The impact of Arctic climate changes on the weather and climate in mid-latitudes

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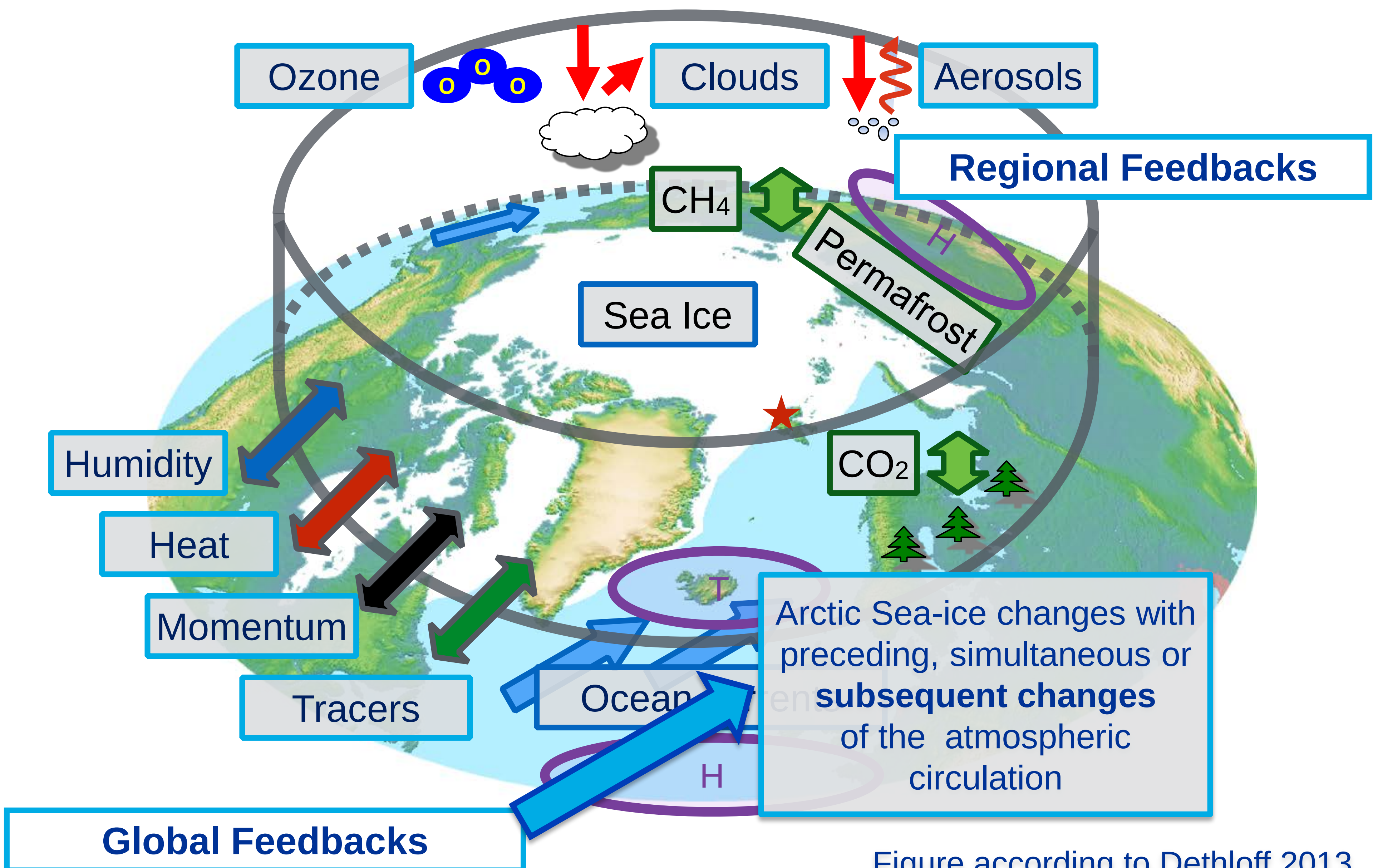
PhD Days, Potsdam, 2. Juni 2016

HELMHOLTZ ASSOCIATION

The Arctic within the global climate system

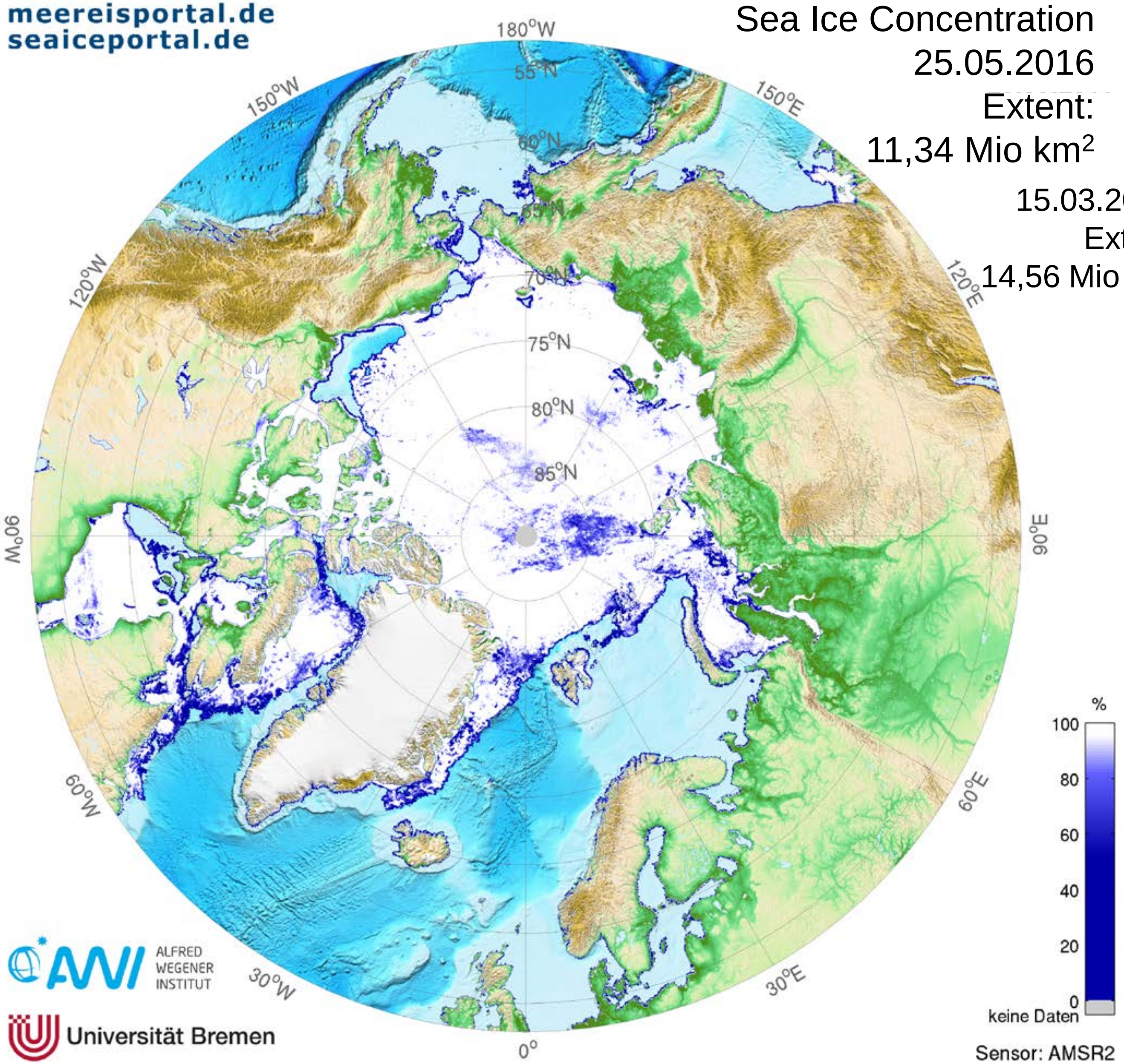


Arctic Sea-ice changes with preceding, simultaneous or **subsequent changes** of the atmospheric circulation

Figure according to Dethloff 2013

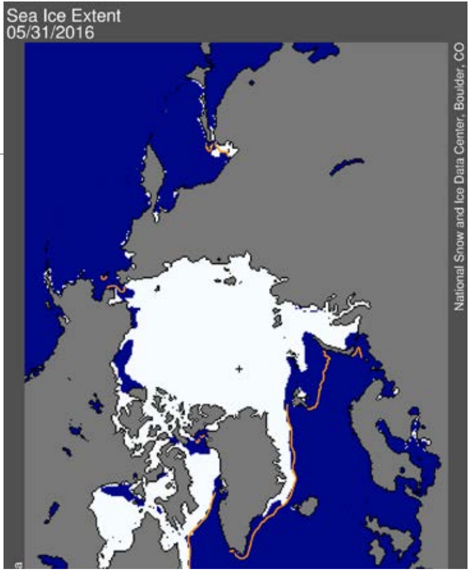
Current situation in the Arctic

meereisportal.de
seaiceportal.de



Sea Ice Concentration
25.05.2016
Extent:
11,34 Mio km²

15.03.2016
Extent:
14,56 Mio km²



- Negative anomaly in sea ice extent in particular over Barents-Sea
- Related to positive temperature anomalies

ALFRED WEGENER INSTITUT

Universität Bremen

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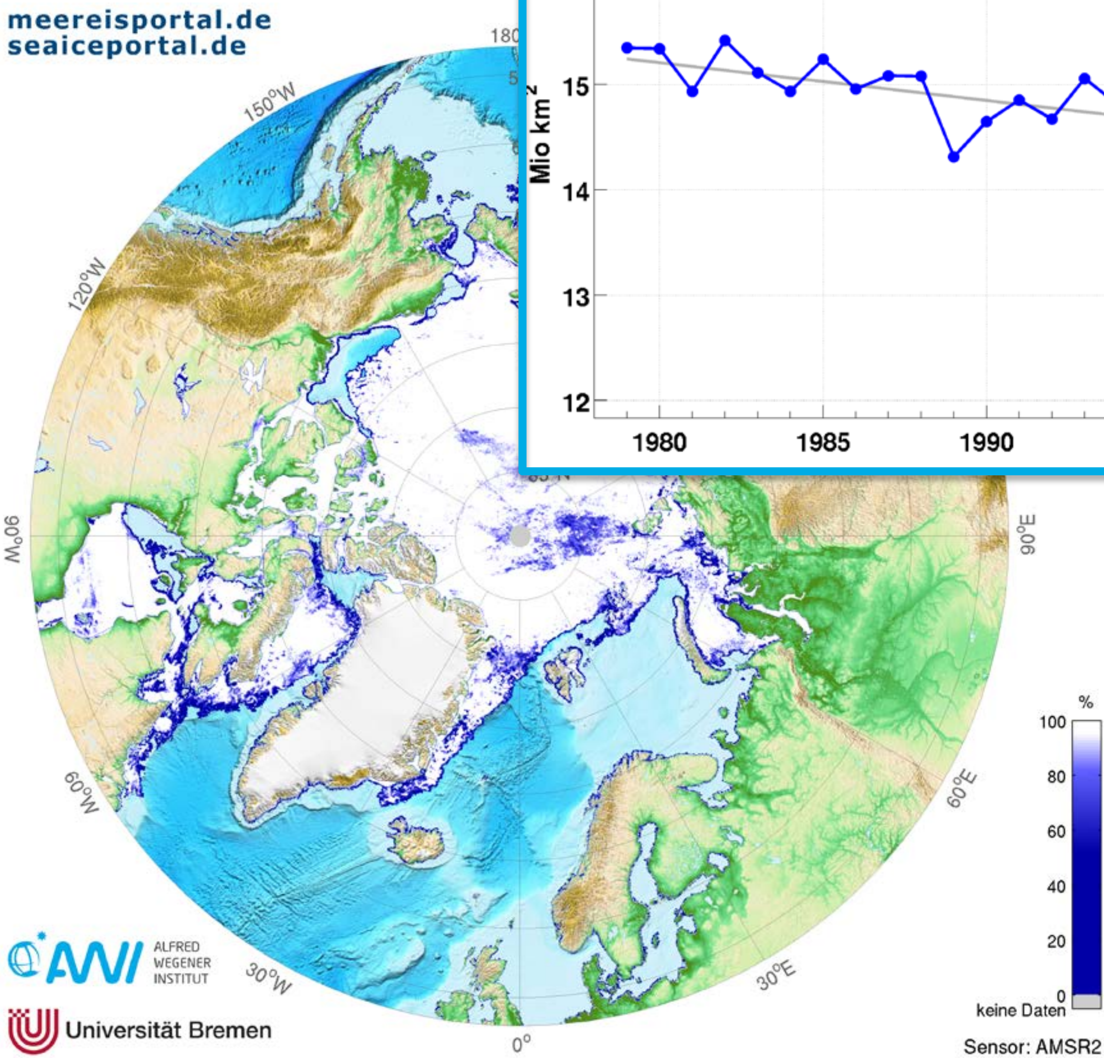
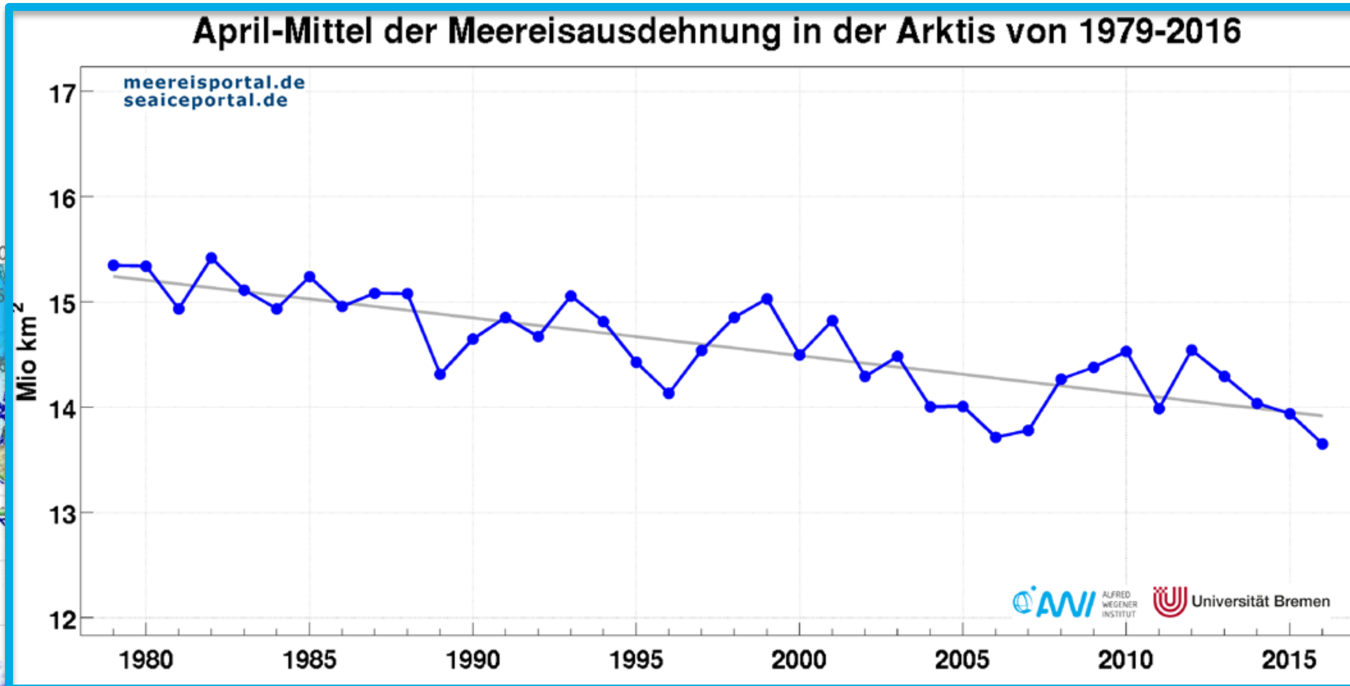
Current situation in the Arctic





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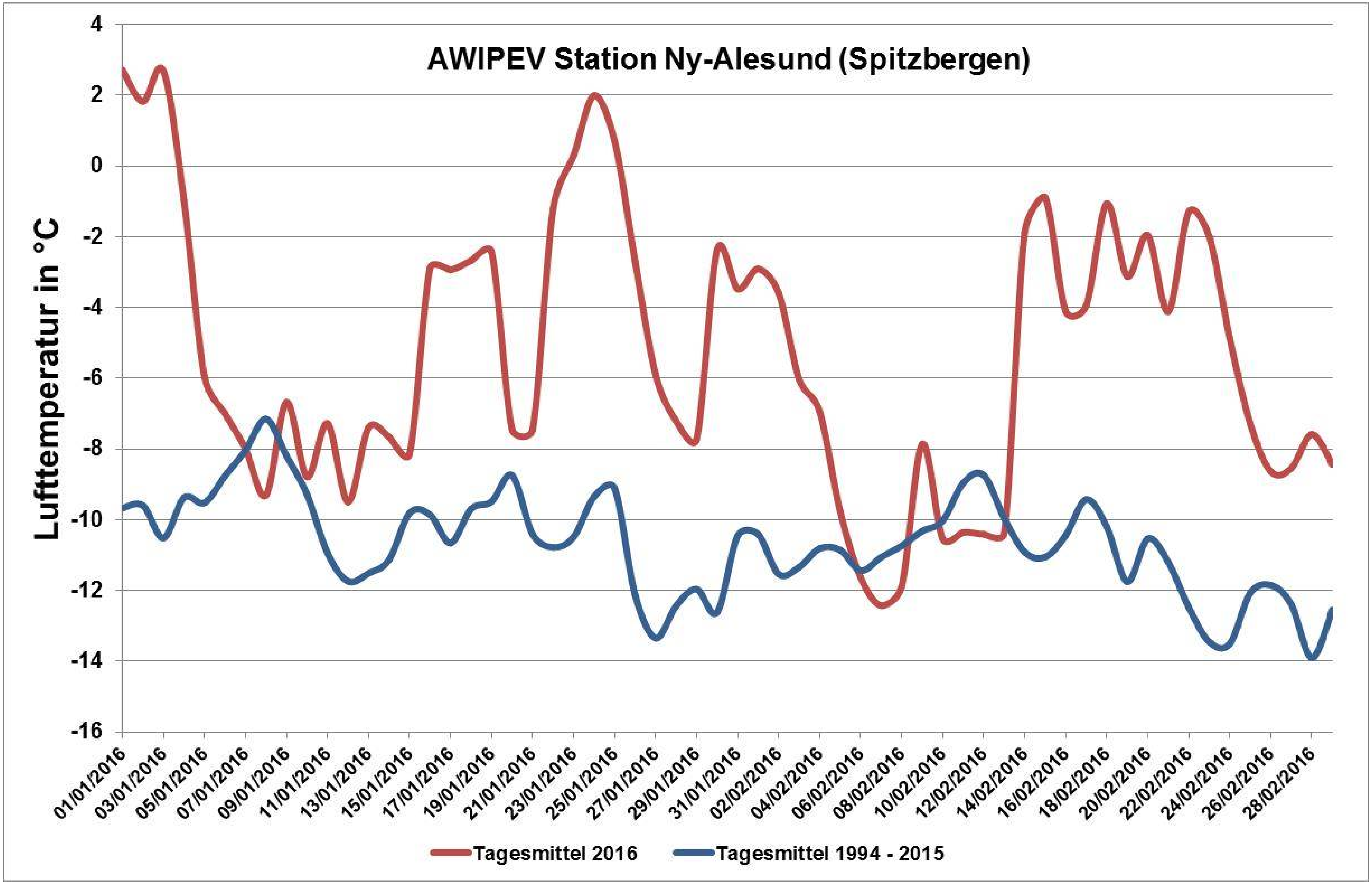
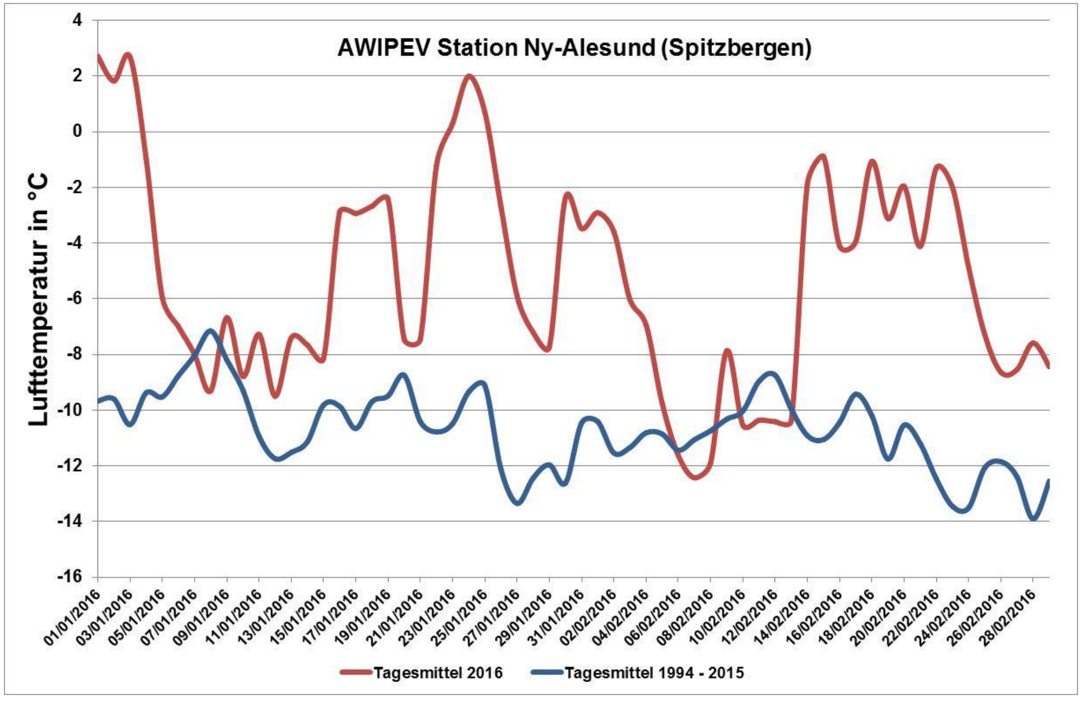


Current situation in the Arctic

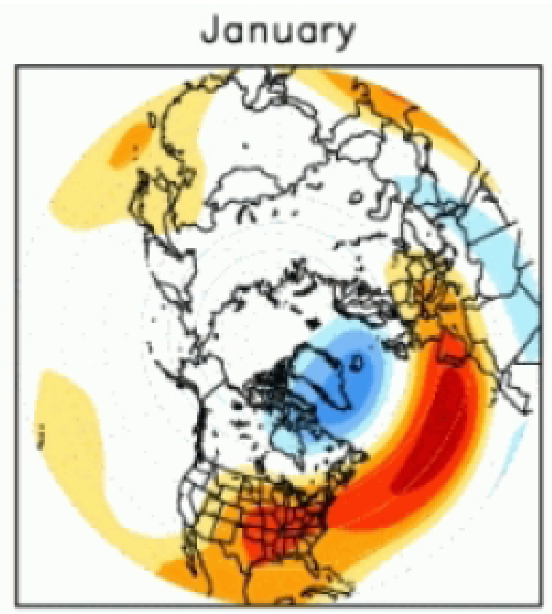


http://www.meereisportal.de

- Atmospheric Circulation in January with North Atlantoc Oscillation mostly negative
- Low rate of sea-ice growth in winter 2015/16
- Currently thin sea-ice
- Expectation: summer minimum very low (comparable to 2012)
- See AWI press release from 21/04/2016 (Marcel Nicolaus, Stefan Hendricks)

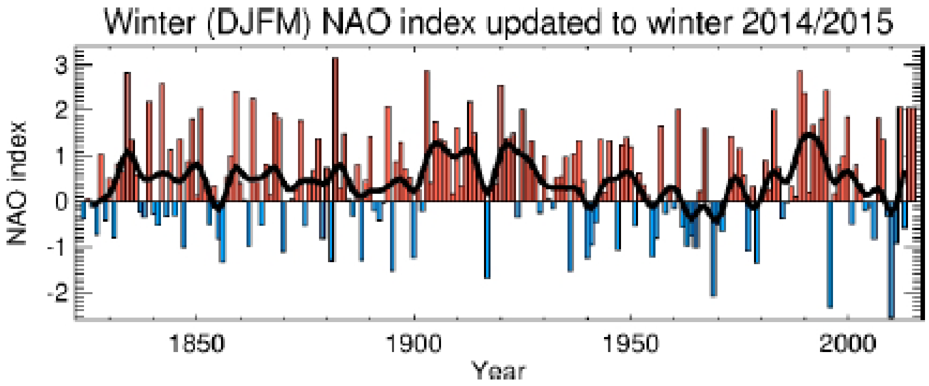
The North Atlantic Oscillation

- NAO-Muster-positive Phase
- Korrelationsmuster zwischen der Anomalie der geopotentiellen Höhe in 500hPa (Monatsmittel) und dem NAO-Index für Januar



(http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml)

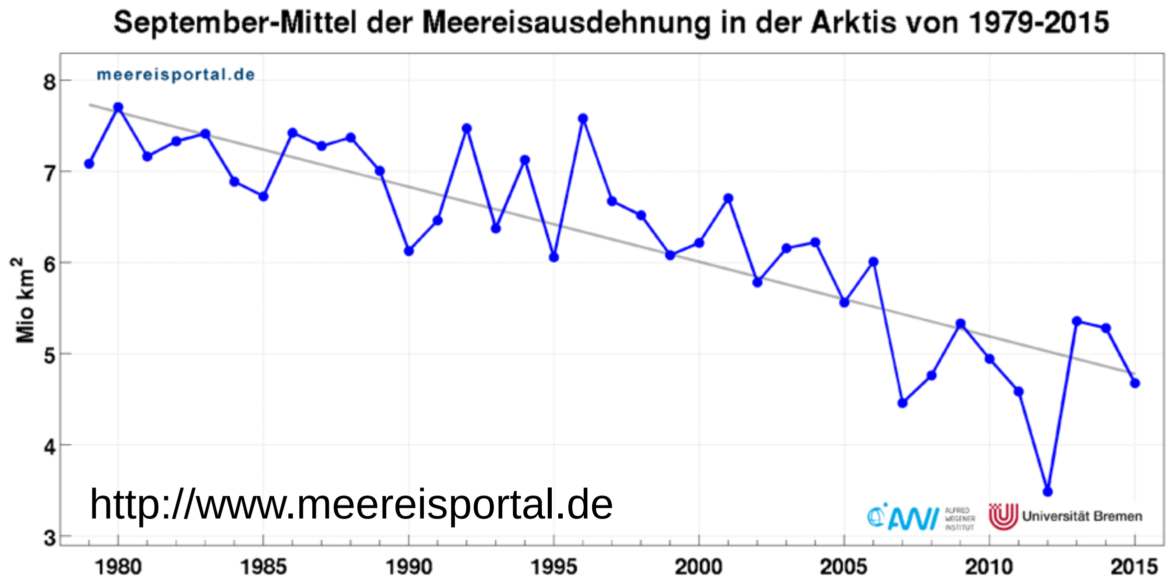
- Zeitreihe des NAO-Index
- Wintermittel (Dezember bis März) des Jones et al. NAO-Index, aktualisiert bis zum Winter 2014/15 (2009/10 negativster NAO-Index der gesamten Zeitreihe)

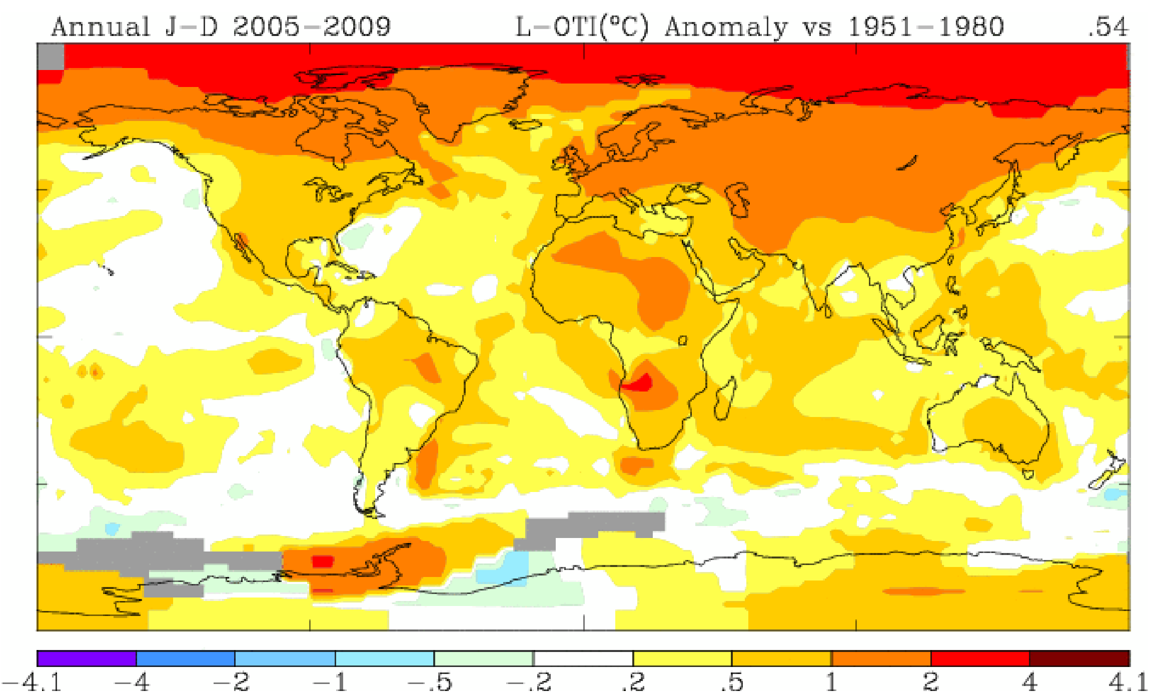


(http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm)

Arctic Amplification and Retreat of Arctic Sea Ice

Retreat of Arctic Sea Ice Extent in September, 1979-2015





Arctic Amplification

Anomalies of Surface Air Temperature 2005-2009 from Mean over 1951-1980

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

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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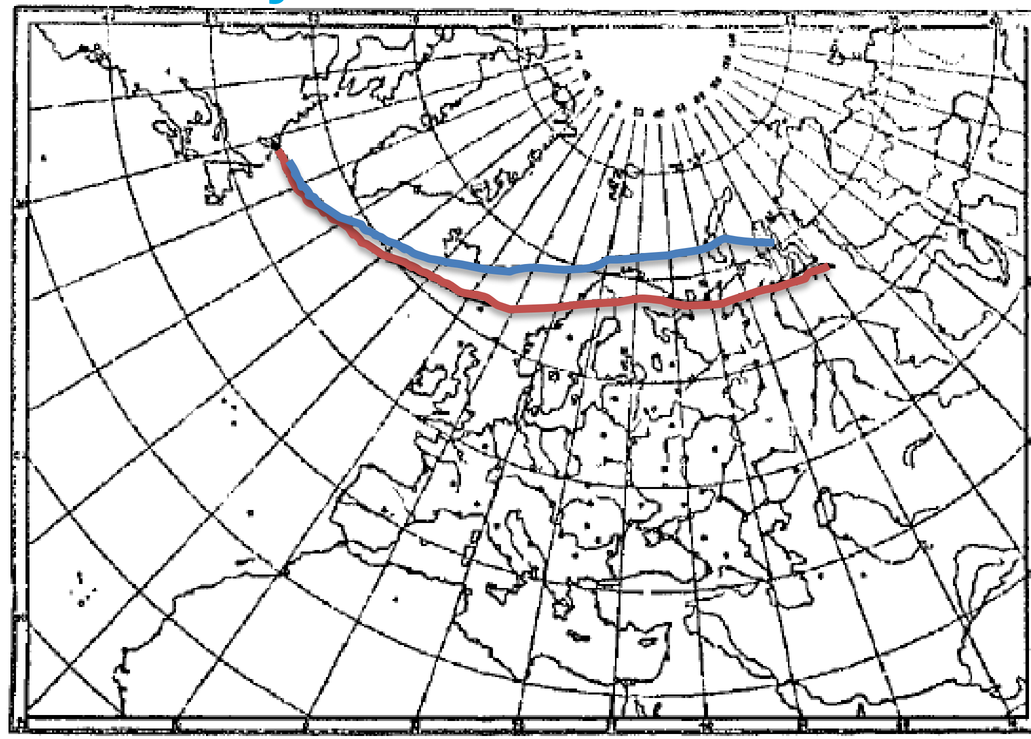

Fig. 10. Mittlere Bahnen nordatlantischer Zyklonen im Herbst.

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

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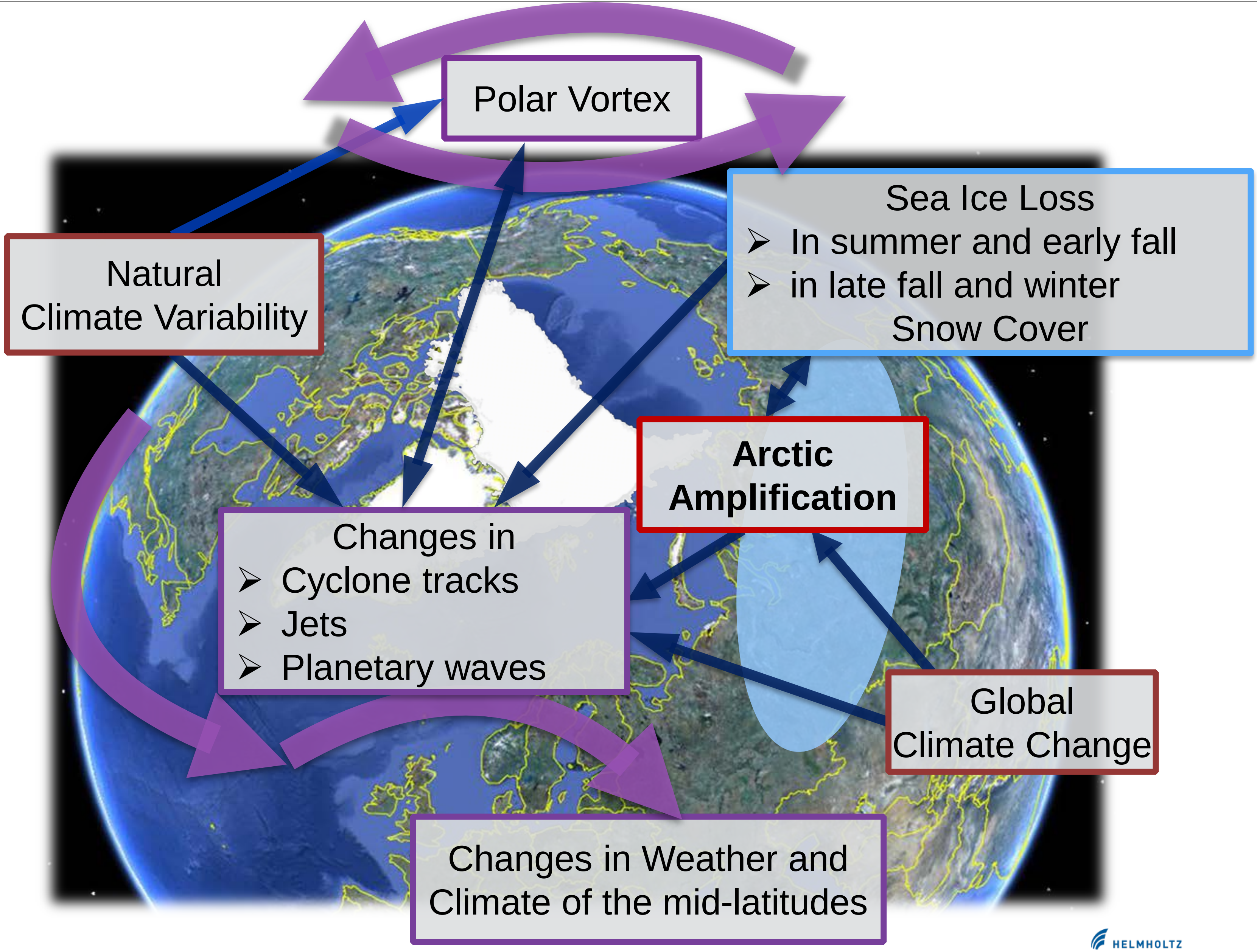
First modelling studies since ca.1971

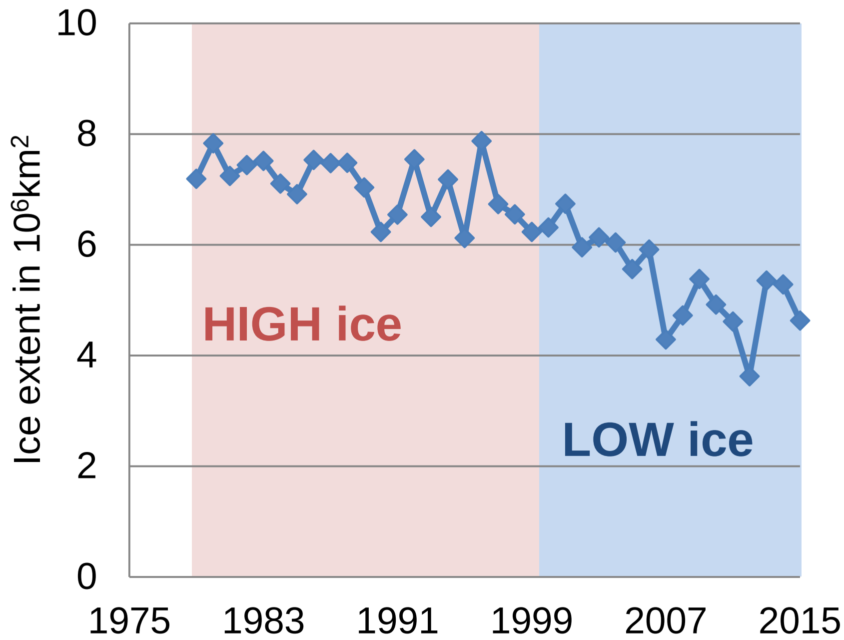
- Herman & Johnson (1978):
  Model experiment with atmospheric General Circulation model: only changes in sea ice extent (observed recent minimum and maximum ice extent)
  Ensemble simulations, winter conditions
  Global circulation changes (pressure, temperature, energy fluxes)

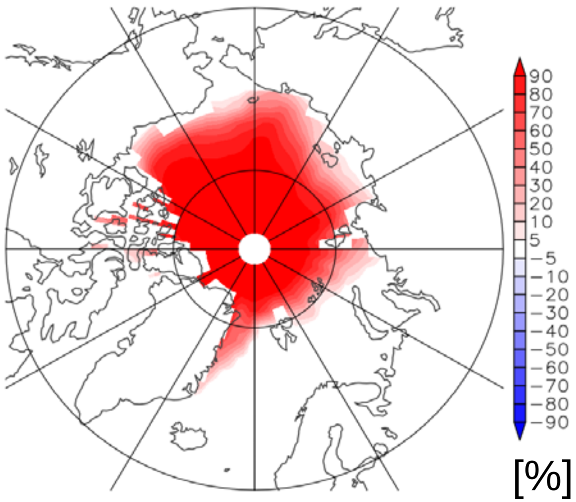
Dynamical linkages between the Arctic and the mid-latitudes



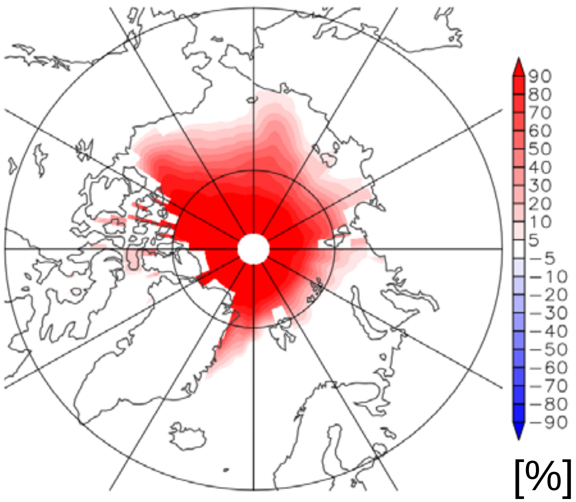
Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data

- **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)

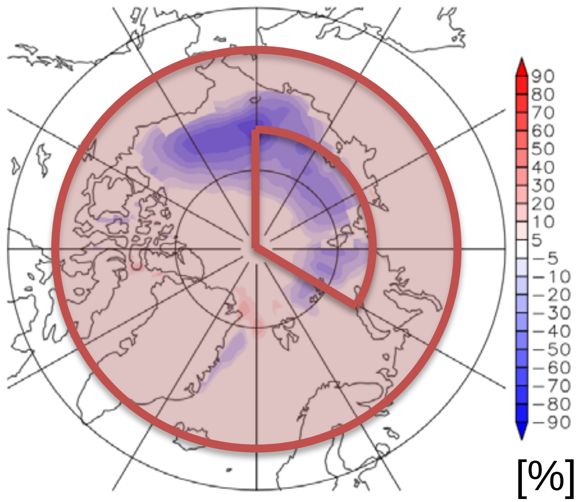




HIGH



LOW



LOW-HIGH

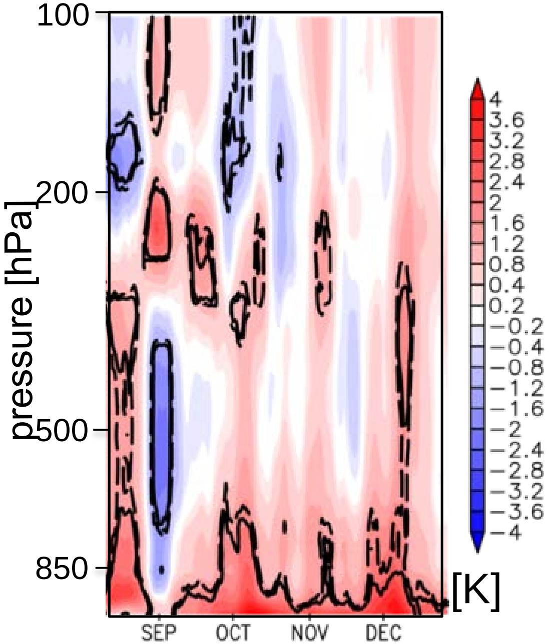
Sea ice retreat & subsequent atmospheric circulation changes – ERA-Interim data

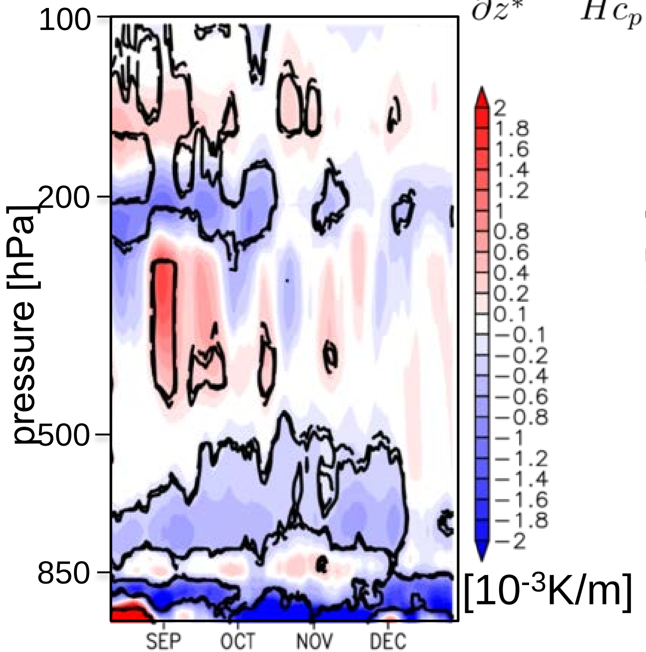
Baroclinic response over the Arctic in autumn

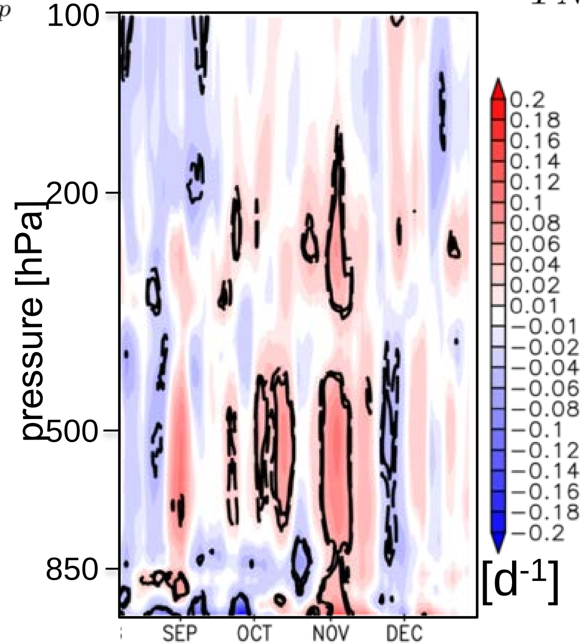
low minus high ice conditions in ERA-Interim,
Area-averaged mean over the Sibirian Arctic Ocean

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

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







Temperature
higher temperatures in lower troposphere

→

Vertical stability
Lower stability in lower/middle troposphere

→

Eady Growth Rate
Increased baroclinicity in middle troposphere

Intensification of cyclolysis

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

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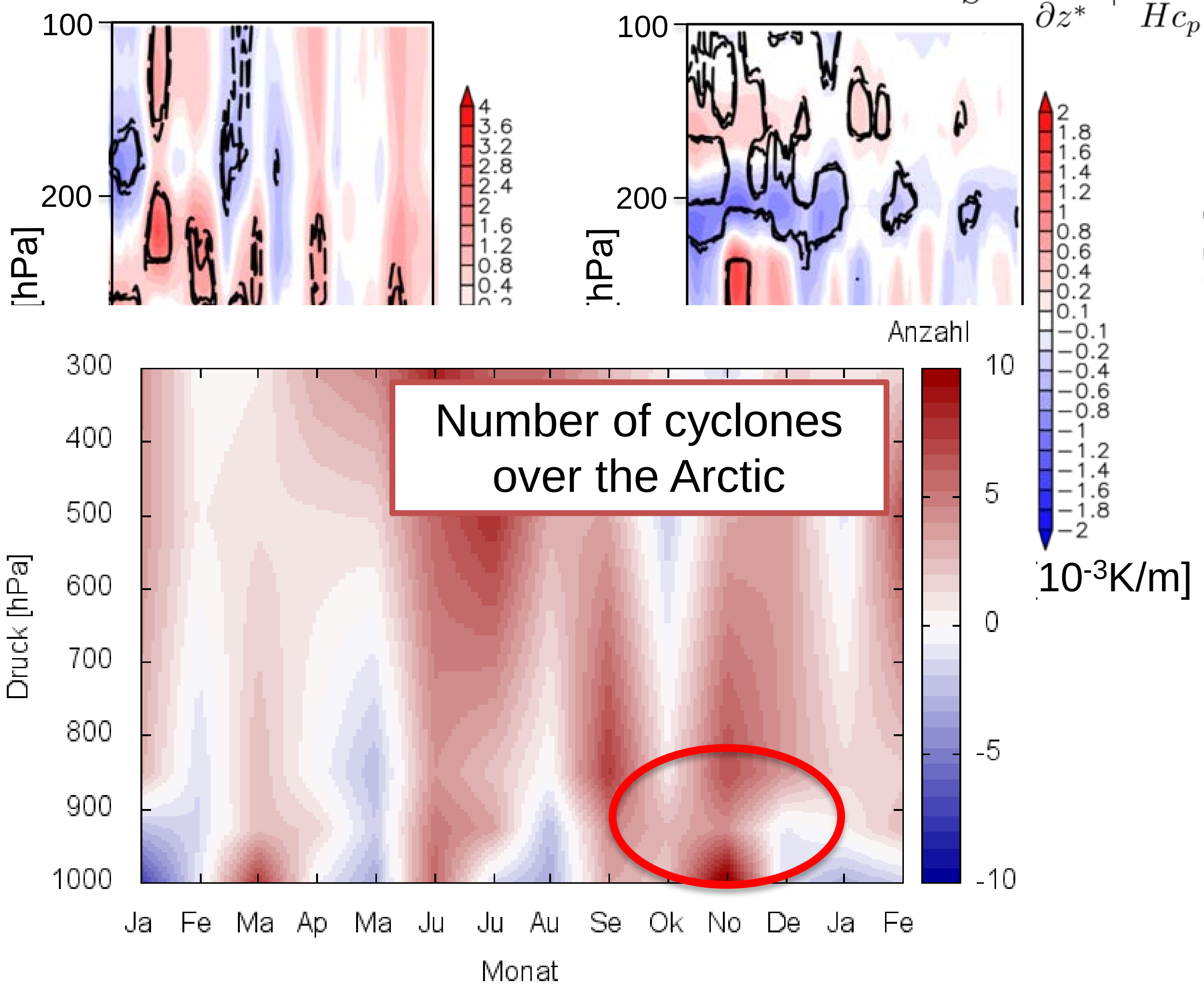
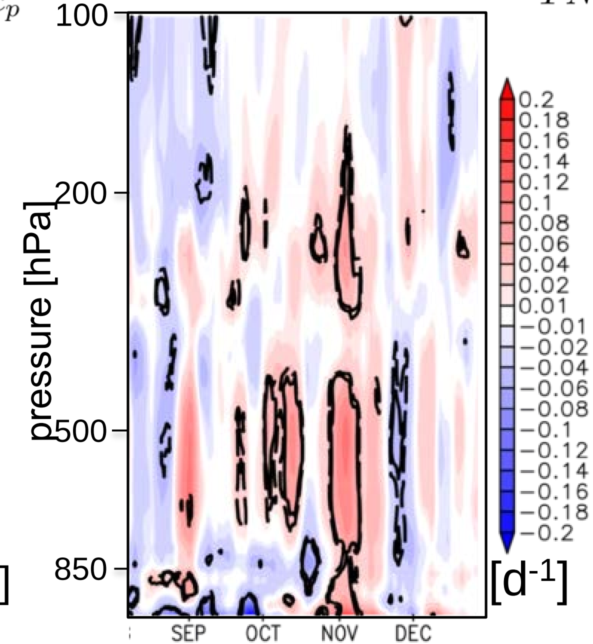




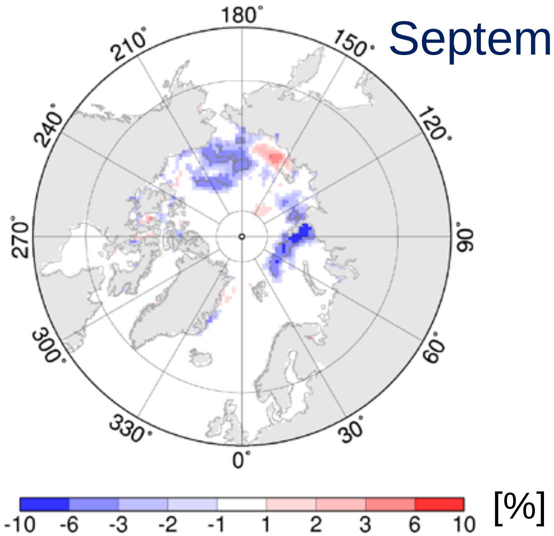
Eady Growth Rate

Increased baroclinicity in middle troposphere

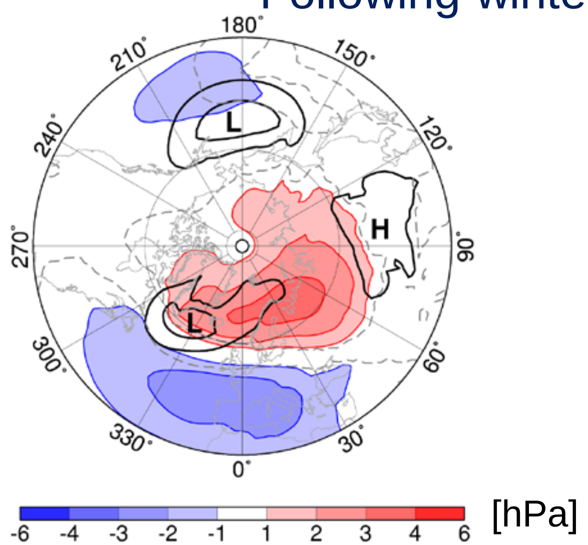
Intensification of cyclolysis

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

Sea ice concentration
September (HadISST Data)



Sea level pressure
Following winter (ERA-Interim)

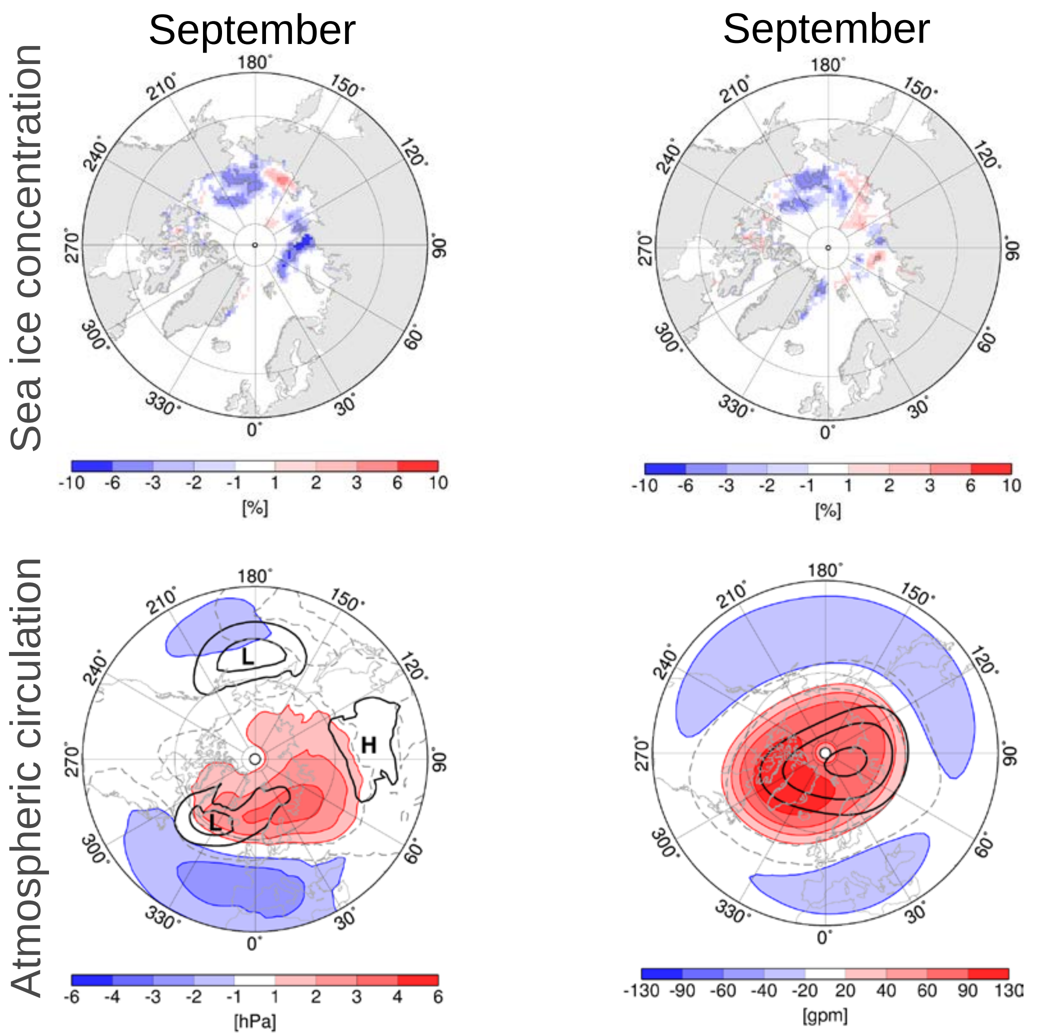


Large-scale Response in Winter

Coupled Patterns 1979-2015

- Statistical relation between sea ice retreat and changes of atmospheric circulation patterns
- Changes of centers of action, pattern of North Atlantic Oscillation (NAO) in negative phase

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



Winter
Se level pressure
42% explained Covariance

Winter
GPH 50hPa
53% expl. Covariance

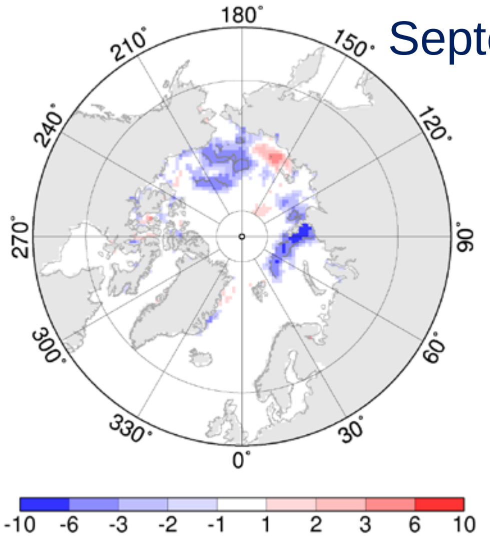
Large-scale Response in Winter

Coupled Patterns 1979-2015

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

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

Sea ice concentration
September (HadISST Data)



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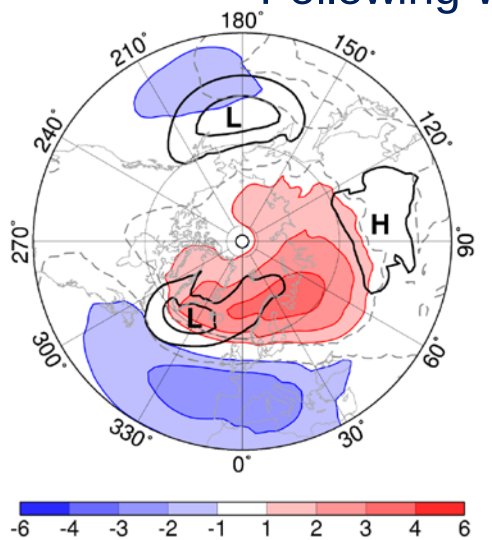


Large-scale Response in Winter

Coupled Patterns 1979-2015

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

- Challenges:
  Mechanisms?
  Representation in models?

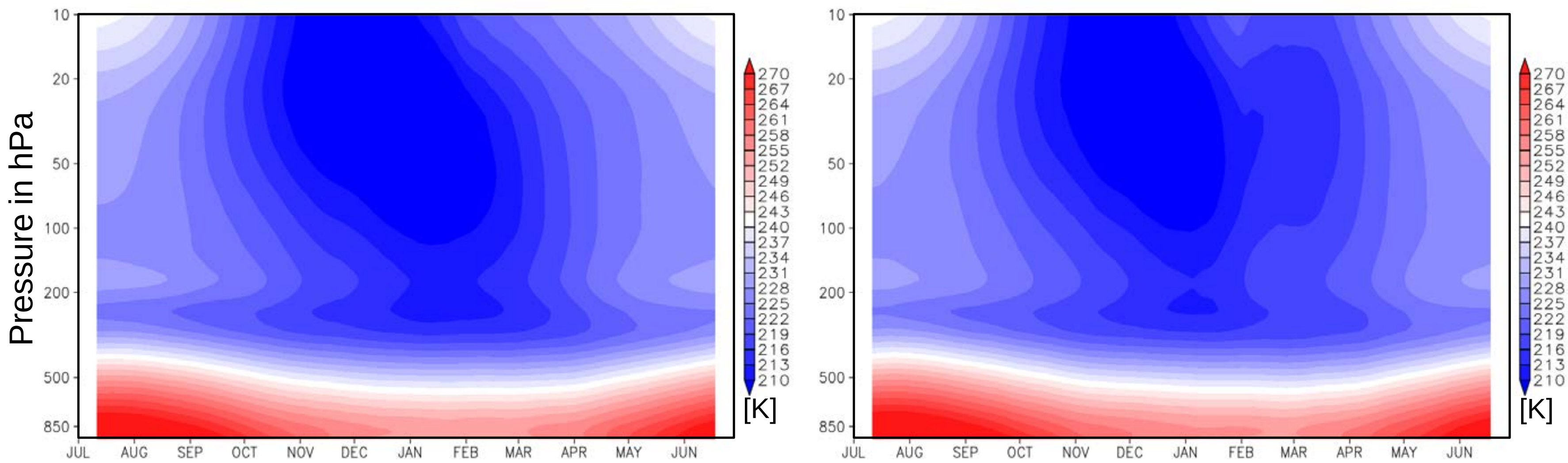
Jaiser et al. 2012, 2013, 2016 (submitted)
Handorf et al. 2015

Polar cap temperature change

Temperature [K] average 65°N-85°N

Climatologies of polar cap temperature

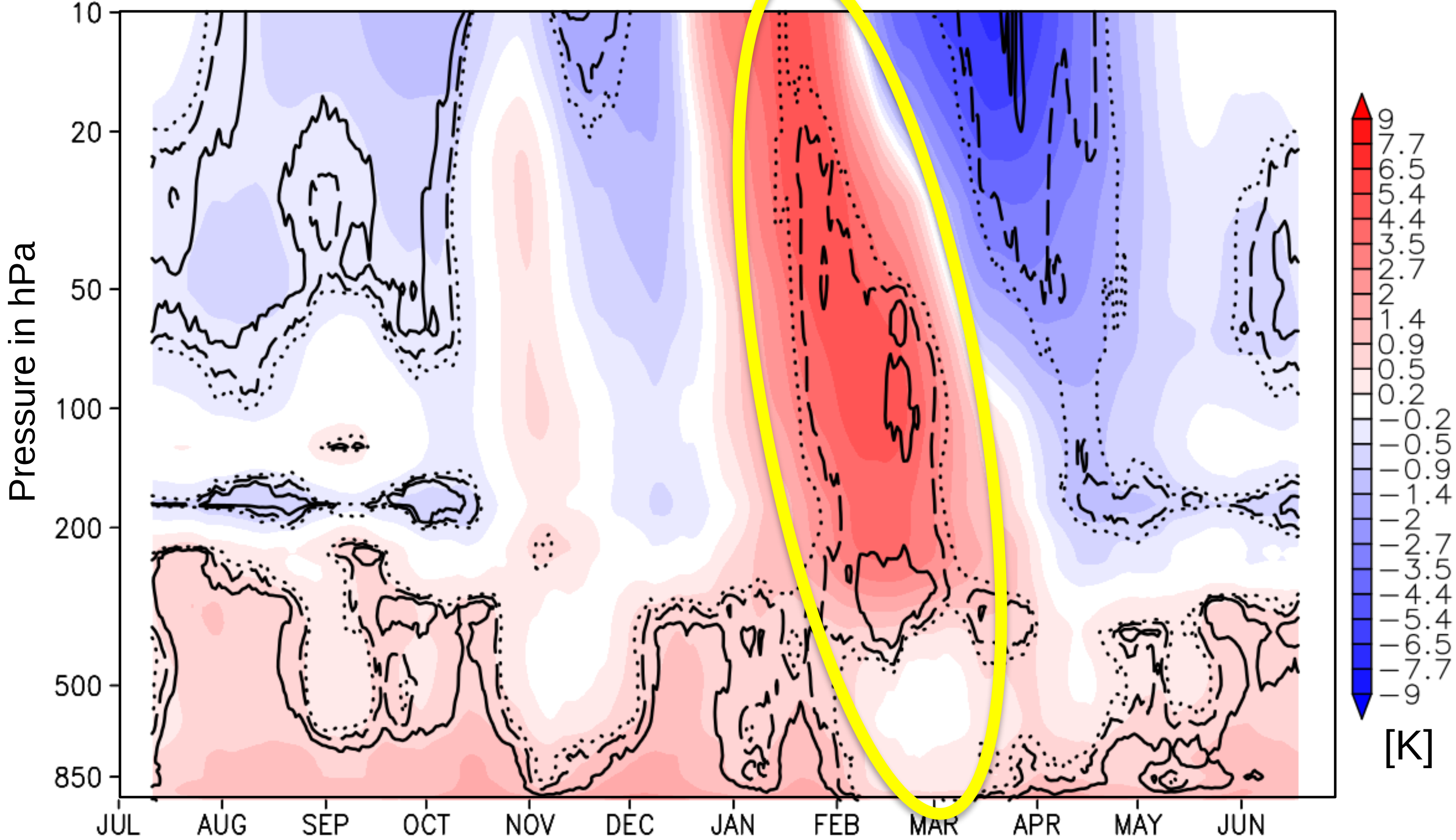
High ice 1979/80-1999/00 | **Low ice** 2000/01-2013/14



- 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

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
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- Strong significant warming of polar stratosphere in late winter
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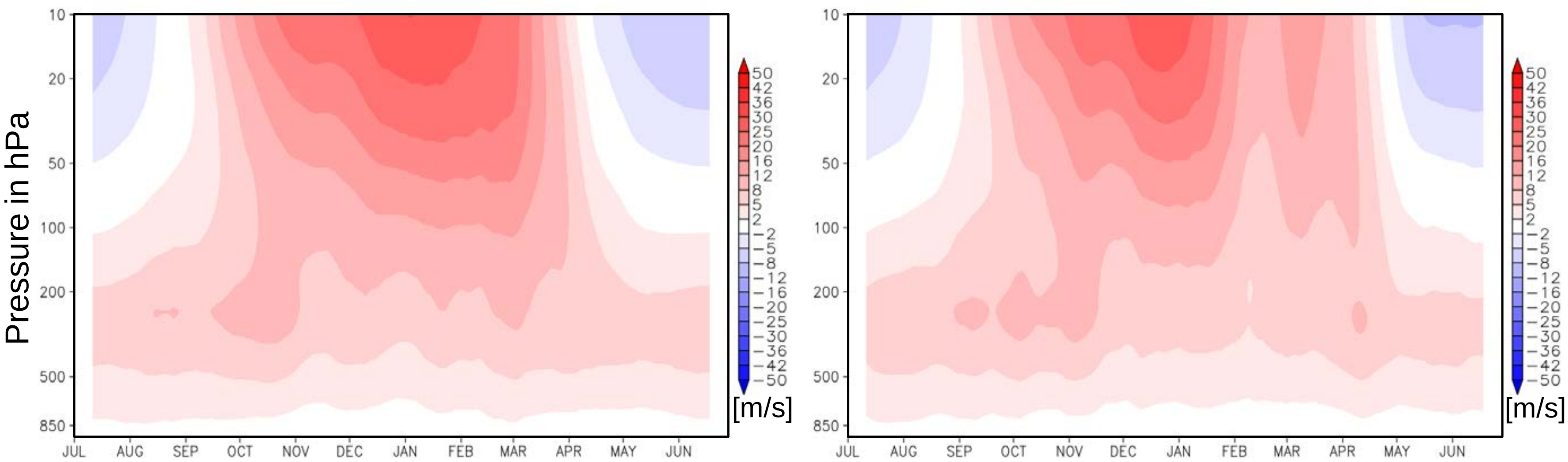
Polar cap zonal wind change

Zonal wind [m/s] average 65°N-85°N

Climatologies of polar cap zonal wind (west wind)

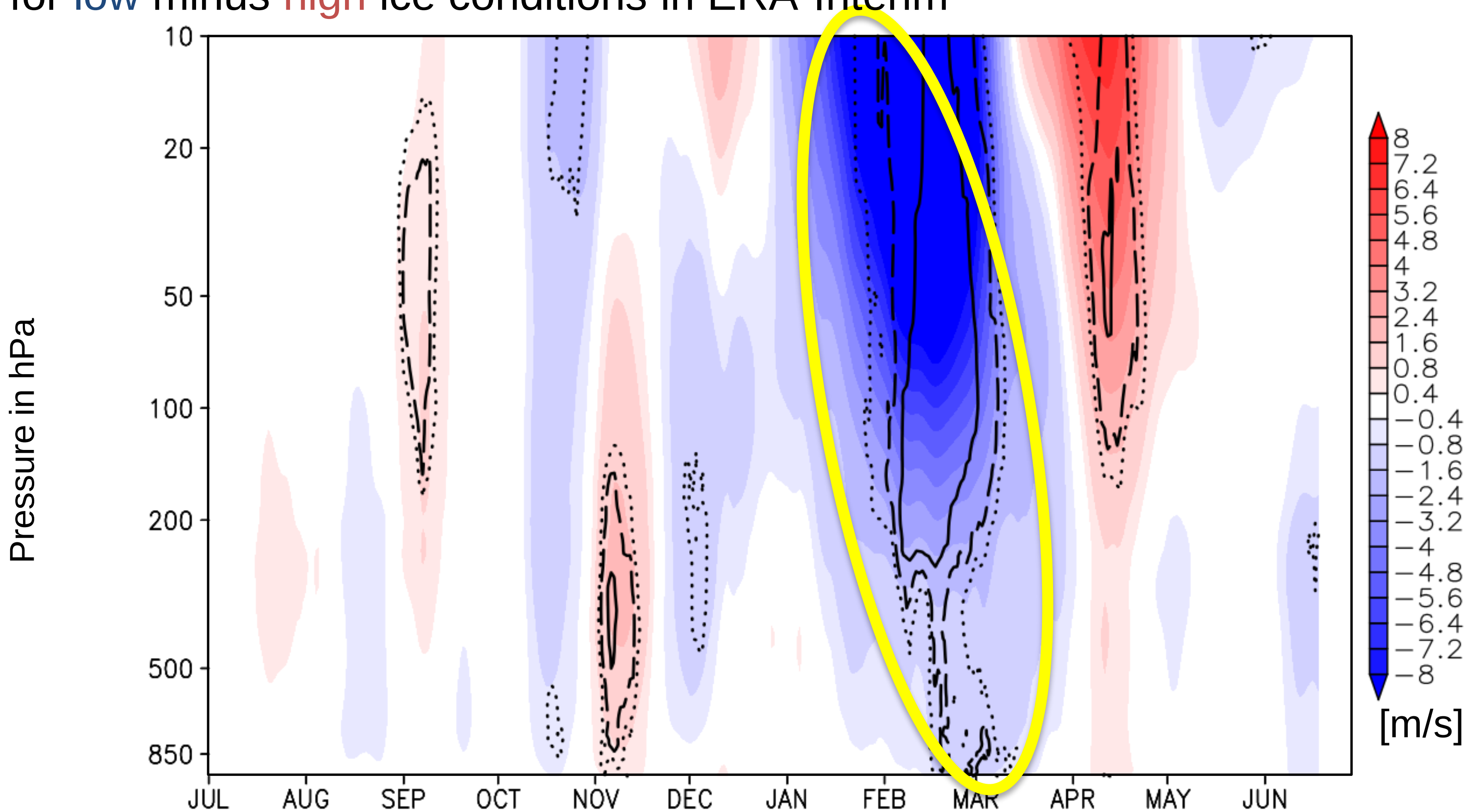
High ice 1979/80-1999/00 — **Low ice** 2000/01-2013/14



- Clear indication of stratospheric vortex breakdown in February
  - Stratospheric westerly winds massively reduced
  - Signal reaching the troposphere

Polar cap zonal wind change

Zonal wind [m/s] average 65°N-85°N
for low minus high ice conditions in ERA-Interim



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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

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

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

- **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

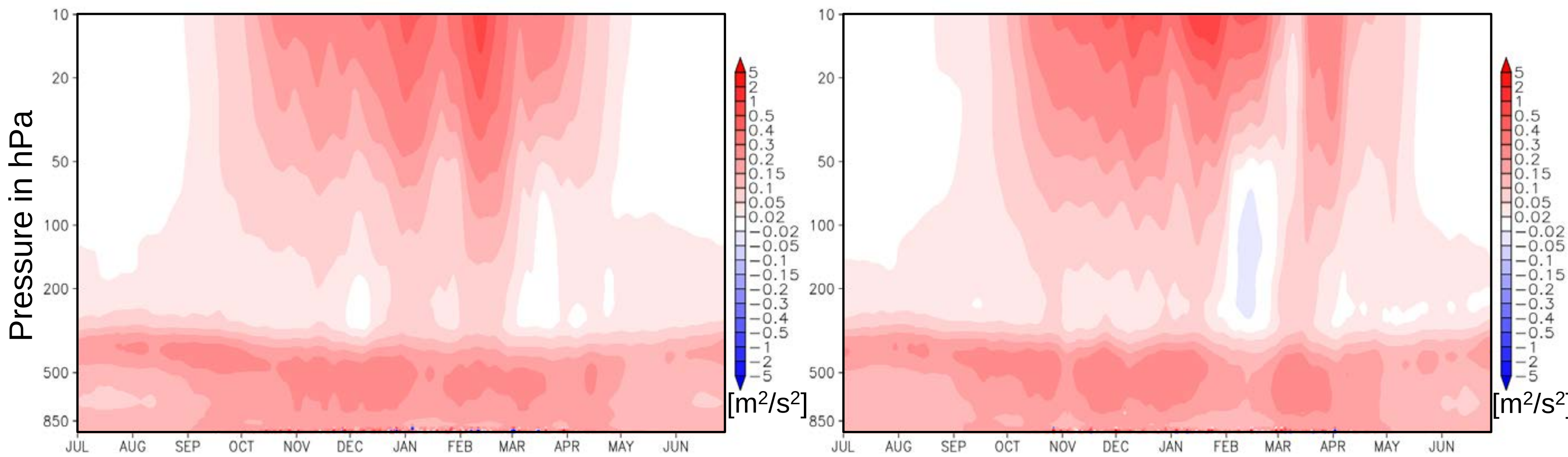
How strong do planetary waves propagate vertically (into the stratosphere)?

Polar cap vertical wave propagation change

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

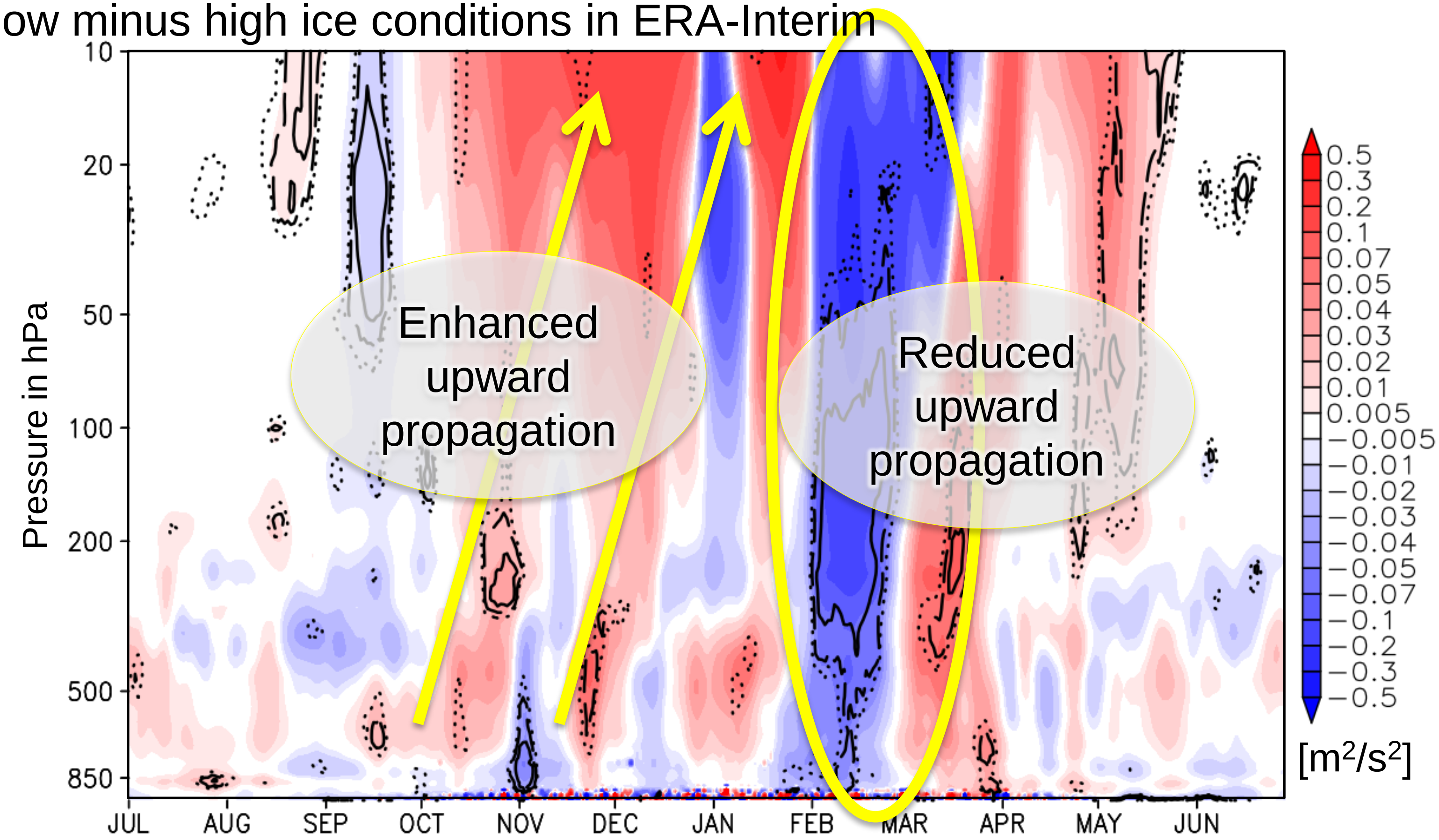
High ice 1979/80-1999/00 **Low ice** 2000/01-2013/14



- 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

Polar cap vertical wave propagation change

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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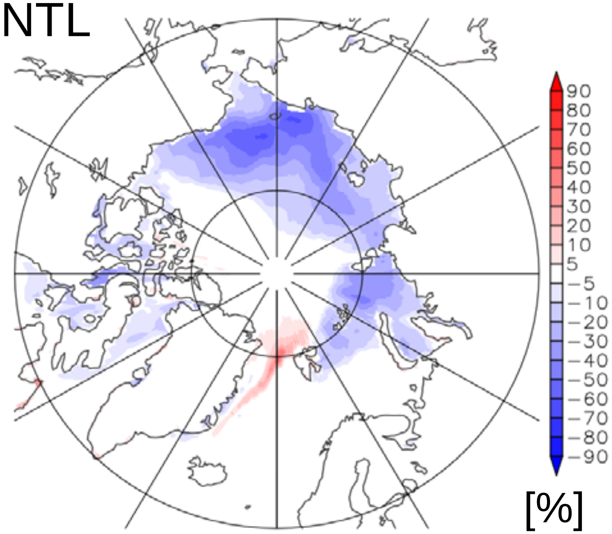
Representation of sea ice impacts in climate models

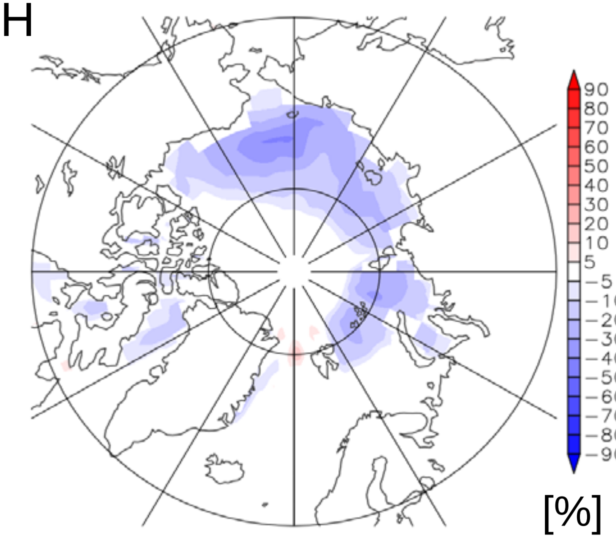
- Model: AFES (Atmospheric general circulation model For Earth Simulator)
- 2 model simulations, with 60 perpendicular years each
  - CNTL: High ice conditions as observed from 1979 to 1983
  - NICE: Low ice conditions as observed from 2005 to 2009
  - **Only sea ice is different between both runs**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

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

AFES
NICE-CNTL



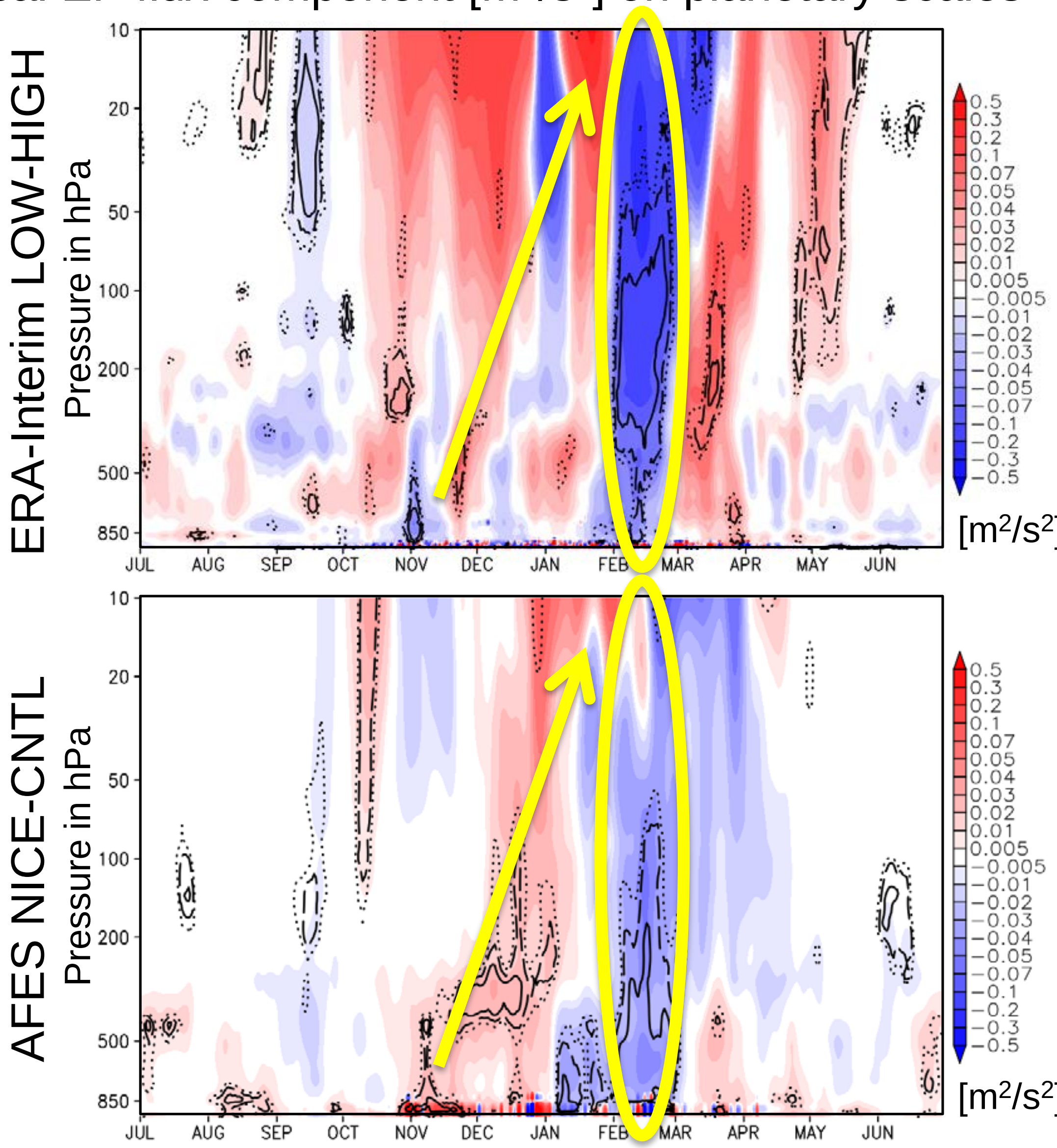
ERA-Interim
LOW-HIGH



Vertical wave propagation

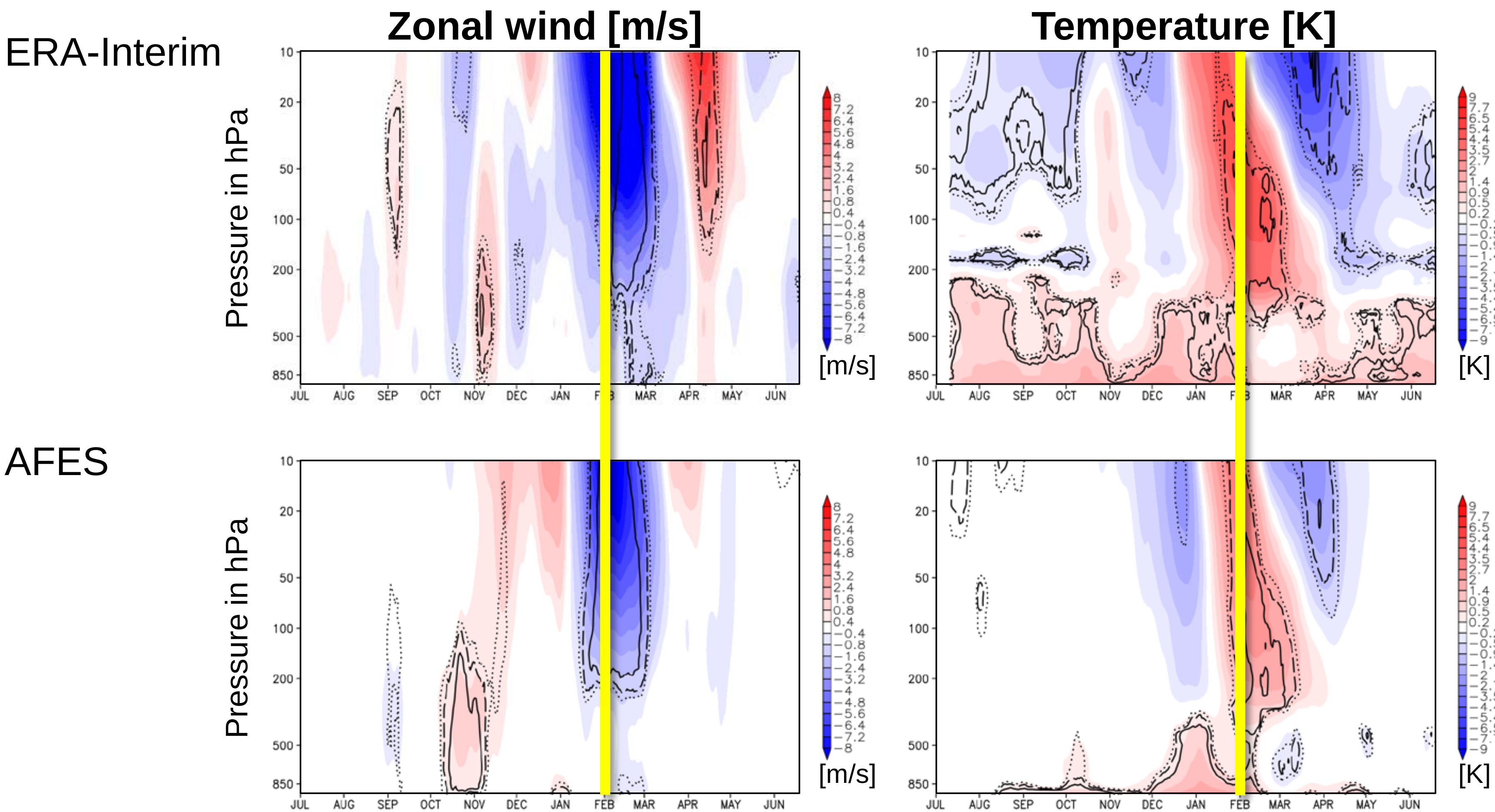
Polar cap mean 65°N-85°N of vertical EP flux component [m^2/s^2] on planetary scales for low minus high ice conditions

- 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



Arctic climatology change

Polar cap mean 65°N-85°N low ice 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

Summary: Sea ice retreat & subsequent atmospheric circulation changes

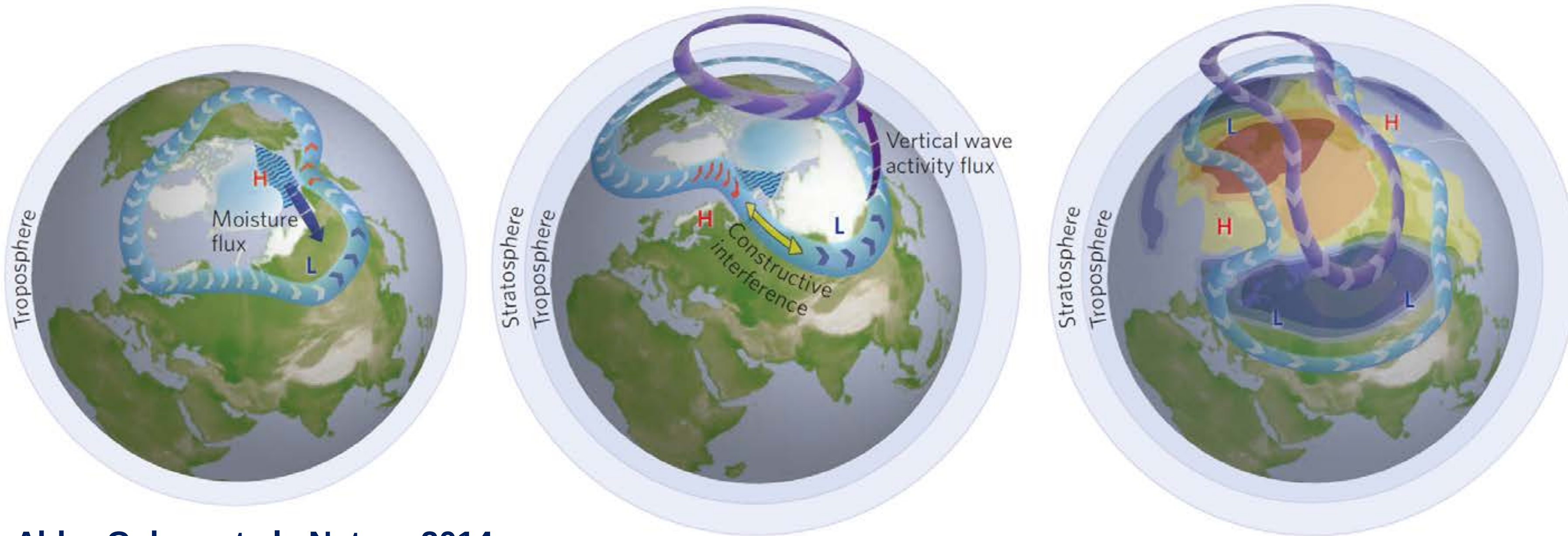


Abb.: Cohen et al., Nature 2014

Sea ice retreat

- Vertical heat- and moisture fluxes
- Increased baro-clinic instability (cyclones)
- Increase in snow cover over Sibiria

Forcing of planetary waves

- Interactions between planetary and synoptic waves
- Diabatic forcing due to
  → changes in snow cover
  → ice anomalies in Nov.
- Decreased meridional temperature gradient

Enhanced planetary waves

- Enhanced vertical wave-propagation up to the stratosphere (EP-fluxes)
- Disturbance of stratospheric polar vortex
- Downward propagating signal
- negative NAO
  → colder European winter

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

References

Cohen, J. J. A. Screen, J. C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, D. Entekhabi, J. Overland, J. Jones, (2014), Recent Arctic amplification and extreme mid-latitude weather. Nature Geoscience, 7, 627–637, doi:10.1038/ngeo2234

Handorf, D., R. Jaiser, K. Dethloff, A. Rinke, and J. Cohen (2015), Impacts of Arctic sea ice and continental snow cover changes on atmospheric winter teleconnections. Geophys. Res. Lett., doi:10.1002/2015GL063203

Jaiser, R., K. Dethloff, D. Handorf, A. Rinke, and J. Cohen (2012), Planetary- and synoptic-scale feedbacks between tropospheric and sea ice cover changes in the Arctic, Tellus, Ser. A, 64, 11595, doi:10.3402/tellusa.v64i0.11595.

Jaiser, R., K. Dethloff, and D. Handorf (2013), Stratospheric response to Arctic sea ice retreat and associated planetary wave propagation changes, Tellus, Ser. A, 65, 19375, doi:10.3402/tellusa.v65i0.19375.

Jaiser, R., T. Nakamura, D. Handorf, K. Dethloff, J. Ukita, K. Yamazaki (2016), Atmospheric winter response to Arctic sea ice changes in reanalysis data and model simulations. JGR, submitted.

Nakamura, T., K. Yamazaki, K. Iwamoto, M. Honda, Y. Miyoshi, Y. Ogawa, J. Ukita (2015), A negative phase shift of the winter AO/NAO due to the recent Arctic sea-ice reduction in late autumn. J. Geophys. Res. Atmos., 120, 3209–3227, doi: 10.1002/2014JD022848.

Brennecke, W. (1904), Beziehungen zwischen der Luftdruckverteilung und den Eisverhältnissen in des Ostgrönländischen Meeres. Ann. Hydrogr. Mar. Meteor., 32(II), 49-62.

Meinardus, W. (1906), Periodische Schwankungen der Eistrift bei Island. Ann Hydrogr. Mar. Meteor., 34, 148-162, 227-239, 278-285.

Hildebrandsson, H.H. (1914), Quelques recherches sur les centres d‘action de l‘atmosphere. Kungl. Svenska vetenskapsakademiens handlingar, 51, 3-16.

Wiese, W. (1924), Polareis und atmosphärische Schwankungen. Geograf. Ann., 6, 273-299.

Herman, G.F. and W.T. Johnson (1978), The Sensitivity of the General Circulation to Arctic Sea Ice Boundaries: A Numerical Experiment. Mon. Weath. Rev., 106, 1649-1664.

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Thank you for your kind attention!