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Revised snow scheme in the ECMWF land surface model: Offline validation and impacts on EC-EARTH

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Motivation

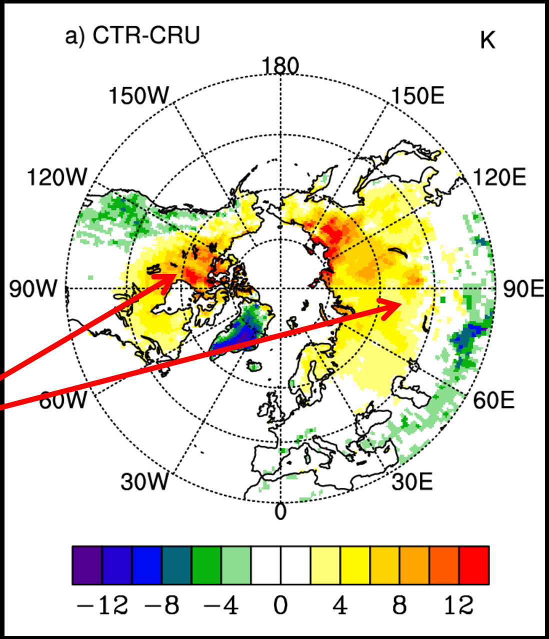
Why is snow important ? weather forecast and Climate modeling

- **Surface characteristics :** changes in the surface albedo, roughness etc.…
- **Processes/feedbacks :** Snow albedo feedback (Chess et al 1991, Science, etc…)
  Impact N. Hemisphere circulation (Gong et al, 2007 G.P.C, etc…)
  Indian summer Monsoon (Robock et al 2003 JGR, etc...)

- **Weather forecast** : errors in the "physics" are attenuated by data assimilation;
- **Climate modeling** : assimilation is not an option;

•Local site simulations (offline) and climate (coupled) runs pointed some deficiencies in the ECMWF land surface scheme (HTESSEL) .

•Is the snow scheme responsible for the warm bias over snow-covered regions ?

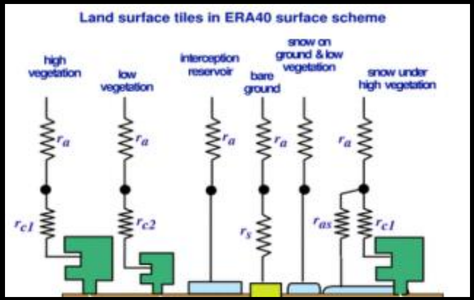


Winter 2 meter temperature biases in the ECMWF model in climate mode (EC-EARTH)

HTESSEL and NEW snow scheme

HTESSEL (**H**ydrology - **T**iled **E**CMWF **S**cheme of **S**urface **E**xchanges over **L**and

Balsamo et al. 2009 J.H



- Up to 5 surface tiles (bare ground, low and high vegetation, interception,) + ocean and sea ice (binary land sea mask);
- **Two tiles for snow**:
  - **exposed snow;**
  - **shaded snow (under high vegetation).**

	CTR	**OPER** (Dutra et al. 2010 J.H)
Liquid water	1-Dry snow 2-Rainfall bypass the snowpack	1-Diagnosed from snow mass and temperature 2-Interception of rainfall 3-Changed snow energy and mass balance
Snow Density	1-Empirical exponential increase 2-Snowfall density constant=100 kg.m^{-3}	1-Physically based (Anderson, 1976) 2- Snowfall density : function of temperature and wind speed
Snow Albedo	1- Exponential(melting) / Linear decay 2- Reset to max (0.85) snowfall > 1 mm hr^{-1} 3- Shaded: constant = 0.15	1- Exponential (when liquid water is present) / Linear decay; 2- Continuous reset to max depending on the amount of snowfall (10 mm to full reset) 3-Shaded : vegetation type dependent (Moody et al. 2007)
Snow fraction	1-Function of snow mass 2- Threshold (SC=1) : 15 mm	1-Function of snow mass and density 2- Threshold (SC=1): 10 cm (10 mm -> 40 mm)

Simulations setup and validation

Increasing computational cost

1) Offline - local sites (HTESSEL)

- SnowMip2 (5 sites x 2 seasons - Rutter et al. 2009 JGR)

Process validation

2) Offline - global (HTESSEL)

- GSWP2 (1°x1° 1986-1995)
- ERA-Interim (0.7° 1989-present)

Global validation (only land surface)

3) Operational runs (IFS: TL255)

- Extended data assimilation
- Hindcasts : 1 year climate runs

Short range forecast

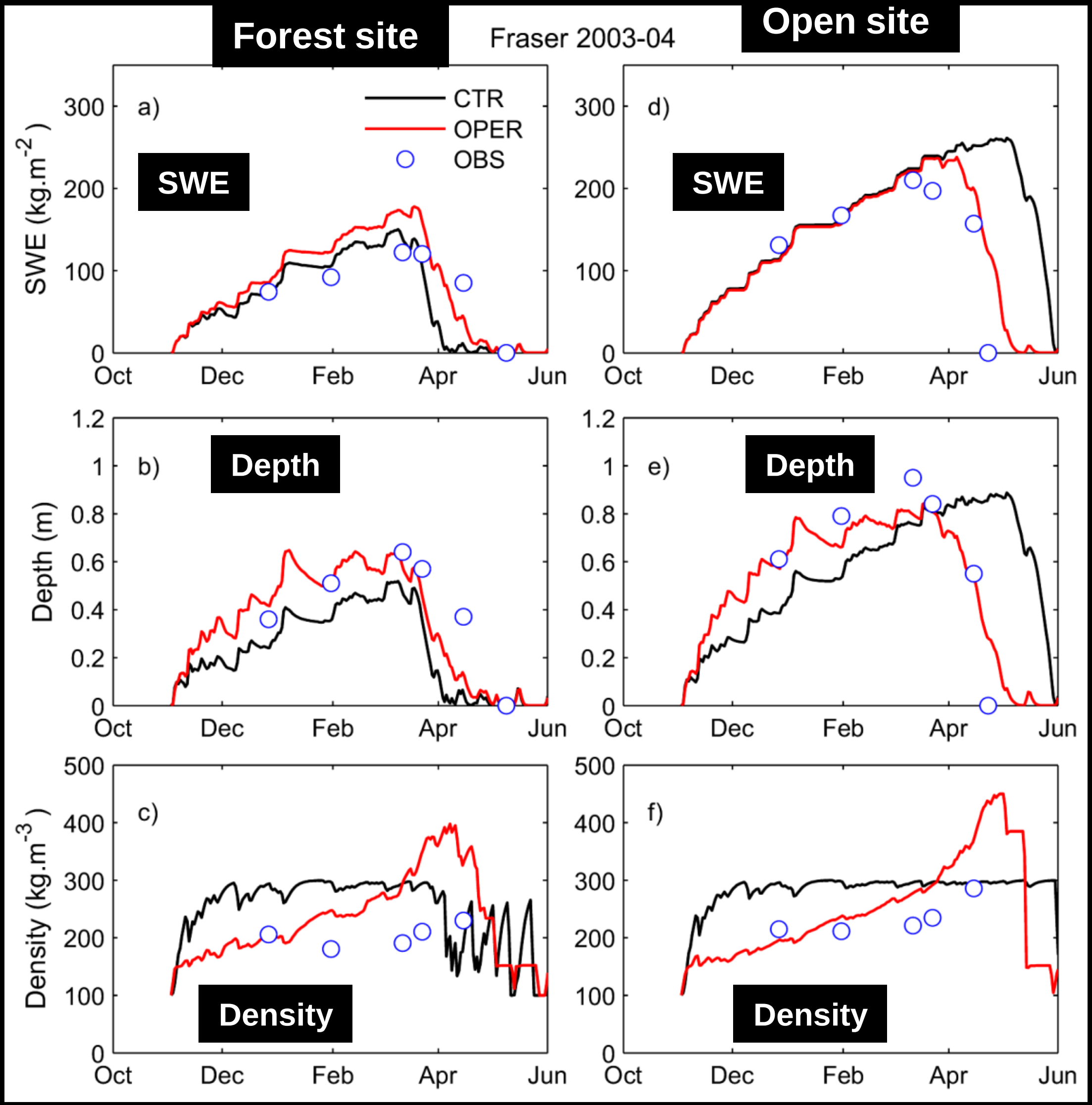
4) Climate runs (EC-EARTH TL159)

- Atmosphere only
  - SSTs and sea ice from observations
  - 30 years run (1979-2008) 3 member ensemble
- Coupled ocean (not shown)

Feedbacks

Snowmip2 (site) simulations

Fraser (Colorado USA)



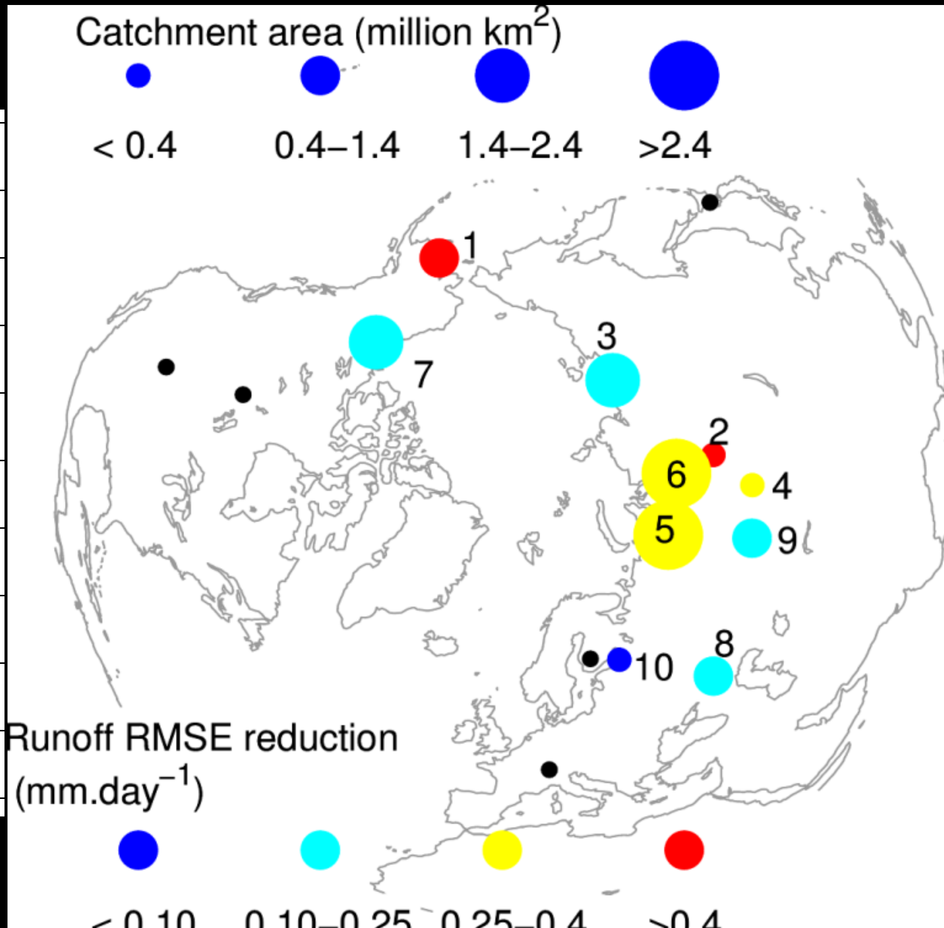
- Early melting in forest sites
  - 21* days –CTR, 13* days OPER
- Late melting in open sites
  - 10* days – CTR, 2* days OPER

*Averaged SnowMip2 sites (5 sites x 2 seasons)

- Snow density:
  - Exponential increase in CTR
  - Closer to observations in NEW

Basin scale validation

1-Yukon
2-Podka. [a]
3-Lena
4-Tom
5-Ob
6-Yenisei
7-Mackenzie
8-Volga
9-Irtish
10-Neva



- **Reduced snow density**
- **Increased snow insulation**
  - Less soil cooling;
  - Less soil freezing;
  - Increased water infiltration;
  - **Reduction of surface runoff**
  - **Increased bottom drainage (lagged in time);**
  - **Improved timing of late Spring/Summer runoff**
  - **Increased soil water storage**

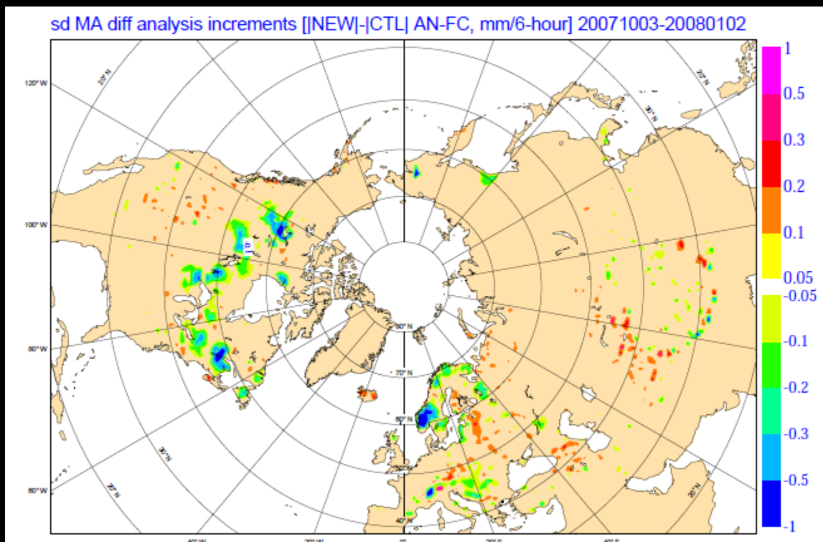
Average RMSE of runoff mm day^{-1}
CTR:0.75
OPER:0.51 (reduction of 32%)

BSWB (runoff data): Hirschi et al. 2006, J.H

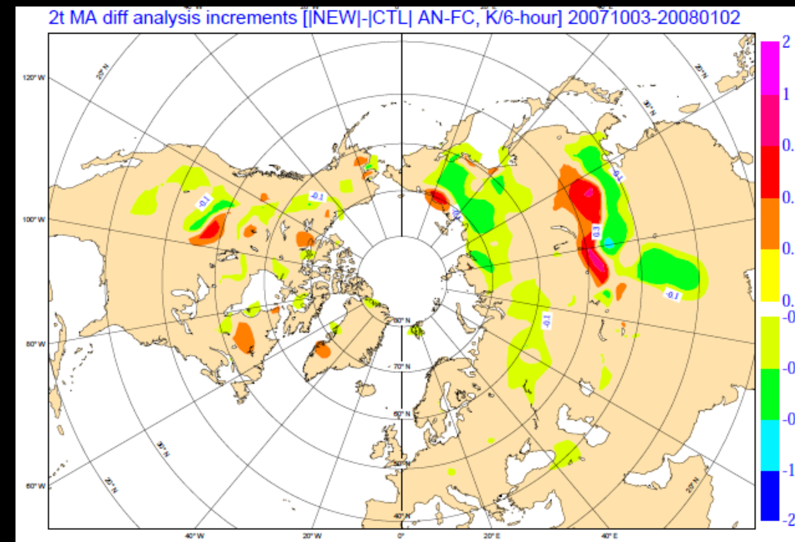
Global offline GSWP2 (1°x1°, 1986-1995)

Extended data assimilation

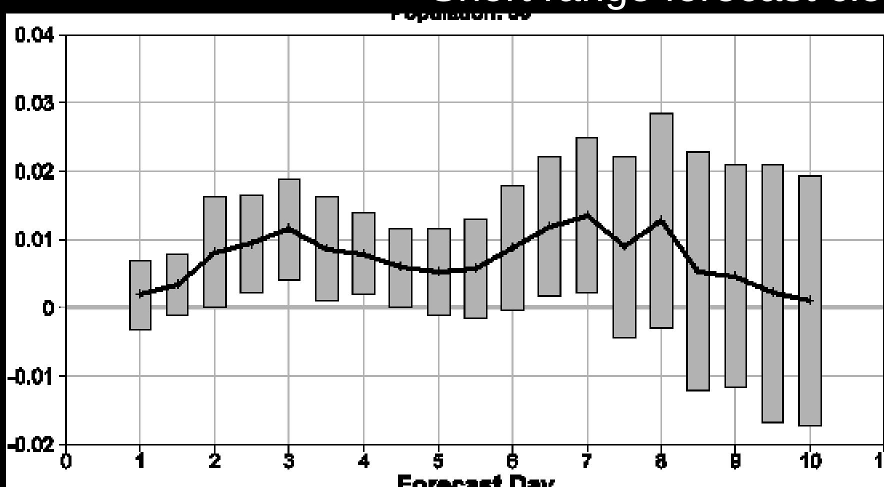
Snow mass analysis increments: |OPER| - |CTR|



2 m temperature analysis increments: |OPER| - |CTR|



Cold colors == reduction of assimilation increments -> Short range forecast closer to observations



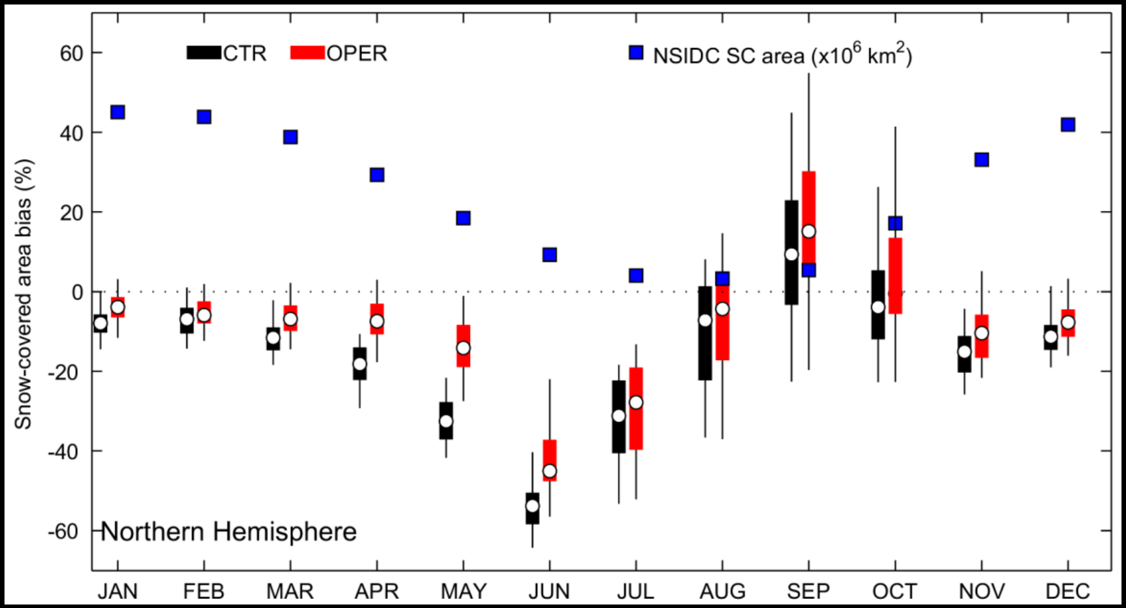
Root mean square error forecast (CTR-OPER)
N. Hemisphere 1000hPa Temperature 00UTC

Significant improvement of near surface temperature up to day 7/8 of forecast

Set of 4d-var experiments :01-10-2007 -> 30-04-2008 (TL255L91)

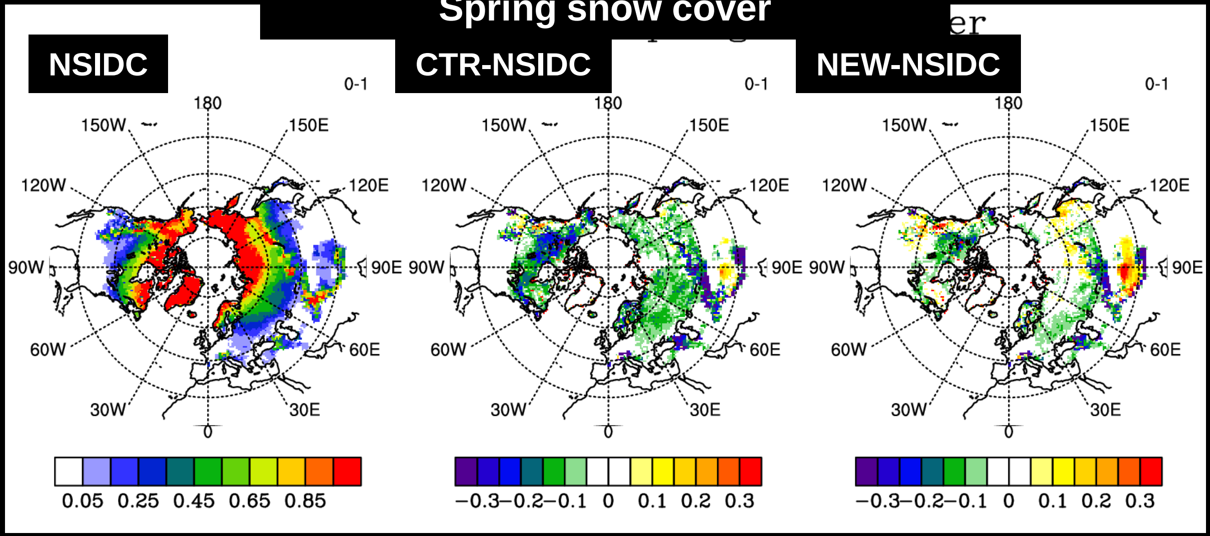
Impact on EC-EARTH (snow cover)

N. Hemisphere snow-covered area bias (% of snow-covered area NSIDC)



- CTR: under-estimation of snow-covered area from March- JUN
  - Early melting
- OPER:
  - Interception of rainfall on the snowpack
  - Revised snow cover fraction
  - Revised snow albedo
  - **Significant improvement of spring snow ablation**

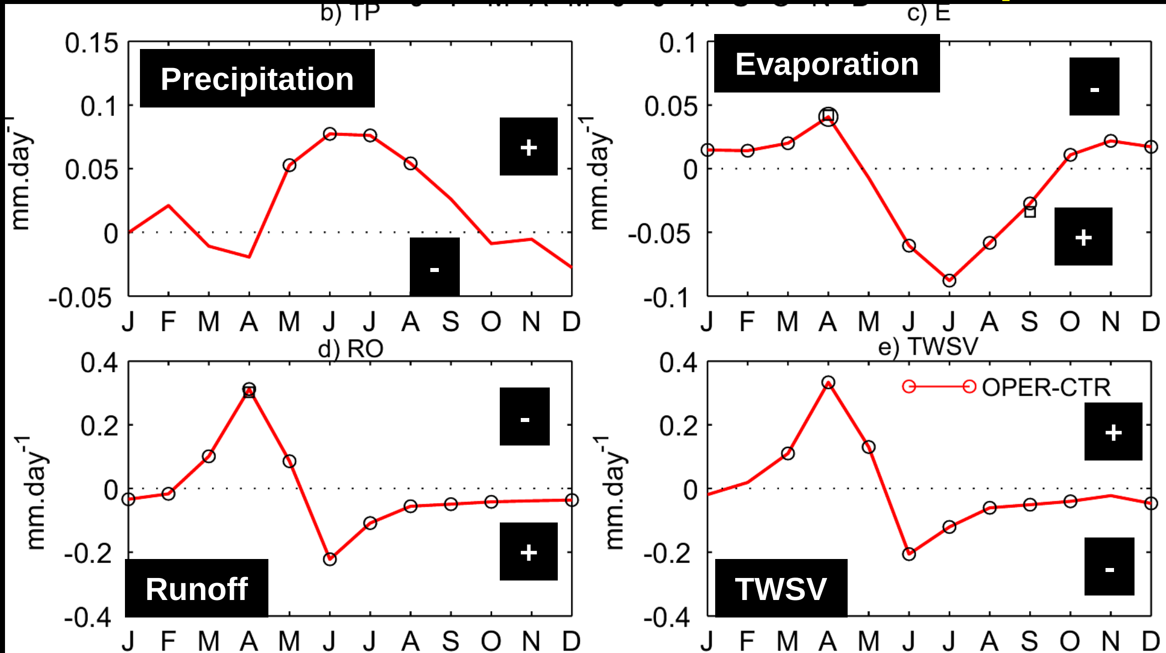
Spring snow cover



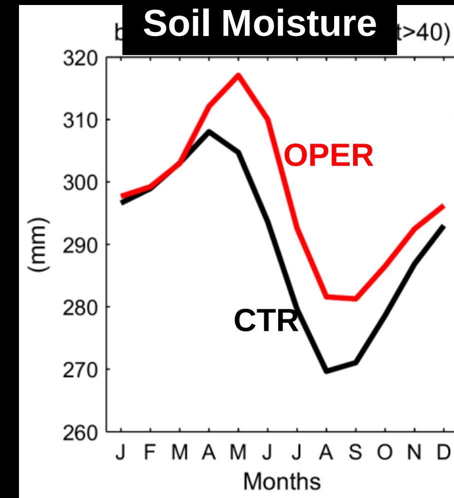
Spring average Scover bias :
-CTR :-9.6 %
-OPER :-5.4 % (reduction of 43 %)

3x 30 yrs (1979-2008) EC-EARTH (atmosphere only with prescribed SSTs and sea ice)

Impact on EC-EARTH (water cycle)



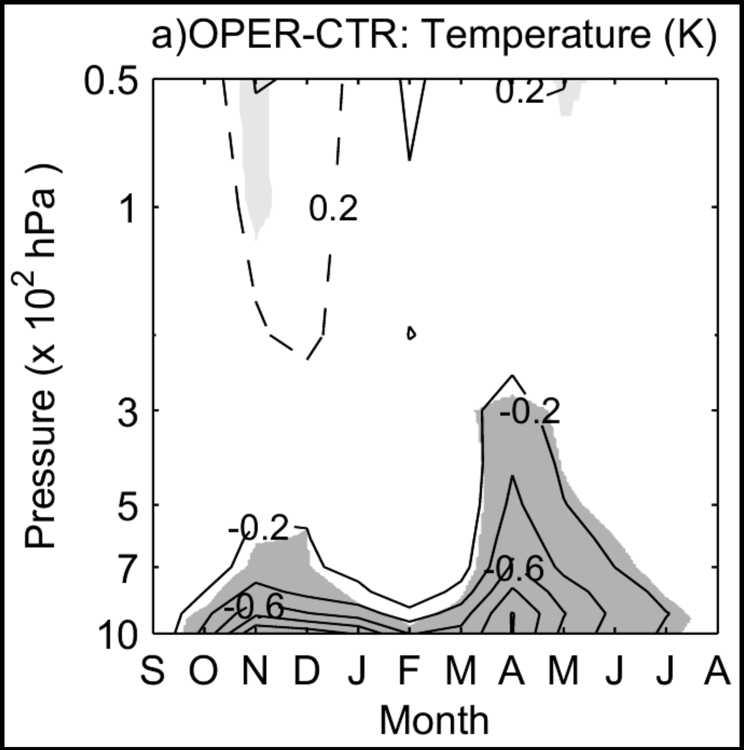
Averages over Eurasia land masses poleward 40° N.
Differences between OPER-CTR (symbols significant at 95 %)

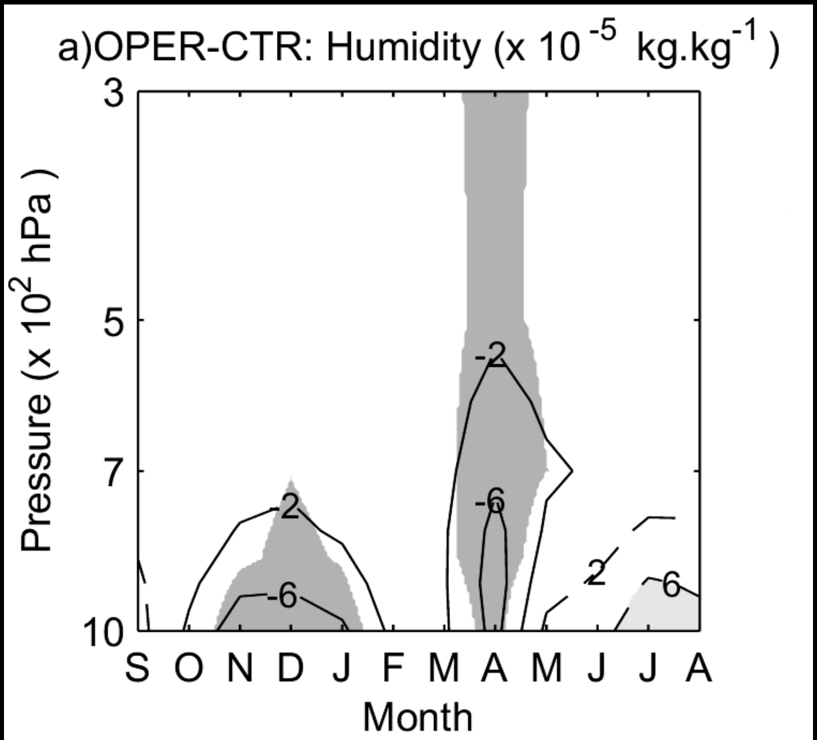


- Increased soil moisture (Spring- Summer)
  - Reduction of early runoff (increased soil water storage)
  - + Evaporation during summer (+ soil moisture available)
  - + Precipitation during summer (more available humidity)
    - Intensification of the soil moisture / Precipitation feedback

3x 30 yrs (1979-2008) EC-EARTH (atmosphere only with prescribed SSTs and sea ice)

Impact on EC-EARTH (upper air)





Averages over **N. Hemisphere** polar cap lat >40° N.

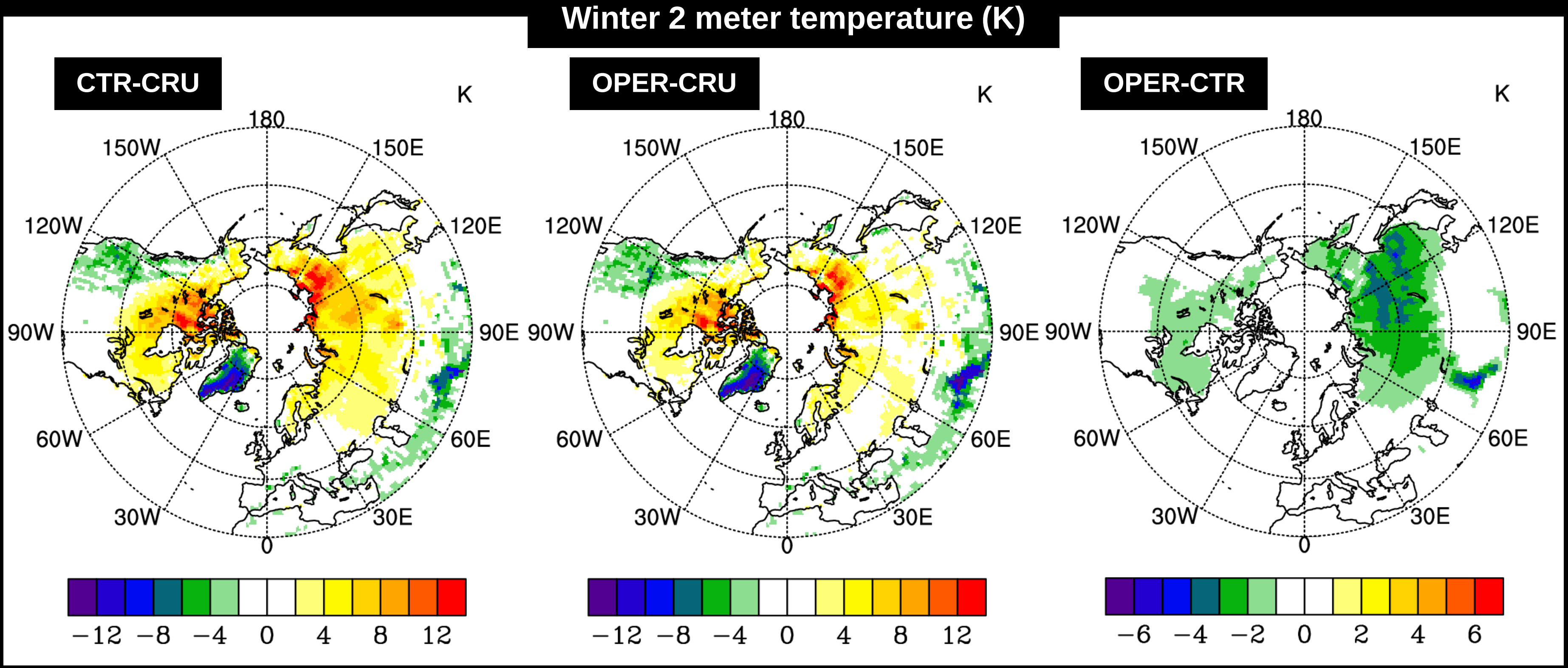
Differences between OPER-CTR (shaded: significant at 95% - dark gray OPER<CTR; light gray OPER>CTR

- Cooling of the troposphere up to 500 hPa during autumn/winter
- Cooling effect reaches 300 hPa during Spring
- Some warming in the top of the troposphere / stratosphere (not significant)

- Cooling of the troposphere + reduction of evaporation -> reduction of specific humidity
- Increased evaporation in summer -> increased humidity (restricted to the lower troposphere)

3x 30 yrs (1979-2008) EC-EARTH (atmosphere only with prescribed SSTs and sea ice)

Impact on EC-EARTH (Temperature)



CTR – Warm bias over snow-covered areas (reaching 12 K)

OPER– Significant reduction of the warm bias (cooling between 4 and 6 K)

Increased snow insulation in OPER

-> decoupling between the PBL and underlying surface.

Winter Mean Absolute Error (Eurasia land masses poleward 60°N):

CTR : **7.23 K**

OPER : **6.29 K** (reduction of 13%)

3x 30 yrs (1979-2008) EC-EARTH (atmosphere only with prescribed SSTs and sea ice)

Final remarks

- Revised OPER snow scheme improved local site simulations (late/early snow melt in open/forest sites);
- Increased snow insulation (due to reduced snow density) improved significantly the runoff on large scale basins;
- 4d-var assimilation tests showed a positive impact in both the assimilation and short range weather forecast;
- On climate EC-EARTH runs OPER:
  - Reduction of the early snow melting in the N. Hemisphere;
  - Intensification soil moisture/precipitation feedback (increased soil water storage in spring – summer);
  - Cooling of air temperature up to 500 hPa polar cap >40°N;
  - Reduction of the warm bias in 2-meter temperature over snow-covered regions (stronger decoupling between the PBL and underlying soil)
- The OPER snow scheme was introduced in the ECMWF operational weather forecast in September 2009 (CY35R3).

Thank you

Dutra, E., Balsamo, G., Viterbo, P., Miranda, P. M. A., Beljaars, A., Schär C., and Elder, K., 2010: An improved snow scheme for the ECMWF land surface model: description and offline validation**. J. Hydrometeorol**., doi:10.1175/2010JHM1249.1 (in press)

Also available as **ECMWF tech memo 607** (http://www.ecmwf.int/publications/library/do/references/show?id=89648)

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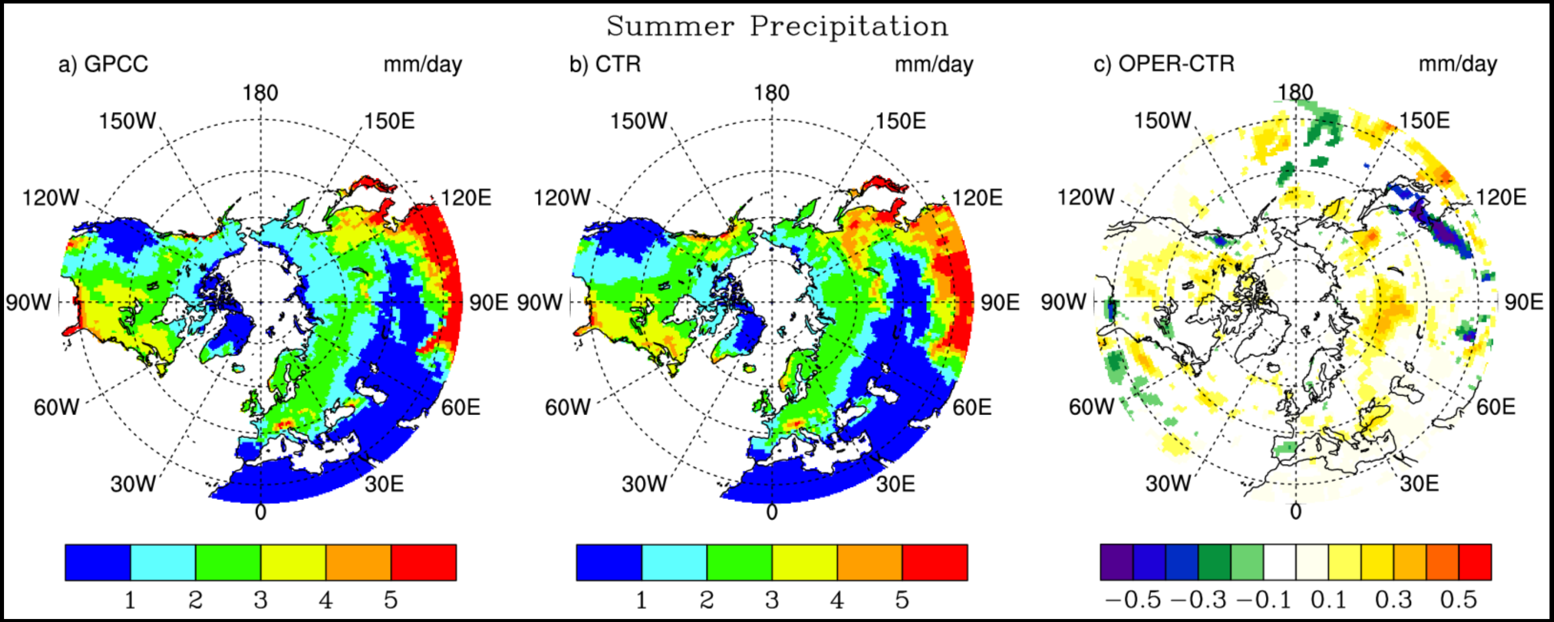
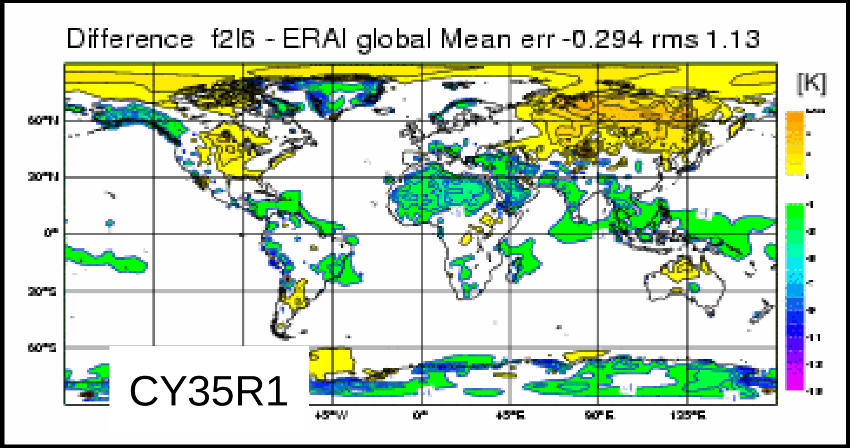
precip

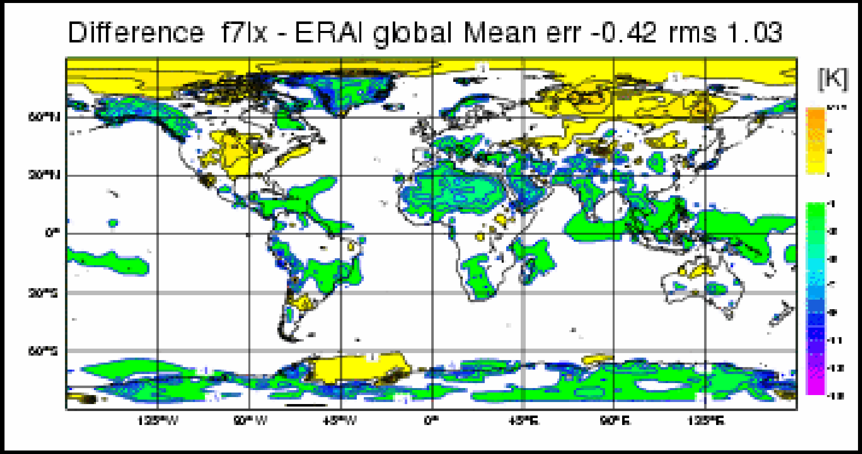


Summer Precipitation
a) GPCC
mm/day
b) CTR
mm/day
c) OPER-CTR
mm/day
180
150W
150E
120W
120E
90W
90E
60W
60E
30W
30E
0
1
2
3
4
5
−0.5
−0.3
−0.1
0.1
0.3
0.5

Hindcasts (1 year climate runs)

The annual mean T2m bias (13-month 4-member hindcasts) is reduced in snow-areas





CY35R3

New snow scheme: description

Snow energy balance

CTR

Dry Snow

$$(\rho C)_{sn} D_{sn} \frac{\partial T_{sn}}{\partial t} = R_{sn}^N - L_s E_{sn} - H_{sn} - G_{sn}^B - L_f M_{sn}$$

NEW Dutra et al. 2010 J.H

$$\left[(\rho C)_{sn} D_{sn} + L_f S_l^c \frac{\partial f(T_{sn})}{\partial T_{sn}}\right] \frac{\partial T_{sn}}{\partial t} = R_{sn}^N - L_s E_{sn} - H_{sn} - G_{sn}^B - L_f M_{sn}$$

Diagnostic of liquid water content from snow mass and temperature:

- Additional snow heat capacity / **heat capacity barrier**

Snow mass balance

$$\frac{\partial S}{\partial t} = F - c_{sn} E_{sn} - M_{sn}$$

Rainfall bypasses the snowpack

$$\frac{\partial S}{\partial t} = F + c_{sn} F_l - c_{sn} E_{sn} - R_{sn}$$

Interception of rainfall on the snowpack

Intercepted water can freeze (warm the snow)

Snow Density

Exponential increase (100-300 kg m^{-3})

$$\rho_{sn}^{t+1} = \left(\rho_{sn}^{*} - \rho_{sn_{max}}\right) \exp\left(-\tau_f \Delta t / \tau_1\right) + \rho_{sn_{max}}$$

Fresh snow (snowfall) density

cte =100 kg m^{-3}

$$\frac{1}{\rho_{sn}} \frac{\partial \rho_{sn}}{\partial t} = \frac{\sigma_{sn}}{\eta_{sn}(T_{sn}, \rho_{sn})} + \xi_{sn}(T_{sn}, \rho_{sn}) + \frac{\max\left(0, Q_{sn}^{INT}\right)}{L_f (S - S_l)}$$

Physically based (Anderson, 1976): Overburden, thermal metamorphism, Melting

Fresh snow (snowfall) density

$$\rho_{new} = a_{sn} + b_{sn}(T_{air} - T_f) + c_{sn}(V_a)^{1/2}$$

Boone and Etchevers 2001, J.H

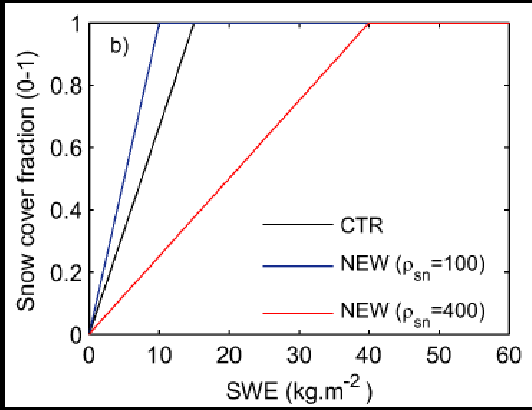
New snow scheme: description

Snow cover

CTR

$$c_{sn} = \min\left(1, \frac{S}{15}\right)$$

Only function of snow mass



NEW

$$c_{sn} = \min\left(1, \frac{S/\rho_{sn}}{0.1}\right)$$

Function of snow depth (snow mass and density)

Snow Albedo

Exposed areas

CTR:

- Linear decay
- **Exponential decay (Melting conditions)**
- Reset to max (0.85) **snowfall > 1 mm hr^{-1}**

NEW:

- Linear decay
- **Exponential decay (presence of liquid water)**
- **Continuous reset** to maximum (0.85)

Shaded snow (under high vegetation)

CTR:

Constant = 0.15

NEW:

- Vegetation type dependent based on MODIS data (Moody et al. 2007)

Index	Vegetation type	Albedo
3	Evergreen needle leaf trees	0.27
4	Deciduous needle leaf trees	0.33
5	Deciduous broad leaf trees	0.31
6	Evergreen broad leaf trees	0.38
18	Mixed forest / woodland	0.29
19	Interrupted forest	0.29