Evaluation of simulated Arctic cloud cover and PBL heights with satellite observations

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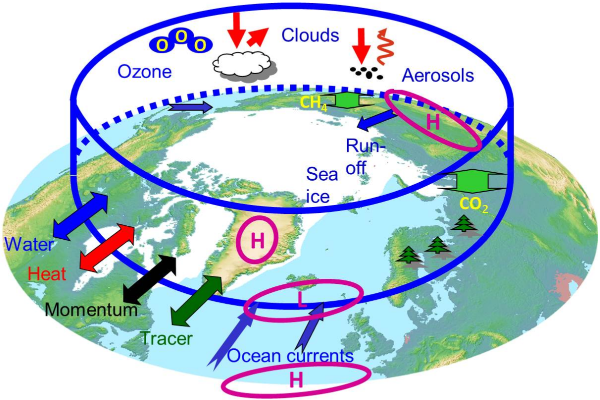
Alfred Wegener Institute for Polar and Marine Research, Potsdam, Germany

January 16, 2013

Arctic: Energy sink of the Earth



- Strong anthropogenic signal (Polar Amplification) and decadal variability
- Insufficient availability of measurements in polar regions
- Global Earth System Models (GESMs) show largest biases in polar regions
- Arctic regional climate model (RCM) as magnifier (higher resolution)
- Added value: Development of adapted/improved model physics

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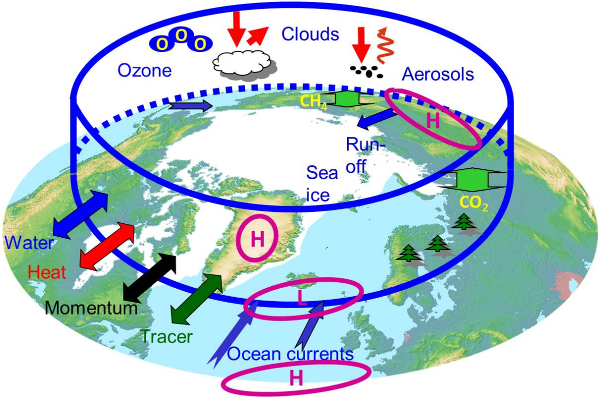

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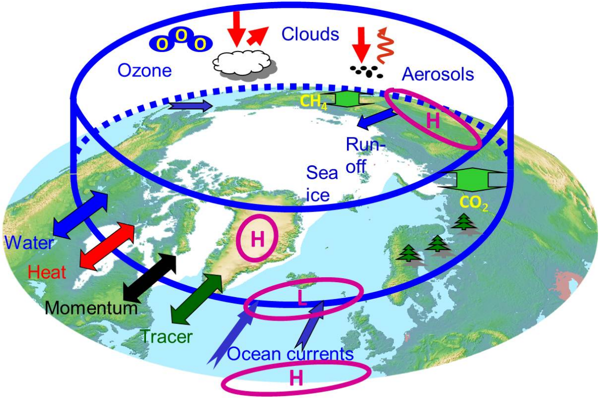

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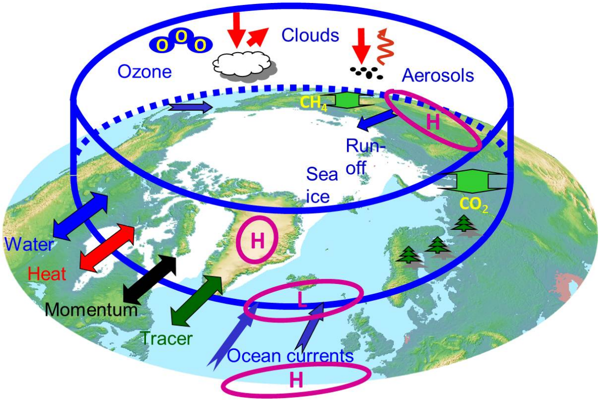

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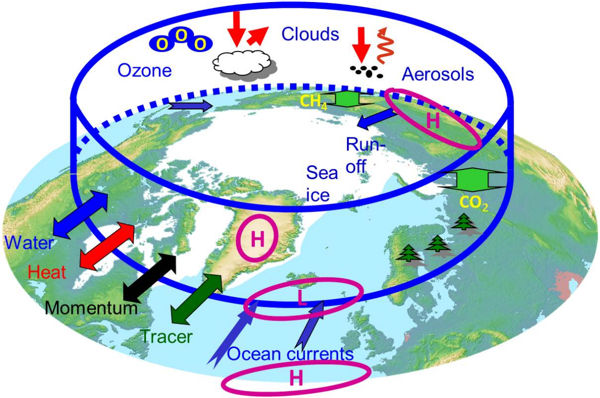

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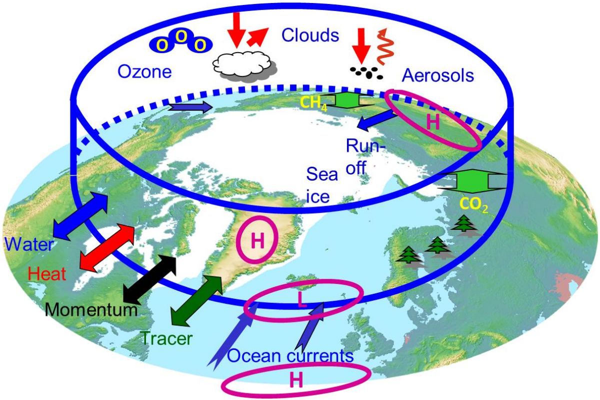

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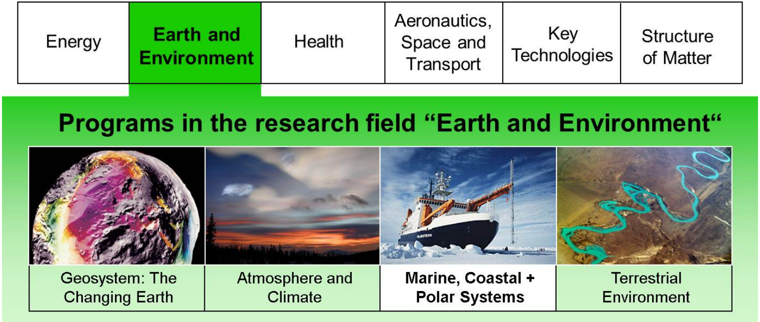
AWI as part of the Helmholtz Association



Helmholtz Association

- 8 German research centers in the research field "Earth and Environment"

AWI	Alfred Wegener Institute for Polar and Marine Research
FZJ	Research Center Jülich
GEOMAR	Helmholtz Center for Ocean Research Kiel
KIT	Karlsruhe Institute of Technology
GFZ	Helmholtz Center Potsdam, German Research Center for Geo-sciences
HZG	Helmholtz Center Geesthacht, Center for Materials and Coastal Research
HMGU	Helmholtz Center Munich, German Research Center for Environmental Health
UFZ	Helmholtz Center for Environmental Research (Leipzig)

- Networking to resolve highly complex environmental and climate problems

AWI as part of the Helmholtz Association

Energy	**Earth and Environment**	Health	Aeronautics, Space and Transport	Key Technologies	Structure of Matter

Programs in the research field "Earth and Environment"

Geosystem: The Changing Earth	Atmosphere and Climate	**Marine, Coastal + Polar Systems**	Terrestrial Environment

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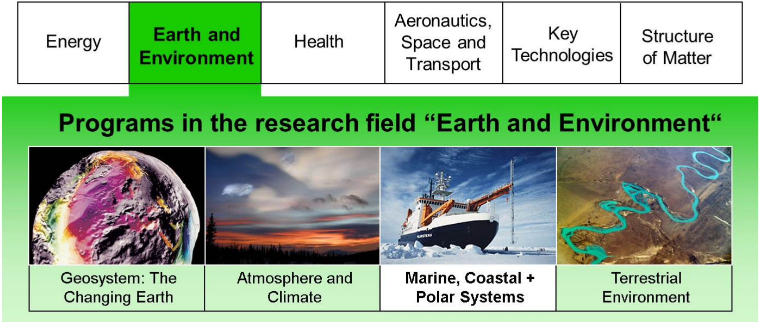

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AWI research units

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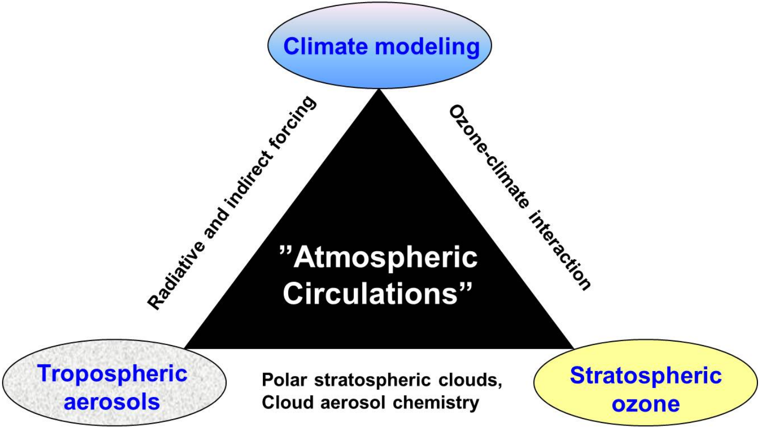
Research unit Potsdam

- ... started work in 1992
- ... accommodates two sections: **Atmospheric Circulations** and **Periglacial Research**
- ... employs 105 staff members

AWI research section "Atmospheric Circulations"



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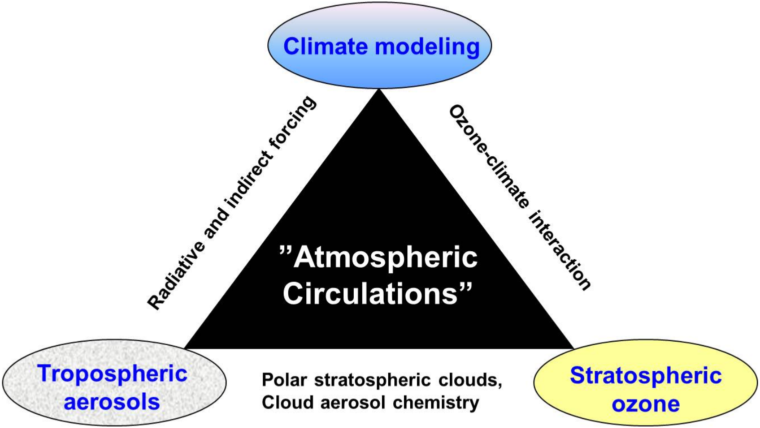

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AWI research platforms

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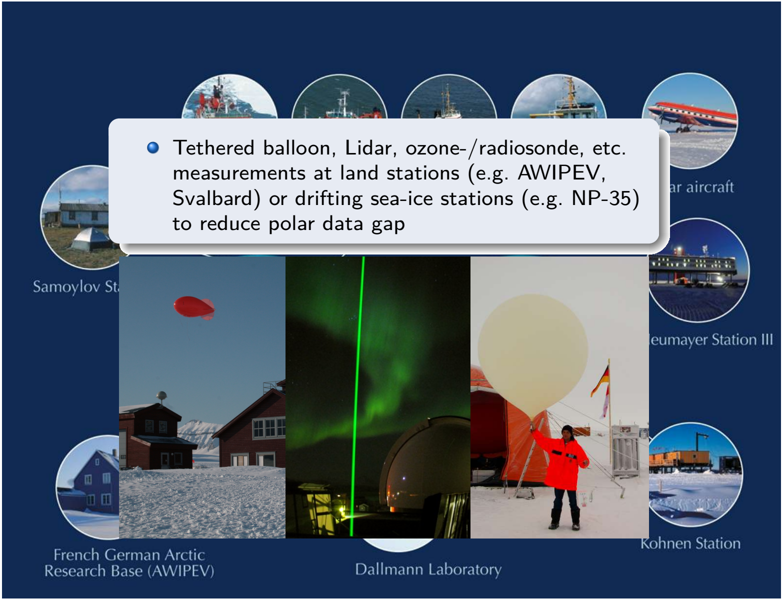
- Tethered balloon, Lidar, ozone-/radiosonde, etc. measurements at land stations (e.g. AWIPEV, Svalbard) or drifting sea-ice stations (e.g. NP-35) to reduce polar data gap



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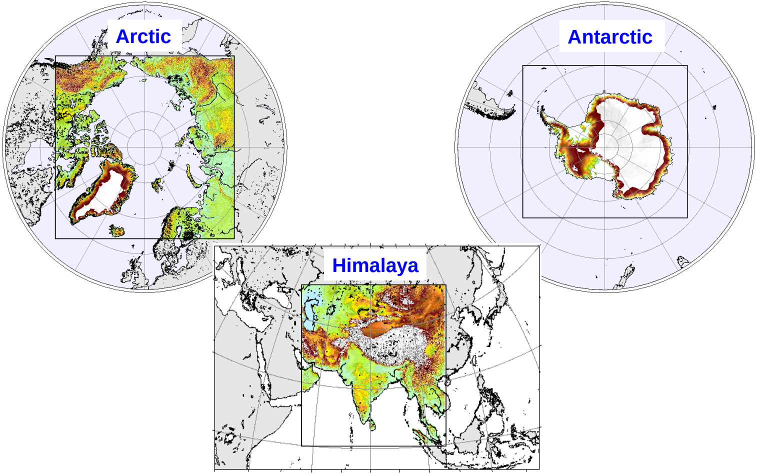
- Validation of CryoSat sea-ice thickness with EM-Bird on board of the Polar 5 aircraft

Polar components of the Earth system at AWI



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- In this talk: Focus on the pan-Arctic integration domain

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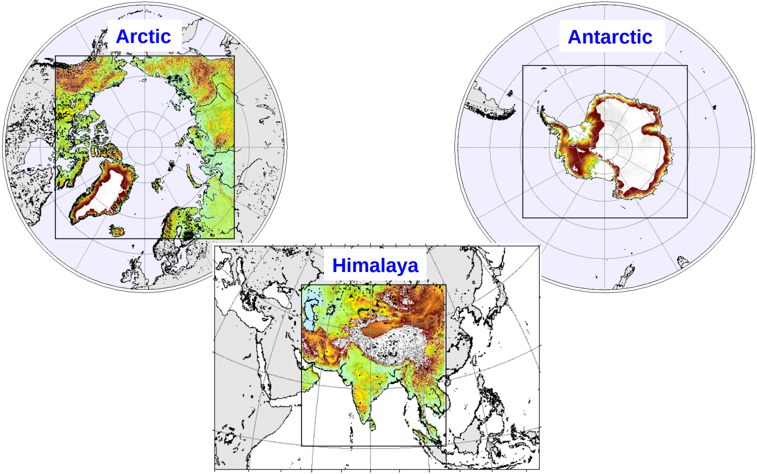

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HIRHAM5

Regional Climate Model
of the Arctic atmosphere

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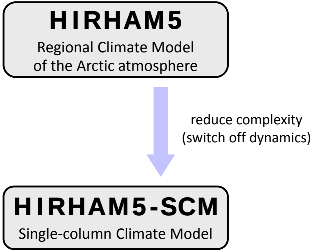
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HIRHAM5-SCM
Single-column Climate Model

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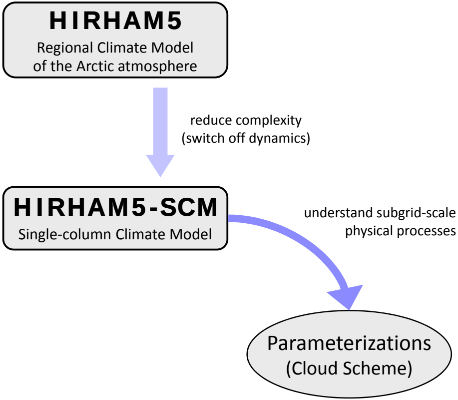
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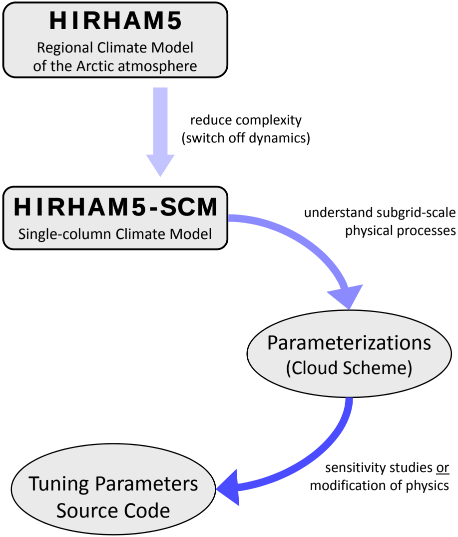
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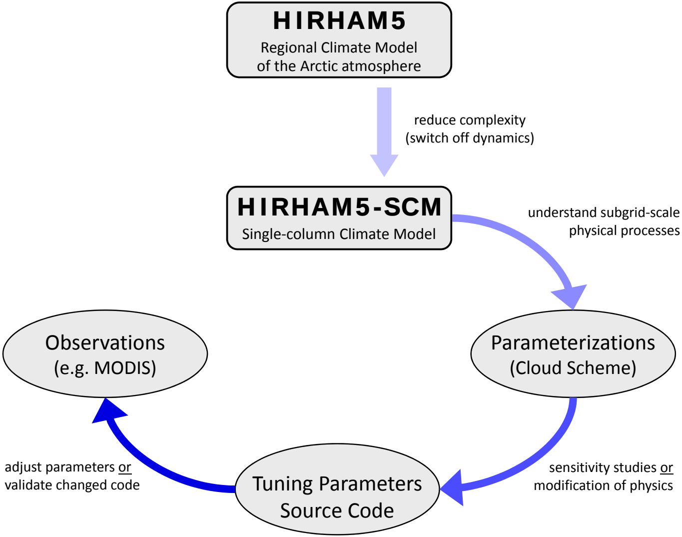
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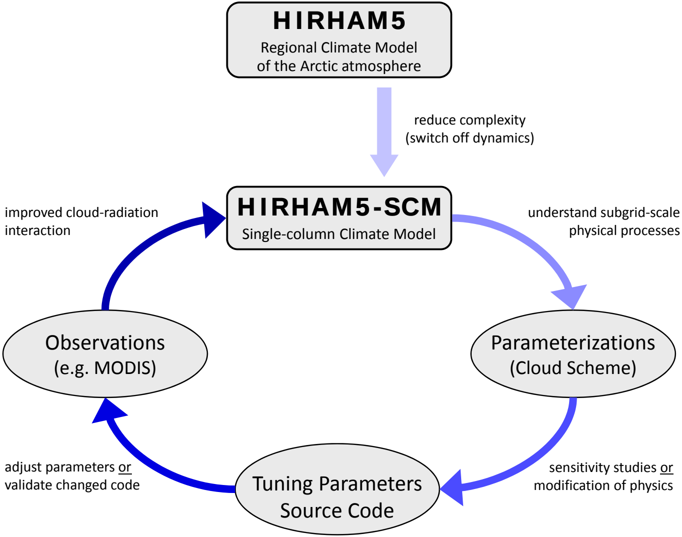
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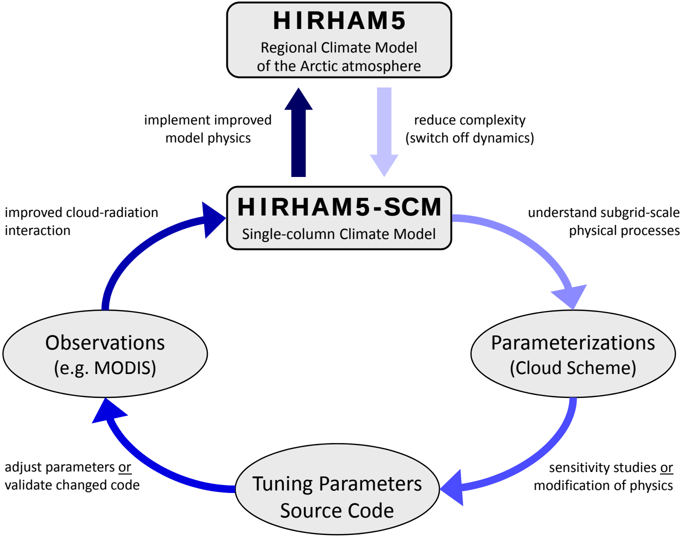
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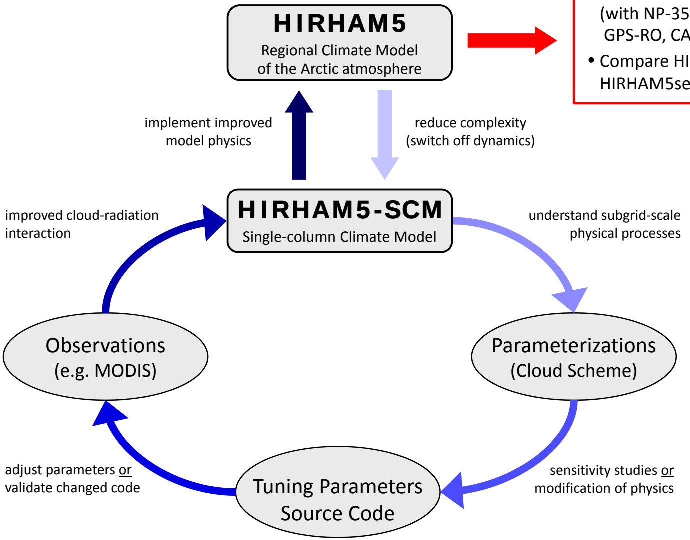

- Evaluation of HIRHAM5ctrl (with NP-35, SHEBA, MODIS, GPS-RO, CALIOP, ...)
- Compare HIRHAM5ctrl with HIRHAM5sens

Outline

1. Model description
   - Regional climate model HIRHAM5
   - Single-column climate model HIRHAM5-SCM
2. Results from HIRHAM5-SCM
   - Modeled vs. observed total cloud cover
   - Parameter sensitivity studies
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3. Results from HIRHAM5
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   - Calculation of PBL height in HIRHAM5
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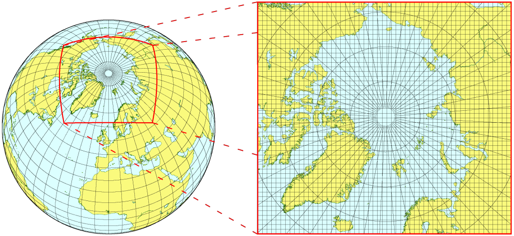
Regional climate model HIRHAM5

- Atmospheric RCM with pan-Arctic integration domain (> 53.5°N)
- Comprises dynamical core of the HIRLAM NWP model and physical parameterizations of the ECHAM5 GCM coupled by an interface



HIRLAM (Undén et al., 2002)

- Hydrostatic model solves 7 prognostic equations

Surface pressure (p_s)	Temperature (T)
Horizontal wind (u,v)	Specific humidity (q)
Cloud water content (q_l)	Cloud ice content (q_i)

- 0.25° horizontal resolution (∼25 km)
- 40 hybrid levels (≤ 10 hPa; 10 in PBL)
- Semi-implicit Euler time scheme ($\Delta t = 2$ min)
- ERA-Interim initialization/lateral boundary forcing

ECHAM5 (Roeckner et al., 2003)

Subgrid-scale parameterizations:

- SW and LW radiation transfer
- Stratiform cloud scheme
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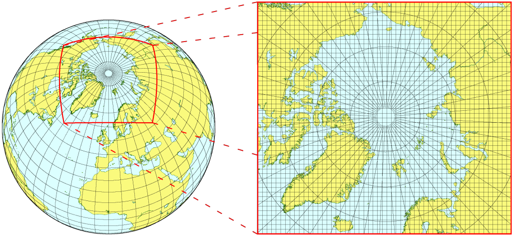

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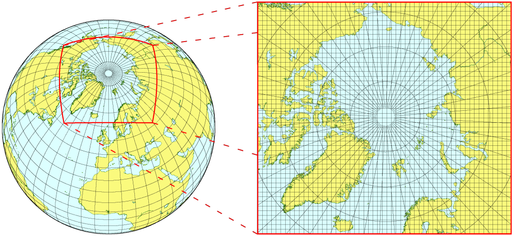

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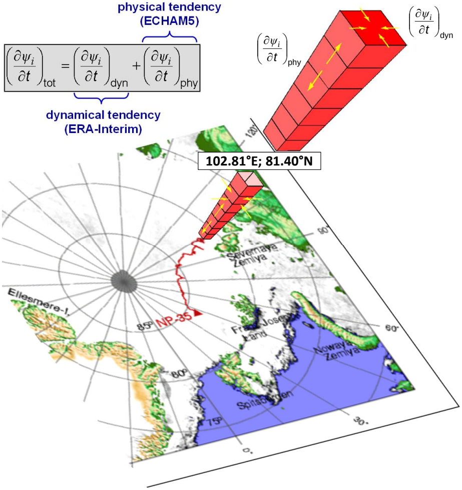

Model setup

- Predefined geographic location
- 60 hybrid levels (≤ 0.1 hPa; 10 in PBL)
- Euler forward time scheme ($\Delta t = 10$ min)
- Initialization with ERA-Interim data set
- Physical tendencies explicitly computed by ECHAM5 parameterizations
- p_s and dynamical tendencies of T, q, u, and v are prescribed 3-hourly from ERA-Interim

Cloud cover parameterization

- Prognostic equations for vapor, liquid, and ice phase
- Bulk cloud microphysics according to Lohmann and Roeckner (1996)
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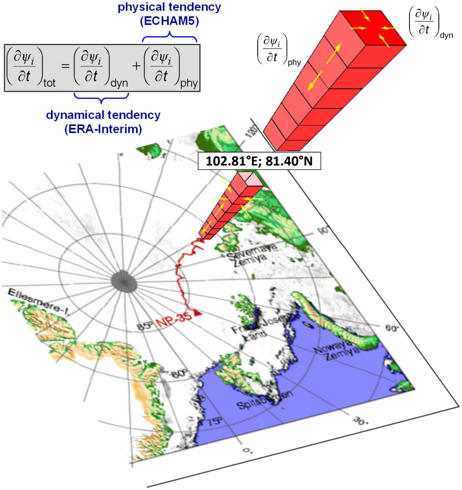

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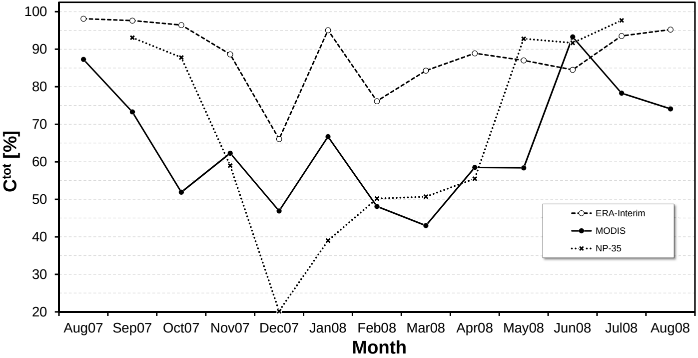
Monthly means of C^{tot} at NP-35 start position (102.81°E; 81.40°N)



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- In general, HIRHAM5-SCM agrees qualitatively but systematically overestimates C^{tot}
- PS-Scheme shows reduced biases and good agreement from November 2007 to January 2008
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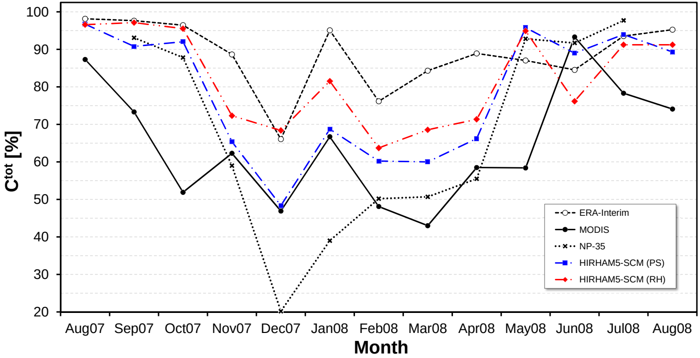

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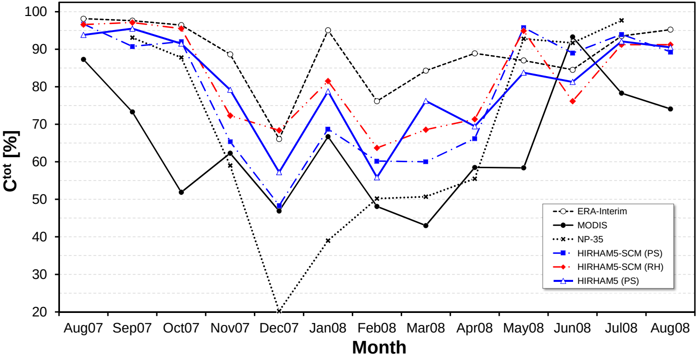

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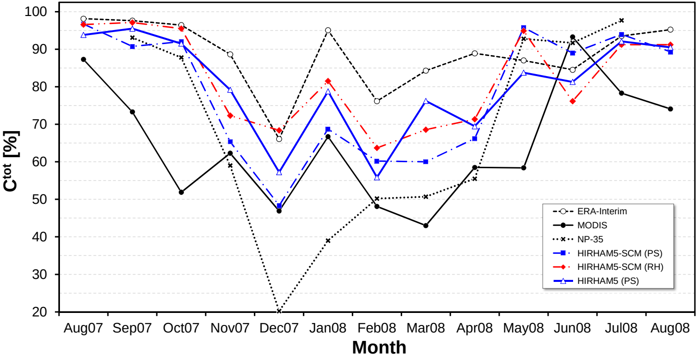

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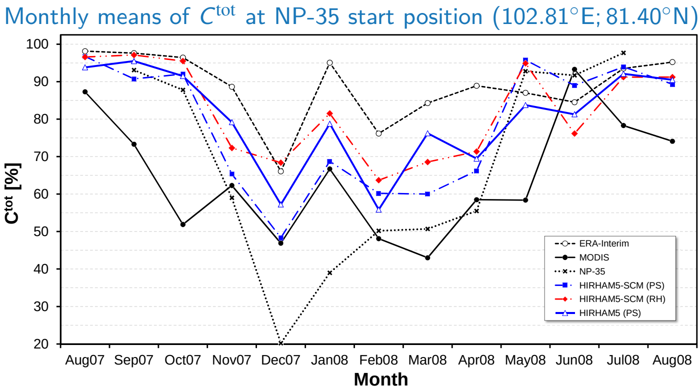

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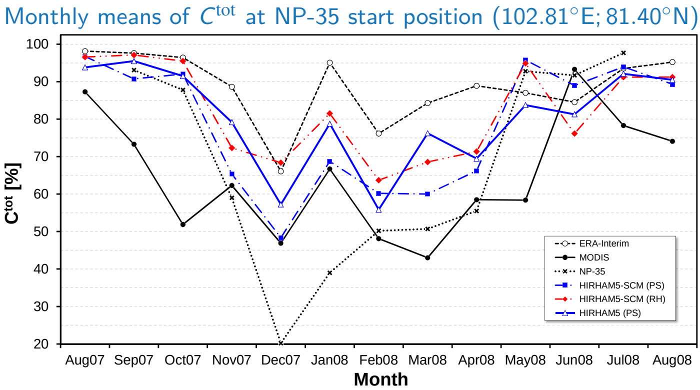

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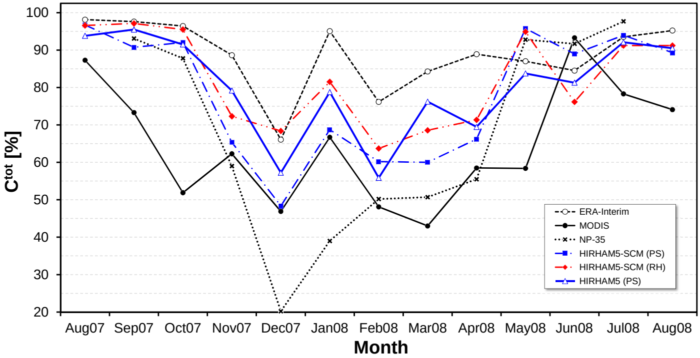
- Best (worst) agreement between MODIS and HIRHAM5-SCM(PS) (ERA-Interim) but systematic overestimation of cloudiness regardless of whether model or reanalysis

Modeled vs. observed total cloud cover

Monthly means of C^{tot} at NP-35 start position (102.81°E; 81.40°N)



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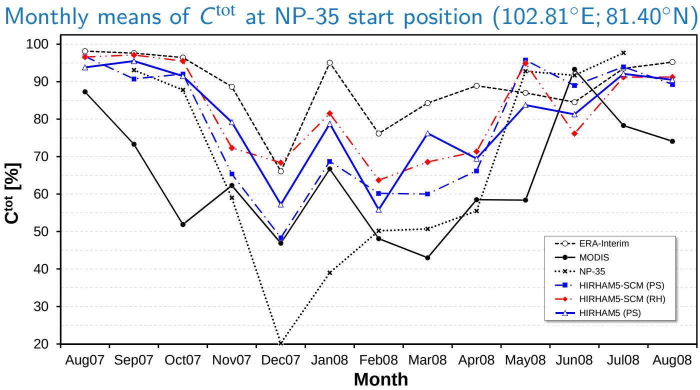

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Parameter sensitivity studies

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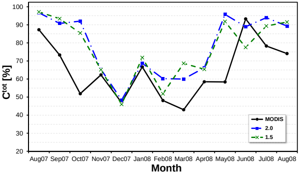
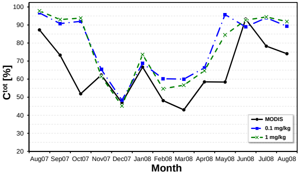
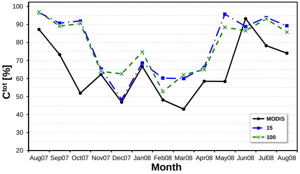


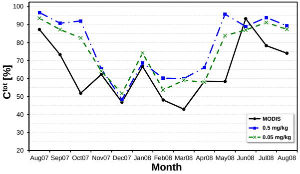
(a) Lower $\tilde{q}_0$ ($\tilde{q}_0^{def} = 2$)



(b) Higher CW_{min} ($CW_{min}^{def} = 0.1\,mg\,kg^{-1}$)



(c) Higher γ_1 ($\gamma_1^{def} = 15$)



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Suitable tuning parameters

$\tilde{q}_0$ – Shape parameter threshold

Controls the shape of the symmetric beta distribution acting as probability density function (PDF)

CW_{min} – Cloud water threshold

Avoids negative cloud water/ice contents and controls the occurrence of clear-sky conditions in the PS-Scheme

γ_1 – Autoconversion rate

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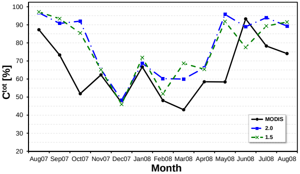

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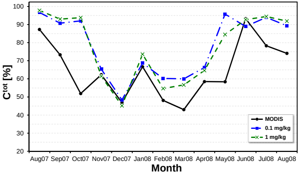

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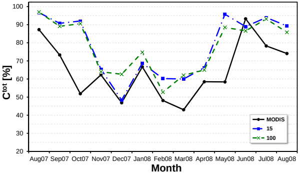

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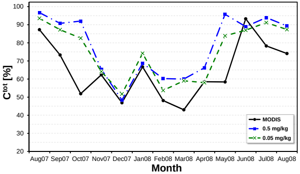

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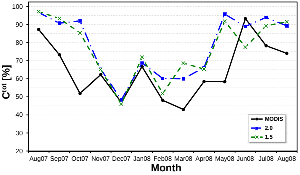

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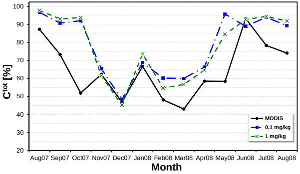

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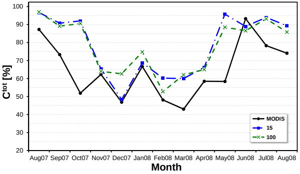

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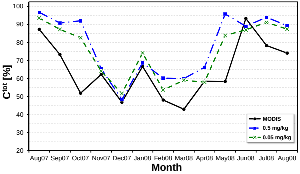

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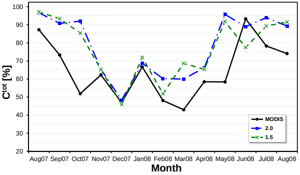

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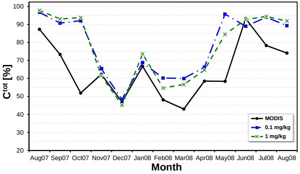

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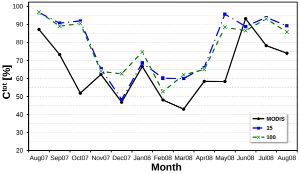

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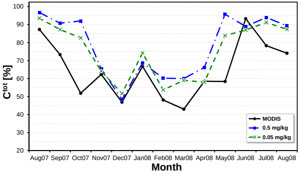

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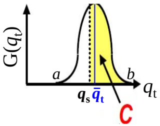
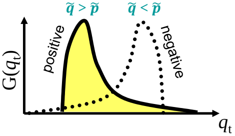
Modification of the PS-Scheme

Default formulation

- Tompkins (2002)
- $\tilde{p} = \tilde{q}_0 = 2$ $(\tilde{q} \geq \tilde{p})$
- positively skewed or symmetrical $\mathrm{G}(q_\mathrm{t})$





Changed formulation

- Tompkins' idea
- $\tilde{p} = \mathrm{F}(\tilde{q}) = \frac{\tilde{q}+1}{\tilde{q}-1}$
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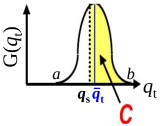

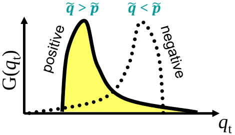

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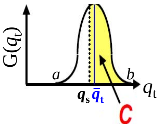

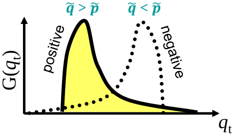

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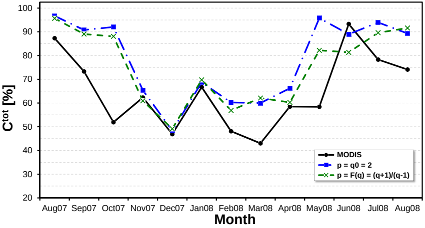

(e) Permit negative skewness, i. e. $\tilde{p} = F(\tilde{q})$

- Reduction of clouds through the introduction of negatively skewed beta distributions is of the same order of magnitude as for lower γ_{thr}

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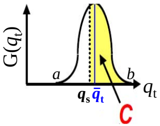

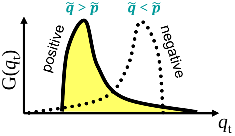

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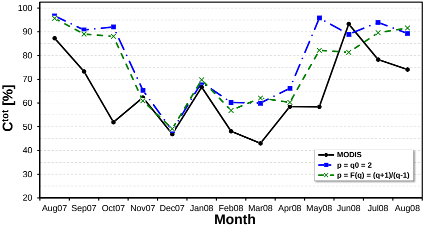

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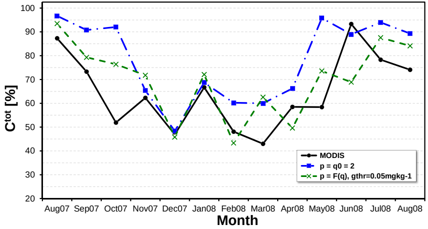

(f) Lower γ_{thr} and negative skewness

- Reduction of clouds through the introduction of negatively skewed beta distributions is of the same order of magnitude as for lower γ_{thr}

- Combined effect of lower γ_{thr} and permitted negatively skewed $G(q_t)$ can be used to adapt the PS-Scheme to Arctic climate conditions

Used observational PBL height datasets

HIRHAM5

- Atmospheric RCM (control run → ctrl)
- pan-Arctic integration domain ($>$ 53.5°N)
- 0.25° × 0.25° horizontal resolution
- 01/01/1979 – 12/31/2011 (33 yrs)

ERA-Interim

- Most recent ECMWF reanalysis
- Global coverage from 90°S to 90°N
- 0.75° × 0.75° horizontal resolution
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GPS-RO

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HIRHAM5 vs. ERA-Interim	→	Jun 2006 – Dec 2011
HIRHAM5 vs. GPS-RO	→	Jan 2007 – Dec 2009
HIRHAM5clr vs. CALIOP	→	Jun 2006 – Dec 2011

- HIRHAM5clr considers only PBL heights associated with $C^{tot} < 10\,\%$

Used observational PBL height datasets

HIRHAM5

- Atmospheric RCM (control run → ctrl)
- pan-Arctic integration domain ($> 53.5°$N)
- $0.25° \times 0.25°$ horizontal resolution
- 01/01/1979 – 12/31/2011 (33 yrs)

ERA-Interim

- Most recent ECMWF reanalysis
- Global coverage from 90°S to 90°N
- $0.75° \times 0.75°$ horizontal resolution
- 01/01/1979 – 12/31/2011 (33 yrs)

GPS-RO

- Global Positioning System - Radio Occultation
- Detects PBL heights under all-sky conditions
- Dataset provided by F. Xie
- Global coverage from 88°S to 88°N
- $5° \times 4°$ horizontal resolution
- 01/01/2007 – 12/31/2009 (3 yrs)

CALIOP

- Cloud-Aerosol Lidar with Orthogonal Polarisation
- Detects PBL height under clear-sky conditions
- Dataset provided by E. McGrath-Spangler
- Global coverage from 82°S to 82°N
- $1.25° \times 1.25°$ horizontal resolution
- 06/13/2006 – 12/31/2011 (5 1/2 yrs)

- Interpolation of observational datasets on rotated HIRHAM5 grid
- Comparison of multi-year seasonal mean PBL heights
  - HIRHAM5 vs. ERA-Interim → Jun 2006 – Dec 2011
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Calculation of PBL height in HIRHAM5

a) Dynamical height (Ekman layer height)

$$h_{\mathrm{dyn}} = C \cdot \frac{u_\star}{f}$$

$C = 0.3$	$\rightarrow$	Dimensionless parameter
$u_\star = \sqrt{\tau_0/\rho}$	$\rightarrow$	Friction velocity as defined by Charnock (1955), where τ_0 = surface drag and ρ = density of air
f	$\rightarrow$	Coriolis parameter

First model level above h_{dyn} defines level number of dynamical PBL height $h_{\mathrm{PBL,d}}$

b) Dry convective level (Using dry static energy)

$$s = c_{\mathrm{pd}}(1 + (\delta - 1)q) \cdot T + g \cdot z = c_{\mathrm{p}} \cdot T + \Phi$$

$\delta = c_{\mathrm{pv}}/c_{\mathrm{pd}}$	$\rightarrow$	Ratio of specific heat capacities for water vapor and dry air
q, T	$\rightarrow$	Specific humidity and air temperature
$\Phi = g \cdot z$	$\rightarrow$	Geopotential

First model level where s exceeds value of the lowermost model level defines level number of convective PBL height $h_{\mathrm{PBL,c}}$

PBL height is then calculated in 3 steps

$$h_{\mathrm{PBL}} = \mathrm{MIN}(h_{\mathrm{PBL,d}}, h_{\mathrm{PBL,c}})$$

$$\Phi_{\mathrm{PBL}} = \mathrm{MIN}(50,000\,\mathrm{m^2 s^{-2}}, \Phi(h_{\mathrm{PBL}}))$$

$$H_{\mathrm{PBL}} = \Phi_{\mathrm{PBL}}/g_{\mathrm{n}}$$

with standard gravity $g_{\mathrm{n}} = 9.80665\,\mathrm{m\,s^{-2}}$

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Definition of PBL height in observational datasets

ERA-Interim

- **Bulk Richardson number-based approach**

$$\mathrm{Ri_B} = \frac{\text{buoyancy production/consumption}}{\text{shear production}} = \frac{g}{\bar{\theta}_\mathrm{v}} \frac{\Delta\bar{\theta}_\mathrm{v}\,\Delta z}{\left[(\overline{\Delta u})^2 + (\overline{\Delta v})^2\right]}$$

- turbulent flow if $\mathrm{Ri_B} < 0$, laminar flow if $\mathrm{Ri_B} > 0.25$
- PBL height is defined as level where $\mathrm{Ri_B}$ exceeds critical value of 0.25

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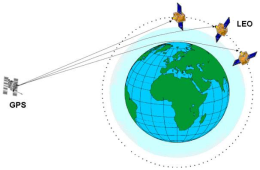
GPS-RO

- **Maximum refractivity gradient method**
  → described e.g. by Anthes et al. (2008)
- GPS receiver on a low Earth orbiting (LEO) satellite detects signal of GPS transmitter
- Vertical refractivity profile depends on temperature, pressure, water vapor pressure, and electron density: $N = N(T, p, e, n_e)$
- Level with maximum refractivity gradient defines PBL height



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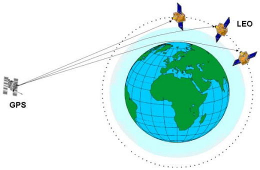

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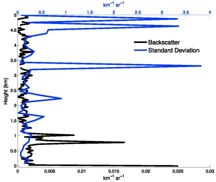
CALIOP

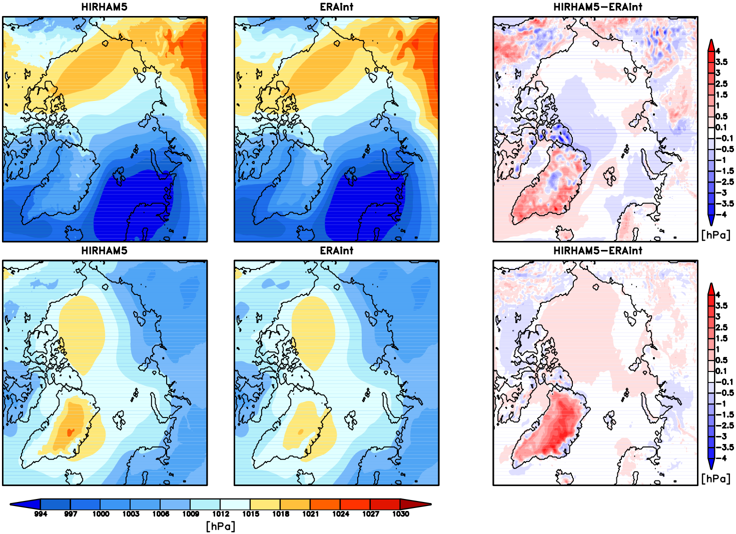
- **Maximum variance technique**
  → described e.g. by Jordan et al. (2010)
- Assumption that at the top of the PBL there exists a maximum in the vertical standard deviation of Lidar backscatter (Melfi et al., 1985)
- First level (lowest altitude) of maximum in standard deviation and backscatter defines PBL height



McGrath-Spangler and Denning (2012)

General performance of HIRHAM5

Mean sea level pressure (top = Jan2007 and bottom = Jul2007)



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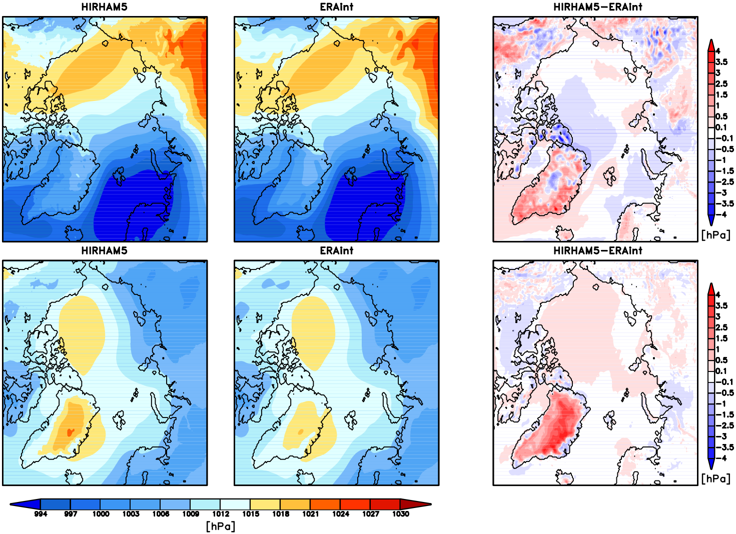

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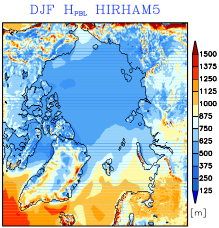
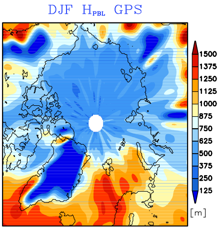
Shortcomings in satellite PBL heights over land

Arctic PBL heights during winter





GPS-RO

- Unrealistic behavior over (high) orography
- Reason: Algorithm of Xie et al. (2012)
- Only RO profiles that penetrate 500 m (above mean sea level) have been used for computing PBL heights
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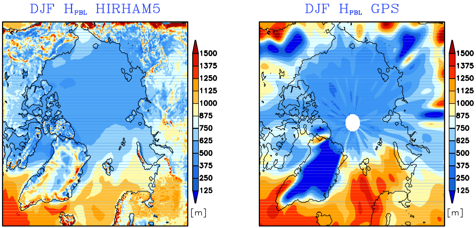

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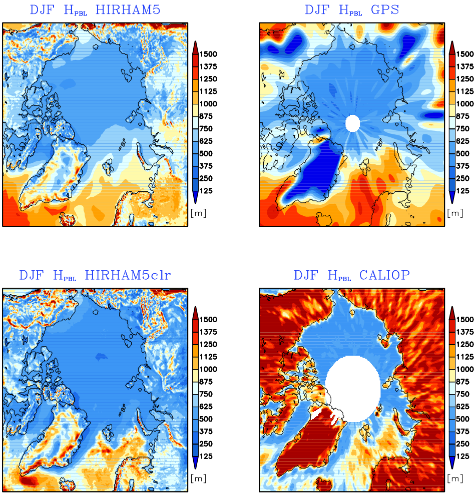

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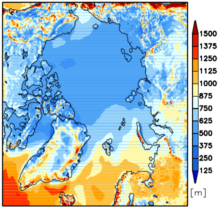
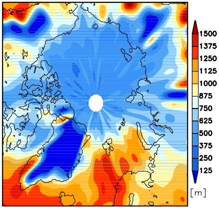
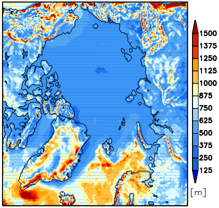


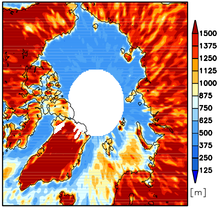
DJF H_{PBL} GPS



DJF H_{PBL} HIRHAM5clr



DJF H_{PBL} CALIOP



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Evaluation of simulated PBL heights I

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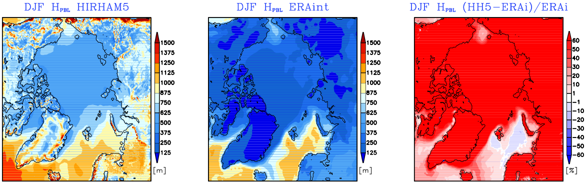

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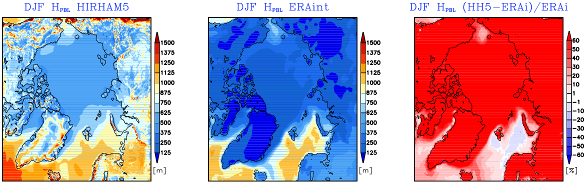

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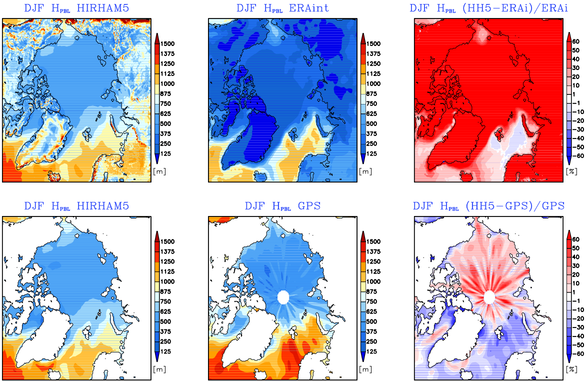

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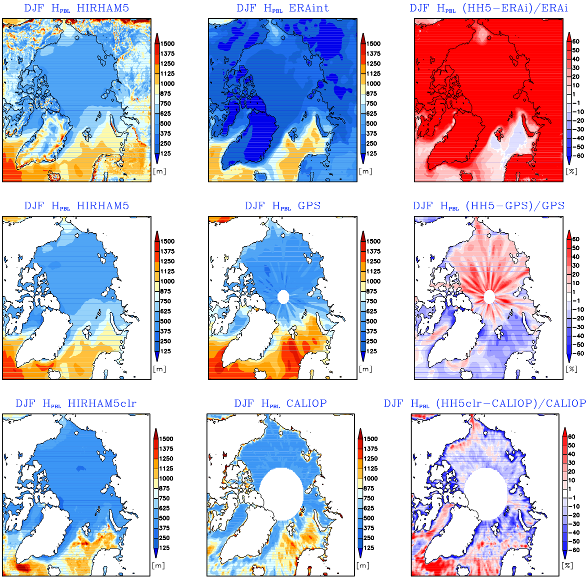

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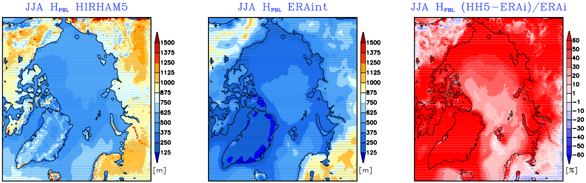
- Spatial patterns agree except for North Atlantic and along seashores
- Tendency to HIRHAM5 positive bias over North Atlantic, Greenland and Barents Sea but negative bias otherwise

Evaluation of simulated PBL heights II

Arctic PBL heights during summer



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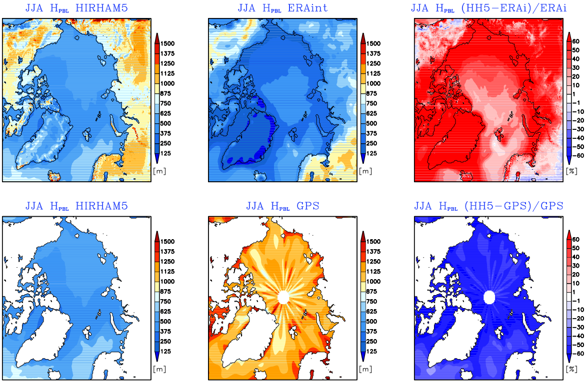

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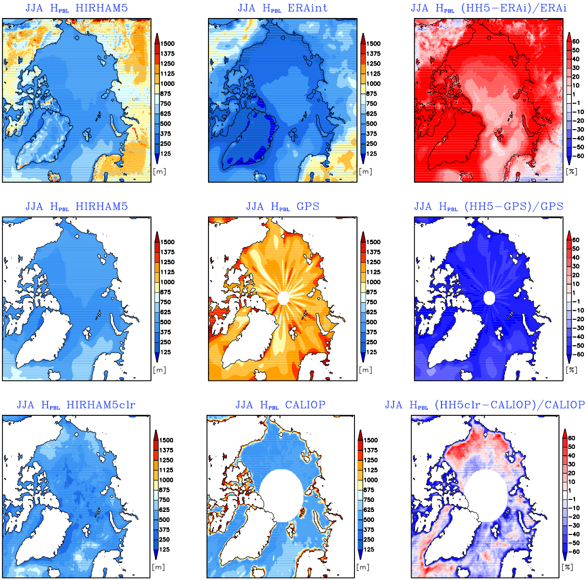

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Summary/Outlook

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- PS-Scheme performs better than RH-Scheme but systematic overestimation of C^{tot}
- Combined effect of lower γ_{thr} and permitted negative skewness of $\mathrm{G}(q_{\mathrm{t}})$ significantly reduces biases relative to MODIS
- HIRHAM5, ERA-Interim, and CALIOP show same annual cycle of H_{PBL} but GPS-RO seems to be biased in JJA and SON
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Outlook

- **Comparison of HIRHAM5 model variables with (satellite) observations**
  - i) More detailed investigation of simulated Arctic PBL heights (Monthly means, Scatter plots)
  - ii) Validation of cloud variables (C, C^{tot}, LWP, IWP, CRF)
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  - i) More detailed investigation of simulated Arctic PBL heights (Monthly means, Scatter plots)
  - ii) Validation of cloud variables (C, C^{tot}, LWP, IWP, CRF)
    → Prepared gridded datasets are welcome
- **Sensitivity run with HIRHAM5 (2006 – 2011)**
  - i) Use $\gamma_{\mathrm{thr}} = 0.05\,\mathrm{mg/kg}$ and permitting negative skewness of $\mathrm{G}(q_{\mathrm{t}})$
  - ii) Comparison of control (HIRHAM5ctrl) and sensitivity (HIRHAM5sens) simulations
    → Also improved performance in the 3D model version?

Summary/Outlook

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- PS-Scheme performs better than RH-Scheme but systematic overestimation of C^{tot}
- Combined effect of lower γ_{thr} and permitted negative skewness of $\mathrm{G}(q_{\mathrm{t}})$ significantly reduces biases relative to MODIS
- HIRHAM5, ERA-Interim, and CALIOP show same annual cycle of H_{PBL} but GPS-RO seems to be biased in JJA and SON
- Found low bias of ERA-Interim H_{PBL} consistent with e.g. von Engeln and Teixeira (2011) and Xie et al. (2012)
- In part contrary patterns of relative differences between HIRHAM5 and GPS-RO (CALIOP)

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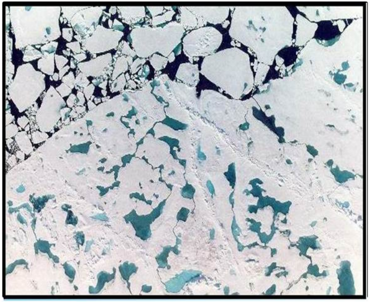
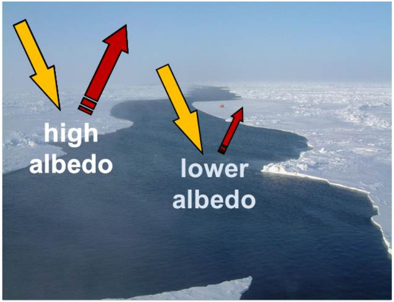
Snow/Ice Albedo Feedback





temperature increase → melting ice and snow → open water forms → reduced solar reflection → temperature increase

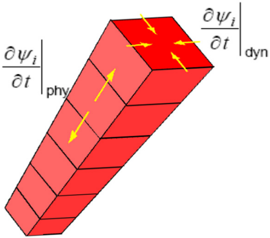
Feedback +

water vapor – cloud feedback changes

A2: Use of dynamical tendencies in HIRHAM5-SCM

Dynamical tendencies from ERA-Interim

- dynamical tendencies of $\psi_i = T, q, u, v$ as dynamical forcing
- ERA-Interim provides:
  - ❶ 3-hourly total tendency of ψ_i
  - ❷ 3-hourly physical tendency from forecast run
- Problem: accumulated data and 12-hourly reinitialization



$$\left.\frac{\partial \psi_i}{\partial t}\right|_{\text{phy,ERA3h}} = \left.\frac{\partial \psi_i}{\partial t}\right|_{step+3h} - \left.\frac{\partial \psi_i}{\partial t}\right|_{step}$$

$$\left.\frac{\partial \psi_i}{\partial t}\right|_{\text{dyn}} = \left.\frac{\partial \psi_i}{\partial t}\right|_{\text{tot,ERA3h}} - \left.\frac{\partial \psi_i}{\partial t}\right|_{\text{phy,ERA3h}}$$

$$\boxed{\left.\frac{\partial \psi_i}{\partial t}\right|_{\text{tot}} = \left.\frac{\partial \psi_i}{\partial t}\right|_{\text{dyn}} + \left.\frac{\partial \psi_i}{\partial t}\right|_{\text{phy}}}$$

→ **Linear interpolation** of 3-hourly dynamical tendencies

↳ available at every time step

A3: Parameterization of stratiform clouds

Fractional cloud cover C

- parameterization consists of three components:
  - [1] prognostic equations for the vapor (q), liquid (q_l), and ice (q_i) phase
  - [2] cloud microphysics according to *Lohmann and Roeckner (1996)*, which considers water phase changes and precipitation processes
  - [3] selectable cloud cover scheme …

Relative Humidity Scheme

(RH-Scheme; *Sundquist et al., 1989*)

- diagnostic relation to the grid box mean of relative humidity ($\overline{RH}$)

$$C = 1 - \sqrt{\frac{1 - \overline{RH}}{1 - RH_{\text{crit}}}}$$

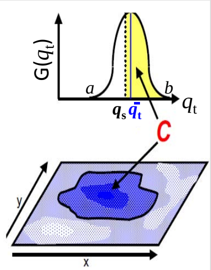
- RH_{crit} is the critical threshold according to *Lohmann et al. (1999)*, controlling the onset of cloud formation

Prognostic Statistical Scheme

(PS-Scheme; *Tompkins, 2002*)

- subgrid-scale variability of total water content $q_t = q + q_l + q_i$ is explicitly specified by the beta distribution G(q_t) acting as PDF
- Integral over the supersaturation range ($q_t > q_s$) below G(q_t) yields

$$C = \int_{q_s}^{b} G(q_t)\,dq_t$$



Total cloud cover C^{tot}

- computed by use of the Maximum-Random Overlap Assumption

A4: Modified tuning parameters I

Parameter	Default	Co-domain	Description (Meaning)
$\tilde{q}_0$	2	$1.00001 \leq \tilde{q}_0 \leq 20$	determines the shape of the symmetric beta distribution, which is used as PDF in the PS-Scheme
$\mathrm{CW_{min}}$	$0.1\,\mathrm{mg\,kg^{-1}}$	$(0 \leq \mathrm{CW_{min}} \leq 750)\,\mathrm{mg\,kg^{-1}}$	avoids negative cloud water and ice contents and additionally controls the occurrence of clear-sky conditions in the PS-Scheme
γ_1	15	$0 \leq \gamma_1 \leq 500$	determines the efficiency of rain drop formation by collision and coalescence of cloud drops (autoconversion rate)
γ_{thr}	$0.5\,\mathrm{mg\,kg^{-1}}$	$(0 \leq \gamma_{\mathrm{thr}} \leq 5)\,\mathrm{mg\,kg^{-1}}$	cloud ice threshold, which determines the efficiency of the Bergeron-Findeisen process

$\tilde{q}_0$

where C_s is a tunable constant. Since the mixing will also reduce the skewness of the distribution, tending toward a symmetric one, the same relaxation is applied to the skewness parameter q

$$\left(\frac{\partial q}{\partial t}\right)_{diss} = (q_0 - q)\left(\tau_v^{-1} + \tau_h^{-1}\right) \qquad (10.22)$$

where q_0 defines the shape of the final distribution.

A5: Modified tuning parameters II

CW_{min}

This parameter is not mentioned by Roeckner et al. (2003).

γ_1

$$Q_{aut} = C\gamma_1 \left[a_2 n^{-b_2} \left(10^{-6} N_l\right)^{-b_3} \left(10^{-3} \rho r_l\right)^{b_4} \right] / \rho \tag{10.45}$$

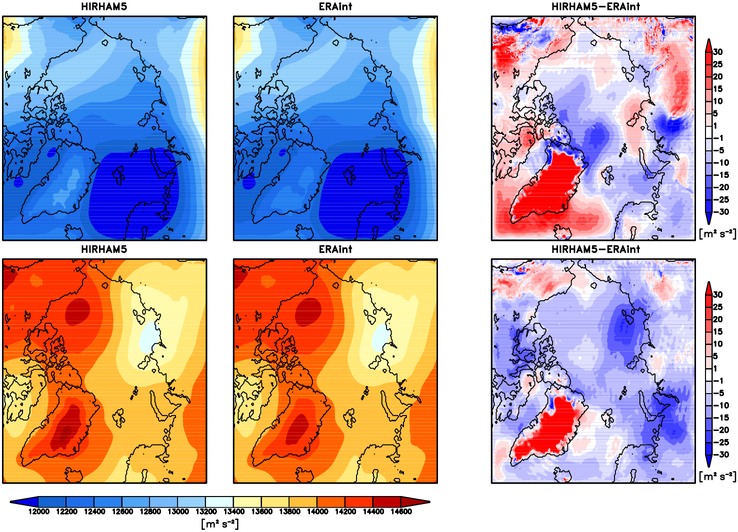
where $a_2 = 6 \cdot 10^{28}$, $n = 10$ is the width parameter of the initial droplet spectrum described by a gamma distribution, $b_2 = 1.7$, $b_3 = 3.3$, $b_4 = 4.7$, and γ_1 is a tunable parameter which determines the efficiency of the autoconversion process and, hence, cloud lifetime.

γ_{thr}

models and cannot be applied to large-scale models without adjustment. The parameter γ_{thr} is a cloud ice threshold which decides on either condensational growth of supercooled cloud droplets or depositional growth of ice crystals (see (10.34) and (10.35)). The following values are used in ECHAM5: $\gamma_1 = 15$; $0 \leq \gamma_2 \leq 0.5$ depending on model resolution; $\gamma_3 = 95$; $\gamma_4 = 0.1$; $\gamma_{thr} = 5 \cdot 10^{-7}$ kgkg^{-1}.

A6: General performance of HIRHAM5 II

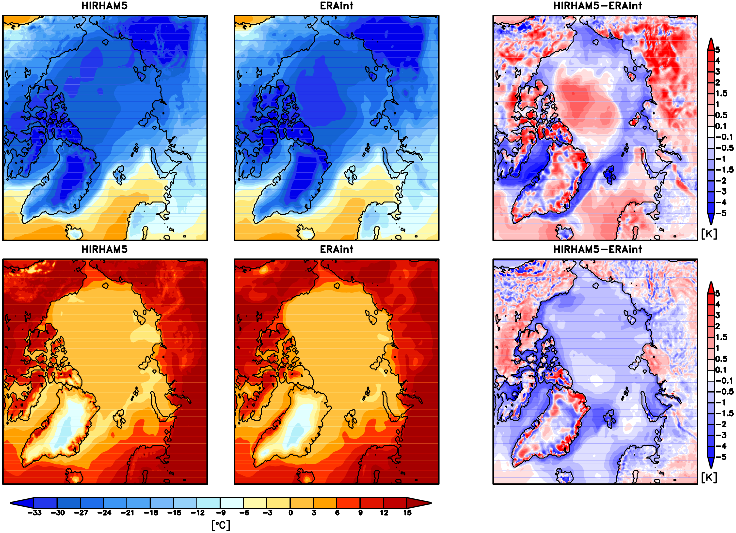
850 hPa Geopotential (top = Jan2007 and bottom = Jul2007)



- Spatial patterns of the geopotential agree well between HIRHAM5 and ERA-Interim

A7: General performance of HIRHAM5 III

2m air temperature (top = Jan2007 and bottom = Jul2007)



- HIRHAM5 and ERA-Interim 2m temperatures differ in part significantly