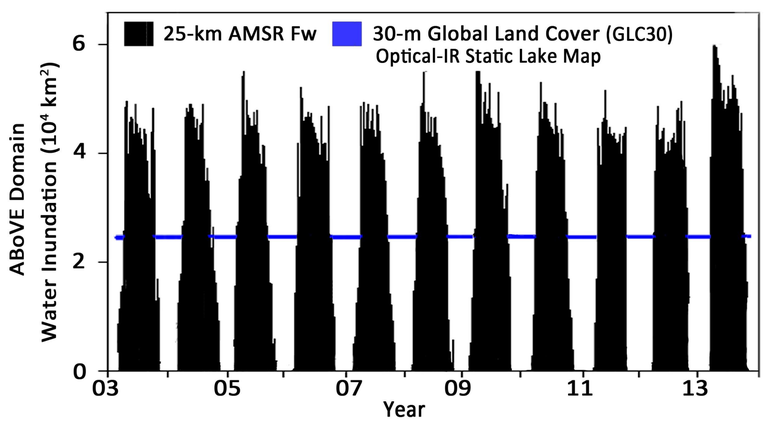
Introduction

Surface water inundation strongly regulates land-atmosphere energy and carbon exchange in northern environments. However, the dynamic nature of inundation in Arctic-boreal landscapes, and the potential impact of changing surface water extent on wetland methane (CH_4) emissions, is not well understood.

Here we examine recent changes in surface inundation across Alaska and northwestern Canada, including the proposed NASA Arctic-Boreal Vulnerability Experiment (ABoVE) domain, using daily passive microwave remote sensing retrievals of fractional open water extent (Fw) derived from calibrated AMSR-E and AMSR-2 sensor records over an 11-year (2003-2013) observation period [1, 3].

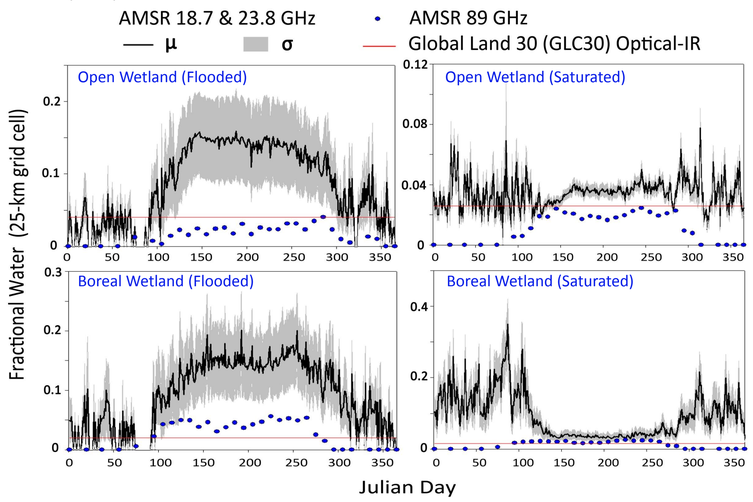
We also investigate the impact of high-temporal Fw variability on regional wetland carbon dynamics using a Joint UK Land Environment Simulator (JULES) model approach, that accounts for primary environmental factors regulating northern CH_4 emissions (i.e. soil temperature, soil wetness, and carbon substrate). We use the combined monitoring of surface hydrology and carbon cycles through satellite remote sensing and ecosystem modeling to identify Arctic-boreal regions vulnerable to longer-term wetting or drying trends and associated changes in annual CH_4 emission budgets [6].

Wetland Surface Inundation Characteristics



The 25-km resolution AMSR Fw record is derived using 18.7 and 23.8 GHz passive microwave remote sensing brightness temperatures (T_b) from AMSR-E (2003-2011) [3, 5] and similar calibrated, overlapping T_b observations from FY3B-MWRI and AMSR-2 sensors (≥ 2011) [1]. The AMSR record provides daily observations of Fw area, including open water lakes and emergent vegetation (**above**), with insensitivity to solar illumination and atmosphere contamination effects that allows for continuous detection of changing surface water area over northern landscapes.

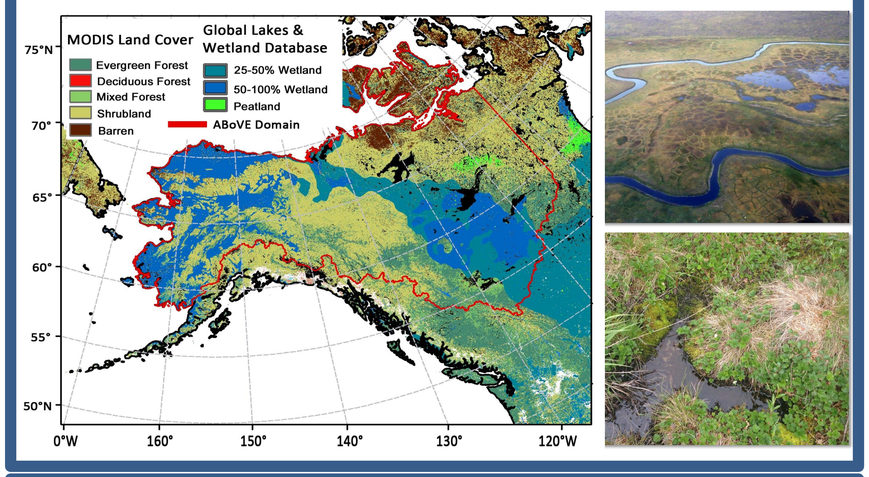
The AMSR 18.7 and 23.8 GHz Fw retrievals capture dynamic wetland inundation and seasonal variability in surface water area (**below; black lines**), in contrast to static surface water products (e.g. 30-m optical-IR GLC30). The 25-km Fw observations are complimented by finer (6.25-km) resolution Fw retrievals from the AMSR 89 GHz record [2] with less sensitivity to flooded vegetation relative to lake bodies (**blue circles**). Analysis of the AMSR Fw record for Alaska wetlands (**below**) reveals sustained water inundation through the summer in wet tundra and marsh landscapes. In contrast, wetlands characterized by saturated soils (e.g. boreal peatlands and tussock tundra) show minimal summer open water extent and strong seasonal flooding following spring snow melt and autumn precipitation events.



Study Area

This investigation extends over Alaska, Canadian Yukon and Northwest Territories, including the ABoVE domain (**bottom-left**). These Arctic tundra and boreal ecosystems are characterized by continuous permafrost in the north, transitioning to discontinuous and sporadic/isolated permafrost in interior and southern portions of the domain.

Over 24% of the region is covered by open water lakes, stream networks (**top-right**), and inundated vegetation (**bottom-right**) in addition to wet surface soil environments [5]. Wet anoxic surface conditions, and abundant soil organic carbon reservoirs, result in environments that are vulnerable to heightened CH_4 emissions with climate warming [4, 6].



Dynamic Wetland CH_4 Sensitivity Analysis

We use the JULES model to estimate daily CH_4 emissions for wetland ecosystems across the ABoVE domain. Input surface (≤ 10 cm) labile carbon substrates, soil temperature (T_{soil}) and freeze/thaw (FThw) indices constrain optimum k_{CH4} emission (3.7×10^{-5} d^{-1}) and metabolic response (T_0 = 273.15 K; Q_{10} = 3.4-3.7) rates calibrated using flux chamber and tower eddy covariance records [6]. Dynamic 15-day mean surface soil moisture (% saturation) and Fw inundation are then applied to regulate CH_4 emission totals (Tonne CH_4) for each 25-km grid cell.

Step 1: $$F_{CH_4} = Carbon \times k_{CH4} \times Q_{10}^{(Tsoil - T_0)/10} \times FThw$$

Step 2: $$F_{CH4} = f(Fw, Soil\,Moisture)$$

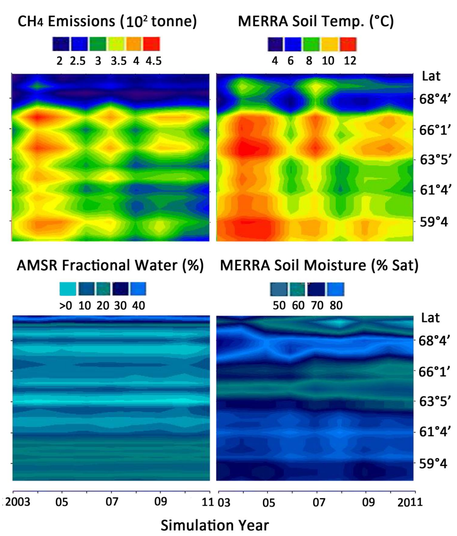
Data Records:

- T_{soil} (K) and surface soil moisture (% sat.) at 0.5° spatial resolution are provided using the Goddard Earth Observing System Model (GEOS-5) MERRA archive.
- Soil metabolic carbon (kg m^{-2}) at 25-km resolution is supplied using Terrestrial Carbon Flux (TCF) model simulations for pan-Arctic environments [6].
- 25-km grid cell surface FThw (0 = frozen, 1 = thaw) and Fw inundation constraints are obtained using the UMT AMSR Global Land Parameter Record [1,3]

Model Simulations for the ABoVE Domain

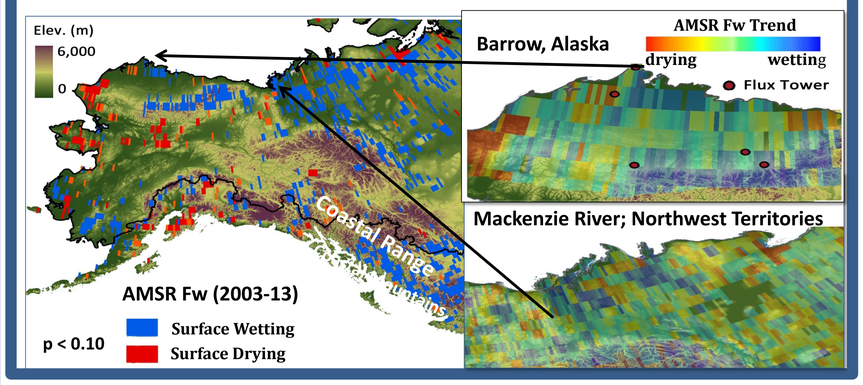
JULES summer (May – August) CH_4 latitudinal averages (**top-left**) for the 2003-2011 simulation period indicate low (< 250 tonne CH_4) 25-km grid cell emissions along the Arctic Rim (> 67°N) relative to wetlands in the Northwest Territories and Interior to coastal Alaska that are characterized by warmer summer climate and longer non-frozen season (**top-right**).

Annual variability (± 0.6 Tg CH_4) in regional CH_4 emission totals relative to the 2003-2011 mean primarily reflects periods of warmer (e.g. 2004, 2010) or cooler (e.g. 2006, 2008) summer soil temperatures (**top-right**), which are enhanced or moderated by dynamic Fw inundation and soil moisture conditions (**bottom**).



Regional Inundation Wetting/Drying Trends

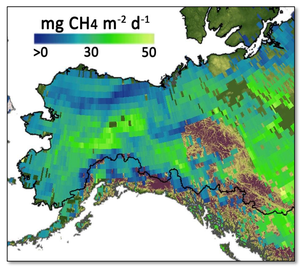
A Mann-Kendall trend analysis applied to 25-km AMSR Fw summer means (May – Aug.) from 2003-2013 reveals distinct wetting and drying patterns across the domain (**bottom-left**). Significant Fw wetting ($p < 0.10$) and drying occurs over 12% and 6% of the domain, respectively. These trends are similar to pan-Arctic observations [5, 6] showing declining inundated wetland and lake area in regions with recent disturbances (e.g. fire and thermokarst activity) and permafrost degradation (e.g. western Alaska; **top-right**). Regions with Fw wetting generally correspond with initial ice melt in continuous permafrost landscapes (e.g. east of Barrow) and amplified seasonal flooding within Arctic river basins including the Mackenzie (**bottom-right**).

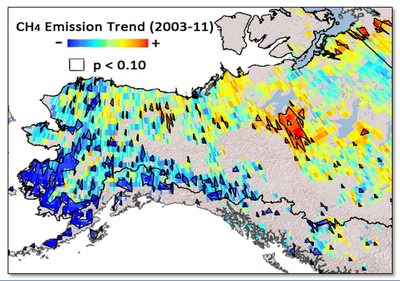


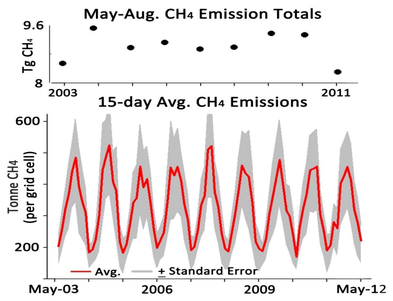
Inundation Impacts on Summer CH_4 Emissions

Average summer (May-Aug.) JULES CH_4 emissions range from 0 to 53 mg CH_4 m^{-2} d^{-1} (**top-right**). Larger CH_4 fluxes (**bottom-right**) correspond with wet surface conditions and warm soil temperatures. An extended non-frozen season also contributes to higher emission totals (Tg CH_4) in 2004, 2009 and 2010.

Longer-term (2003-2011) trend analyses indicate declining CH_4 emissions influenced by soil drying and/or cooling patterns (**bottom-left, in blue**), in contrast to local warming and wetting which increases CH_4 emissions (**in red**) across northern Alaska and Canada.







Study Conclusions

The AMSR Fw record reveals large seasonal and interannual variability in surface inundation over the ABoVE domain. Longer-term (2003-2013) wetting and drying patterns correspond with regional disturbances, including fires and thermokarst activity. A CH_4 model sensitivity study indicates respective summer emissions of 3.4 and 8.9 ± 0.6 Tg CH_4 yr^{-1} for Alaska and the extended ABoVE domain. High peak CH_4 emissions occur in years with warm and wet summers (e.g. 2004, 2007) or an extended non-frozen season (e.g. 2009). Regional declines in CH_4 emissions reflect surface drying and soil cooling patterns. In contrast, landscapes with heightened CH_4 emissions reflect warming soils and inundation increases. Continued satellite monitoring of Fw inundation, including ongoing AMSR-2 operations, is needed to identify Arctic-boreal regions vulnerable to changing surface hydrology and CH_4 emissions in a warming climate.

References

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