Snow modelling and cryosphere-atmosphere interactions

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ECMWF, Earth System Modelling Section

With contributions from many people in Research and Forecast departments

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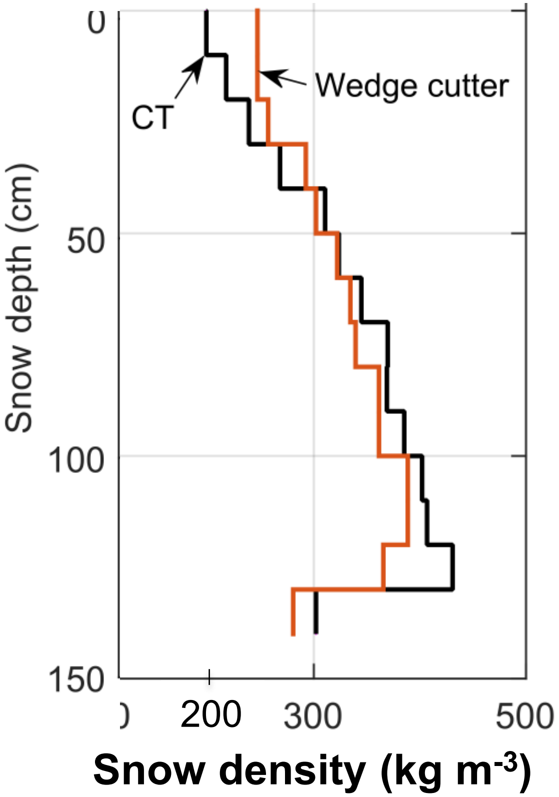
YOPP
YEAR OF POLAR PREDICTION

Snow characteristics and properties

Snow is a stratified porous medium

- Complex microstructure (grain size/shape)
- Thermal conductivity is usually related to density
    - ➢ Snow is an effective thermal insulator
- Density greatly varies with depth

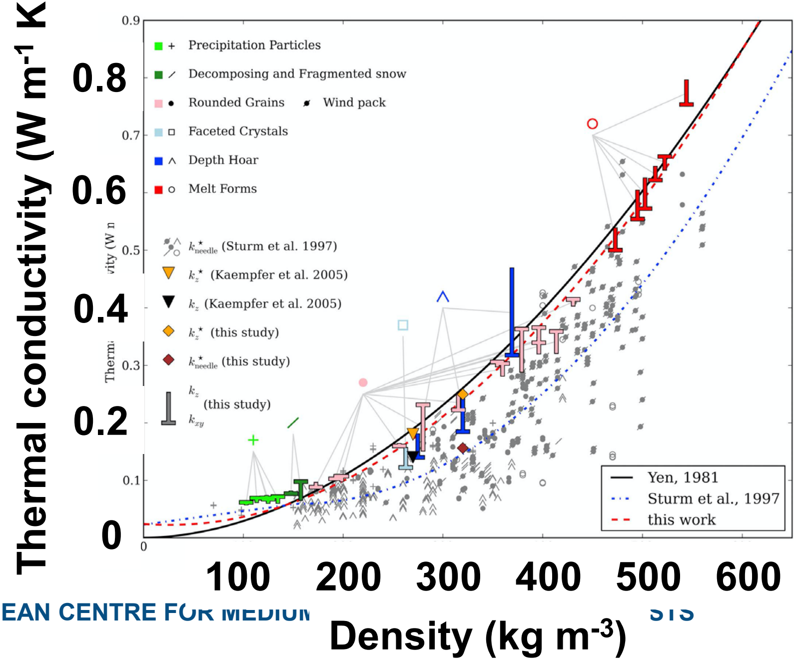
Proksch et al. 2016



Domine et al 2018

Observations

Calonne et al. 2011 - GRL



Snow thermal insulation – atmosphere

The low thermal conductivity may lead to a thermal decoupling between the atmosphere and soil underneath in clear-skies

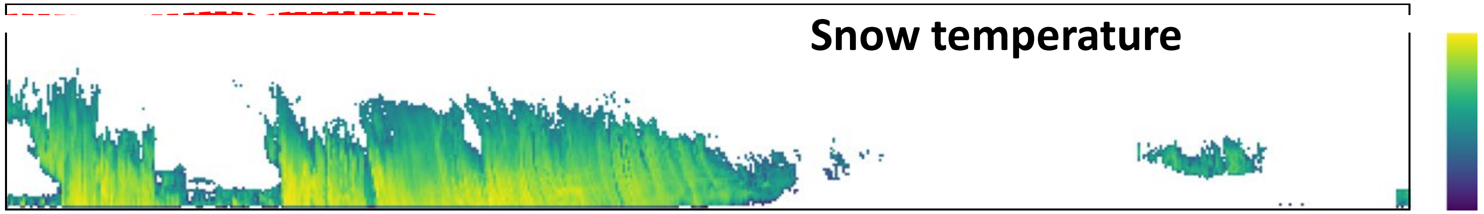
Implications for near-surface temperature forecasts in snow-covered regions

Important to get clouds right!

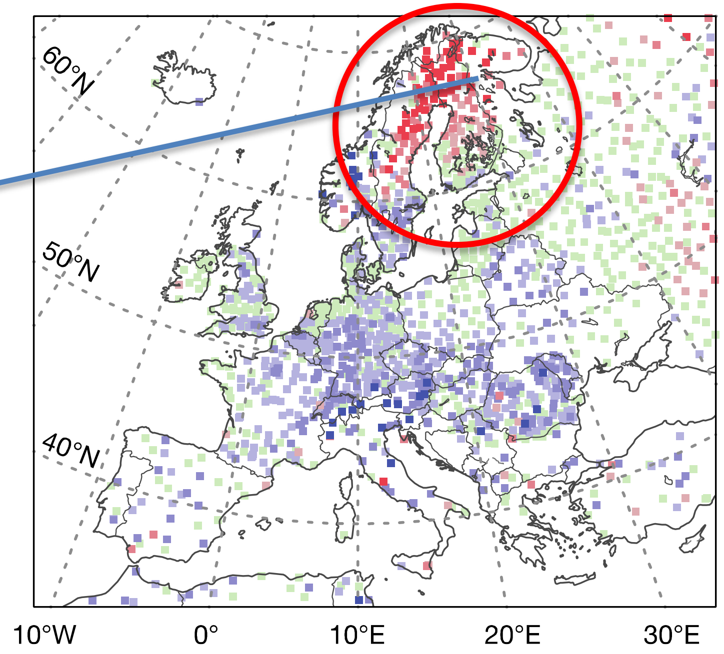
Sodankyla, Finland

Cloud reflectivity

Snow temperature



Bias of T2m in ECMWF operational model at day 3 for DJF 2017/2018



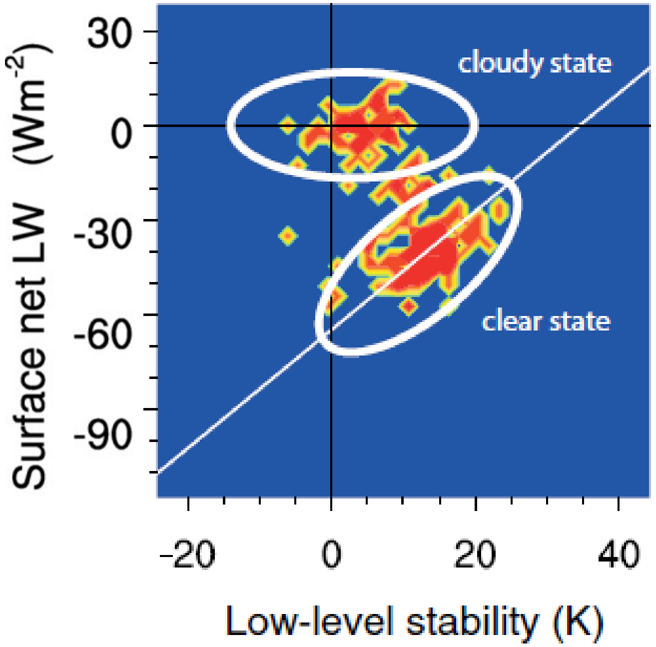
Day et al. 2020

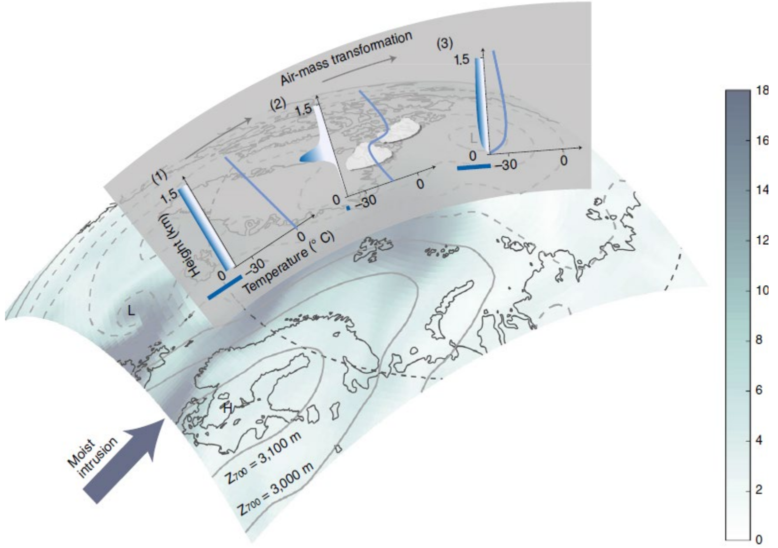
A more holistic view on coupled BL processes

Arctic boundary Layer:

- Predominantly in a cloudy and clear-sky states
- Mixed phase clouds are key radiative drivers for transition between states
  - Challenging to represent!

SHEBA observations



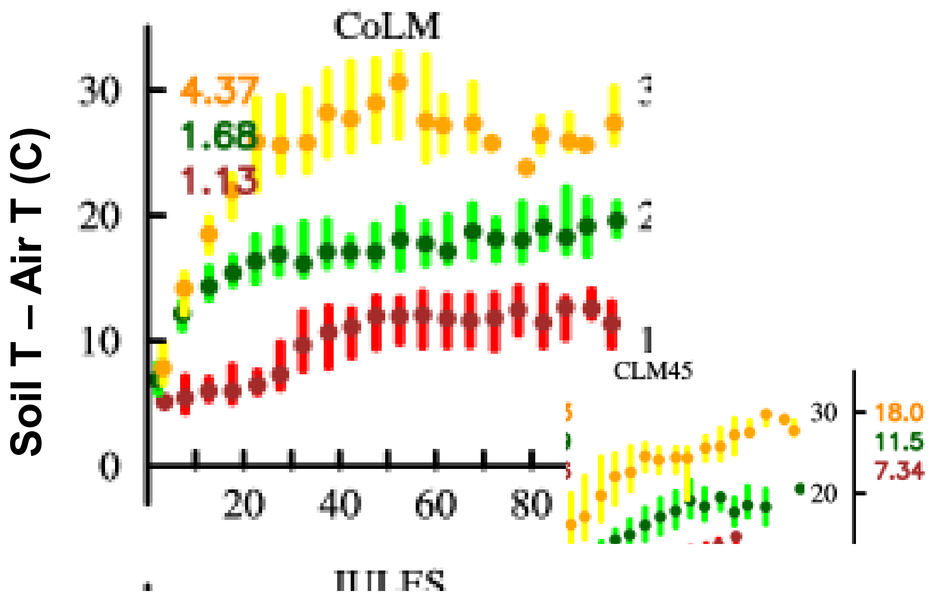


Pithan et al. (2018, 2016, 2014)

Snow thermal insulation – soil

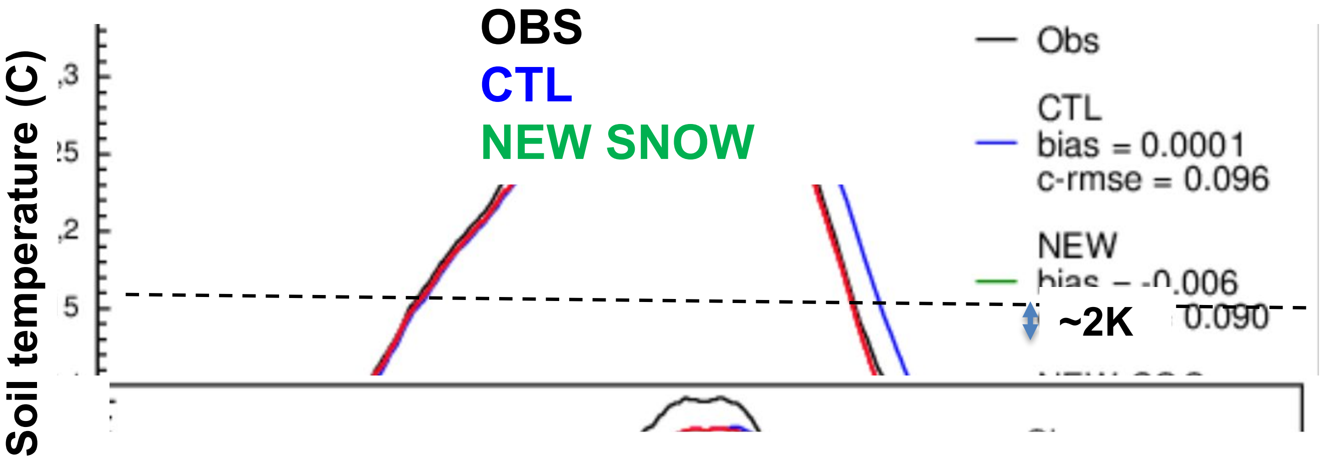
Snow cover and depth are key drivers of soil temperature in high-latitude

- Impact on permafrost (e.g. Koven et al. 2013)
- Impact on water cycle (e.g. Ploum et al. 2019)
- Important for longer time-scales and reanalyses



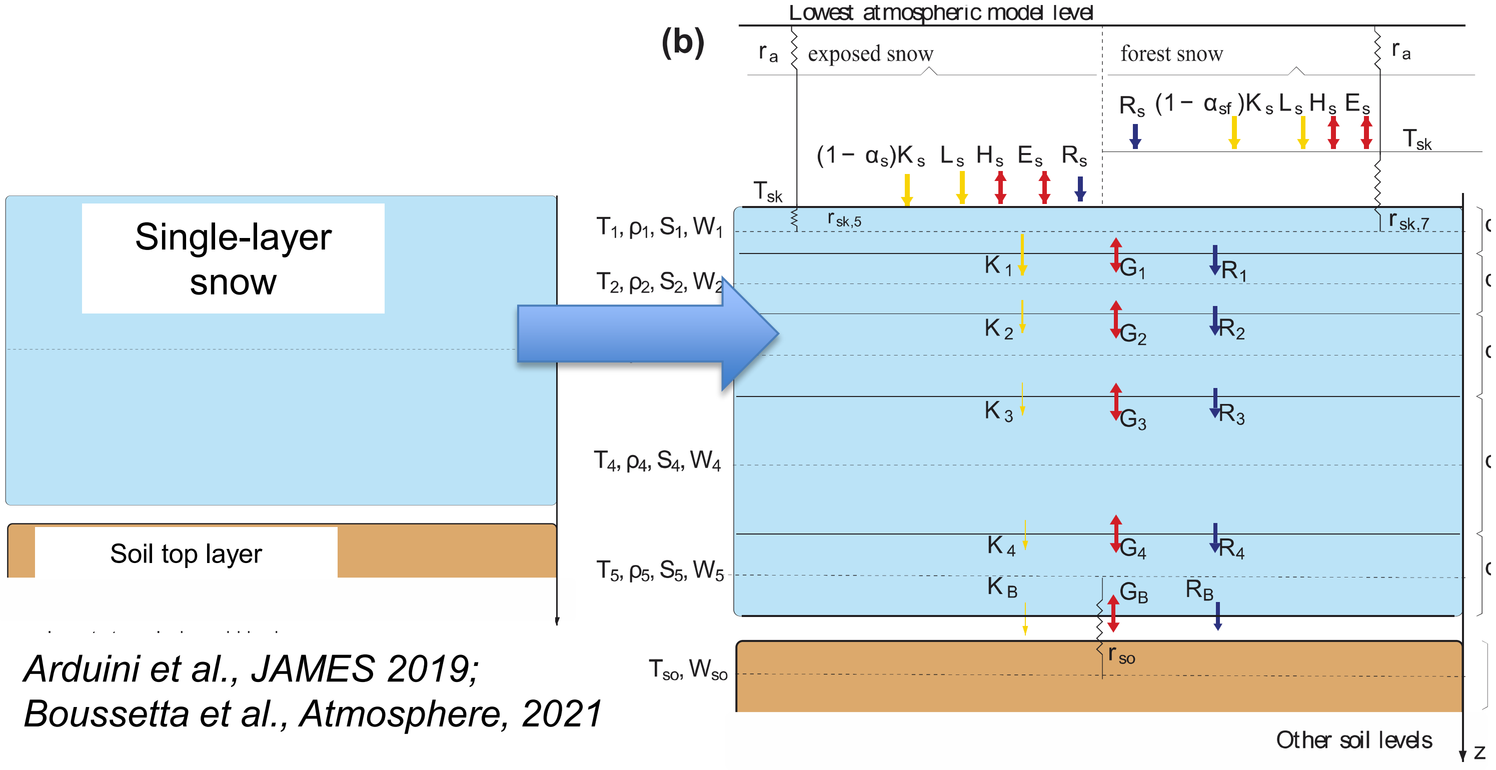
Wang et al 2016

Mean annual cycle of **soil temperature** at **1.60m** depth compared to simulations with different snow (and soil) components



Decharme et al. 2016

Developing a multi-layer snow scheme for the IFS



Arduini et al., JAMES 2019;
Boussetta et al., Atmosphere, 2021

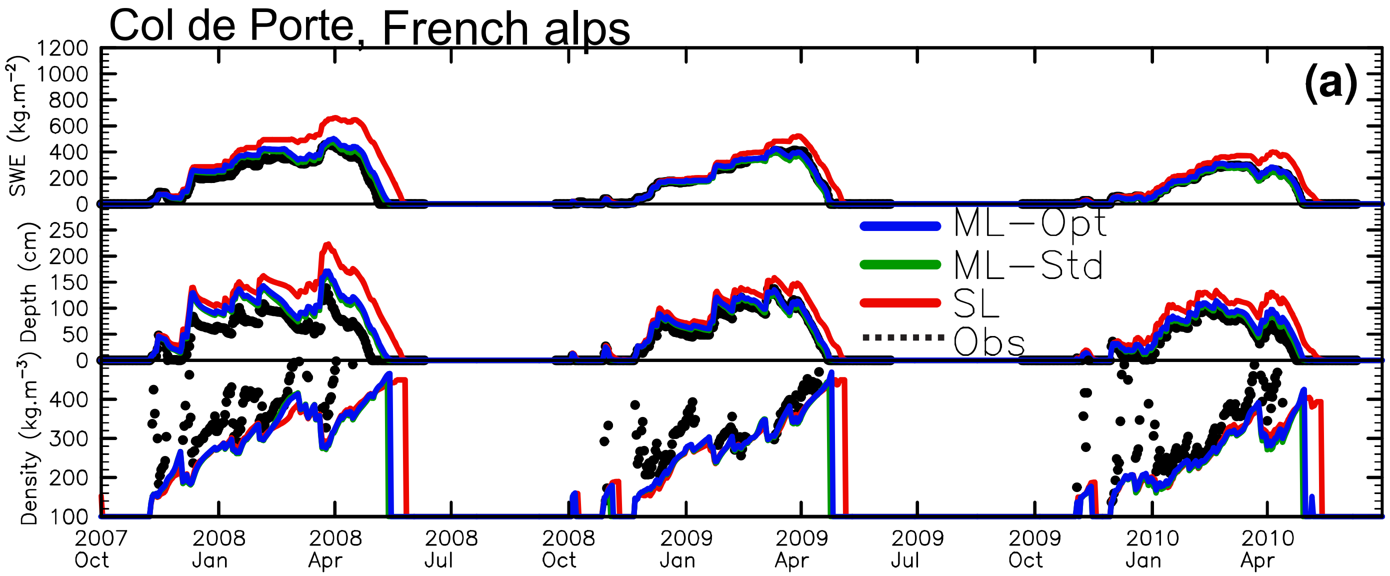
New multi-layer snow scheme:

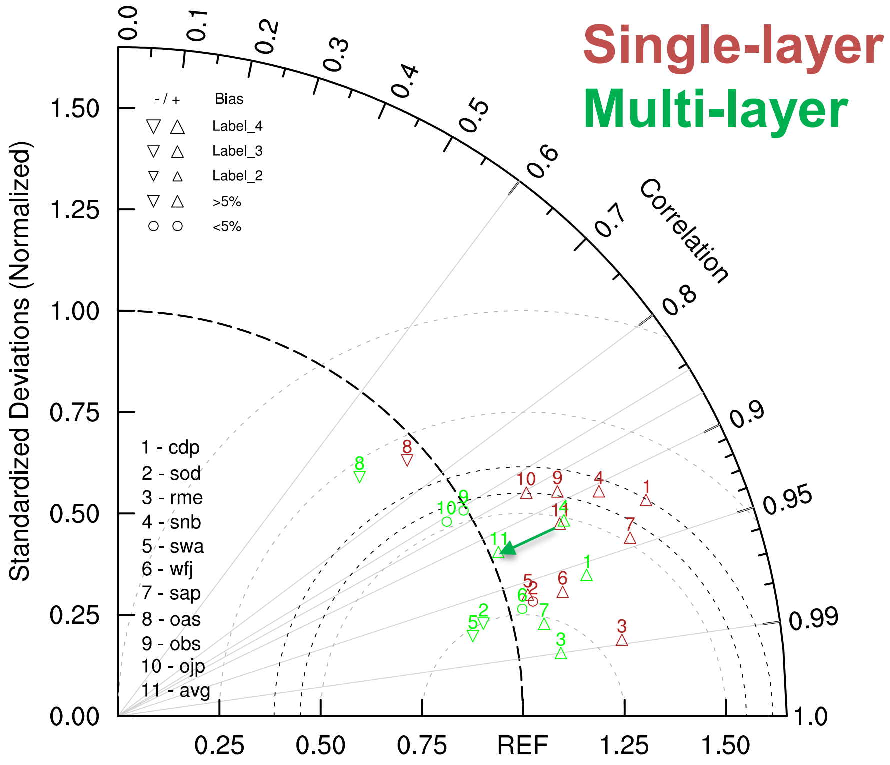
- Targeted for cycle 48r1
- Intermediate complexity:
  - No microstructure
- 5-layer snow scheme
- Prognostic liquid water content
- Improved snow physics

Snow processes at ESM-SnowMIP – site (point-scale) simulations

Observational sites measuring forcing variables to run land-surface models

- ➢ reducing compensating errors due to uncertainties in atmospheric fields

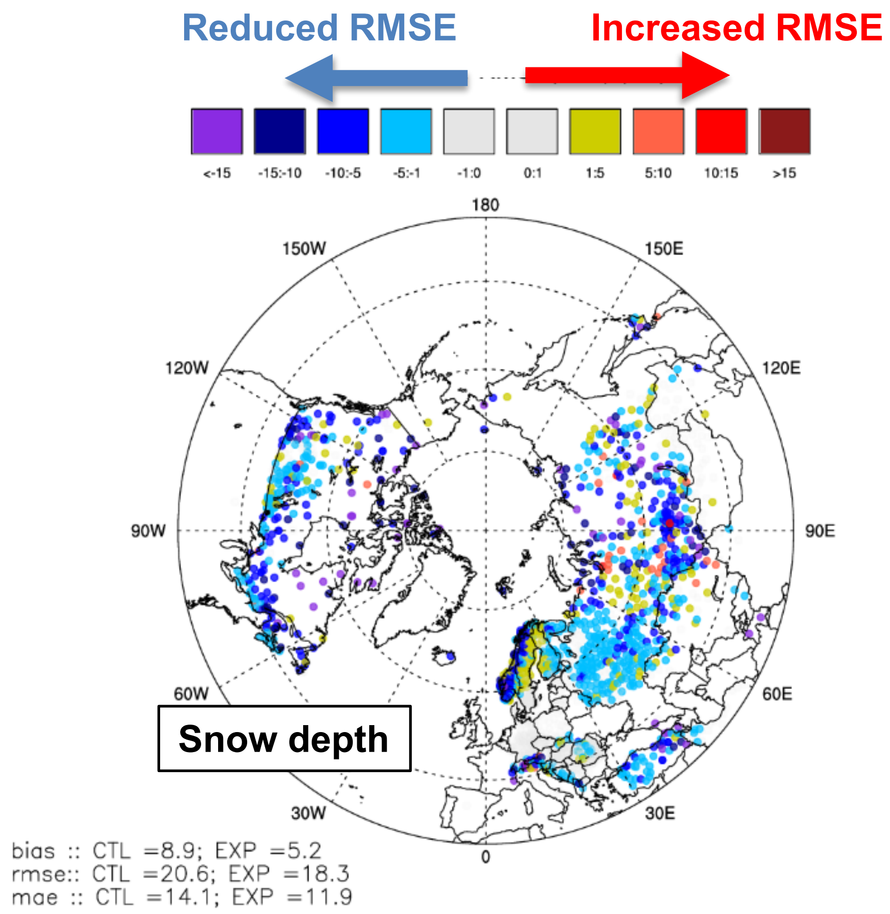




Arduini et al., JAMES 2019;
Boussetta et al., Atmosphere, 2021

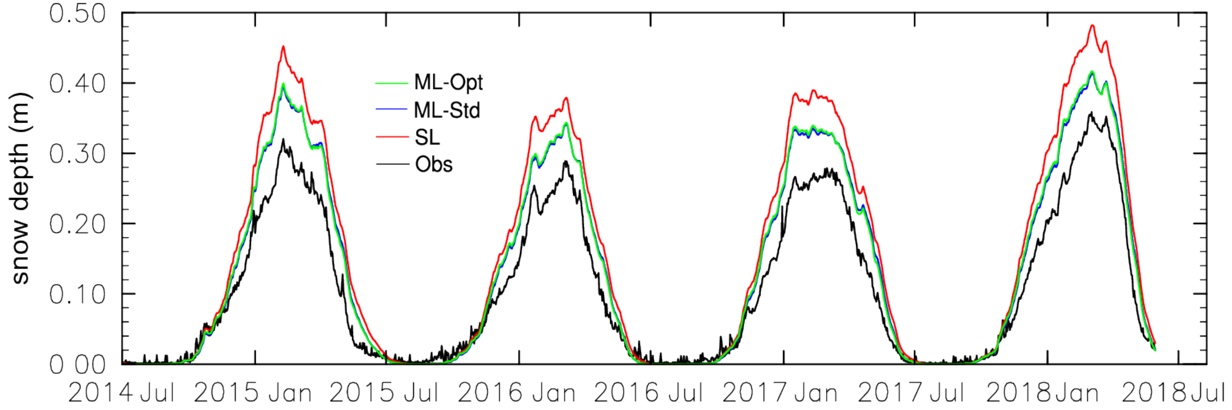
Impact on snow depth at the global scale (land-surface only)

- Offline: land-surface model driven by ERA5 meteorological forcing
- Evaluation using global synop network of snow depth observations, **2014 to 2018**



bias :: CTL =8.9; EXP =5.2
rmse:: CTL =20.6; EXP =18.3
mae :: CTL =14.1; EXP =11.9

Time-series from avg of synop stations



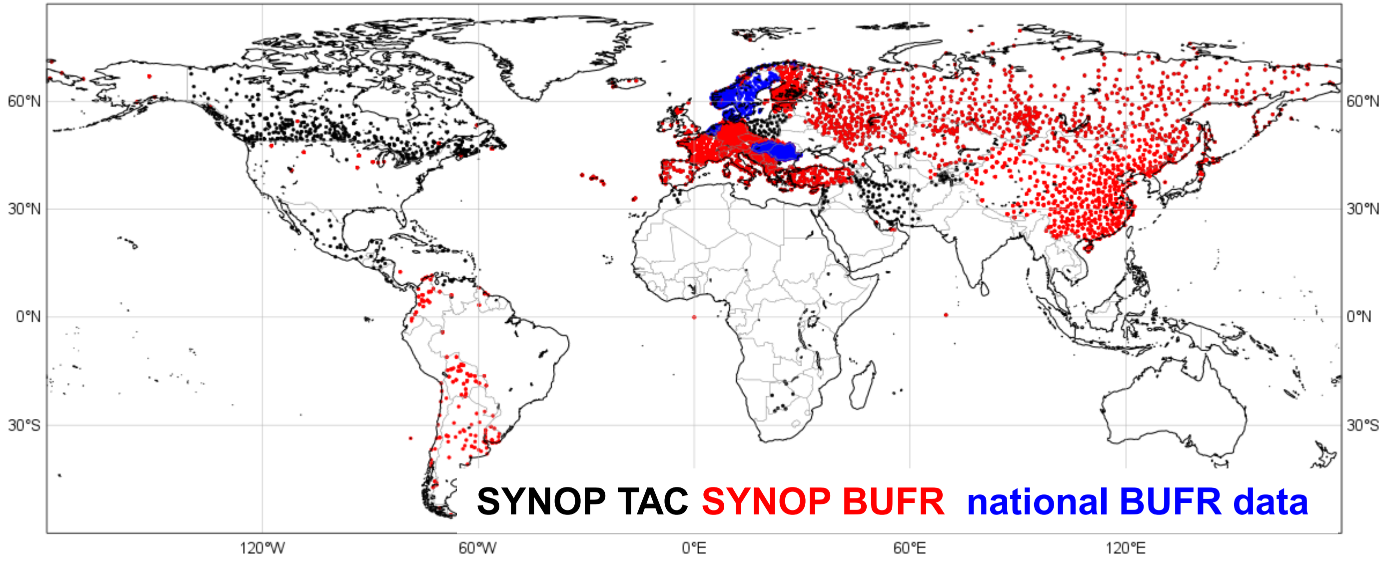
General improvement of snow depth with the multi-layer snow scheme over the NH in offline simulations

Snow data assimilation and observations

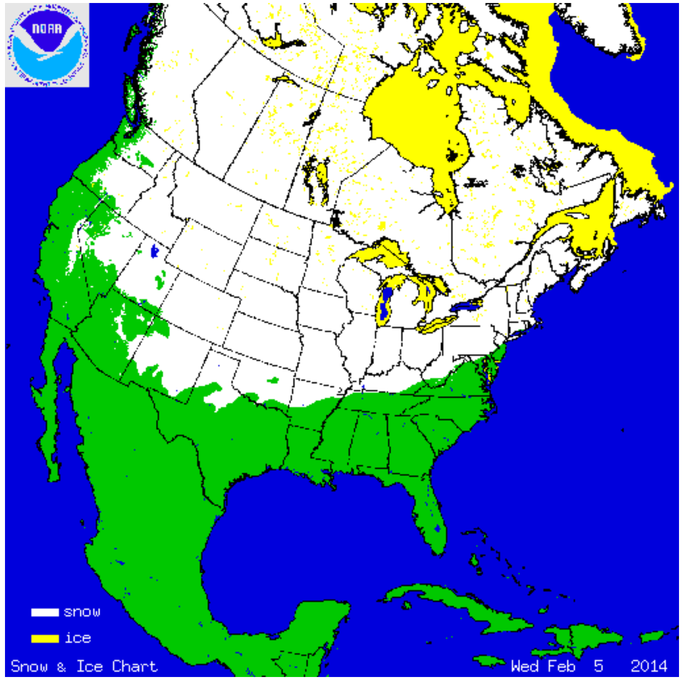
Data Assimilation: *de Rosnay et al SG 2014*

- **Optimal Interpolation** (OI) is used to optimally combine the model first guess, in situ snow depth and IMS snow cover
- **Multi-layer snow**: No variations in the algorithm, analysis performed using the total snow depth

GTS Snow depth (e.g., availability for 15 January 2020)



NOAA/NESDIS
IMS Snow extent data

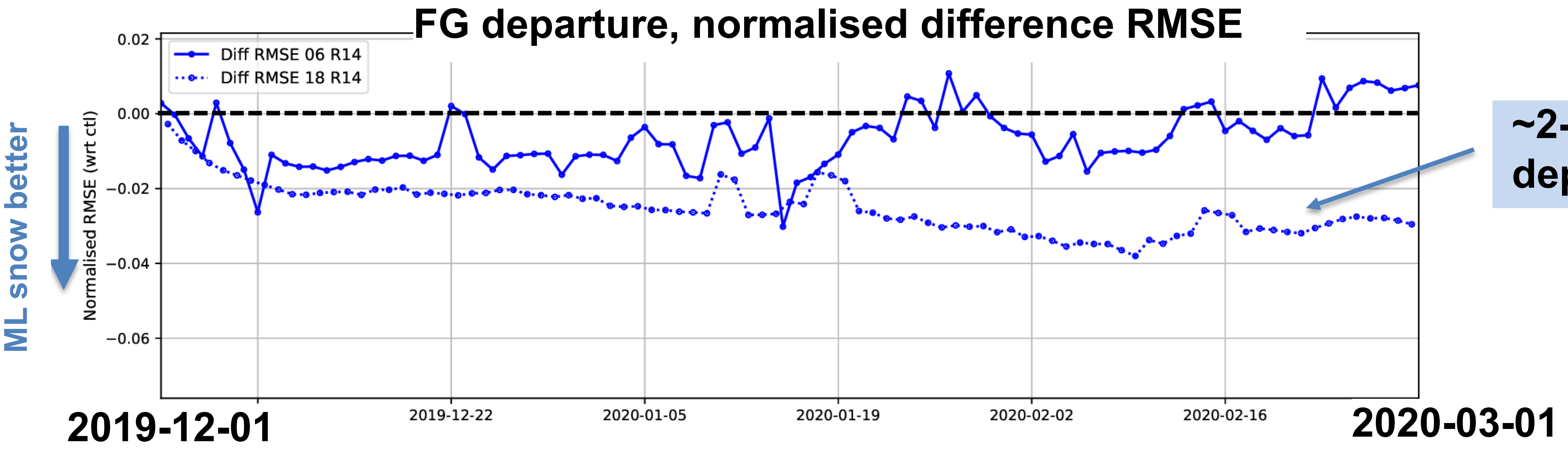


http://nsidc.org/data/g02156.html

Multi-layer snow impact in the snow data assimilation system

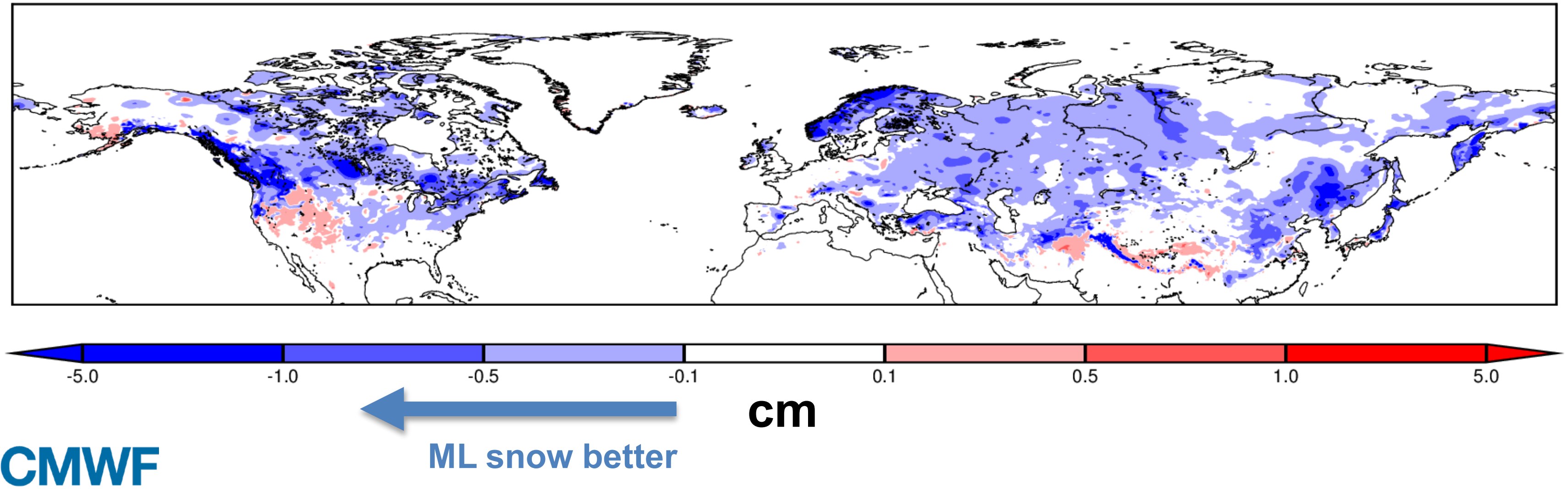
Winter 2019/2020, 3 months analysis, compared to analysis using the single-layer snow scheme

FG departure, normalised difference RMSE



~2-3% reduction of snow depth FG departure

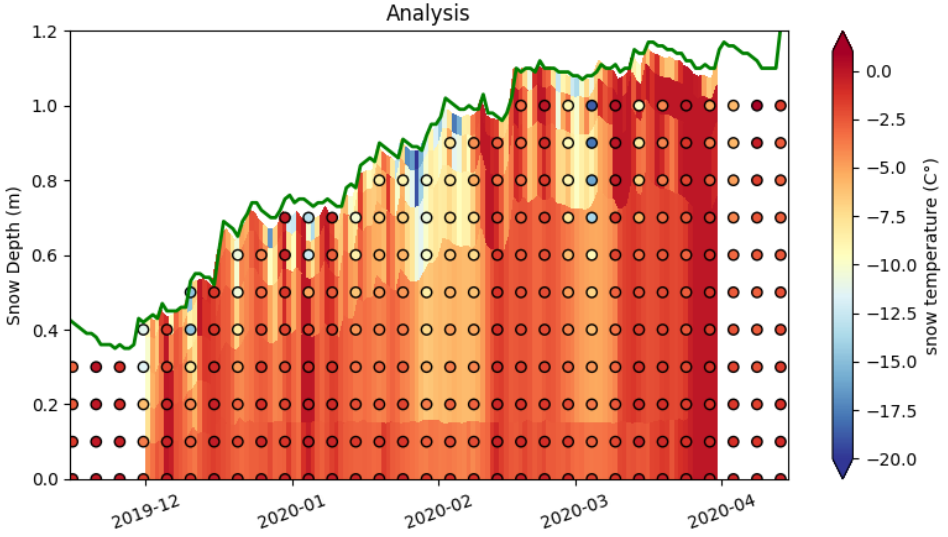
RMSE diff in AN increments of snow depth for Jan 2020, 06UTC/18UTC



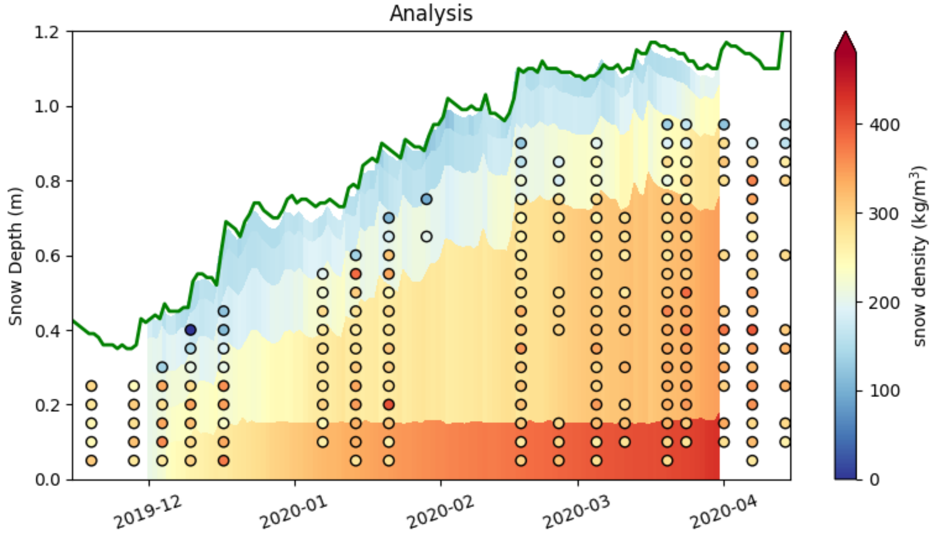
General reduction of analysis increments

Snow temperature and density diagnostics – Sodankyla, Findland

Temperature profile at analysis time



Density profile at analysis time



Thanks to Jonny Day

Variability of snow temperature is qualitatively well captured

Realistic snow density in the top layers

Overestimation of snow density in bottom layers

- missing upward water vapor fluxes?

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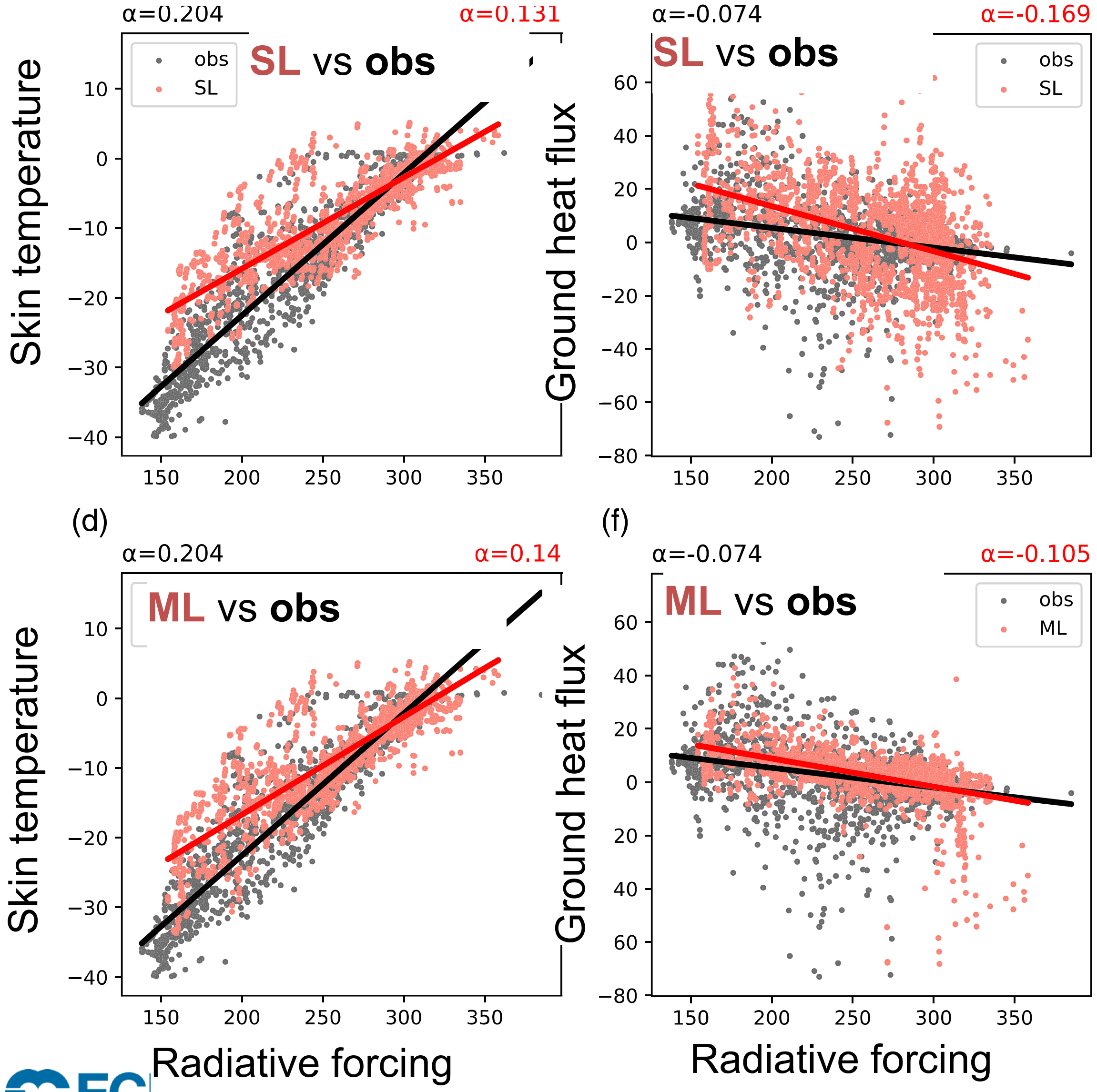
Process-based snow-atmosphere coupling – Sodankyla, Findland



Day et al. 2020

Improving relationship between surface energy fluxes and atmospheric radiative forcing

Improved simulation of cold surface temperatures

Reduced coupling strength between heat flux into the snowpack and radiative forcing

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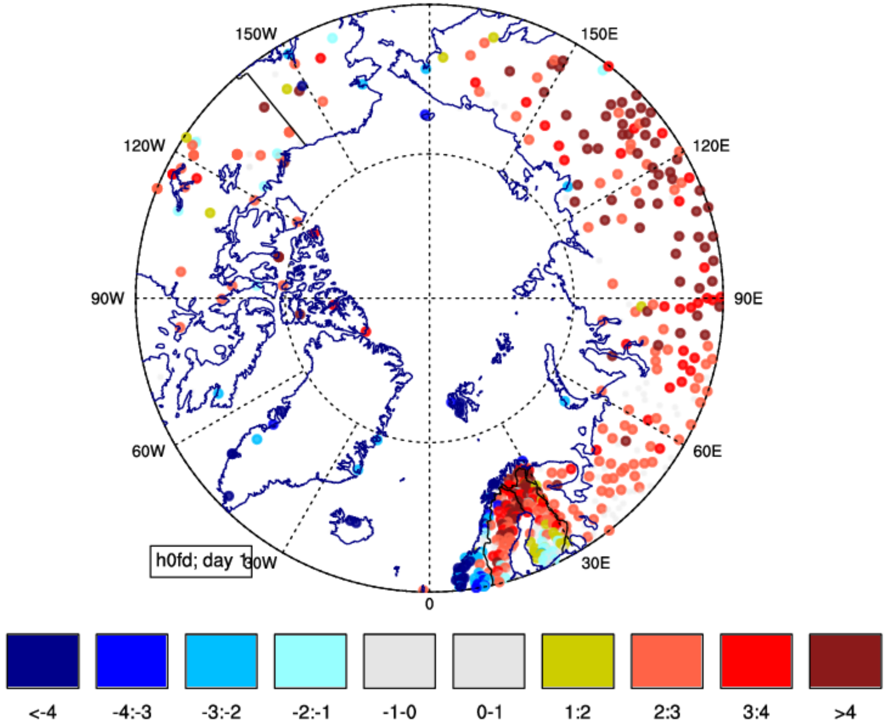
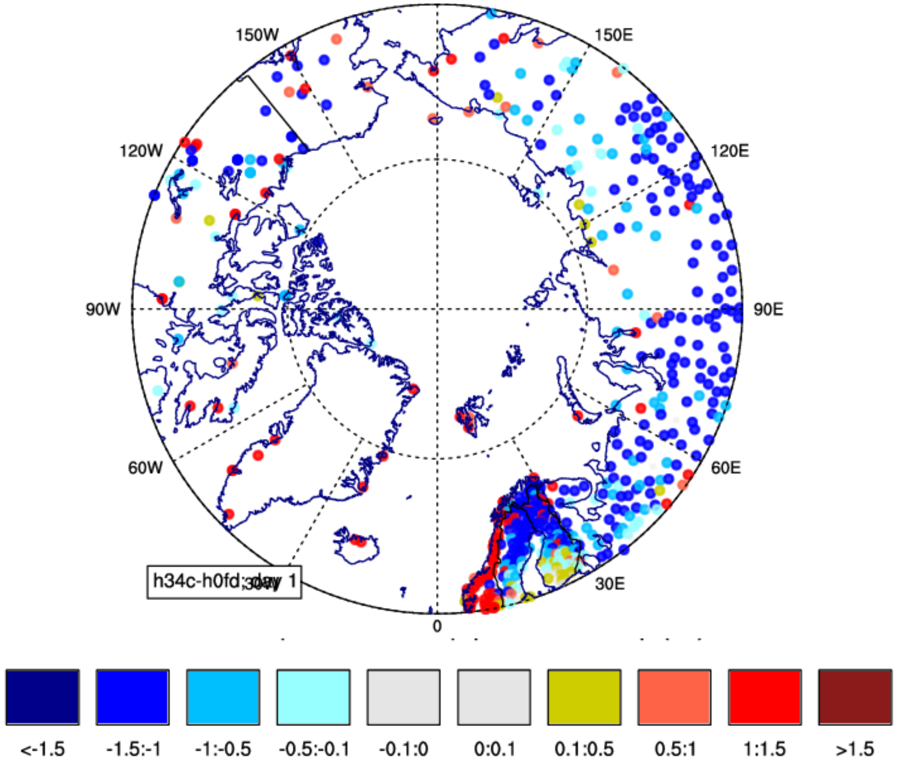
Impact of multi-layer snow modelling in **coupled land-atmosphere forecasts**

Coupled forecasts for winter 2016/2017 (December to February), t+24 hours,

Bias minimum 2-metre temperature (T2m) single-layer snow (CTL) against obs



Absolute bias difference T2m (multi-layer snow) – (single-layer snow)



ML snow reduces bias

- Forecasts with current single-layer snow scheme show widespread positive (warm) bias in minimum T2m
- Improved simulation of daily minimum temperature with multi-layer snow

Arduini et al. 2019

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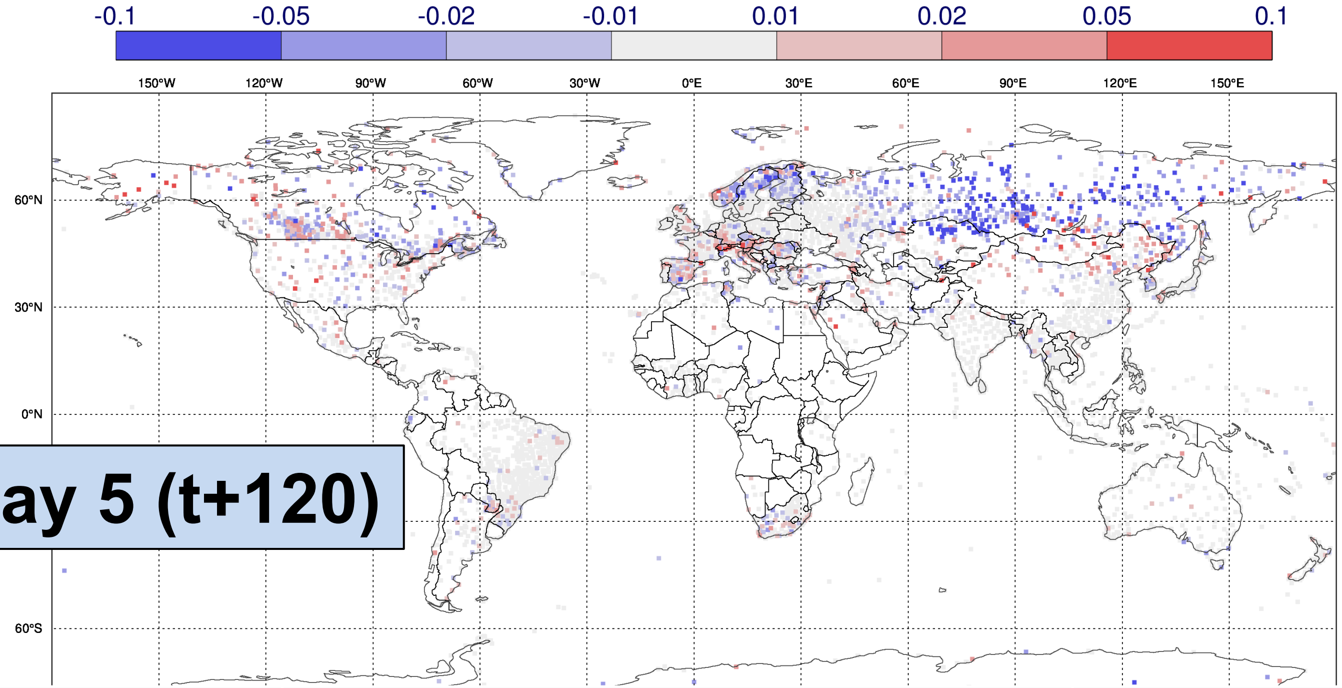
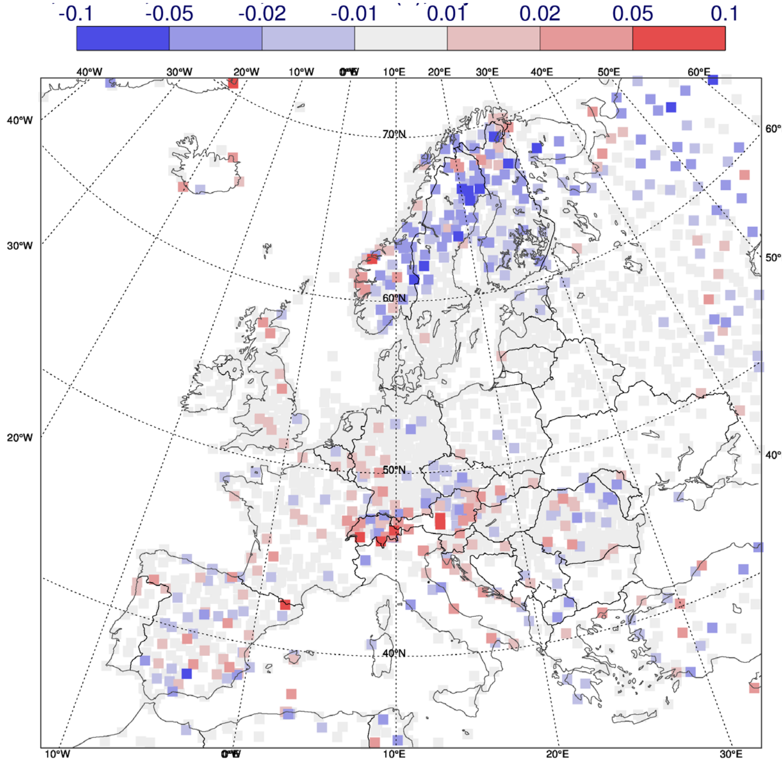
What do we gain in a probabilistic sense? – **Fraction of CRPS err > 5K**

Winter, DJF 2019/2020

Forecasts initialized from analysis using consistent snow scheme (multi-layer or single-layer)



Day 5 (t+120)

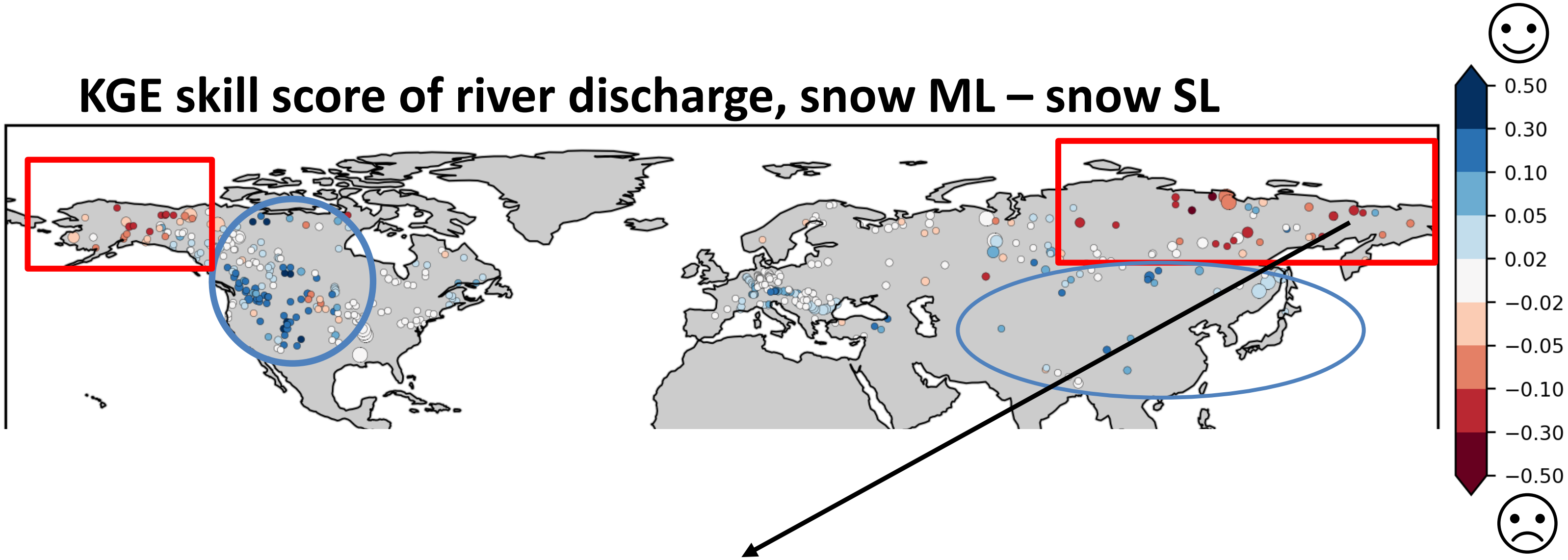


DAY 5	Rel.Difference RMSE (ML-SL)	Frac. CRPS>5K
ExTrop	-2.2%	**-4.8%**
Arctic	-3.9%	**-7.2%**
Europe	-0.7%	**-2.8%**

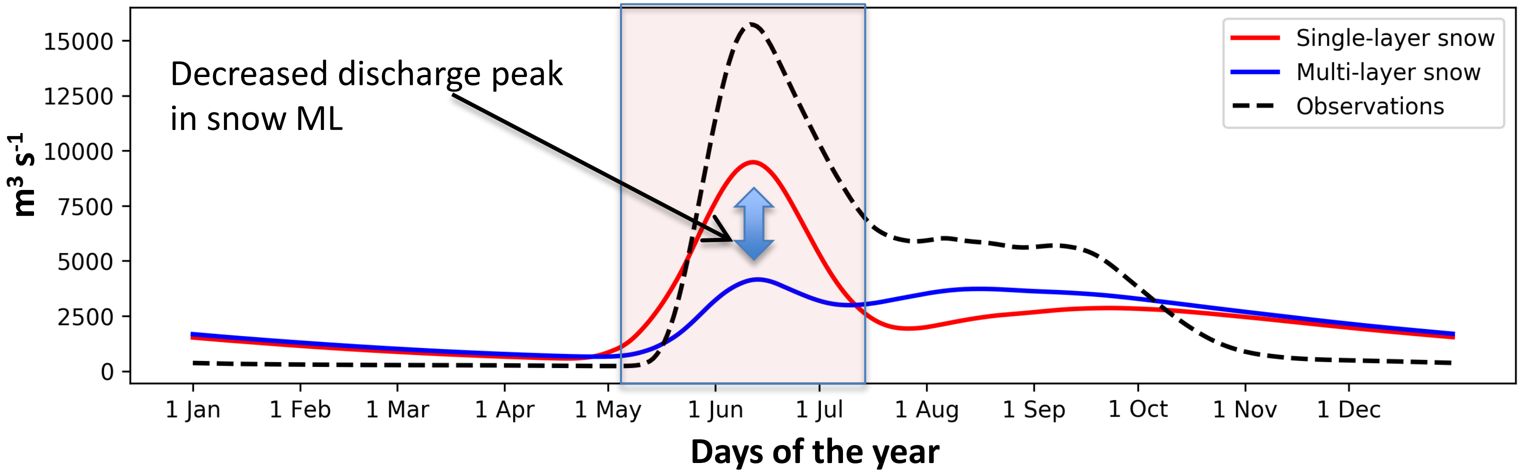
Thanks to Thomas Haiden for the maps and statistics

Evaluating the impact of multi-layer snow on hydrology – River discharge

KGE skill score of river discharge, snow ML – snow SL



Daily mean annual cycle of river discharge for Kolyma river, lat=68.72; lon=158.71



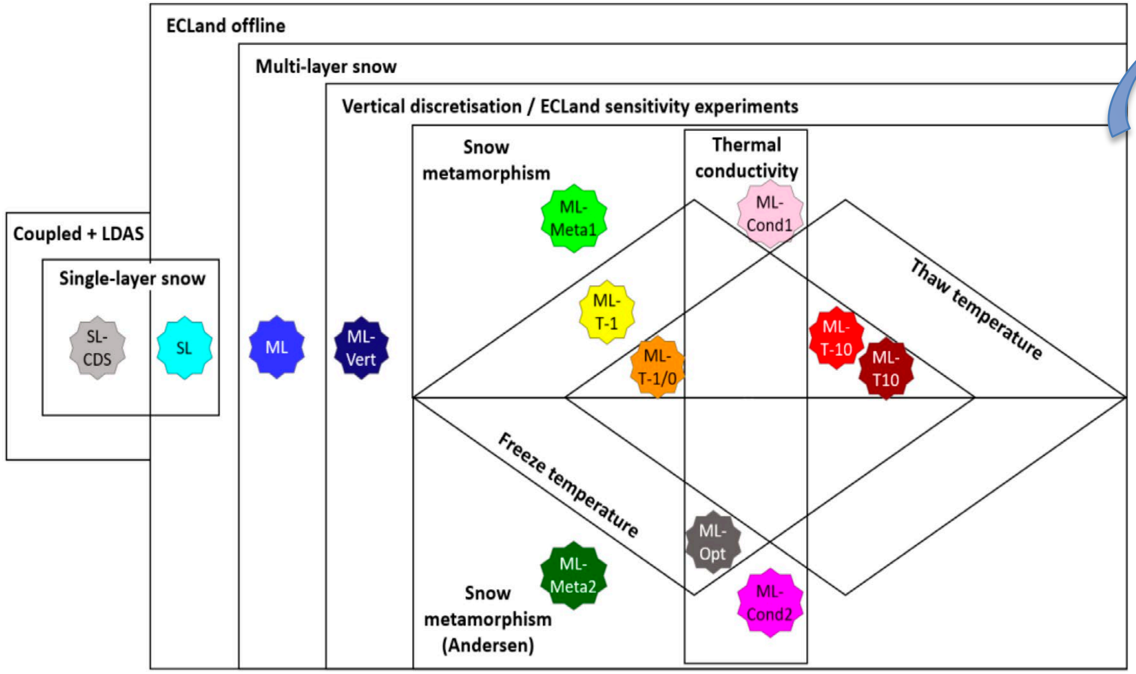
Decreased discharge peak in snow ML

- More catchments show improvements, in particular over Rockies and mid-latitude Eurasia
- Many catchments in cold climates show lower skills (permafrost regions)
- In permafrost areas, excess of water infiltrating into the soil amplifies river discharge biases. Main causes:
    - warmer soil temperature in snowML
    - Frozen soil thawing for sub-zero temperatures

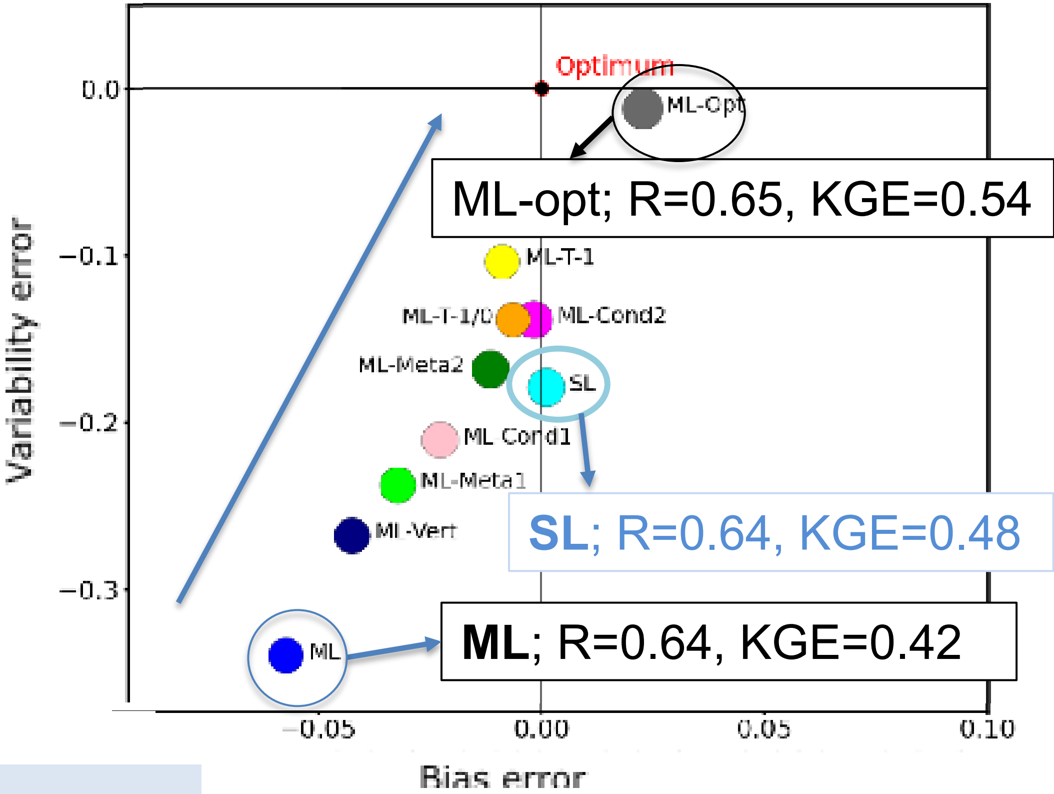
Zsoter et al. 2022

Optimising land-surface model developments with hydrology

Optimising parameters related to the frozen soil – snowpack interaction for better runoff



Sensitivity in permafrost catchments



ML-opt; R=0.65, KGE=0.54

SL; R=0.64, KGE=0.48

ML; R=0.64, KGE=0.42

Zsoter et al. 2022

Sensitivity to **frozen soil, snow density** and **vertical discretization** indicate an improvement in river discharge in permafrost catchments

Also improvements in snow depth and soil temperature (see *Cao et al 2022*)

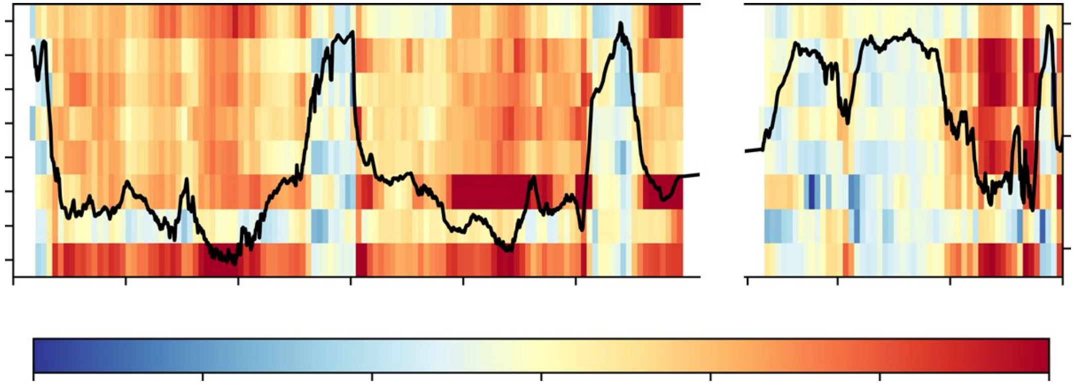
Some of these under testing for future IFS cycles – CY49R1

Modelling of snow over ice surfaces

Substantial temperature biases over sea-ice surfaces

- Implications for ice growth

Biases of different reanalysis surface temperature against in-situ observations



Bias in wintertime clear-sky surface temperature between ERA5 and satellite product

Warm biases of several K in reanalyses and operational IFS

Biases focussed on high snow cover over the Arctic

No thermodynamic effect due to snow (insulation)

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-019-11975-3 OPEN

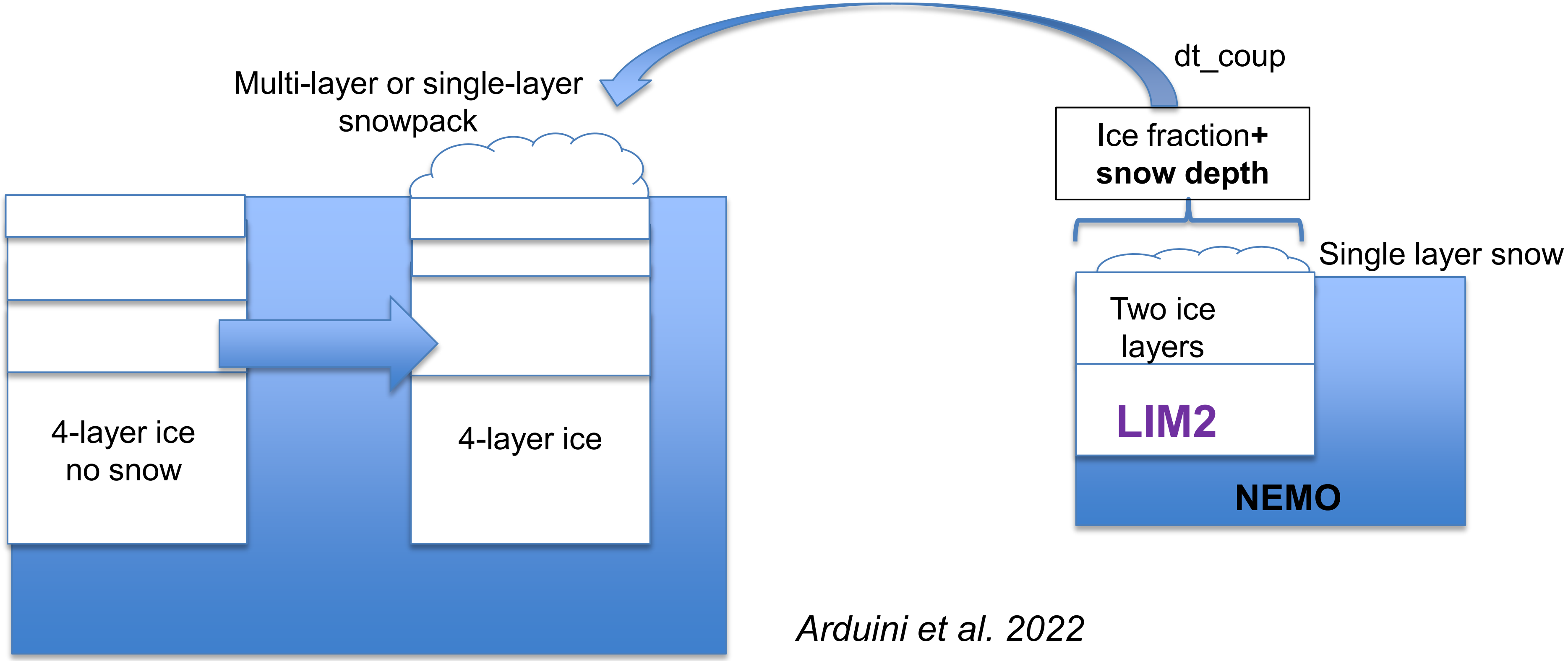
On the warm bias in atmospheric reanalyses induced by the missing snow over Arctic sea-ice

Yurii Batrak[1] & Malte Müller[1]

Testing the impact of snow over sea-ice in the ECMWF IFS

Accounting for the thermal effect of snow on top of sea-ice in the IFS

Coupling of ice fraction **and snow depth** from sea-ice model



Arduini et al. 2022

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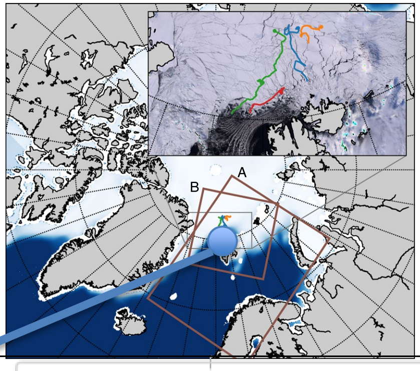
Evaluating the impact of snow over sea-ice in the ECMWF IFS – **in situ**

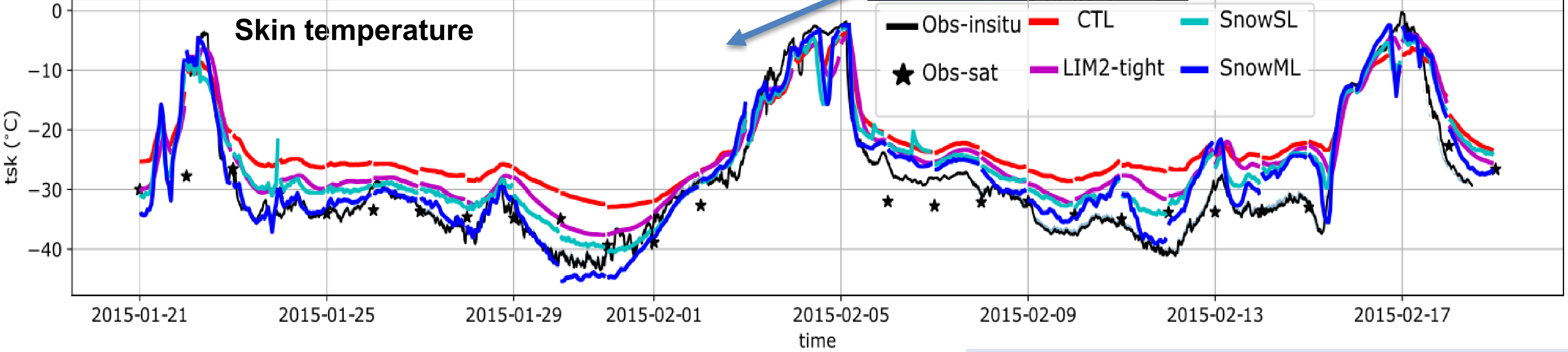
Evaluation using *in situ* observations from **N-ICE2015** campaigns and co-located CMEMS satellite observations, Jan/Feb 2015



Obs *in-situ*

★ **Obs *satellite***

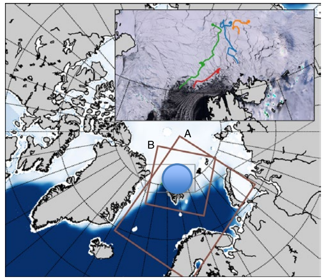
Ctl (no snow) **Multi layer snow**

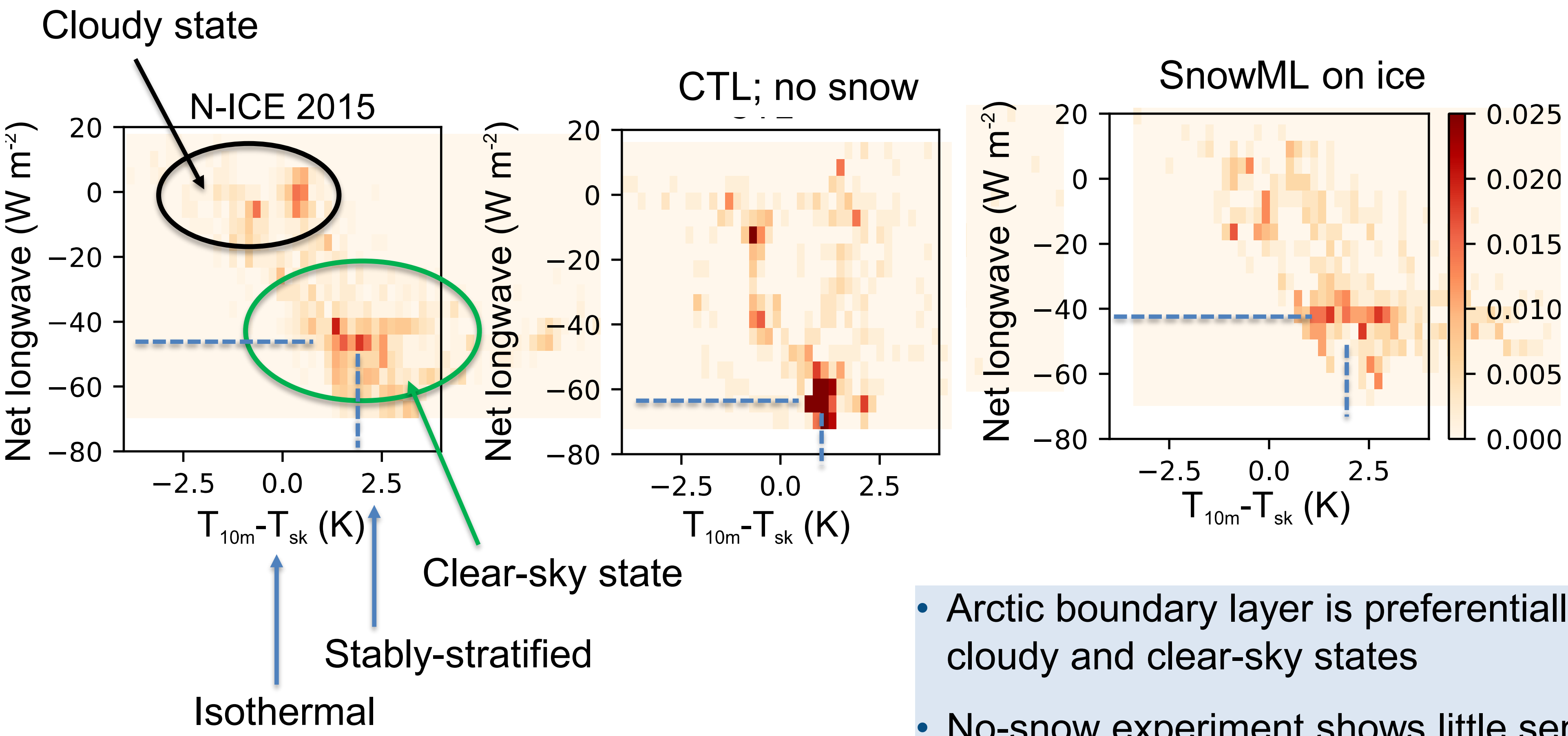


Arduini et al. 2022

- Accounting for snow over sea-ice improves the match of the short-range FC to in-situ observations
- Variability of surface temperature more consistent with observations

Impact on Arctic winter states – NICE2015 case





Cloudy state

N-ICE 2015

CTL; no snow

SnowML on ice

Clear-sky state

Stably-stratified

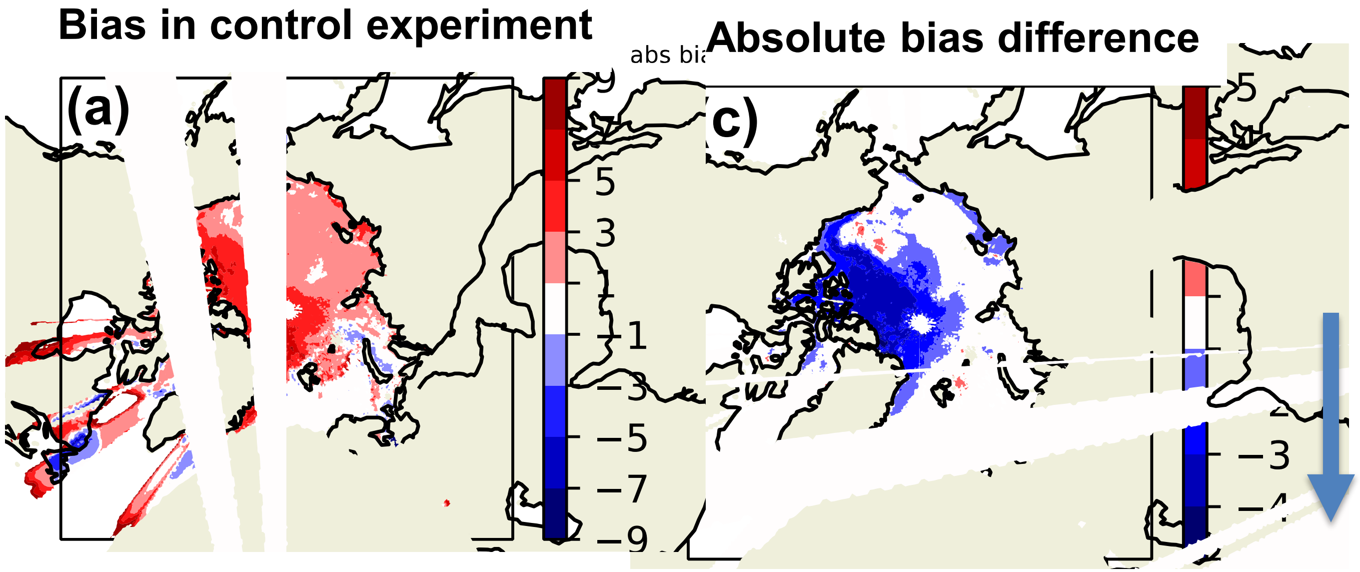
Isothermal

- Arctic boundary layer is preferentially in two states – cloudy and clear-sky states
- No-snow experiment shows little sensitivity in temperature inversion to net longwave variations
- Accounting for snow over sea-ice enables a better description of the clear-sky state and atmospheric inversions

Arduini et al. 2022

Evaluating the impact of snow over sea-ice in the ECMWF IFS – Arctic

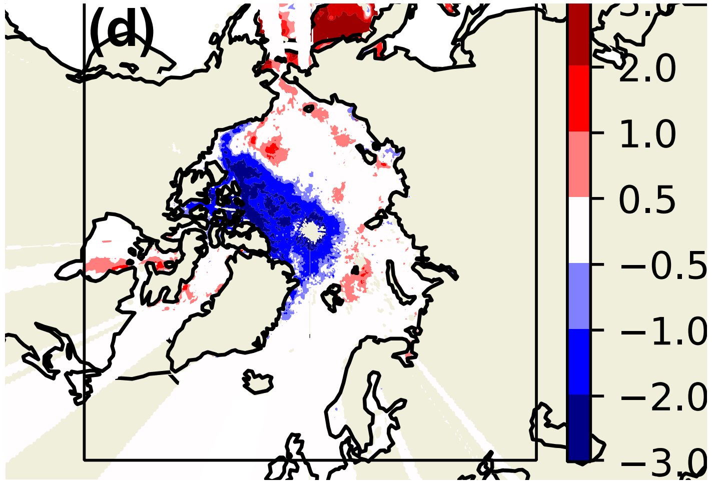
Skin temperature of **analysis** against CMEMS satellite surface temperature observations, DJF 2020/2021


Bias in control experiment

Absolute bias difference

Snow on ice better

RMSE diff against satellite Surface temperature



Snow on ice better

Conclusions and additional thoughts

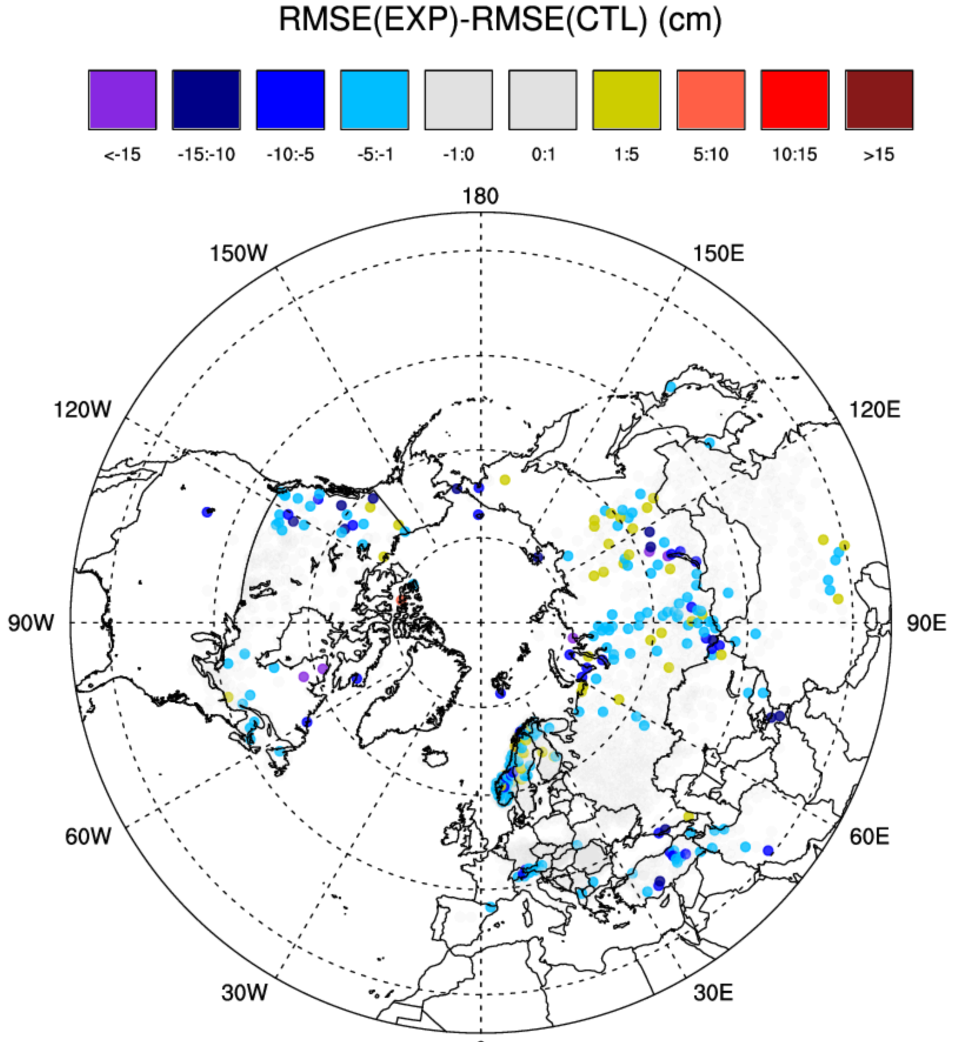
- Multi-layer snow model **targeted for operational** implementation in **IFS cycle 48r1** improves the the simulation of snow and of near-surface temperature biases over cold surfaces. Still,
  - Challenges associated with upward water vapor fluxes in Arctic snowpack
  - Challenges associated with development of more physically-based albedo
- Hydrological evaluation of land-surface model developments can highlight parametrization issues
- Accounting for snow over sea-ice can largely reduce biases in surface temperature over ice
  - How do we initialize snow depth in a coupled NWP system over sea-ice?
- Challenges related to compensating errors between cloud and surface processes in the Arctic

Extra slides

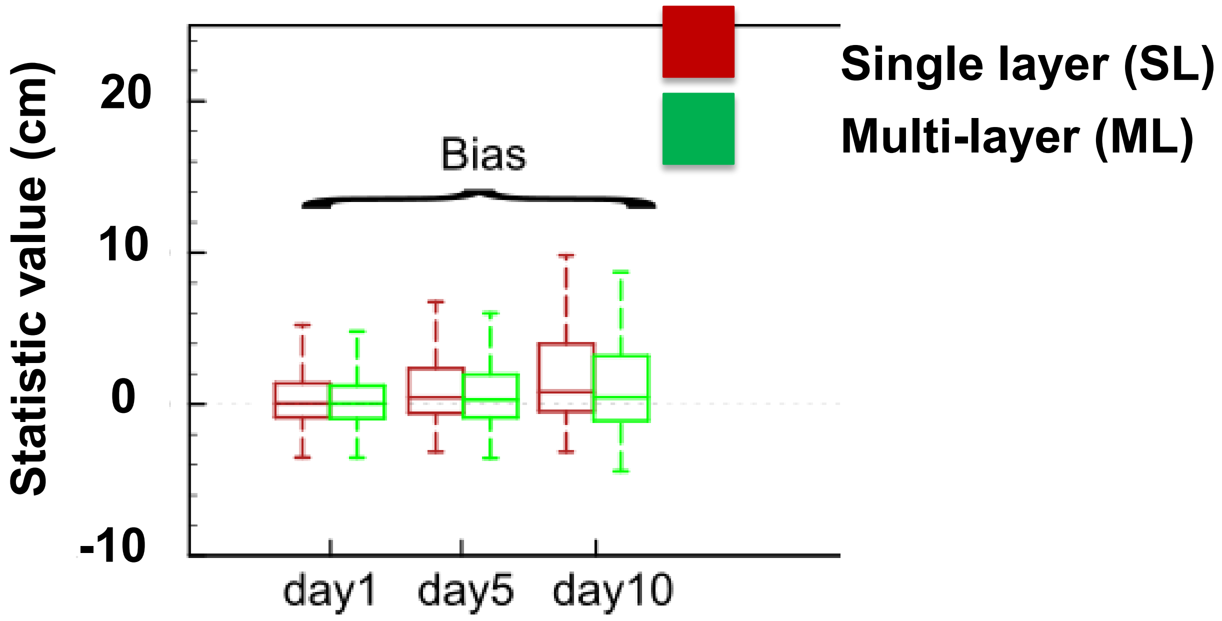
Impact on snow depth in forecasts initialized from analysis using the multi-layer snow

Winter, 3 months (DJF 2019/2020), verification with synop observations.

FC at DAY 5, 00UTC



Boxplot of bias distribution of the synop stations used for the evaluation

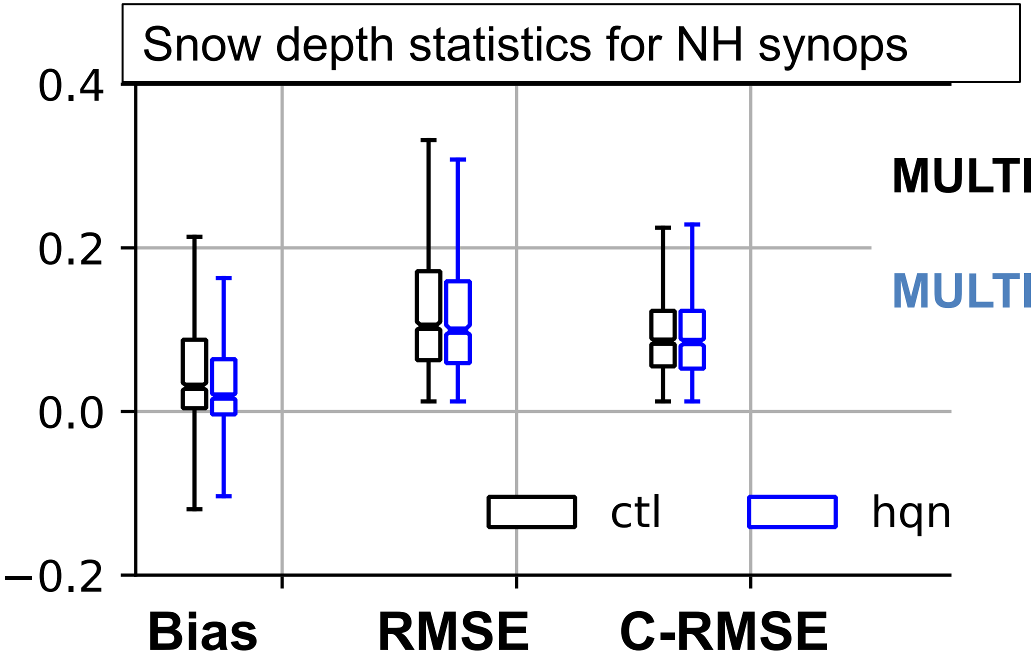


Positive impact on snow depth
in medium-range FC in North Hemisphere

Snow depth bias reduced at day 5 and day 10

ECMWF

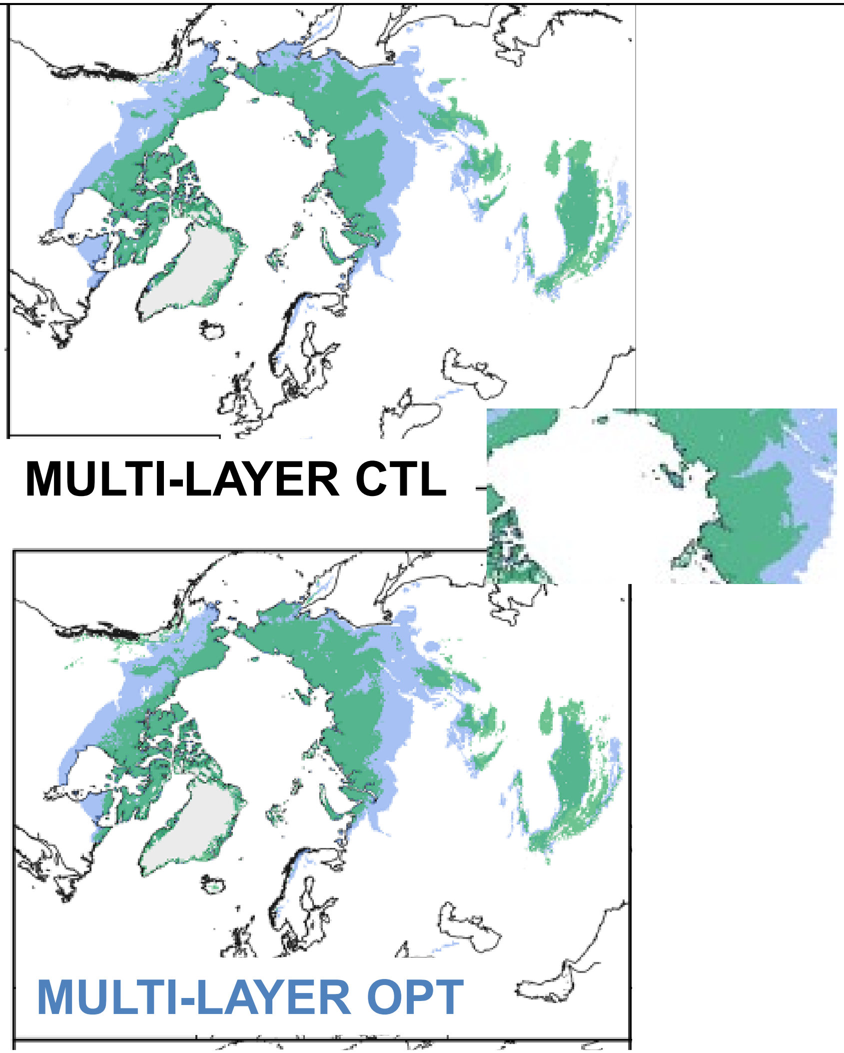
Optimising land-surface model developments with hydrology - feedback



MULTI-LAYER CTL

MULTI-LAYER Hydro Opt

Permafrost extent from obs (cyan) and model (green) for 2002



MULTI-LAYER CTL

MULTI-LAYER OPT

Cao et al. 2022

Optimised processes also improves land-surface components

Snow depth biases reduced

Improved soil temperature and permafrost extent

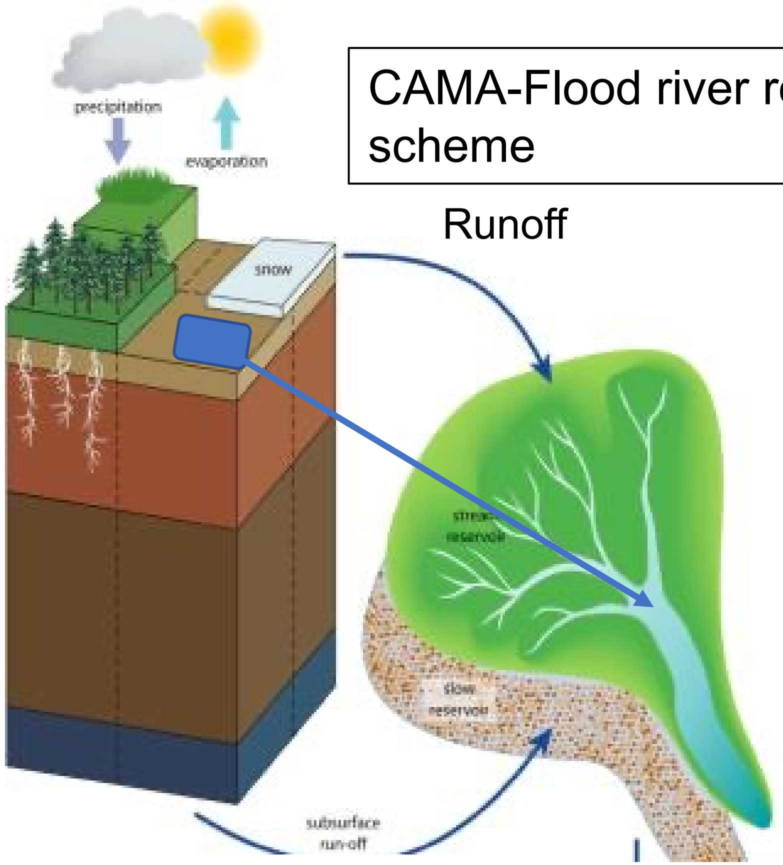
Testing now in coupled forecasts for future cycles – initial results positive

Assessing the impact of multi-layer snow modelling on the hydrological cycle

River discharge informing land-surface model developments on the integrated hydrological cycle, highlighting compensating errors between components

HTESSEL driven by **ERA5** meteorological forcing

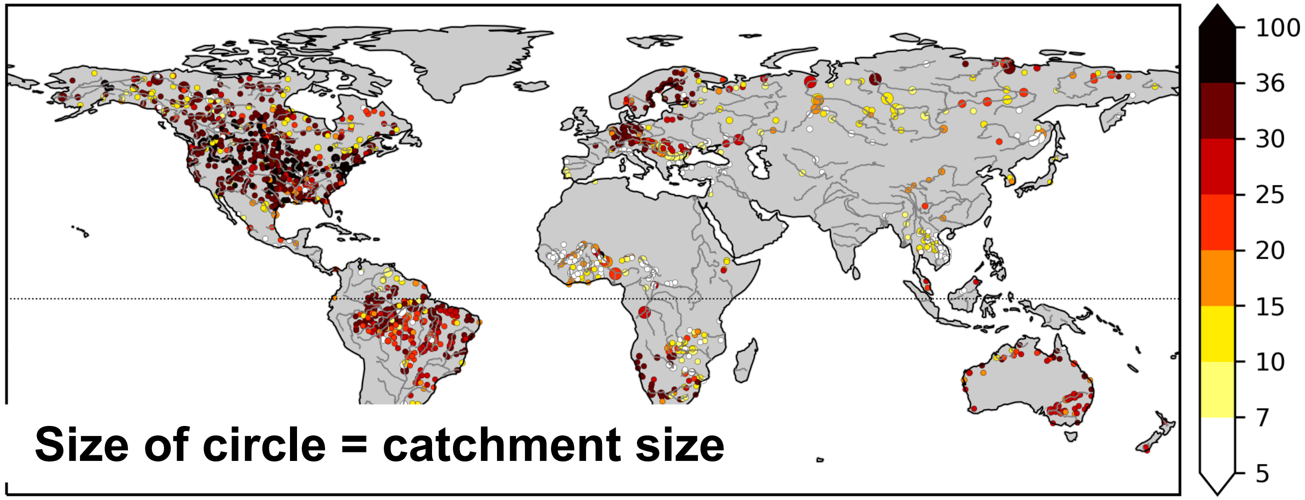
CAMA-Flood river routing scheme



Runoff

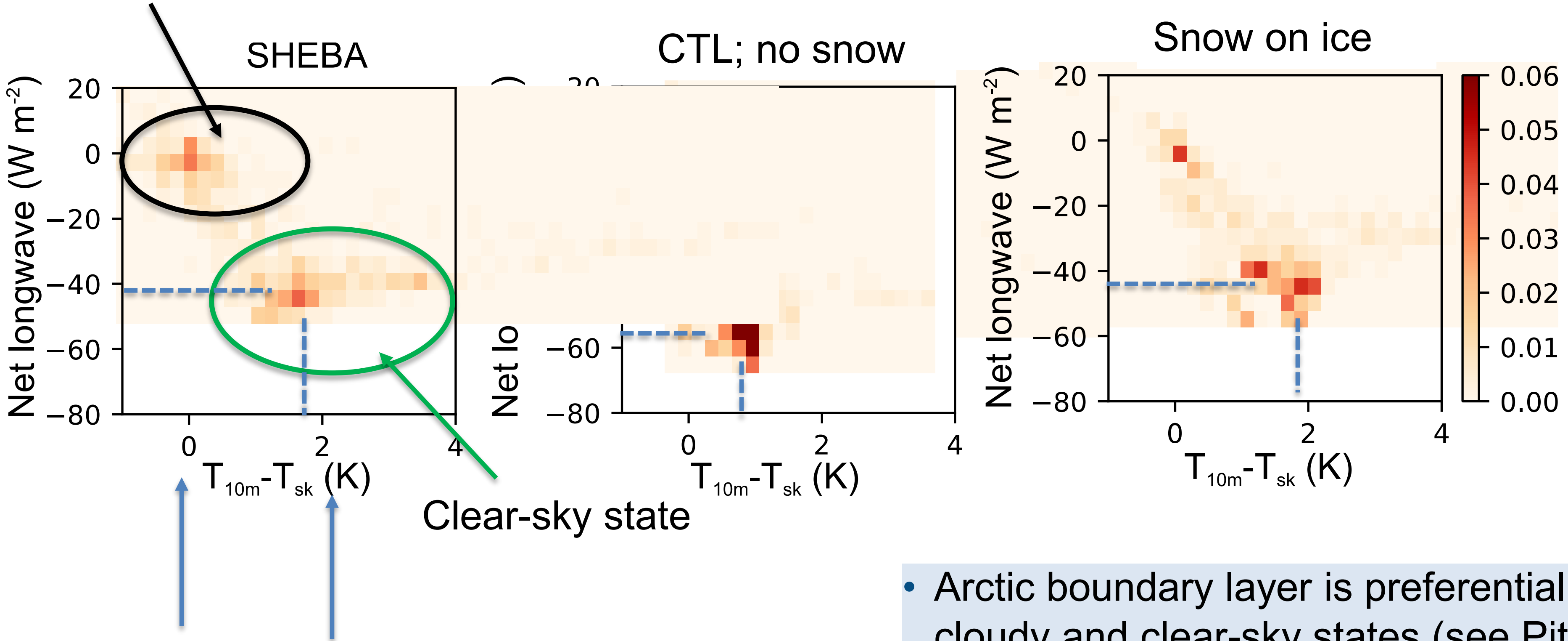
Sub-surface runoff

River discharge observations from **GRDC** network (colours indicate number of years with data)



Size of circle = catchment size

Impact on Arctic winter states – SHEBA case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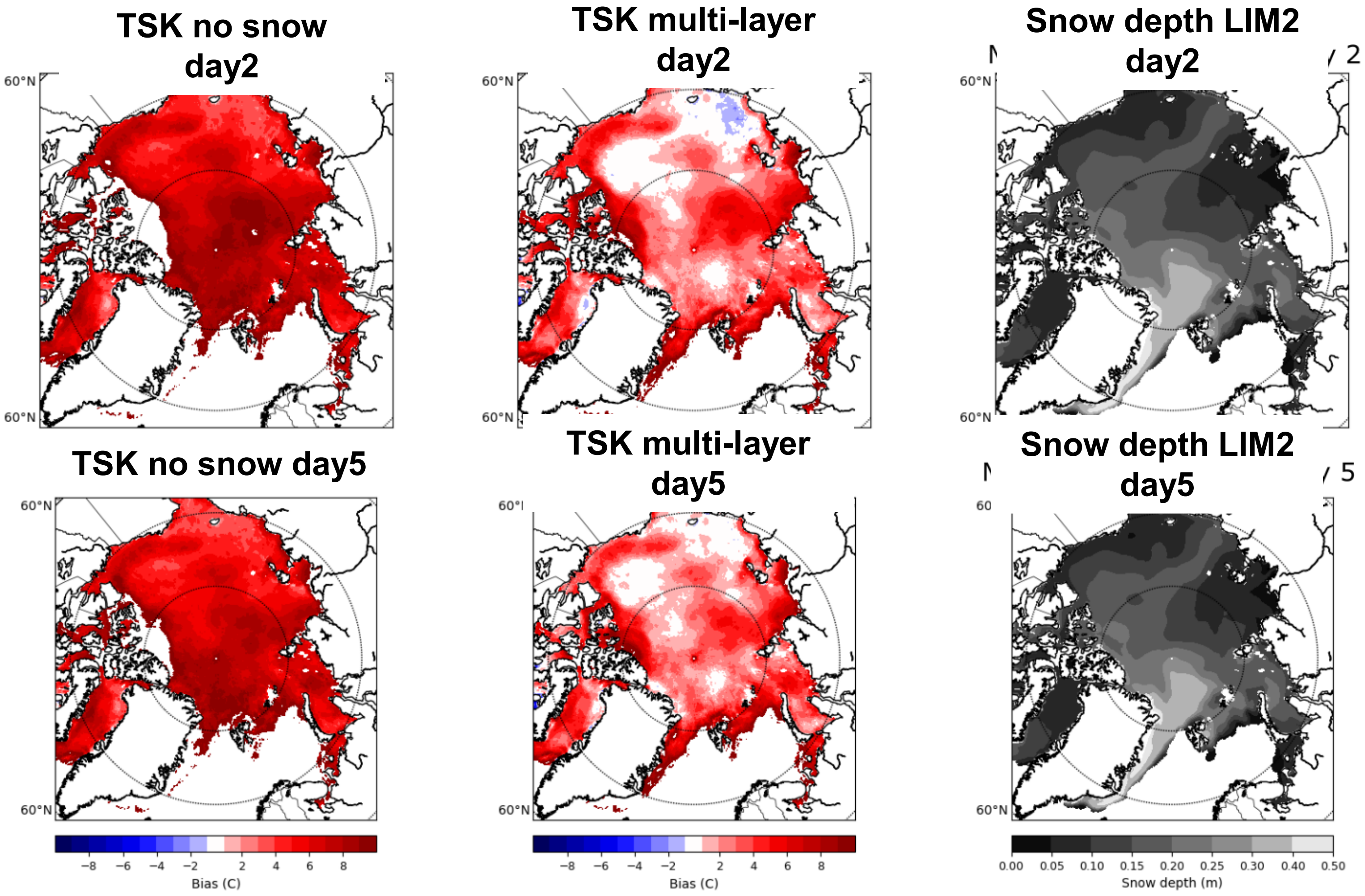
Evaluating the impact of snow over sea-ice in the ECMWF IFS – Arctic

Coupled ocean-atmosphere forecasts at day 2 and 5 for Winter 2015



TSK no snow day2

TSK multi-layer day2

Snow depth LIM2 day2

TSK no snow day5

TSK multi-layer day5

Snow depth LIM2 day5

- General reduction of the bias in snow on ice experiment compared to satellite product
- Errors are most reduced where snow depth is largest
- What is the uncertainty of the satellite?

Arduini et al. 2022

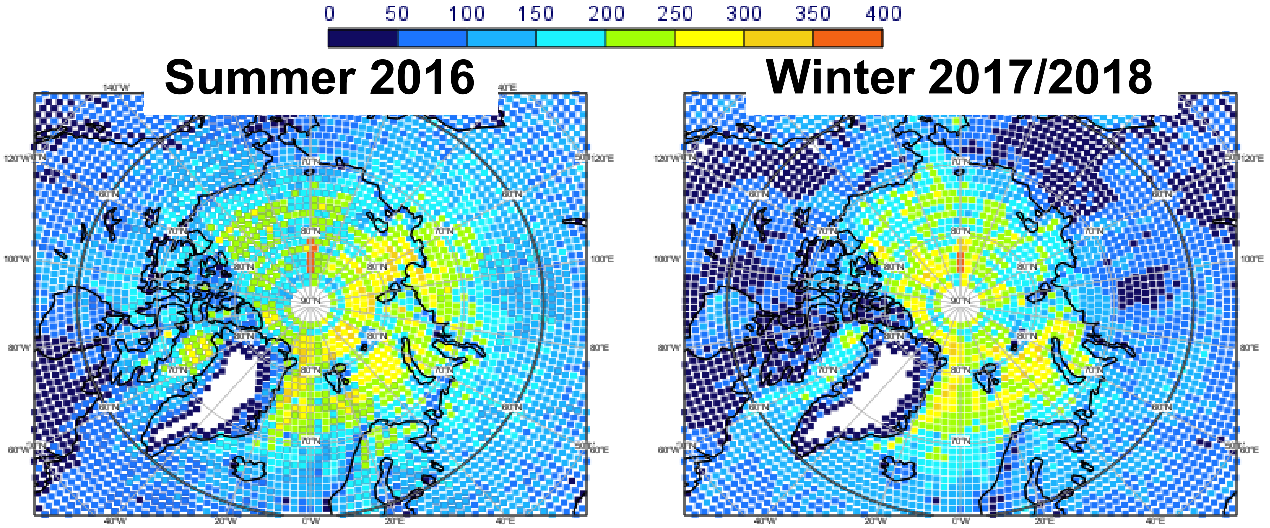
Observation usage challenges

Errors in the surface (skin) temperature, may affect the uptake of satellite observations (together with other sources of errors, e.g. observation operator)

Number of satellite observations

NOAA-15
AMSU-A channel 5
(peaks 500-700hPa)

First guess departure (Obs – FC)

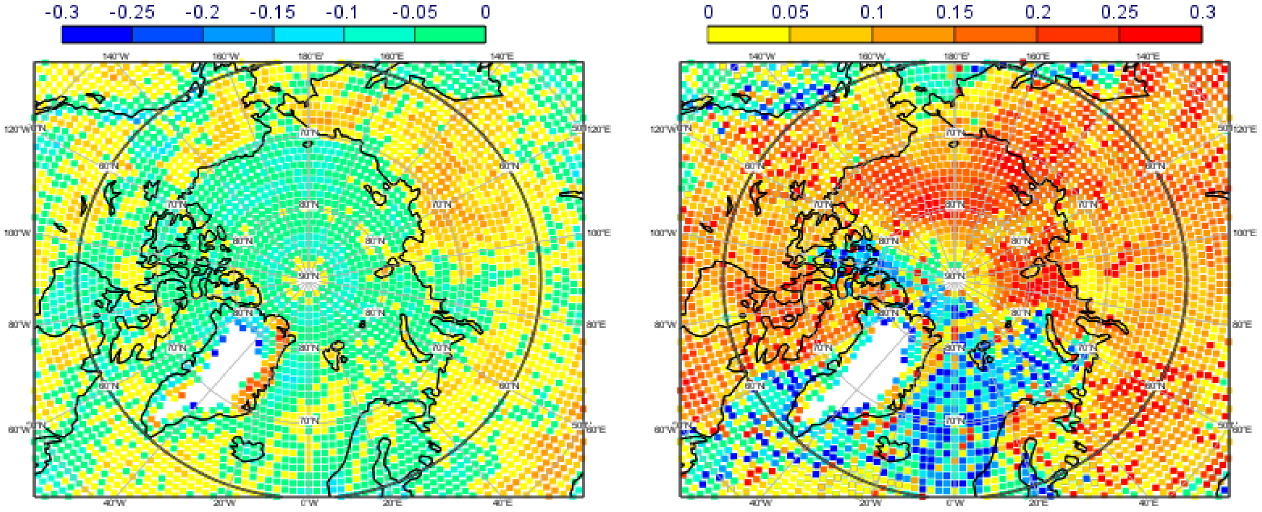


Summer 2016

Winter 2017/2018

a) AMSU-A channel 5 mean O - B summer

b) AMSU-A channel 5 mean O - B winter



- better coverage from polar orbiting satellites than anywhere else
- more challenges with their use
  - model errors
  - radiative transfer modelling
- more data rejected for tropospheric channels in winter, in particular over snow and sea-ice

Lawrence et al, ECMWF, TM845, 2019