Multi-layer snow modelling and cryosphere-atmosphere interactions in the ECMWF Integrated Forecasting System

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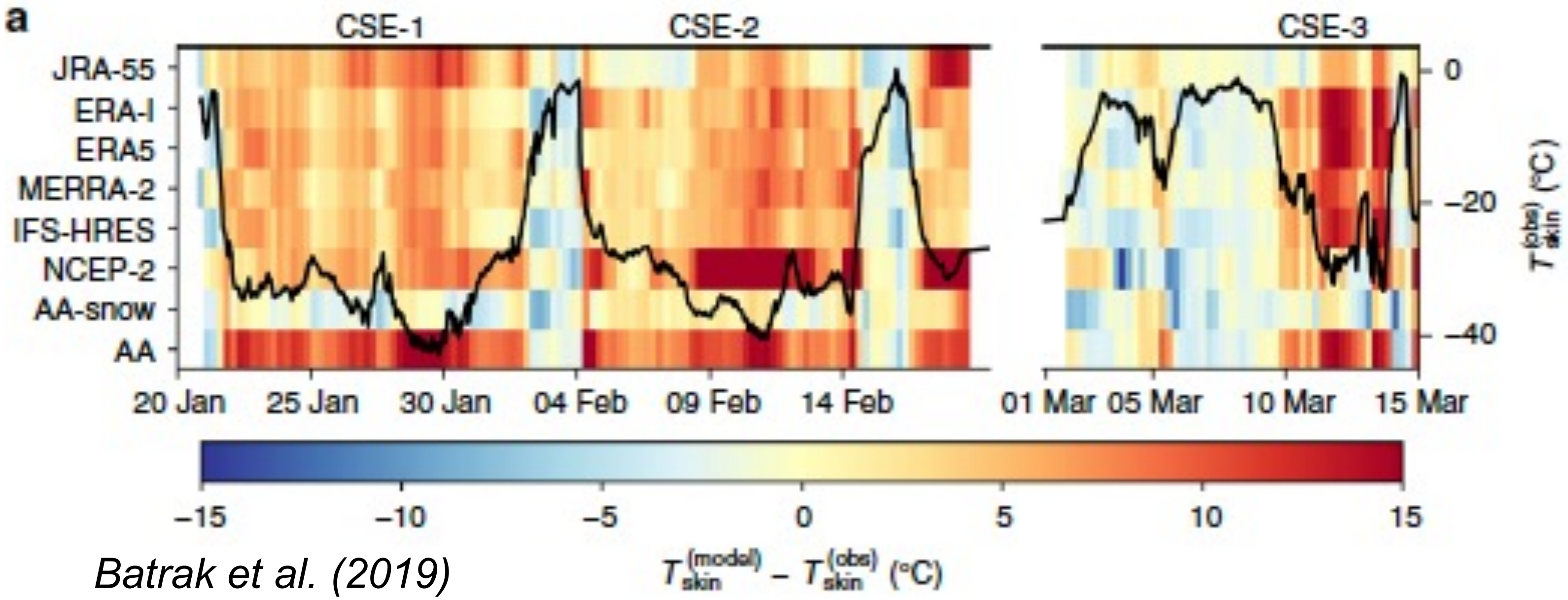
Thanks to Sarah Keeley, Patricia de Rosnay, Ervin Zsoter, Irina Sandu, Jonathan Day, the coupled processes team and many others

Coupled NWP modelling in polar regions

Large errors still exists in current NWP systems

- (Near-) Surface temperature over land/sea-ice, in particular over snow-covered surfaces
- Relevant for reanalysis as well

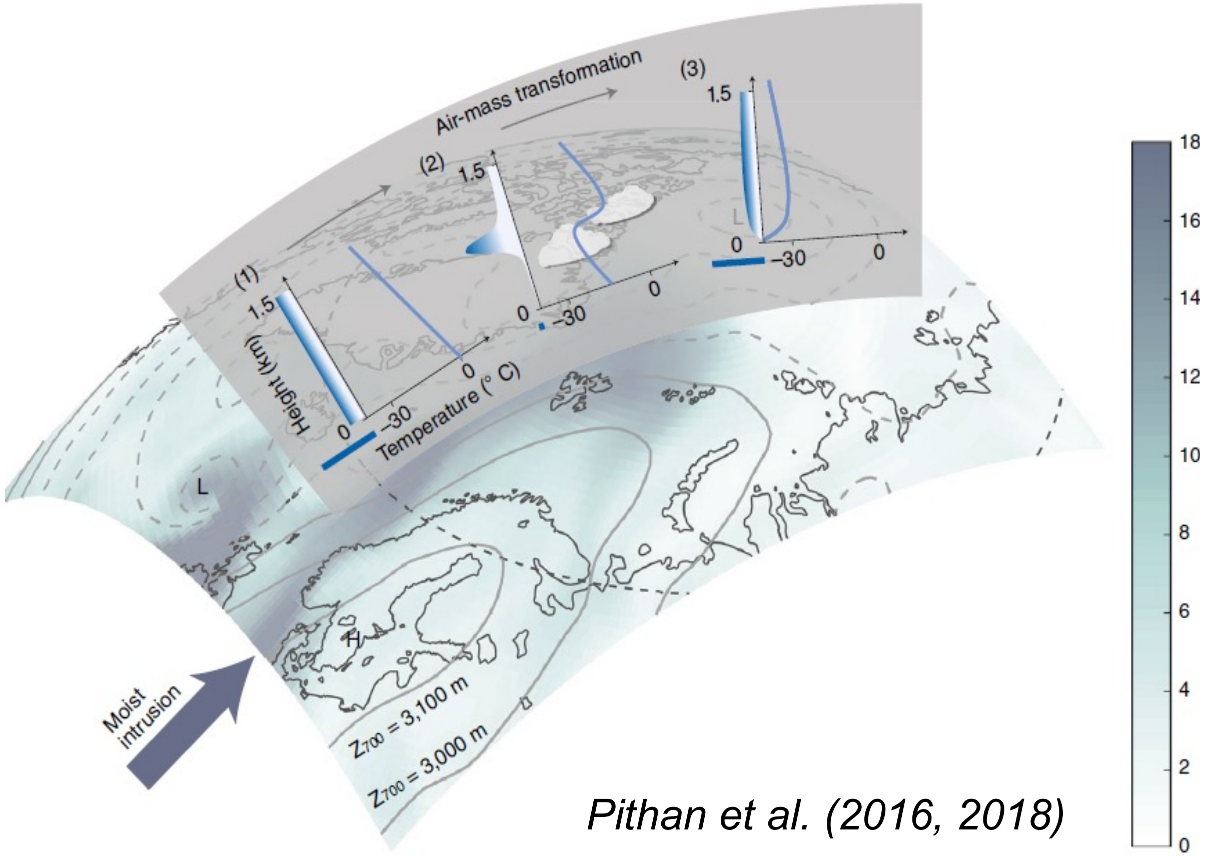


Batrak et al. (2019)

Modelling challenges

Modelling improvements are challenging in polar area

- Range of scales and processes, e.g. ”air mass transformation”
    - Mixed phase clouds, stable boundary layers, sea-ice, snow
- Lack of detailed observations of the coupled processes

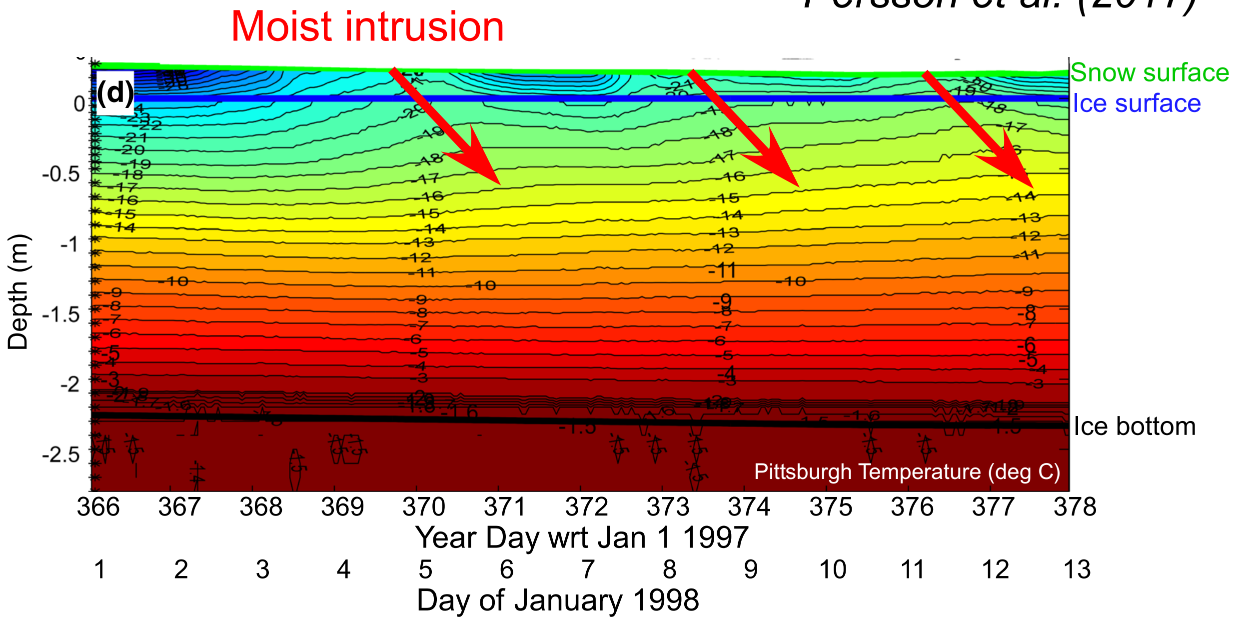


Pithan et al. (2016, 2018)

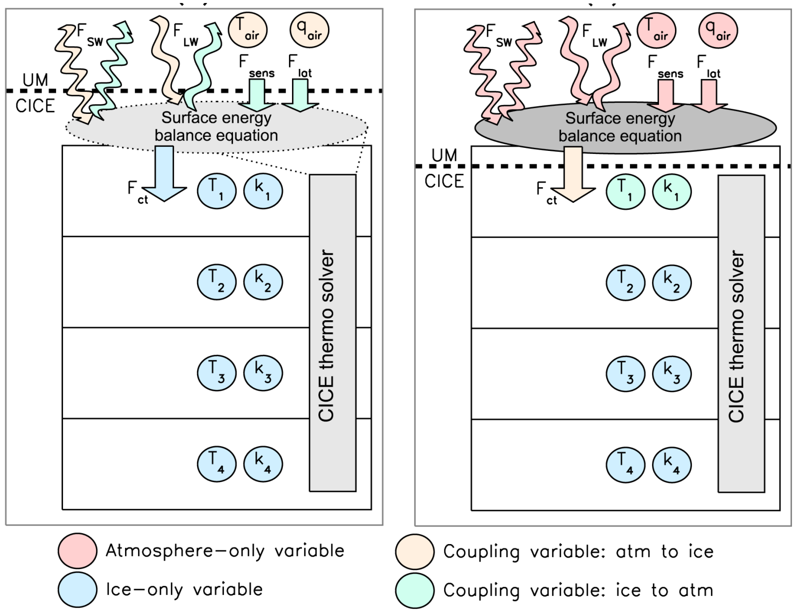
Modelling challenges – Coupled modelling at the surface interfaces

Persson et al. (2017)

- Snow and sea ice insulate the atmosphere and the land/ocean underneath, with large impact on surface fluxes
  - Thermal/Radiative properties depend on the snow/ice characteristics



- Different earth system components (e.g. atmosphere, sea-ice):
  - Which variables and where do we couple?
  - How do we initialize them consistently in NWP?



West et al., GMD (2016)

Needs for modelling surface energy balance

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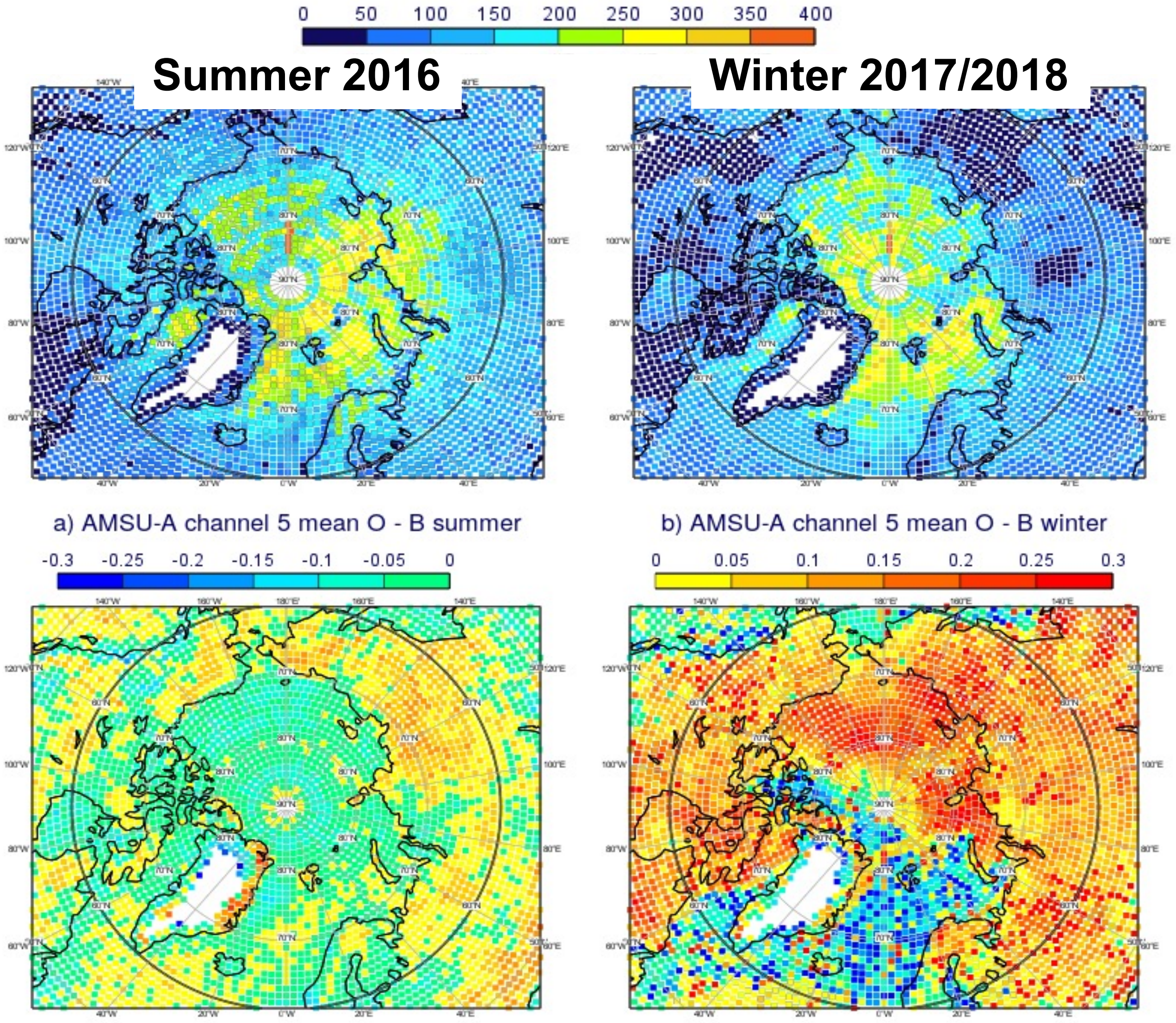
Errors in the surface (skin) temperature, may affect the uptake of satellite observations (together with other sources of errors, e.g. observation operator)

Number of satellite observations

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

First guess departure (Obs – FC)



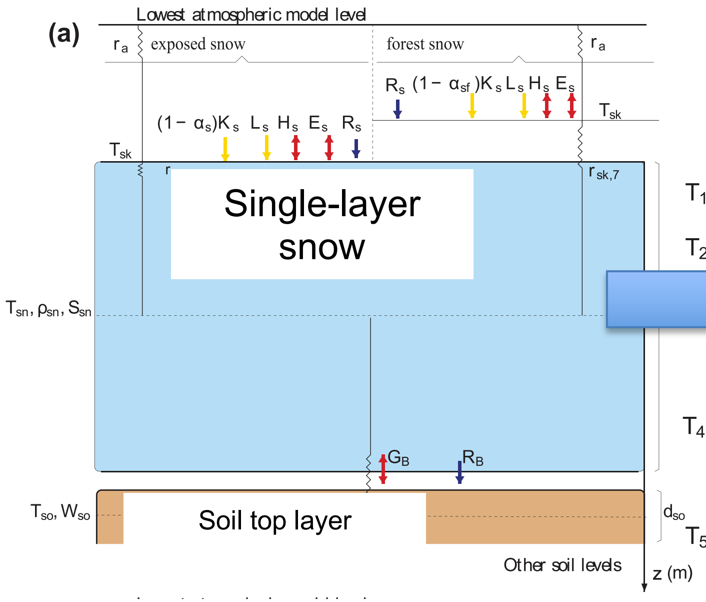
- better coverage from polar orbiting satellites than anywhere else
- more challenges with their use
  - model errors
  - radiative transfer modelling
- more data rejected for tropospheric channels in winter, in particular over snow and sea-ice

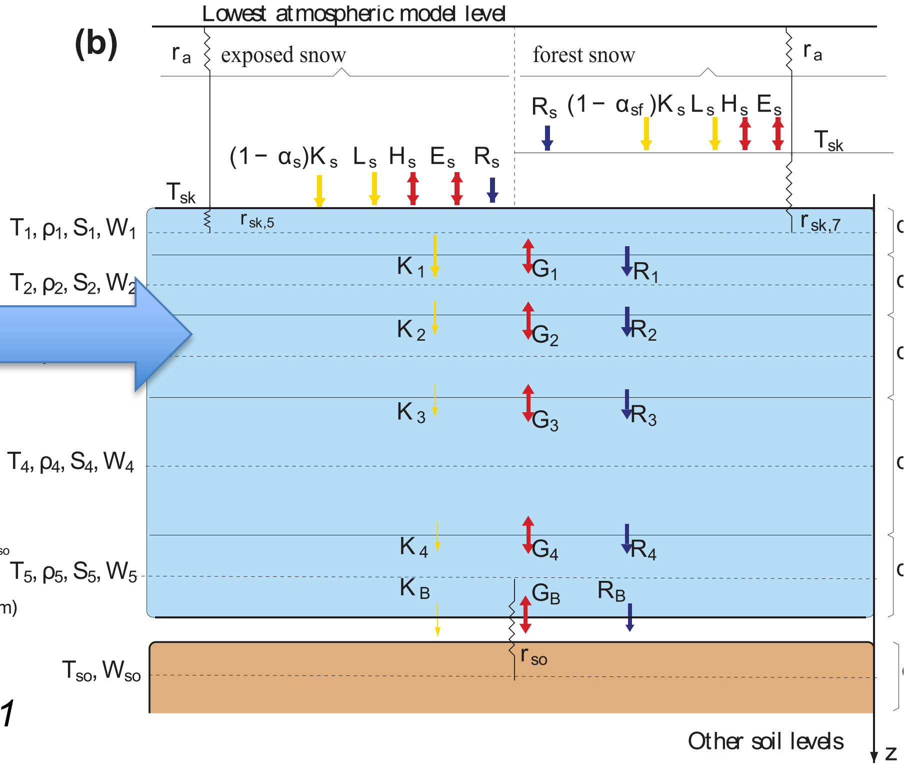
Lawrence et al, ECMWF, TM845, 2019

ECMWF

How are cold surfaces modelled in the ECMWF IFS land-surface model?

Over land:





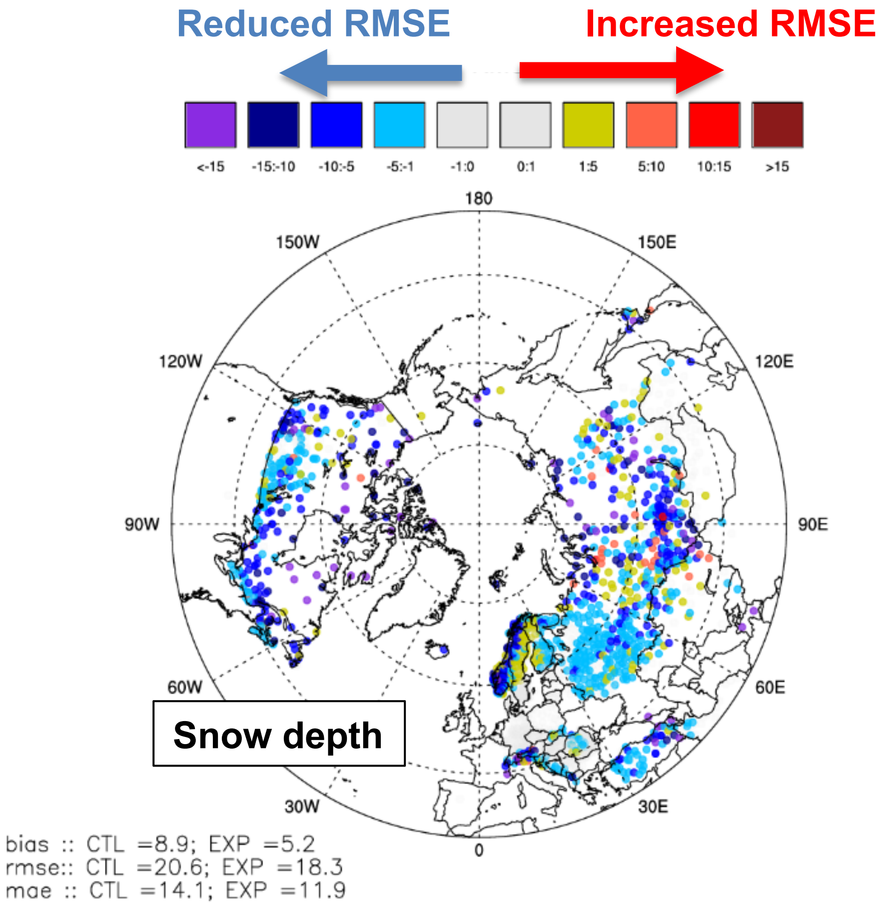
Arduini et al., JAMES 2019;
Boussetta et al., Atmosphere, 2021

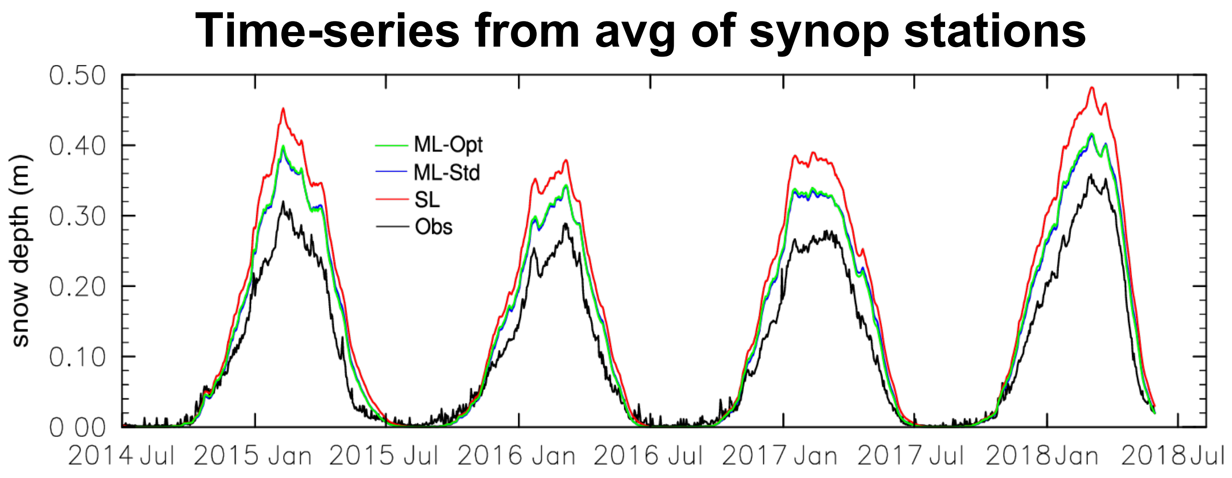
New multi-layer snow scheme:

- Targeted for cycle 48r1 (2022/2023)
- 5-layer snow scheme
- Prognostic liquid water content
- Improved snow physics

Impact of multi-layer snow modelling on snow **depth** in **land-surface only (offline) simulations**

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

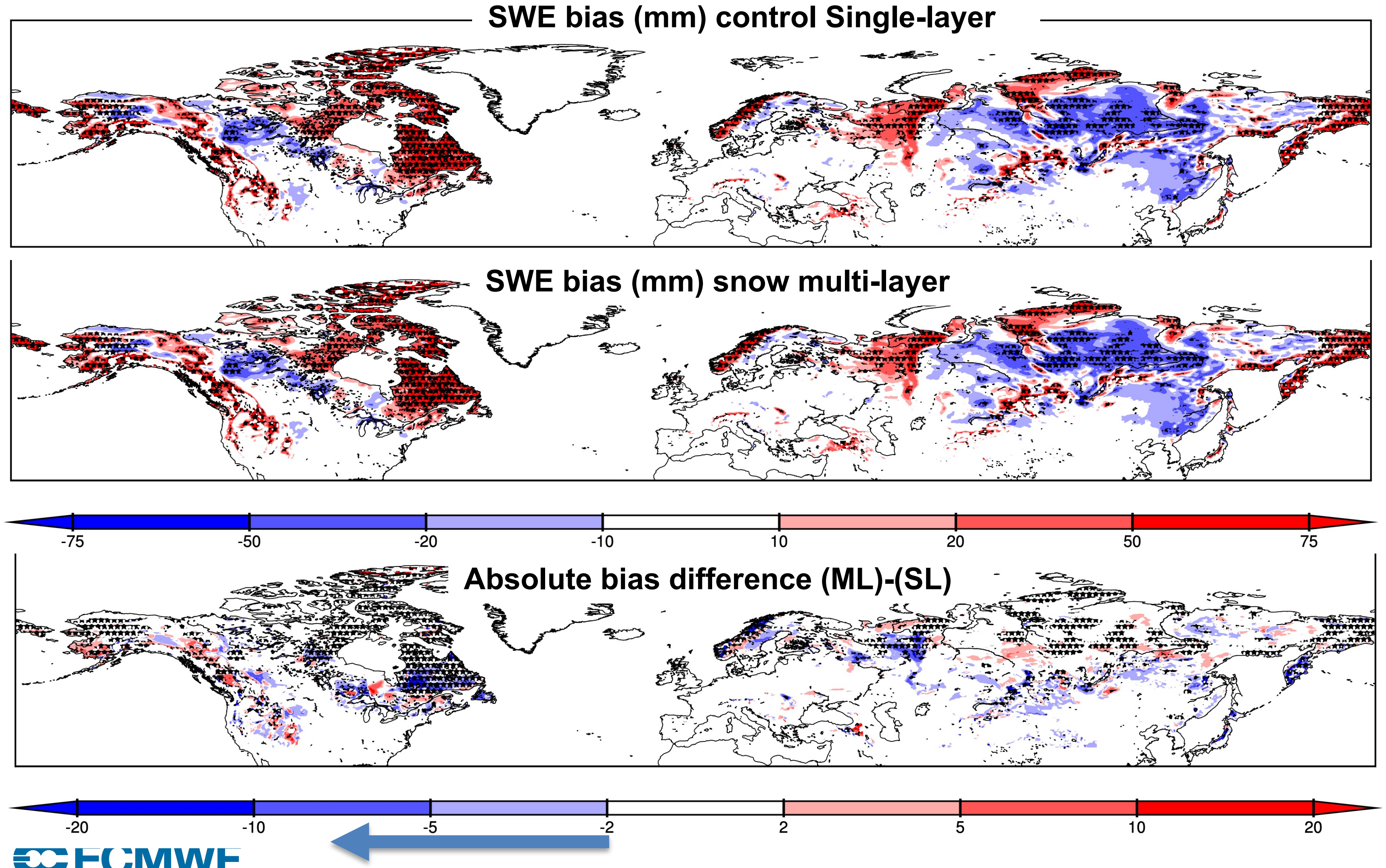




General improvement of snow depth with the multi-layer snow scheme over the NH in offline simulations

Impact of multi-layer snow modelling on snow **mass** in **offline** simulations

- Evaluation using Snow Water equivalent Copernicus GLS product
- Comparison for shallow snowpack and for the accumulation period (Dec/Jan) for 3 years



ML snow reduces bias

Large positive biases over North America, Scandinavia, Rockies; negative biases in central Siberia

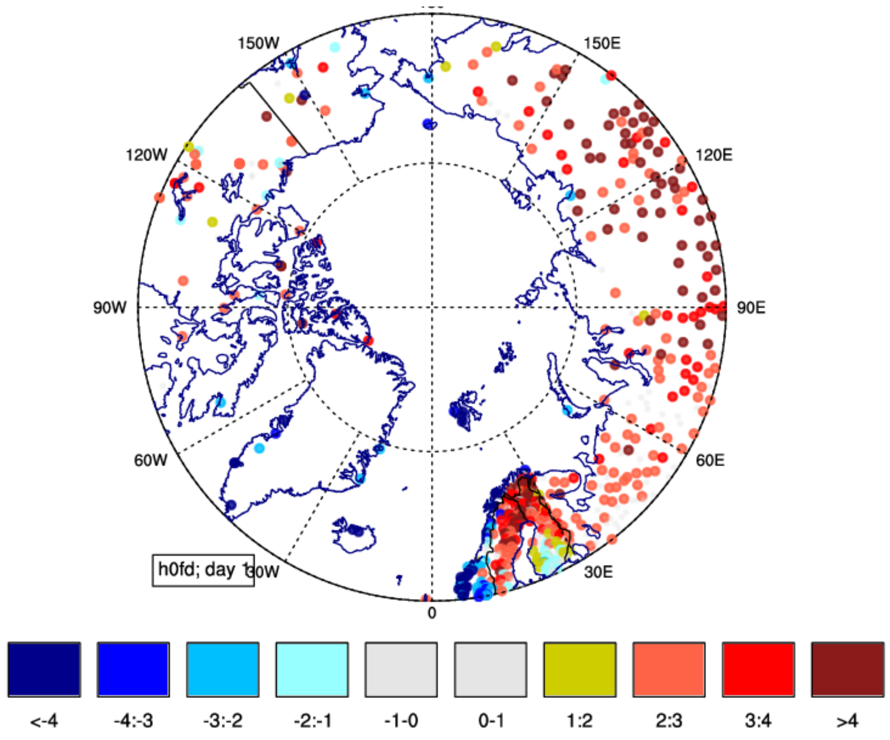
Multi-layer snow has small but positive impact (North America)

How much can we trust the SWE product?

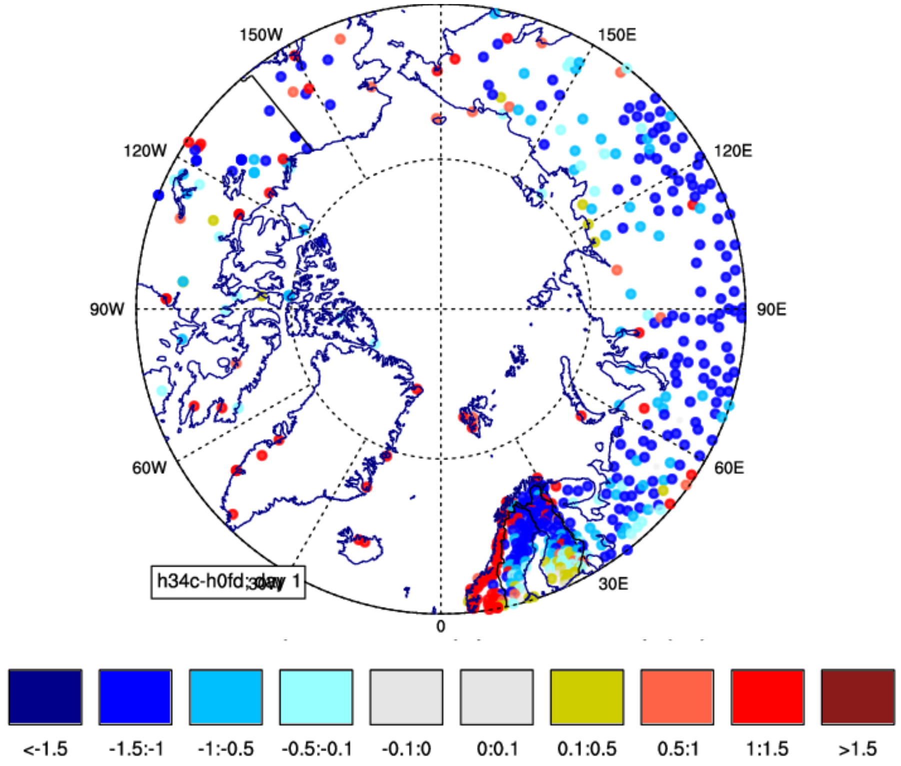
Impact of multi-layer snow modelling in **coupled land-atmosphere forecasts**

Coupled forecasts for winter 2016/2017 (December to February), t+24 hours,
Initialised from ECMWF operational analysis

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 cold episodes with multi-layer snow

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

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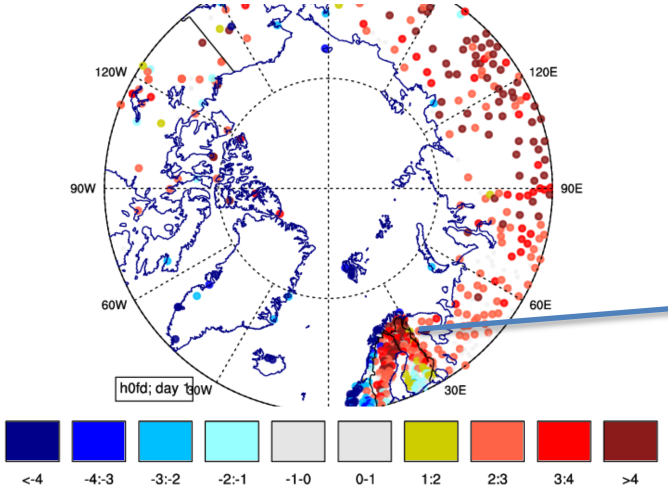
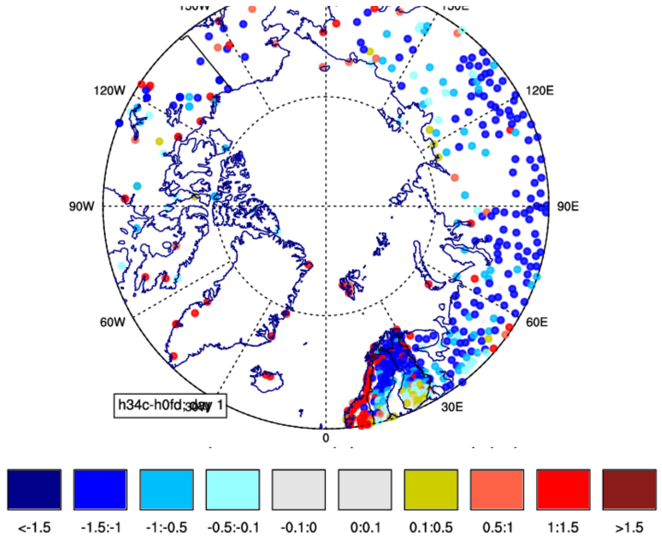
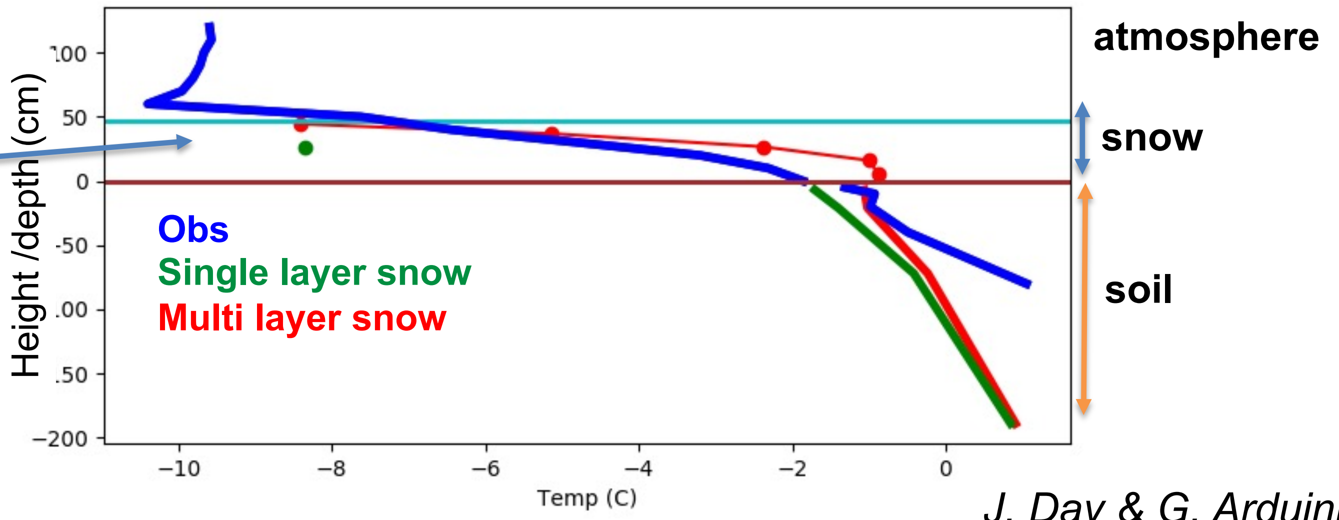
Bias minimum 2-metre temperature (T2m) single-layer snow (CTL) against obs



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



Temperature profile within the snowpack for Jan-Feb 2017 at Sodankyla, Finland

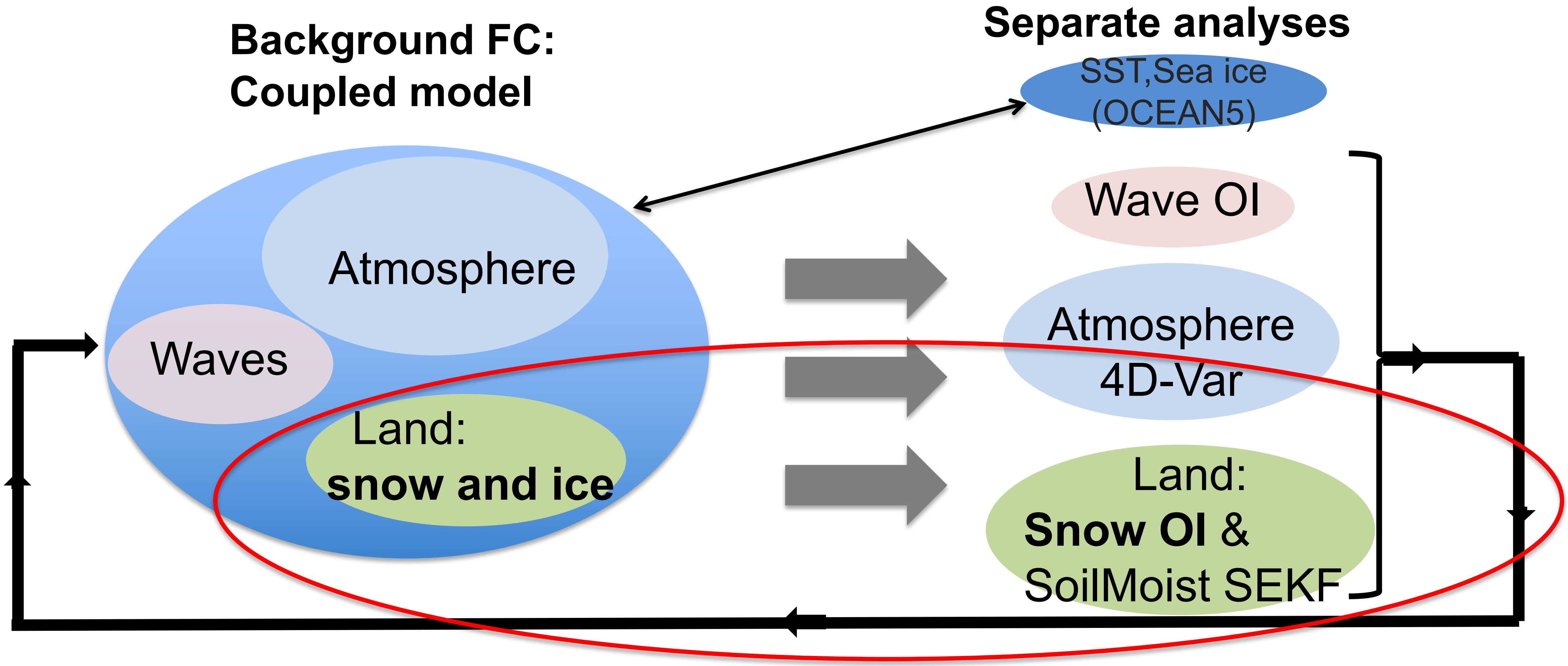


J. Day & G. Arduini

Improved simulation of snow internal temperature/density gradients

- ➢ Coupling to snow emission models, see Hirahara et al., Rem. Sens. 2020

Coupling approach of different Earth System Components in the ECMWF IFS

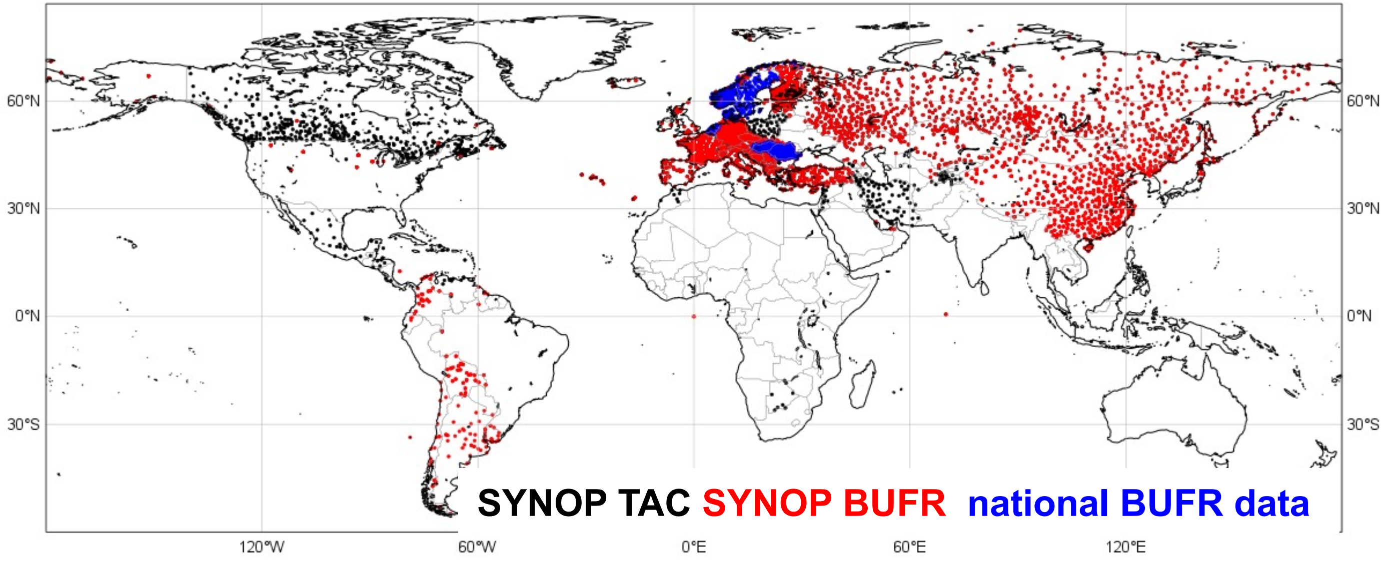


Snow data assimilation and observations

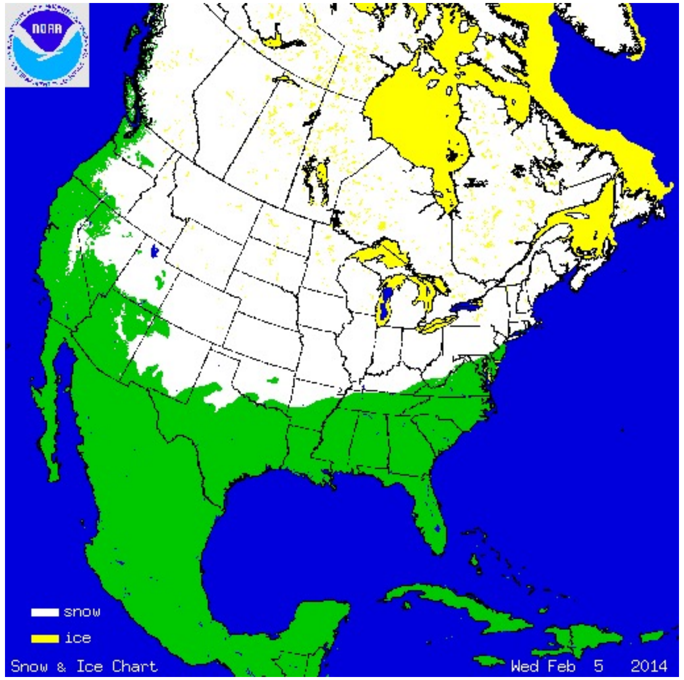
Data Assimilation: *de Rosnay et al SG 2014*

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

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



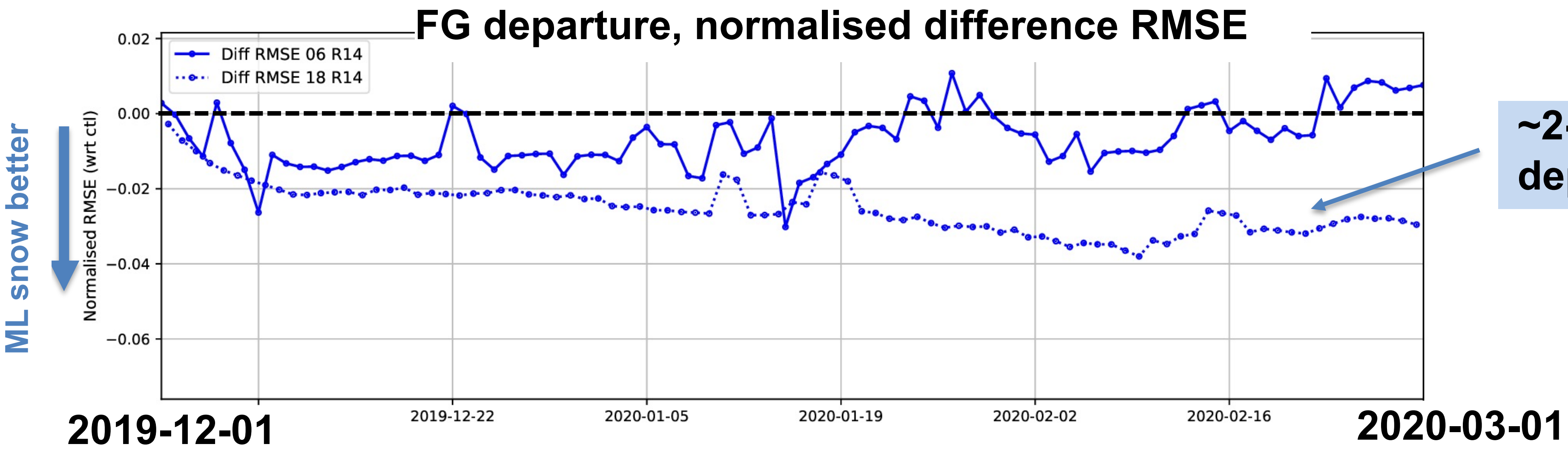
NOAA/NESDIS IMS Snow extent data



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

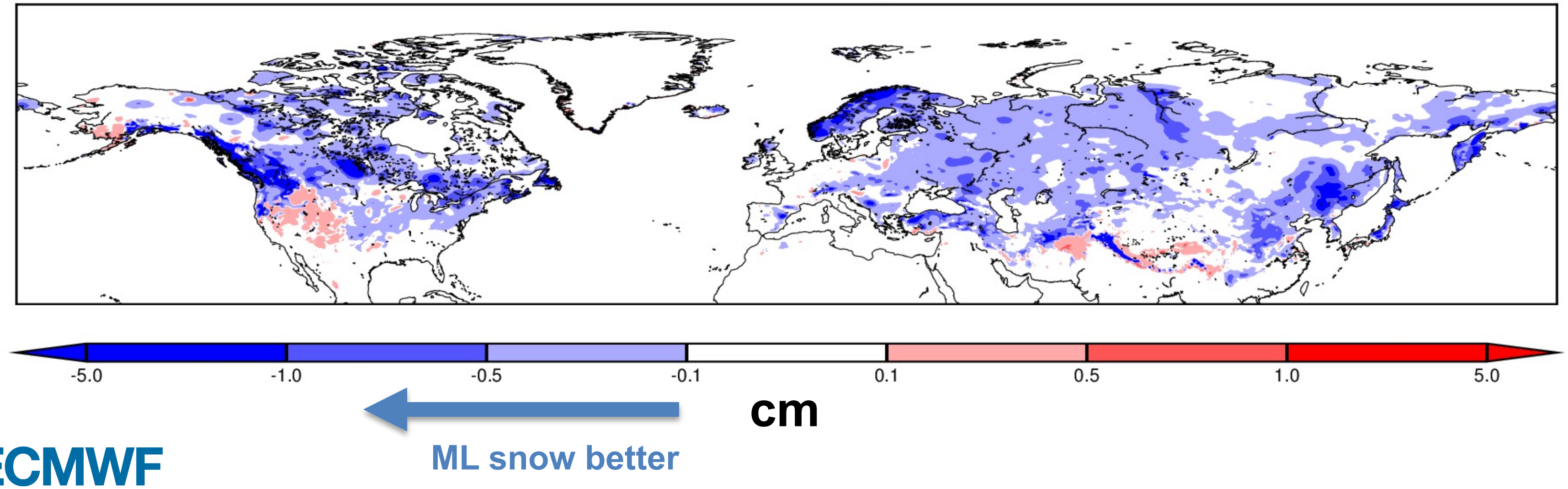
Multi-layer snow impact in the snow data assimilation system

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



~2-3% reduction of snow depth FG departure

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



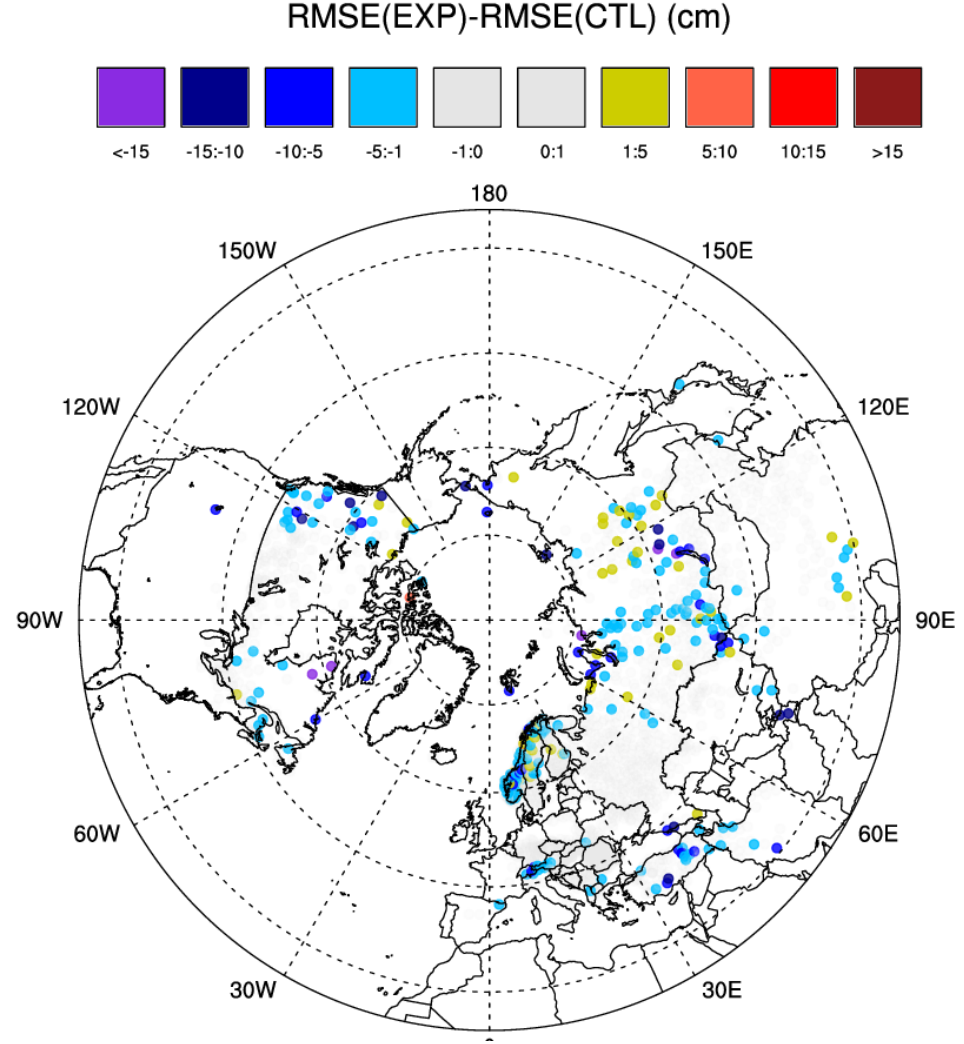
General reduction of analysis increments

ECMWF

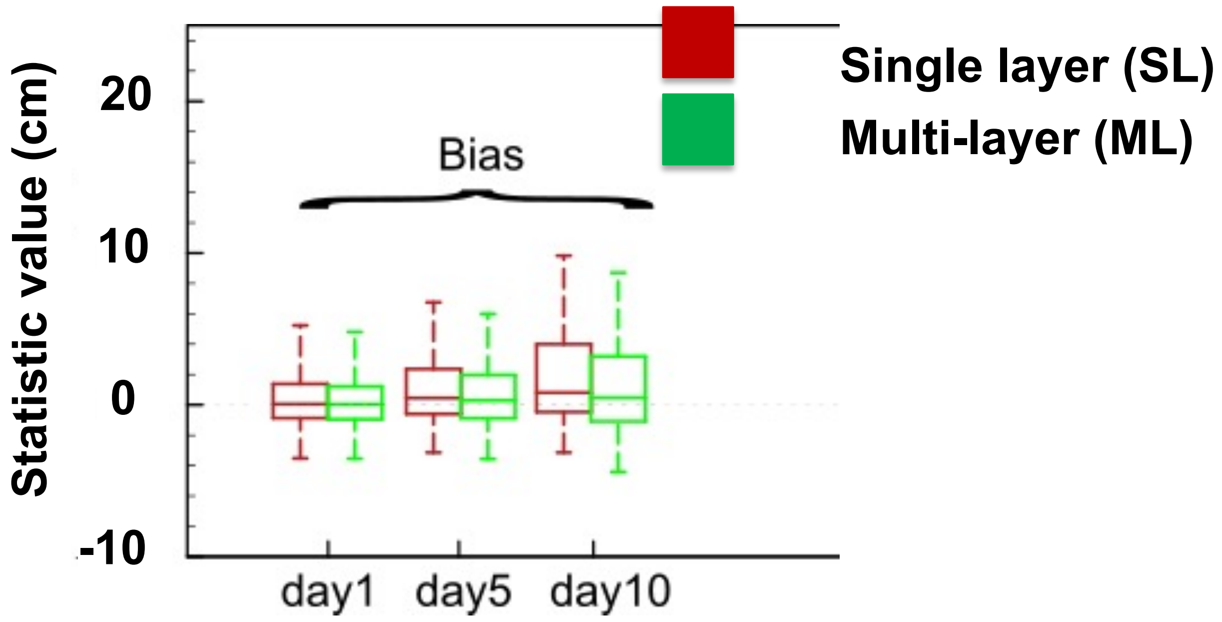
Impact on snow depth in forecasts initialized from analysis using the multi-layer snow

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

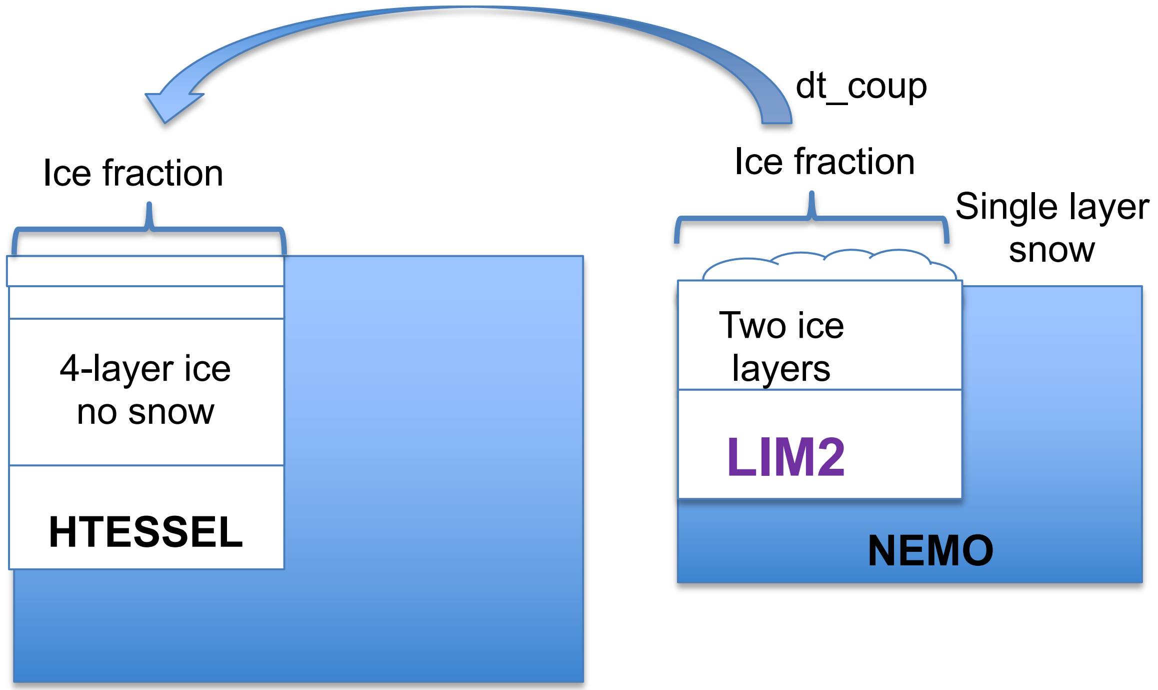
How are cold surfaces modelled in the ECMWF IFS land-surface model?

Over sea-ice

How are cold surfaces modelled in the ECMWF IFS land-surface model?

<u>Over sea-ice</u>

- 4-layer thermodynamic ice-scheme, no snow on top
- Ice fraction from sea-ice model (LIM2) **coupled** every coupling step



Keeley and Mogensen, ECMWF, 2018

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

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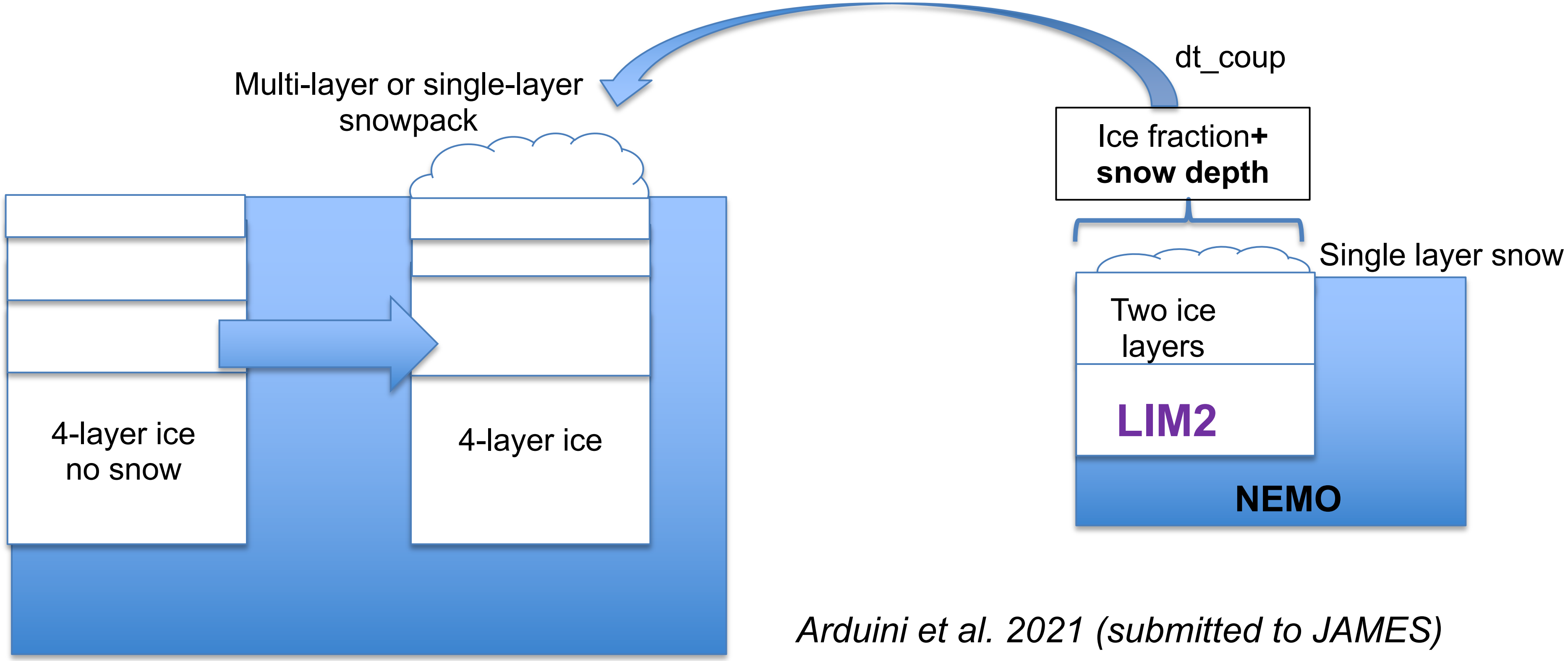
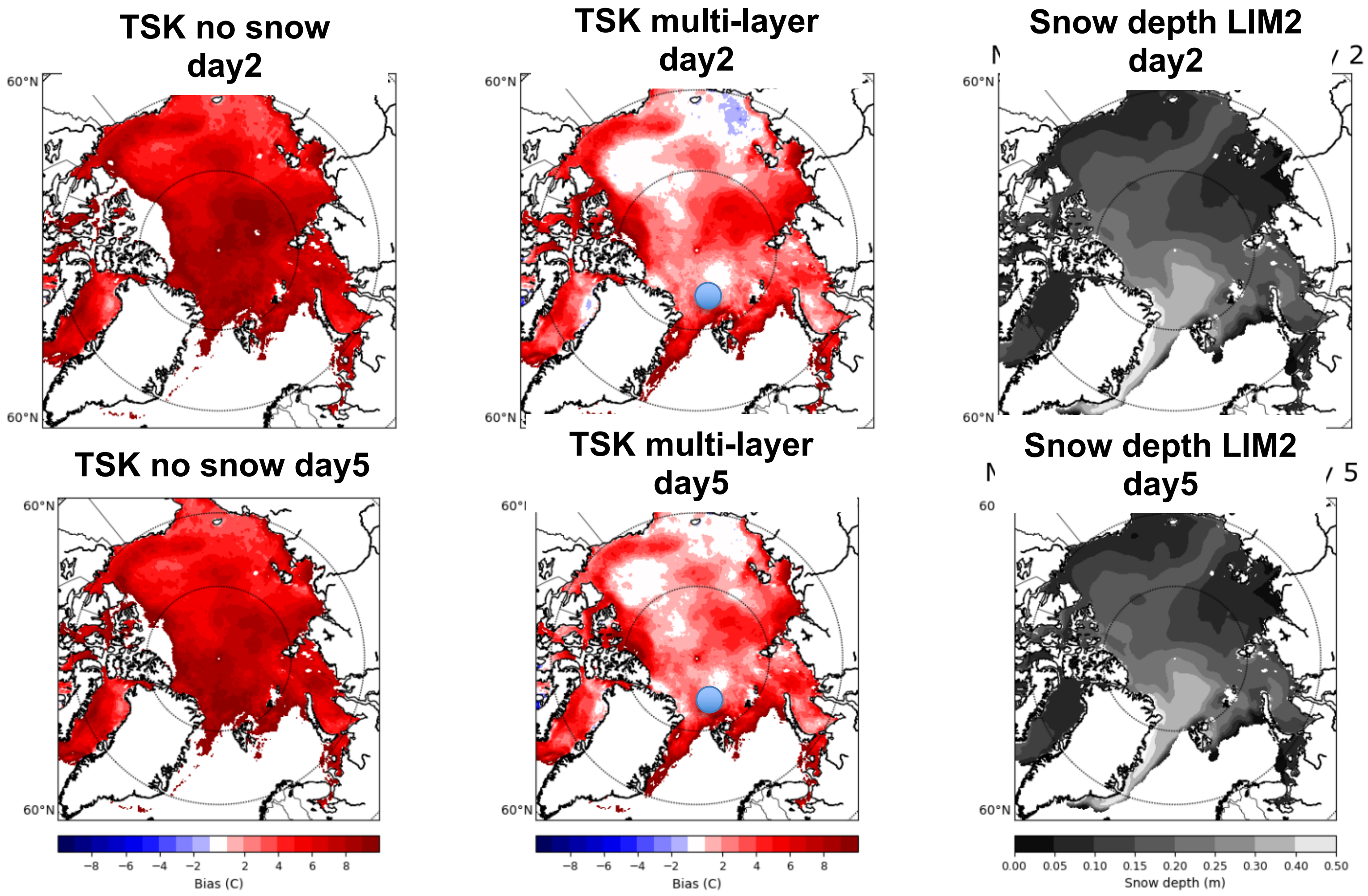
- Accounting for the thermal effect of snow on top of sea-ice in the IFS
- Coupling of ice fraction and snow depth from LIM2



Arduini et al. 2021 (submitted to JAMES)

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

- Evaluation using surface temperature from Copernicus Marine Environmental Monitoring Service (CMEMS)
- Coupled ocean-atmosphere forecasts at day 2 and 5 for Winter 2015



- General reduction of the bias in snow on ice experiment compared to satellite product
- Are the biases reduced for the right reason?
  - Compensation between snow and sea-ice (e.g. thickness)
- How good is the snow depth represented on a pan-Arctic scale?
- What is the uncertainty of the satellite?

Arduini et al. 2021 (submitted to JAMES)

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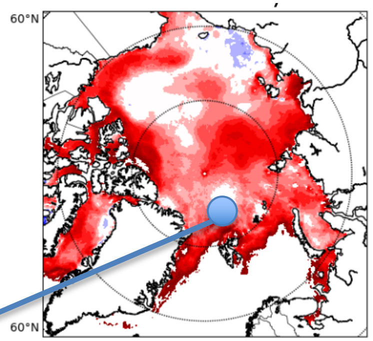
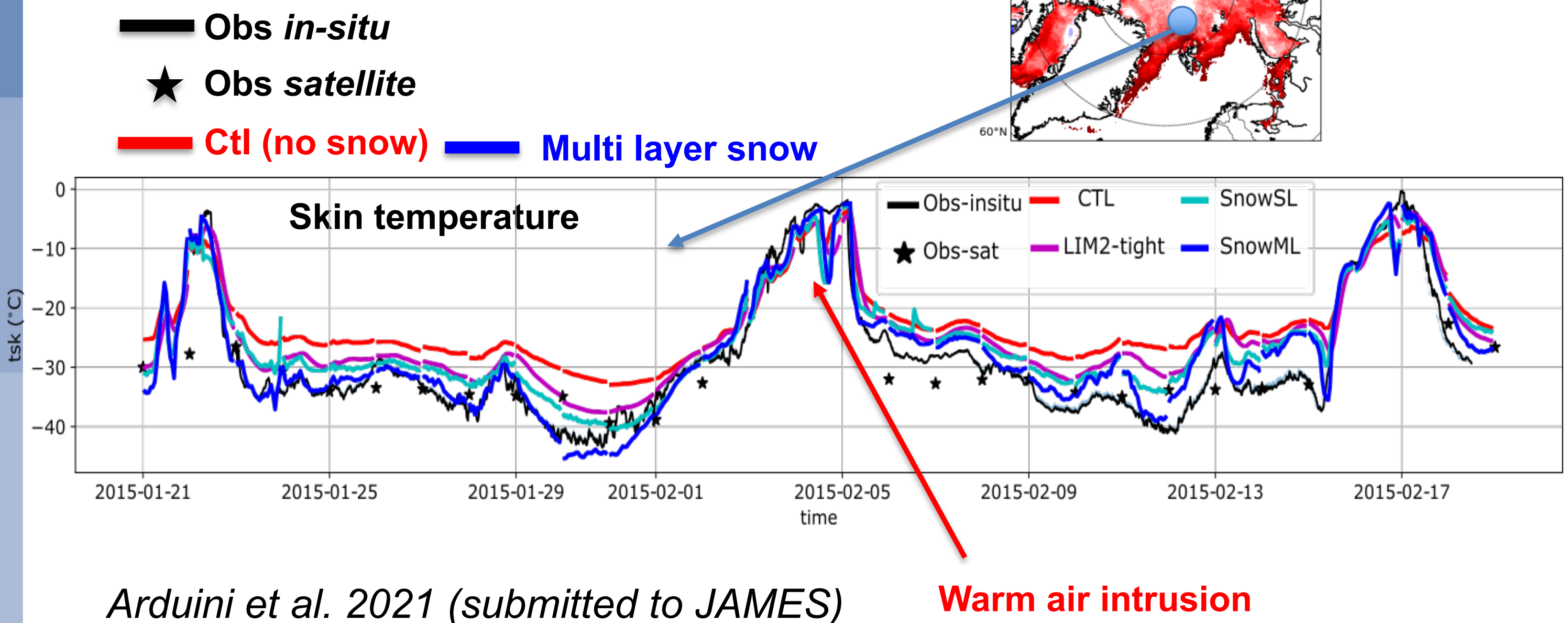
Evaluating the impact of snow over sea-ice in the ECMWF IFS, good case

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





Arduini et al. 2021 (submitted to JAMES)

- 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
- Satellite observations of Tskin hardly show the *in situ* variability

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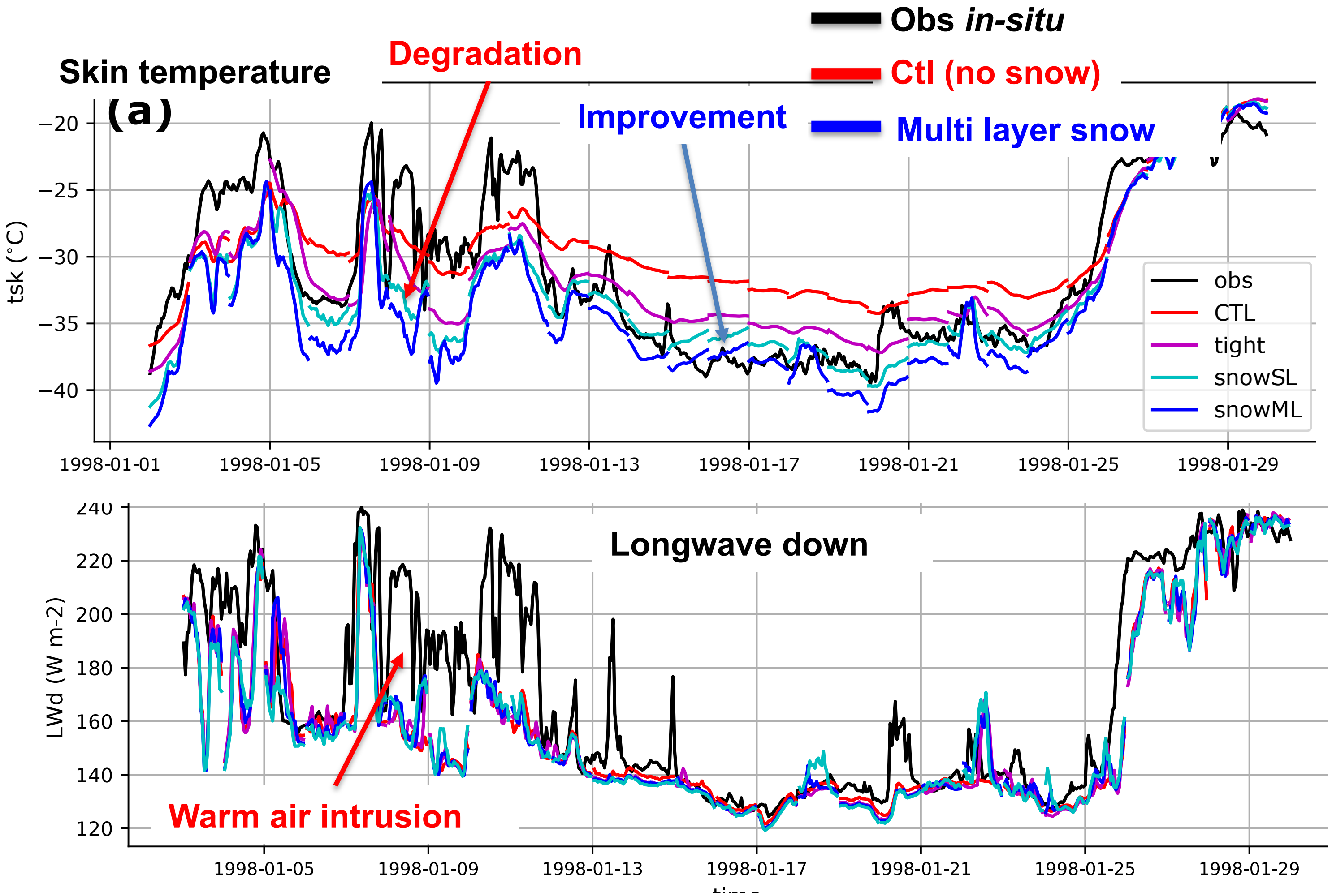
Evaluating the impact of snow over sea-ice in the ECMWF IFS, less good case

Evaluation using *in situ* observations from **SHEBA** campaign, January 1998
→ no satellite observations



- Accounting for snow over sea-ice improves skin temperature in certain situations but degrades in others
- Errors in skin temperature linked to large underestimation of LW down, e.g. errors in mixed-phase clouds
- Compensating errors between rapidly changing LWdown (e.g. cloud cover/phase) and surface response, degrading the skin temperature in the experiments with snow

Arduini et al. 2021 (submitted to JAMES)

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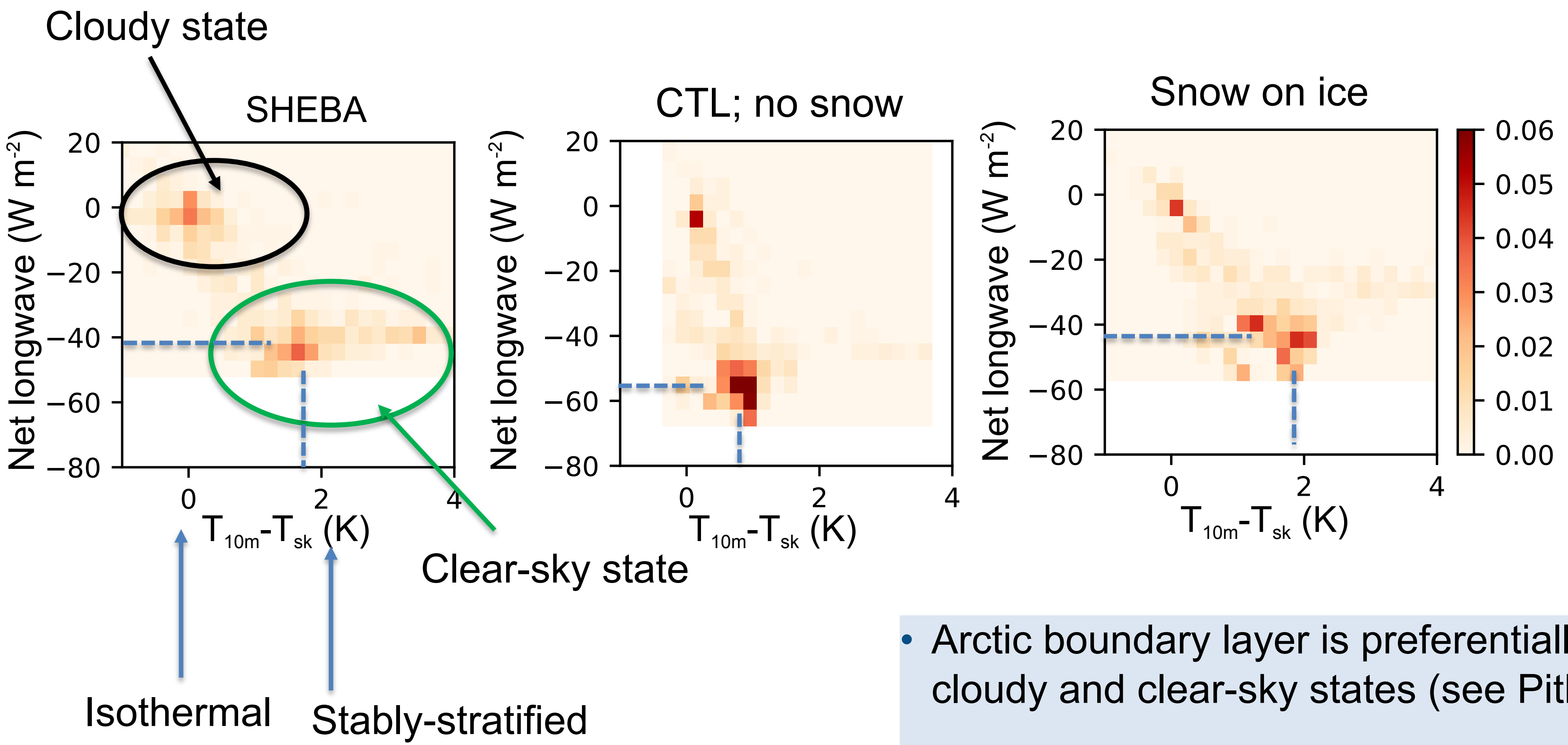
Impact on Arctic winter states – SHEBA case



- Arctic boundary layer is preferentially in two states – cloudy and clear-sky states (see Pithan et al. 2016)
- 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

Summary and additional thoughts

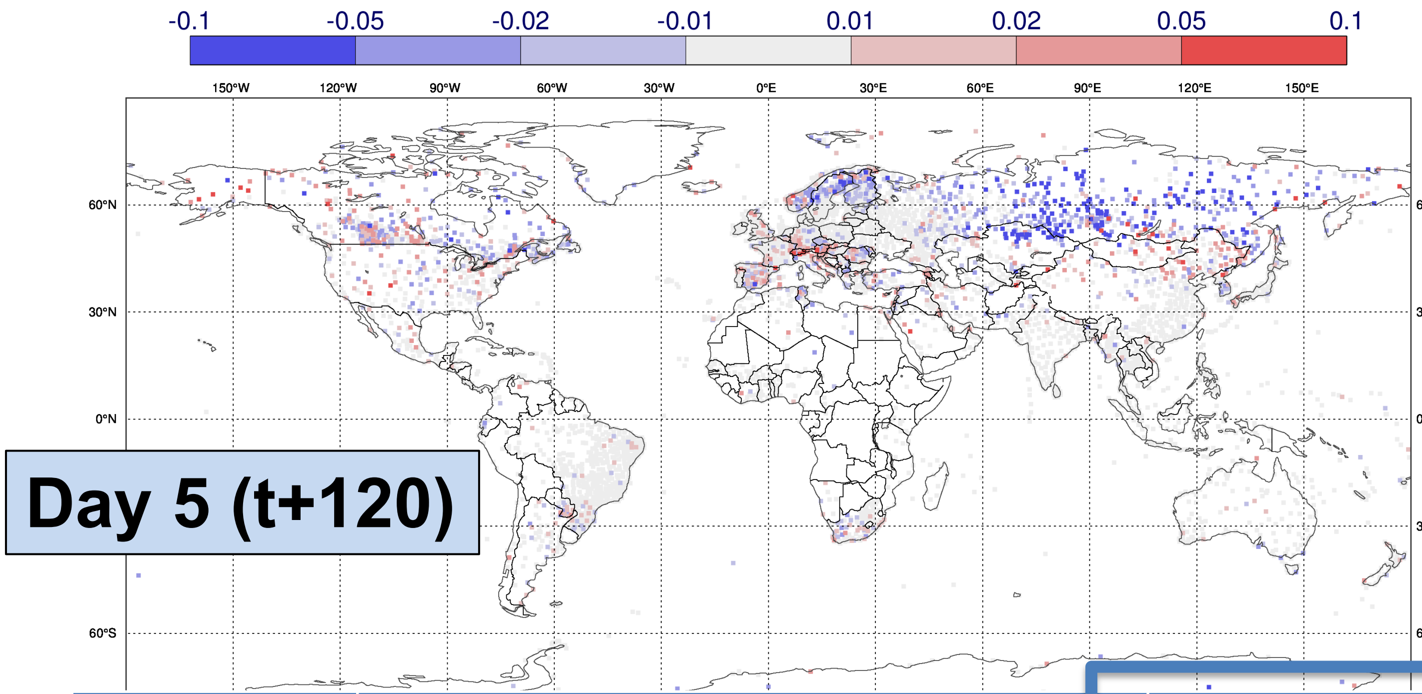
- Improving coupled modelling of **snow and sea-ice** can also enable to improve our use of microwave satellite observations in the polar regions (”all-sky”, ”all-surface” assimilation)
- Multi-layer snow model **targeted for operational** implementation in **IFS cycle 48r1** (2022/2023) improves the snow representation and near-surface temperature biases over cold surfaces
- Accounting for snow over sea-ice can help in addressing biases in surface temperature
  - How do we initialize those components in a coupled NWP system, e.g. snow depth/cover over sea-ice?
    - Benefitting from future satellite missions, e.g. CIMR?
  - Challenges related to compensating errors between cloud and surface processes: having confidence that our model developments bring the model closer to observations *for the right reason* is crucial

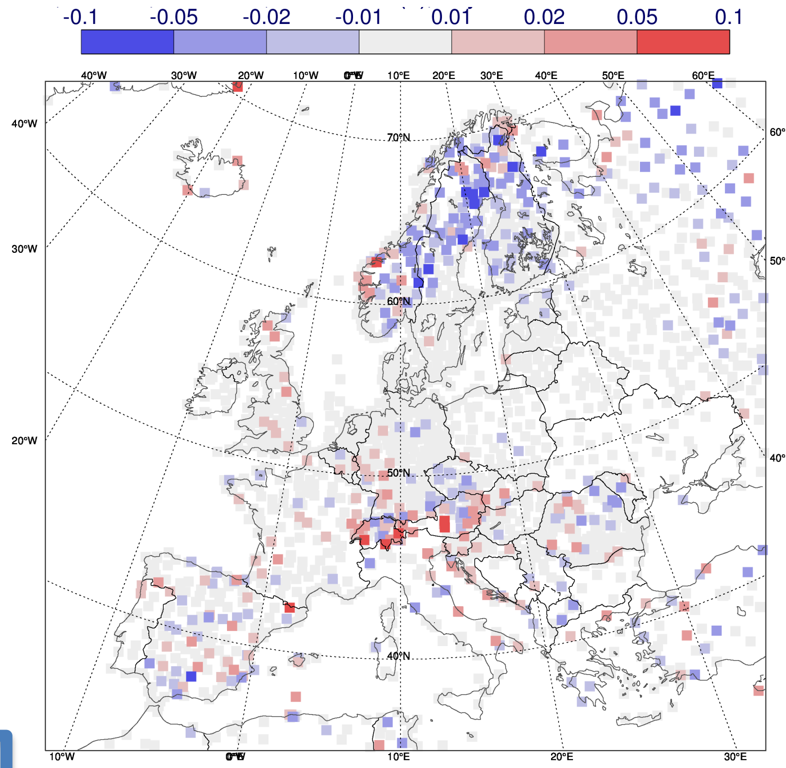
Extra slides

Impact on T2m in ensemble forecasts (8 members) – **Fraction of CRPS err > 5K**

Winter, DJF 2019/2020

FC initialized at 00UTC from analysis using consistent snow scheme (multi-layer or single-layer)





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%**

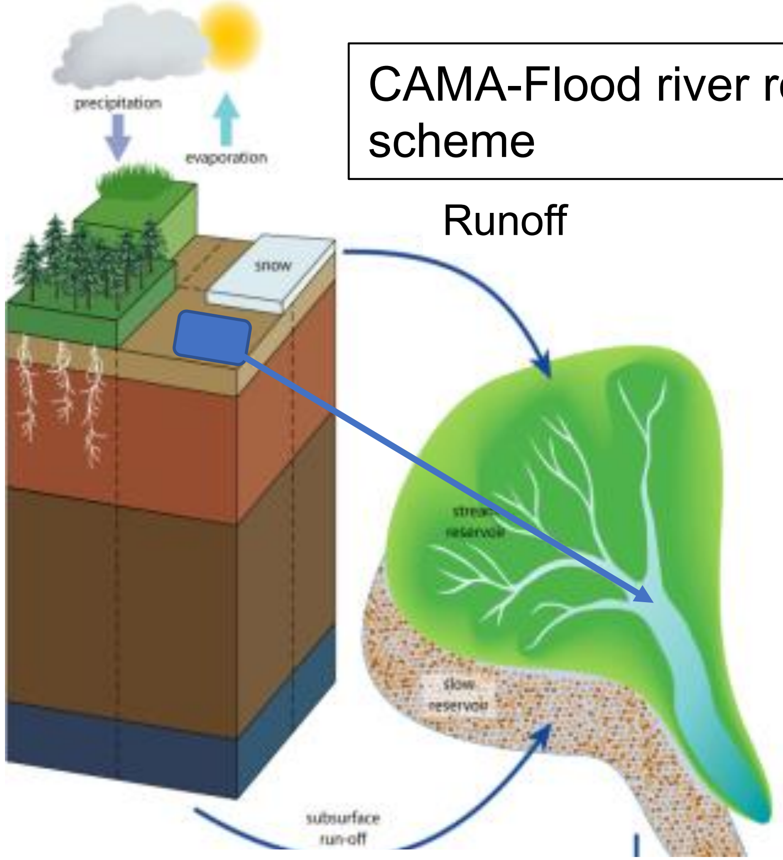
Thanks to Thomas H. for the maps and statistics

HTESSEL coupled to CAMA-Flood river-discharge for hydrological studies

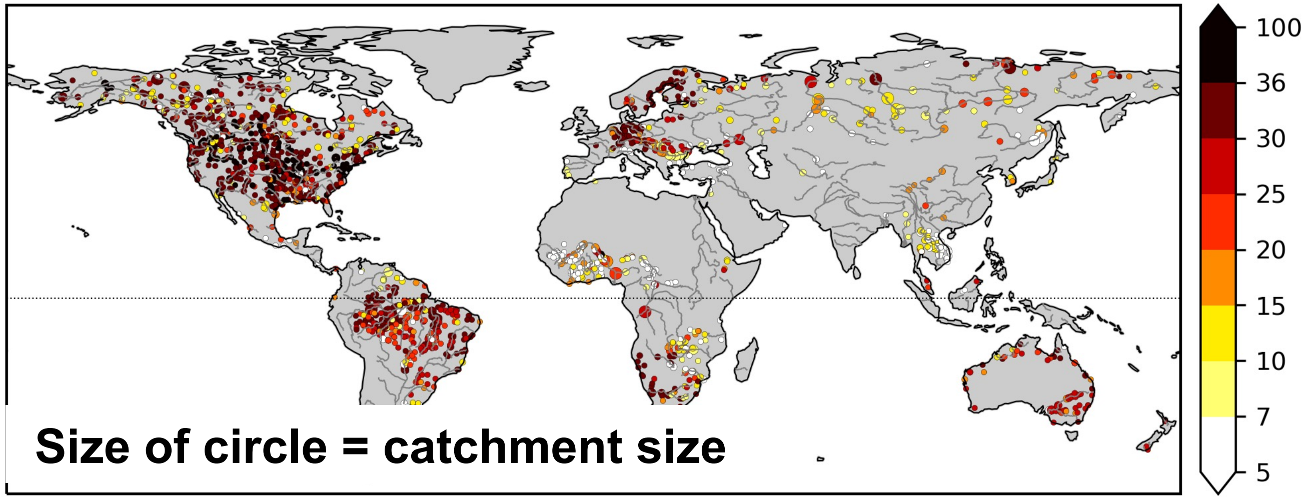
Coupling river-discharges allow using in-situ EO of river discharge to inform land-surface model developments on the impact on the hydrological cycle

HTESSEL driven by **ERA5** meteorological forcing

CAMA-Flood river routing scheme



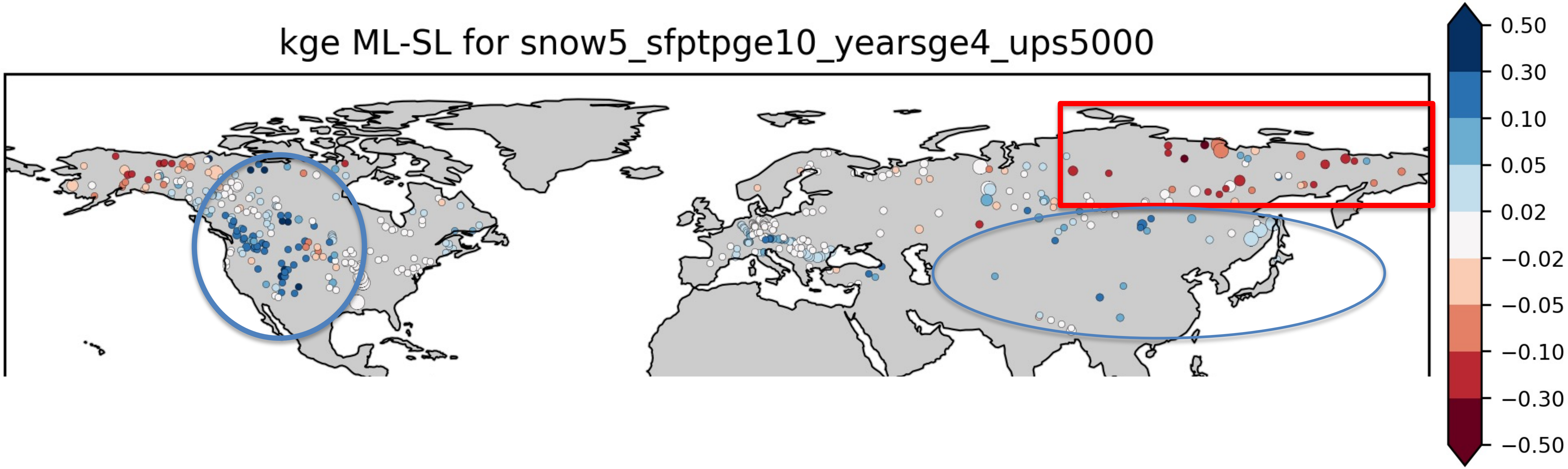
River discharge observations from **GRDC** network (colours indicate number of years with data)



In preparation for **SWOT** Mission

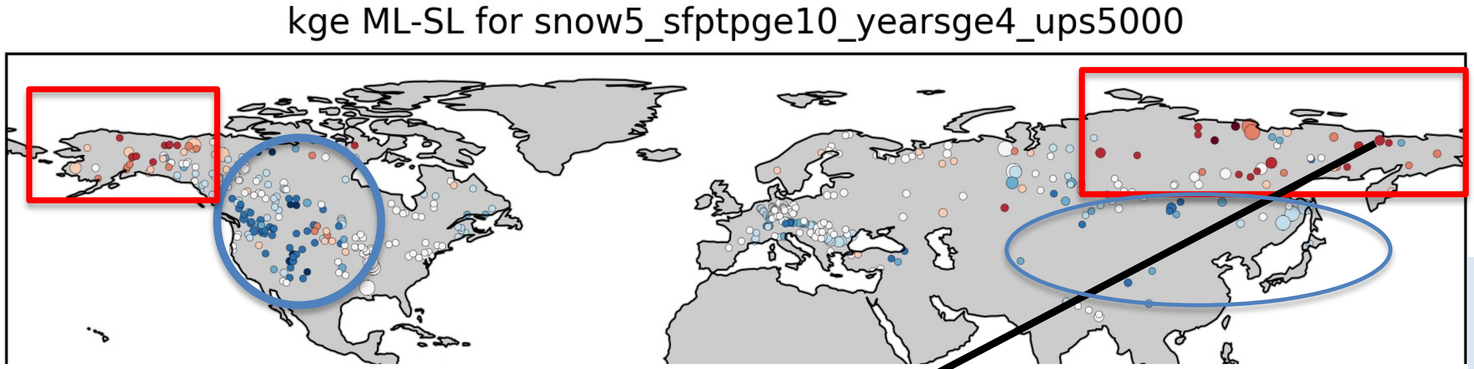
Evaluating land-surface model developments with hydrology, the example of the multi-layer snow scheme

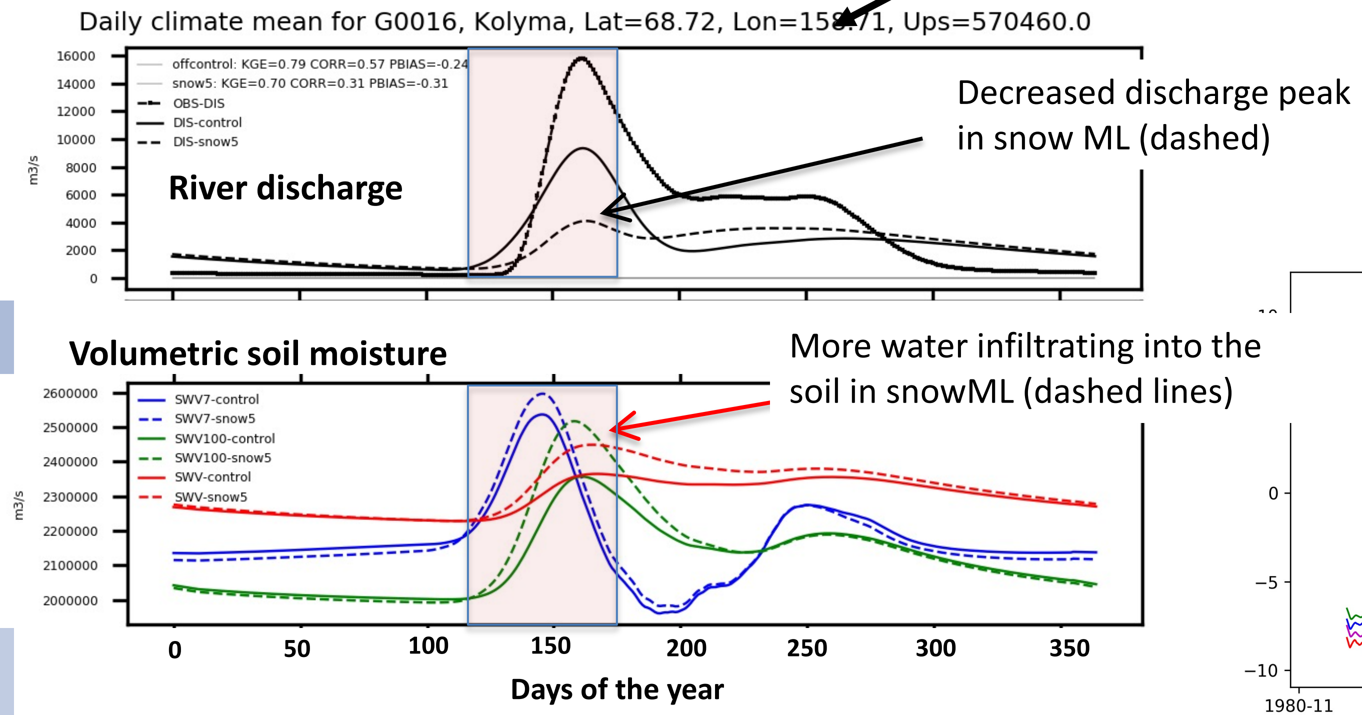
- More catchments show improvements, in particular over Rockies and mid-latitude Eurasia
- However many catchments in high latitude show lower KGE/correlation than the single-layer snow experiment (Siberia and Alaska, e.g. permafrost regions)



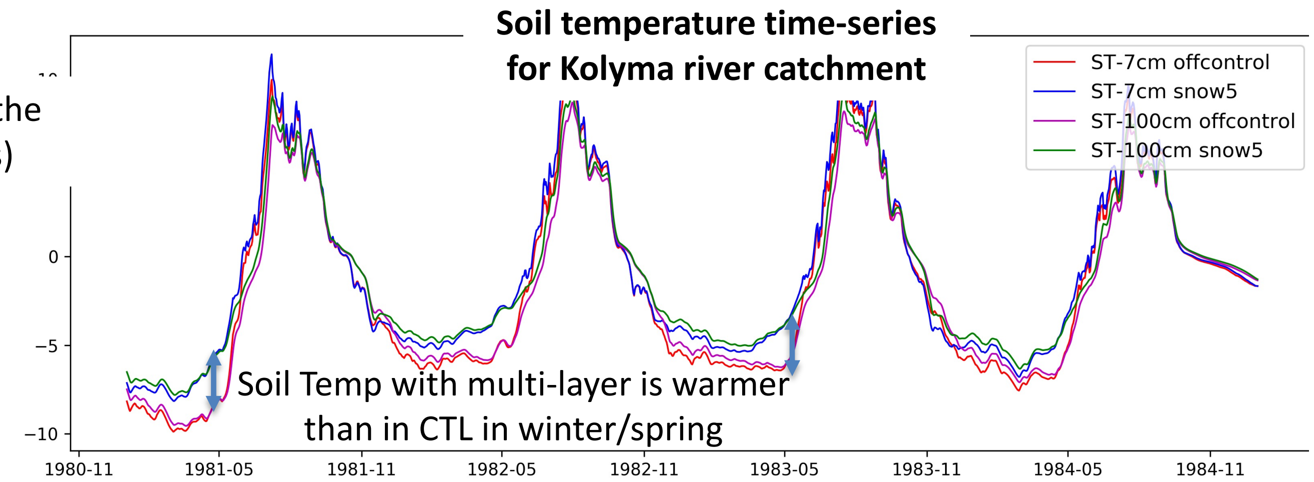
Zsoter, Arduini et al. in preparation

Evaluating land-surface model developments with hydrology, the example of the multi-layer snow scheme





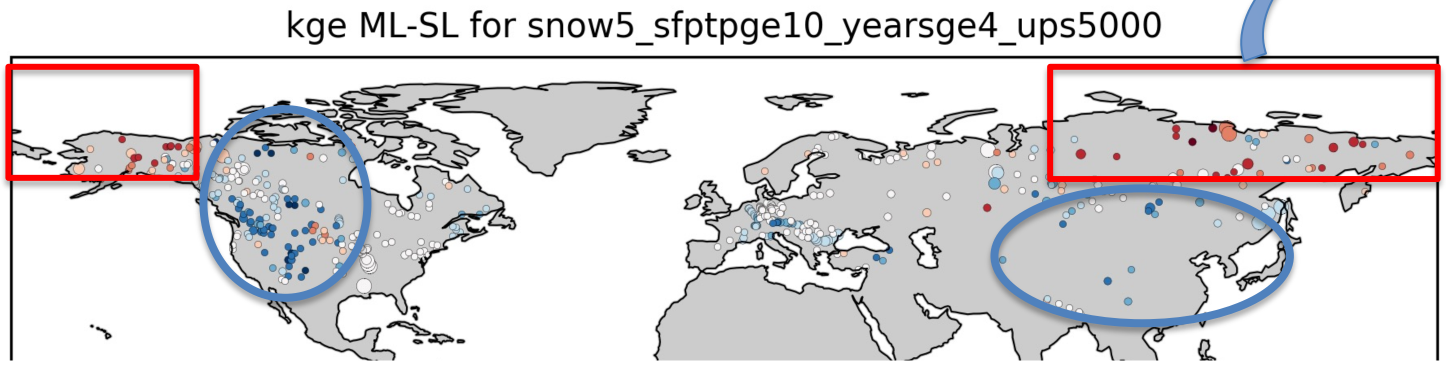
- In permafrost areas, the increase in water infiltrating into the soil **due to warmer soil temperature in snowML**, amplifies pre-existent biases in the river discharge.



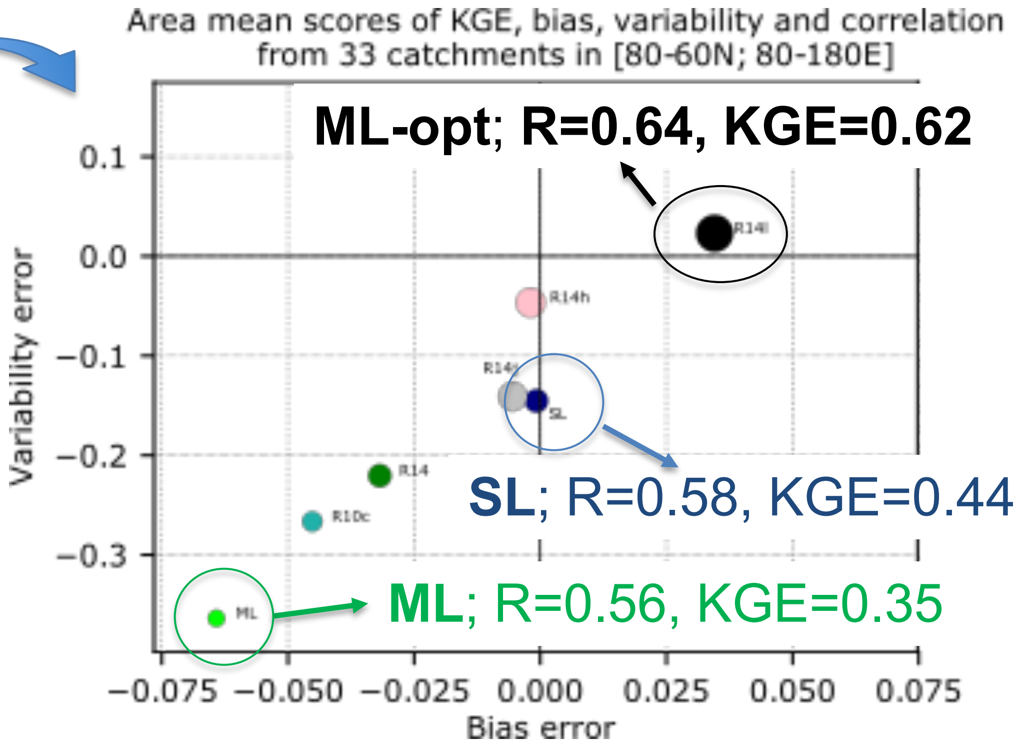
Zsoter, Arduini et al. in preparation

Optimising land-surface model developments with hydrology, multi-layer snow and frozen soil example

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



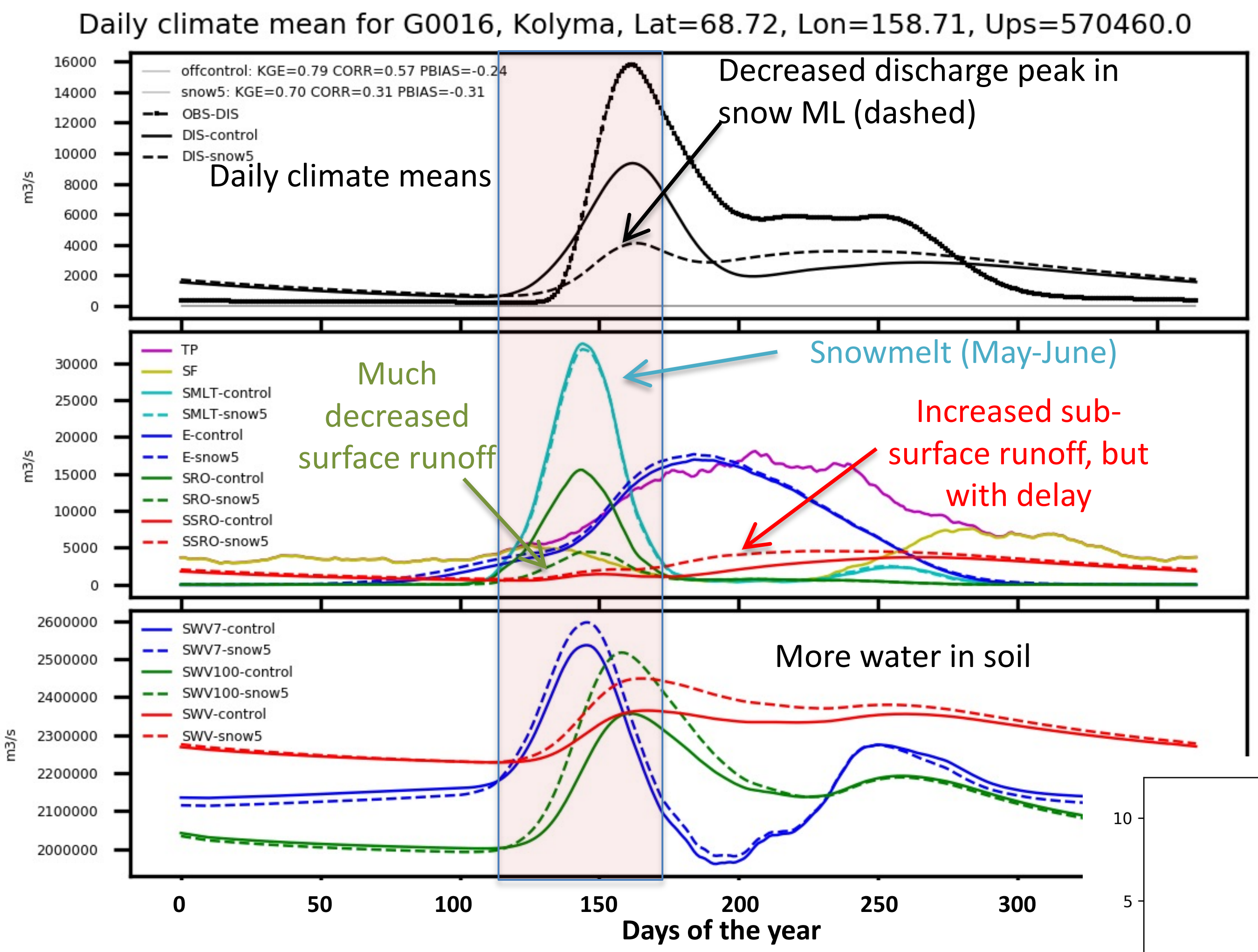
Sensitivity to permafrost-related parameters

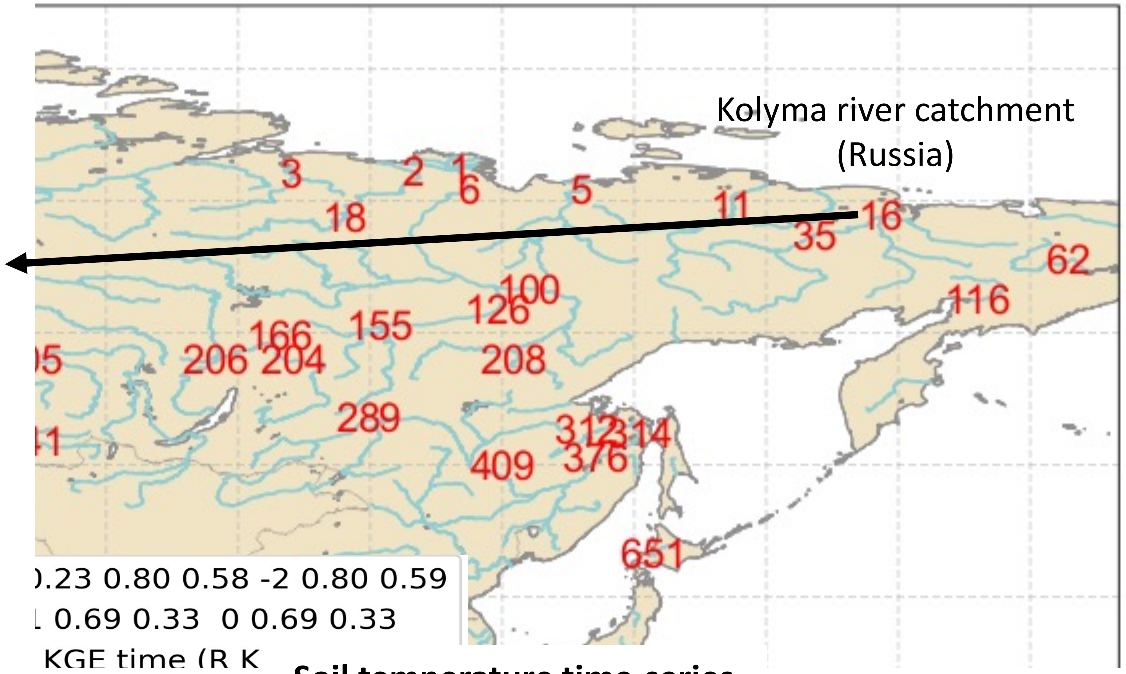


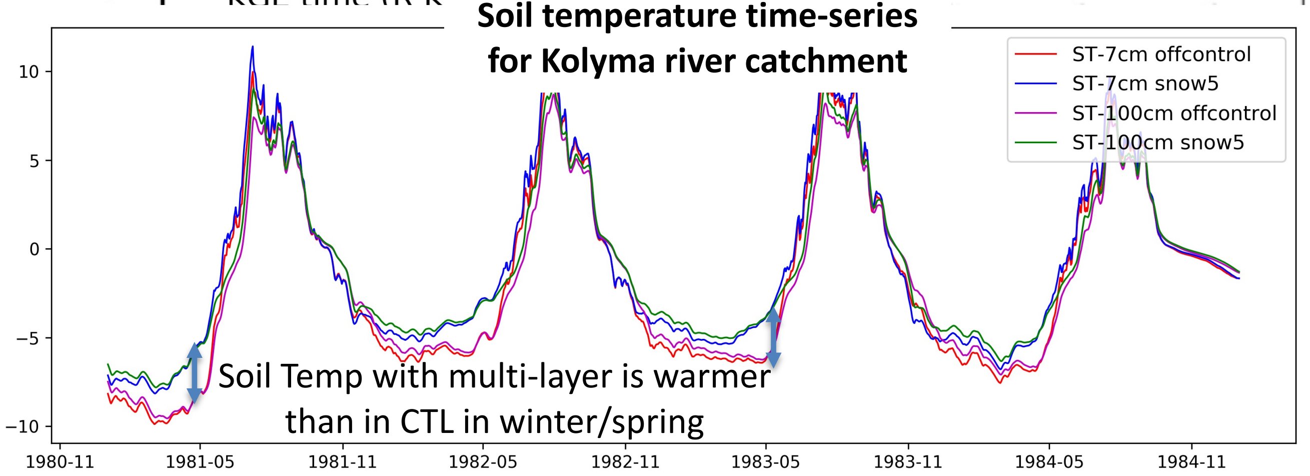
Sensitivity to frozen soil, snow discretization and snow density parametrization indicate an improvement of 0.27 in KGE for ML-Opt compared to standard ML over Siberia

Zsoter, Arduini et al. in preparation

Surface processes in a "bad" catchment



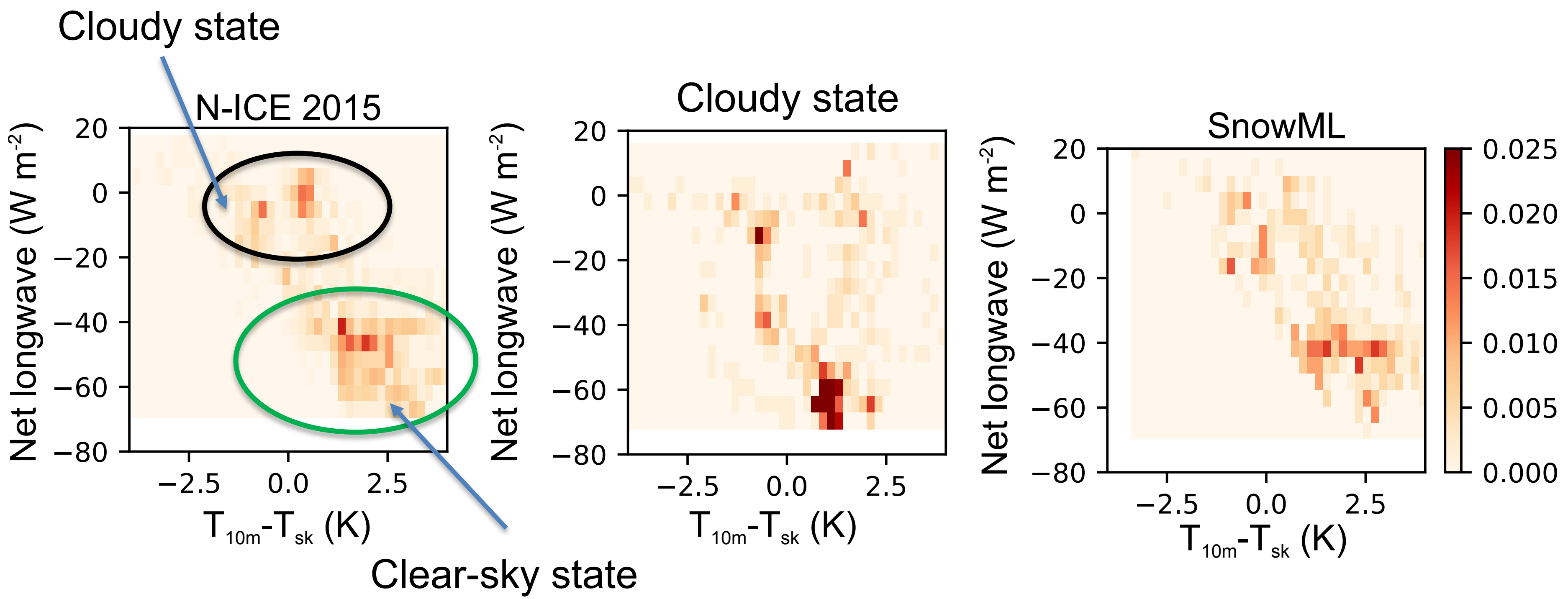




Too much melt water infiltrating into the soil

Soil temperature in permafrost regions too warm with multi-layer snow?

Impact on Arctic winter states – N-ICE2015 case



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Role of Resolution, snow model, land DA on global snow mass reanalysis

Courtesy of Patricia De Rosnay

- HTESSEL (ERA5land): no DA, high res., single-layer snow
- HTESSEL SL: no DA as E5L but @E5 res. → res impact
- HTESSEL ML: → no DA , snow ML impact (on SWE)
- ERA5 snow: Land DA but no IMS snow cover → insitu snow DA impact (vs HTESSEL SL) and IMS snow cover impact (vs ERA5)
- ERA5: DA of in situ + snow cover (IMS) → spurious step decrease in snow in 2004 (also reported in Zsoter et al. 2020, Mortimer et al. 2020)