The impact of Arctic climate changes on weather and climate in mid-latitudes – The role of tropo-stratospheric coupling

Dörthe Handorf[1]

Joint work with: Ralf Jaiser[1], Annette Rinke[1], Klaus Dethloff[1], Judah Cohen[2], Tetsu Nakamura[3], Jinro Ukita[4], Koji Yamazaki[3]

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[2]Atmospheric and Environmental Research, Inc., Lexington, Massachusetts, USA
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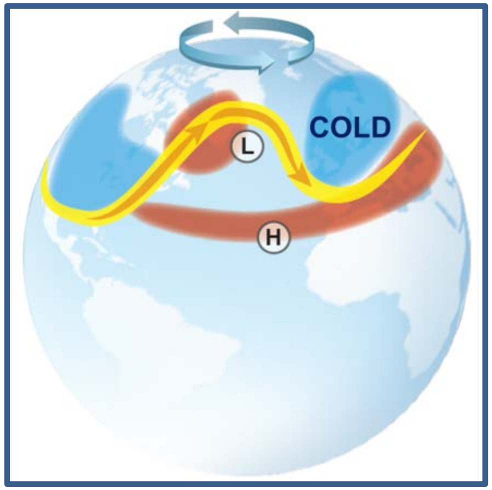
[4]Niigata University, Niigata, Japan

GOTHAM Summer School, Potsdam, 19th September 2017

Arctic climate change
Impacts on weather and climate in mid-latitudes



- Arctic climate change
- Planetary-scale atmospheric circulation
- Observed Arctic-midlatitude linkages
- Mechanisms of linkages
- Representation in climate models

The Arctic within the global climate system

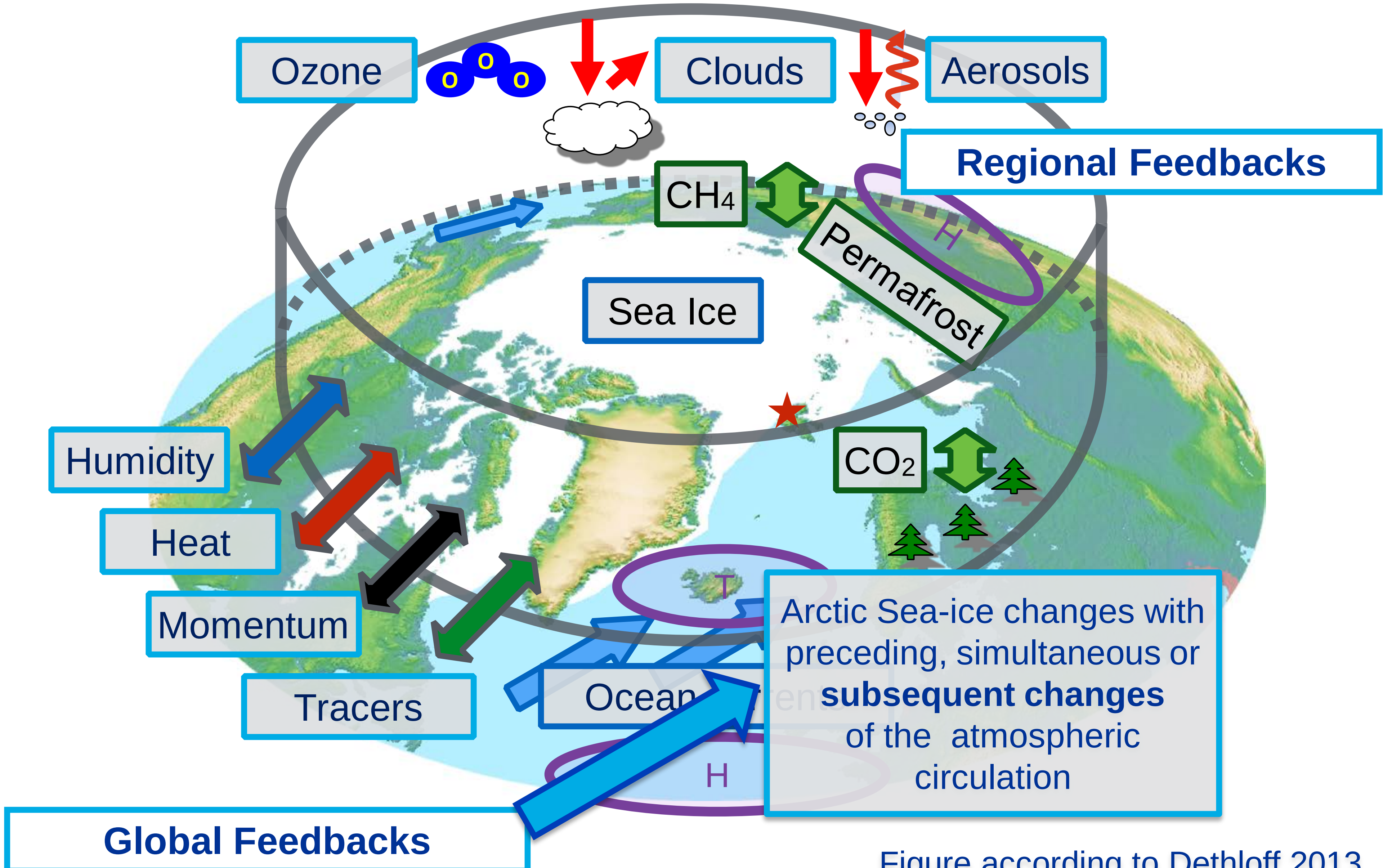
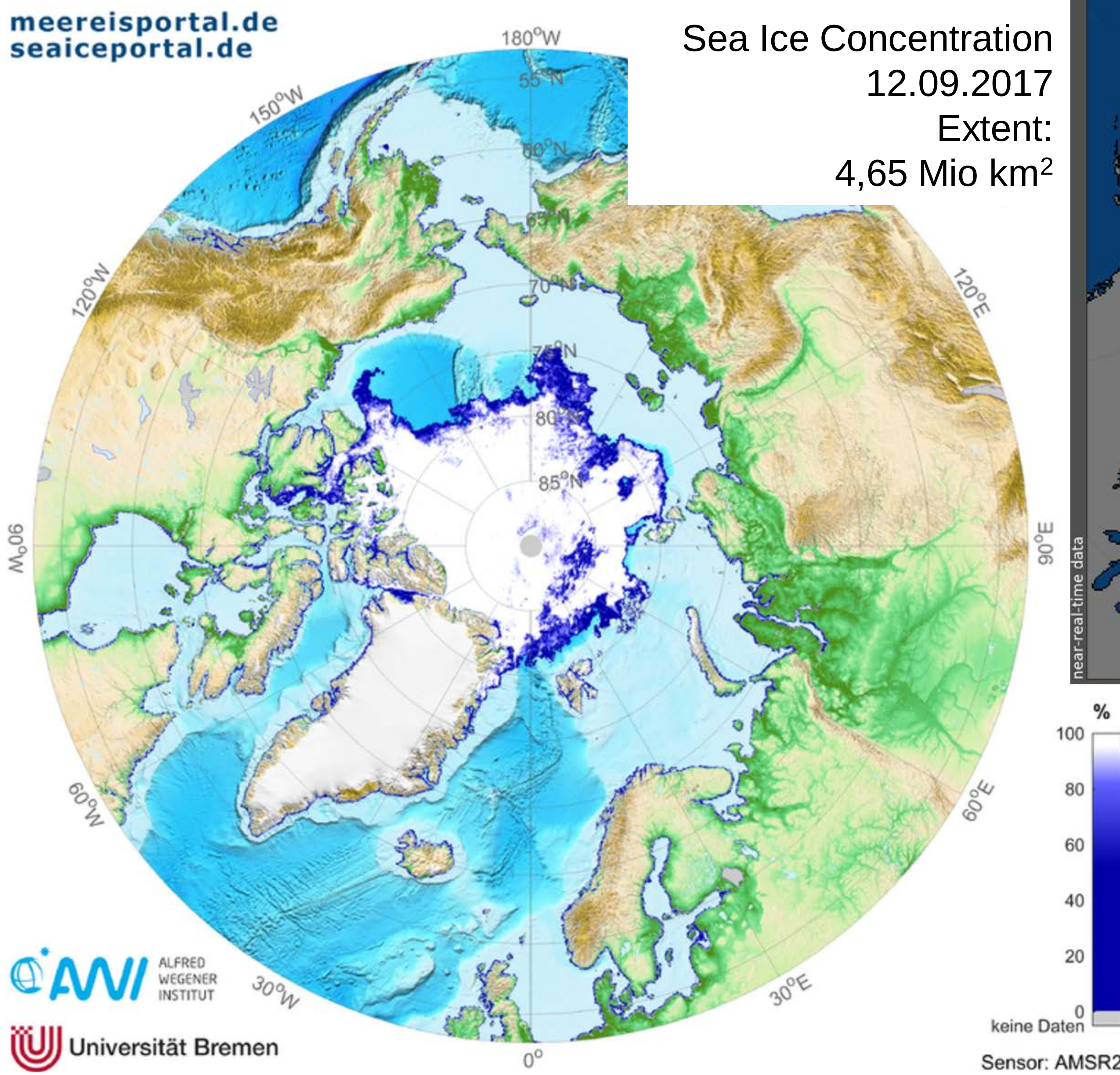
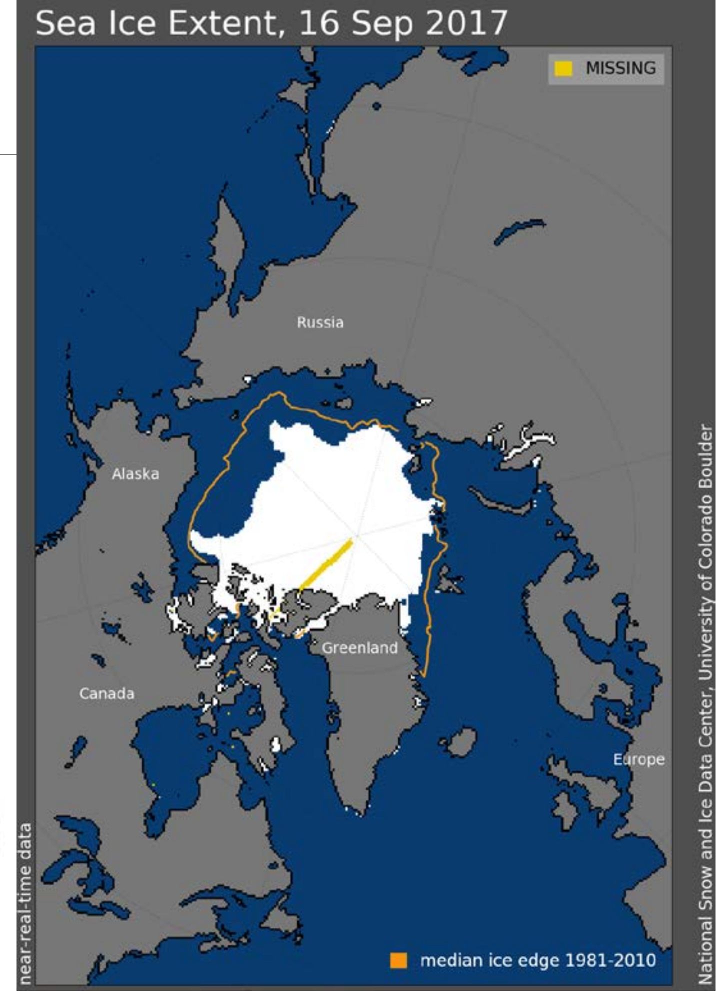


Figure according to Dethloff 2013

Current situation in the Arctic – Sea ice minimum





- Sea-ice retreat over the Beaufort, East Siberian, Laptev, Kara and northern Barents

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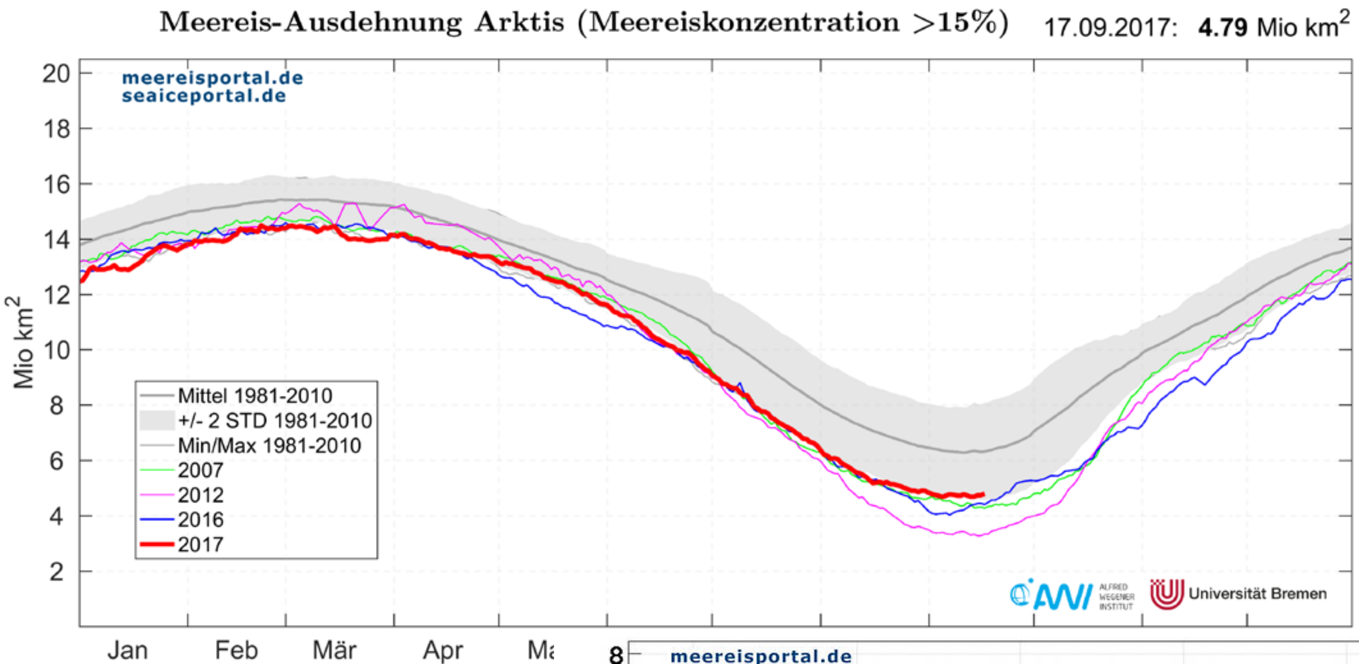
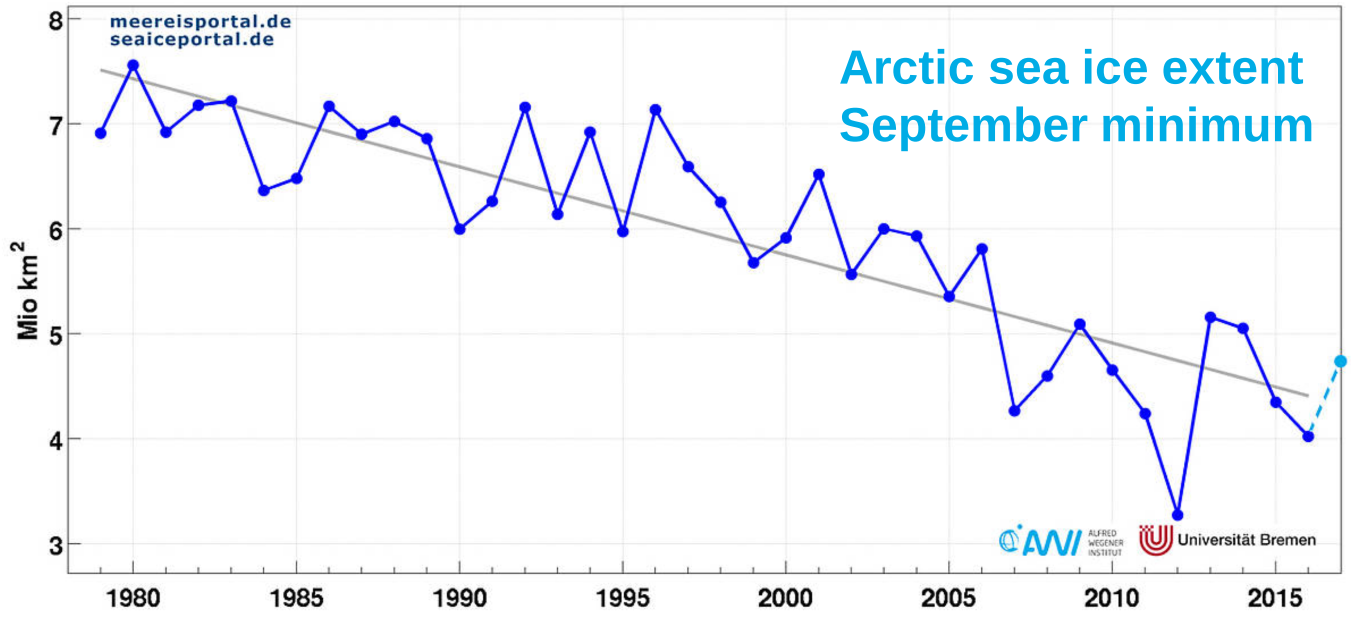
Current situation in the Arctic – Sea ice minimum



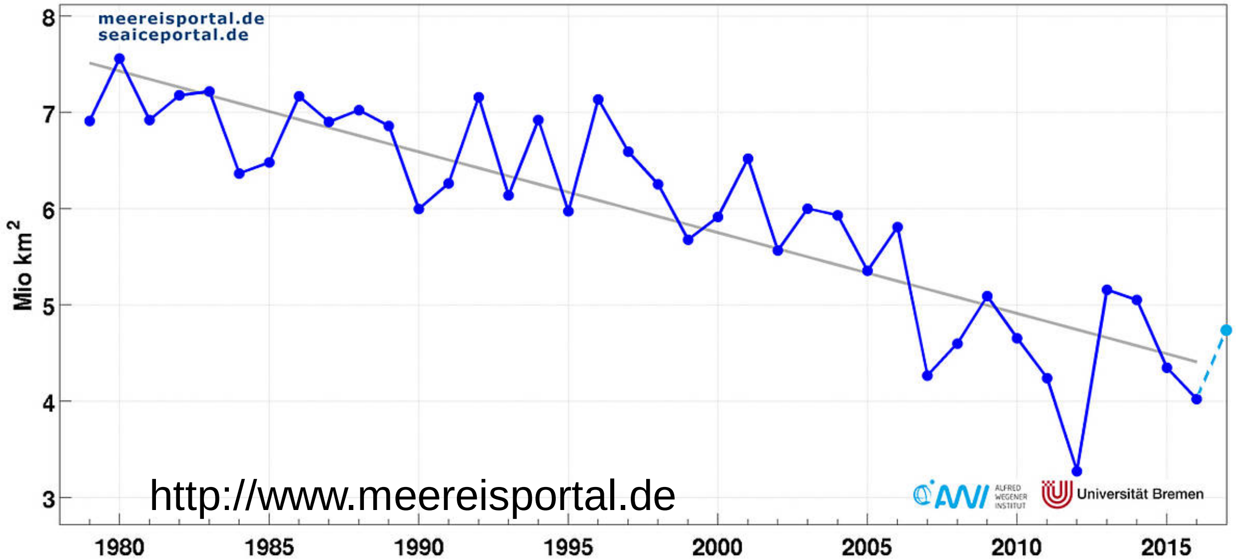
Sea ice extent

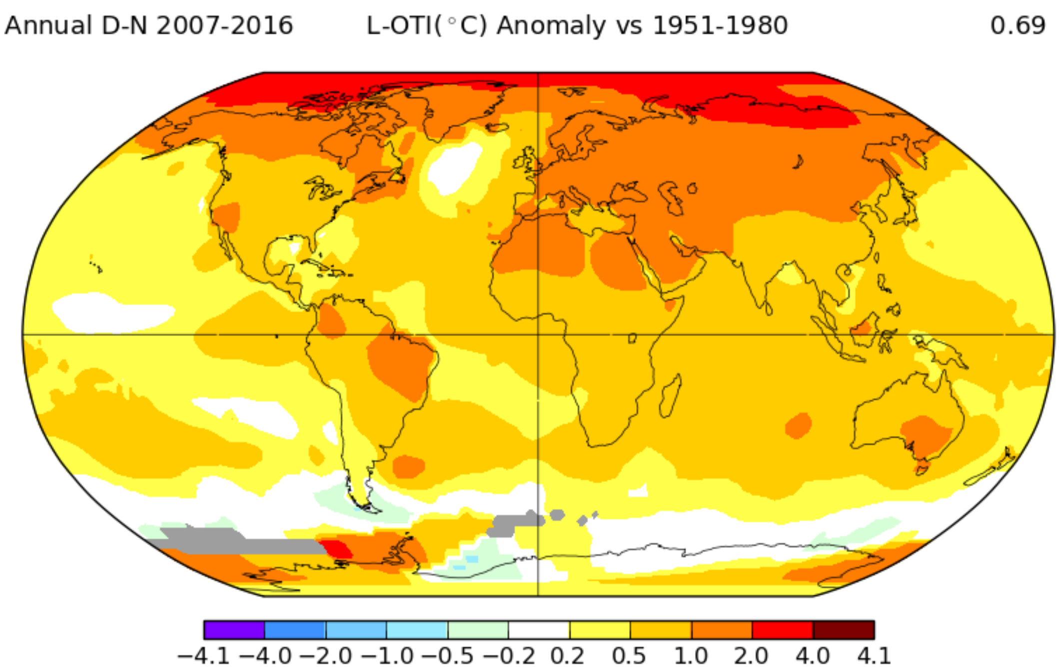


Arctic sea ice extent September minimum

Arctic Amplification and Retreat of Arctic Sea Ice

Retreat of Arctic Sea Ice Extent in September, 1979-2017





[K]

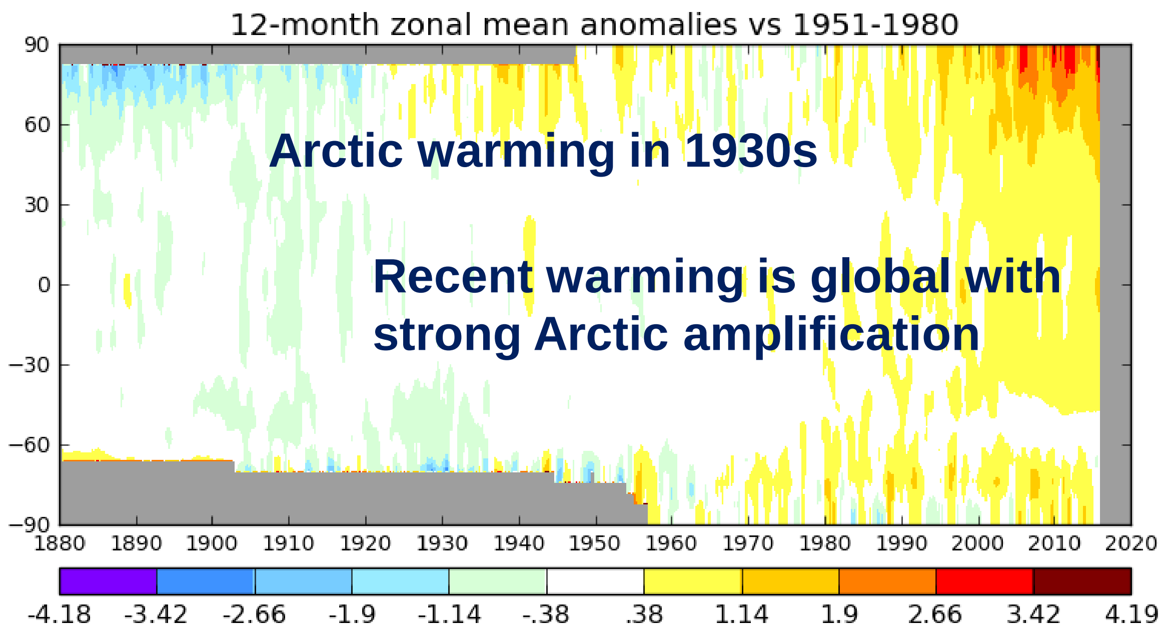
Arctic Amplification

Anomalies of Surface Air Temperature 2007-2016 from Mean over 1951-1980

Goddard Institute for Space Studies, 2014
http://data.giss.nasa.gov/gistemp/

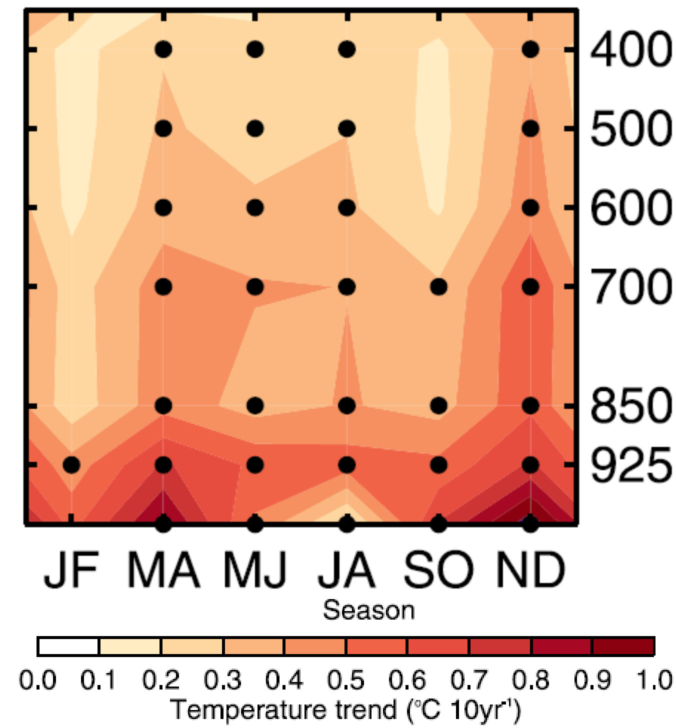
Arctic Amplification

Surface Air Temperature (NASA GISS) Annual zonal mean anomalies 1880-2016 relative to 1951-1980



http://data.giss.nasa.gov/cgi-bin/cdrar/do_LTmaoE.cgi

Vertical & seasonal structure of Arctic-mean temperature trends ERA-I reanalyses 1979–2008

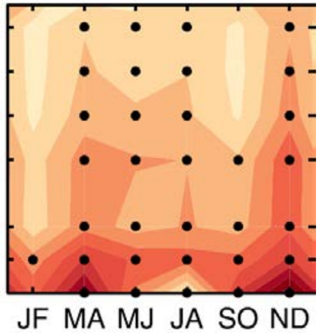


Screen et al., GRL, 2012

- ➢ **Amplification is greatest in autumn and winter**
- ➢ **Amplification is greatest near the surface**

Arctic amplification – Possible Feedback Explanations

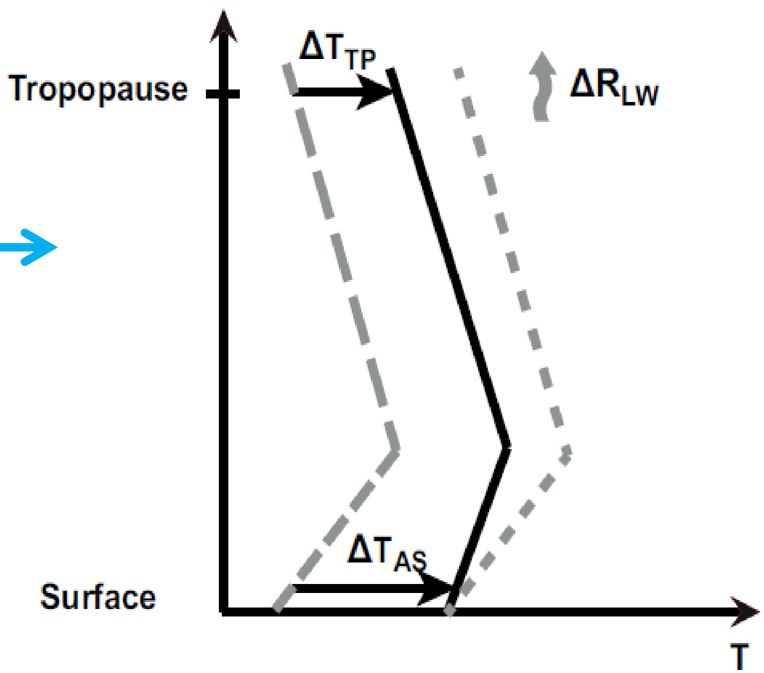
Ice/Snow Albedo-Temperature Feedback
No direct influence in the Arctic winter
Water Vapour Feedback
No winter trend in precipitable water
Cloud Feedback
Open question
Dynamical Feedback
Changes in meridional energy transport



Amplification is greatest in autumn/winter near surface

Thinning Sea Ice Feedback
Enhanced heat flux from ocean through sea ice

Lapse-rate feedback
Stronger warming at the surface than in the middle and upper troposphere
→ Positive lapse rate feedback in the Arctic

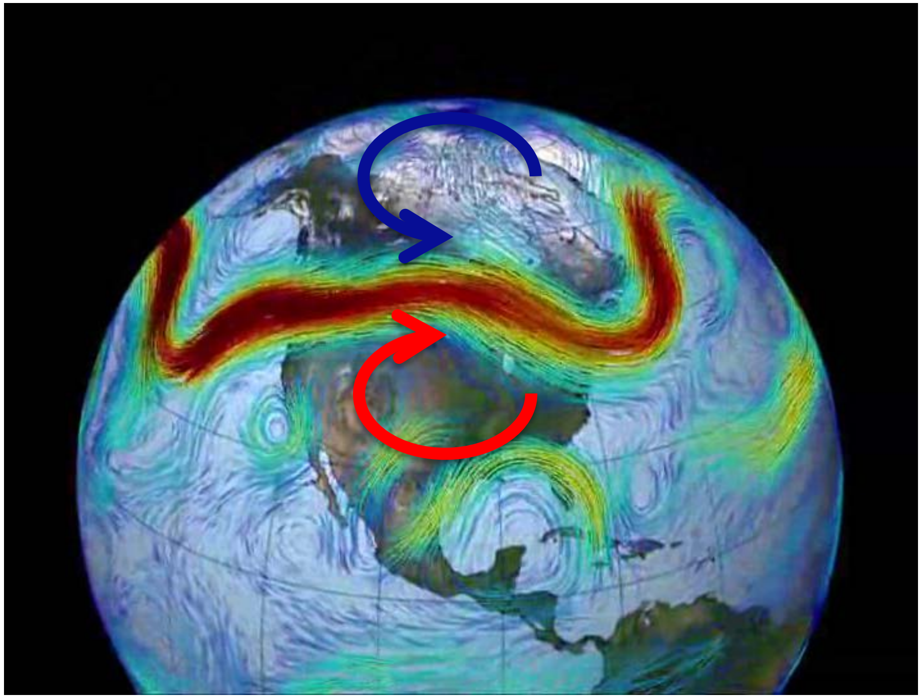


Pithan & Mauritsen, JC, 2013

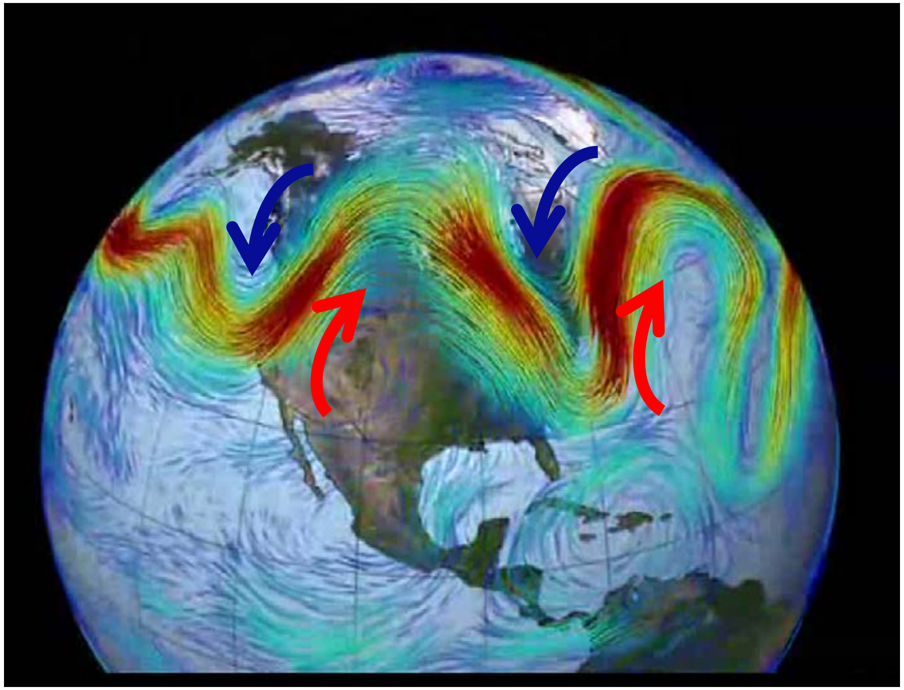
Atmospheric circulation in the mid-latitudes – Jet streams-Planetary Waves-Circulation patterns

Polar jet stream at ca. 10 km height
Two states of atmospheric circulation

Zonal jet stream
Small-amplitude planetary waves



Meandering jet stream
Large-amplitude planetary waves

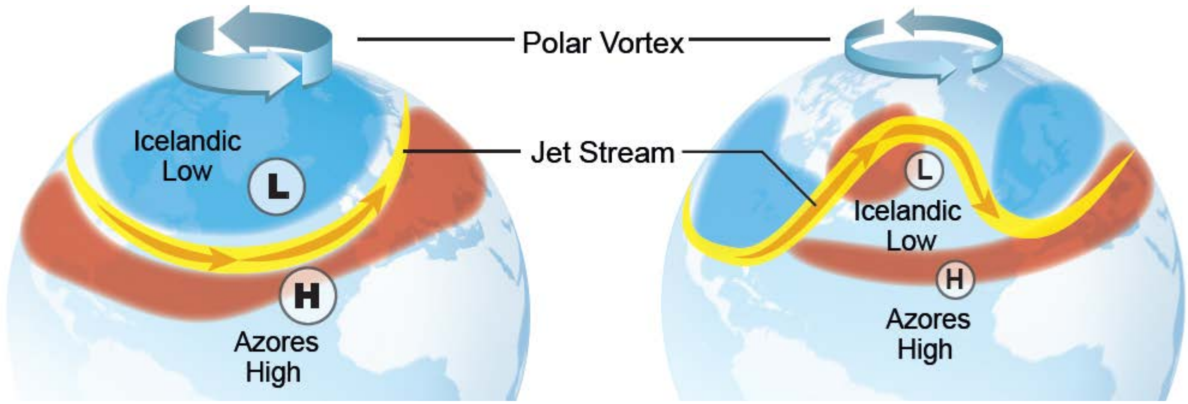


MERRA data, Jan. 2012, NASA

Atmospheric circulation in the mid-latitudes – Jet streams-Planetary Waves-Circulation patterns

Two states of atmospheric circulation over the North Atlantic-European sector

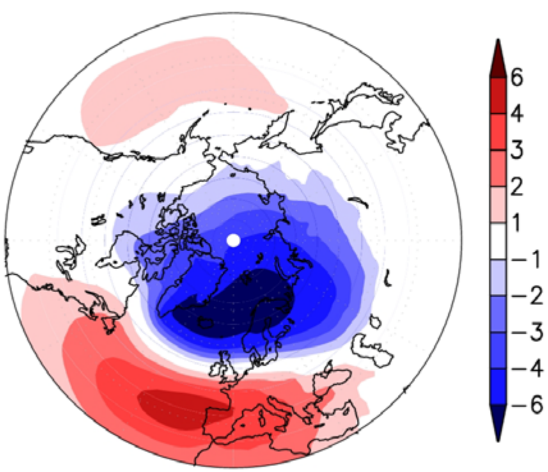
Zonal jet stream
Small-amplitude planetary waves

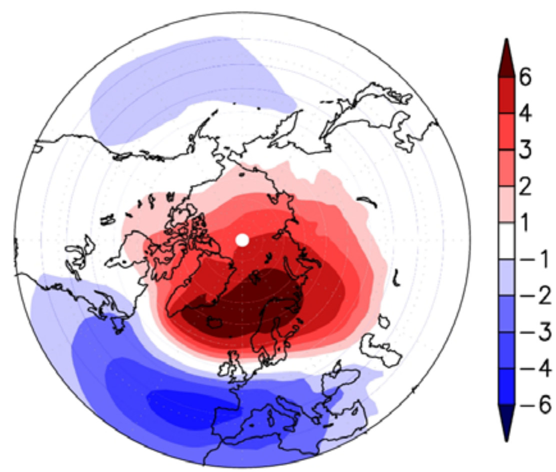


Meandering jet stream
Large-amplitude planetary waves

Corresponding **patterns of sea-level pressure anomalies**
(deviation from mean pressure distribution)

North-Atlantic Oscillation in positive phase (NAO+)





North-Atlantic Oscillation in negative phase (NAO-)

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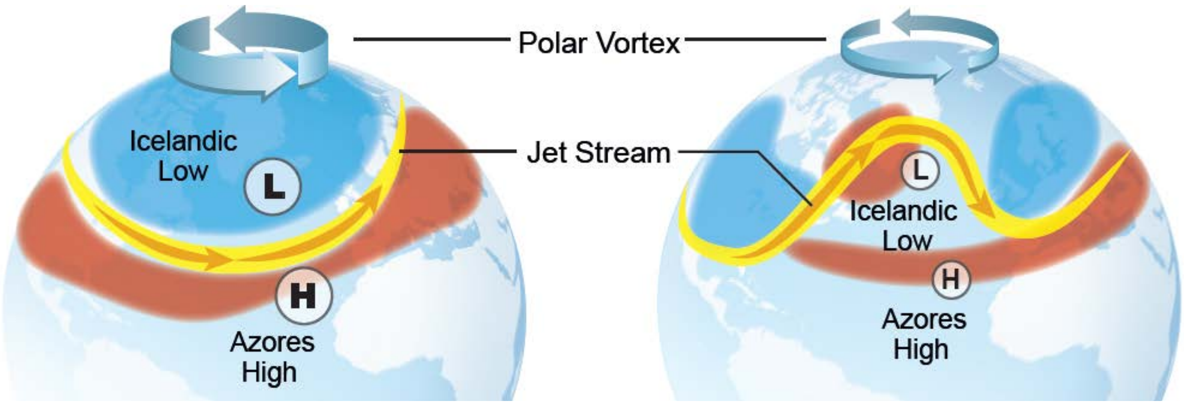
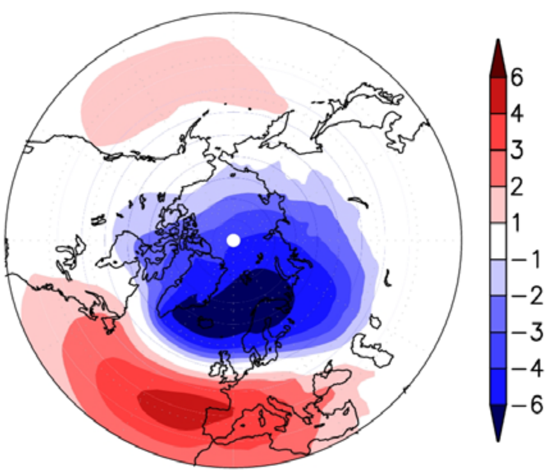
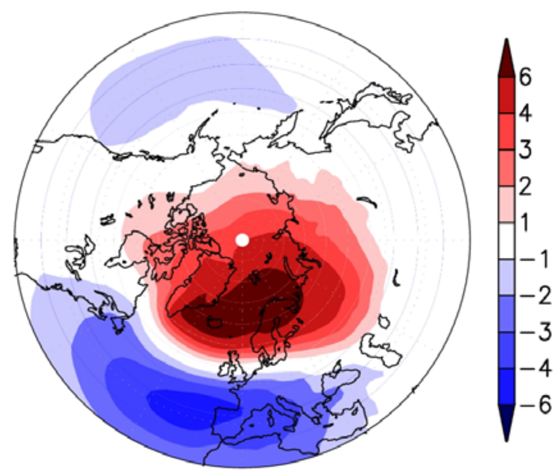


Meandering jet stream
Large-amplitude planetary waves

➢ **Can Arctic changes contribute to changes in the frequency of occurrence of circulation states (NAO-phases)??**

North-Atlantic Oscillation in positive phase (NAO+)





North-Atlantic Oscillation in negative phase (NAO-)

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Arctic Sea Ice and atmospheric Circulation changes – Some History

Analysis of observational data

- Brennecke (1904), Meinardus (1906)
  local synoptic situation ↔ Position of ice edge

Wilhelm Brennecke (1875–1924), Oceanographer,
2nd German Antarctic Expedition 1911/12

Wilhelm Meinardus (1867–1954), Geographer,
Nestor of German Polar Research

Arctic Sea Ice and atmospheric Circulation changes – Some History

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  local synoptic situation ↔ Position of ice edge

Hugo Hildebrand Hildebrandsson (1838-1925)
Meteorologist, Discoverer of Southern Oscillation

- Hildebrandsson (1914)
  Hypothesis: Mean winter conditions over Europe depend on the summer Sea Ice extent in the Greenland Sea

Wladimir Juljewitsch Wiese (1886-1954)
Oceanographer, Geographer,
Meteorologist and Polar researcher

- Wiese (1924)
  Relationships between:
  (1) Air pressure distribution and Barents Sea ice extent (Sea ice prediction)
  (2) Sea ice extent in East-Greenland-/Norwegian Sea and air pressure distribution (incl. Storm frequency/cyclone tracks over the North Atlantic)

Arctic Sea Ice and atmospheric Circulation changes – Some History

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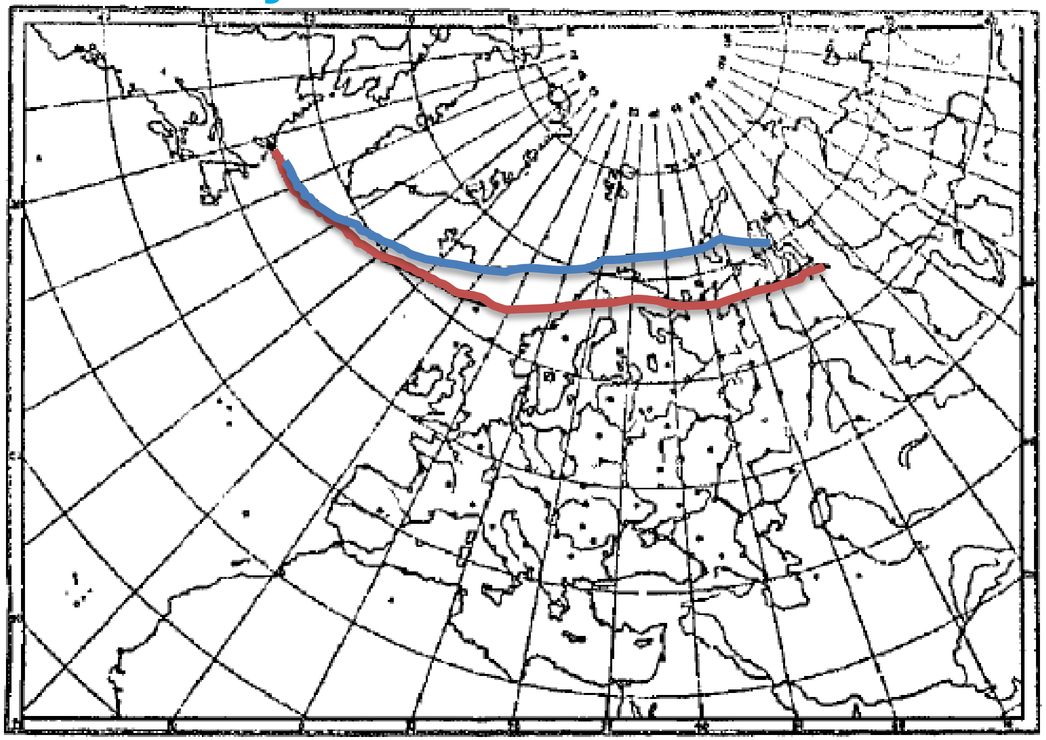

Fig. 10. Mittlere Bahnen nordatlantischer Zyklonen im Herbst.

Schwere Eisverhältnisse im Grönländischen Meere im April—Juli.
Leichte Eisverhältnisse im Grönländischen Meere im April—Juli.

Mean cyclone tracks in autumn for
Heavy ice conditions in Greenland Sea in April to July
Light ice conditions in Greenland Sea in April to July

Arctic Sea Ice and atmospheric Circulation changes – Some History

Analysis of observational data

- Brennecke (1904), Meinardus (1906)
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First modelling studies since ca.1971

- Herman & Johnson (1978):
  Model experiment with atmospheric General Circulation model: only changes in sea ice extent (observed recent minimum and maximum ice extent)
  Ensemble simulations, winter conditions
  Global circulation changes (pressure, temperature, energy fluxes)

Sea ice retreat & subsequent atmospheric circulation changes

Reduced sea ice in August/September

Additional heat stored in ocean

Warmer surface temperatures in following seasons

Reduced atmospheric vertical stability

Snow cover changes

A possible dynamical pathway for Arctic-midlatitude linkages?

Weaker stratospheric Polar Vortex/
Negative North Atlantic Oscillation

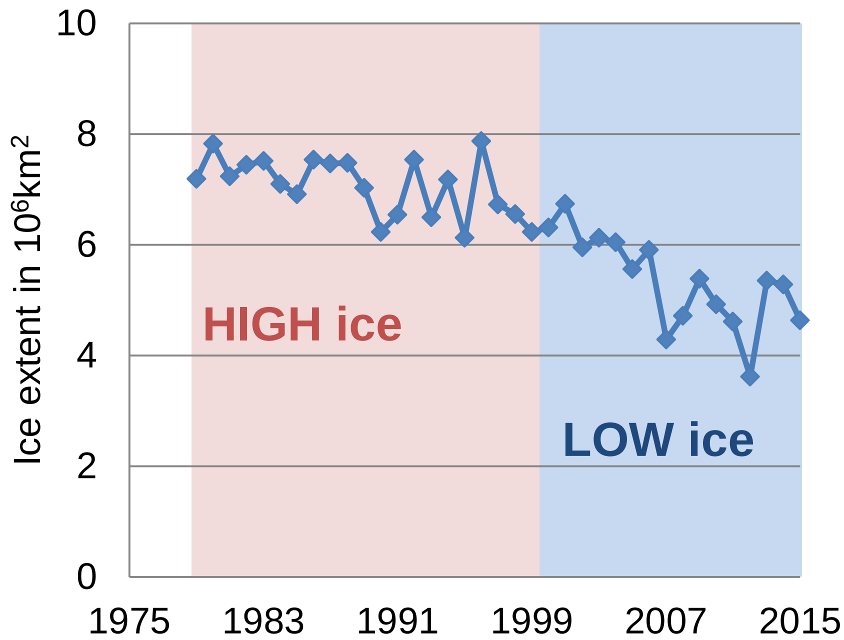
Enhanced possibility of cold winters over Eurasia

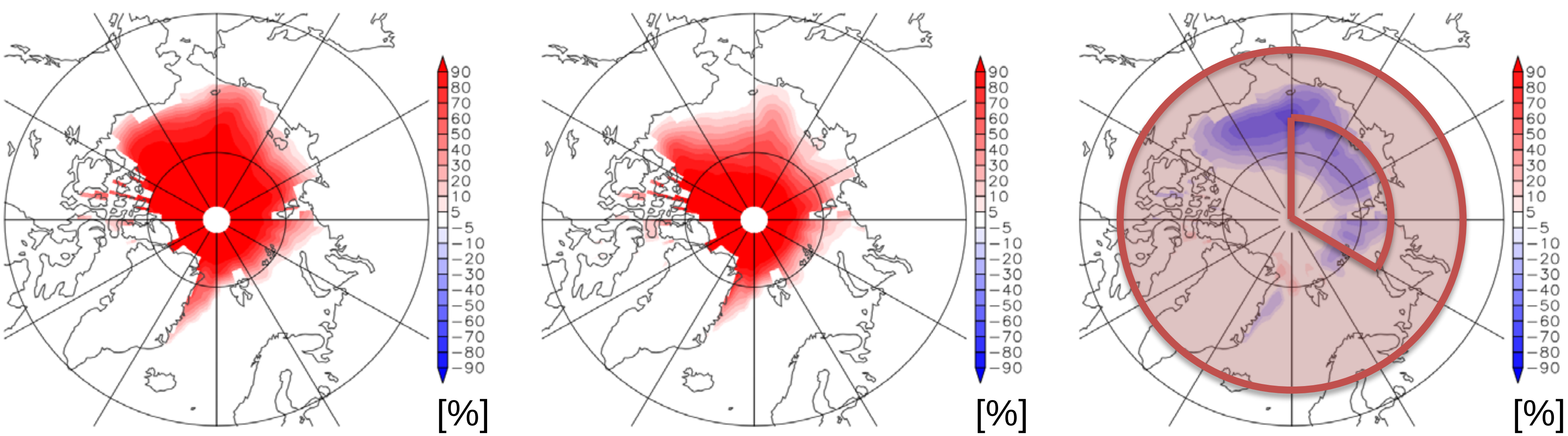
Synoptic-scale Arctic Response

Planetary-scale Response

Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data

- **ERA-Interim**
- Reanalysis data set = Model assimilated atmospheric observations
- Analyses for 1979-2014
- **September Sea ice concentration (%)**
- **High sea ice extent**
  HIGH ice (1979/80-1999/00)
- **Low sea ice extent**
  LOW ice (2000/01-2013/14)



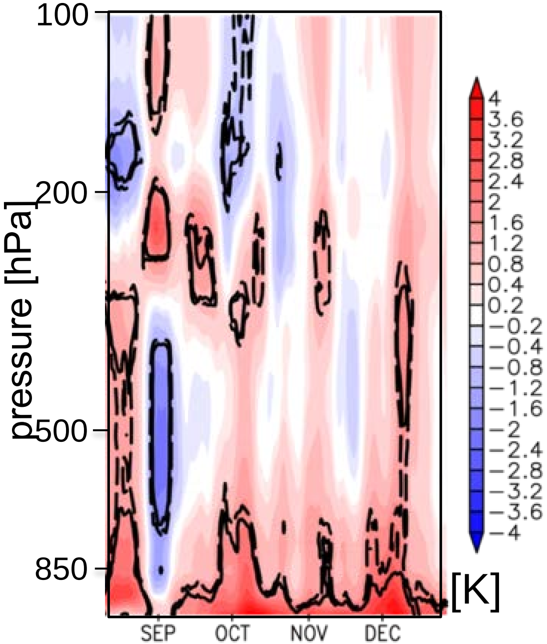


HIGH **LOW** **LOW-HIGH**

Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data

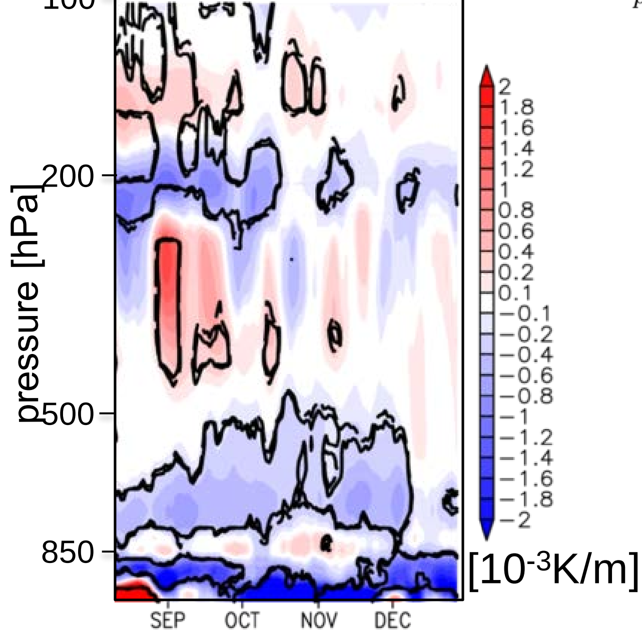
Baroclinic response over the Arctic in autumn

low minus high ice conditions in ERA-Interim,
Area-averaged mean over the Sibirian Arctic Ocean



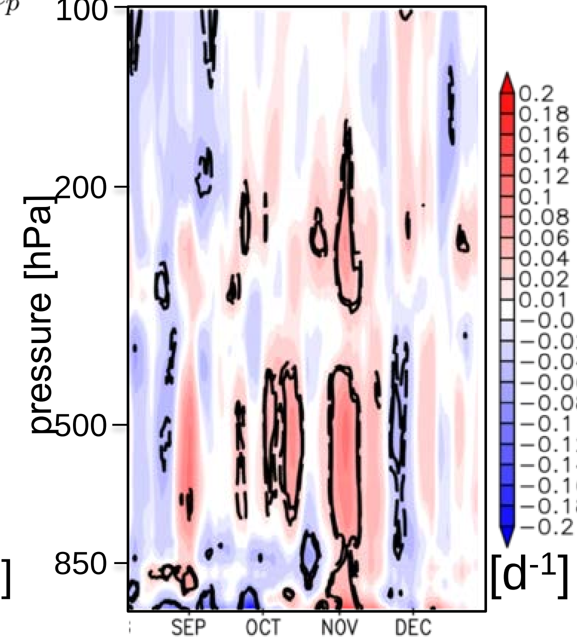
Temperature
higher temperatures in lower troposphere

$$S = \frac{\partial T}{\partial z^*} + \frac{R}{Hc_p}T$$



Vertical stability
Lower stability in lower/middle troposphere

$$\sigma_{EGR} = 0,3125\frac{g}{TN}\left|\frac{\partial T}{\partial y}\right|$$



Eady Growth Rate

Increased baroclinicity in middle troposphere

Intensification of cyclolysis

Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data

Baroclinic response over the Arctic in autumn

low minus high ice conditions in ERA-Interim,
Area-averaged mean over the Sibirian Arctic Ocean

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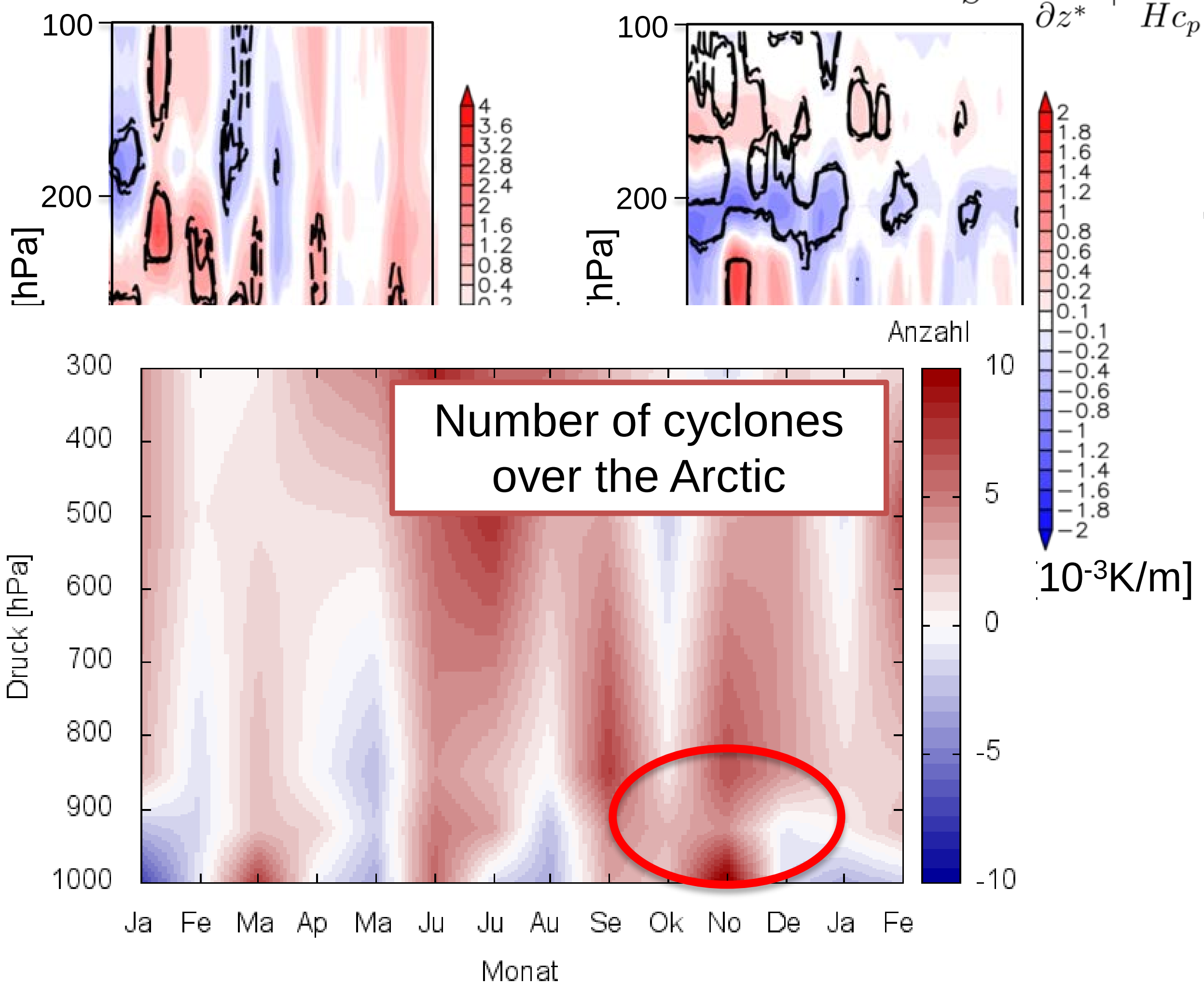
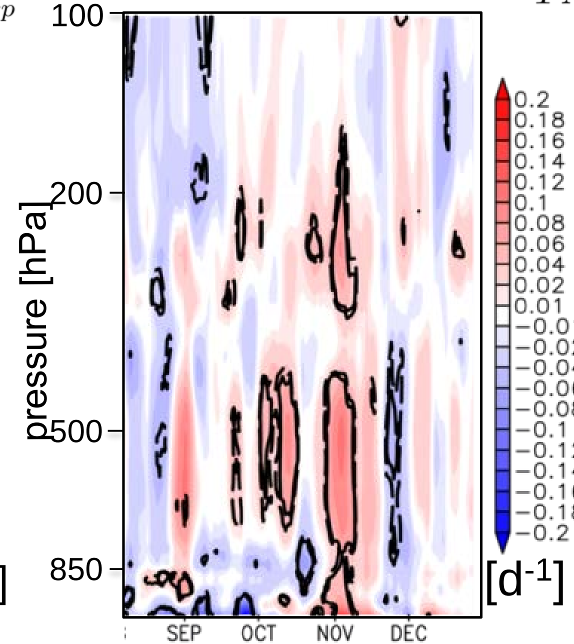




Eady Growth Rate

Increased baroclinicity in middle troposphere

Intensification of cyclolysis

Sea ice retreat & subsequent atmospheric circulation changes

- ✓ **Reduced sea ice in August/September**
- ✓ Additional heat stored in ocean
- ✓ Warmer surface temperatures in following seasons
- ✓ Reduced atmospheric vertical stability
- ✓ Amplified weather systems in autumn

Synoptic-scale Arctic Response

Snow cover changes

Impact on planetary waves in winter-
Changes in wave propagation

Negative North Atlantic Oscillation/
Weaker stratospheric Polar Vortex

Enhanced possibility of cold winters over Eurasia

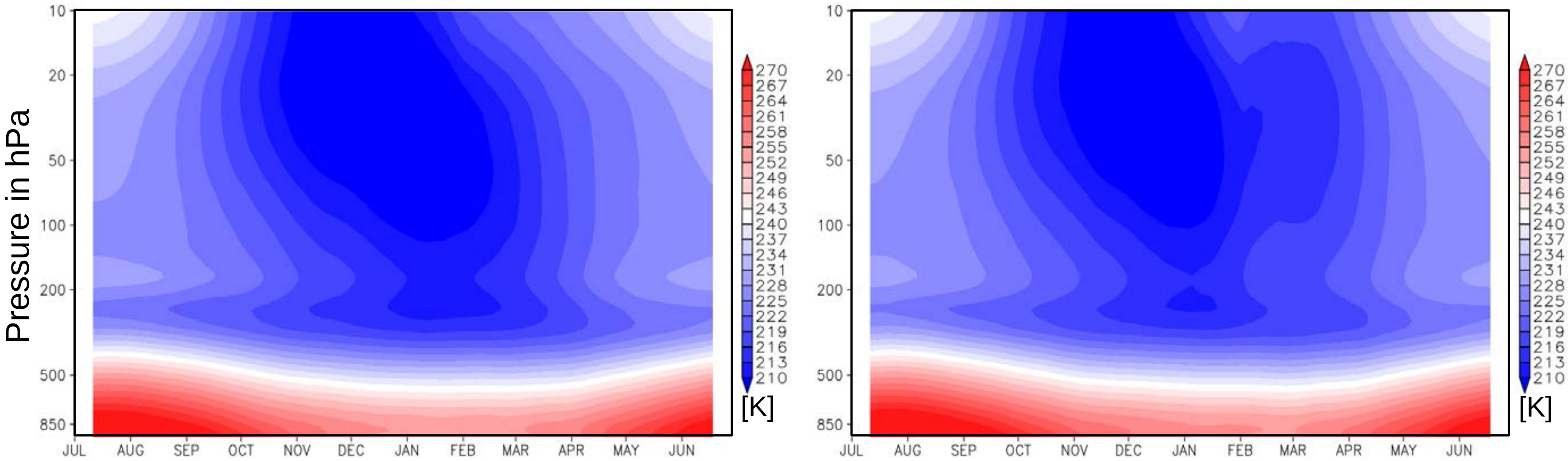
Planetary-scale Response

Polar cap temperature change – ERA-Interim data

Temperature [K] average 65°N-85°N

Climatologies of polar cap temperature

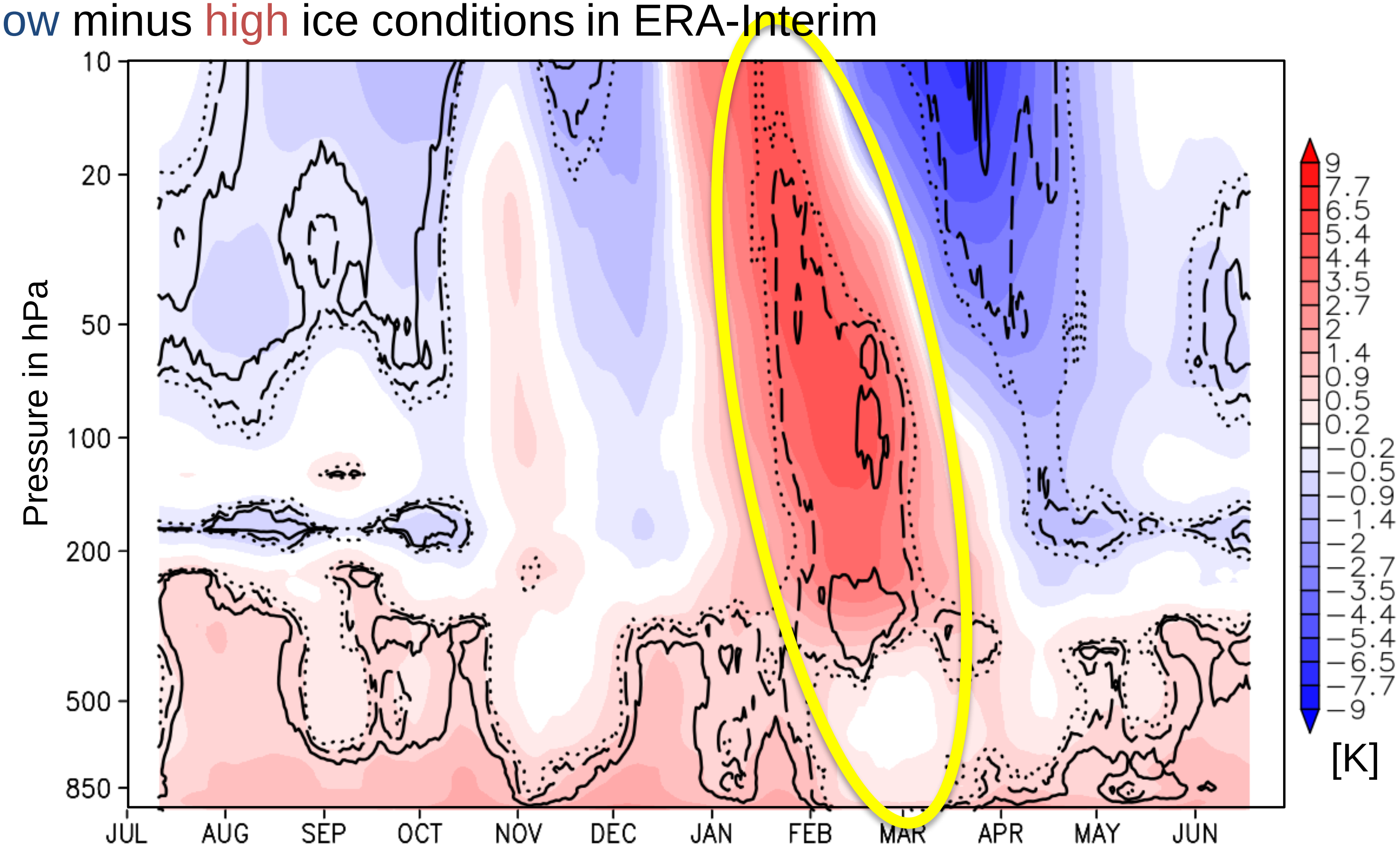
High ice 1979/80-1999/00 **Low ice** 2000/01-2013/14



- Higher tropospheric temperatures all over the year
  - Global warming impact
  - Arctic amplification impact
- Strong significant warming of polar stratosphere in late winter
  - Polar vortex breakdown?

Polar cap temperature change – ERA-Interim data

Temperature [K] average 65°N-85°N
for low minus high ice conditions in ERA-Interim



- Higher tropospheric temperatures all over the year
  - Global warming impact
  - Arctic amplification impact
- Strong significant warming of polar stratosphere in late winter
  - Polar vortex breakdown?→ Yes, strato. westerly winds massively reduced

Troposphere-Stratosphere coupling through planetary waves

Localized Eliassen-Palm flux (EP flux, Trenberth 1986)

- Interaction between waves and mean flow
- Description of coupling between troposphere and stratosphere through waves

$$\frac{D\bar{u}}{Dt} - fv^* = \nabla \cdot \vec{E}_u$$ EP flux divergence

$$\vec{E}_u = \left[\frac{1}{2}\left(\overline{v'^2} - \overline{u'^2}\right), -\overline{u'v'}, f\frac{\overline{v'T'}}{S} \right]$$ 3D EP flux vector

- **Divergence** of EP flux vector describes the **zonal wind forcing** by transient eddies
- **Vector** describes the **direction** of wave propagation
- **Magnitude** of EP flux vector is a qualitative measure of transient **eddy activity**
- Scale seperation between **synoptic** and **planetary scales**

We actually use:

Planetary scale vertical component of EP flux vector

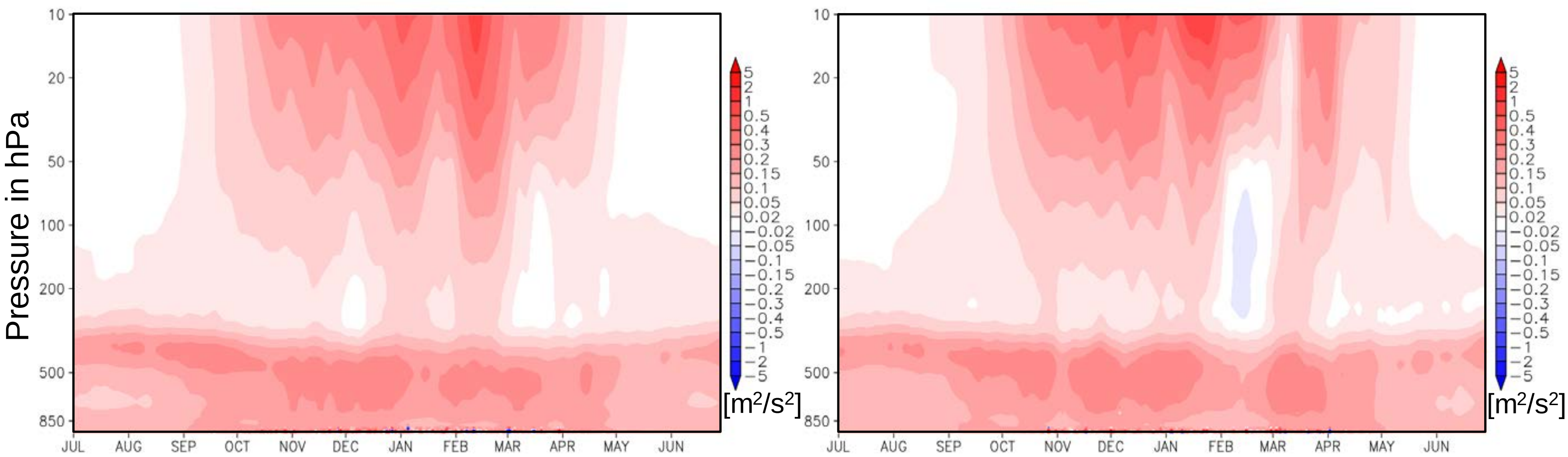
How strong do planetary waves propagate vertically (into the stratosphere)?

Polar cap vertical wave propagation change – ERA-Interim data

Vertical component of Eliassen-Palm flux vector [m^2/s^2] average 65°N-85°N

Climatologies of polar cap vertical component EP flux vector

High ice 1979/80-1999/00 **Low ice** 2000/01-2013/14



- ➢ Enhanced upward propagation of planetary waves in autumn and early winter
  - ➢ Disturbing the polar vortex, leading to a vortex breakdown
- ➢ Vertical wave propagation is reduced in February due to the vortex breakdown
  - ➢ Without westerly winds vertical wave propagation is not allowed

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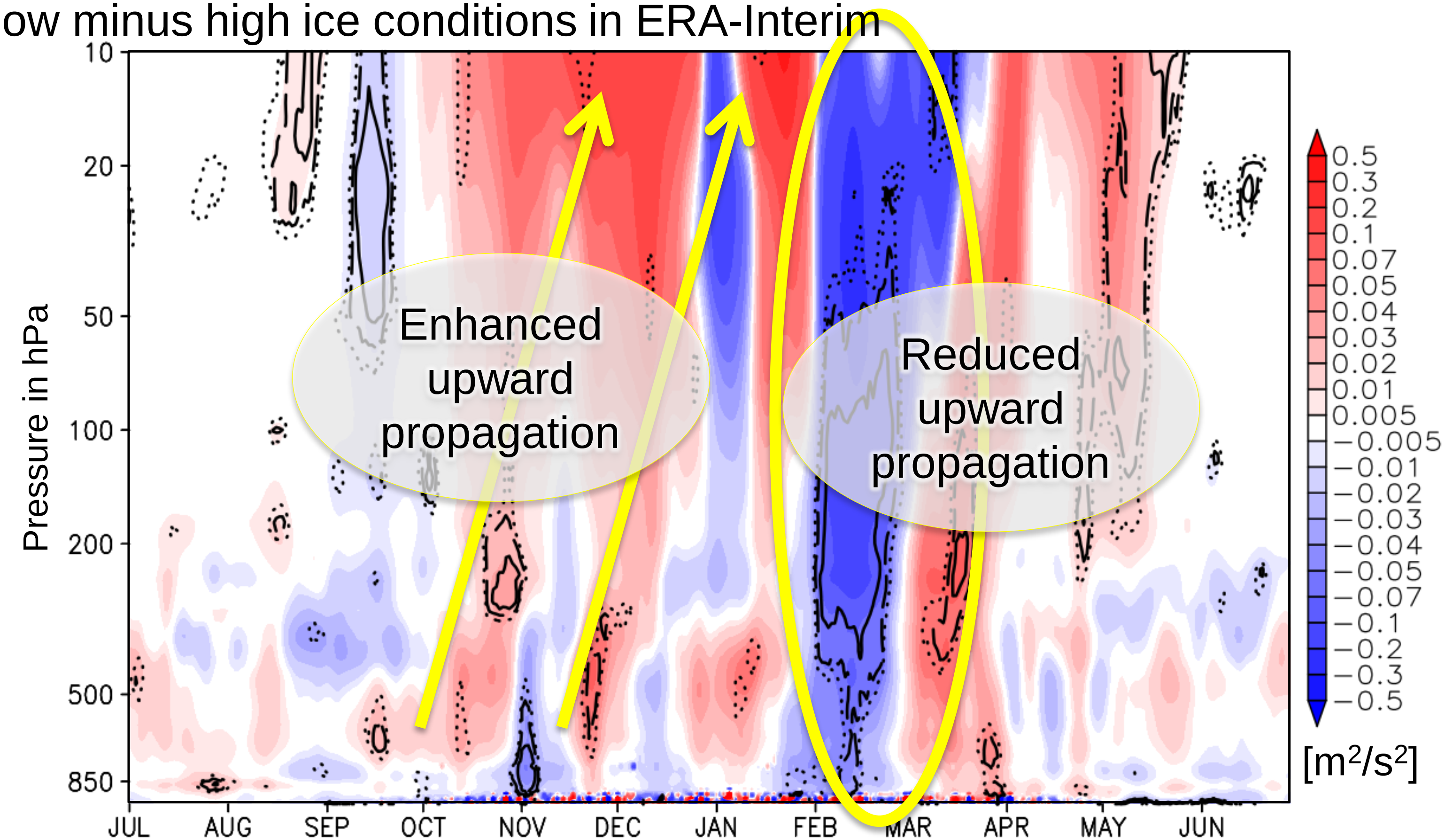
Polar cap vertical wave propagation change – ERA-Interim data

Vertical component of Eliassen-Palm flux vector [m^2/s^2] average 65°N-85°N for low minus high ice conditions in ERA-Interim



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✓ Reduced sea ice in August/September

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✓ Amplified weather systems in autumn

Synoptic-scale Arctic Response

Snow cover changes

✓ Impact on planetary waves in winter-
Changes in wave propagation

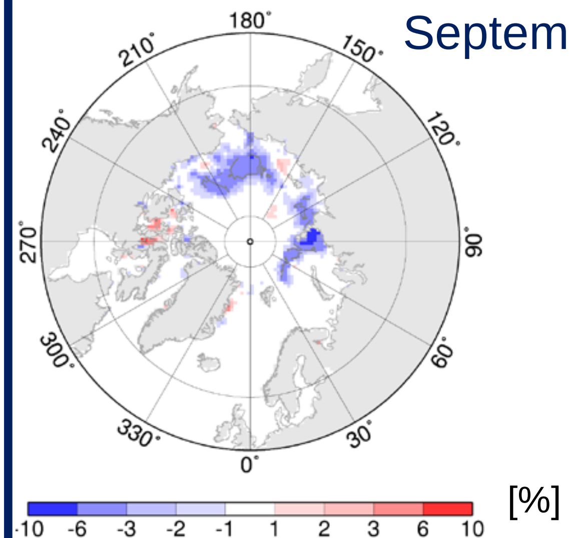
Negative North Atlantic Oscillation/
Weaker stratospheric Polar Vortex

Enhanced possibility of cold winters over Eurasia

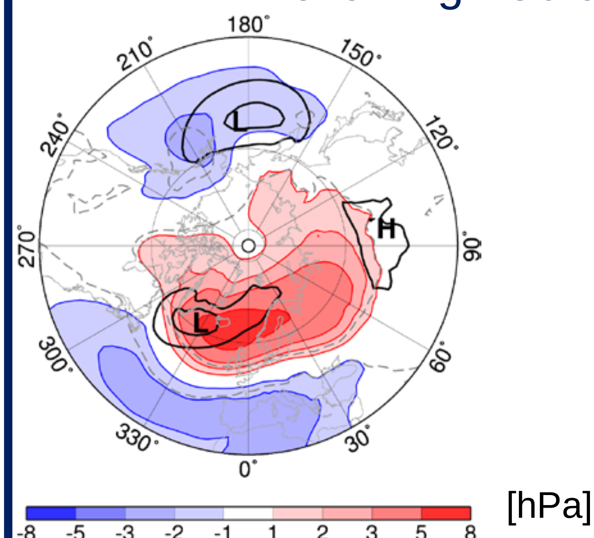
Planetary-scale Response

Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data

Sea ice concentration
September (HadISST Data)



Sea level pressure
Following February (ERA-Interim)

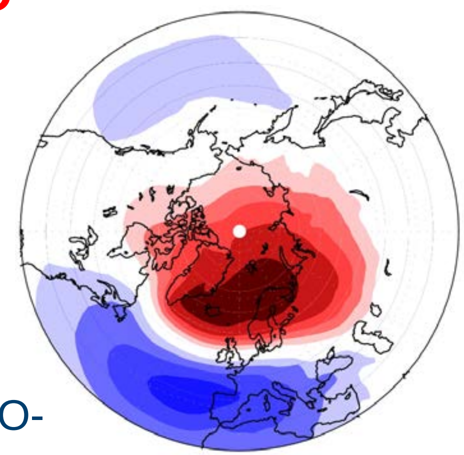


Planetary-scale response in February

Coupled Patterns 1979-2015

- Statistical relation between sea ice retreat and changes of atmospheric circulation patterns

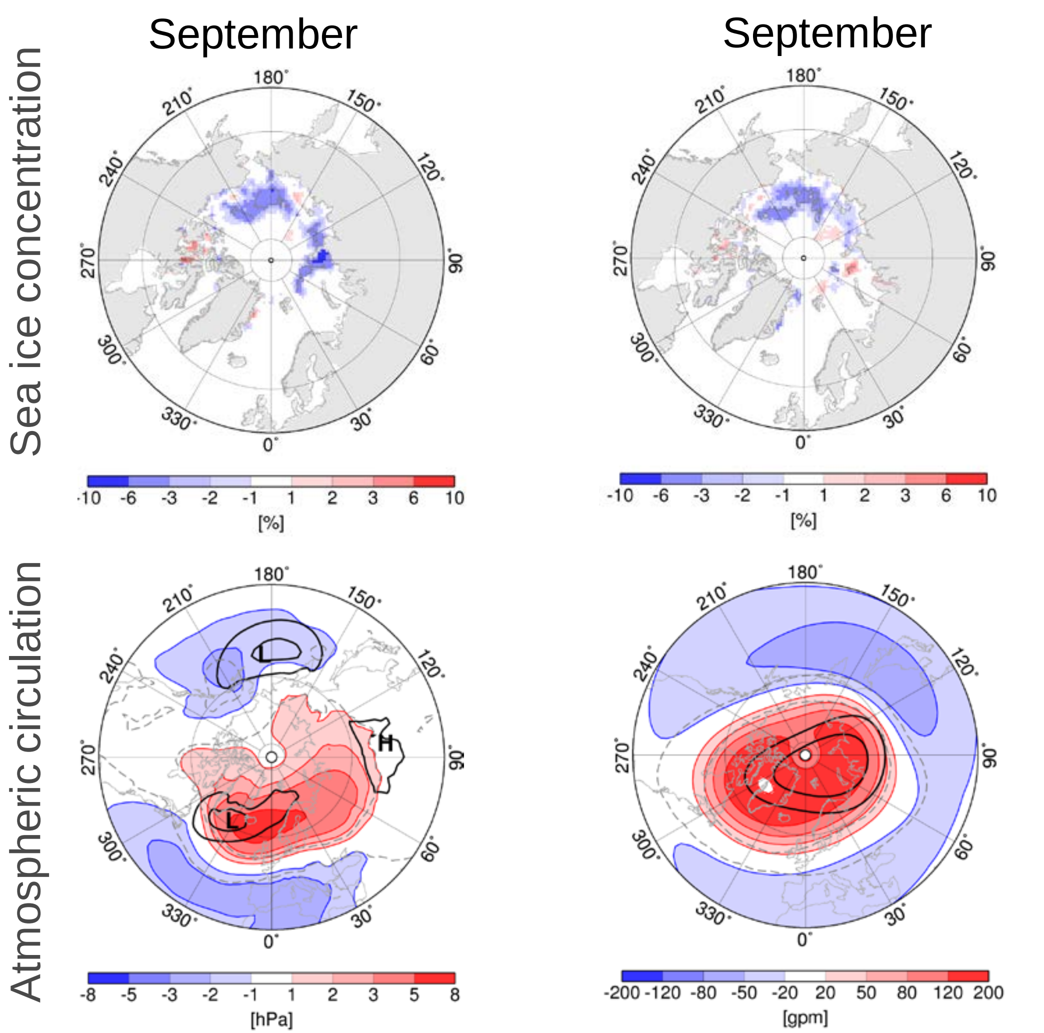
- Changes of centers of action, similarity with pattern of **NAO** in negative phase



Pattern of NAO-

HELMHOLTZ GEMEINSCHAFT

Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data



February
Sea level pressure
36% explained Covariance

Winter
GPH 50hPa
63% expl. Covariance

Planetary-scale response in Feb.

Coupled Patterns 1979-2015

- Statistical relation between sea ice retreat and changes of atmospheric circulation patterns
- Changes of centers of action, similarity with pattern of **NAO** in negative phase
- Associated changes in stratosphere→ Weaker stratospheric Polar Vortex

Jaiser et al. 2012, 2013, 2016
Handorf et al. 2015

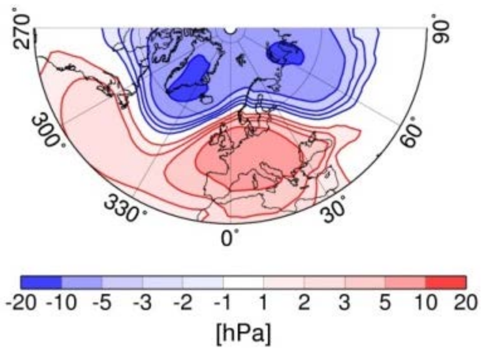
Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data

Preferred large-scale patterns (circulation regimes) over North-Atlantic-Eurasian region

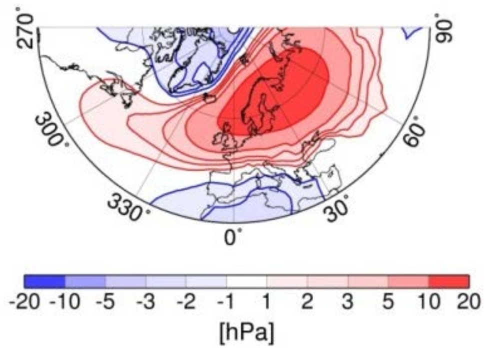
Cluster analysis of daily SLP fields
ERA-Interim 1979-2015, DJFM

SLP anomalies of the five preferred large-scale patterns

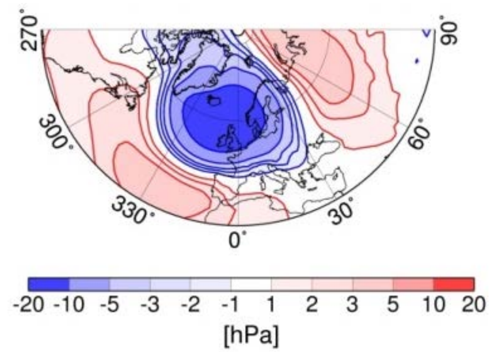
NAO+



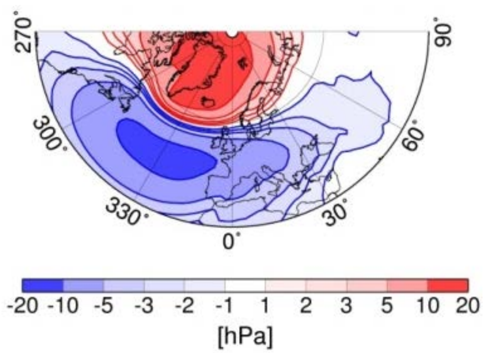
SCAN/SIB Blocking



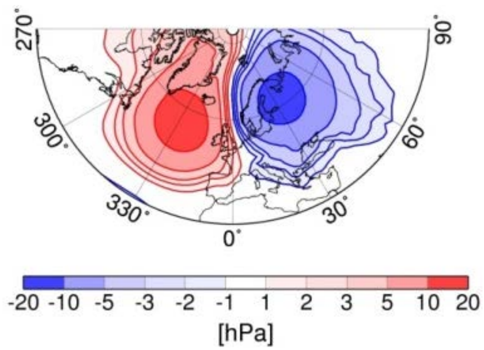
ATL-



NAO-



DIPOLE

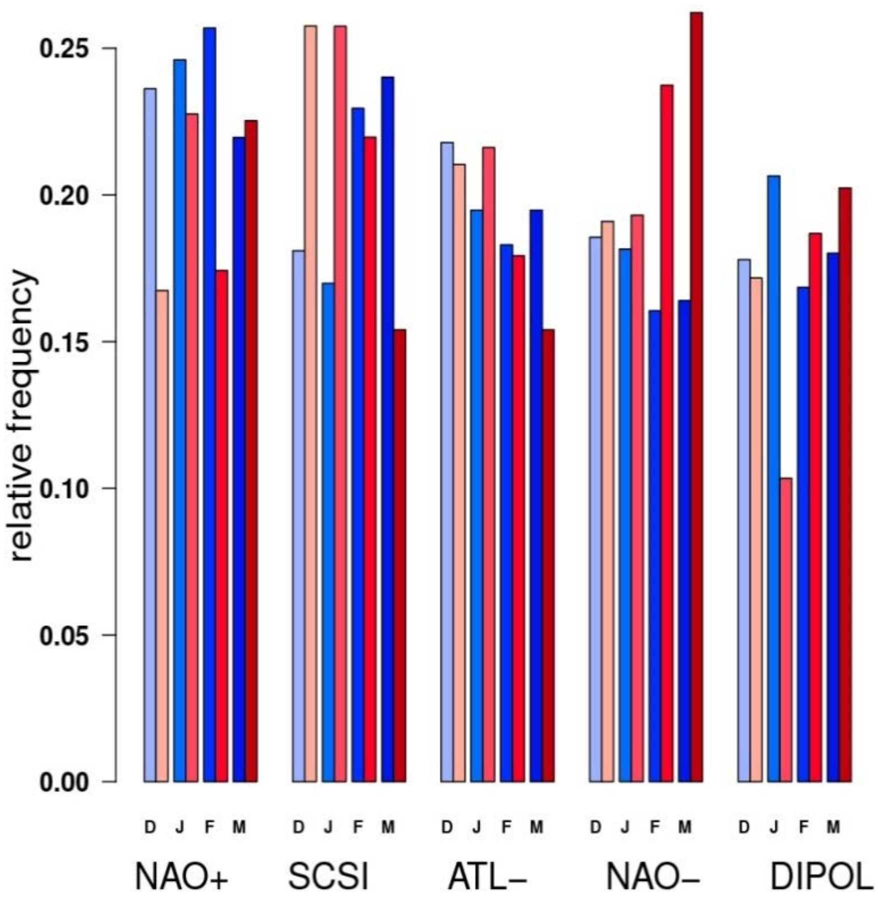


Crasemann et al., (2017) Polar science

Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data

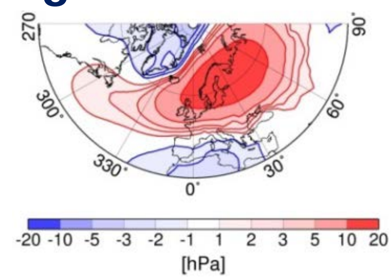
Frequency of occurrence of preferred large-scale patterns over North-Atlantic-Eurasian region

Relative frequency of occurrence for high ice conditions (blue bars) & for low ice conditions (red bars)

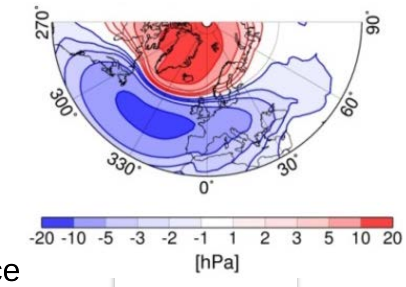


Patterns with significant more frequent occurrence for low ice conditions

- **December and January**
  More frequent occurrence of
  SCAN/SIB Blocking



- **February and March**
  More frequent occurrence of
  NAO-



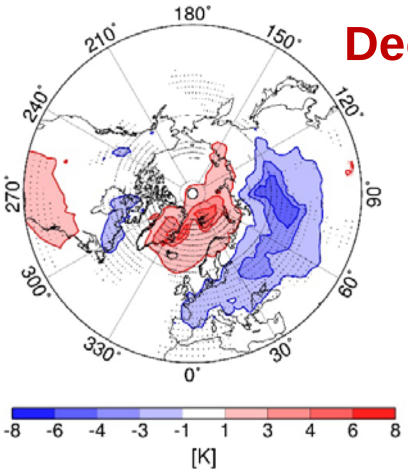
Crasemann et al., (2017) Polar Science

Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data

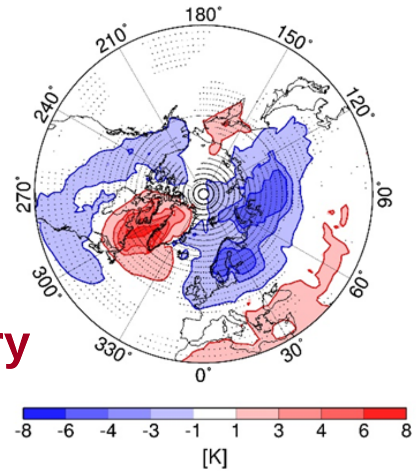
Frequency of occurrence of preferred large-scale patterns over North-Atlantic-Eurasian region

Associated patterns of anomalies of 2m-temperature

December



February



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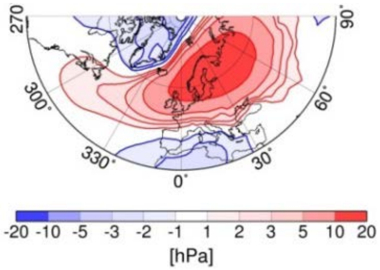

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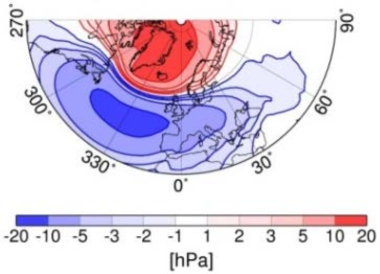

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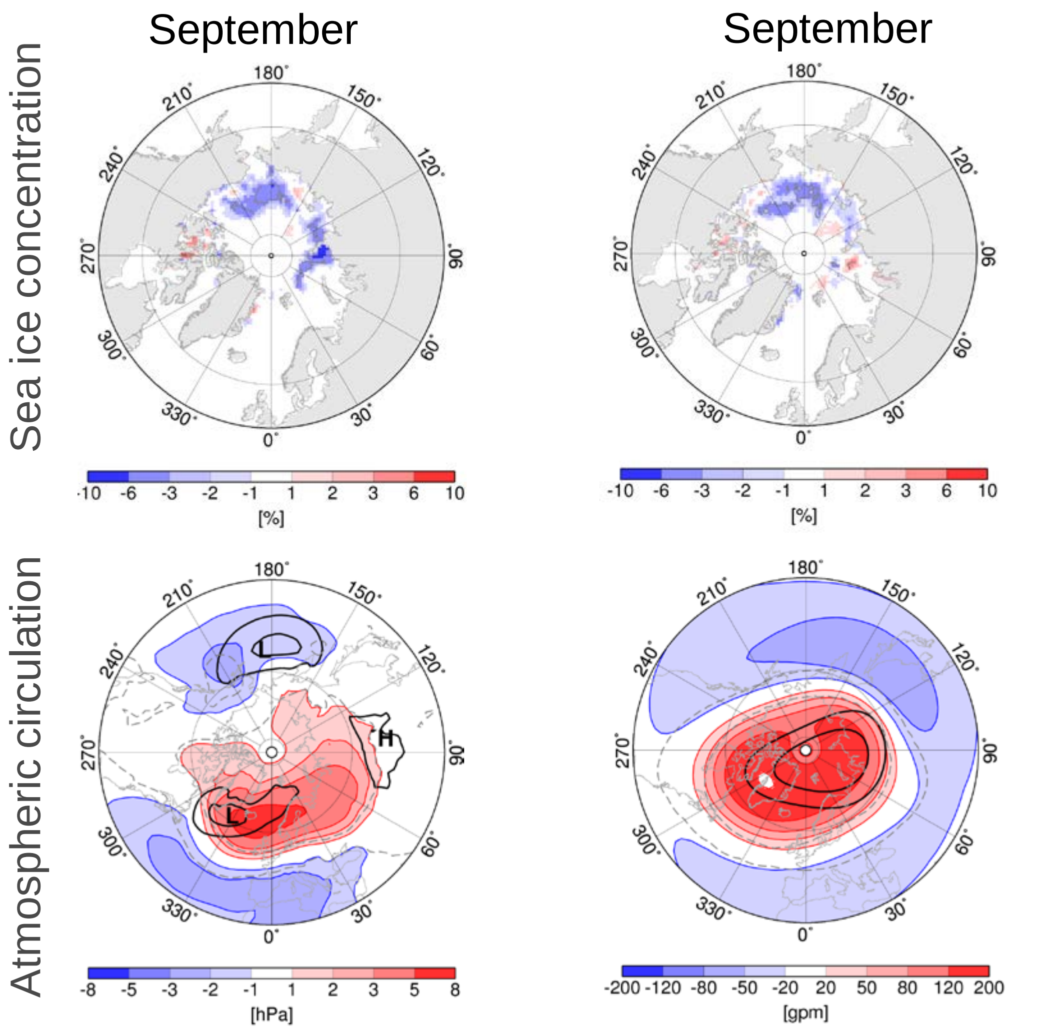
Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data



February
Sea level pressure
36% explained Covariance

Winter
GPH 50hPa
63% expl. Covariance

Planetary-scale response in Feb.

Coupled Patterns 1979-2015

- Statistical relation between sea ice retreat and changes of atmospheric circulation patterns
- Changes of centers of action, similarity with pattern of **NAO** in negative phase
- Observed changes in troposphere and stratosphere

- **Challenge: Representation in models?**

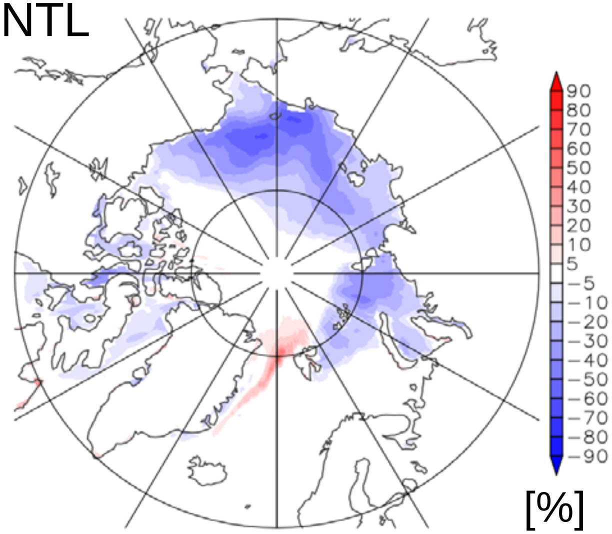
Jaiser et al. 2012, 2013, 2016
Handorf et al. 2015

Representation of sea ice impacts in climate models

- Model: AFES (Atmospheric general circulation model For Earth Simulator)
- 2 model simulations, with 60 perpendicular years each
  - CNTL: High ice conditions as observed from 1979 to 1983
  - NICE: Low ice conditions as observed from 2005 to 2009
  - **Only sea ice is different between both runs**
- Improved representation of heat fluxes through sea ice
- Nakamura et al. (2015, JGR); Jaiser et al. (2016)

Maps of sea ice concentration in fall (SON) for low minus high ice conditions

AFES
NICE-CNTL



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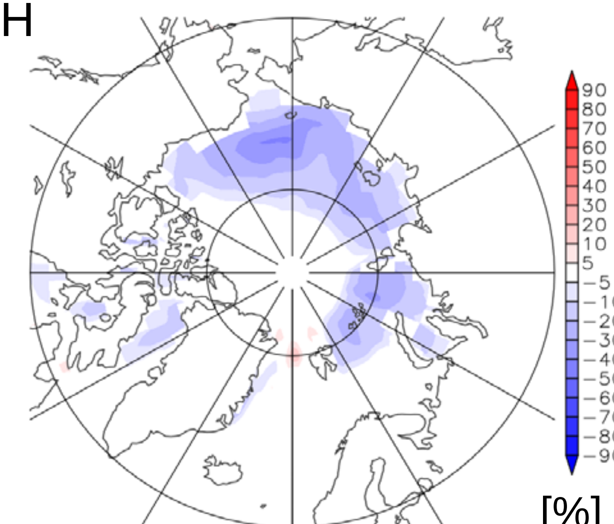
ERA-Interim
LOW-HIGH



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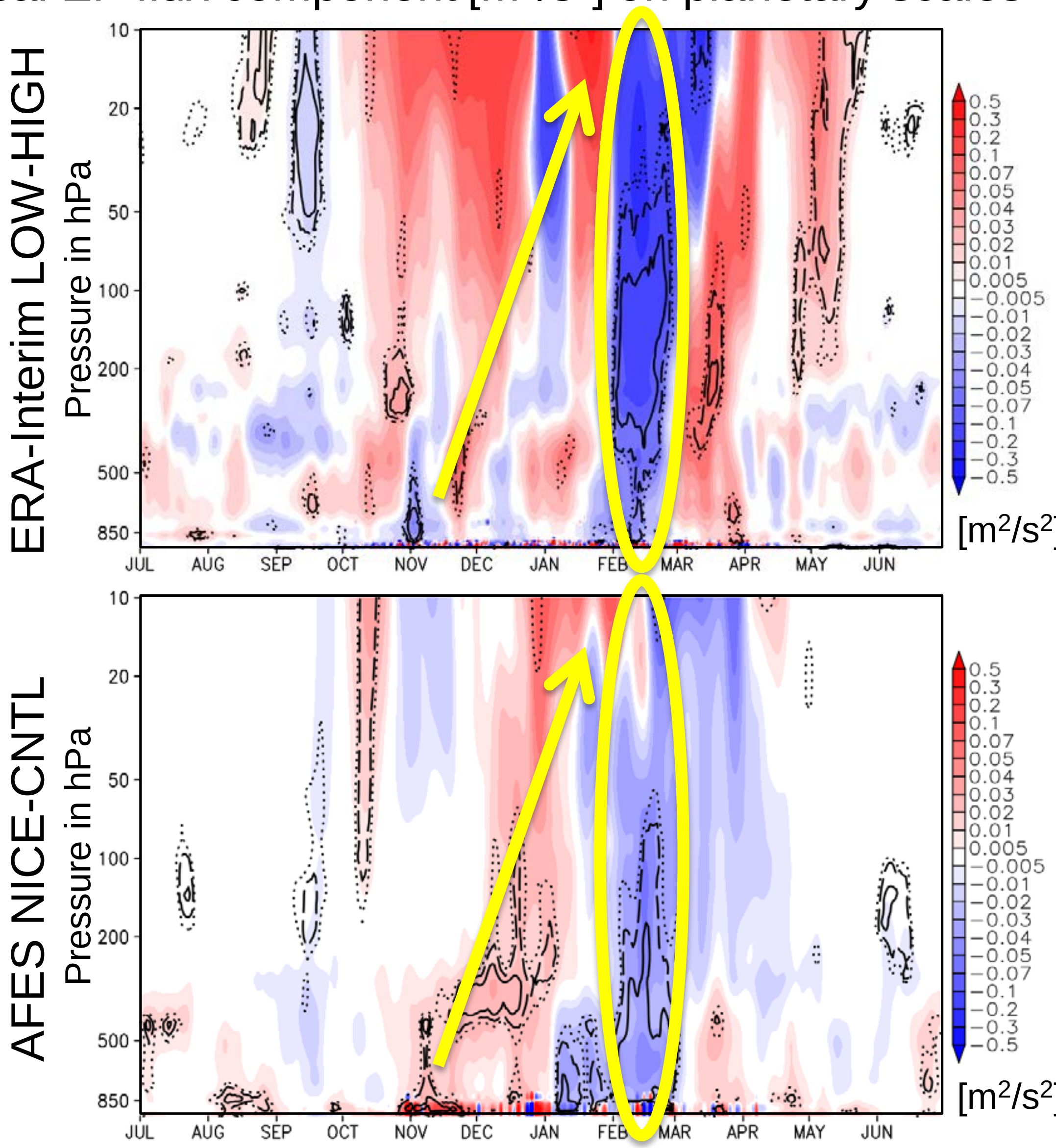
Polar cap vertical wave propagation change – Climate model & ERA-Interim data

Polar cap mean 65°N-85°N of vertical EP flux component [m²/s²] on planetary scales for low minus high ice conditions

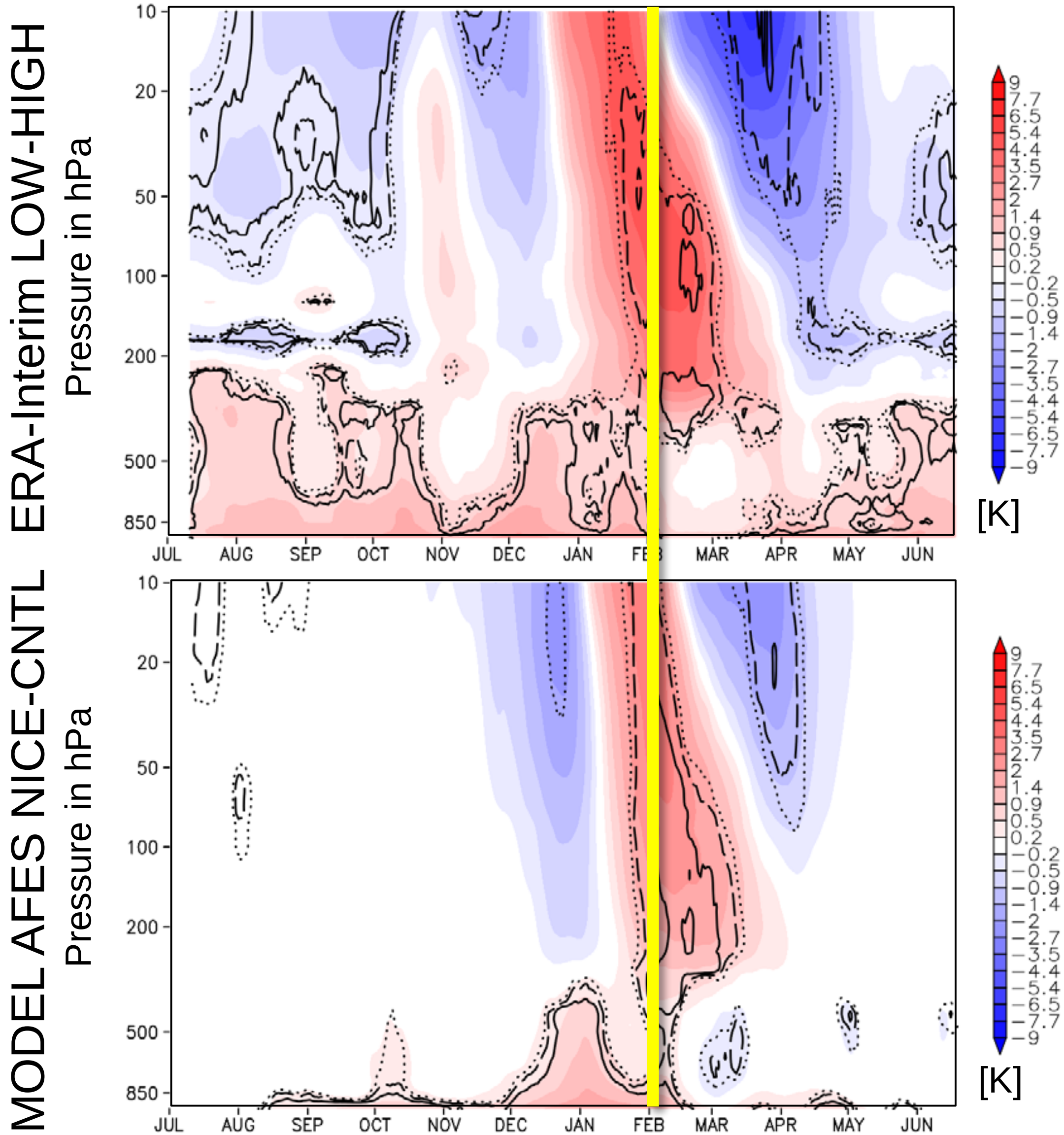
- Similar upward/downward anomalies in Winter
- Reduced vertical flux in February is highly significant in both datasets
- **Consistency of datasets indicates clear impact of sea ice changes**
- ERA-Interim is more disturbed in early winter
  - Impact of additional processes



Polar cap temperature change – Climate model & ERA-Interim data

Polar cap mean 65°N-85°N of **Temperature [K]** for low minus high ice conditions

- Very good agreement between model and reanalysis in winter (and autumn)
- ERA-Interim shows a general global warming signal
- AFES surface warming related to sea ice alone
- Atmospheric models with well implemented sea ice forcing are able to reproduce the observed **negative NAO Signal in (late) winter** and the related dynamical processes

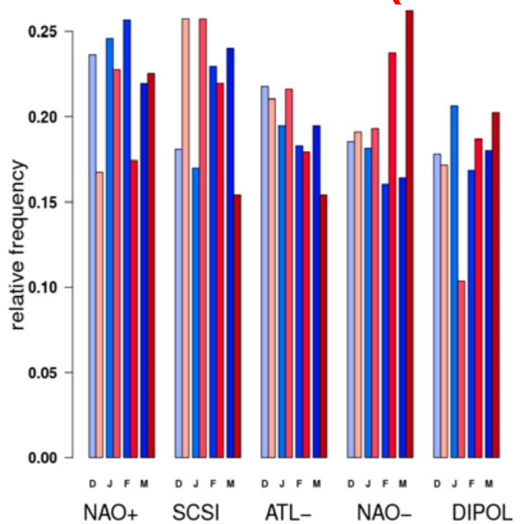


Sea ice retreat & changes in atmospheric circulation regimes – Climate model & ERA-Interim data

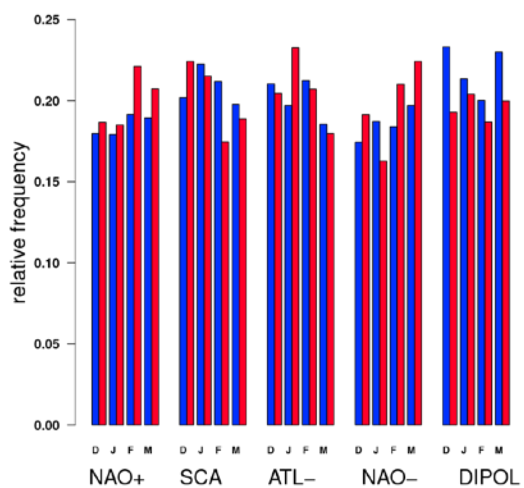
Preferred large-scale patterns over North-Atlantic-Eurasian region

Relative frequency of occurrence for high ice conditions (blue bars) & for low ice conditions (red bars)

ERA-Interim

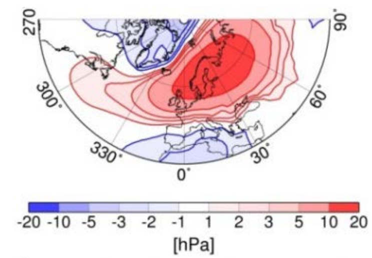


Model AFES



Patterns with significant more frequent occurrence for low ice conditions

- **December and January**
  More frequent occurrence of **SCAN/SIB Blocking**



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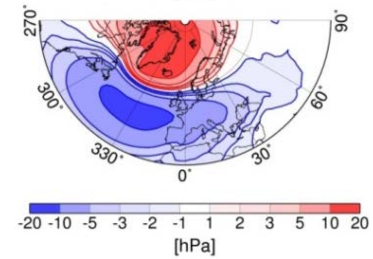
  More frequent occurrence of **NAO-**



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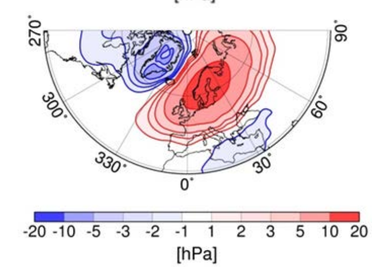

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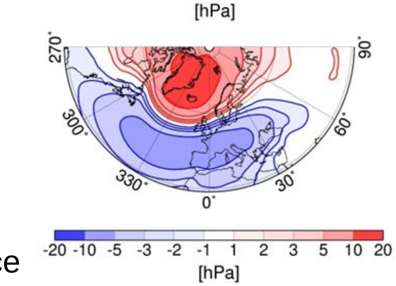
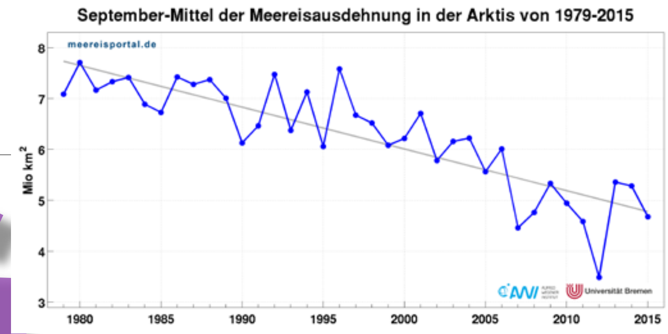
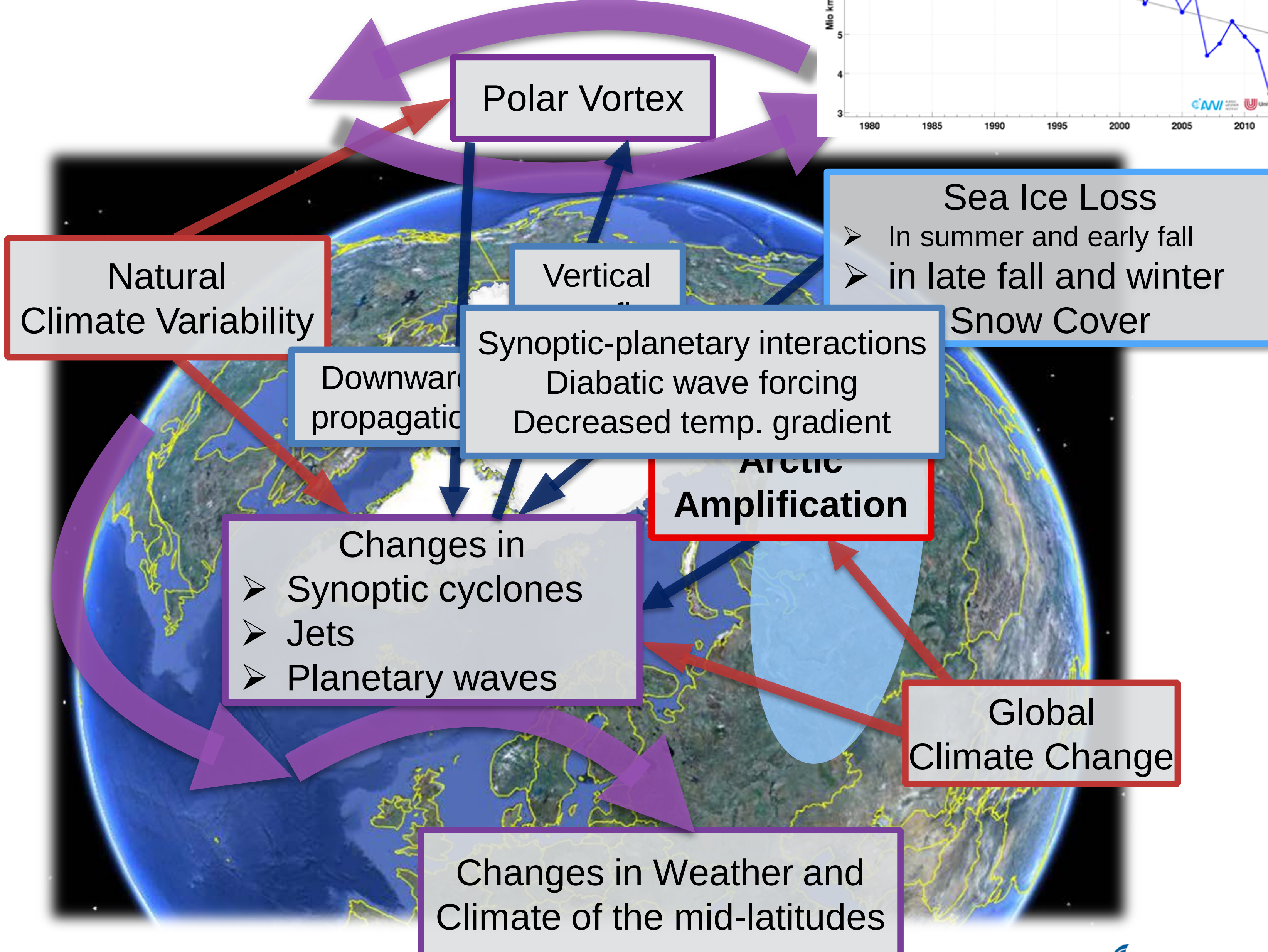


Crasemann et al., (2017) Polar science

Dynamical linkages between the Arctic and the mid-latitudes





Outlook

Sea ice change is a fundamental driver of atmospheric circulation anomalies

- Atmospheric models with well implemented sea ice forcing and more realistic surface fluxes are able to reproduce the observed **negative (N)AO Signal in (late) winter** and the related dynamical processes
- Sea ice forcing changes the occurrence of **preferred circulation states** of the chaotic atmosphere
- Dependence of the signal on the regional pattern of sea ice changes has to be analysed
- Changes in other forcing factors have to be studied, e.g.
  → Changes in snow cover or sea surface temperatures
  → Changes in natural varibility patterns (e.g. ENSO)
- Detailed studies of linkages and underlying mechanisms in other seasons are still to be done

Outlook

Conclusions for the modelling of the impact of Arctic climate changes on the weather and climate in mid-latitudes

- Fundamental dynamic processes in the atmosphere have to be well represented, in particular wave forcing and wave propagation
- Adequate implementation of surface forcing is essential
  → important for coupled atmosphere-ocean-sea-ice models
- Potential for improved **predictions on seasonal to decadal time scales** and subsequent climate impact studies

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Thank you for your kind attention!

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