Satellite Year-Round Methane Measurements for the Arctic: Towards Elucidation of Methane Growth After 2014

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Abstract

On decadal timescales, the greenhouse gas methane (CH4) is ˜100 times more potent than carbon dioxide. Its abundance is increasing, many of its sources are temperature dependent. The Arctic is the site of the fastest warming globally. Feed-backs between Arctic temperature and CH4 emissions and concentrations need investigation. Unfortunately, available Arctic in situ data are extremely sparse with no marine observations outside summer. Satellite instruments measuring solar radiation reflected from the surface are ineffective in the Arctic. Thus, we leverage satellite data from AIRS, IASI-1, and IASI-2 Thermal Infrared (TIR) spectrometers, which provide year-round, day/night CH4 observations. Available in situ high latitude NOAA/ESRL surface coastal (50-85°N) flask atmospheric CH4 concentrations were compared with satellite data. We find: 1) remote sensing data revealed 150% (IASI-1, mid-upper troposphere) and 80% (surface data for Arctic stations) increases in atmospheric CH4 concentration growth rates between 2010-2014 and 2014-2017 time spans. Global NOAA/ESRL surface concentration rates increased by 90% for the same period; 2) maximum CH4 seasonal emission from the Arctic land occurs in boreal summer, while that from the Barents Kara Sea (BKS) occurs in boreal winter (Nov–Mar). Total annual Arctic Ocean CH4 emissions are preliminary estimated as ˜40% of all land emissions North of 50°N; 3) marine emissions are concentrated in shelf areas within ˜100 km of the coasts of major Arctic BKS lands; 4) CH4 anomalies over BKS, defined as surplus over its concentration at the North Atlantic area, grew after 2014; 5) the strongest SST increase was observed every year in the southeast Barents Sea in June due to strengthening of the warm Murman Currents and in the south Kara Sea in Sept. Direct in situ CH4 flux measurements during polar night over sea are necessary to test the satellite results.

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ATMOSPHERIC CH_4 SATELLITE DATA

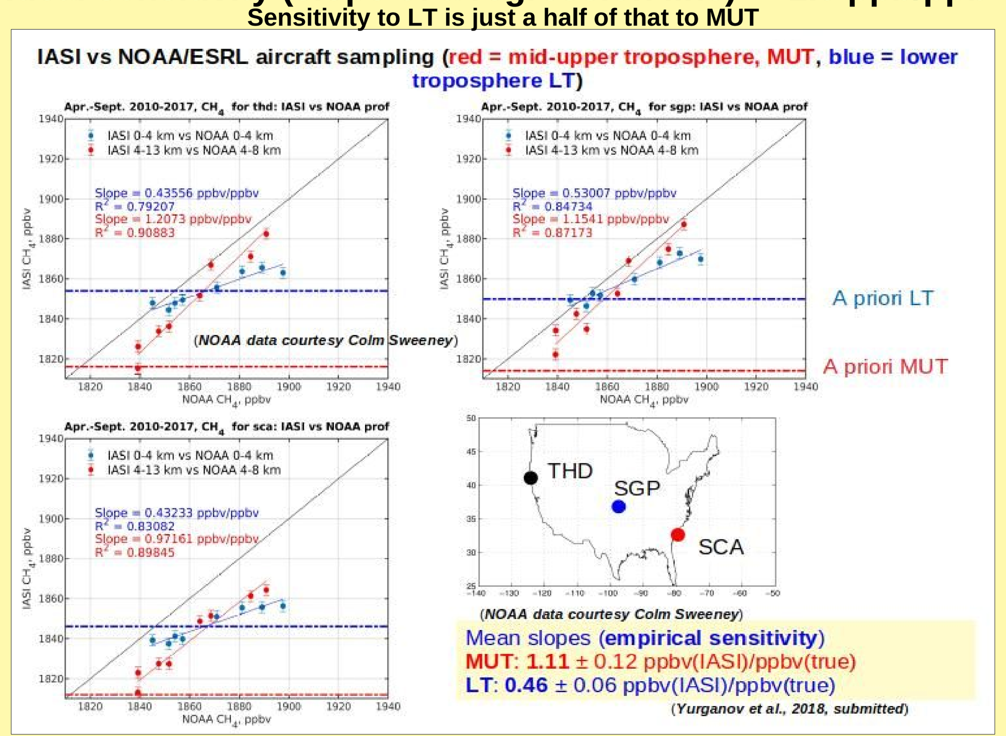
Are satellite instruments capable to measure CH4 concentrations in lower and upper troposphere?

IASI-1 (Infrared Atmospheric Sounder Interferometer) is a polar orbiting instrument deployed on European MetOP-A satellite. It looks downward (*nadir*) with a plus/minus 1100 km swath from the track. Space nadir resolution is 12 km, effective resolution 24x24 km. It revisits high latitude sites at least twice daily, at ~9:30 am and ~9:30 pm of local time.

VALIDATION USING NOAA AIRCRAFTS

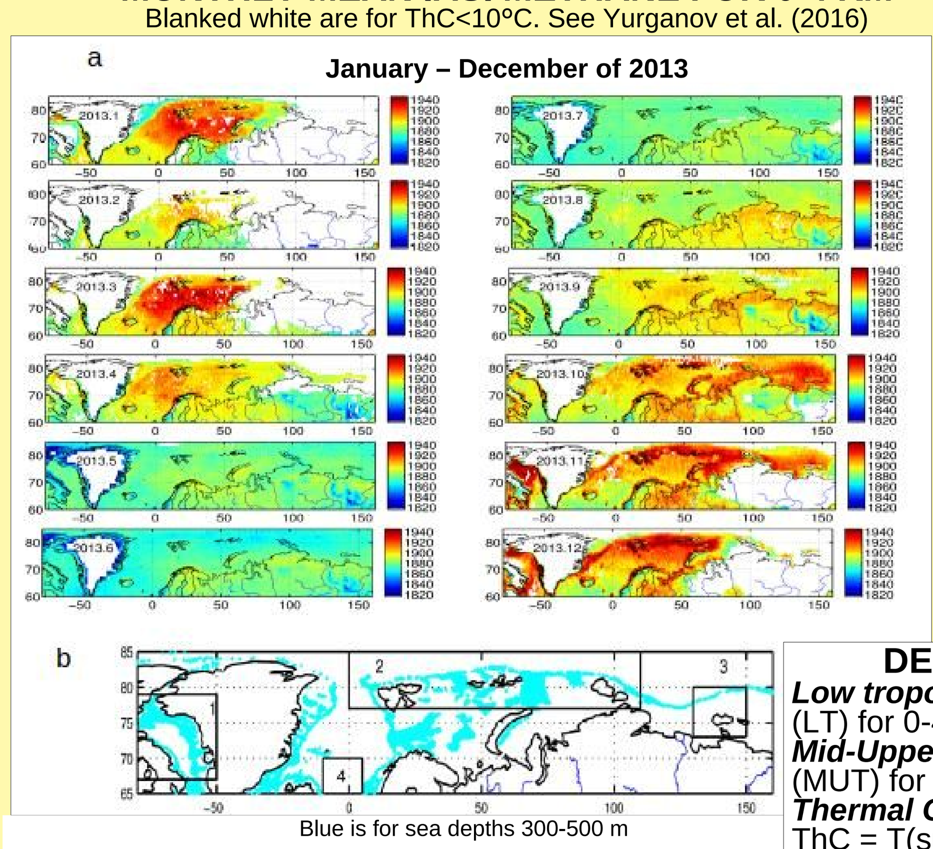
Ideal sensitivity (slope of a regression line) = 1.0 ppb/ppb

Sensitivity to LT is just a half of that to MUT



MONTHLY MEAN IASI METHANE FOR 0-4 KM

Blanked white are for ThC<10°C. See Yurganov et al. (2016)



DEFINITIONS

Low troposphere (LT) for 0-4 km altitude

Mid-Upper troposphere (MUT) for 4-13 km

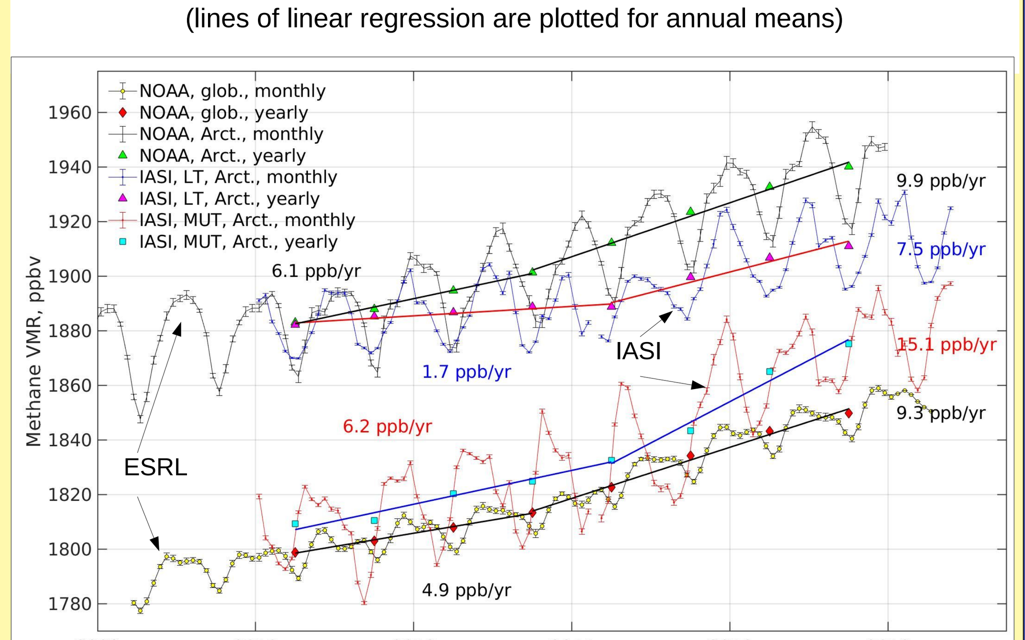
Thermal Contrast(ThC) ThC = T(surf)-T(4 km)

BKS=Barents/Kara seas

RECENT GLOBAL AND ARCTIC METHANE TRENDS

Note an acceleration in 2013-2014

(lines of linear regression are plotted for annual means)



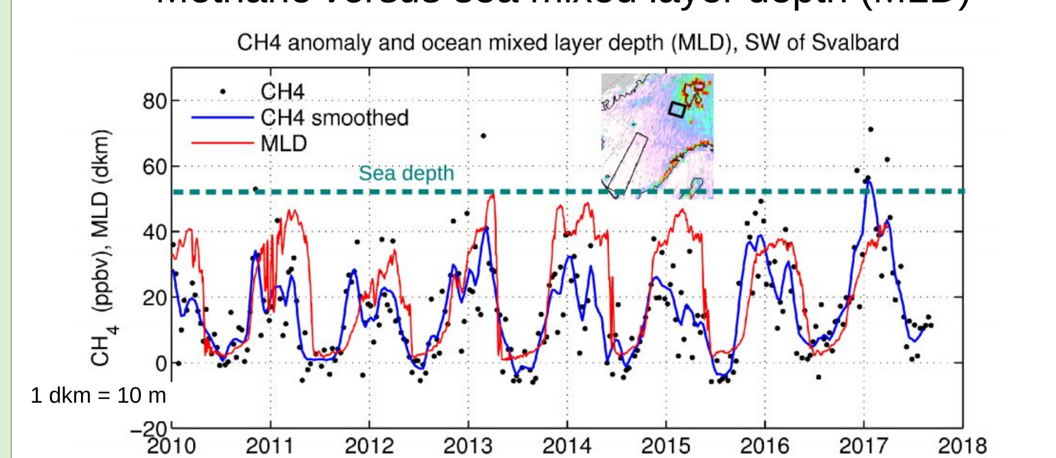
Monthly and annual means.

NOAA/ESRL data for surface sampling in the Arctic (upper curve, 10 coastal stations) and global (lower curve). IASI [50° N-85° N] data for LT (upper curve) and MUT (lower curve). A more gradual trend for LT is explained by a lower sensitivity of IASI to LT (see validation). Yurganov et al. (2017).

ARCTIC IASI LT CH_4 ANOMALIES, 2010-2017

Marine methane anomaly over sea has a winter maximum

Methane *versus* sea mixed layer depth (MLD)

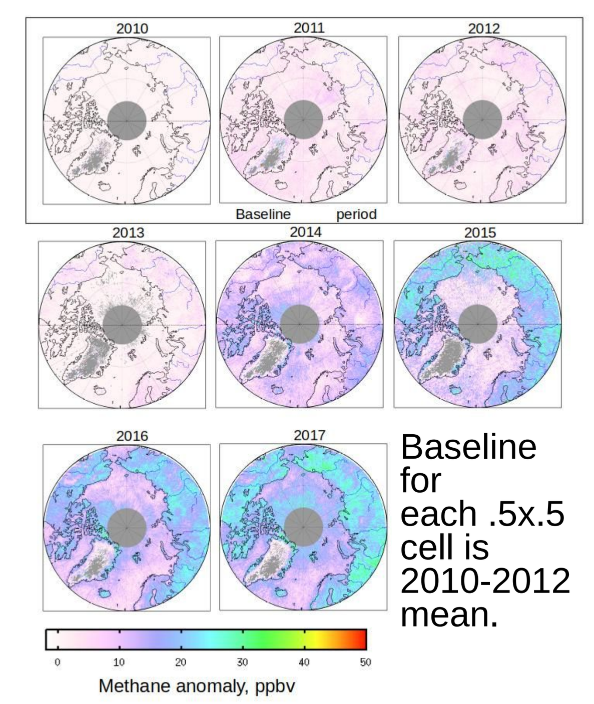


Methane anomaly (the difference between concentration near Svalbard and the N. Atlantic) is minimal in summer and maximal in winter. It correlates with the seawater MLD. A shallow pycnocline appears in May and disappears in November.The pycnocline separates surface mixed layer from deeper water. Mixing (turbulence) in the near-bottom layer is caused by ocean currents. Stratification reduces vertical exchange between ocean layers and the atmosphere.

IASI detected a few areas of marine methane positive anomalies late autumn-winter

Methane anomalies are growing

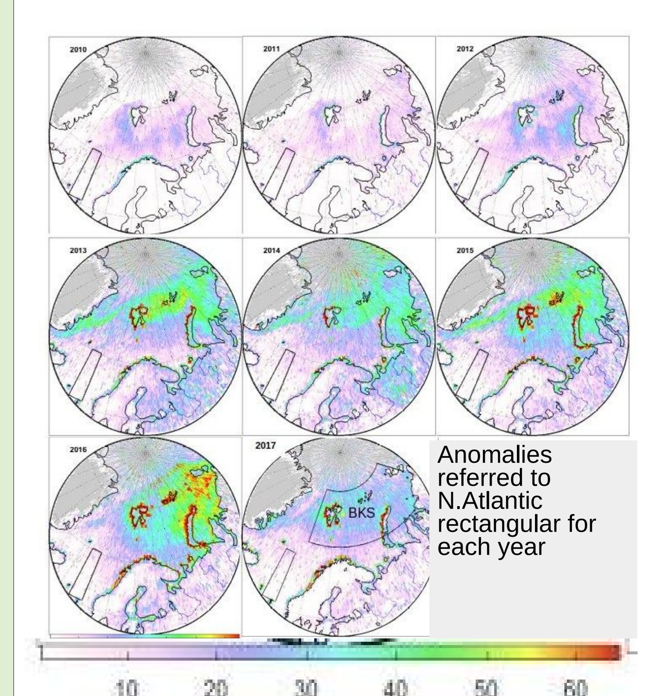
June-September



Baseline for each .5x.5 cell is 2010-2012 mean.

In summer CH_4 anomaly over land grows faster than over sea, sea-air flux is low

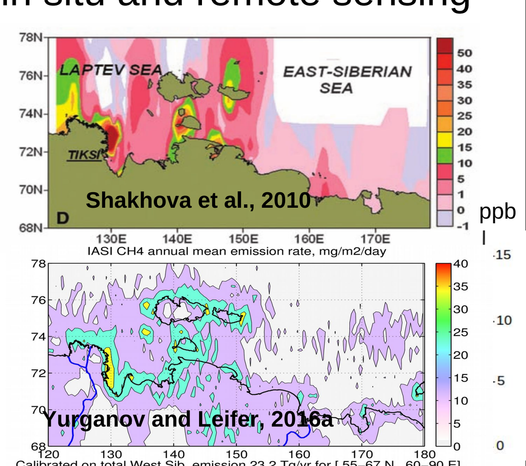
November-December



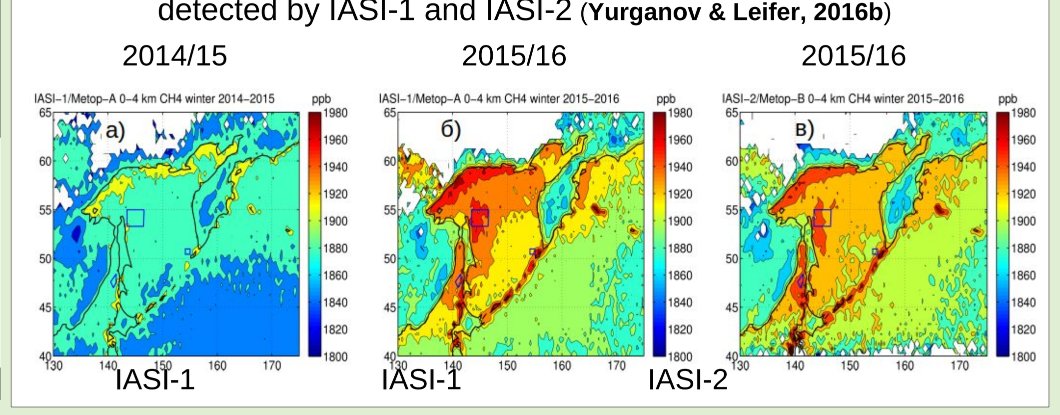
CH4 anomalies at BKS, ppbv

East Sib. Arct. Shelf (ESAS):

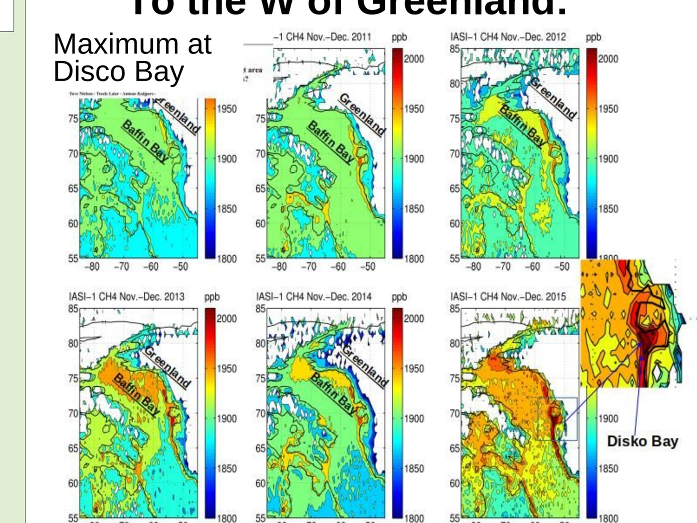
in situ and remote sensing



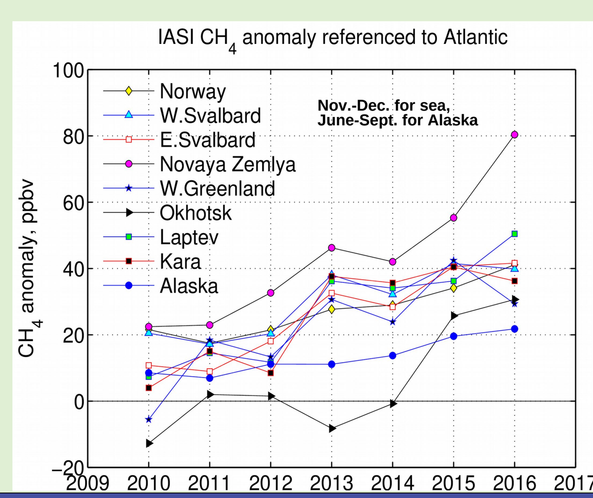
Sea of Okhotsk: CH4 VMR increase in 2015.12-2016.02 was detected by IASI-1 and IASI-2 **(Yurganov & Leifer, 2016b)**



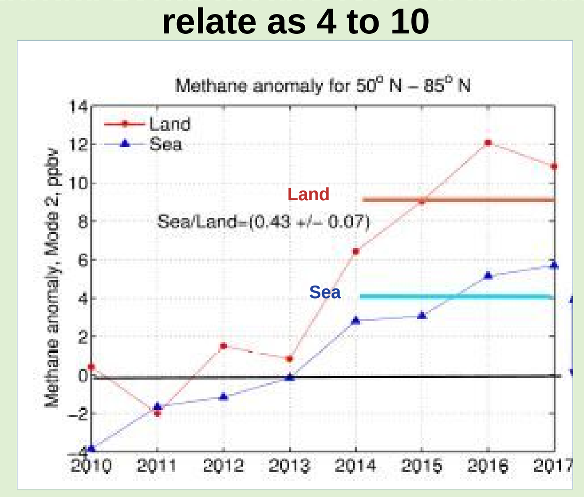
To the W of Greenland:



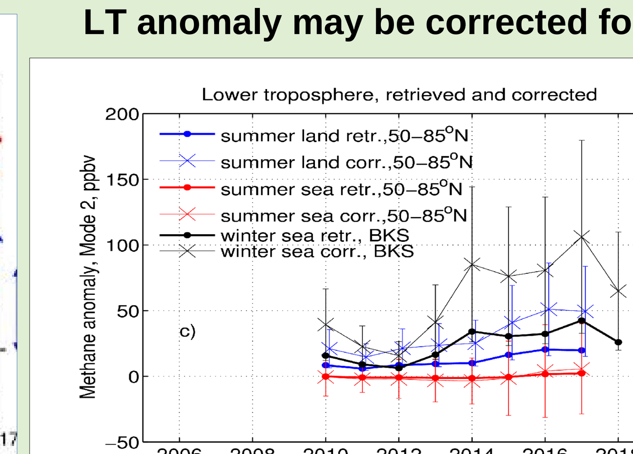
Anomalies for areas grow with years



Annual zonal means for sea and land relate as 4 to 10

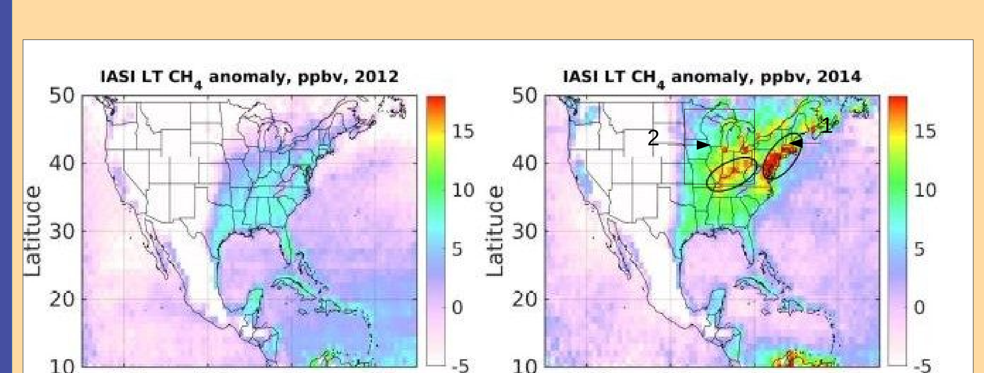


LT anomaly may be corrected for a reduced sensitivity



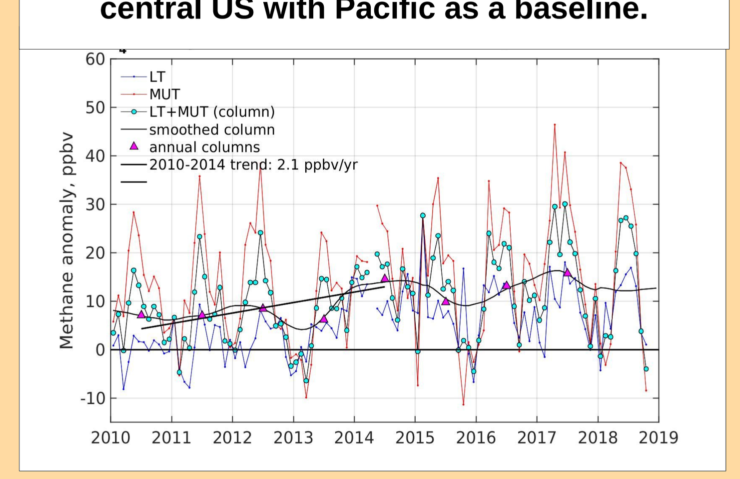
Sensitivity for LT anomaly is ~0.5. Two black lines are anomalies over winter BKS as retrieved (thick line) and multiplied by 2 (thin line), respectively. So, over sea (**thin black line**) methane anomaly increased from ~40 ppb before 2014 to ~ 80 ppb after that. Similarly, summertime anomalies over Arctic land increased from ~ 20 ppb to ~ 50 ppb (blue line). Summer anomaly over sea (red line) did not change at all.

US CH_4 ANOMALIES REFERENCED TO PACIFIC



The LT annual anomalies are positive over land and an outflux to the Atlantic is observed. The DC-NYC area (#1) is polluted throughout 2014-2017 and much less polluted before 2014. A significant pollution at the Ohio valley (#2) was observed in 2014 only. Elevated topography is blanked out.

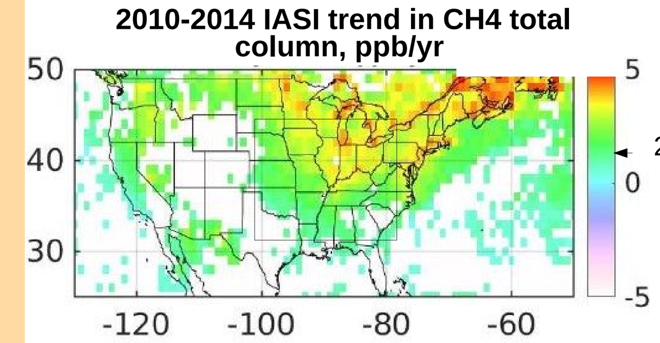
CH4 monthly and annual anomalies over the central US with Pacific as a baseline.

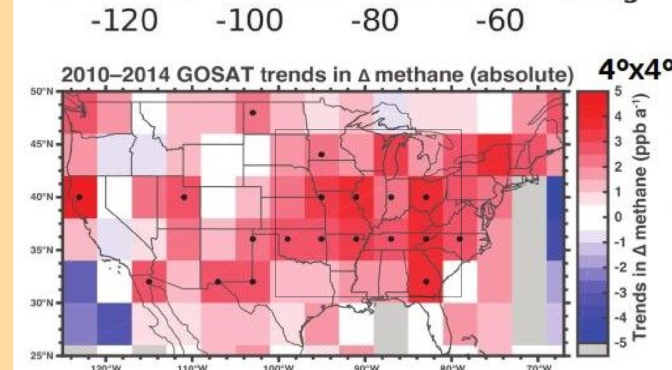


The anomalies for a rectangular at the central US (see map) vary seasonally with a summer maximum. They dramatically increased after 2013. Column anomalies may be compared to GOSAT SWIR data. Turner et al. (2016) estimated a trend for 2010-2014 as ~ 2 ppb/yr in agreement with IASI. A transport of extra methane from the Arctic is not ruled out.

Comparison with GOSAT data

2010-2014 IASI trend in CH4 total column, ppb/yr

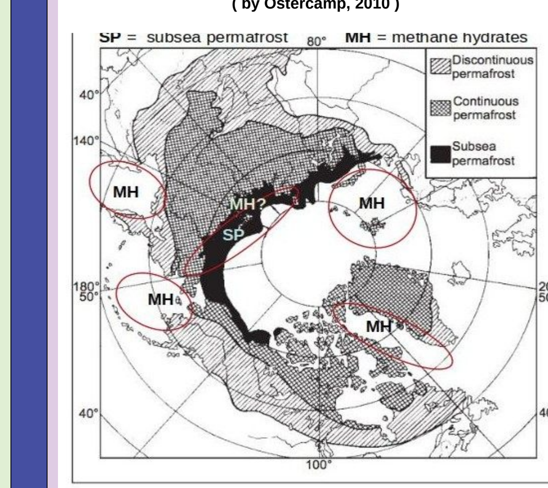




*"A large increase in US methane **emissions** over the past decade inferred from satellite data and surface observations" by A. J. Turner et al., 2016*

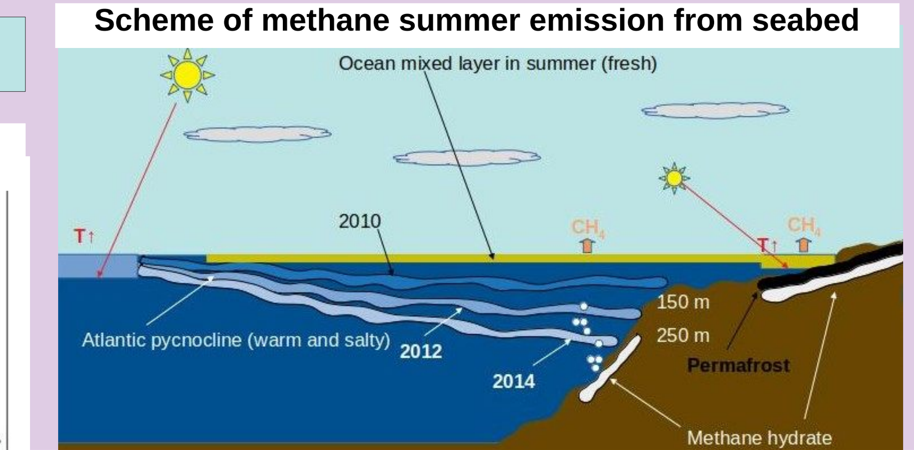
DISCUSSION

Arctic permafrost (by Ostercamp, 2010)



MH: Methane hydrates;
SP: subsea permafrost
ESAS: East Siberian Arctic Shelf

Scheme of methane summer emission from seabed



The inflow of Atlantic water along the Norwegian Continental Slope is ~500 m thick. The warmest and most saline part of this flow is normally ~100-150 m deep. We propose that its warmth, salinity, and density has increased. The thickness of the desalinated surface layer may increase as well. Both are leading to faster descent (sinking) of Atlantic flow. Once this flow reaches Type I MH depths (~250 m) – post 2014 – there is enhanced hydrate decomposition and CH_4 seabed emissions. For the shallow ESAS another mechanism works: ice retreat induces warming of sea water and increasing CH4 emission from degradation of subsea permafrost.

Long-term trends. Our analysis of IASI data, processed by NOAA show increasing methane growth since 2014. This agrees with surface NOAA sample data both for Arctic coastal stations and globally. Mid-upper tropospheric (MUT, 4-13 km of altitude) methane growth rate between 50° N and 85° N increased **from 6 to 15 ppb/yr**. According to NOAA, global surface methane growth rate increased **from 5 to 9 ppb/yr** and Arctic surface methane growth increased **from 6 to 11 ppb/yr**. IASI methane for the Low Troposphere (LT, below 4 km) is less sensitive than for MUT, therefore Arctic LT CH4 increased **from 2 to 7 ppb/yr**. IASI Arctic data are for land and sea; NOAA data are only for coastal terrestrial locations. **Methane anomaly** is defined as a surplus in concentration over N. Atlantic methane. The anomaly was found to grow after 2014 as well. A ratio of annual methane emitted by sea to land for North of 50° N is estimated at ~40% (preliminary).

Seasonal cycles. Analysis of IASI data found different seasonal cycles for land and sea methane anomalies. **Land methane anomaly has a summer maximum** (between July and September); marine methane anomaly is low in May-September and starts growing in October (East Siberian Arctic Shelf, ESAS) or in November (BKS and Baffin Bay). **Seasonal maximum of the marine anomaly is December-January**. During some years a secondary marine maximum is observed in March. The ESAS is difficult for remote sensing after November due to cold icy surface. The methane emission seasonal maximum seems to occur after the autumn mixing breaks down the near-surface summer pycnocline. The summer regime shifts to the winter regime in early November for the BKS and in the middle of October for the ESAS. Return to the summer regime in BKS is in late April.

Locations and nature of sources. **Temperature-dependent Arctic seabed** sources may be responsible for increasing atmospheric methane. We selected five areas with enhanced CH4 emission (a map at the top). Black areas correspond to the subsea permafrost at the shallow ESAS. Its degradation may explain the October seasonal maximum over ESAS, detected by IASI. Emission from methane hydrates (MH, a cartoon above) in this area seems unlikely at present. For other areas MH is the most plausible source of growing marine methane emission. Also there are seabed seepages from thermogenic sources, e.g. leaking petroleum reservoirs, which are expected to be mitigated by hydrate formation and decomposition. Coastal marine methane reaches the atmosphere after November and **is transported offshore by winds**. In the ocean, **methane shoaling** may take place as well (Leifer et al., 2018). Specifically, CH4 below the pycnocline may drift with currents that drive it upslope into the mixed layer where it can escape to the atmosphere, possibly distant from its seabed origin. Methane shoaling also enhances transport of shallower dissolved CH4 to the atmosphere.

Nature of sinks. The prevailing summer methane sink most likely is oxidizing in part by methanotrophic bacteria. Timescales are uncertain, estimated a few weeks to few months. Its temperature dependence is unknown. Since early November the sea to air flux prevails over microbial oxidation.

Global perspectives. The Arctic clearly plays a role in the current methane global trends but its significance can not be quantified yet. Our analysis confirms Turner et al. (2016) conclusion about growing methane anomaly over the USA. This US anomaly may not necessarily be from anthropogenic US sources; all temperature-dependent natural and anthropogenic emissions play a role as does transport from the Arctic. Future trends will depend strongly on positive feedbacks around the Globe including Arctic amplification.

CONCLUSIONS

1. IASI data show an acceleration of methane concentration growth after 2014 and provide evidence of significant (~ 40% of the Arctic flux from land annually) methane flux from the Arctic seas, mostly in winter.

2.Intensification of seawater mixing due to cooling surface combined with stormy weather after November may explain seasonality in emissions.

3.Methane hydrates seem the most likely explanation of the emission for most of source areas.

4. Methane anomalies over sea were growing with time after 2014.

5. The observed amplification of global and Arctic CH_4 may be a realization of a positive feed-back with temperature.

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