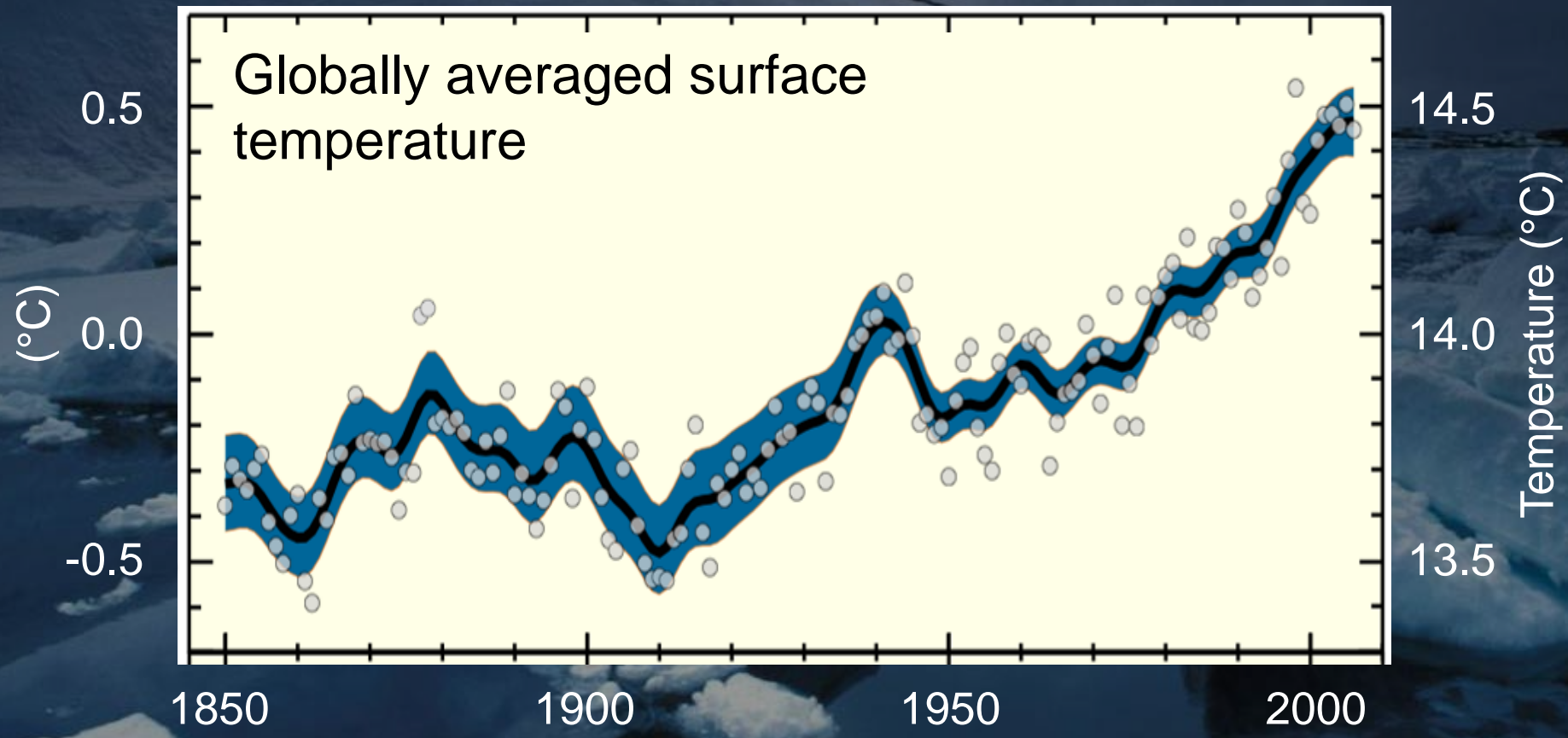


The vertical structure of Arctic warming

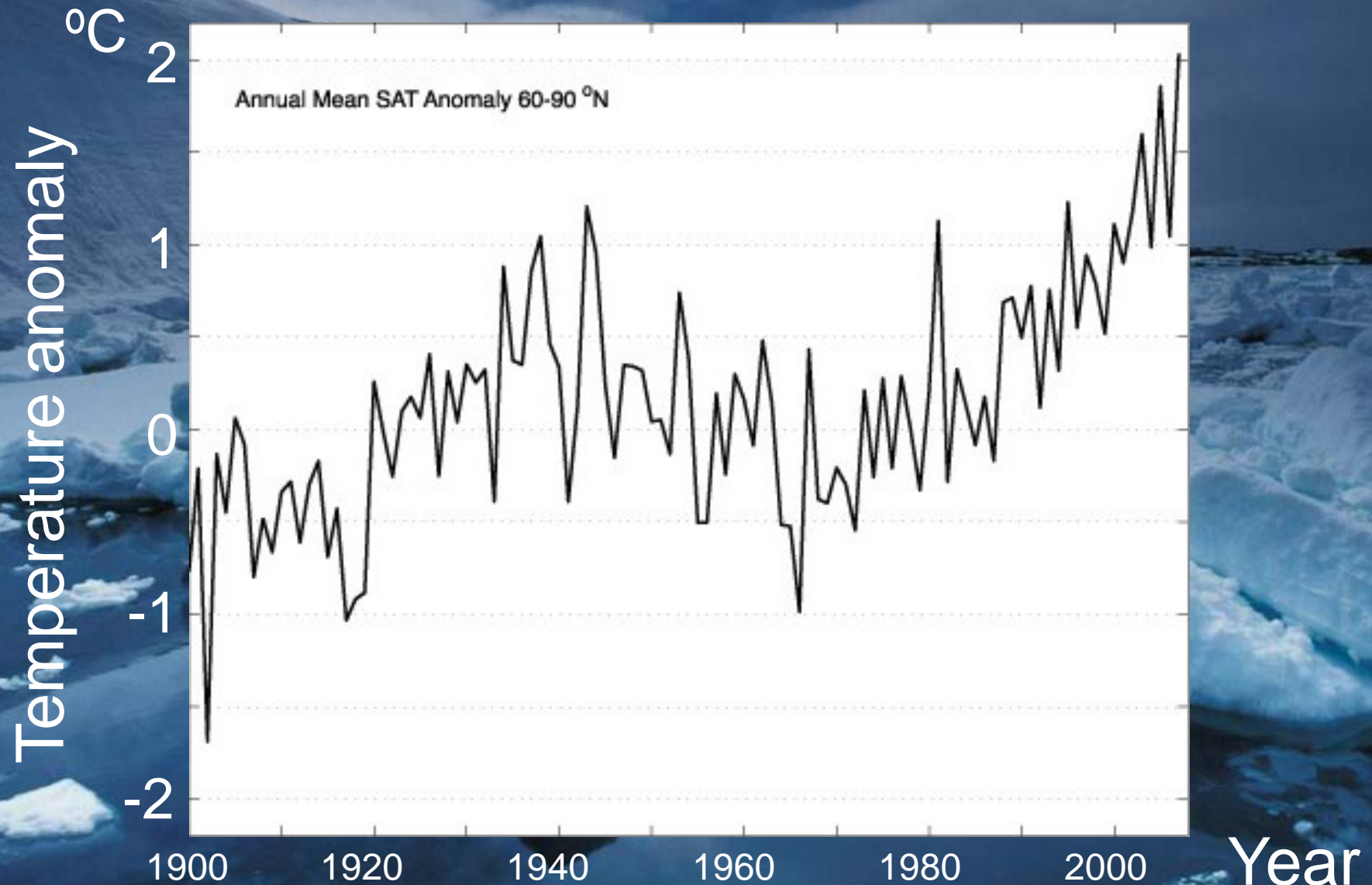
Erland Källén
Department of Meteorology
Stockholm University
Sweden



Global warming



Arctic warming



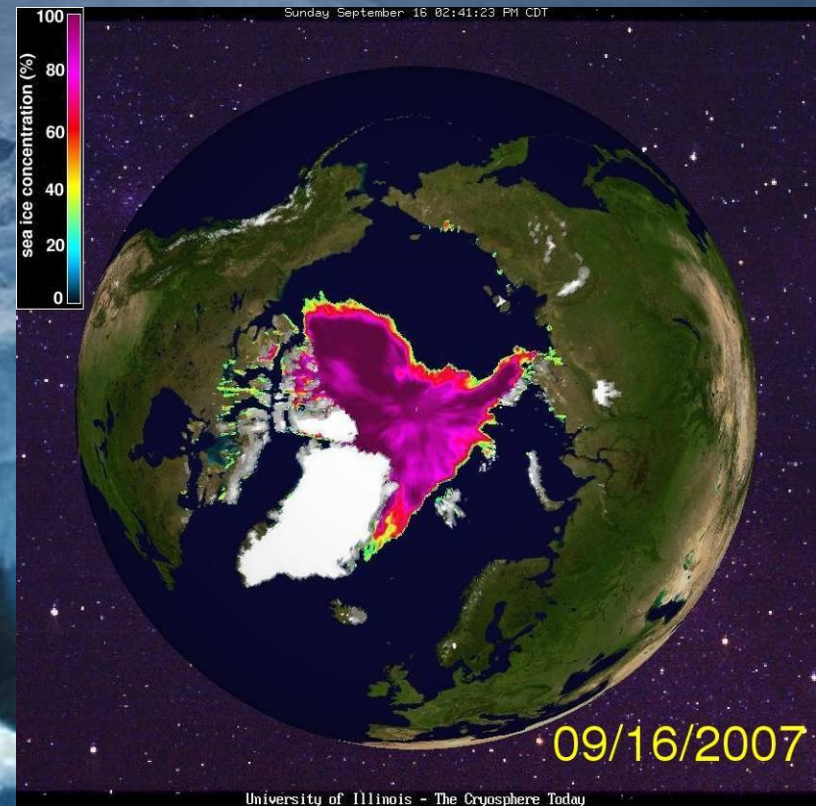
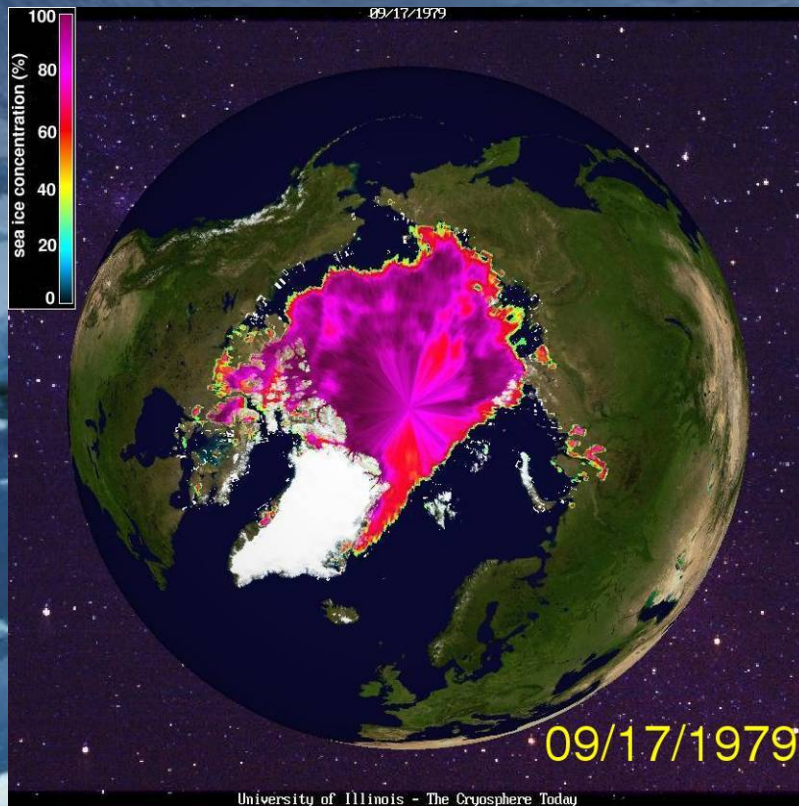
Effects of Arctic warming

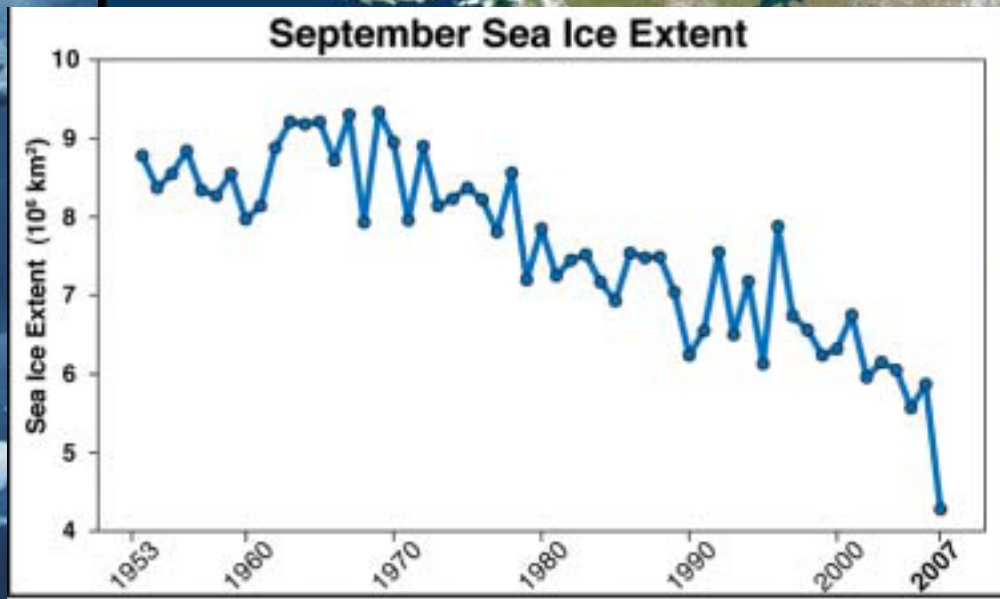
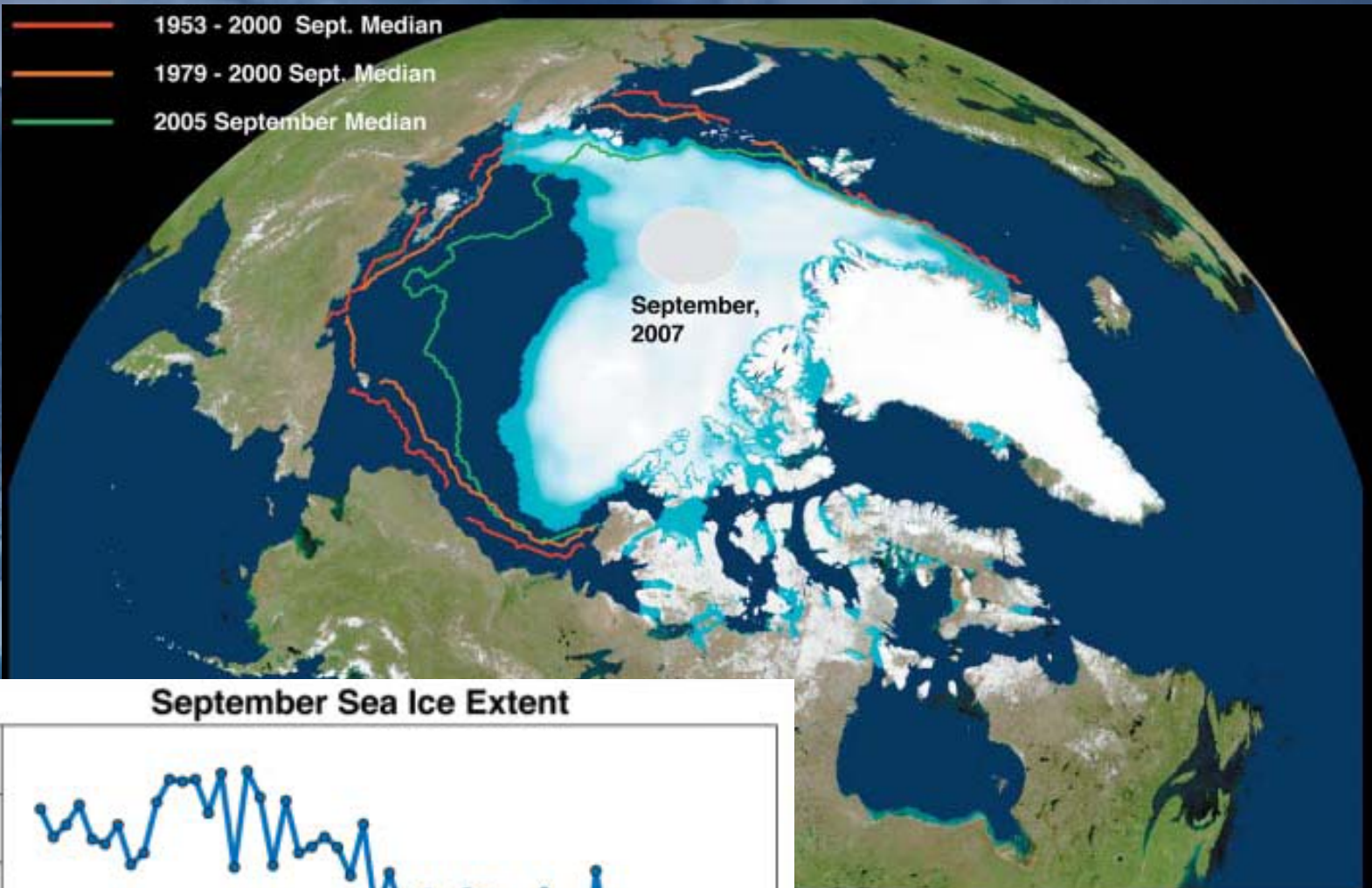
- Retreat of Arctic sea ice
- Melting of glaciers
- Shrinking snow and permafrost areas

Arctic sea ice September

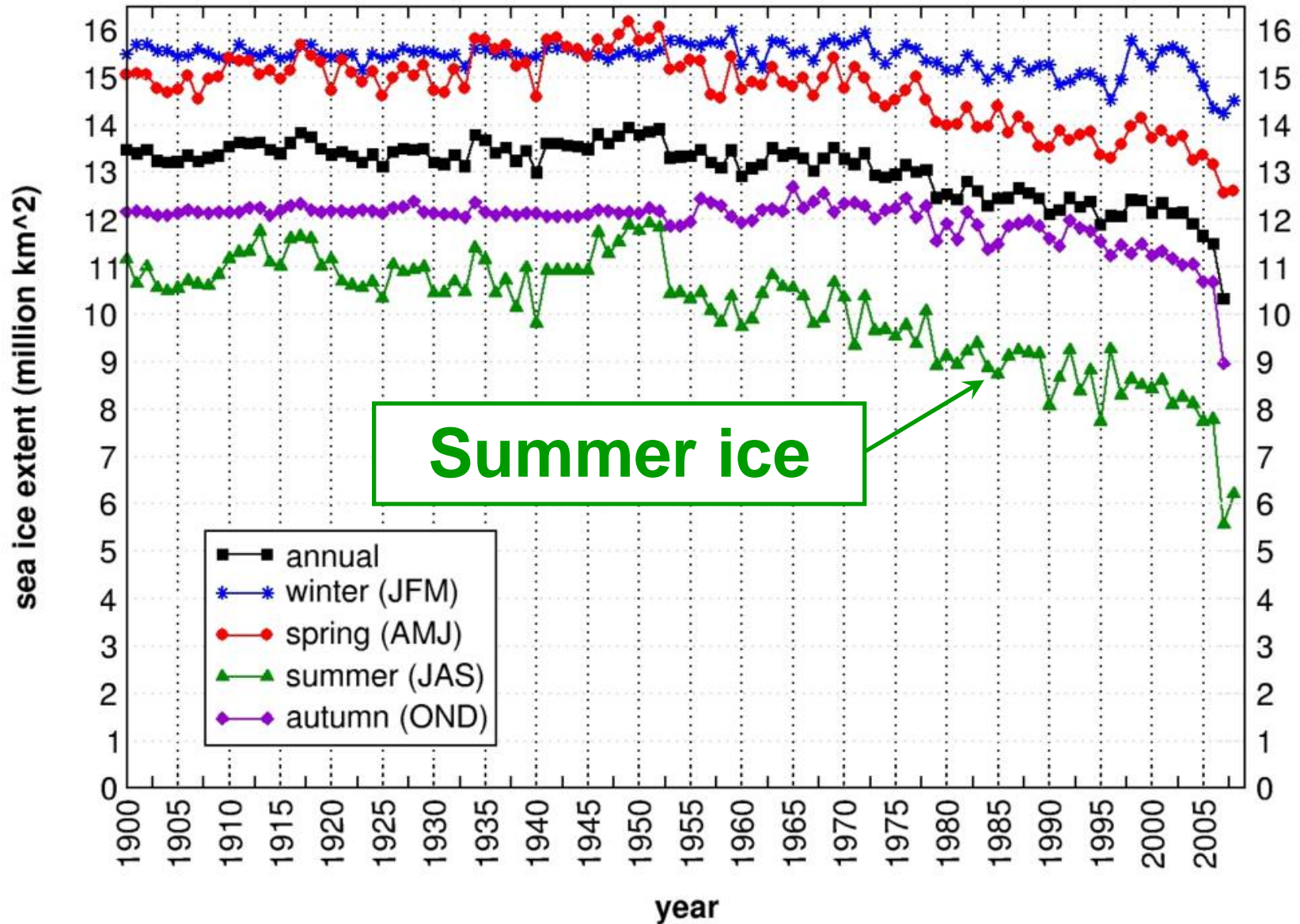
1979

2007





Arctic sea ice extent



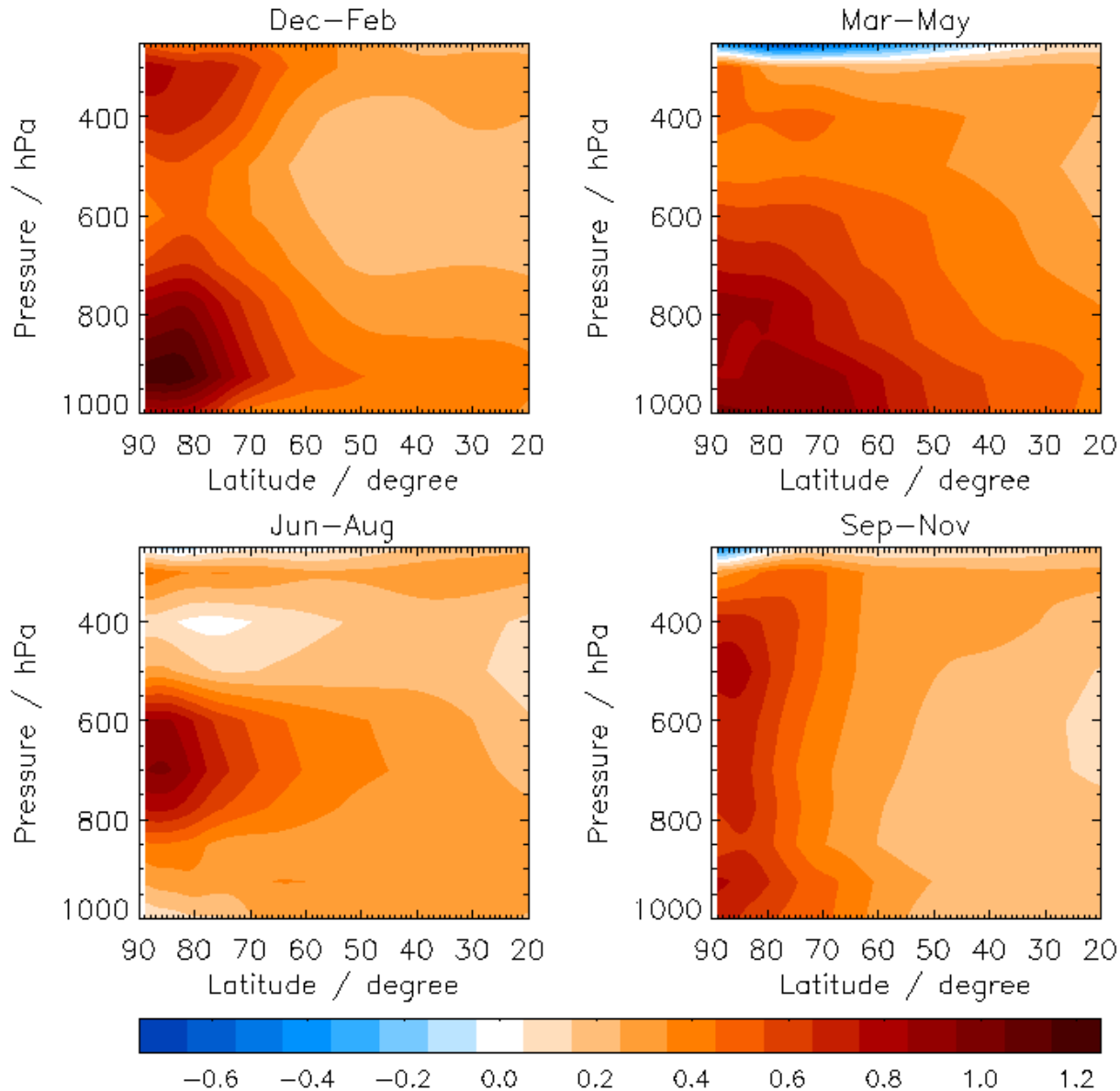
Why global warming?

An increased global greenhouse effect due to increasing concentrations of *carbon dioxide* and other greenhouse gases

Why Arctic amplification?

- Ice-albedo feedback.
- Increased heat transport in atmosphere and ocean.
- Atmospheric surface layer greenhouse warming.

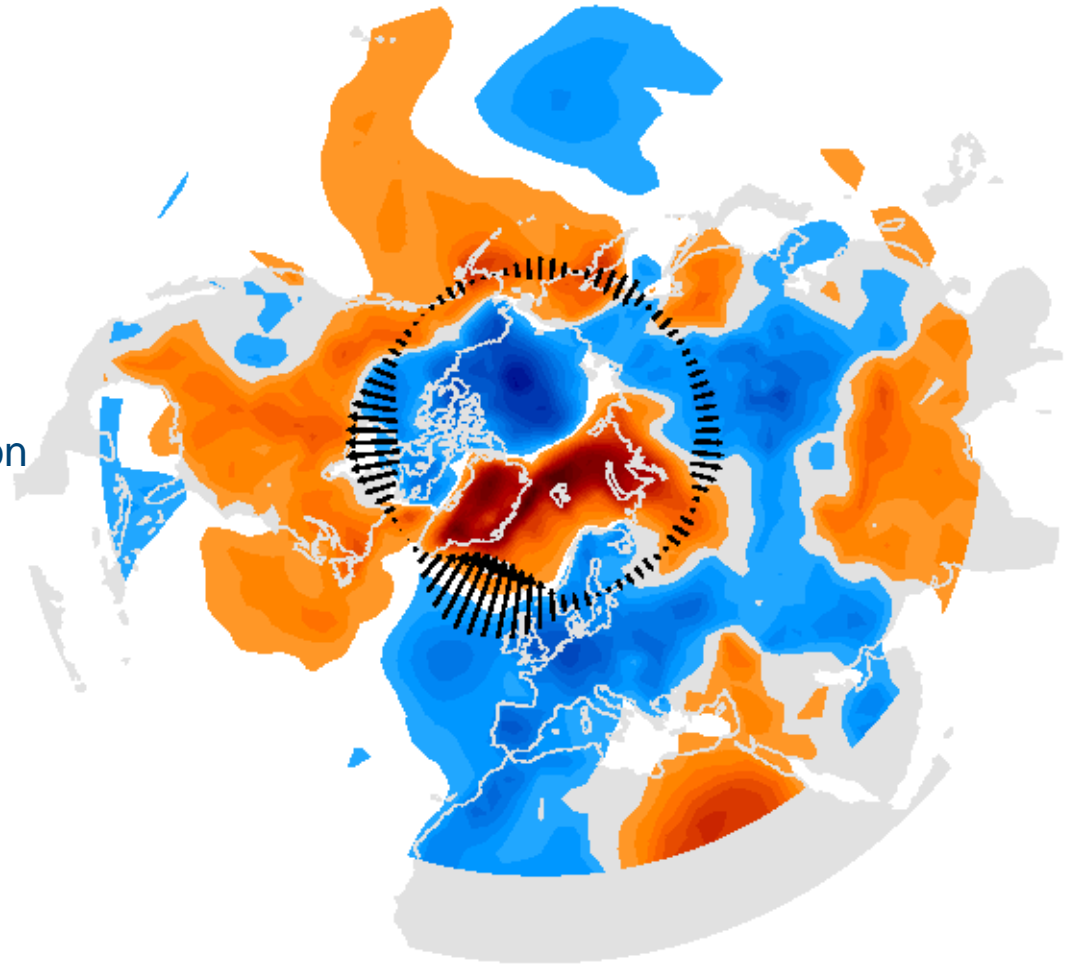
Vertical structure of Arctic warming in ERA-40



Heat transport across 60° N

Blue and red colour: negative and positive temperature anomalies on March 16 1996

Arrows: energy transport anomalies on March 11 1996

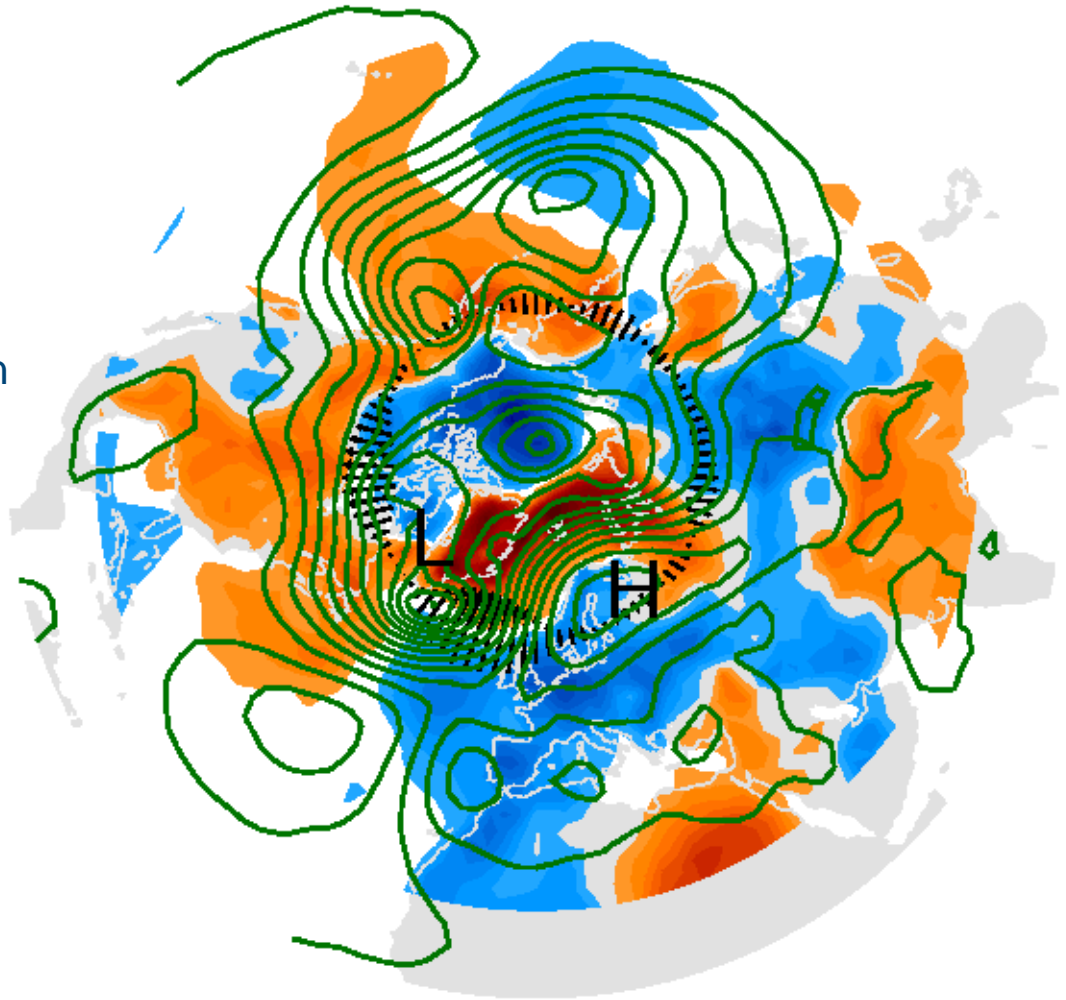


Heat transport across 60° N

Blue and red colour: negative and positive temperature anomalies on March 16 1996

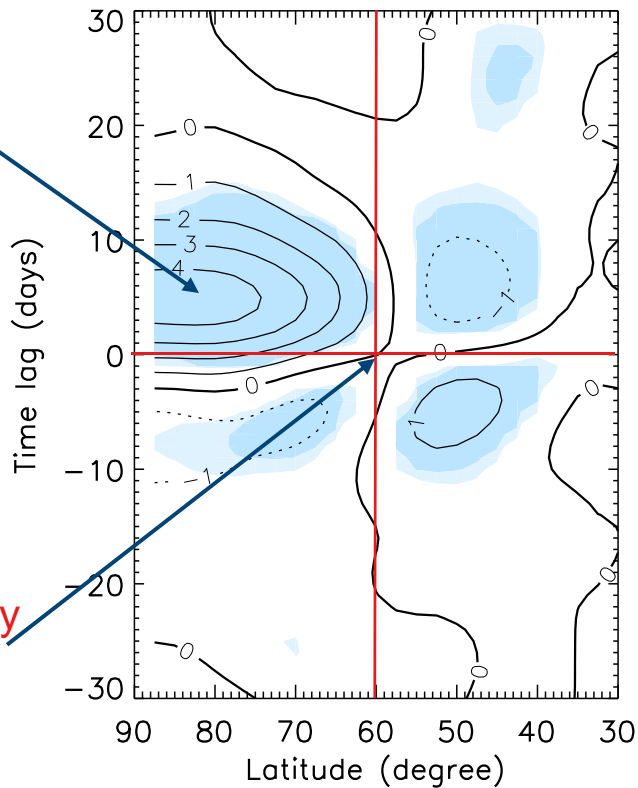
Arrows: energy transport anomalies on March 11 1996

Green contours: 850-hPa geopotential heights on March 11 1996



Composite lagged regression of Arctic temperature on energy transport from ERA-40 reanalysis

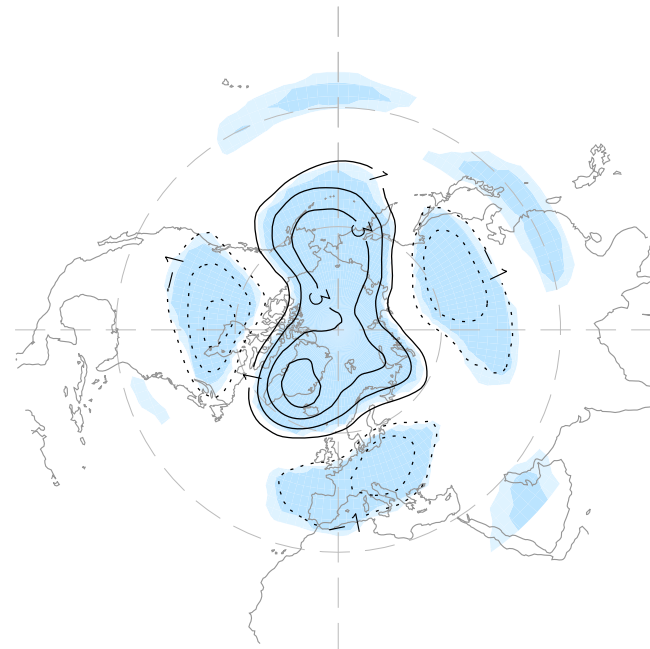
Normalized regression



5-day delayed warming

ANET anomaly happens here

Spatial pattern



Atmospheric Northward Energy Transport (ANET)

Atmospheric energy components

$$I = c_v T \quad \text{Internal}$$

$$\Phi = gz \quad \text{Potential}$$

$$k = \frac{1}{2} U^2 \quad \text{Kinetic}$$

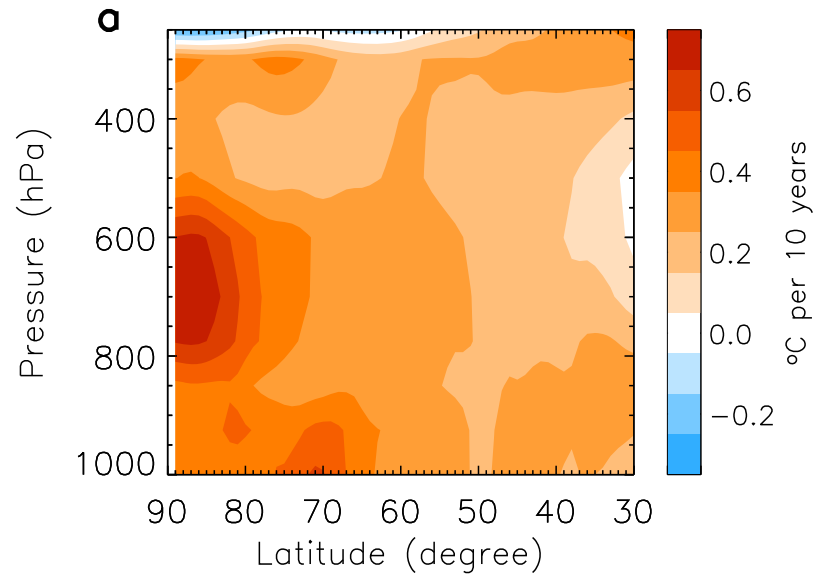
$$H = Lq \quad \text{Latent}$$

Energy transport across 60°N

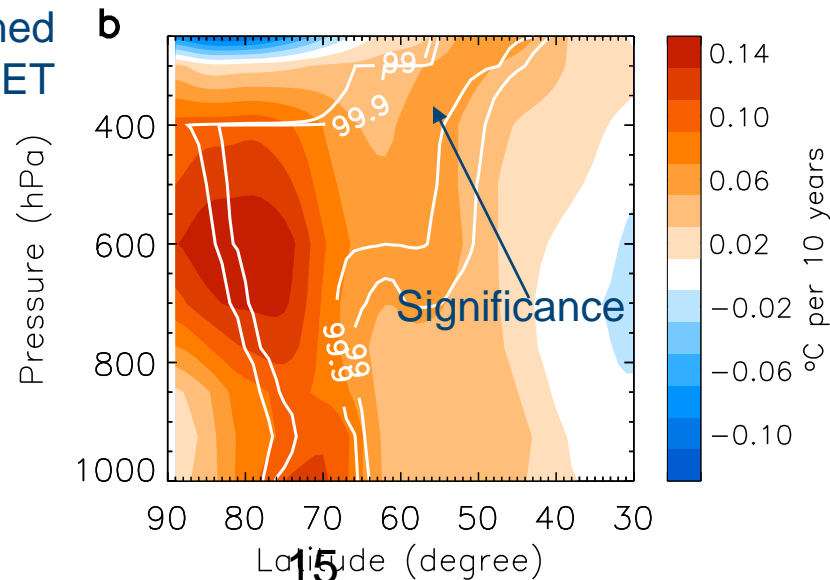
$$\oint_{\Phi=60N} \int_{p_t}^{p_b} v (I + \Phi + k + H) \frac{dp}{g} dx$$

Vertical structure of Arctic warming in ERA-40

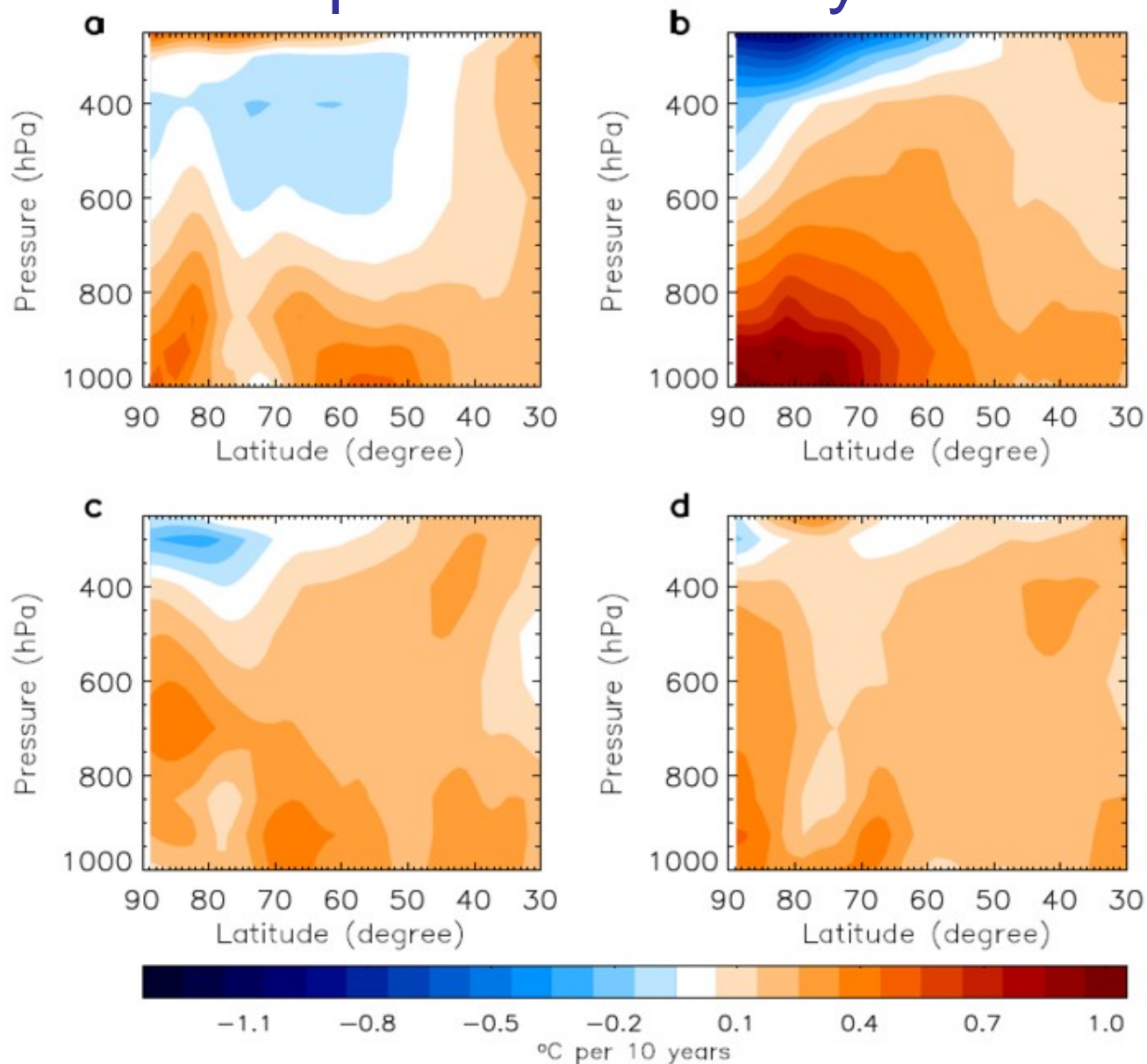
Total summer warming



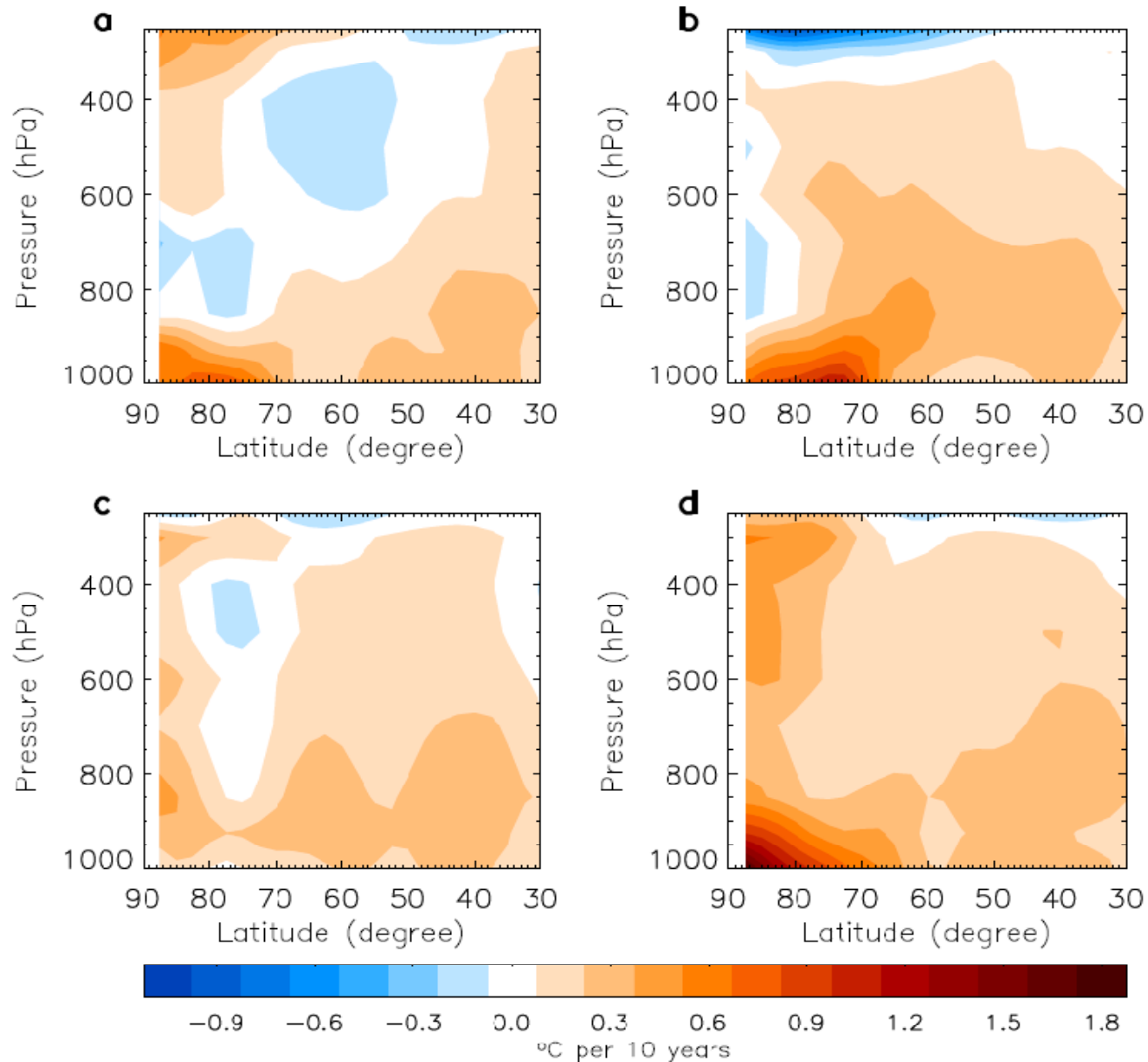
Fraction explained by ANET



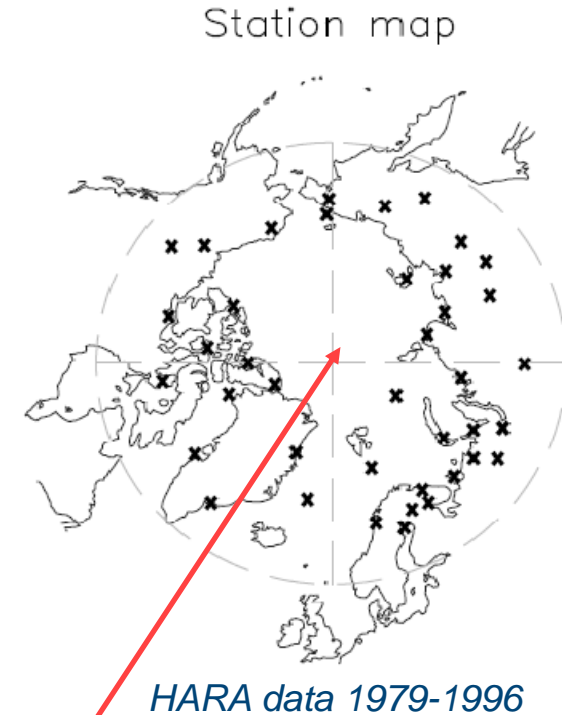
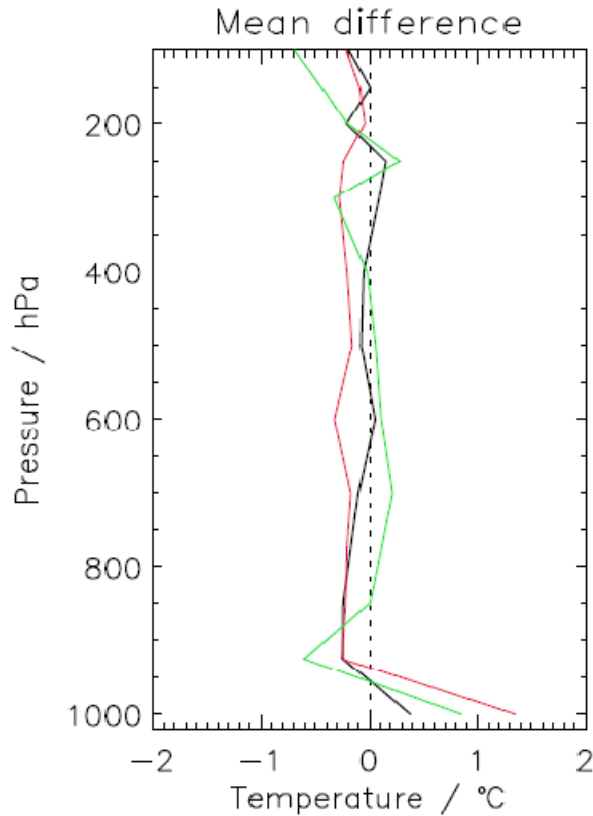
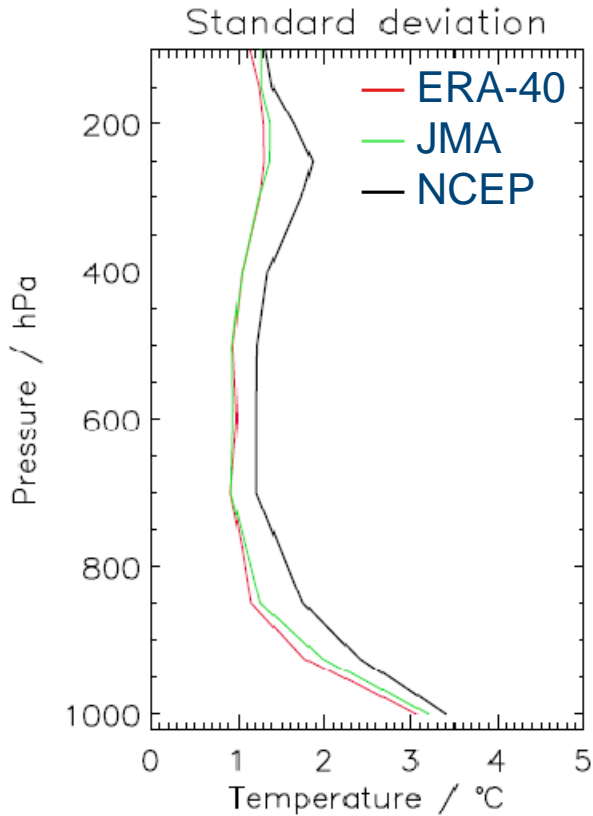
Vertical structure of Arctic warming in Japanese re-analysis



Vertical structure of Arctic warming in NCEP/NCAR re-analysis

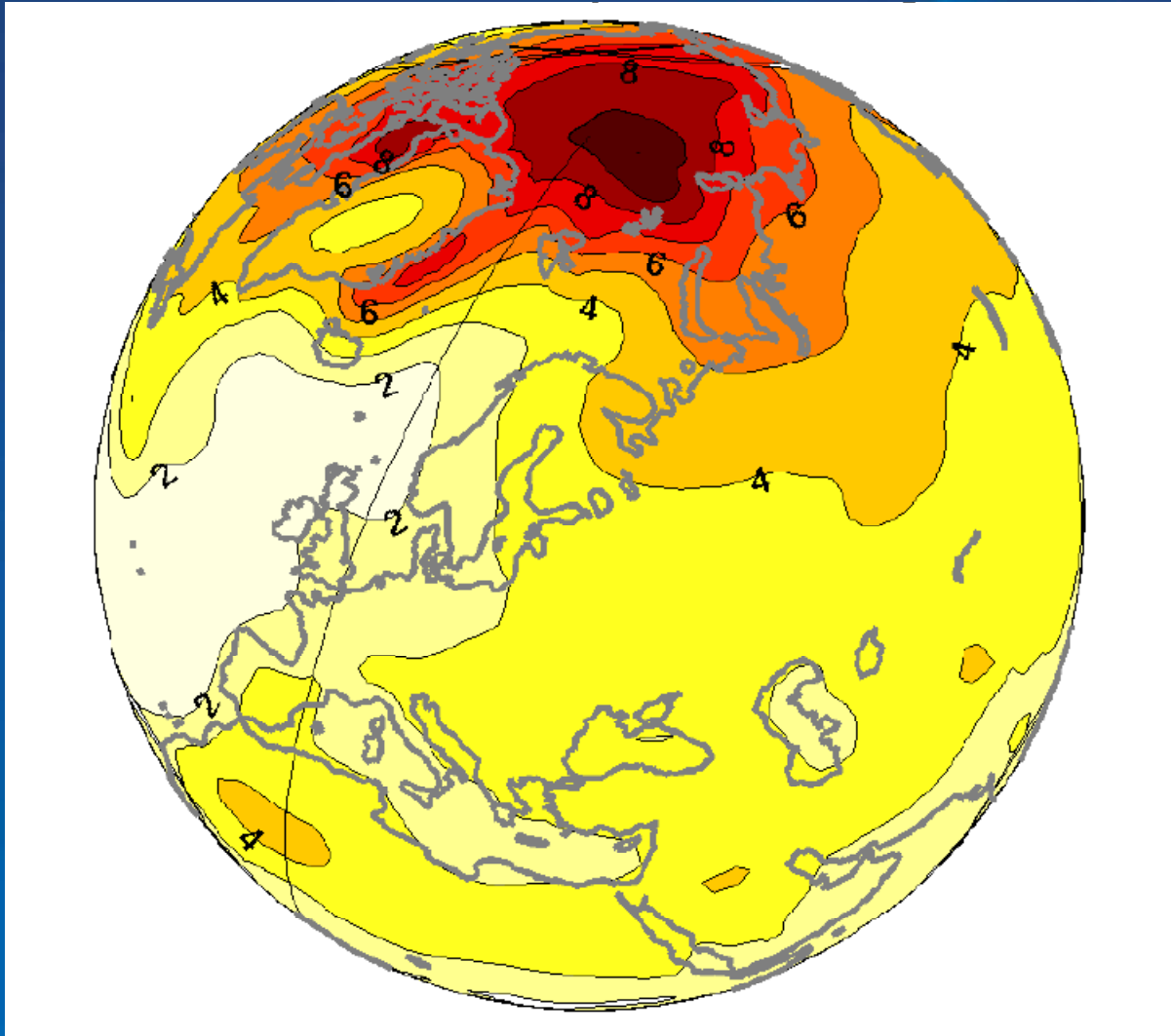


Comparing re-analyses with HARA (radiosonde archive)



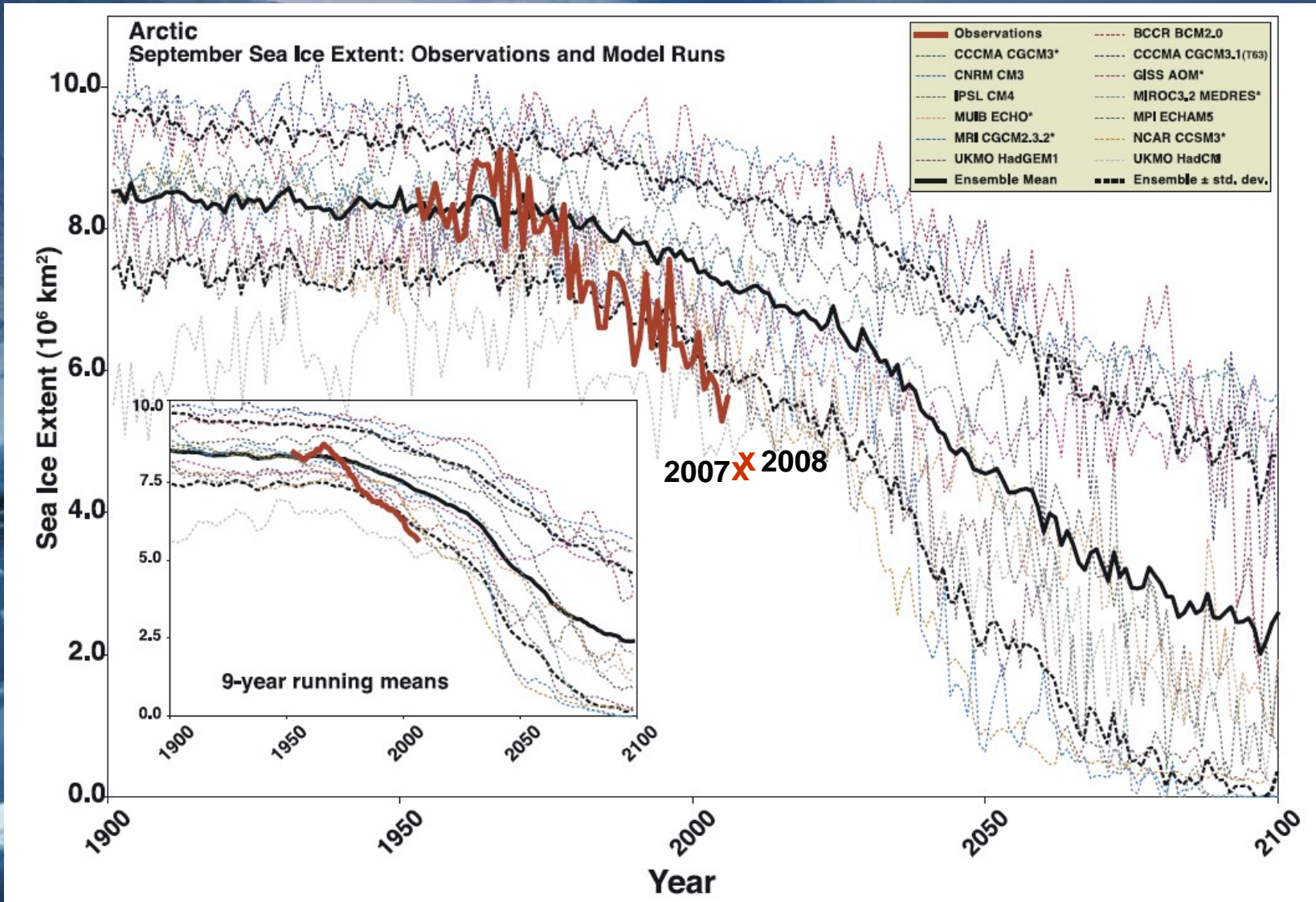
Empty!

Future climate warming Year 2100



Future Arctic sea ice

(Stroeve et al., 2007)



Conclusions

- The Arctic is warming rapidly.
- Arctic sea ice quickly vanishing.
- A significant fraction of the Arctic amplification is due to increased heat transports.
- Future warming: Ice-albedo feedback and heat transports.