

An Introduction to the Changing Arctic Atmosphere

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Overview of my lectures

- Lecture 1: Background on the Arctic Atmosphere/Climate System and how it is changing.
- Lecture 2: Impact of the retreat of sea ice on ocean convection in the Greenland and Iceland Seas.
- Lecture 3: Winter warming events at the North Pole and the 2017 collapse of the Beaufort High. Responses to thinning and retreating sea ice?



What determines the surface temperature of the earth?

Incoming Sunlight (shortwave radiation)



Outgoing Heat (longwave radiation)



In simplest terms, the earth is in radiative balance.
=> Incoming solar radiation is balanced by outgoing terrestrial radiation.

What determines the surface temperature of the Earth?

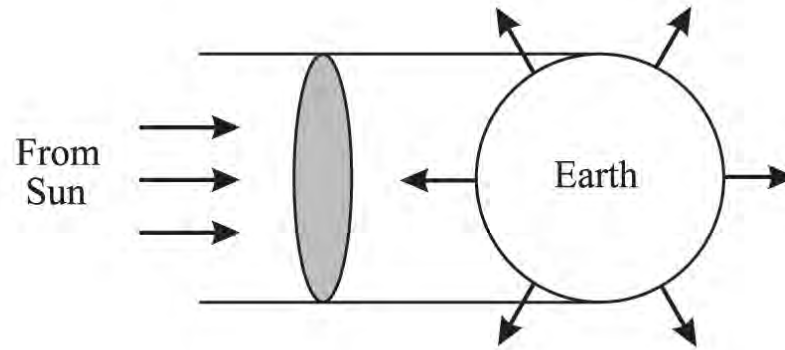


Fig. 1.1

Illustrating the calculation of the temperature of the Earth, ignoring any absorption of radiation by the atmosphere. The parallel arrows indicate solar radiation, confined within a tube of cross-sectional area πa^2 . The radial arrows indicate outgoing thermal radiation from the total surface area $4\pi a^2$ of the Earth.

In simplest terms, the earth is in radiative balance.

=> Incoming solar radiation is balanced by outgoing terrestrial radiation.

What determines the surface temperature of the Earth?

Let:

S be the solar constant (the solar radiative flux incident on the Earth $\sim 1365\text{W/m}^2$),

R be the radius of the Earth (6371km),

A be the albedo of the Earth (fraction of incoming solar radiation reflected back to space ~ 0.3) and

T be surface temperature ($^{\circ}\text{C}$).

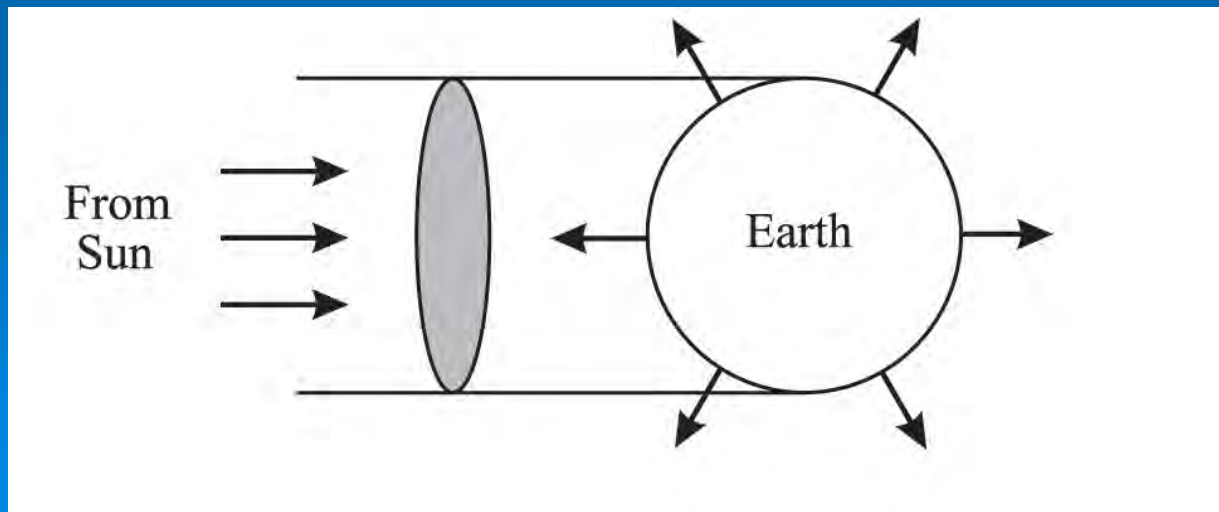
Then

Incident solar radiation on the earth $= (1 - A)S\pi R^2$

Outgoing longwave radiation from the earth $= \sigma T^4 4\pi R^2$

(comes from the so-called blackbody equation that total longwave radiation $\propto T^4$)

The different geometric factors are the result that only the cross-sectional area (πR^2) of the Earth absorbs incoming solar radiation while the entire surface area ($4\pi R^2$) emits the longwave radiation.



What determines the surface temperature of the Earth?

Therefore the net radiation at the top of the atmosphere (TOA)

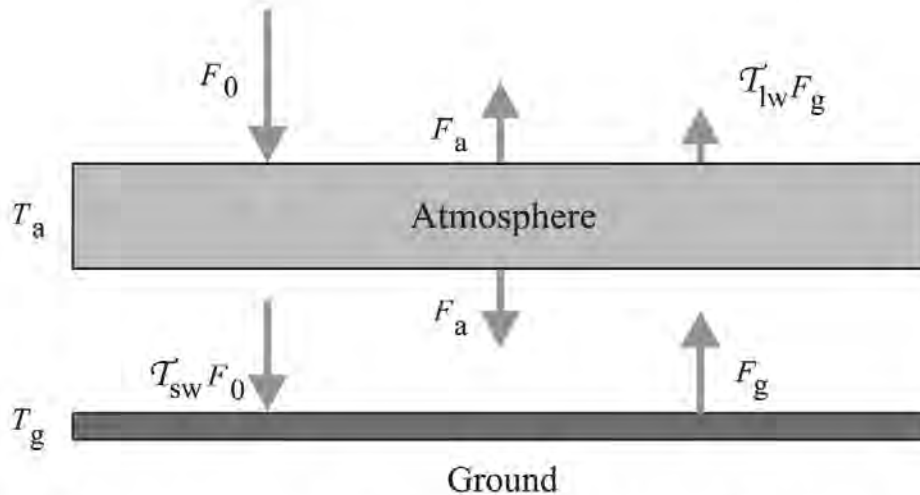
$$R_{top} = (1 - A)S\pi R^2 - \sigma T^4 4\pi R^2$$

If the Earth is in radiative balance, then $R_{top} = 0$ and one can solve for T .

Assuming above values for the various terms results in $T \approx 255K$ or $\approx -18^\circ C$ or $0^\circ F$!

Actual average surface temperature $\sim 288K$ so what is warming the planet up?

The atmosphere is transparent to incoming solar radiation but partially absorbs outgoing terrestrial radiation.



A simple model of the greenhouse effect. The atmosphere is taken to be a layer at temperature T_a and the ground a black body at temperature T_g . Various solar and thermal irradiances are shown.

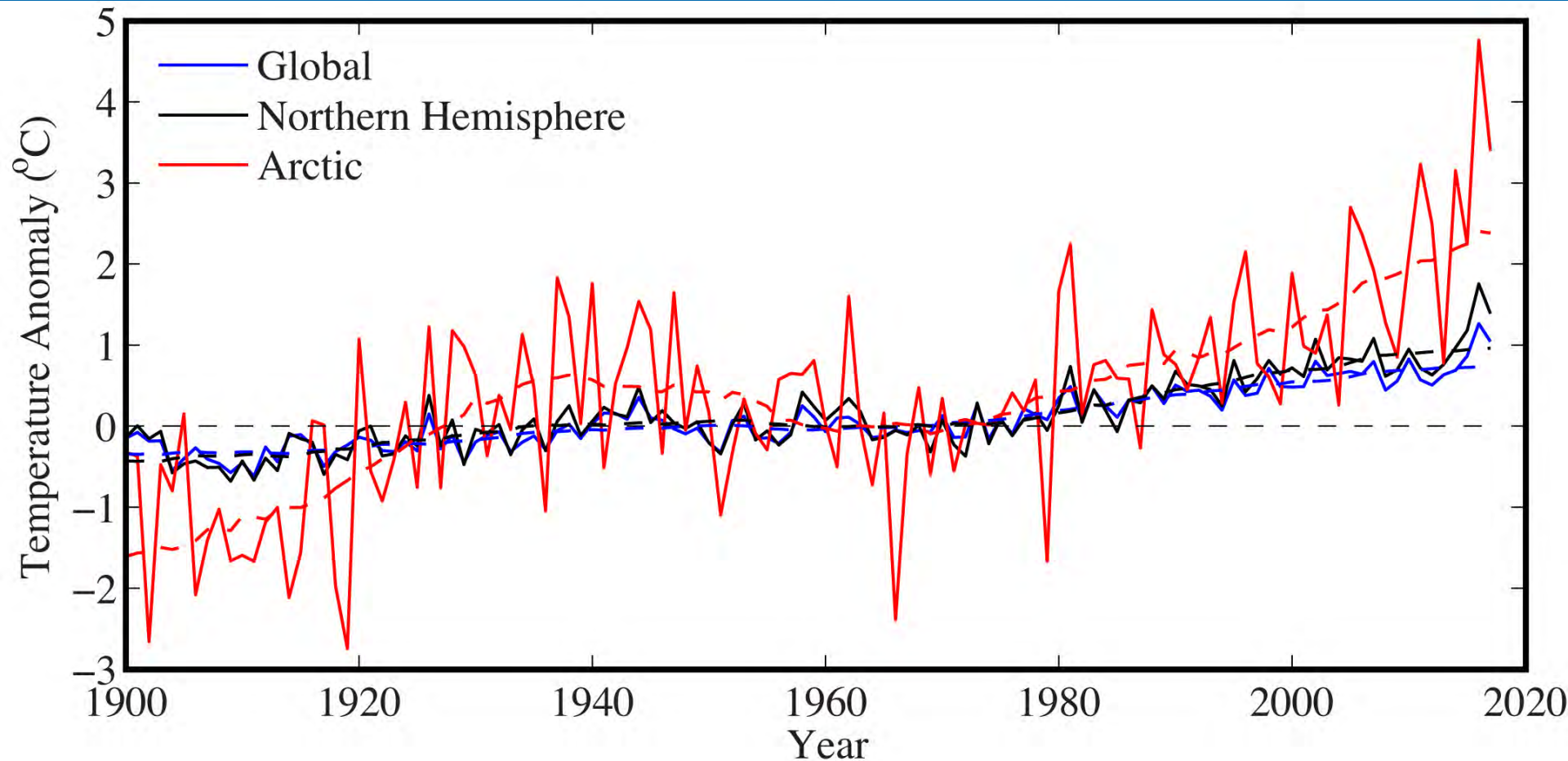
$\tau_{sw} \sim 0.9$
Shortwave
transmittance
close to 1.
 $\tau_{lw} \sim 0.2$
Longwave
transmittance
close to zero.

What determines the surface temperature of the Earth?

$$\sigma T^4 = \frac{1}{4}(1 - \alpha)S \frac{(1 + \tau_{sw})}{(1 + \tau_{lw})}$$

assuming $\tau_{sw} \sim 0.9$ (weak absorption of incoming shortwave)
and $\tau_{lw} \sim 0.2$ (strong absorption of outgoing longwave), then:
 $T \sim 288K$

What determines the surface temperature of the Earth?



Winter mean surface air temperature anomaly (°C) from the NASA GISS Surface Temperature Analysis

Is $R_{\text{top}} = 0$?

- High latitude regions characterized by polar night/polar day.
- Implies that incoming solar radiation is zero during the winter and maximum during the summer.
- Outgoing longwave non zero all the time.
- $\Rightarrow R_{\text{top}} \neq 0$!

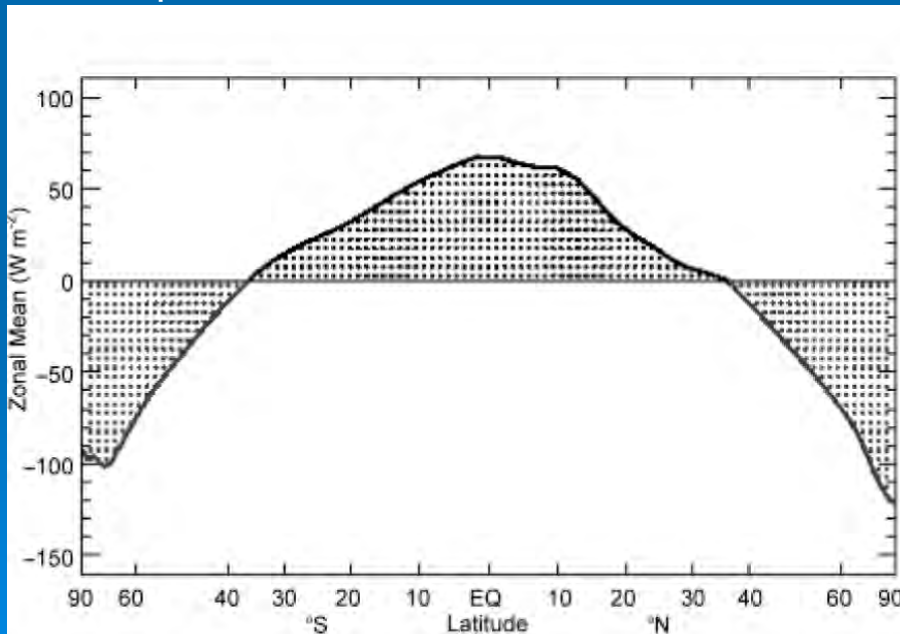
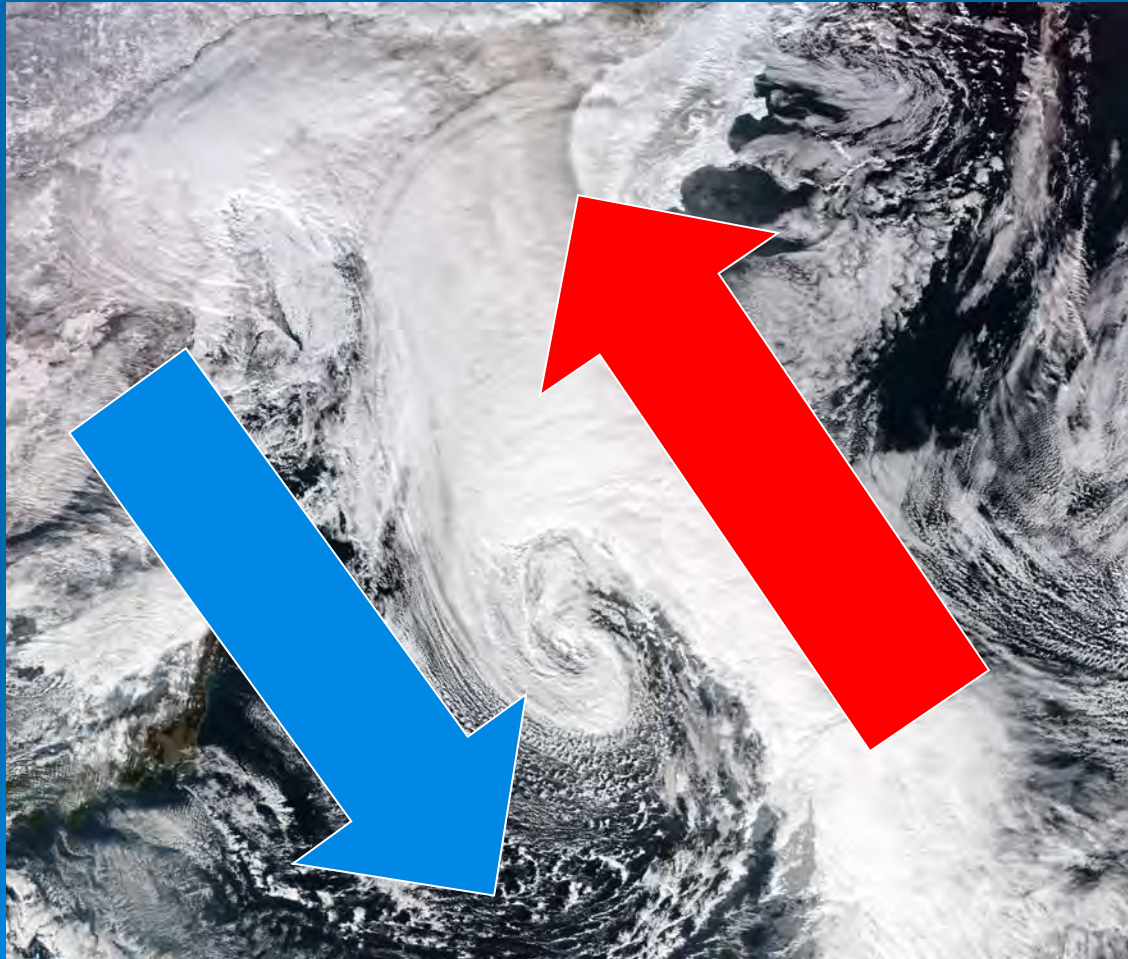


Figure 3.1. Zonal averages (averages by latitude) of the annual mean net radiation budget at the top of the atmosphere based on ERBE data (from Trenberth and Caron, 2001, by permission of AMS).

*Poles regions of net loss of radiation
 \Rightarrow Climate system must transport energy (heat polewards)*

How does the climate system transfer energy polewards?

- atmosphere
- ocean



Extra-tropical
cyclones act
to move cold
air
equatorward
and warm air
poleward
Net effect is
poleward
energy
transport

Extra-tropical cyclone over North Pacific Jan 10 2017

How does the climate system transfer energy polewards?

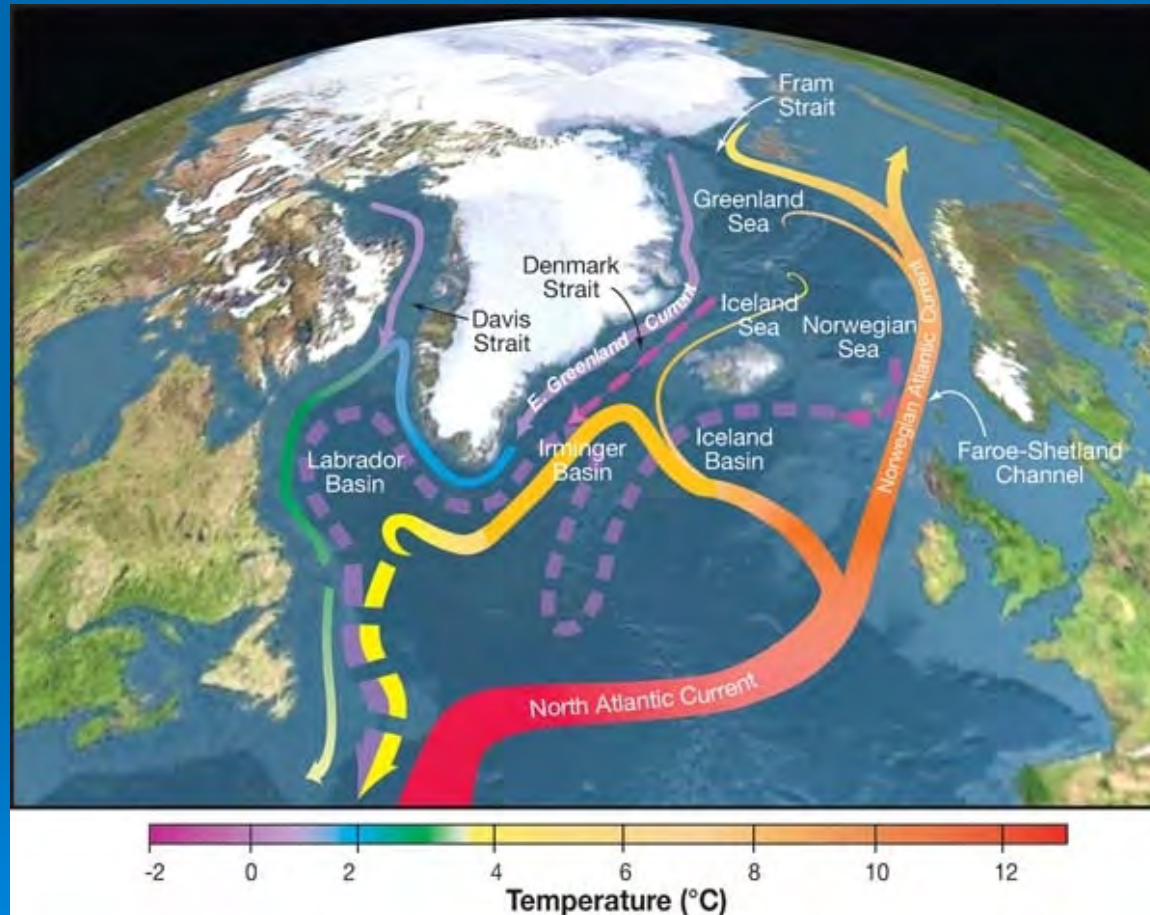
- atmosphere
- ocean



Extra-tropical cyclone over North America Sept 27 2011

How does the climate system transfer energy polewards?

- atmosphere
- ocean

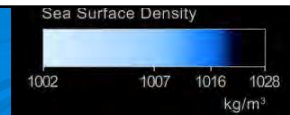


Net effect is polewards energy transport

Surface ocean currents in the North Atlantic transport warm tropical water northwards and cold polar water southwards

How does the climate system transfer energy polewards?

- atmosphere
- ocean



Animation of North Atlantic ocean currents

How does seasonality impact the energy transport?

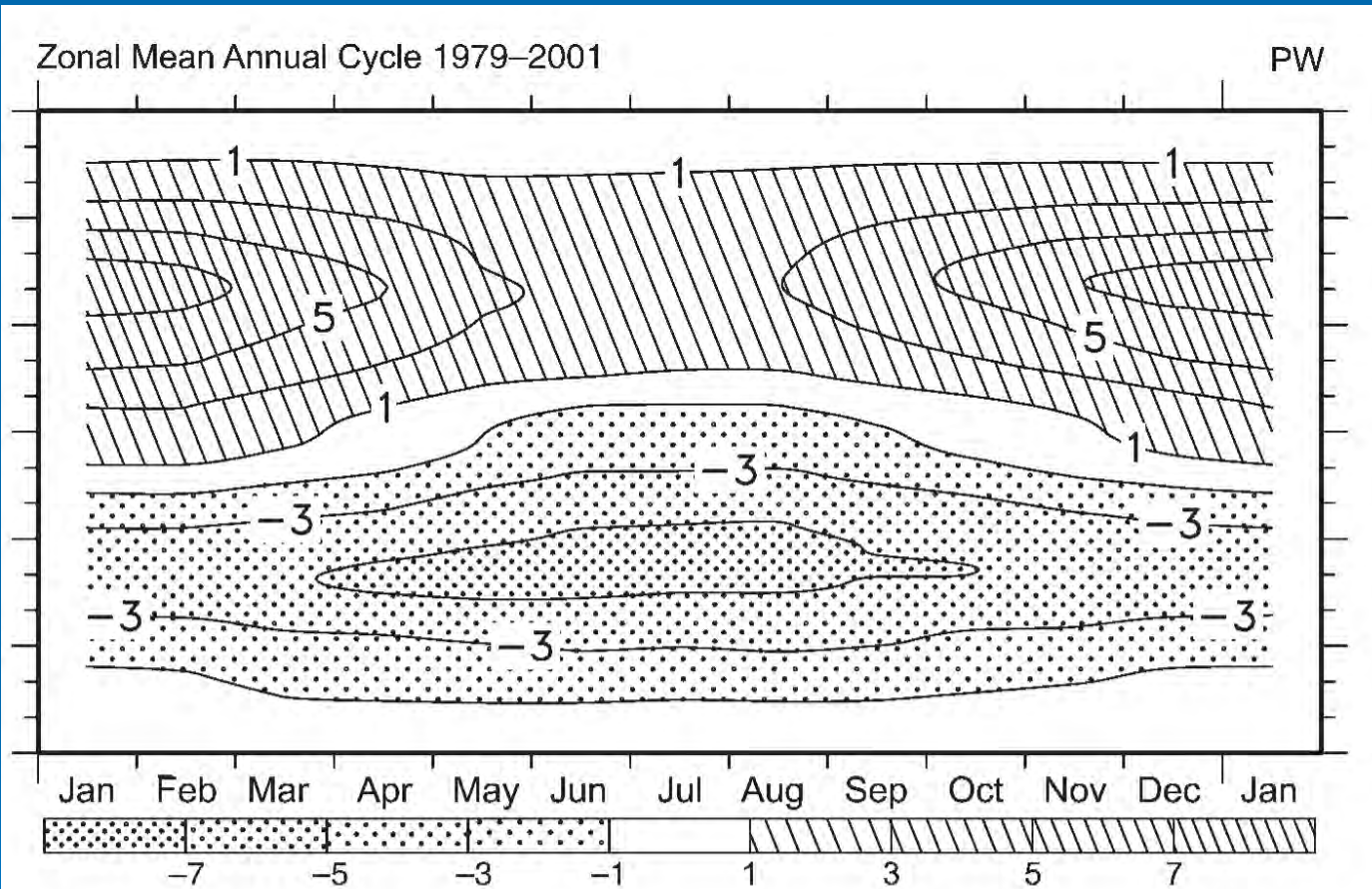
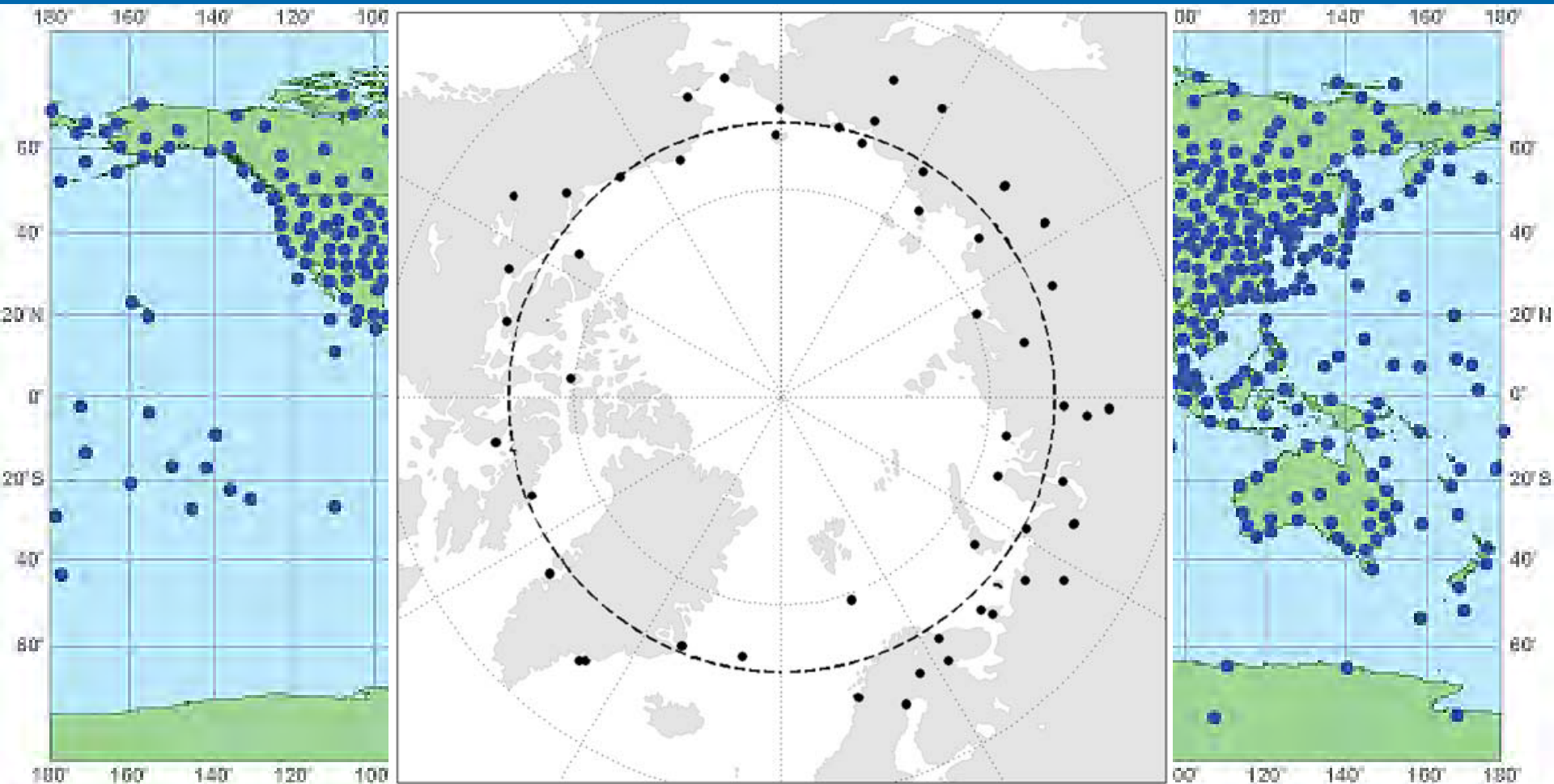


Figure 3.4. The zonal mean (averages by latitude) annual cycle of northward atmospheric energy transport, averaged for 1979–2001 (PW). Negative values in the Southern Hemisphere mean transport to the south (toward the South Pole) (from Trenberth and Stepaniak, 2003, by permission of AMS).

ds during
ds during
urn on/off).
ween winter
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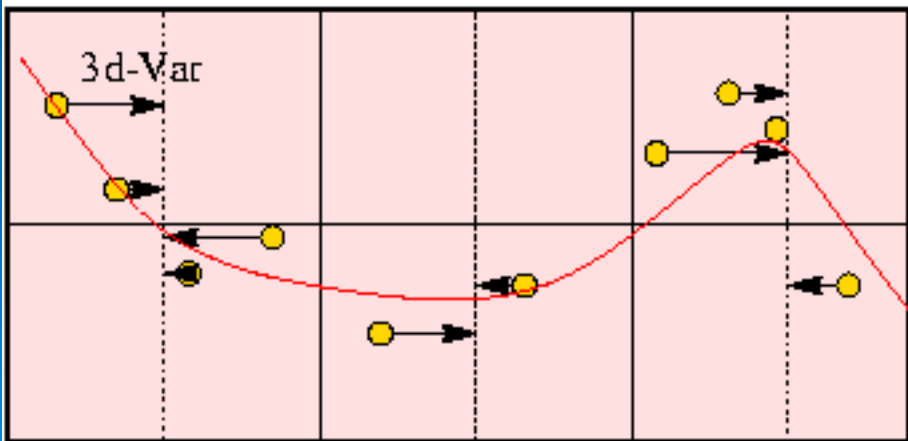
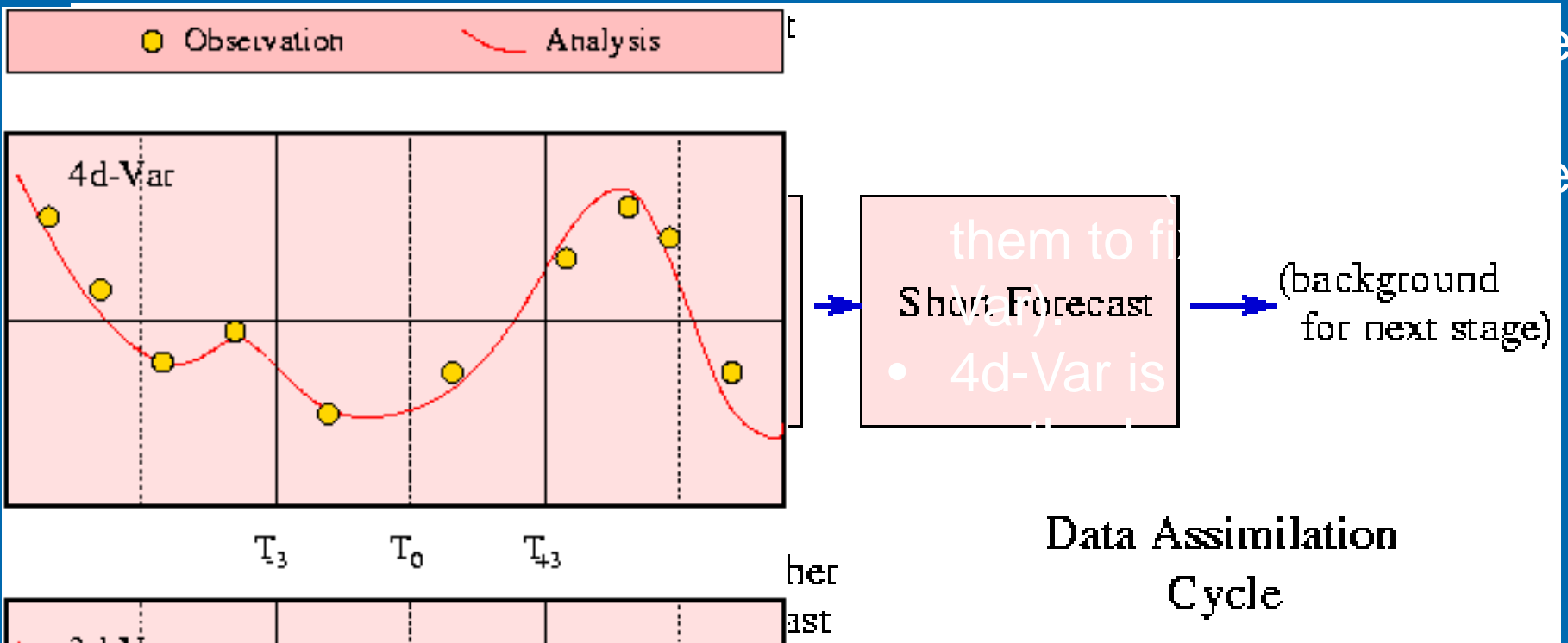
Poleward
energy
transport
largest in
the winter
hemisphere

How do we Characterize Atmospheric Motion?



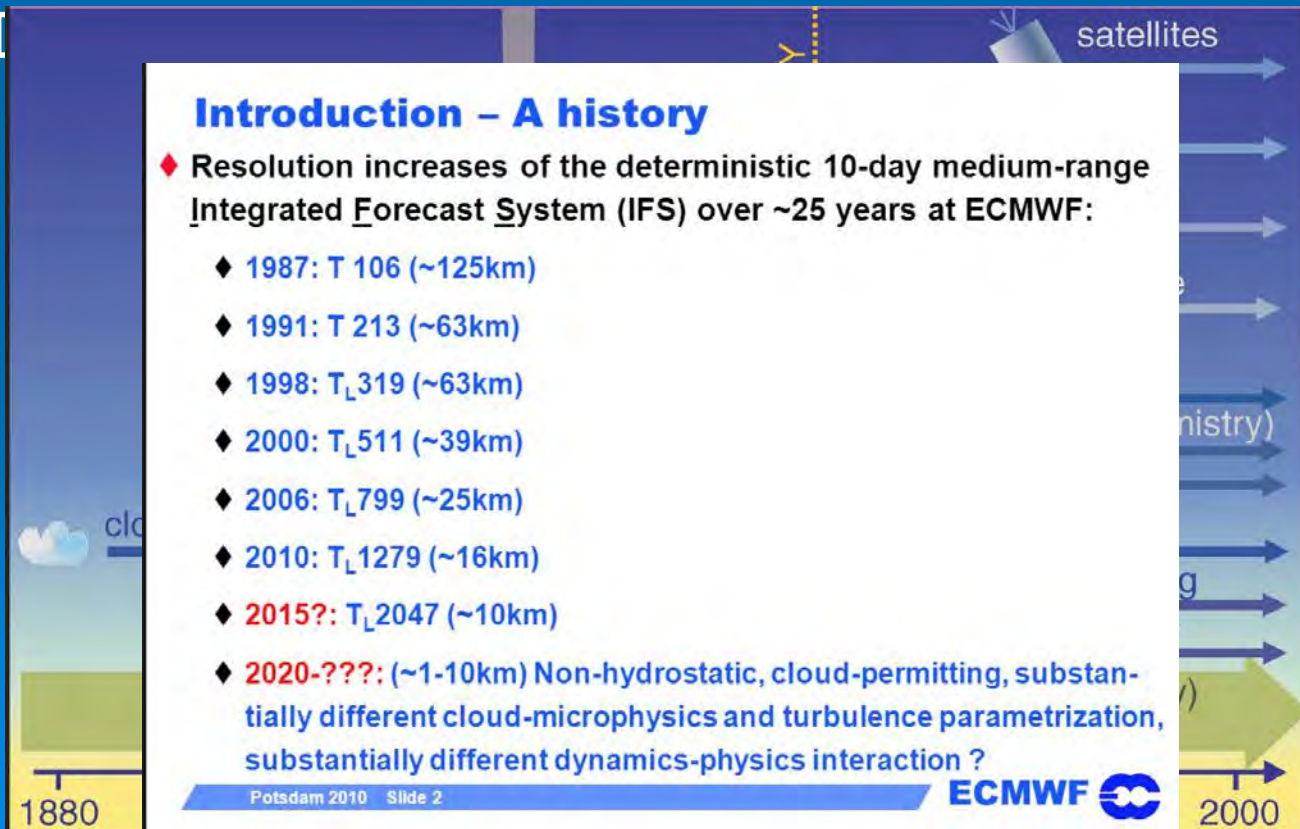
Global Upper Air Network

How do we Characterize Atmospheric Motion?



How do we Characterize Atmospheric Motion?

- In principal, atmospheric analyses represent our best estimate as to the state of the atmosphere as a function of space and time.
- There are *at least* two problems:
 - Input data varies with time.



How do we Characterize Atmospheric Motion?

- Retrospective Analyses (Reanalyses) are a recent development that minimizes some of these problems.
 - They use a modern (frozen) data assimilation system.
 - They assimilate all available data.
- Typically there are reanalyses that cover:
 - the satellite era (1979-onwards: ERA-I).
 - the radiosonde era (late 1940s-onwards: NCEP).
 - the surface data era (1850s-onwards: 20CR).



A comparison of the regional Arctic System Reanalysis and the global ERA-Interim Reanalysis for the Arctic[†]

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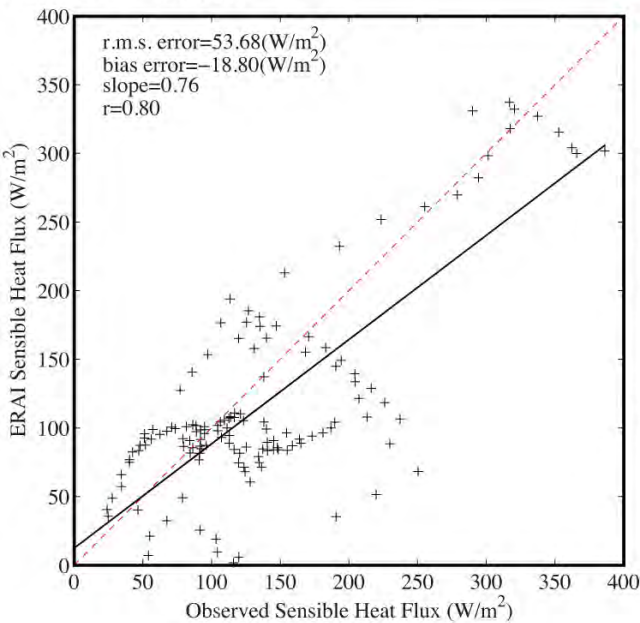
,^d B.
let,^{i,l}
er,^m
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Cited over
~~2,500 times!~~
2,500 times!

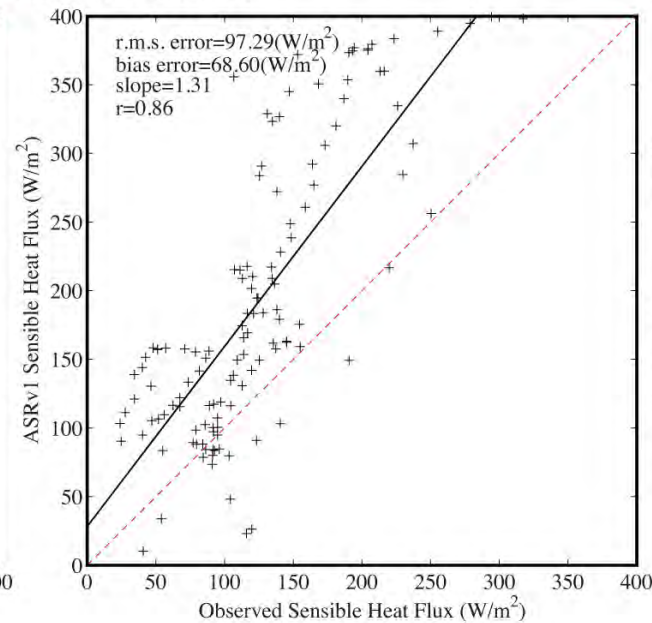
How do we Characterize Atmospheric Motion?

- Retrospective Analyses (Reanalyses) still suffer from the problem that they are dependent on a forecast model and fields (like precipitation and air-sea fluxes) that are not strongly constrained by observations may have biases.

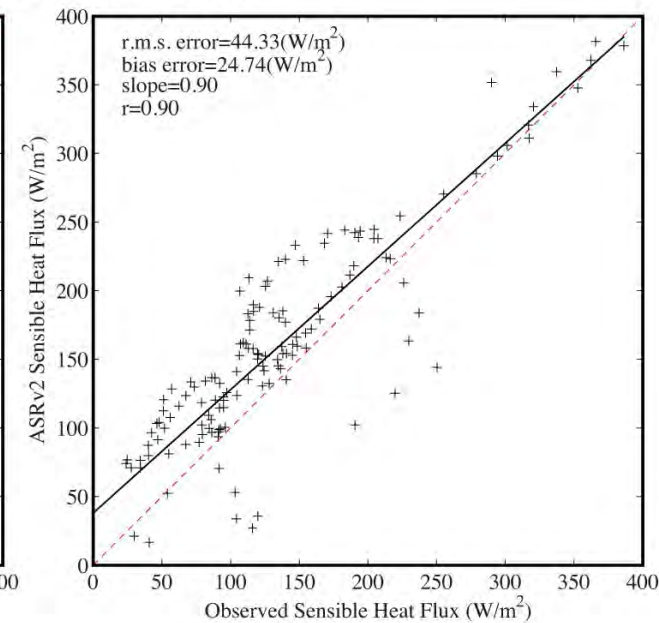
ERA-I ~75km



ASRv1 30km



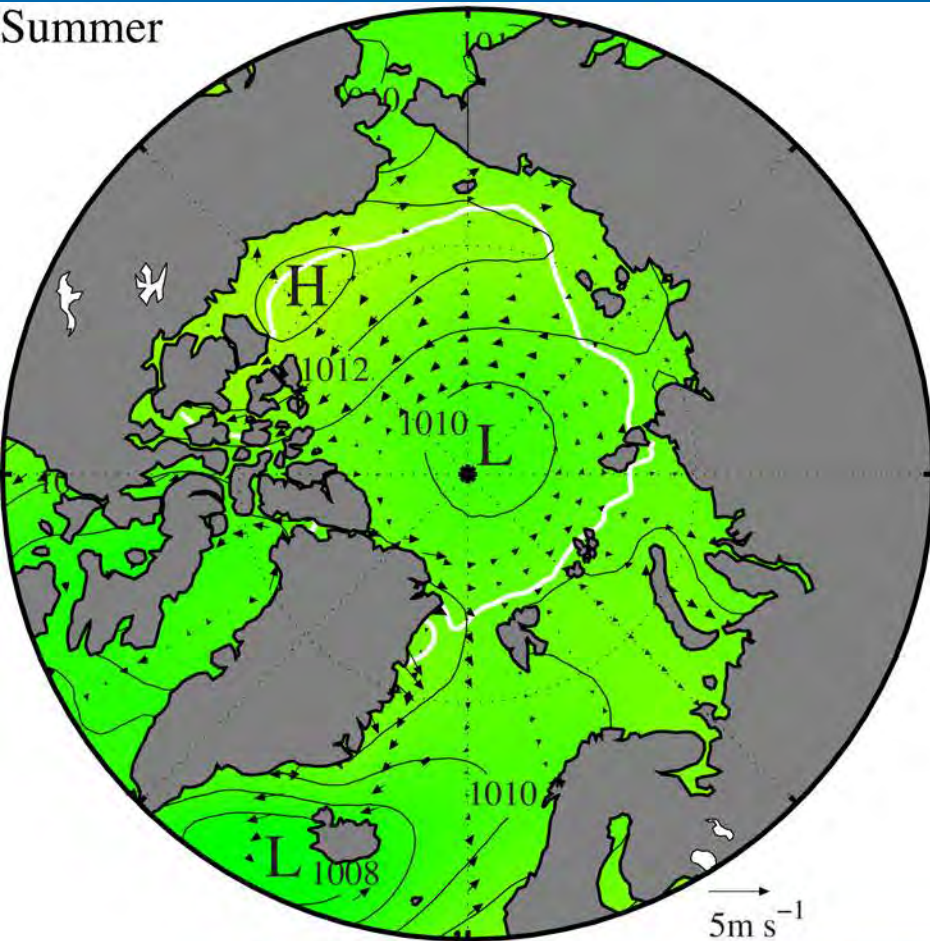
ASRv2 15km



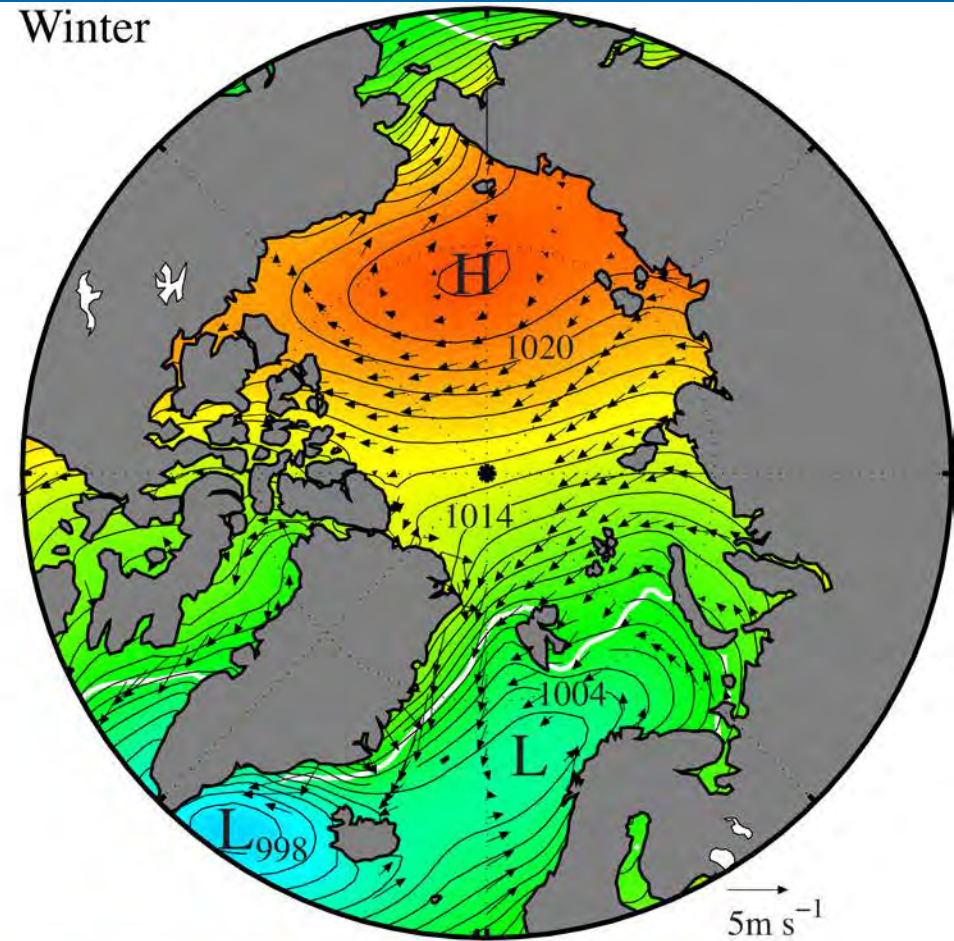
Observed vs Reanalysis Sensible Heat Flux over the Denmark Strait as represented in the ERA-I and the Arctic System Reanalysis

The Arctic Atmosphere

Summer



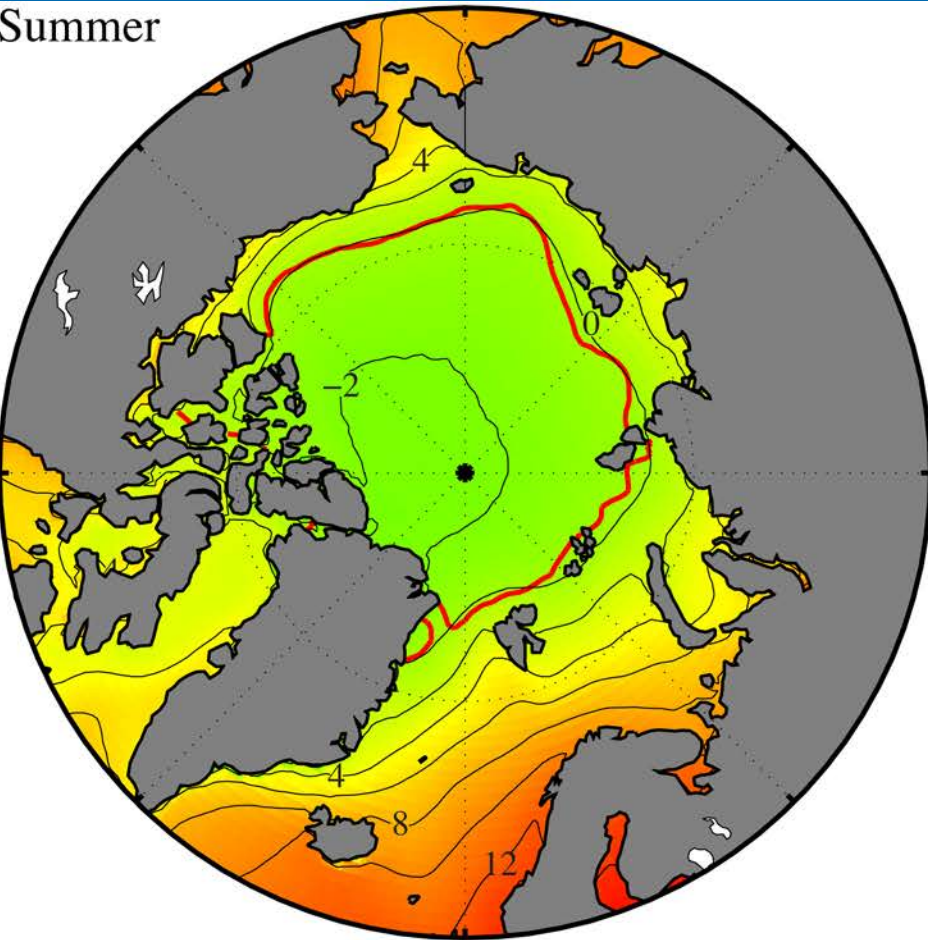
Winter



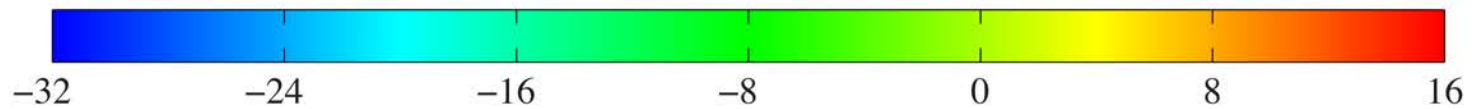
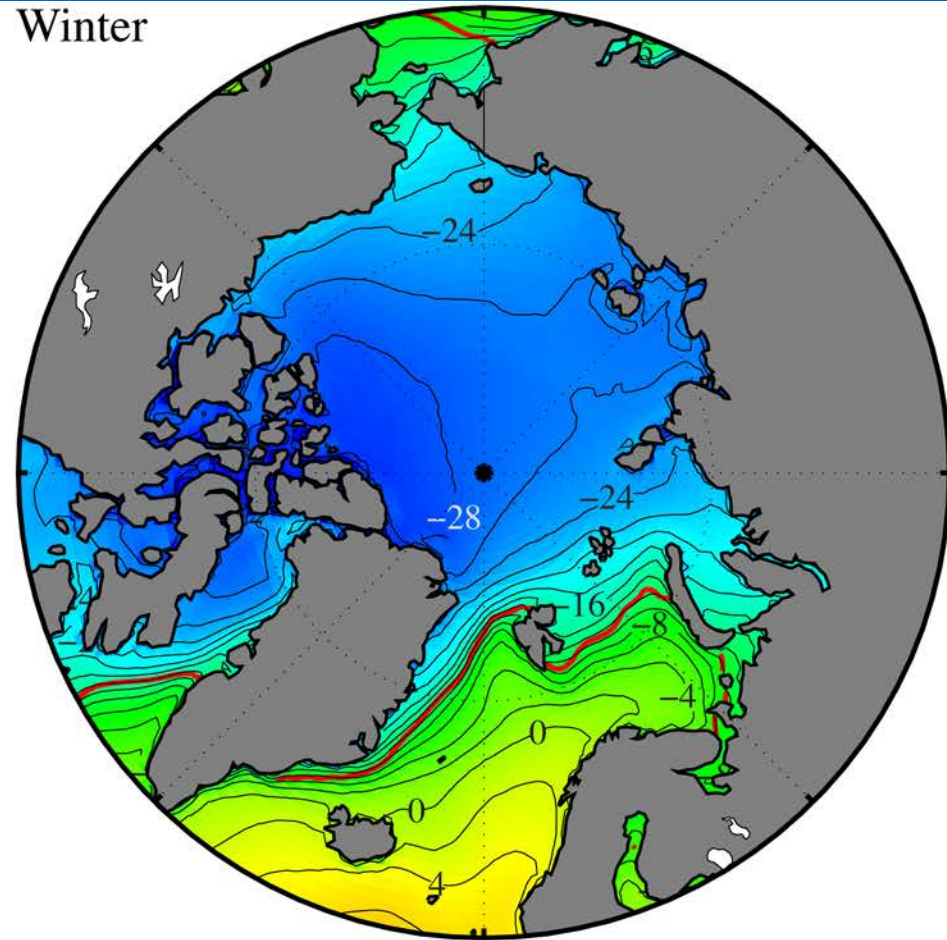
Sea-level pressure (shading & contours-mb) and 10m wind (vectors-m/s) with 50% sea ice concentration contour in white

The Arctic Atmosphere

Summer



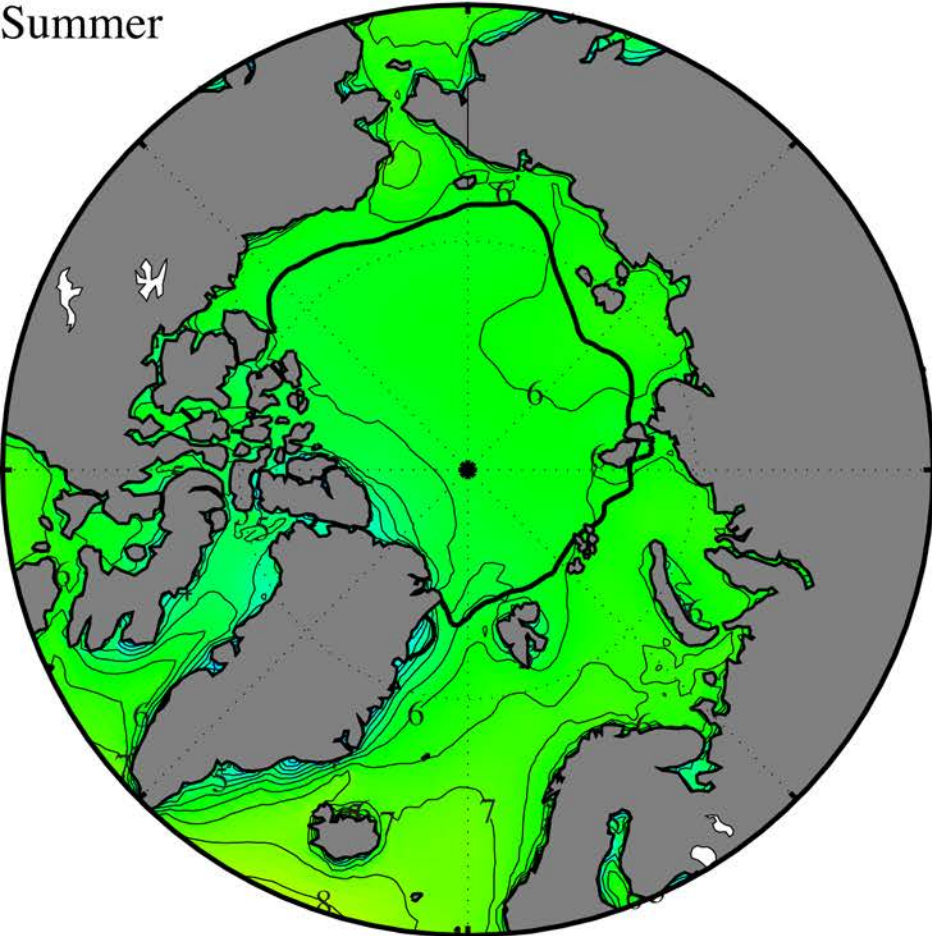
Winter



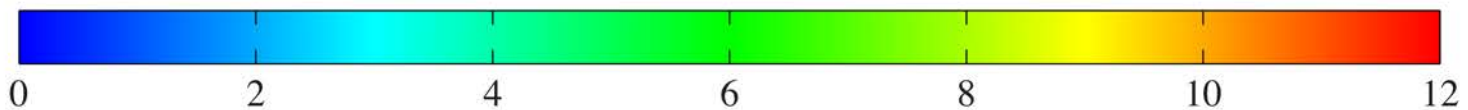
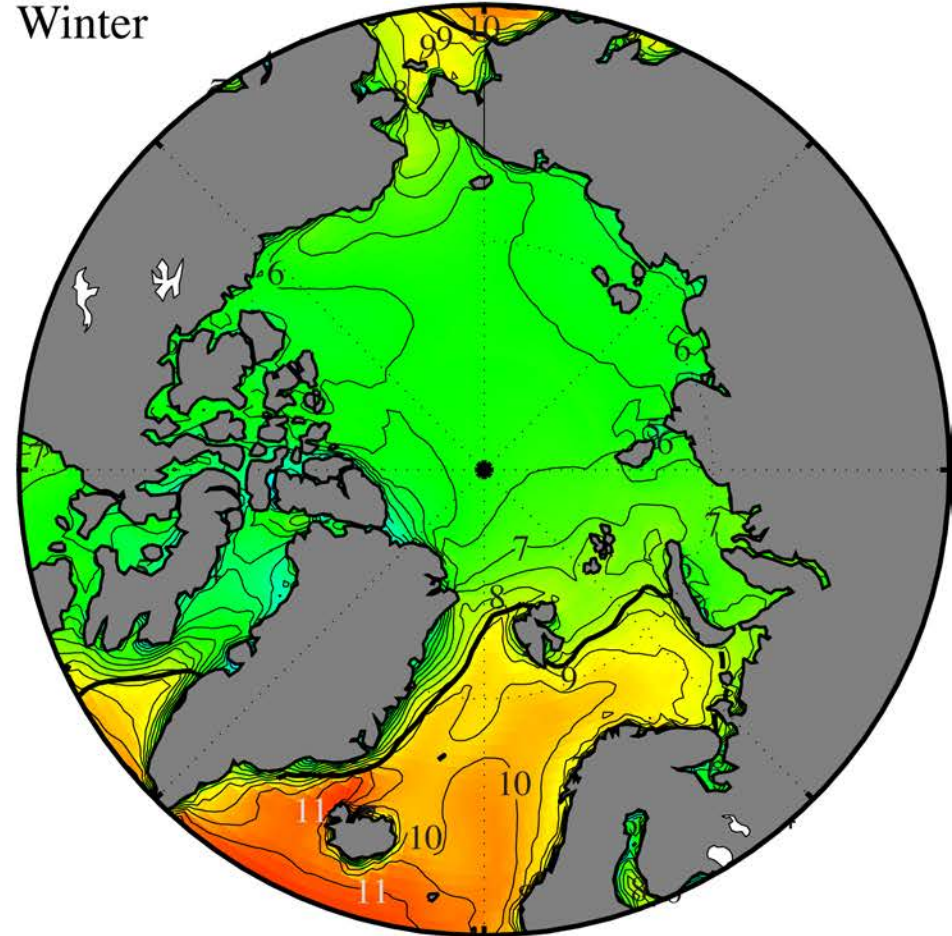
2m air temperature (shading & contours-°C)
with 50% sea ice concentration contour in red

The Arctic Atmosphere

Summer



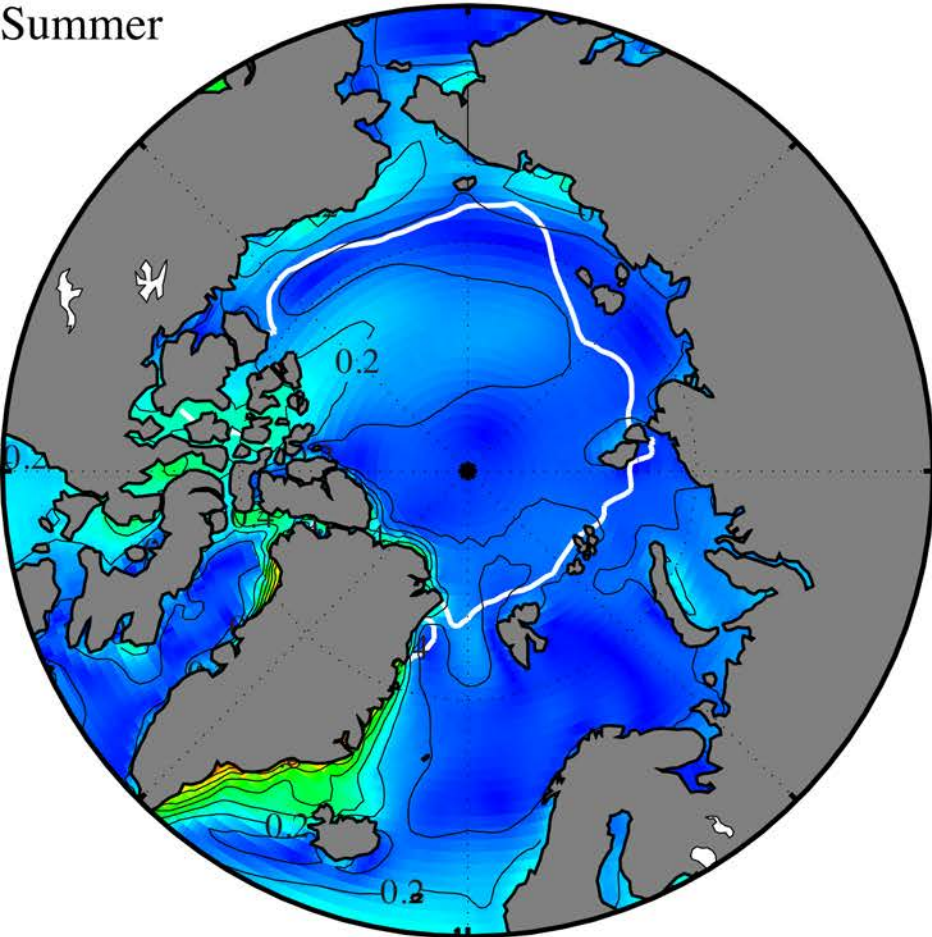
Winter



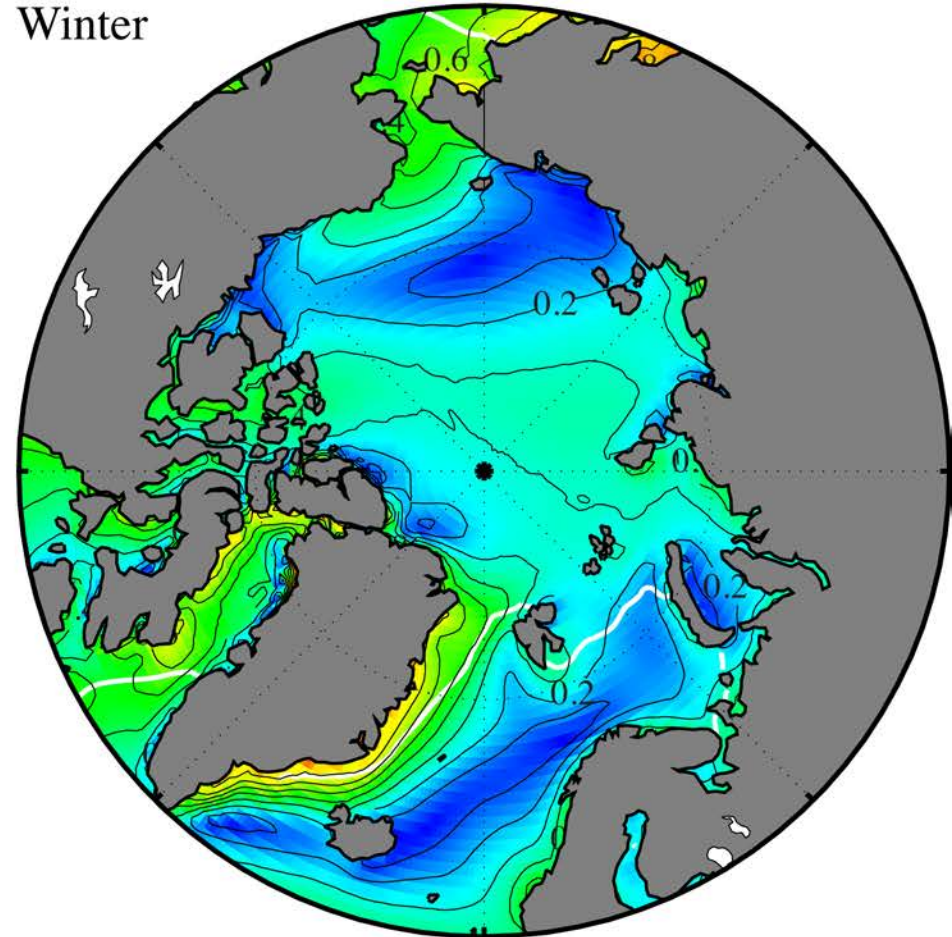
10m wind speed(shading & contours-m/s)
with 50% sea ice concentration contour in black

The Arctic Atmosphere

Summer

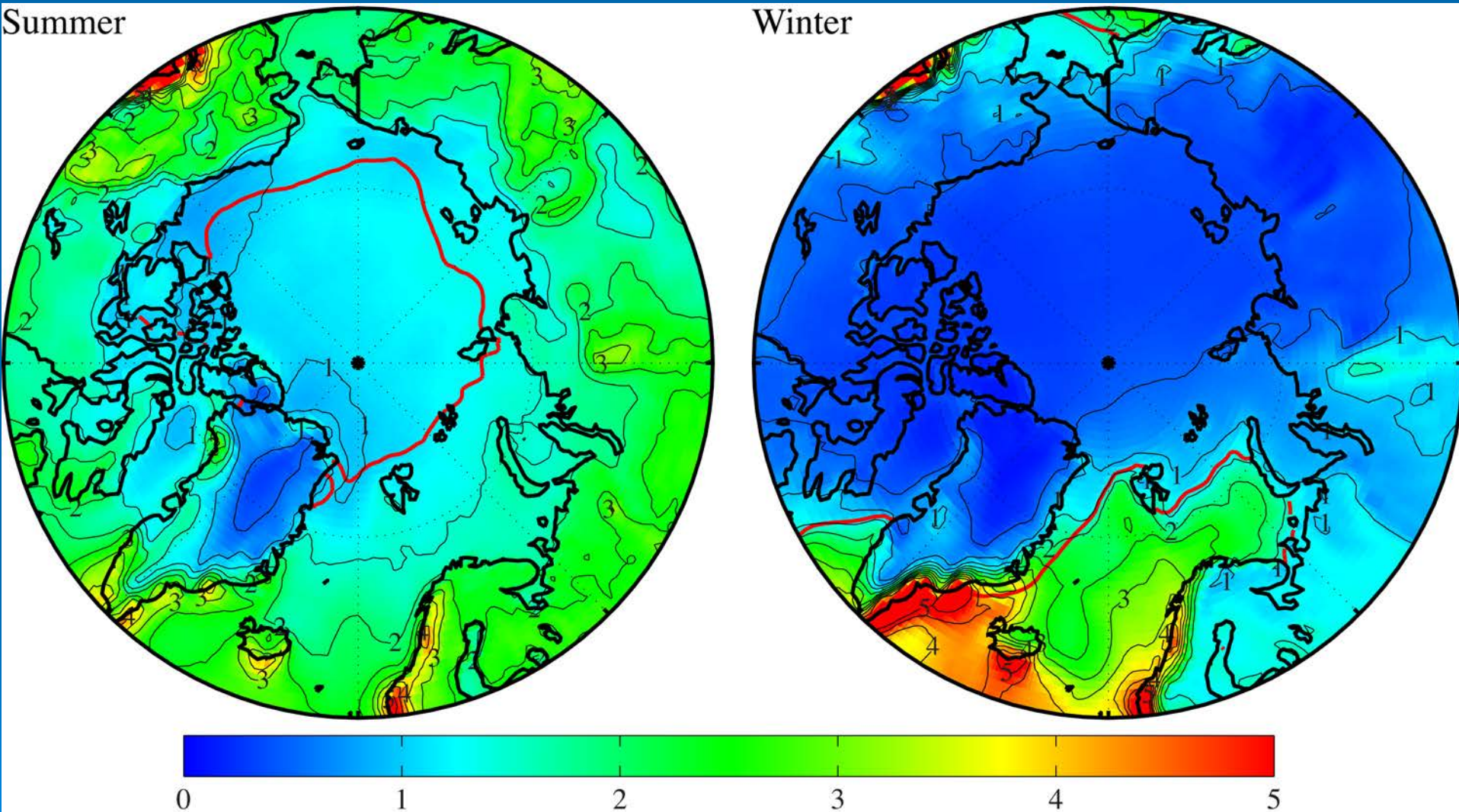


Winter



Directional constancy of the 10m wind (shading & contours)
with 50% sea ice concentration contour in white

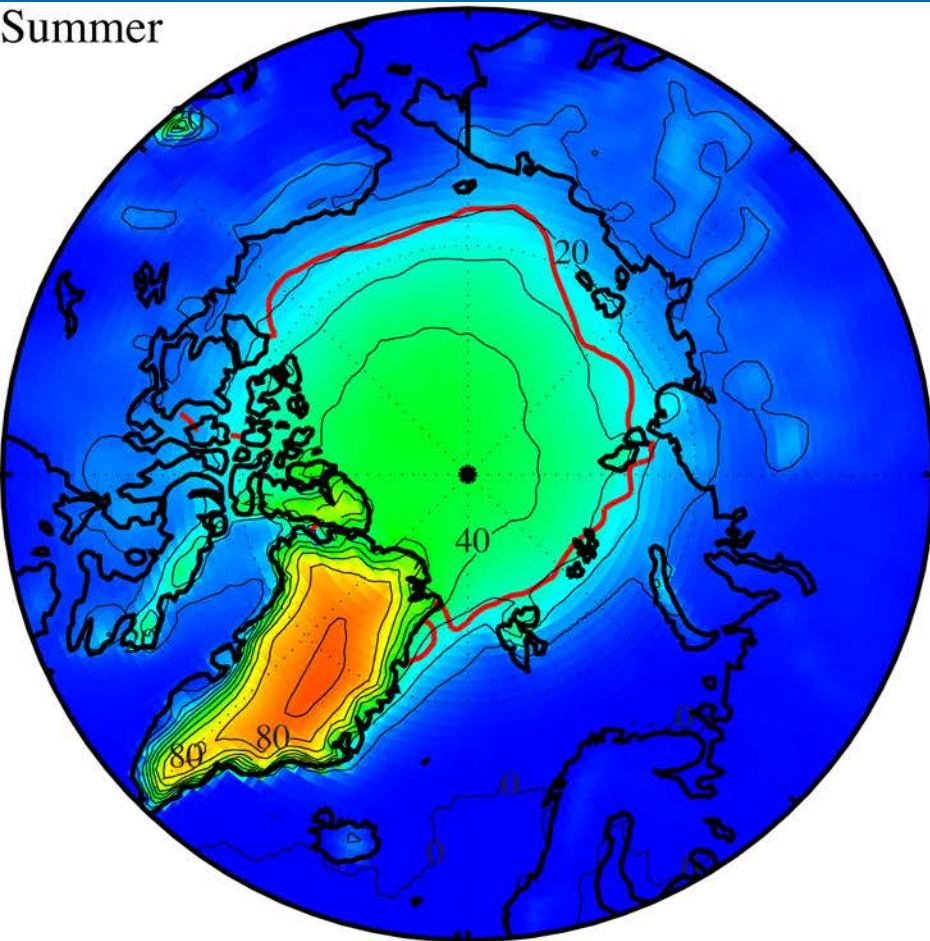
The Arctic Atmosphere



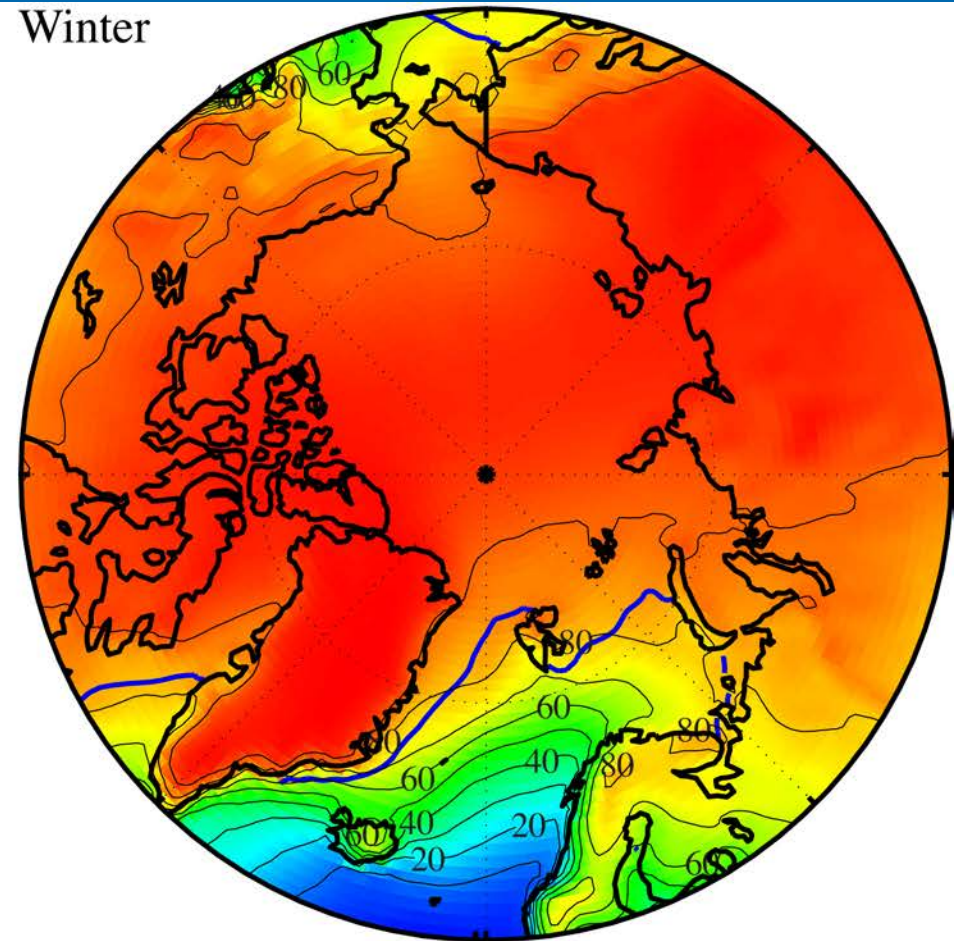
Precipitation (shading & contours-mm/day)
with 50% sea ice concentration contour in red

The Arctic Atmosphere

Summer



Winter

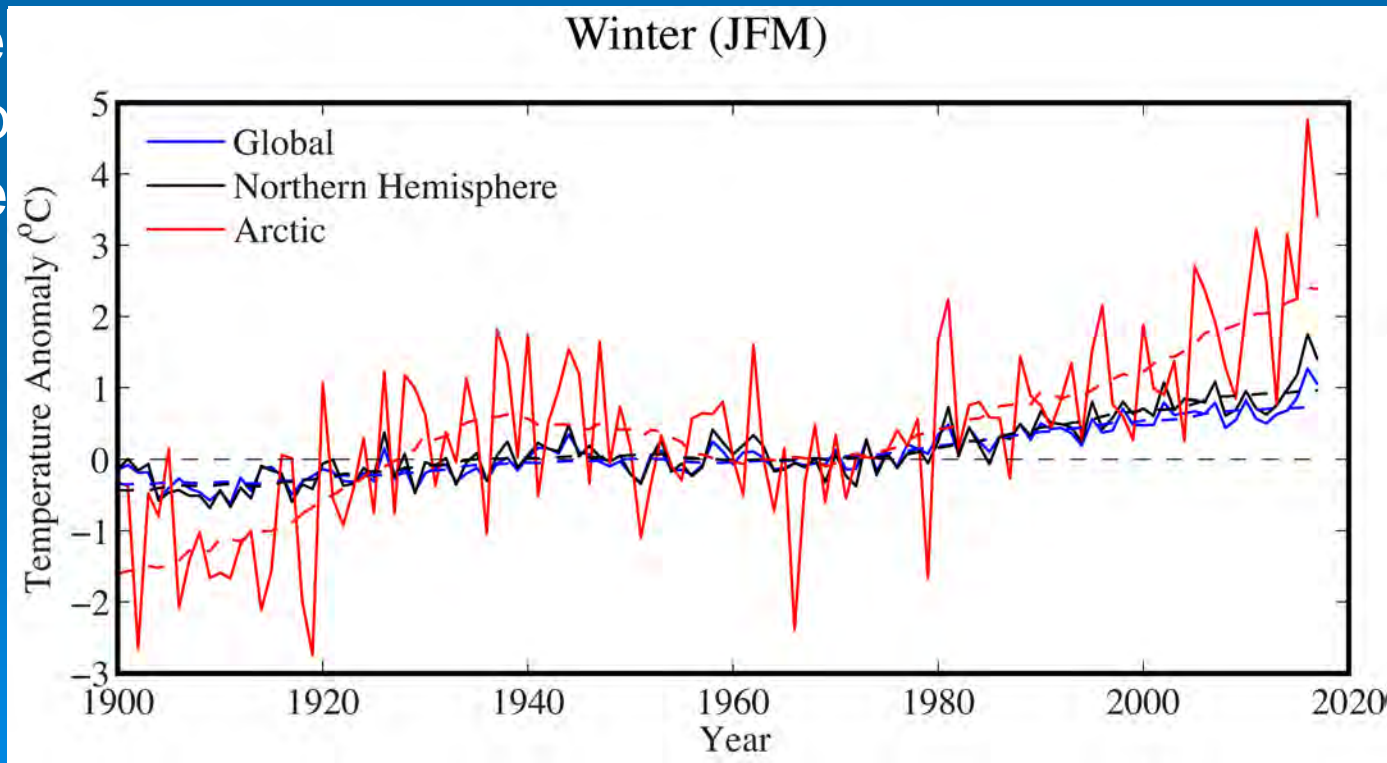


Snow fraction (shading & contours-%)
with 50% sea ice concentration contour in red/blue

The Arctic Atmosphere

- We have shown that there is strong seasonality in the Arctic Atmosphere that is related to the need to transport energy polewards during the winter.
- Do the changes that we are observing also have a seasonal imprint?

- Yes
- April
- trend

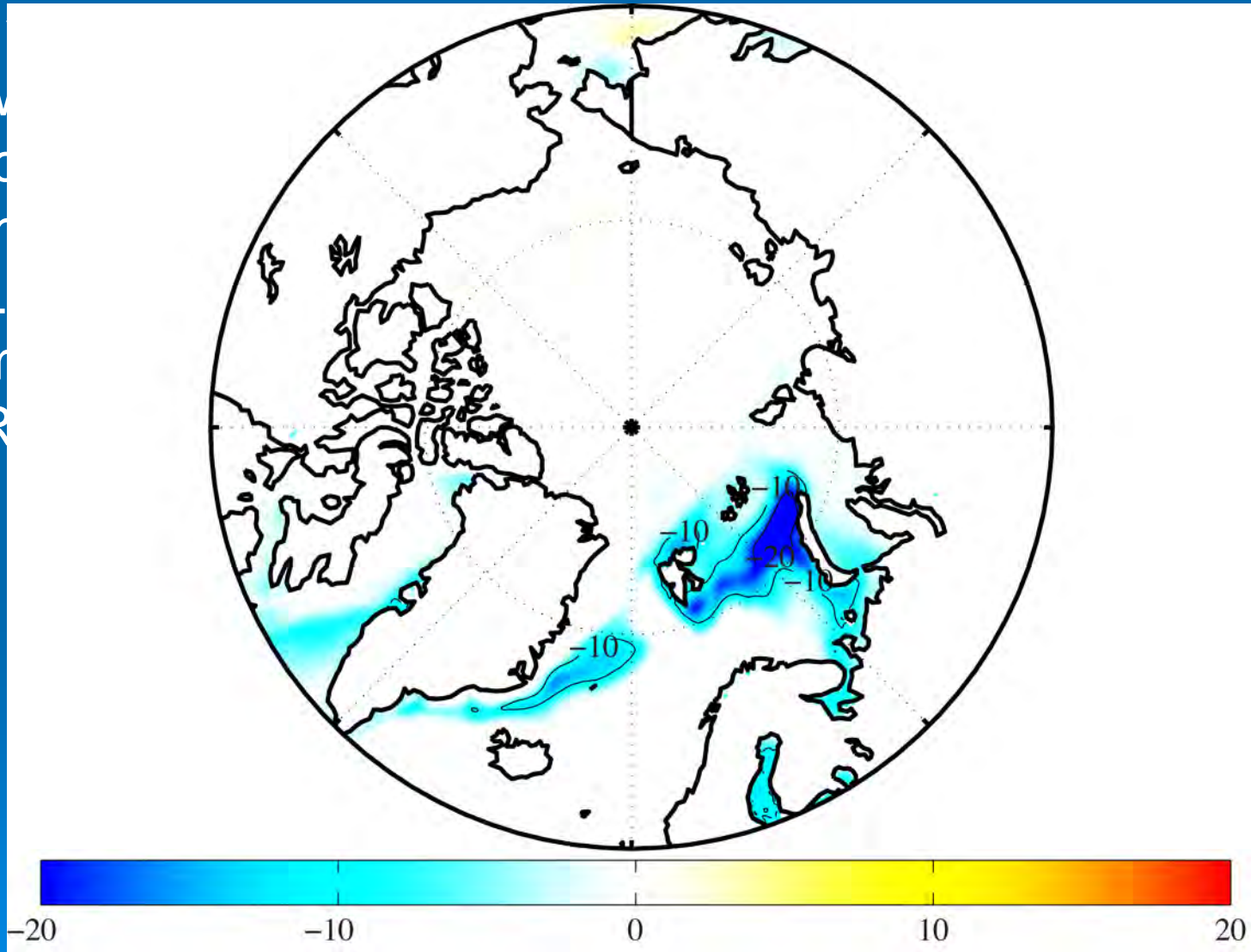


GIS Surface Temperature Anomaly

ter!
m

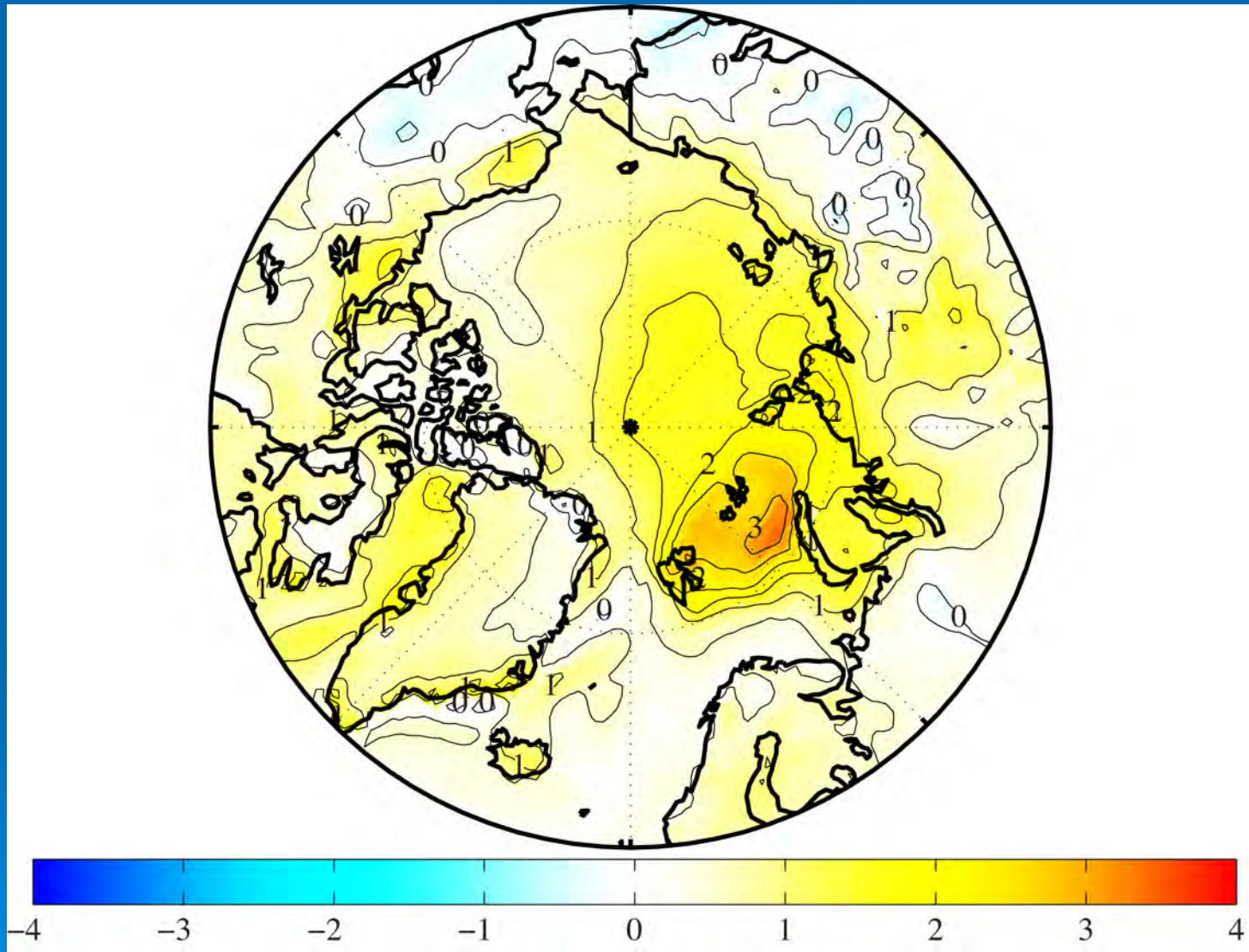
The Changing Arctic

- I
- W
- L
- R



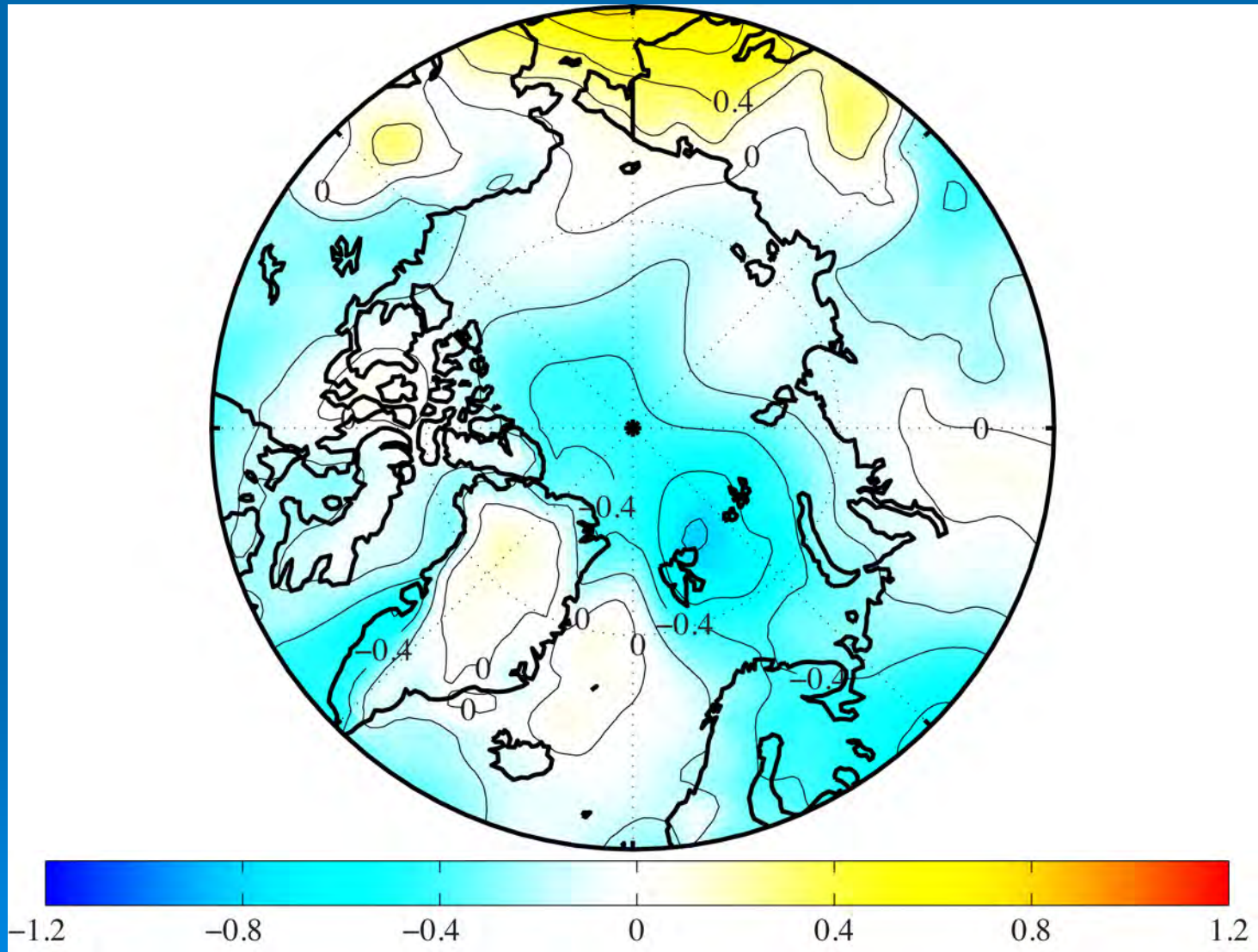
Winter trend in sea ice concentration (%/decade) from Bootstrap Dataset

The Changing Arctic Atmosphere



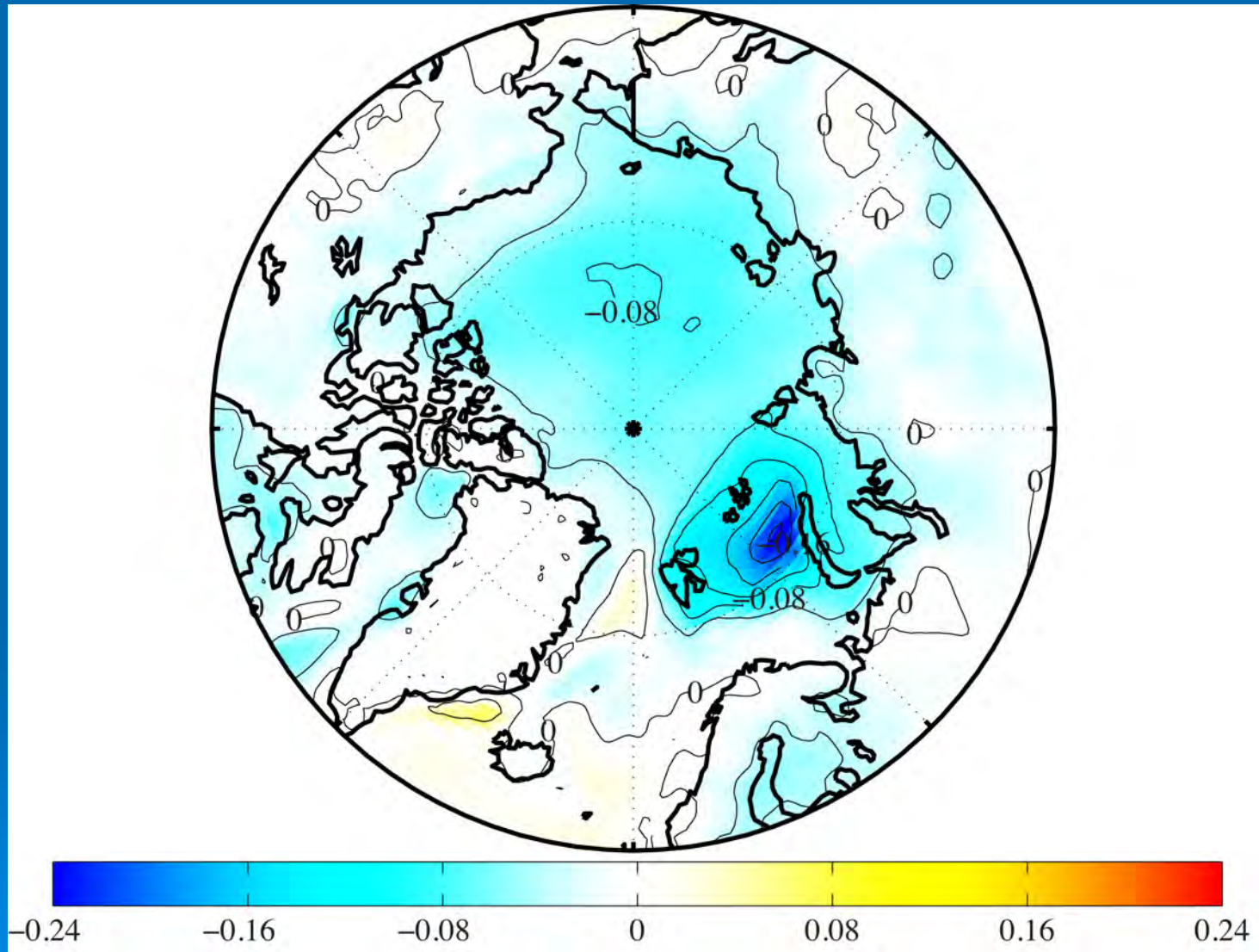
Winter trend in 2m air temperature ($^{\circ}\text{C}/\text{decade}$) from ERA-I

The Changing Arctic



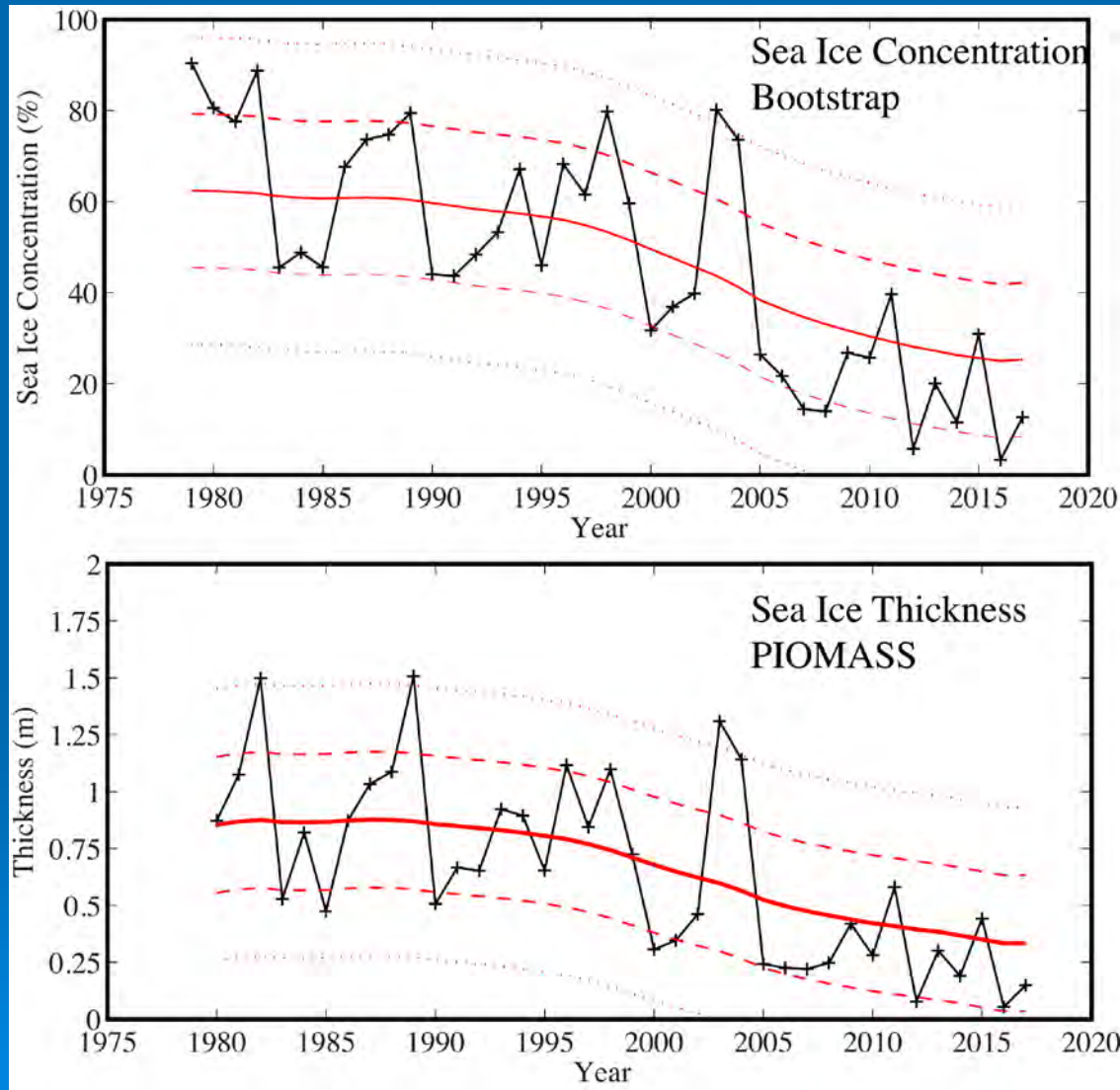
Winter trend in sea-level pressure (mb/decade) from ERA-I

The Changing Arctic



Winter trend in Brunt-Väisälä frequency (s⁻¹/decade) from ERA-I

The Changing Arctic



Time series of Barents Sea Winter sea ice concentration (%) and thickness (m)

Summary:

- Earth is in thermal equilibrium (incoming solar radiation=outgoing terrestrial radiation).
- Atmospheric and oceanic motion to first order is the result of the need to transport heat polewards during the winter.
- As a result, the summer and winter circulation in the Arctic are very different (annual mean generally not representative).
- Winter most active time in the Arctic with much of the energy focused in the Eastern Arctic and Greenland (result of North Atlantic Storm track).



Summary:

- Arctic Amplification most pronounced during cool period of year when ice-albedo feedback not active.
- Amplification most likely the result of reduction and thinning of sea ice cover that is allowing the ocean and the atmosphere to transfer heat (warm ocean/cold atmosphere).
- This surface heating is leading to enhanced cyclogenesis in the Arctic that is distributing the heat westwards along the Siberian Coast.





Thank-You