

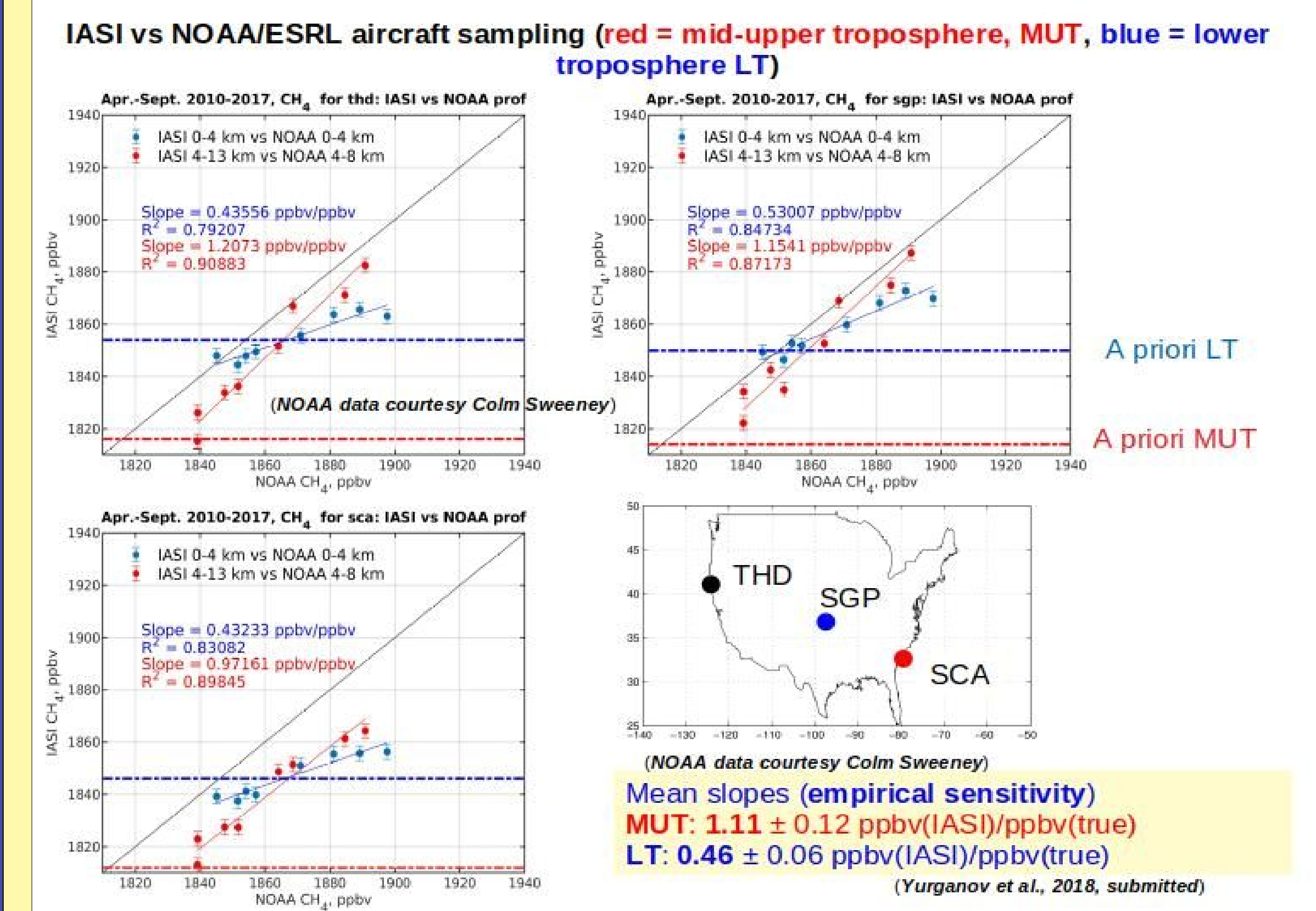
## ATMOSPHERIC CH<sub>4</sub> SATELLITE DATA<sup>4</sup>

Are satellite instruments capable to measure CH<sub>4</sub> 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.

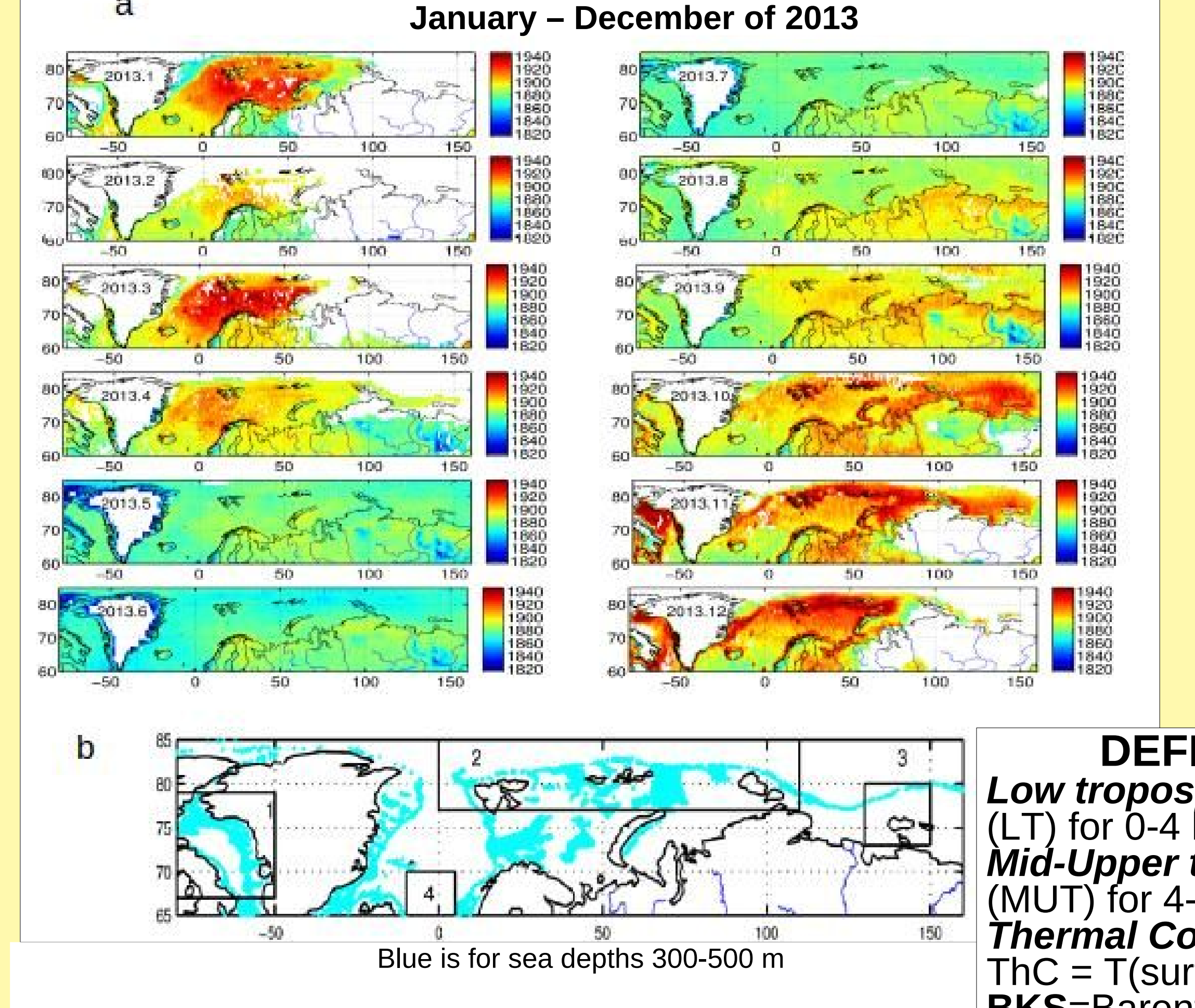
### VALIDATION USING NOAA AIRCRAFTS

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

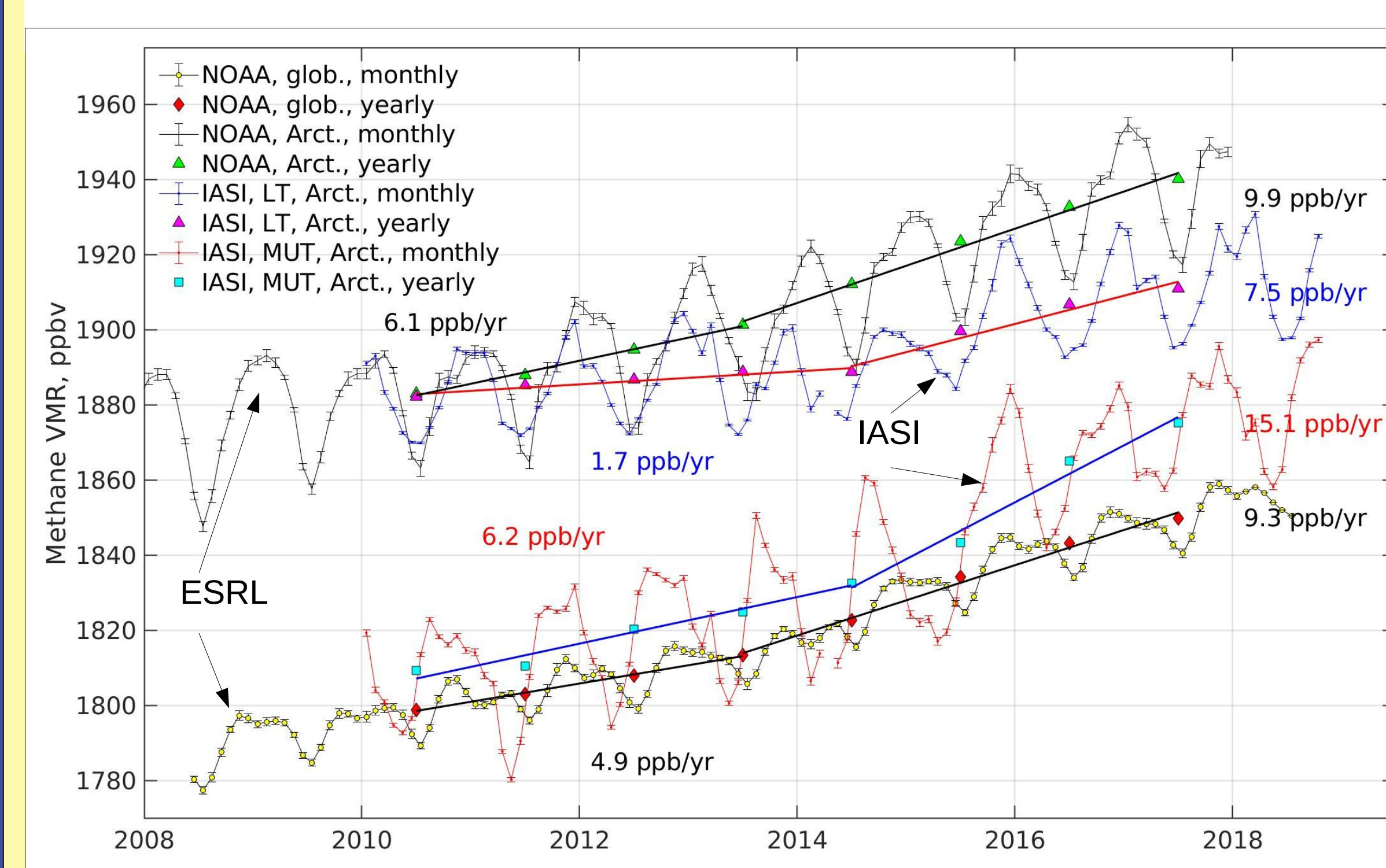
Blanked white are for ThC<10°C. See Yurganov et al. (2016)



### 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).

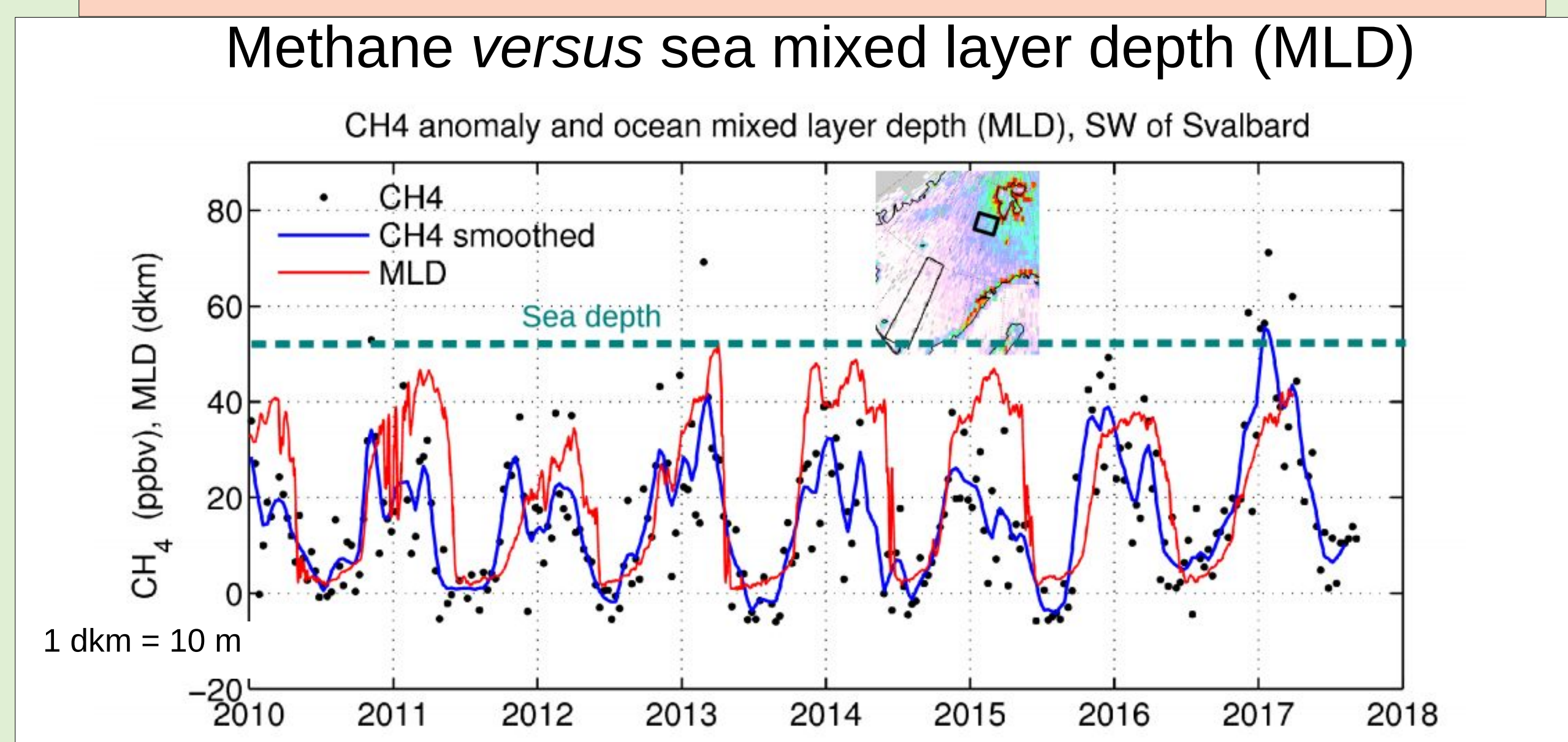
# SATELLITE YEAR-ROUND METHANE MEASUREMENTS FOR THE ARCTIC: TOWARDS ELUCIDATION OF METHANE GROWTH AFTER 2014.

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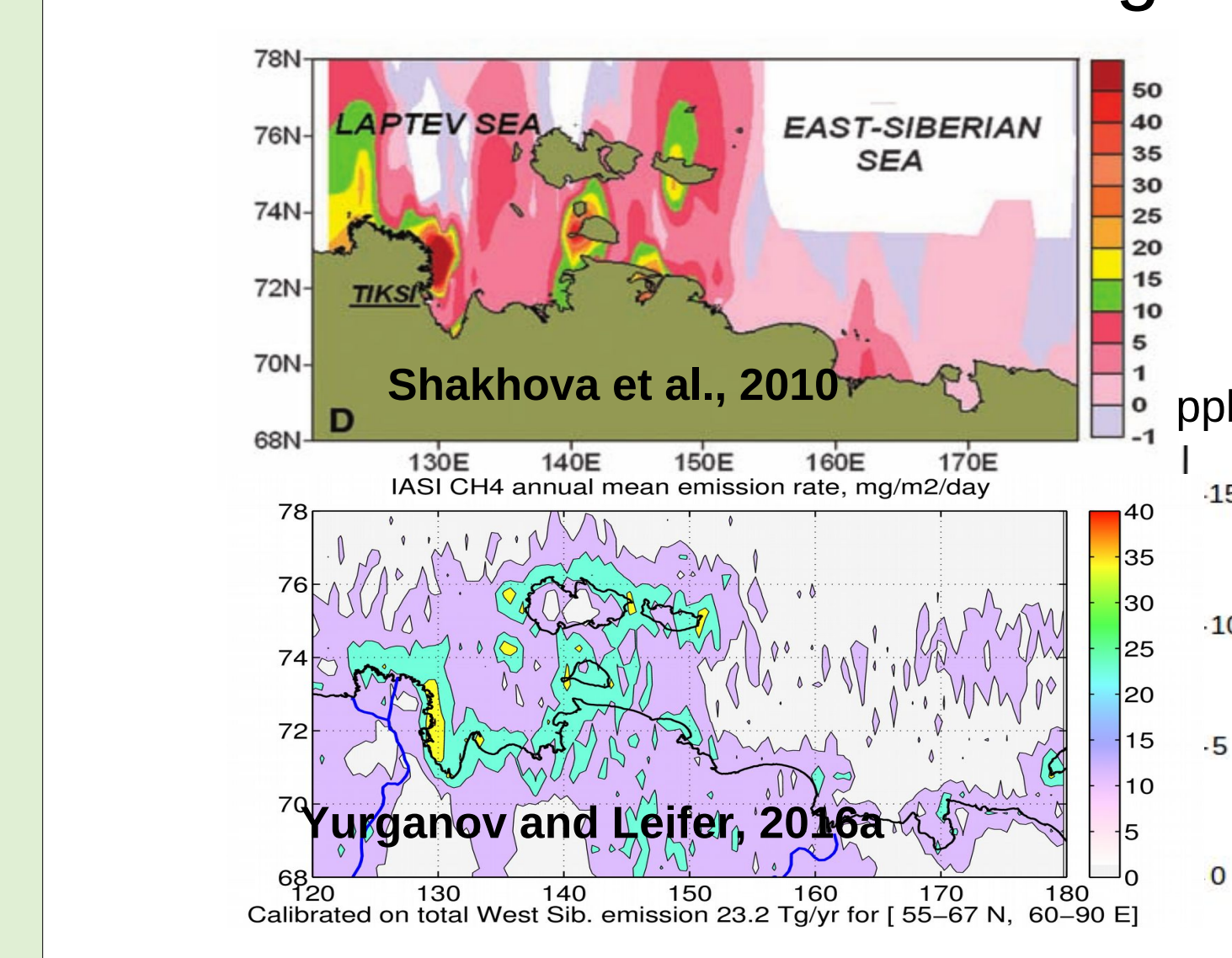
## ARCTIC IASI LT CH<sub>4</sub> ANOMALIES, 2010-2017

### Marine methane anomaly over sea has a winter maximum

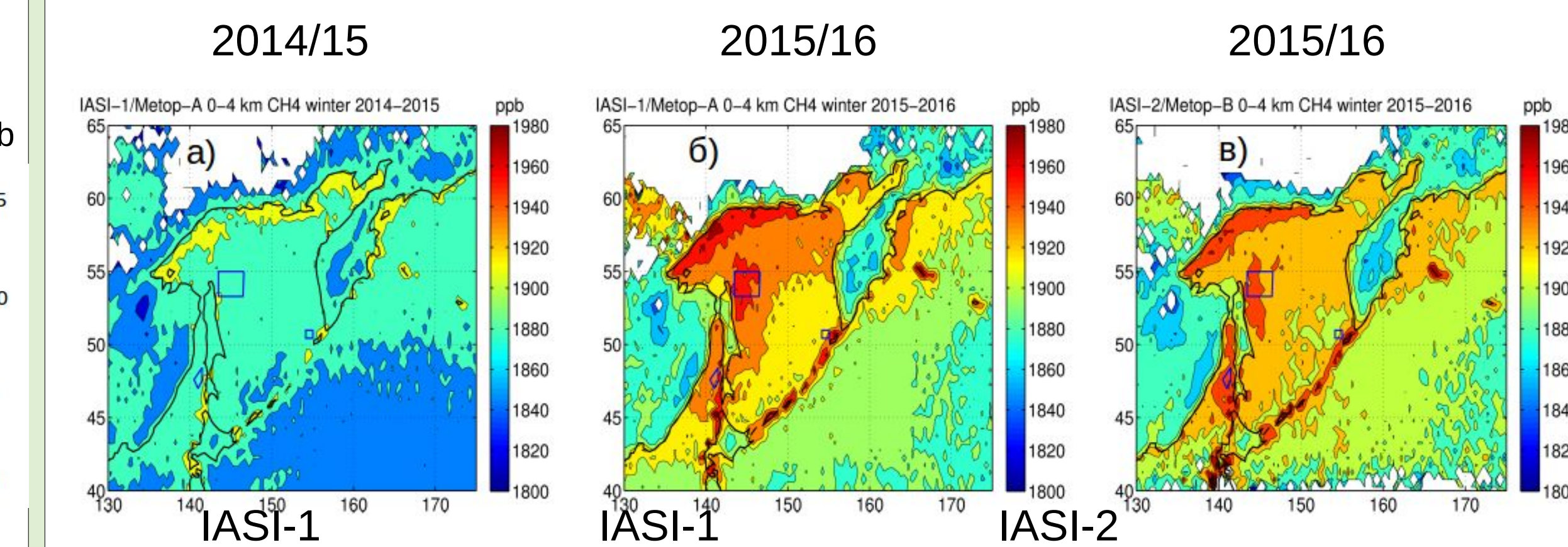


Methane anomaly (the difference between concentration near Svalbard and the N. Atlantic) is minimal in summer and maximal in winter. It correlates with the seawater MLD. A shallow pycnocline appears in May and disappears in November. The pycnocline separates surface mixed layer from deeper water. Mixing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

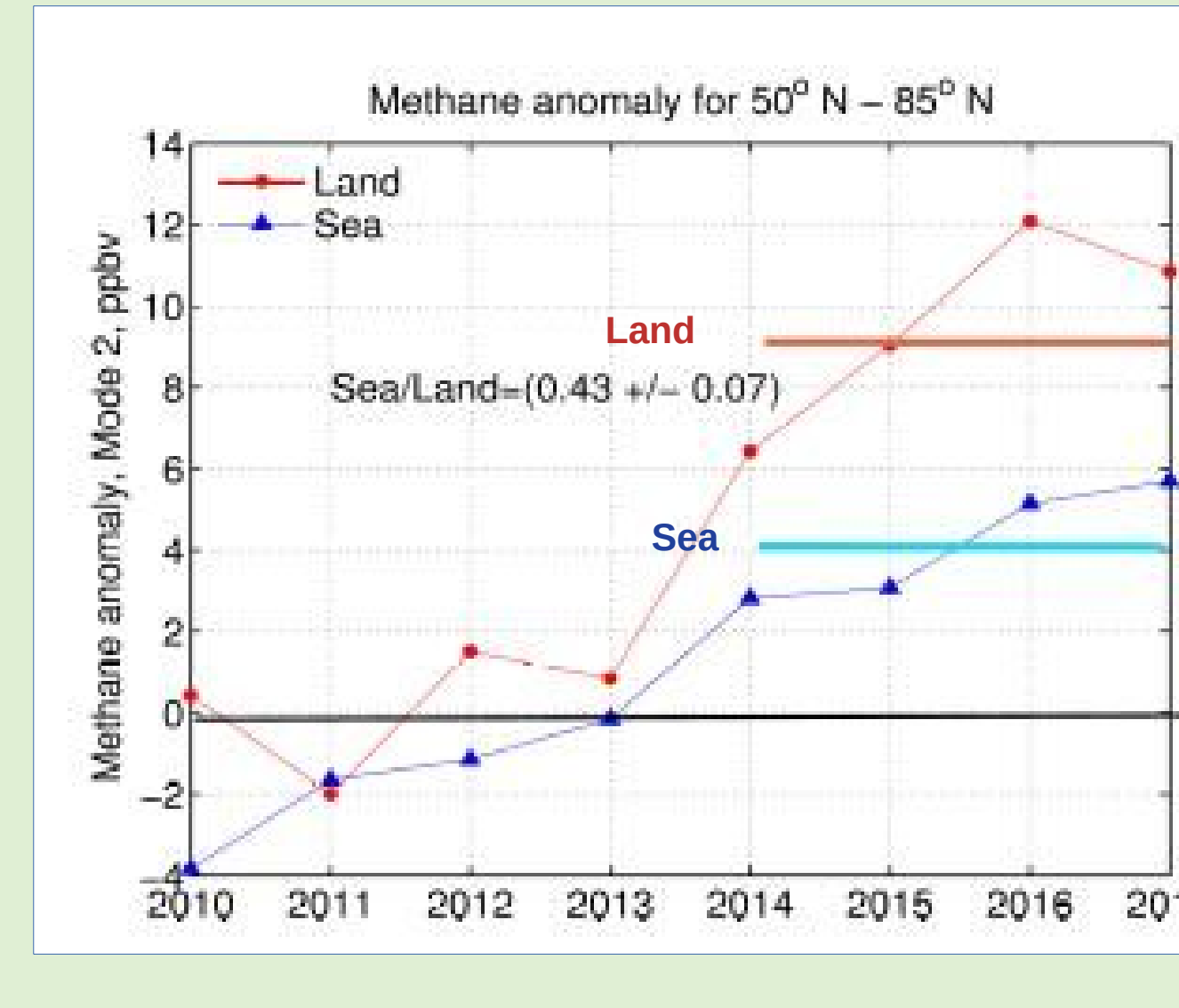
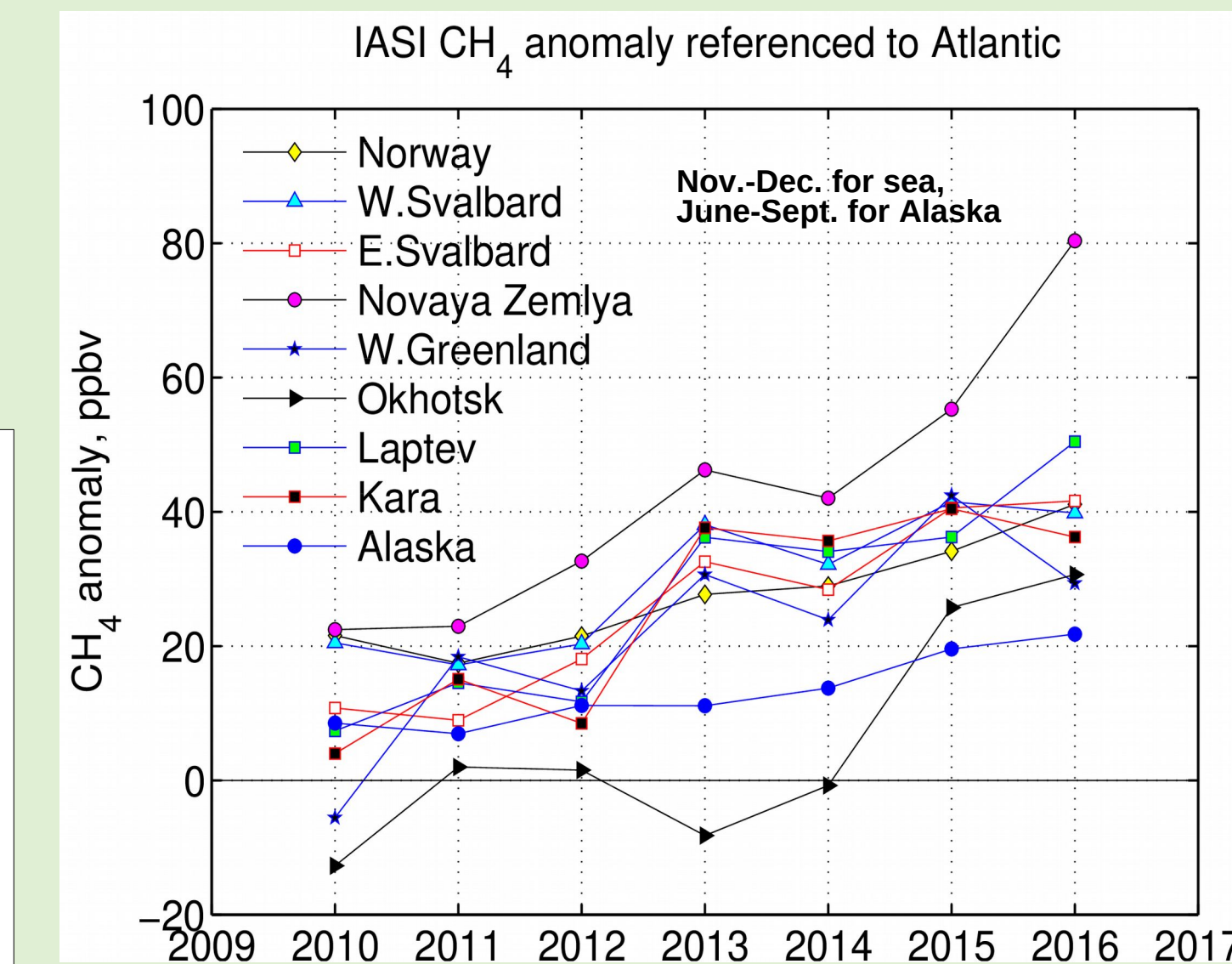
### East Sib. Arct. Shelf (ESAS): in situ and remote sensing



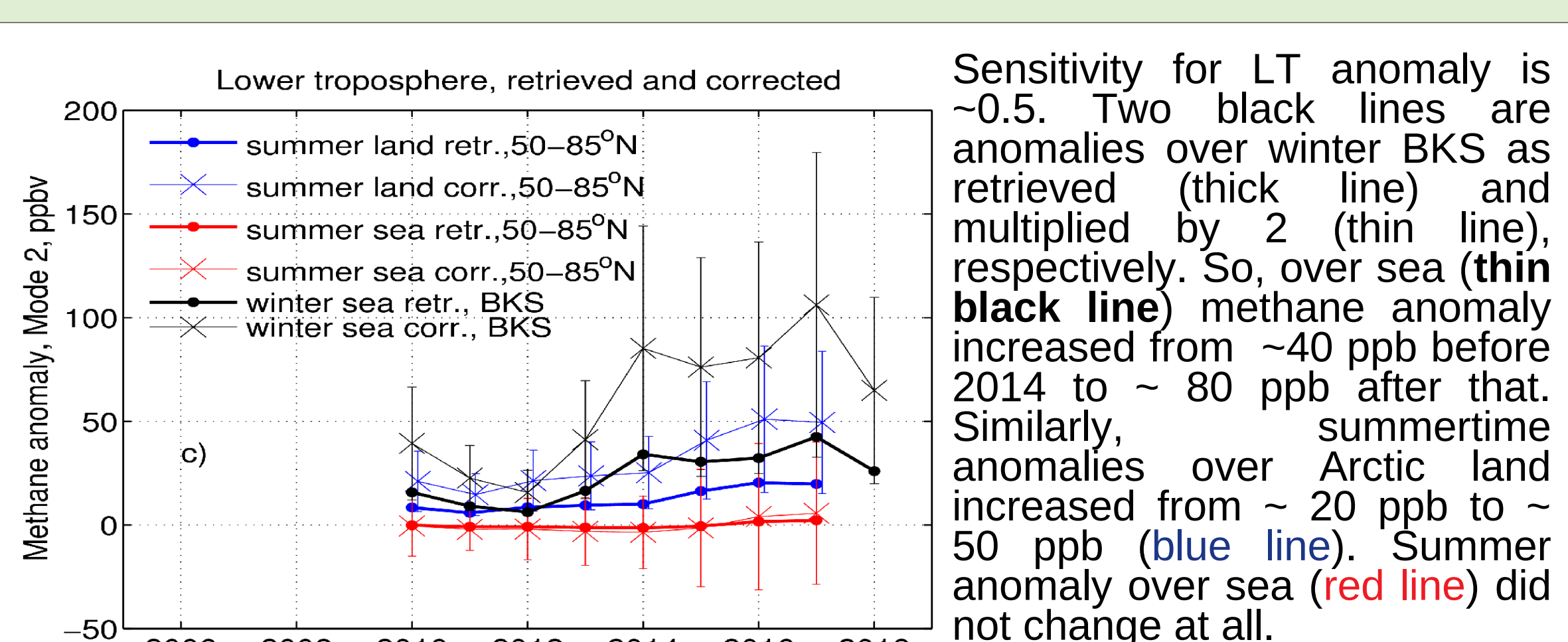
### Sea of Okhotsk: CH<sub>4</sub> VMR increase in 2015.12-2016.02 was detected by IASI-1 and IASI-2 (Yurganov & Leifer, 2016b)



### Anomalies for areas grow with years Annual zonal means for sea and land relate as 4 to 10

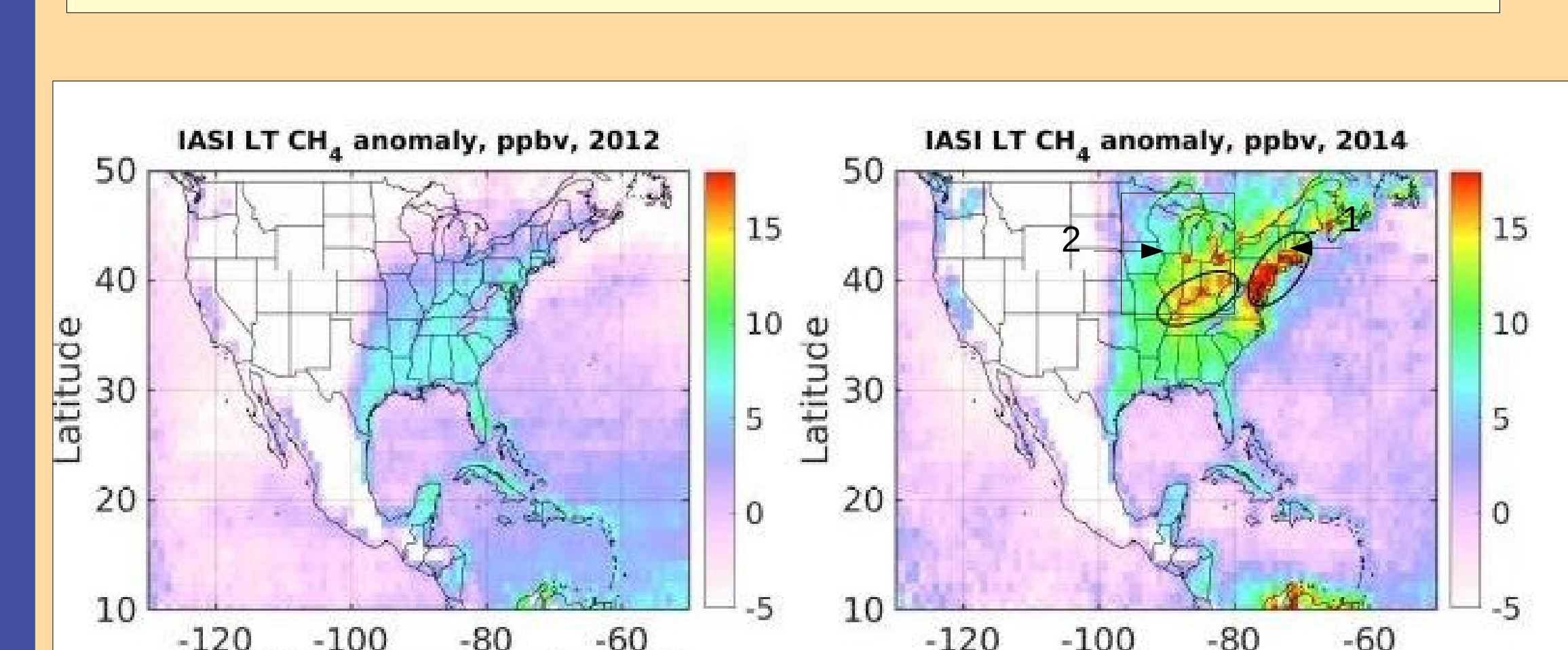


### LT anomaly may be corrected for a reduced sensitivity



## US CH<sub>4</sub> ANOMALIES

### REFERENCED TO PACIFIC



The LT annual anomalies are positive over land and an outflow 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.

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.

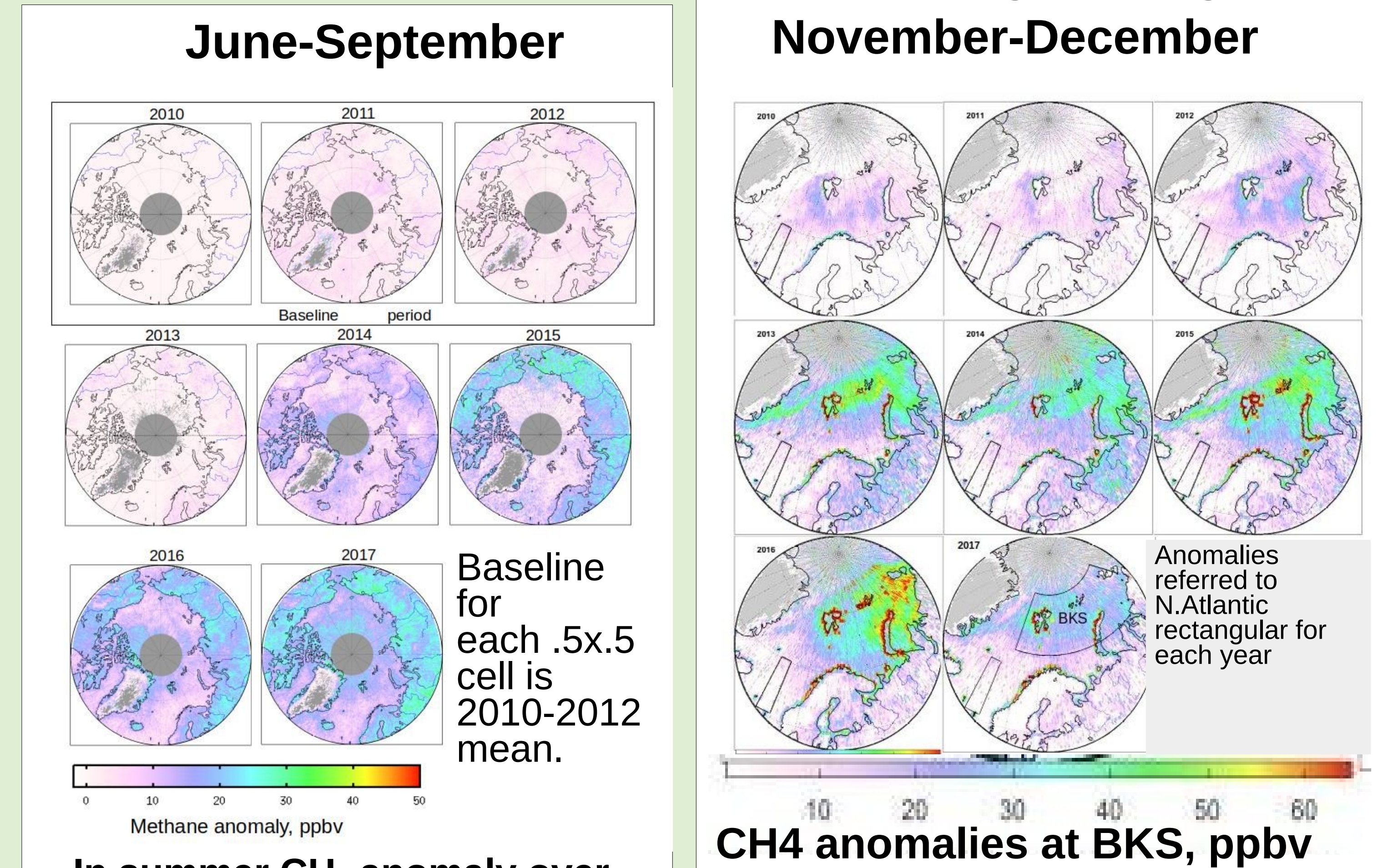
### REFERENCES

1. Leifer et al., The Cryosphere Discuss., <https://doi.org/10.5194/tc-2018-237>, in review, 2018.
2. McClimans, Rec. Res. Adv. In Fluid Mech. Turb. Jets Plumes, Kluwer Academic Publishers, Dordrecht, Germany, 1994.
3. Osterkamp, Subsea Permafrost. In: Climate and Oceans, Academic Press, 2010.
4. Shakhova et al., Science, 5:327(5970):1246–50, 2010

5. Turner et al. GRL, 43, 2218–2224, 2016
6. Yurganov et al., CPRSES, 13, 107–119, 2016
7. Yurganov and Leifer, CPRSES, 13, 173–183, 2016a
8. Yurganov and Leifer, CPRSES, 13, 231–234, 2016b
9. Yurganov et al., CPRSES, 14, 193–203, 2017

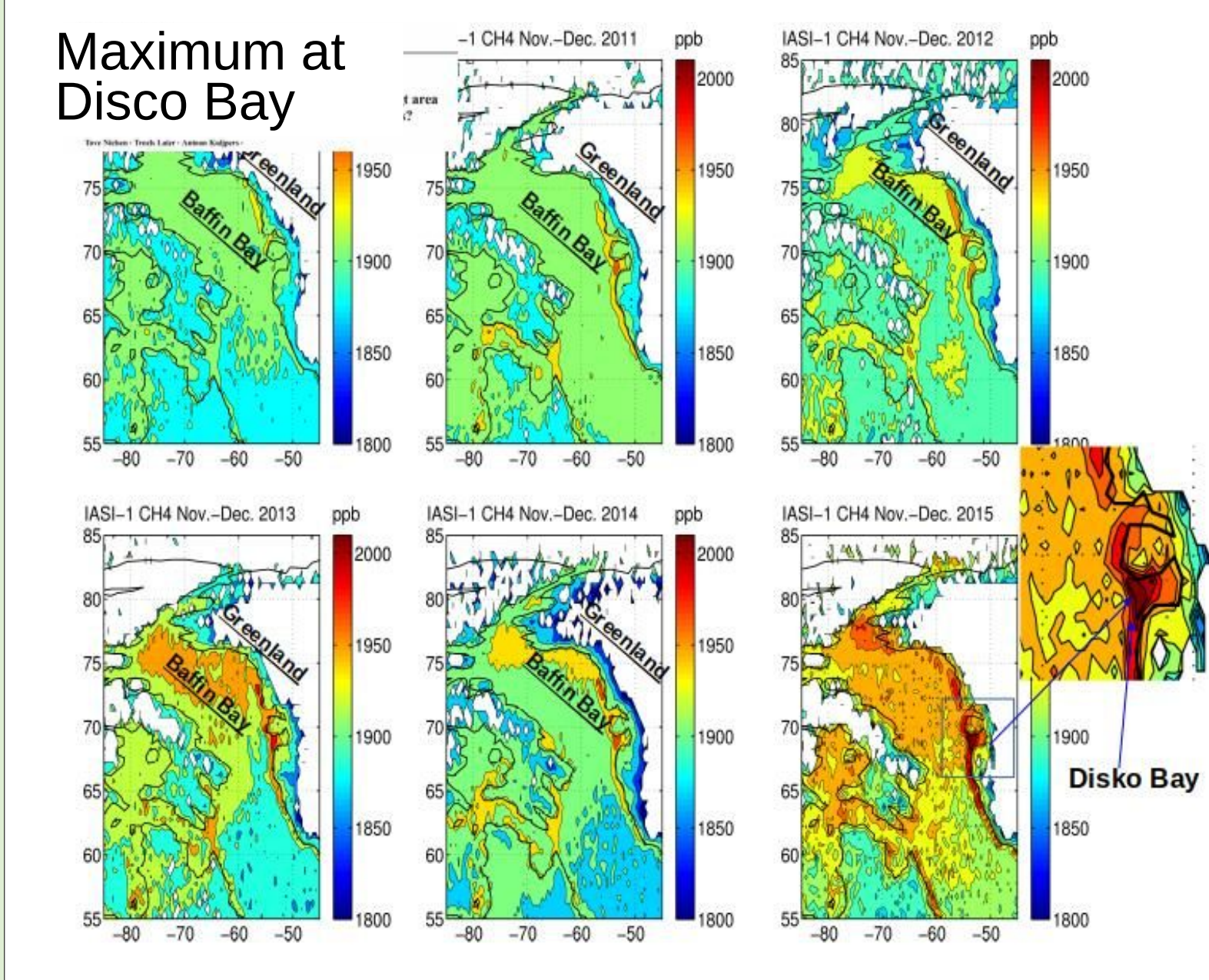
### IASI detected a few areas of marine methane positive anomalies late autumn-winter

### Methane anomalies are growing

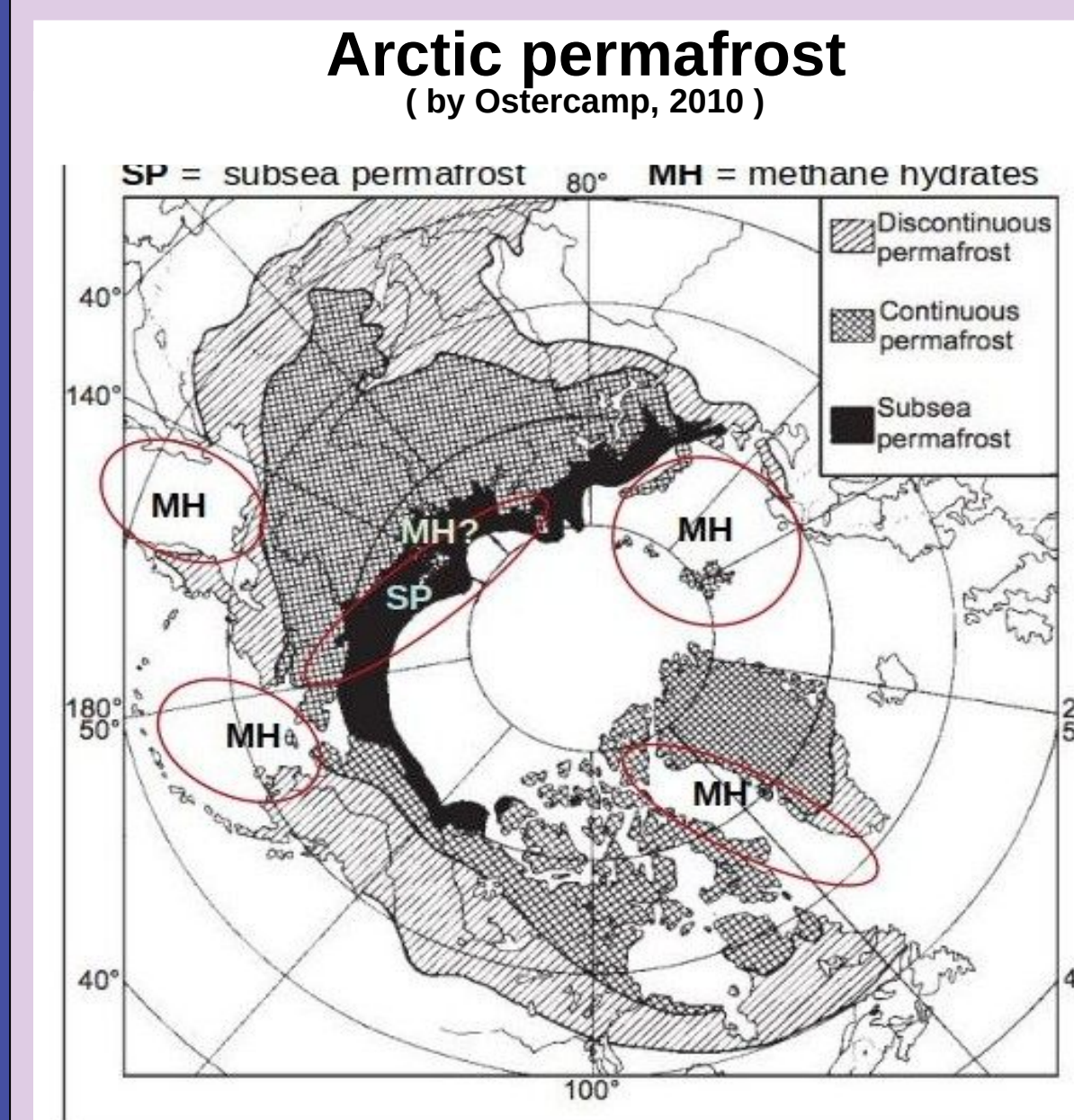


In summer CH<sub>4</sub> anomaly over land grows faster than over sea, sea-air flux is low

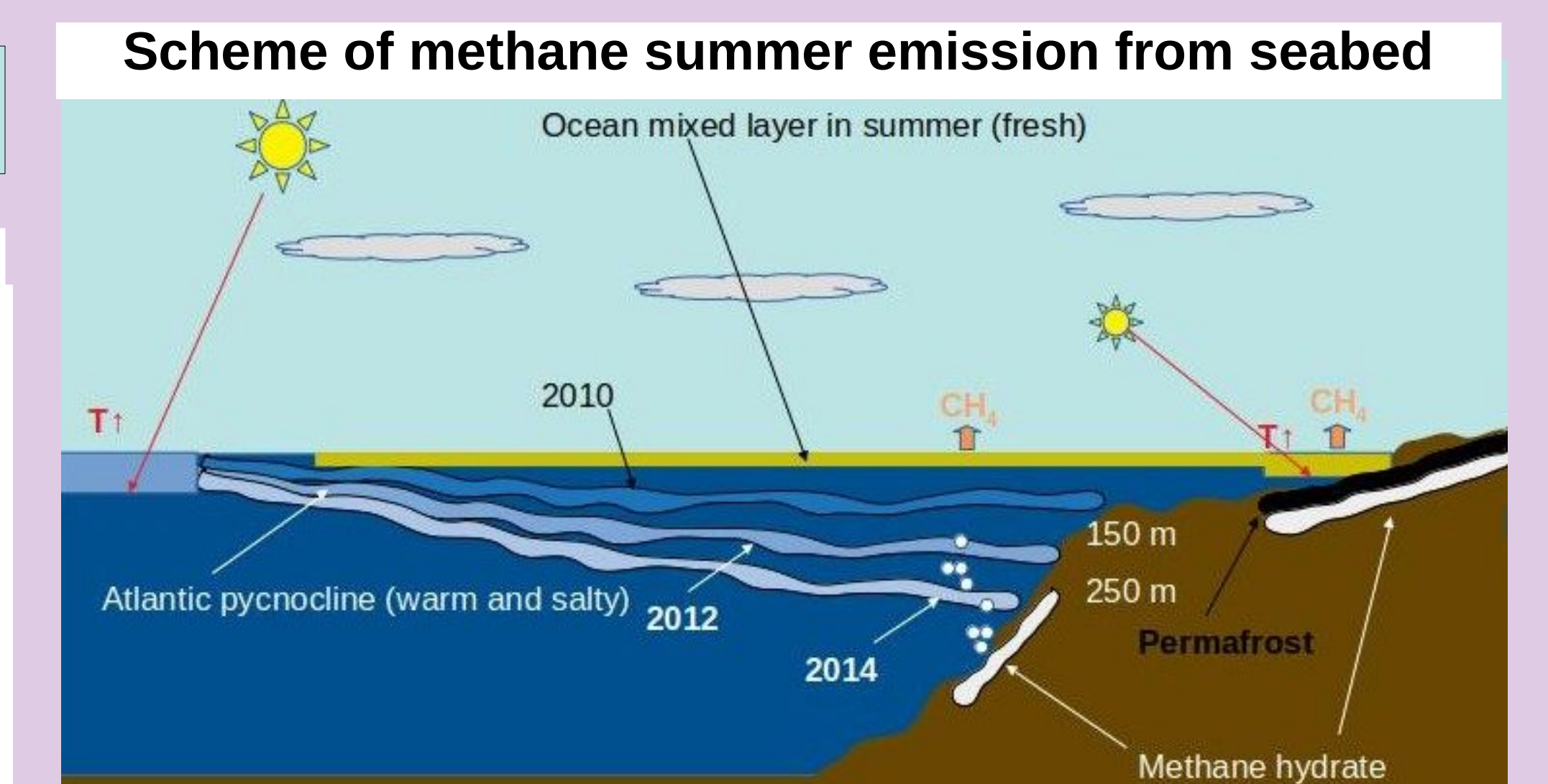
### To the W of Greenland:



## DISCUSSION



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



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<sub>4</sub> seabed emissions. For the shallow ESAS another mechanism works: ice retreat induces warming of sea water and increasing CH<sub>4</sub> 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 rate 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 CH<sub>4</sub> 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 CH<sub>4</sub> 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, CH<sub>4</sub> 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 CH<sub>4</sub> 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<sub>4</sub> may be a realization of a positive feed-back with temperature.

**Acknowledgements.** We appreciate a support from the NASA project “Science of Terra and Aqua: Long-term Satellite Data Fusion Observations of Arctic Ice Cover and Methane as a Climate Change Feedback”. NOAA made results of NUCAPS IASI retrievals publicly available. Dr. Colm Sweeney and Dr. Ed Dlugokencky (NOAA) contributed the most recent data of regular NOAA monitoring of methane.