Dynamic and thermodynamic drivers of Arctic lower tropospheric warm extremes

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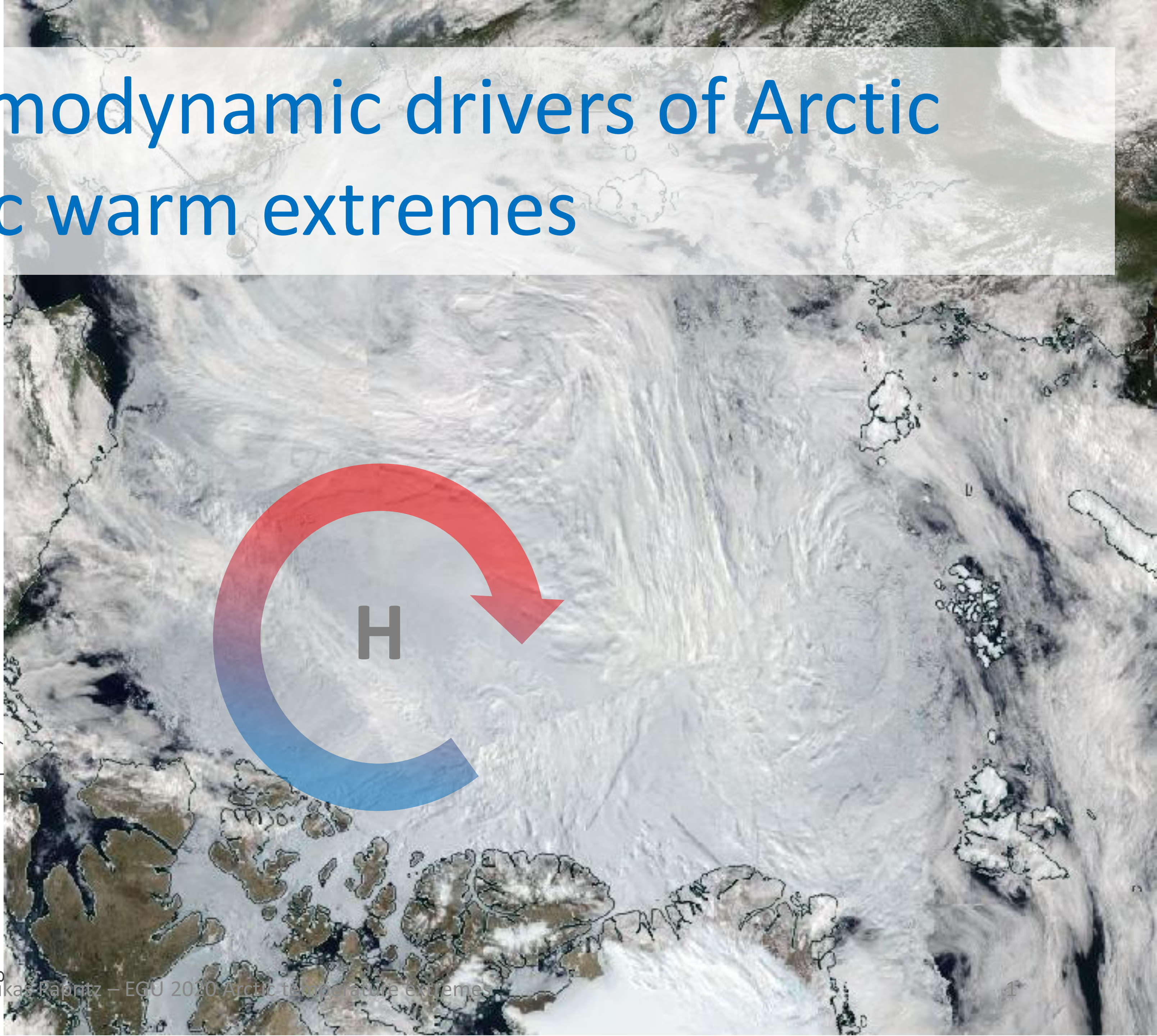

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Overview

Summary

Key questions

Background on warming mechanisms

Trajectory calculation
Classification of trajectories

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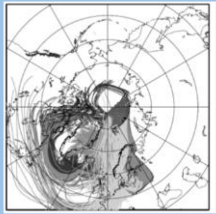
Air mass origin



Relative importance of warming processes

Nature of diabatic heating

Importance of high-latitude blocking

Summary

Kinematic trajectories combined with weather system analyses reveal that warm extremes in the high Arctic (> 80°N) form due to:

- Winter: **Subsidence** in blocking anticyclones in the Barents and Kara Seas and diabatic warming by **surface sensible heat fluxes and latent heating** during **marine cold air outbreaks** in the Nordic Seas contributing **40% each**
- Winter: **Poleward transport** of warm air masses from low latitudes contributes **20%,** shift of North Atlantic storm track is key
- Summer: **Subsidence in anticyclones in the high Arctic** contributing about **70%**

➢ Results emphasize importance of thermodynamic and dynamic processes taking place in the Arctic, e.g., blocking anticyclones in Barents and Kara Seas (winter) and the high Arctic (summer)

Key questions

(1) How much do the various thermodynamic (warming) mechanisms contribute to the formation of warm extremes?

- Poleward transport of warm air masses
- Adiabatic warming by subsidence
- Diabatic heating

(2) What is the role of dynamical weather systems for inducing warm extremes?

- Blocking anticyclones
- Extratropical cyclones (=> see paper)

(3) Are thermodynamic and dynamical mechanisms different in summer than in winter?

Background on warming mechanisms

Adopt a **Lagrangian** point of view, following air masses:

$$\frac{D\boldsymbol{x}}{Dt} = \boldsymbol{u}(\boldsymbol{x})$$

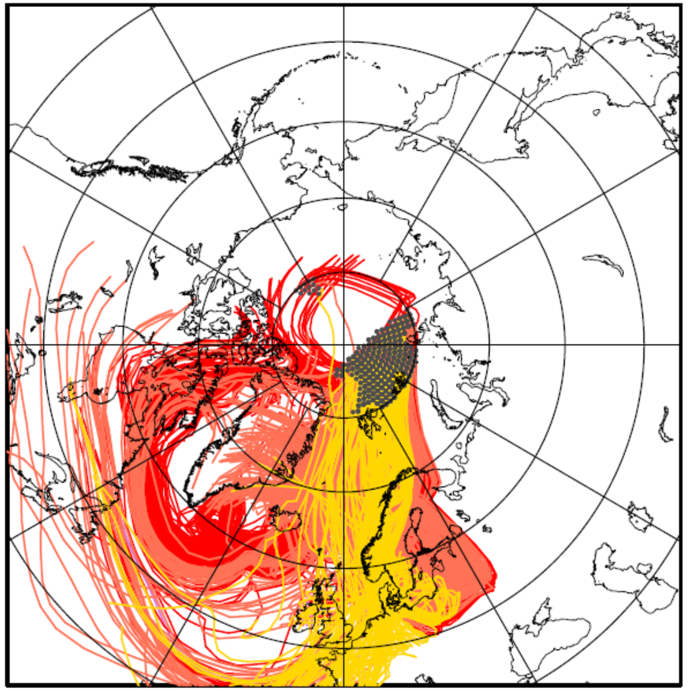
Thermodynamic energy equation:

$$\underline{\frac{DT}{Dt}} = \underline{\frac{\kappa T \omega}{p}} + \underline{\left(\frac{p}{p_0}\right)^{\kappa} \frac{D\theta}{Dt}}$$

- Lagrangian temperature tendency
  - Poleward transport of warm air masses
- Adiabatic compression / expansion due to vertical motion
  - Subsidence is an efficient heat source (descent of 100 hPa ~ 10 K warming)
  - Known as an important process in mid-latitude heatwaves Bieli et al. 2015, Quinting and Reeder 2017, Zschenderlein et al. 2019
- Diabatic heating and cooling
  - Moist processes
  - Surface sensible heating (and mixing)
  - Radiative cooling

Data & methods

0000 UTC 01 Jan 2016



Dataset: ERA-Interim 1979 – 2017, DJF / JJA

10 day kinematic backward trajectories:

- 80 km x 80 km grid (> 80°N) every 20 hPa from 10 hPa to 90 hPa above ground level
- consider potential temperature anomaly $\theta^* = \theta - \theta_c$

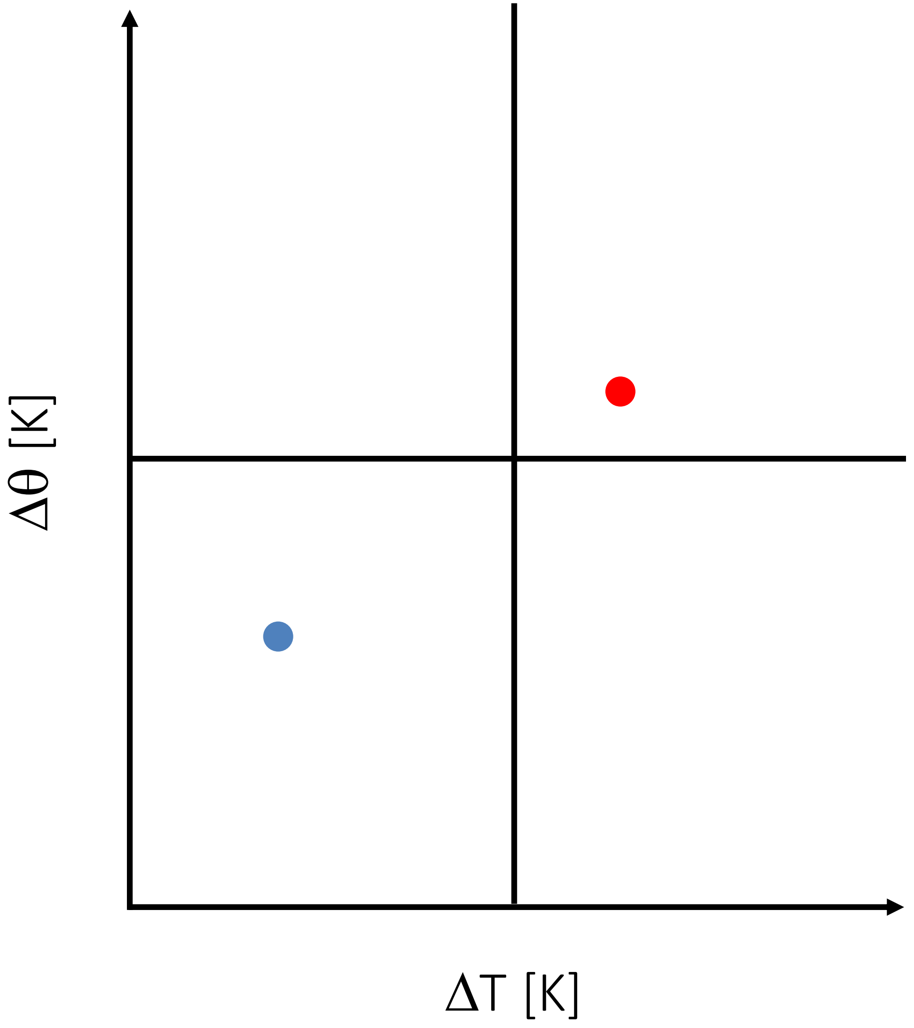
Warm extremes: θ^* > 95th percentile

Potential temperature climatology (θ_c):

- «Transient» climatology to accomodate for non-linear warming trend in the Arctic
- 9 year running mean of 21 day running mean

(similar to Messori et al. 2018)

Classification of trajectories

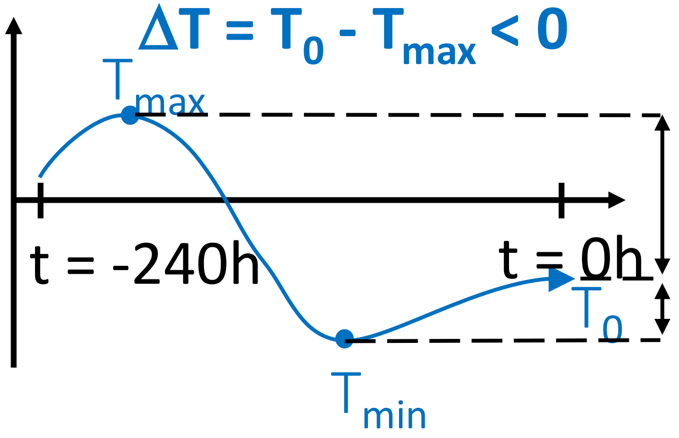


Define maximum absolute changes of T and θ (denoted χ): cf. Binder et al. 2017 and Zschenderlein et al. 2019

$$\Delta\chi = \begin{cases} \chi_0 - \chi_{\min}, & \text{if } |\chi_0 - \chi_{\min}| \geq |\chi_0 - \chi_{\max}| \\ \chi_0 - \chi_{\max}, & \text{else} \end{cases}$$

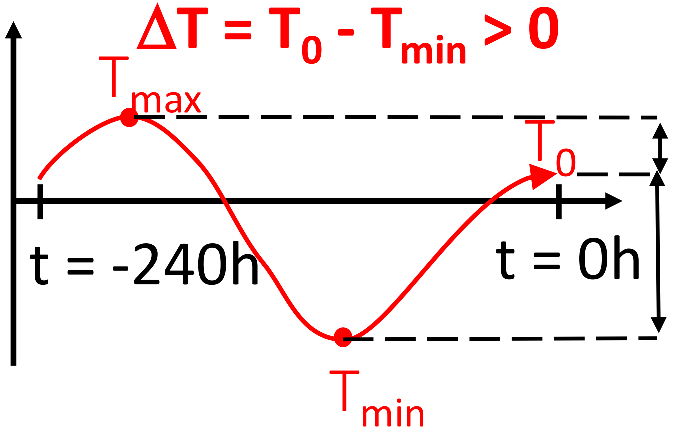
overall cooling

$\Delta T = T_0 - T_{max} < 0$



overall warming

$\Delta T = T_0 - T_{min} > 0$



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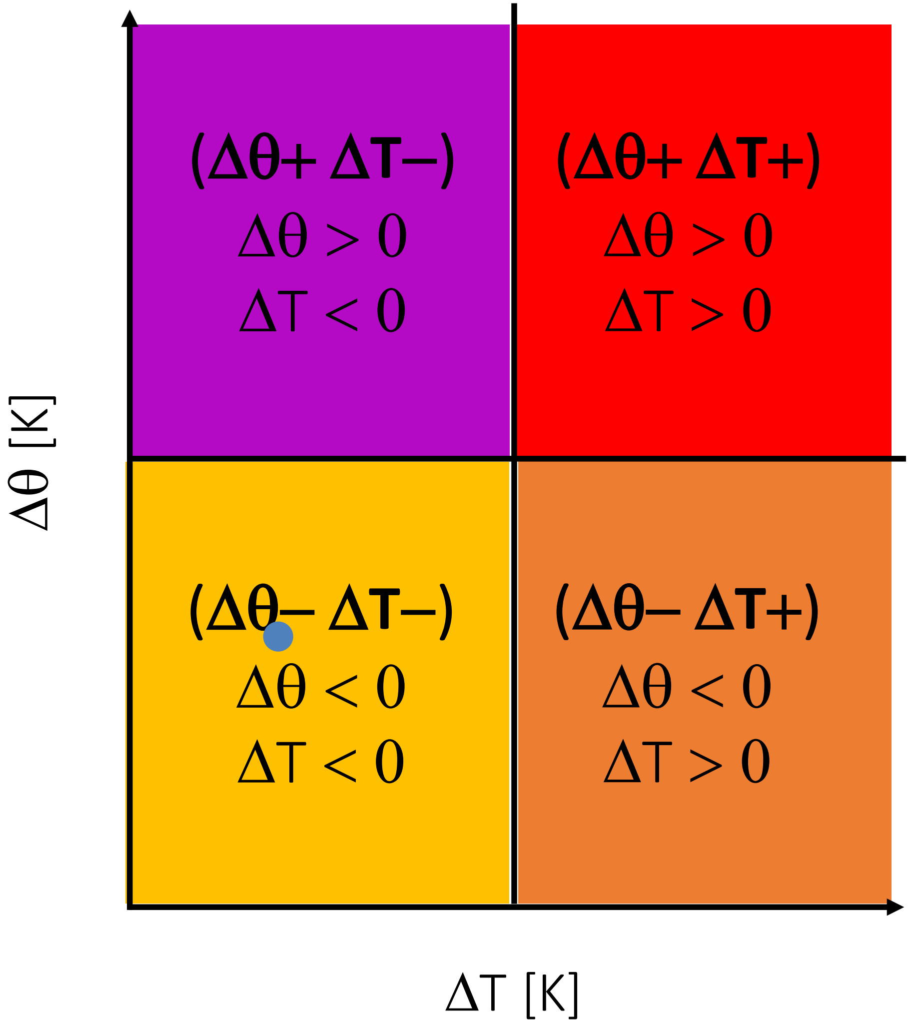

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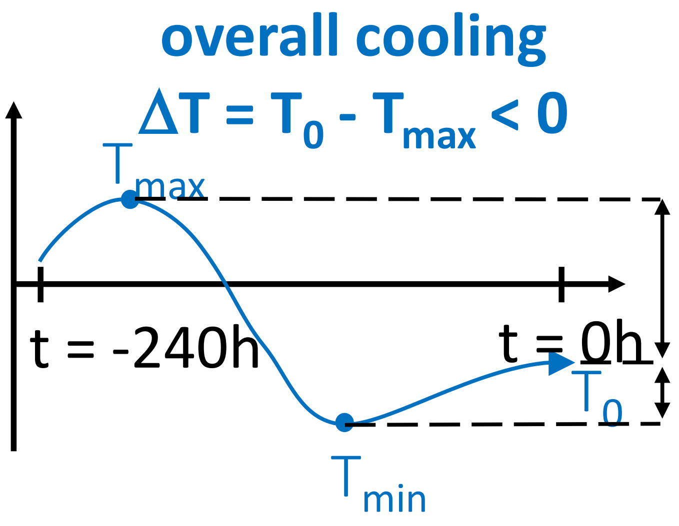

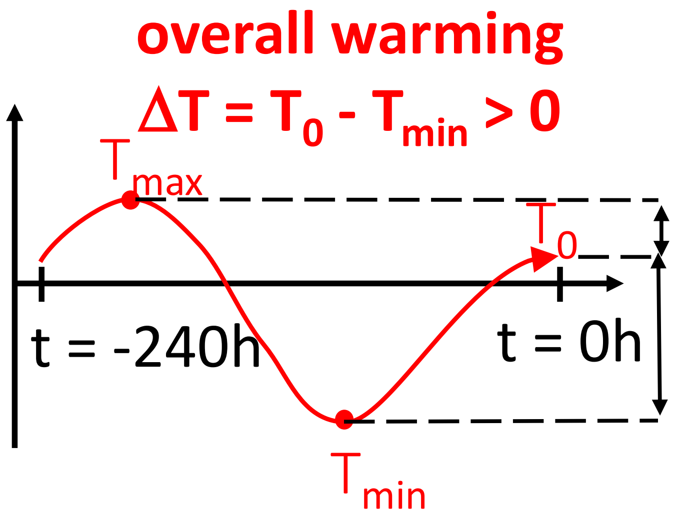

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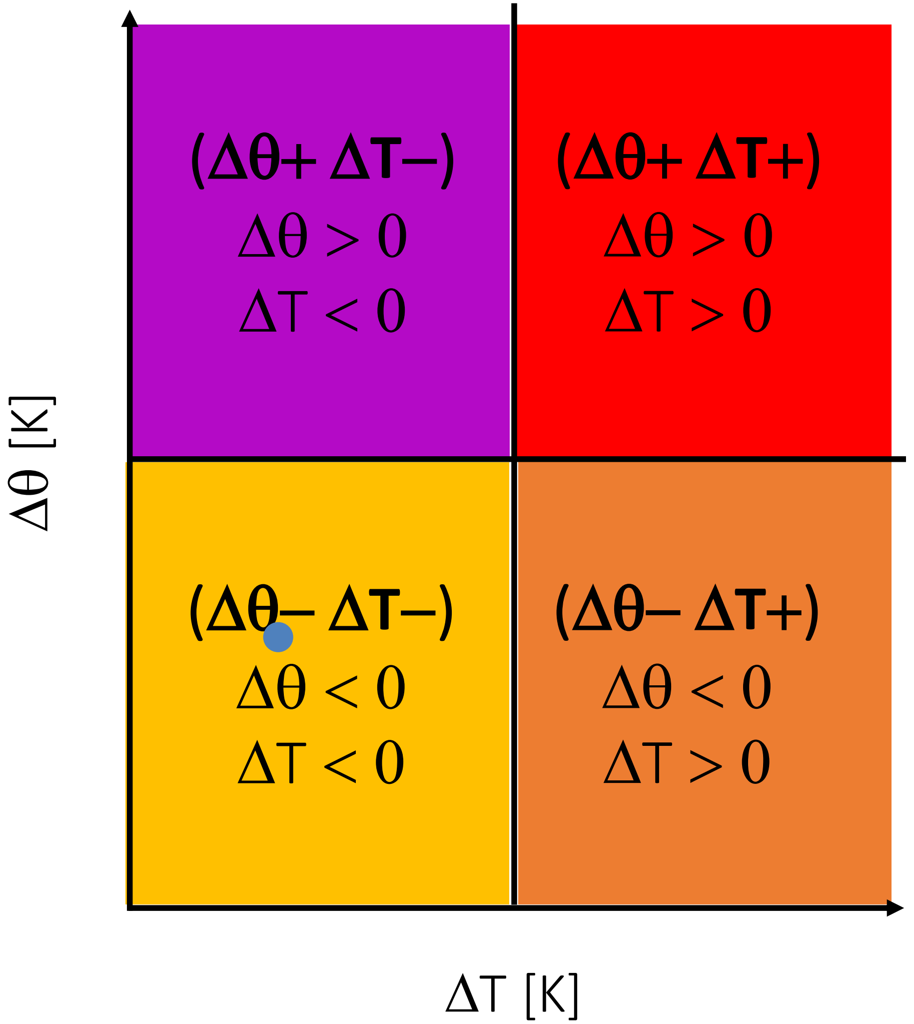
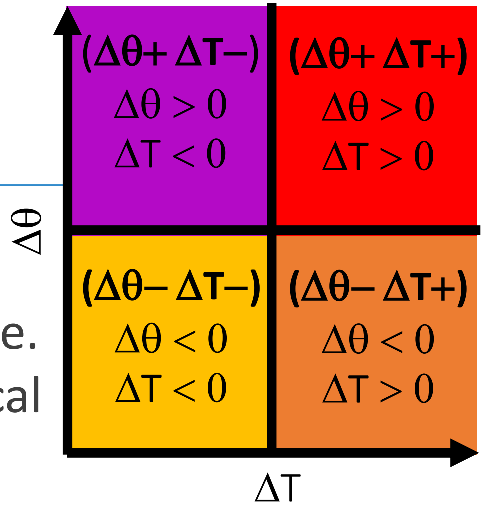


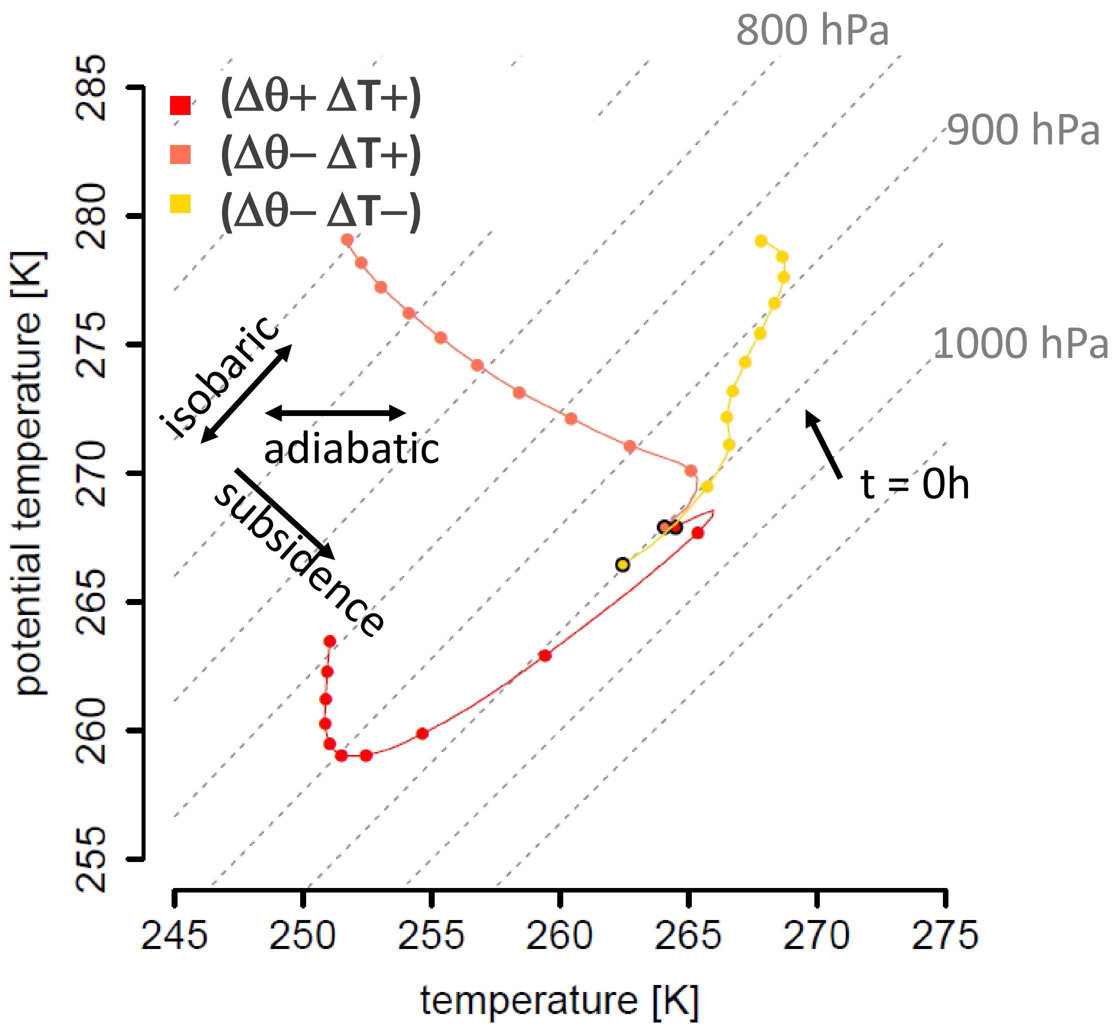
Example air streams:

(Δθ+ ΔT–) *warm conveyor belt*
(Δθ+ ΔT+) *marine cold air outbreak*
(Δθ– ΔT+) *subsidence in blocking anticyclone*
(Δθ– ΔT–) *low latitude air mass moving poleward*

(Δθ+ ΔT–) requires ascent => likely unimportant for lower tropospheric temperature extremes

Results: Thermodynamic evolution (DJF)



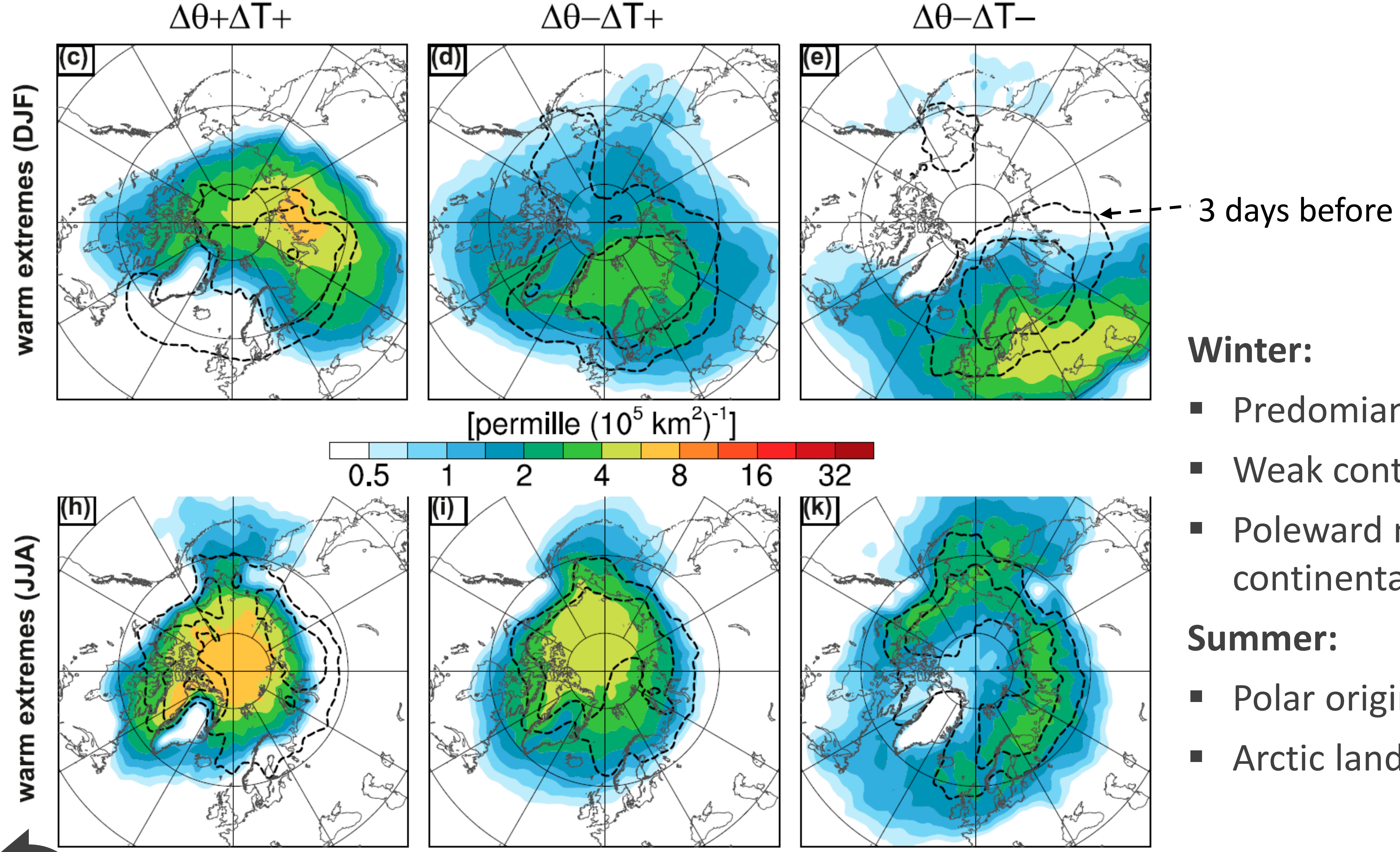


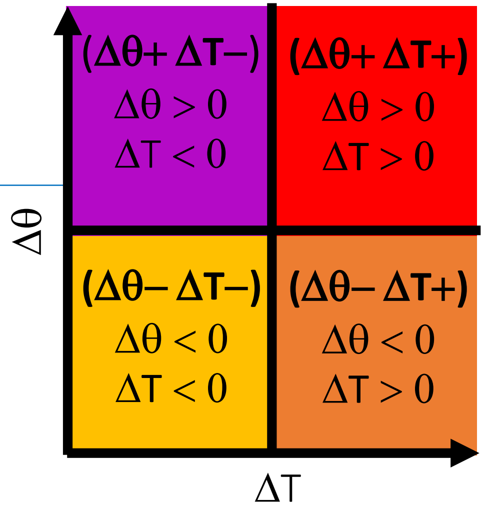
Consider thermodynamic evolution of median of air masses in $\theta - T$ space. This reveals contributions from vertical motion (across dashed isobars) and diabatic heating (along y-axis):

- **(Δθ+ ΔT+):** Initially cold, lower tropospheric air masses undergoing rapid diabatic warming
- **(Δθ– ΔT+):** Subsiding air masses subject to strong adiabatic warming and diabatic (radiative) cooling
- **(Δθ– ΔT–):** Warm, moderately subsiding air masses subject to radiative cooling

➢ Classification captures different air masses with distinct thermodynamic evolution

Results: Air mass origin (10 days before)





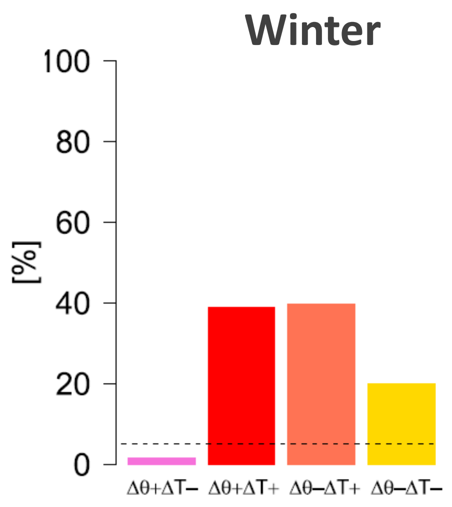
Winter:

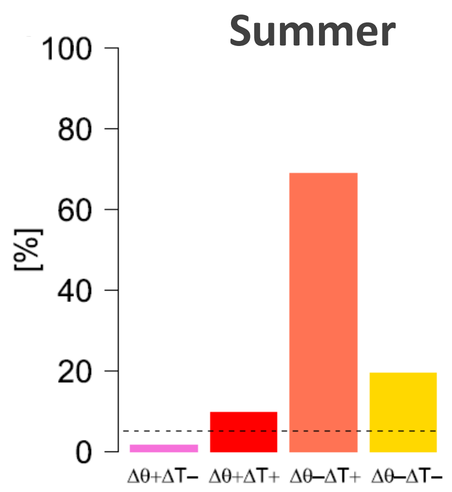
- Predomiantly Arctic origin (Eurasia)
- Weak contributions from North Atlantic
- Poleward moving air masses are mostly continental

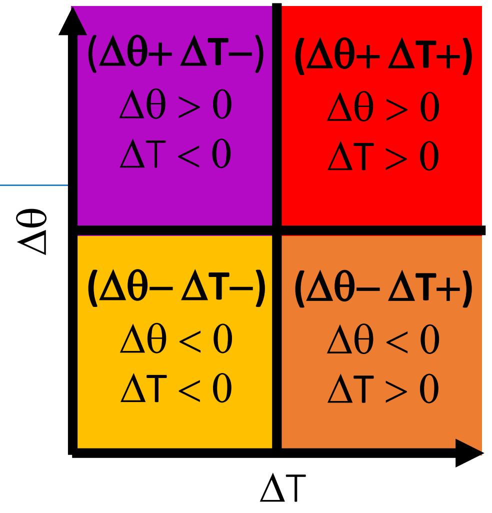
Summer:

- Polar origin of air masses
- Arctic land masses

Results: Relative contributions





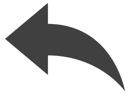


Winter:

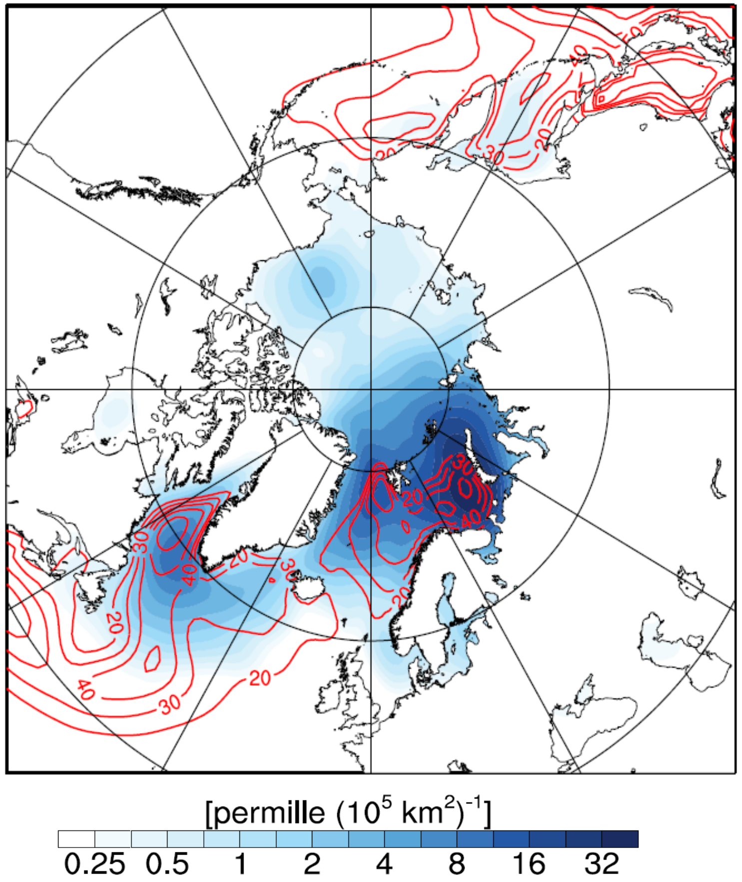
- 40% of air masses experience diabatic heating **(Δθ+ ΔT+)**
- 40% of air masses dominated by subsidence **(Δθ– ΔT+)**
- poleward transport of warm air masses **(Δθ– ΔT–)** is of secondary importance (20%)

Summer:

- category of subsiding air masses is most important (70%, Δθ– ΔT+)
- poleward transport of warm air masses contributes as much as in winter (20%, Δθ– ΔT–)



Results: Nature of diabatic heating (DJF, $\Delta\theta$+ ΔT+)

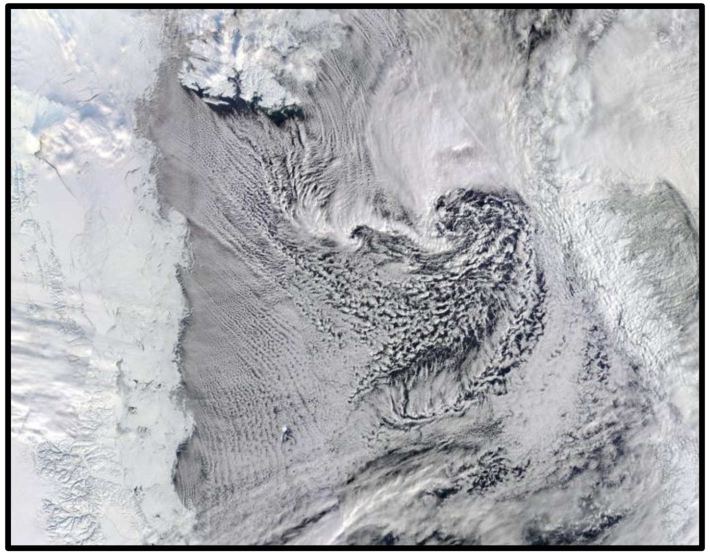


Left figure: Location of air masses at time of most intense 24h averaged diabatic heating (DJF)

– Frequency of cold air outbreaks [%] ($\theta_{SST} - \theta_{900} > 4K$) Papritz and Spengler 2017

Right figure: Typical cold air outbreak in the Nordic Seas

- Most intense diabatic heating coincides with location of air mass in hot spot regions of marine cold air outbreaks
- Located near sea surface (980 hPa median pressure) and max. $\theta_{SST} - \theta \sim 8K$ in median
- Marine cold air outbreaks are associated with strong upward fluxes of sensible and latent heat



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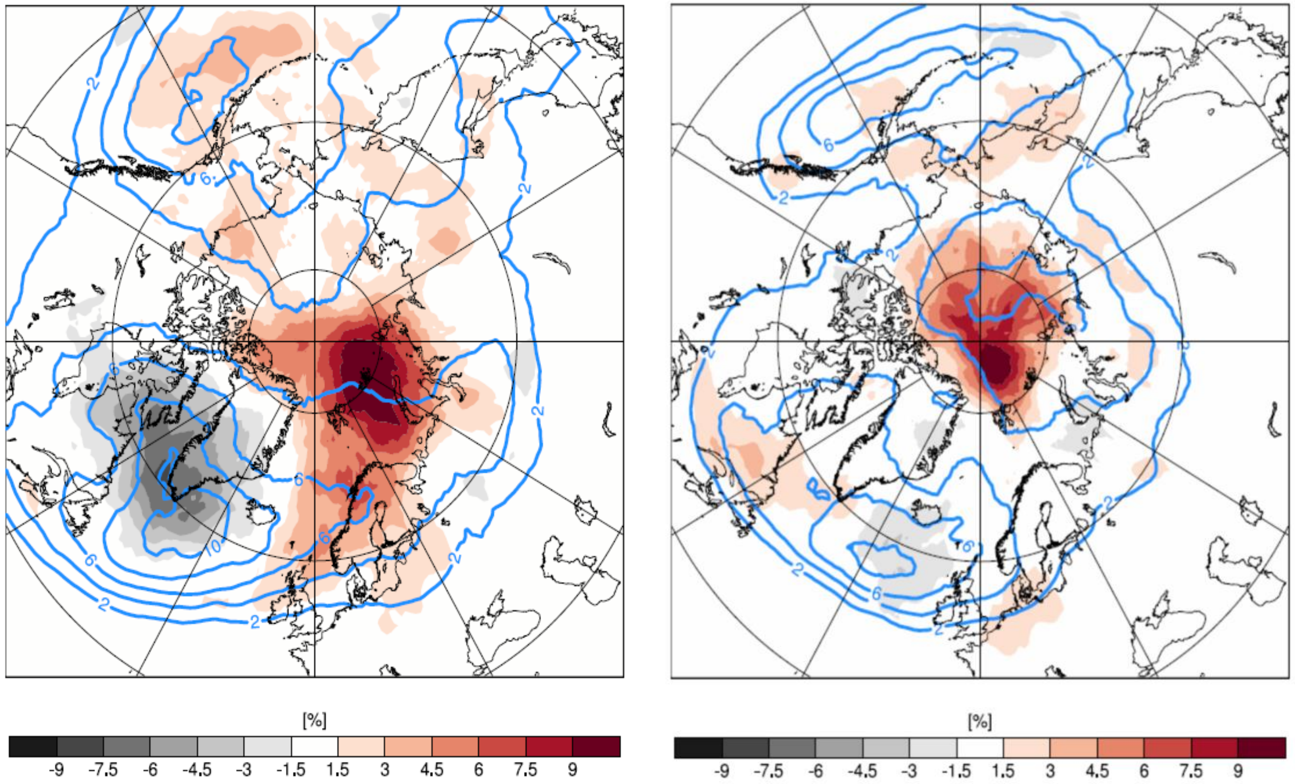
Importance of high-latitude blocking

Blocking frequency anomalies ([%]; vertically averaged PV anomaly < -1.3 PVU Croci-Maspoli et al. 2007)

— climatological blocking frequency [%]

Winter **Summer**



Composites of 3 days prior to top 100 warm extremes:

Winter:

- Anomalous blocking in Barents – Kara Sea region
- Blocking drives subsidence and transport of cold air masses from Siberia over ocean

Summer:

- Blocking in central Arctic; collocated with origin of subsiding air masses ($\Delta\theta-$ $\Delta T+$)

If you want to learn moren or have any questions, remarks, or suggestions, please get in touch:

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