Trends and variations in heat uptake of the Arctic climate system 1993-2019

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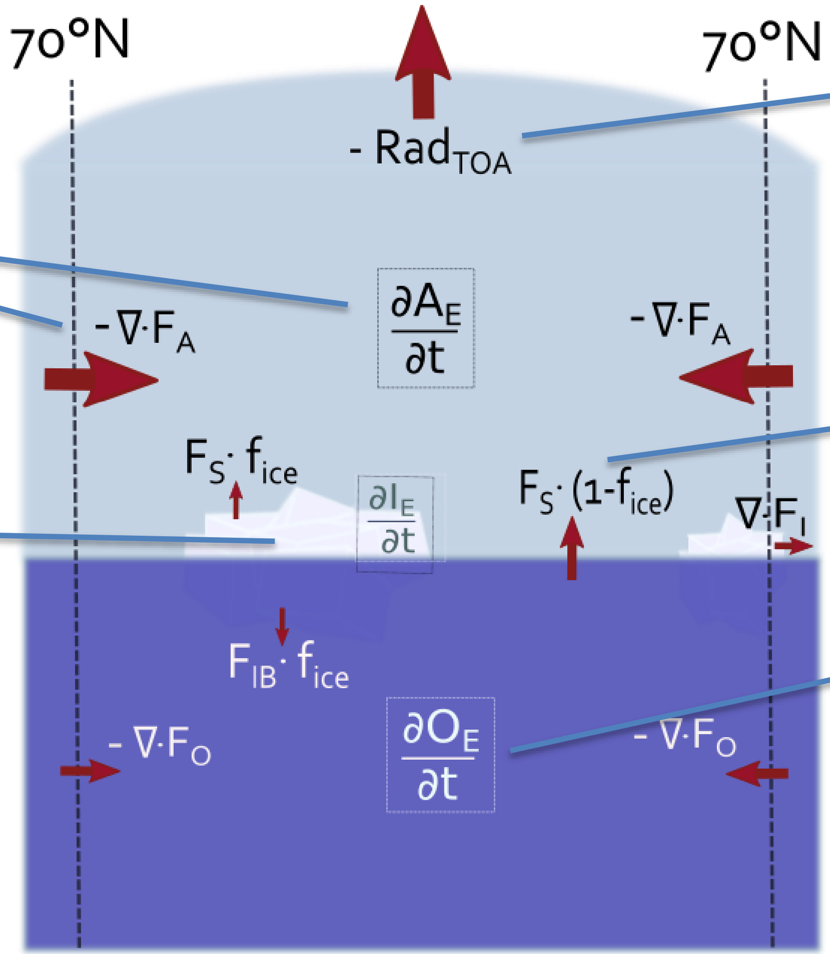
Introduction

- **In earlier studies** we found that
  - The rate of long-term Arctic energy accumulation as estimated from observations and reanalyses is similar to the global average, with 2/3 of the absorbed heat going into the ocean and 1/3 going into sea ice melt (when considering 70N-90N). Negligible amounts of energy are absorbed by the atmosphere. This reveals an interesting facet of “Arctic Amplification”: it can be seen in tropospheric air temperatures, but not in vertically integrated ocean warming (Mayer et al. 2019)
  - While the long-term heat accumulation in the Arctic is similar to its global average, we find an amplification of the seasonal cycle of Arctic heat budgets, with enhanced heat uptake in summer and enhanced heat release in fall, with interesting implications for seasonal atmospheric energy transports (Mayer et al. 2016)
- **In this contribution**, we provide updated diagnostics of the trends in the Arctic energy budget, using new data and longer time series
  - Atmospheric energy transports from ECMWF’s ERA5 reanalysis
  - Ocean heat content data from the Copernicus Marine Environment Service’s (CMEMS) Global Reanalysis Product (GREP), including 4 global ocean reanalyses ran at ¼° resolution
  - Study period encompasses 1993-2019 for ocean heat content evolution and 2000-2019 for exploration of seasonal budget trends

Data used in this presentation

Atmospheric energy transport and storage (ERA5)

Sea ice mass changes (ocean reanalysis)



Net radiation at top-of-the atmosphere (satellite data CERES-EBAF v4.1 and data from University of Reading)

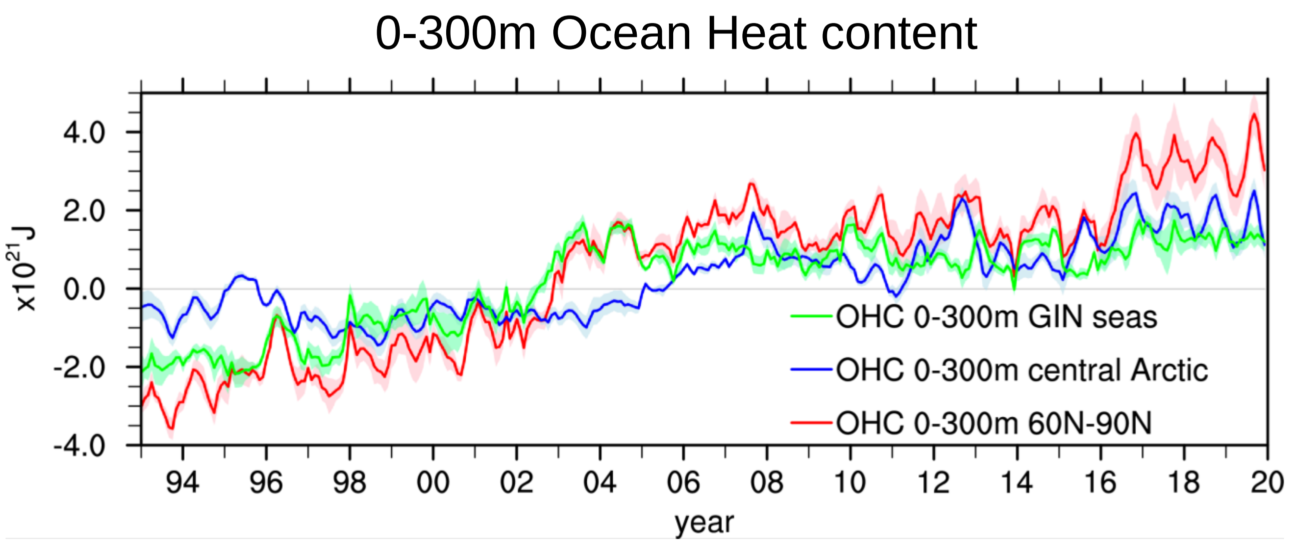
Net surface energy flux inferred from atmospheric budget, i.e. as a residual from Rad$_{TOA}$, atmospheric energy convergence and storage

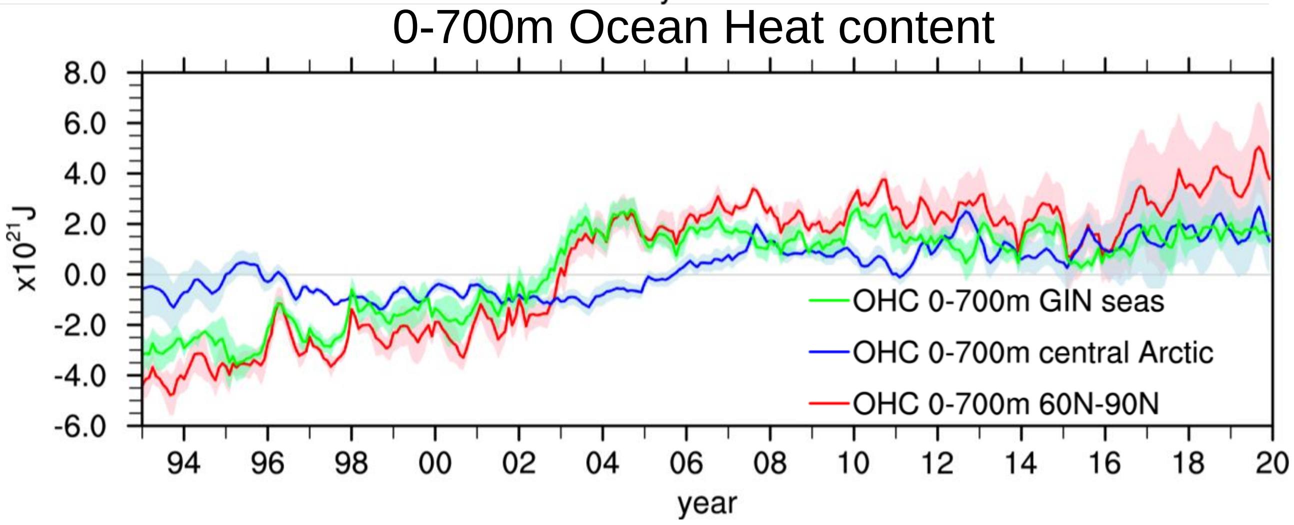
Ocean heat content changes from CMEMS GREP ensemble

For quantification of oceanic transports see Mayer et al. 2019!

Arctic ocean warming 1993-2019

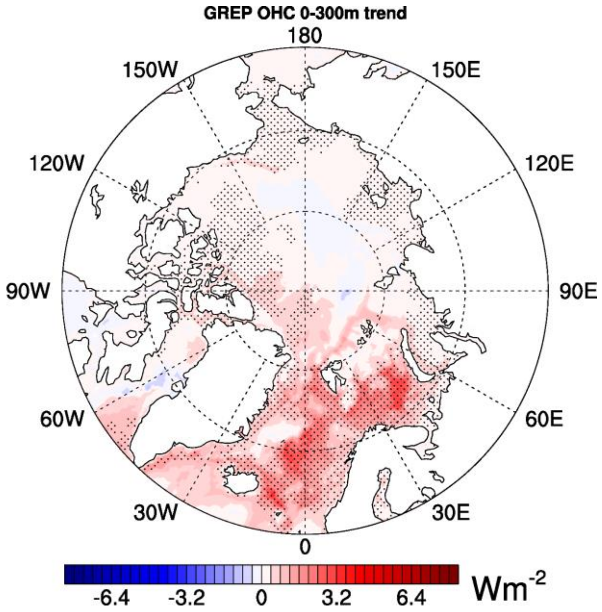
- These are time series of ocean heat content (OHC) anomalies 1993-2019 (w.r.t 1993-2014 climatology)
- Shown are values for all ocean north of 60N and two sub-regions Greenland-Iceland-Norwegian („GIN“) Seas and „central Arctic“ (basically everything north of 60N minus GIN seas)
- We see
  - Rapid OHC increase in 2002-2004 stems from GIN Seas
  - Upper 300m and upper 700m OHC evolution is very similar
  - Slightly enhanced signals and moderately increased spread in OHC 0-700m compared to 0-300m

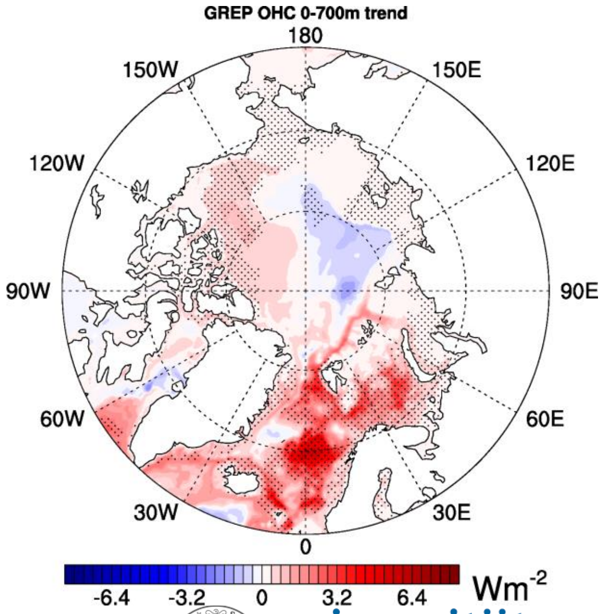




Spatial patterns of Arctic ocean warming 1993-2019

- Maps on the right show pointwise linear trends of ensemble mean OHC (converted to warming in Wm^{-2}), including stippling where trends are significant at 95% confidence level
- Uncertainty for significance testing factors in both random and structural uncertainty
- Ensemble mean linear OHC trends 1993-2019 show strongest warming in GIN Seas and Barents Sea Opening
- Strongest warming found in Norwegian Seas (order $5Wm^{-2}$)
- Weaker but still significant warming in Beaufort Gyre



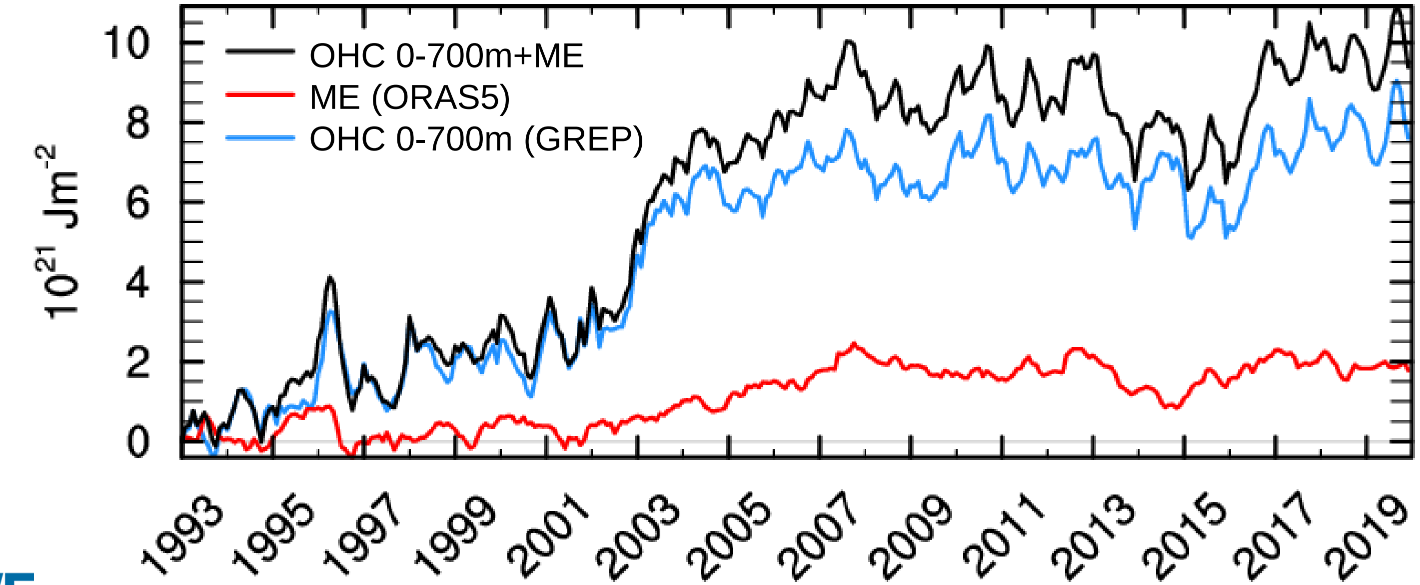


OHC linear trends 1993-2019 (asterisk denotes significant trends)

	Arctic Ocean 60N-90N		Central Arctic Ocean		GIN seas	
	Wm^{-2}	TW	Wm^{-2}	TW	Wm^{-2}	TW
0-300m	0.43±0.06*	7.5±1.0*	0.29±0.07*	3.3±0.8*	1.00±0.23*	3.9±0.9*
0-700m	0.55±0.14*	9.5±2.5*	0.29±0.11*	3.3±1.3*	1.47±0.50*	5.8±1.9*

Heat uptake by sea ice melt

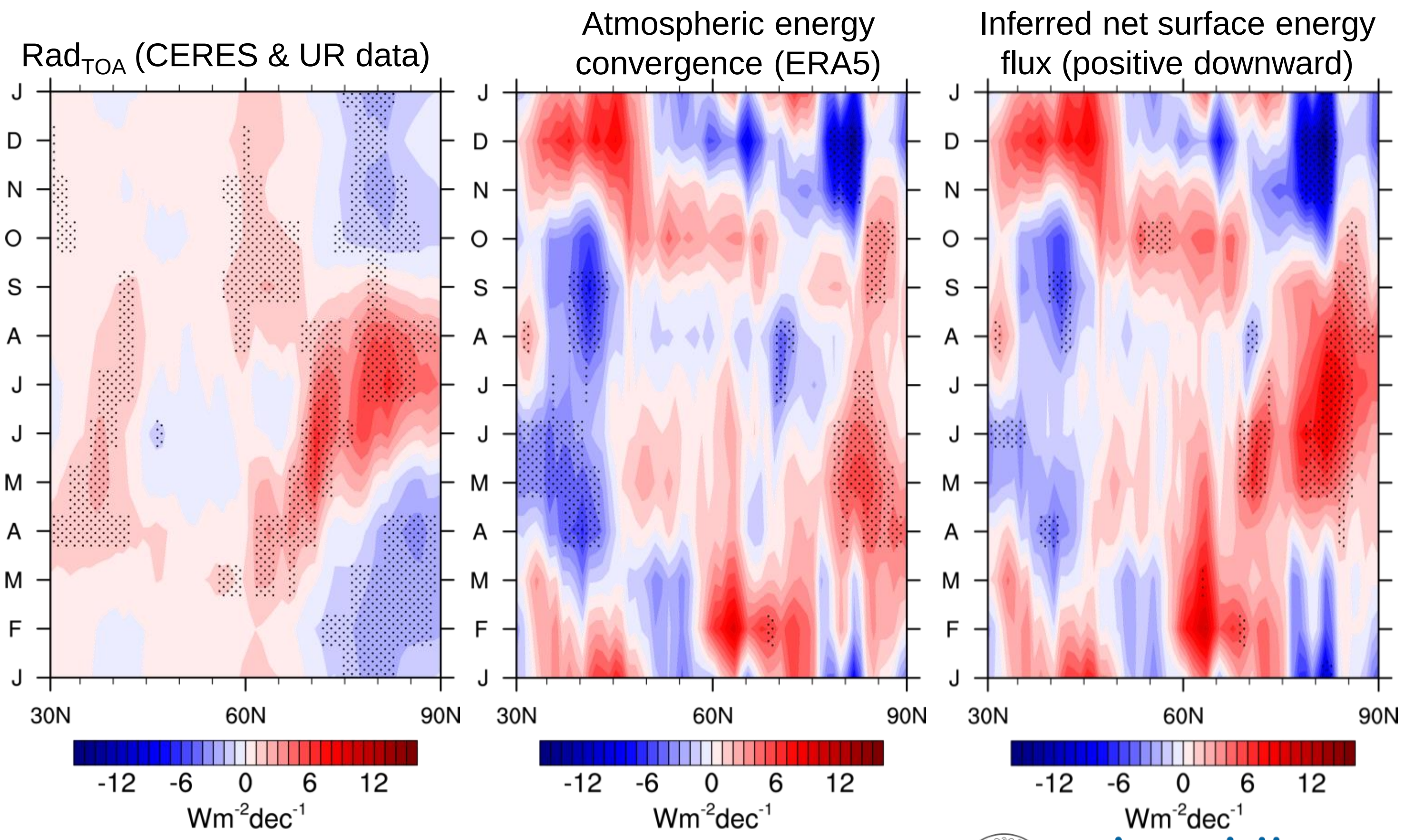
- This time series shows 0-700m OHC increase and the energy required for sea ice melt (ME) north of 60N
- Linear 1993-2019 trends are 0.55±0.12 Wm^{-2} for OHC and 0.15±0.04 Wm^{-2} for ME
- For the ocean north 60N, only ~21% of heat uptake goes into sea ice melt (because the sea ice area is relatively small)
- The rate of OHC+ME accumulation north of 60N is 0.70±0.16 Wm^{-2}. The global mean 0-700m OHC increase in GREP is 0.82±0.08 Wm^{-2} (also 1993-2019). This confirms our earlier finding that the vertically integrated long-term warming of the Arctic currently is not enhanced compared to the global energy imbalance.



Note that here we show sea ice data only from ECMWF's ocean reanalysis ORAS5

Trends in seasonal cycle of Arctic energy budget 2000-2019

- Here we explore seasonal trends in the Arctic energy budget
- The figures show linear seasonal trends of relevant atmospheric energy budget terms as a function of latitude and calendar month (data includes only land points to be consistent with oceanic fields – see next slide)
- Rad_{TOA} in the Arctic exhibits marked positive trends in summer (ice-albedo feedback) and negative trends in fall-winter
- Atmospheric energy convergence has a positive trend north of 80N in spring and early summer (=stronger poleward heat transports) and a pronounced negative trend at 75-85N in fall
- Net surface energy flux has a strongly positive trend in summer (mainly driven by Rad_{TOA} trends) and a negative trend in fall (stemming from negative trends in atmospheric heat convergence)



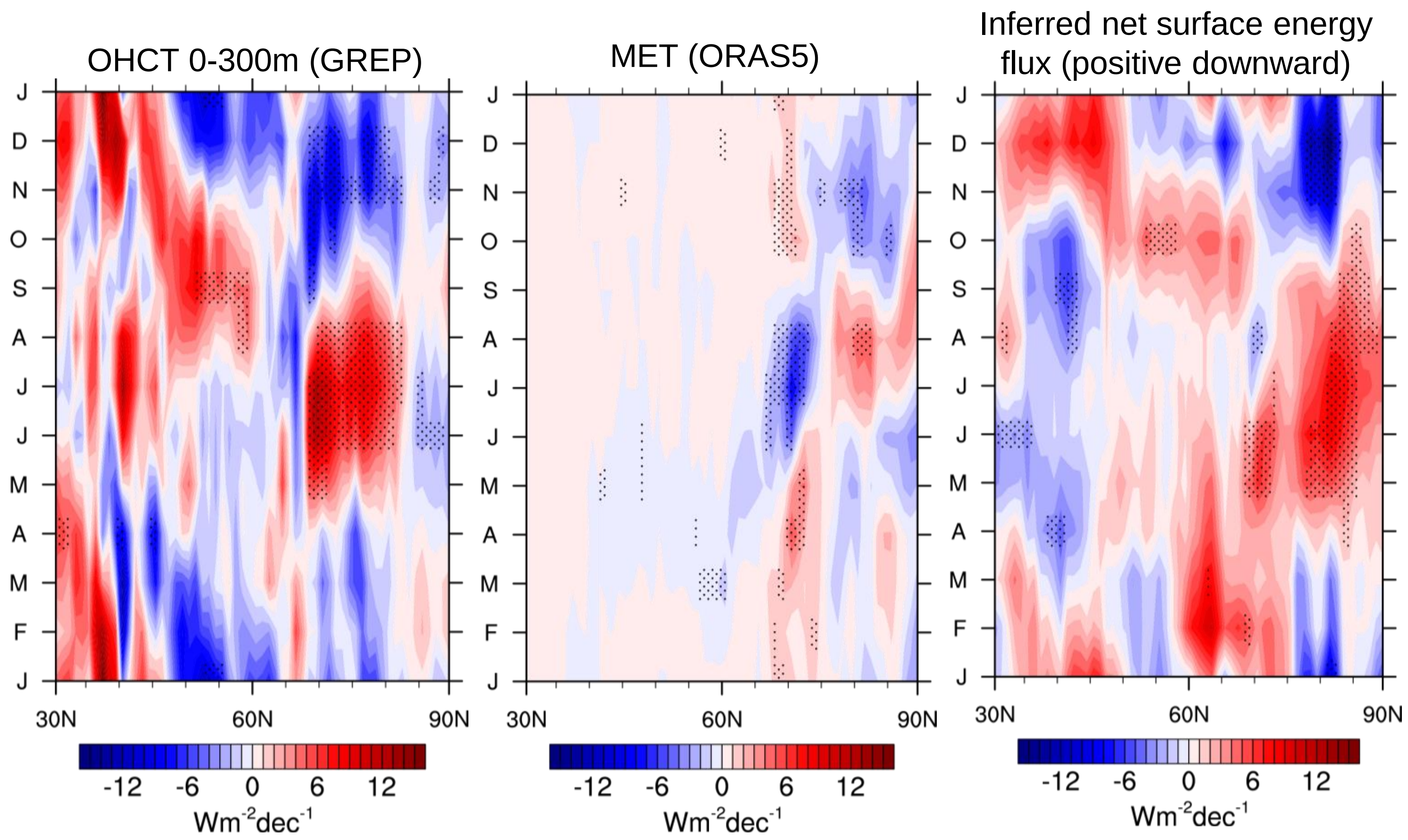
Trends in seasonal cycle of Arctic energy budget 2000-2019

- Now we have a look at seasonal trends in oceanic heat storage: ocean heat content tendency (OHCT=monthly rate of OHC change) and melt energy tendency (MET=monthly rate of energy required for sea ice mass change; positive for melt, negative for freeze)

- Evidently most of the net surface flux trends is balanced by trends in OHCT: stronger warming in summer, stronger cooling in fall)

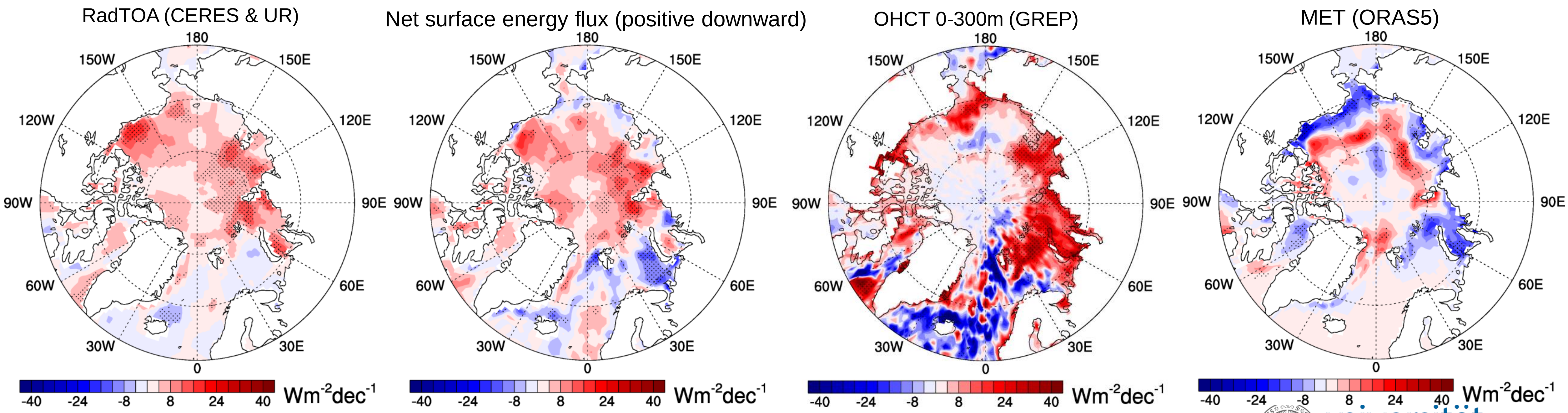
- MET trends show stronger melt around 70-75N in spring (earlier start of the melt season) and stronger high latitude melt in summer. Negative trends at 70-75N in JJA is because there is a trend towards ice-free conditions (thus leaving nothing to melt in JJA)

- Negative MET trends in fall suggest a trend towards stronger refreeze



Summer (JJA) trends in the energy budget 2000-2019

- The maps below show linear trend maps for some fields with pronounced trends in JJA
- We can see positive Rad_{TOA} trends where sea ice declines. **Rad_{TOA} trends govern the surface flux trends.**
- Seasonal warming of the ocean (OHCT) shows strongly positive trends where sea ice declines, while sea ice melt gets enhanced towards the north and weakened towards the south (where less ice is available to melt)
- OHCT trends are stronger than implied by surface flux trends – an apparent data inconsistency (possibly cold ocean biases below sea ice, mixed layer depth biases, etc…)



ECMWF

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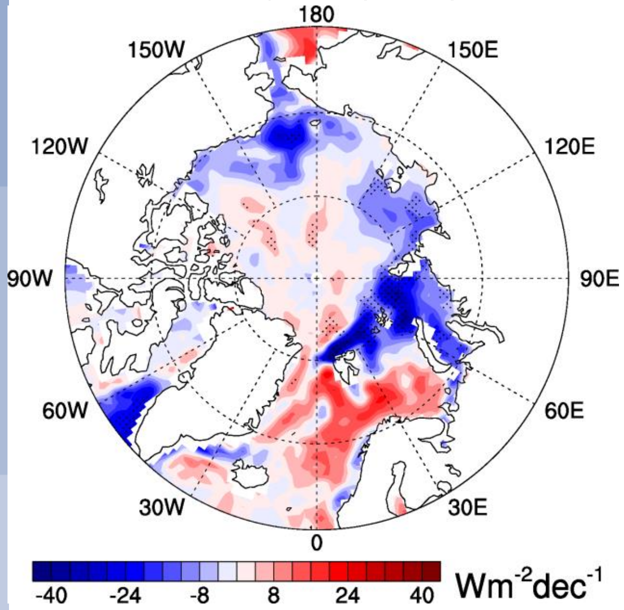
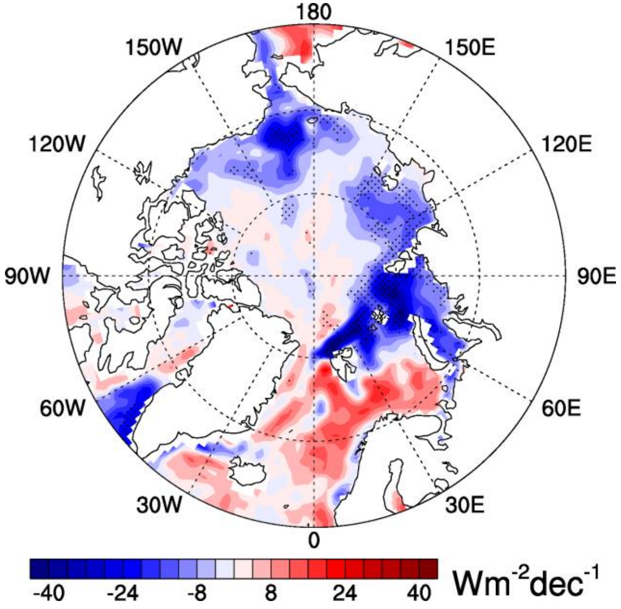
Autumn (OND) trends in the energy budget 2000-2019

- The maps below show linear trend maps for some fields with pronounced trends in OND
- We see strongly negative net surface flux trends in areas with reduced sea ice concentration
- **Surface flux trends are largely governed by trends in atmospheric heat convergence**
- Surface flux trends balance enhanced seasonal ocean cooling (negative OHCT trends) and enhanced sea ice refreeze (negative MET trends)

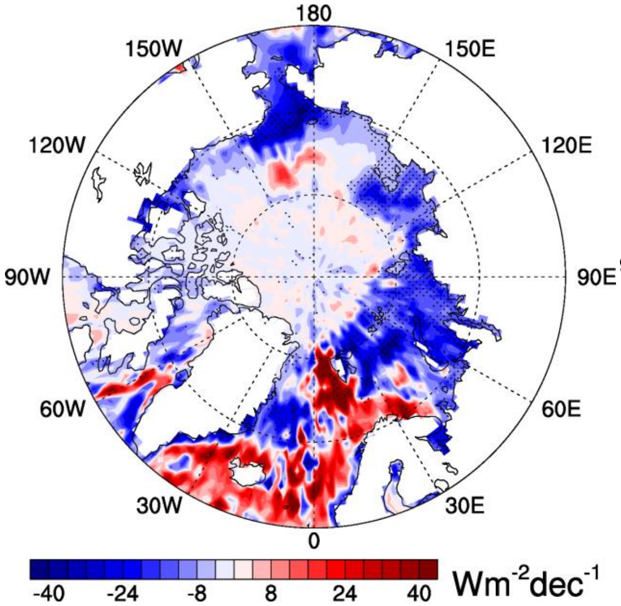
Atmospheric energy convergence (ERA5)



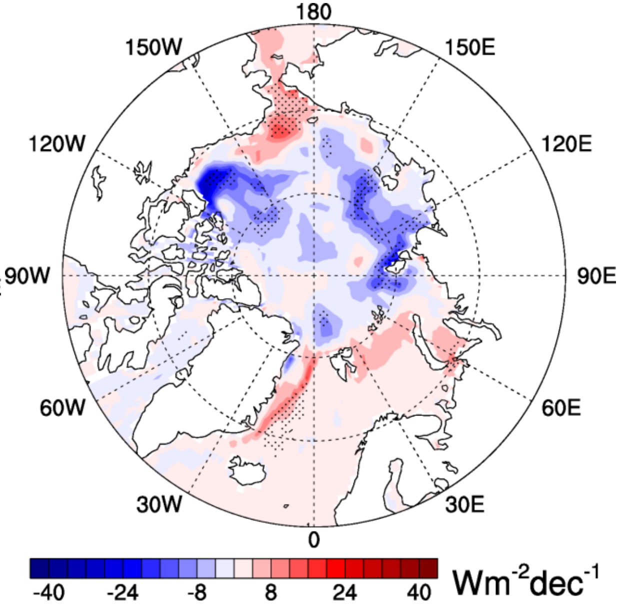
Net surface energy flux (positive downward)



OHCT 0-300m (GREP)

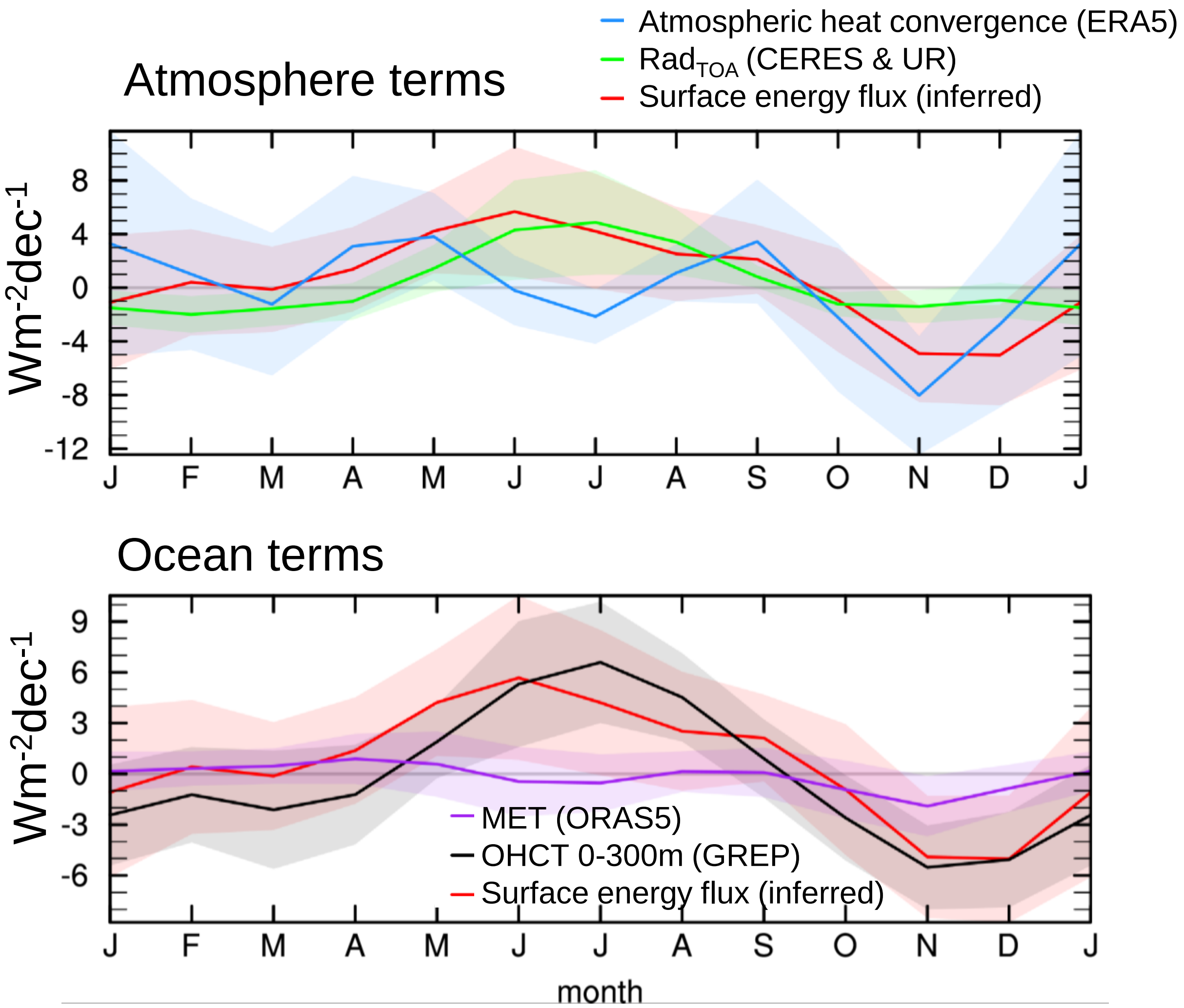


MET (ORAS5)



Trends in the seasonal cycle of the heat budget 70N-90N

- As a summary diagnostic, we look at decadal trends in the seasonal cycle of the Arctic heat budget (area-averages 70-90N). Shading shows 90% confidence intervals.
- One can see that positive surface energy flux trends in summer are driven by stronger energy absorption at TOA, while the negative trend in fall is at least partly balanced by a (significant) reduction in atmospheric heat convergence
- The agreement between area-averaged OHCT and surface flux trends is good, which indicates that seasonal trends in ocean heat transports play a minor role
- The net energetic effect of seasonal trends in sea ice growth/loss is small in an area-averaged sense



Conclusions

- We presented diagnostics of trends in the Arctic energy budget, using new observational and reanalysis data and a longer study period than before.
- The warming rate of the Arctic Ocean north of 60N is 0.70±0.16 Wm^{-2} (1993-2019), with ~80% of that energy going into ocean warming and 20% going into sea ice melt. This warming rate is similar to the global energy imbalance.
- The seasonal cycle of the Arctic has amplified over the past 20 years (2000-2019), with interesting asymmetries:
  - The enhanced OHC seasonal cycle is mainly balanced by surface energy flux
  - In summer, surface flux trends are largely driven by enhanced radiative energy input
  - In fall, however, enhanced surface heat loss reduces meridional temperature gradients. As a result, atmospheric heat convergence in the Arctic (north of 70N) is reduced
  - Consequently, poleward atmospheric heat transport across 70N in autumn show a declining trend over 2000-2019
- The main features of the trends in the seasonal cycle are robust. It will be interesting to assess the atmospheric transport trends in more detail. Does this have implications for lower latitudes?

Further reading

- Mayer, M., Tietsche, S., Haimberger, L., Tsubouchi, T., Mayer, J. and Zuo, H. (2019), ‘An improved estimate of the coupled arctic energy budget’. *Journal of Climate*, 32(22), 7915-7934.T
- Mayer, M., Haimberger, L., Pietschnig, M., & Storto, A. (2016). Facets of Arctic energy accumulation based on observations and reanalyses 2000–2015. *Geophysical research letters*, *43*(19), 10-420.