Impact of Snow

Snow-atmosphere coupling and evaluation of snow forecasts

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Overview

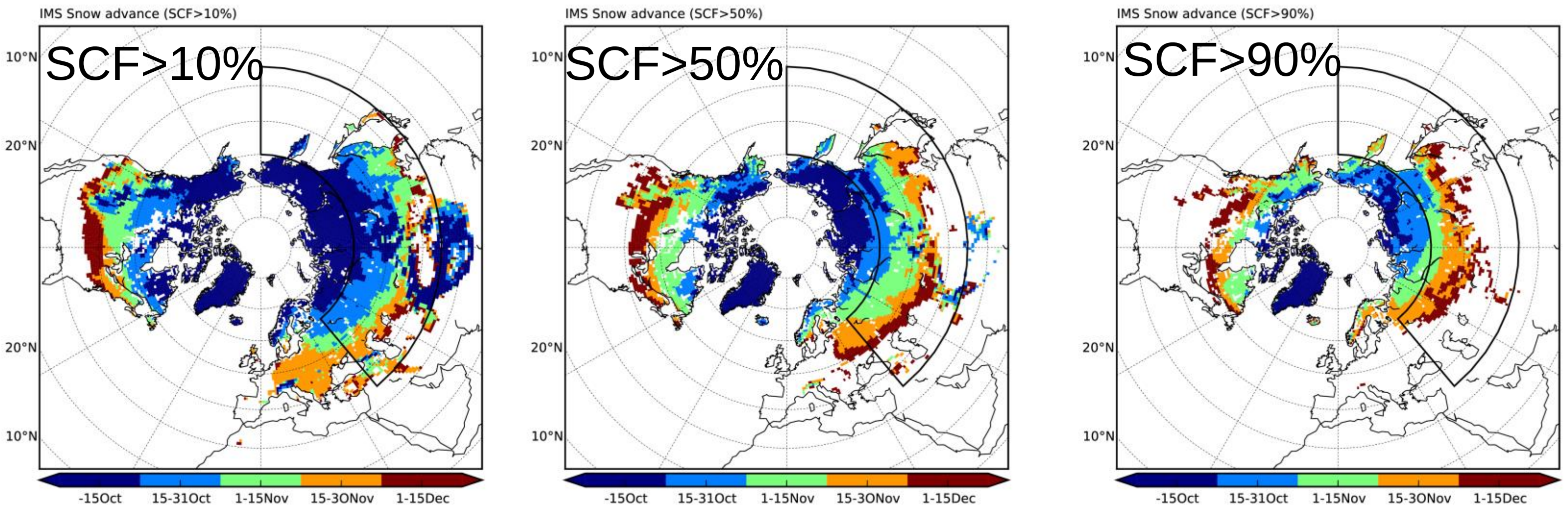
- Part 1: Snow atmosphere coupling:
  - Role of snow controlling heat/moisture/momentum exchanges;
  - Snow influence on atmospheric circulation: known mechanisms;
  - Sub-seasonal predictability studies: Impact of snow initialization;

- Part 2: Current performance of ECMWF reanalysis & sub-seasonal forecasts of snow
  - Snow representation in the ECMWF model;
  - Surface reanalysis & forecasts initialization;
  - Evaluation of sub-seasonal forecasts of snow depth and cover

Importance of snow

- Several fundamental physical properties of snow modulate the momentum/energy/water exchanges between the surface and the atmosphere:
  - **Surface reflectance:**
    - Albedo, snow-albedo feedback.
  - **Thermal properties:**
    - Effective de-coupling heat and moisture transfers.
  - **Surface roughness**:
    - Smoother than the underlying soil/vegetation: de-coupling of momentum transfers;
  - **Phase changes:**
    - Delayed warming during the melt period.
- Snow cover acts as a **fast climate switch**. Surface temperature falls by about 10 K with fresh snowfall and rises by a similar amount with snowmelt (Betts et al., 2014)
- Implications for all forecasts ranges (medium to seasonal).
- Predictability impact: role of initial conditions & anomalies persistence;
- Climate change impacts.

Autumn Inter-annual variability



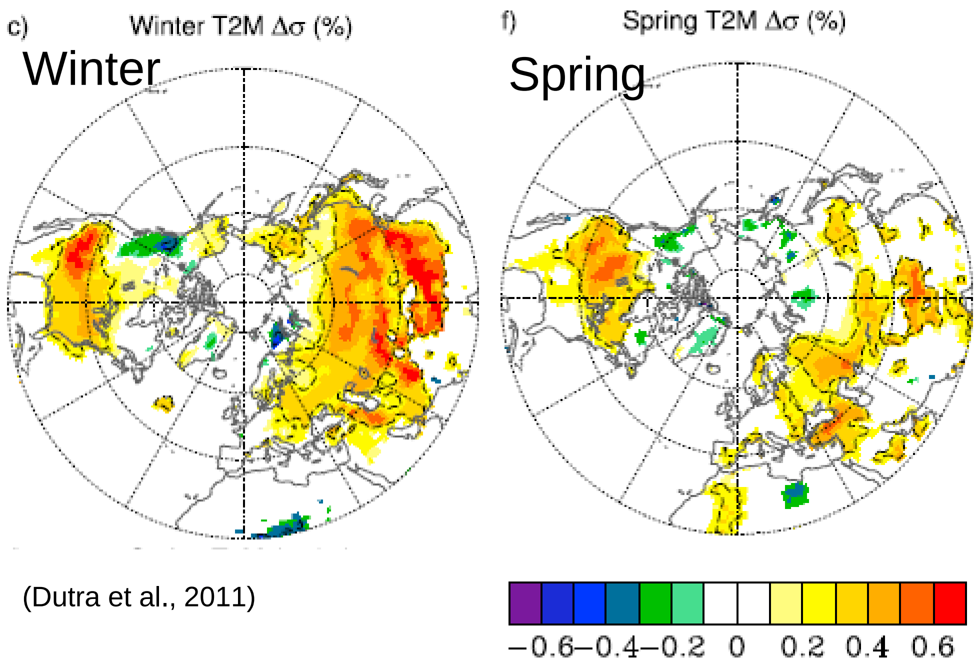
Snow cover advance (Oct-Dec)
1997-2014 mean based on satellite (IMS)

- Snow covers a substantial part of the Northern hemisphere land;
- Large inter-annual variability, in particular during the accumulation period (Oct-Nov)

- Is it a potential source of long-range predictability (local/remote) ?
    - Local feedbacks (intensified cooling + stronger land/atmosphere decoupling);
    - Interaction with large-scale circulation ?
    - Role of initial conditions (data assimilation) ?
    - Role of snow representation (model/parameterizations) ?

Inter-annual variability due to snow cover

Changes in T2M inter-annual variability

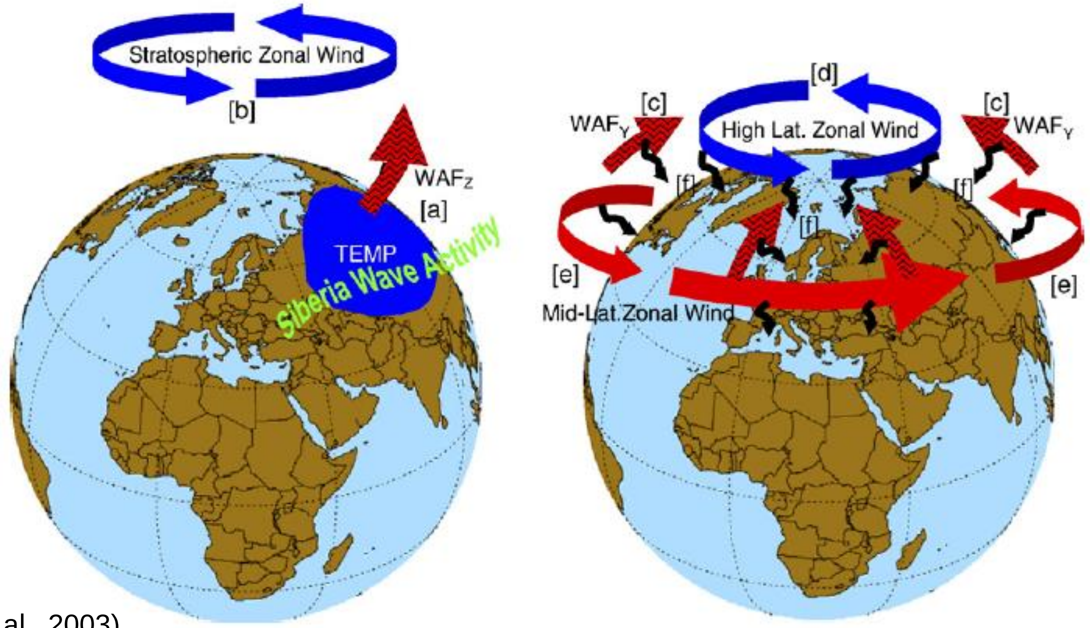


(Dutra et al., 2011)

- 30 years climate simulations (EC-EARTH) with free evolving snow and with prescribed snow climatology (uncoupled snow)
- Snow cover and variability explain almost 60% of the winter 2-meters temperature inter-annual variability in predominantly snow-covered regions;
- Both snow cover and depth play a fundamental role decoupling the soil evolution from the overlying atmosphere.

Mechanisms

Autumn Siberian Snow & Hemispheric Winter Circulation



(Gong et al., 2003)

- Positive snow forcing in Autumn -> local diabatic cooling and strengthening of the wave energy center that propagates to the troposphere (a) and weakens the stratospheric polar vortex (b).
- Weakened zonal winds drawn down into the upper troposphere in high latitudes (d) and development of mid-latitude positive zonal wind anomalies (e) that are characteristic of a negative AO.

- **Mechanism supported by observations (e.g. Cohen et al., 2014, Gong et al., 2003) and modeling studies (e.g. Fletcher et al., 2007, Peings and Magnusdottir, 2015);**

- **Insufficient to initiate the teleconnection pattern, i.e. only modulates;**

- **Blanford hypothesis (1884)**: Inverse relation between Himalayan winter/spring snow accumulation and the strength of Indian summer monsoon; Many observational and modeling studies have focused on this topic but there is no general agreement (e.g. Robock et al., 2003, Dickson, 1984, Peings and Douville, 2010, Fasullo, 2004, Turner and Slingo, 2011).

Snow in predictability studies

- **Orsolini and Kvamsto, 2009:** Arpege-Climat, 1979-2000 with free evolving snow and with nudging to satellite snow cover. With realistic snow there is a **propagation of wavetrains downstream of the Eurasian land mass and into the stratosphere**; Increased potential predictability over eastern Eurasia and North Pacific;
- **Peings et al., 2010** : Arpege-Climate, prescribed SST, 1950-2000 with without snow nudging. Forecast with nudging snow improves both potential and actual predictability of springtime surface air temperature over Central Europe and North America, but the **impact is confined to the lower troposphere** and there is no clear improvement in the predictability of the large-scale.
- **Jeong et al., 2012**: NCAR CAM3, seasonal forecasts with/without snow initialization (September-April). **Potential predictability increases up to 2 months with snow initialization**. Main impact over East Asia, Western Russia and western Canada. Regions with larger impact are associated with stronger **snow-albedo feedback**. Impact on actual predictability also found but small (without coupled ocean, snow initialization not consistent with the atmosphere);
- **Orsolini et al., 2013**: ECMWF CY36R1, 2 months forecasts with realistic snow / randomized snow (October-December). Modest improvement in the first 15 days over snow-covered land. **Improvements up to 30 days over part of the Artic and Northern Pacific**. Short period 2004-2009 snow initialization from ERA-Interim.
- **Senan et al., 2015**: ECMWF S4, 4 months 1981-2010 hindcasts for 1st April with ERA-Interim/land initial conditions vs randomized snow over the Himalayan-Tibetan Plateau (HTP). Realistic snow initialization in the HTP region accounts for **50% of the delay in the monsoon onset** in high snow years. **See Poster for more details.**

Overview

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  - Sub-seasonal predictability studies: Impact of snow initialization;

- Part 2: Current performance of ECMWF reanalysis & sub-seasonal forecasts of snow
  - Snow representation in the ECMWF model;
  - Surface reanalysis & forecasts initialization;
  - Evaluation of sub-seasonal forecasts of snow depth and cover.

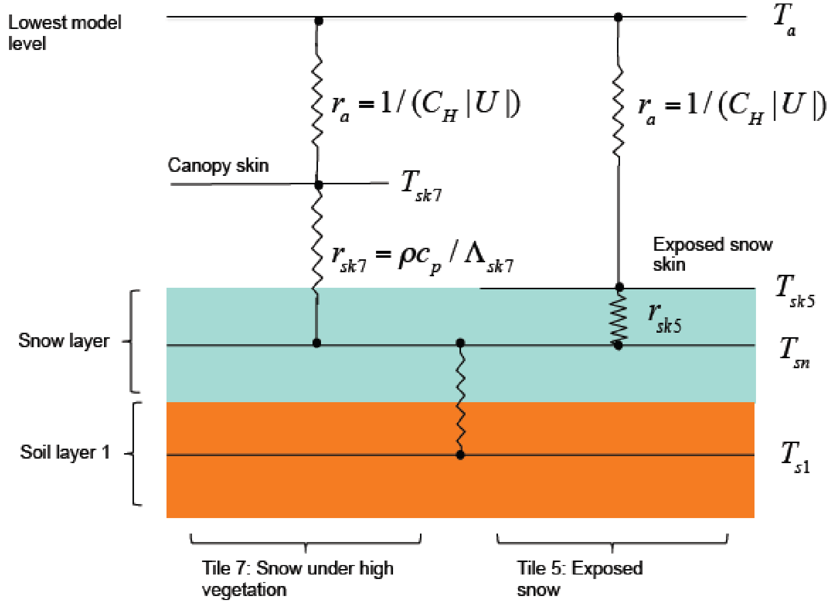
  - **Why evaluating snow forecast** ? Skilful snow forecasts are important to keep the memory/forcing and to represent the feedbacks.

Snow representation in the ECMWF model

HTESSEL:

- Two tiles:
  - Exposed snow;
  - Snow under high vegetation;
    - Single snow-pack evolution
- Prognostic evolution (1 layer):
  - Snow mass;
  - Snow density;
  - Snow temperature;
  - Snow Albedo;
- Diagnostics:
  - Snow depth;
  - Snow cover fraction
  - Liquid water content

(Dutra et al., 2010)



- Snow depth data assimilation:
  - **Methods**: Cressman for ERA-Interim, 2D Optimal interpolation (OI) operationally and for future reanalysis;
  - **Conventional obs**: in-situ snow depth;
  - **Satellite data**: NOAA/NESDIS IMS Snow cover (daily);

(de Rosnay et al 2015)

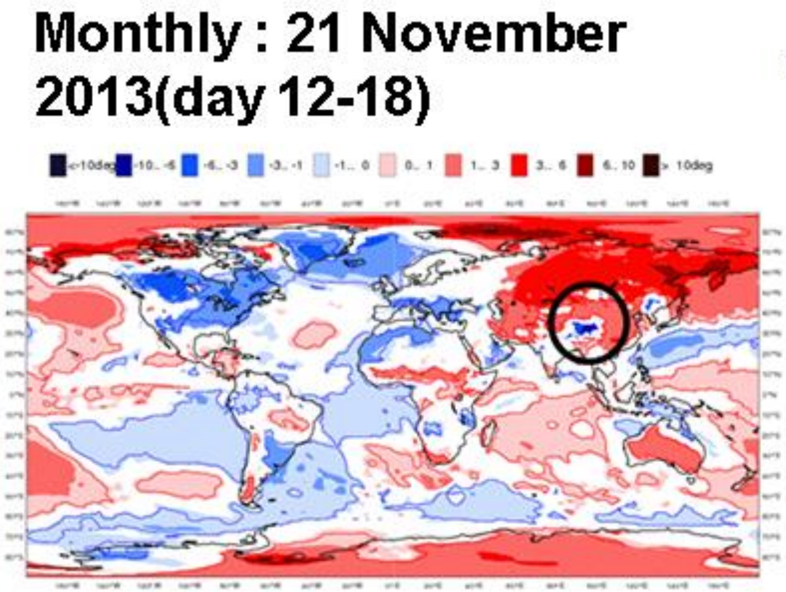
Initialization of re-forecasts

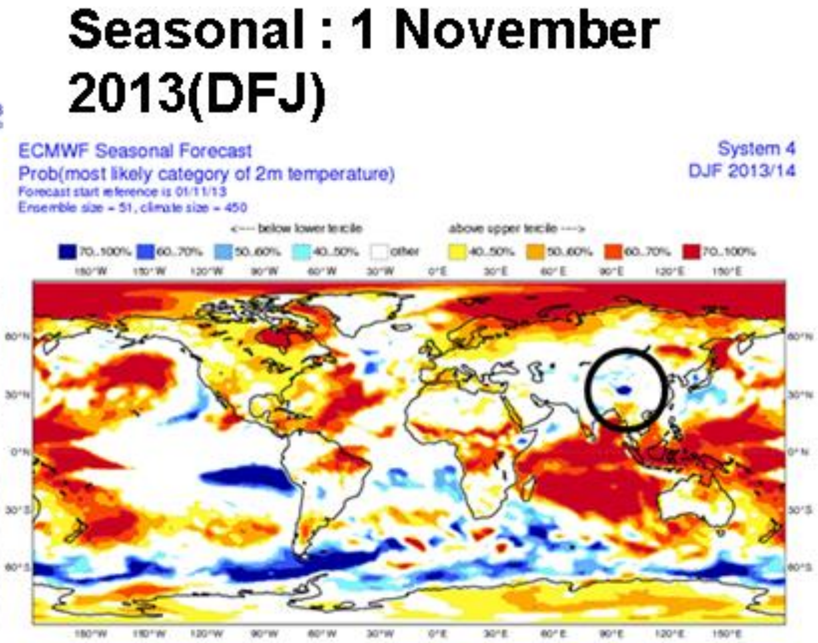
- Seasonal & ENS require past surface initial conditions for the re-forecasts;
- ERA-Interim is not an option due to the inconsistencies in the model versions;
- ERA-Interim/Land (**EIL** Balsamo 2015):
  - Land-surface only simulation with the current model version forced with ERA-Interim meteorology & bias corrected precipitation using GPCP. No data assimilation yet.
- **EILU**: Same configuration as EIL, but without precipitation correction;

- Re-forecasts:
  - Seasonal **S4**: initialized with **EIL**;
  - ENS: initialized with **EILU** (since May 2015, before was with EIL);
- Real-time forecasts:
  - Both S4/ENS use the operational analysis

Initialization of re-forecasts

Cold anomaly in Western China:
Both ENS and S4 presented a persistent cold anomaly: Predictable signal ? Or an inconsistency ?





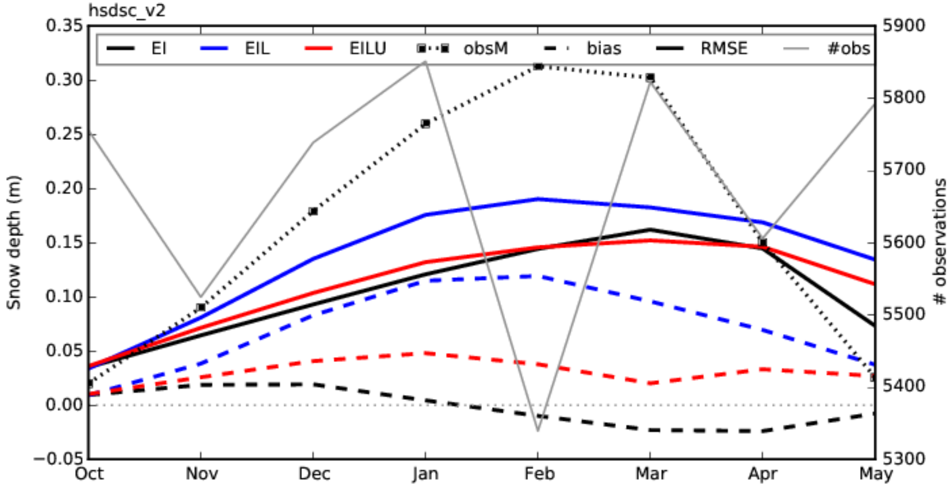
Difference in snow mass initial conditions between real-time forecasts and reforecasts
- Re-forecasts : no snow in the region;
- Real-time forecasts: snow-covered

Current operational ENS uses new initial conditions with no precipitation rescaling (**EILU)**. **Current 2015 forecasts show a consistent warm anomaly in the same region.**

Inconsistencies in the initialization of the re-forecasts and real-time forecasts can lead to misleading forecasts anomalies (i.e. persistent forecast anomalies and not predictable signals)

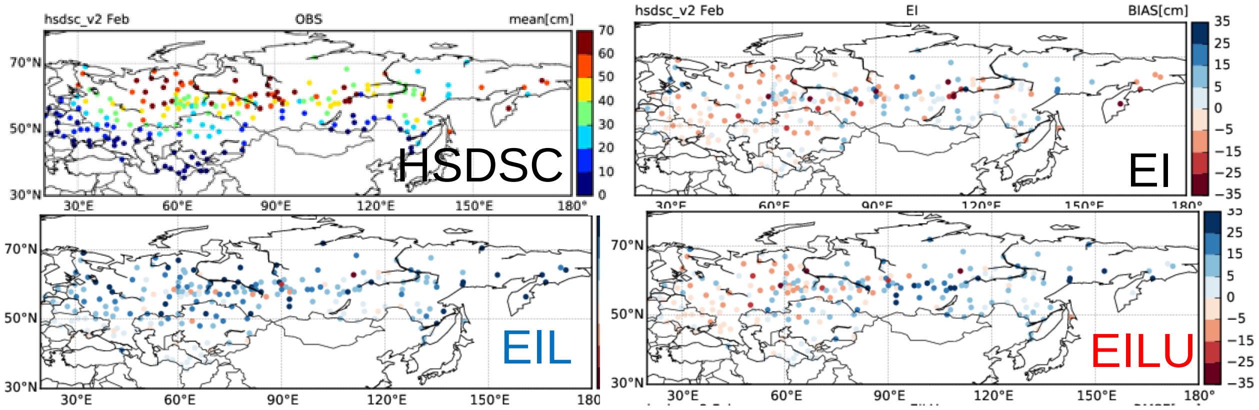
Reanalysis evaluation: snow depth

HSDSD 1979-1995 mean annual cycle snow depth



EI
EIL
EILU
Solid: RMSE
Dashed: Bias
Grey: # obs
Dots : mean obs

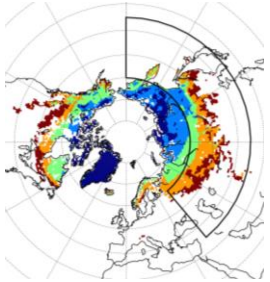
HSDSD 1979-1995 February



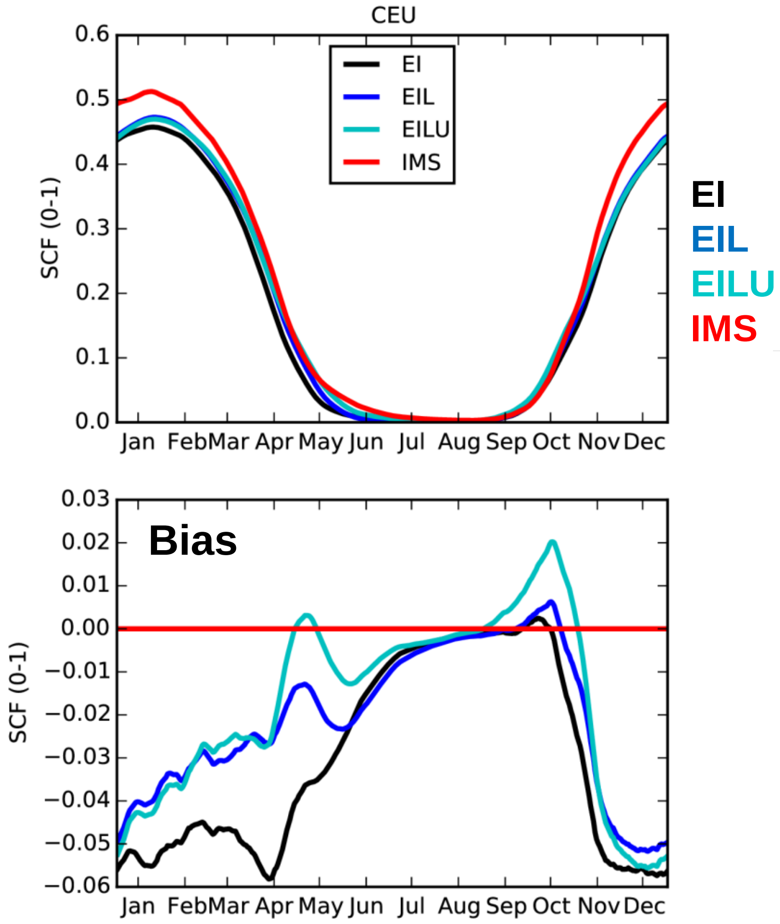
- EIL systematic overestimation of snow depth (consistent with an overestimation of river discharge in some northern basins – not shown). Limitation of the GPCP datasets (low # of rain gauges & under catch corrections);
- EILU without data assimilation has a similar performance to EI – most of the HSDSD data was assimilated in EI;
- RMSEs >= mean during Oct-Nov & April-May: challenging accumulation/melting periods (model limitations, forcing problems, spatial variability);
- Consistent results after 1995 to present using GHCN (Global Historical Climatology Network);

Historical Soviet Daily Snow Depth (HSDSD, Armstrong 1999): Daily snow depth in 284 stations, 1881-1995.

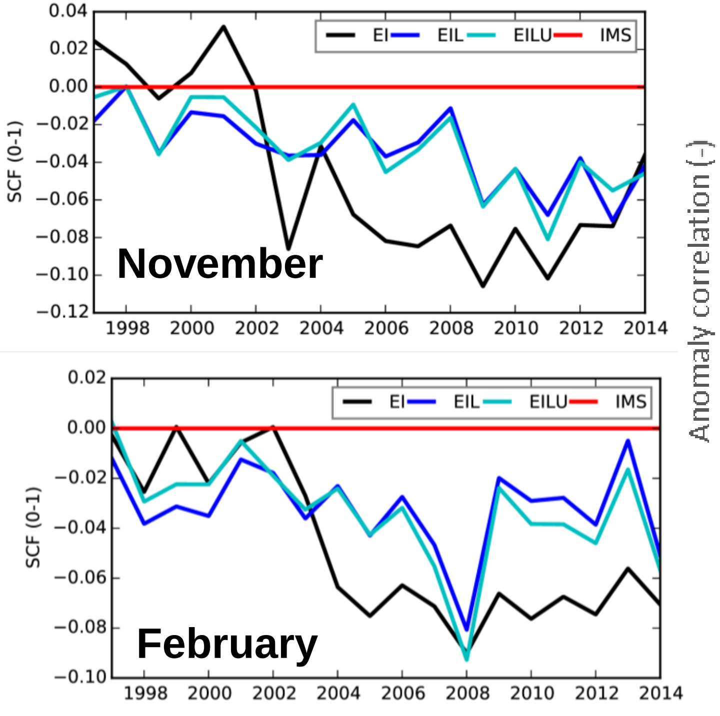
Reanalysis evaluation: Snow cover (SCF)

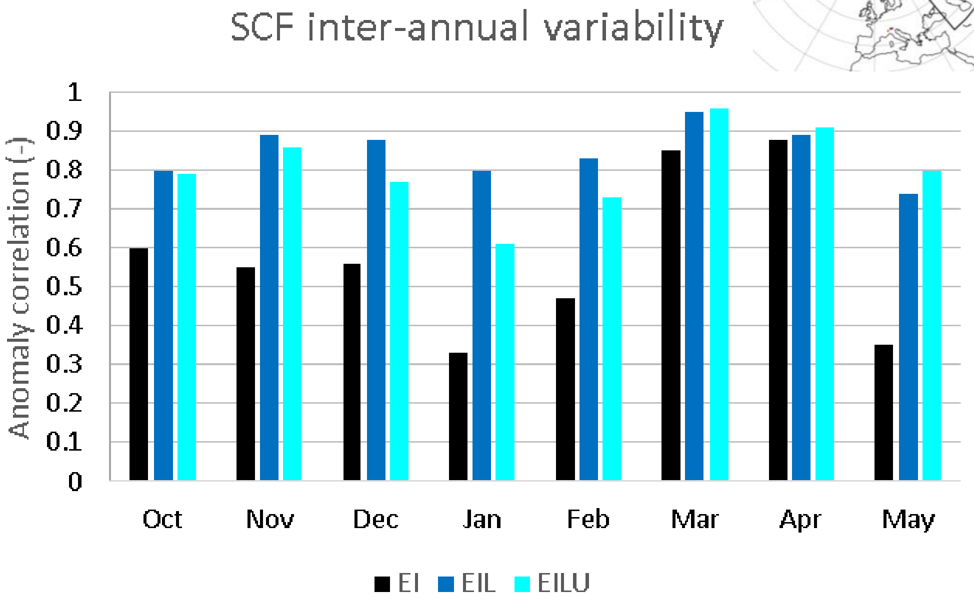


Mean snow cover 1997-2014



Year-to-year mean bias

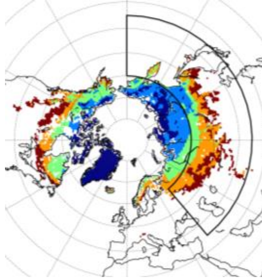




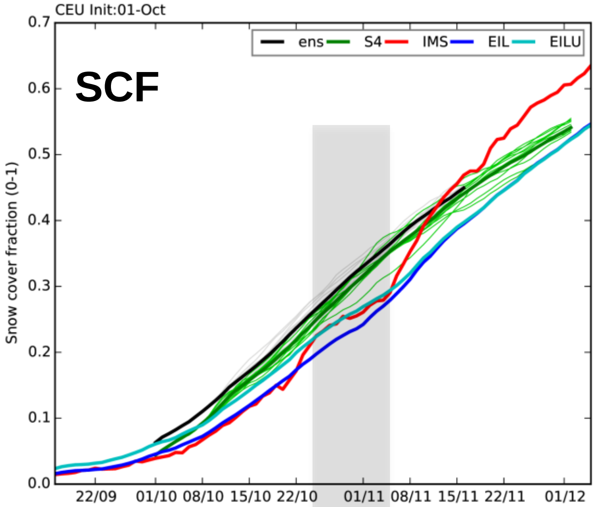
- General underestimation of SCF (SCF parameterization, resolution);
- The EIL overestimation seen in snow depth is not present in SCF.
- The inter-annual variability 1997-2014 is consistently better in EIL/EILU.
- EI inconsistent 2004 onwards due to several issues in the assimilation of satellite data (also seen in the snow depth verification).

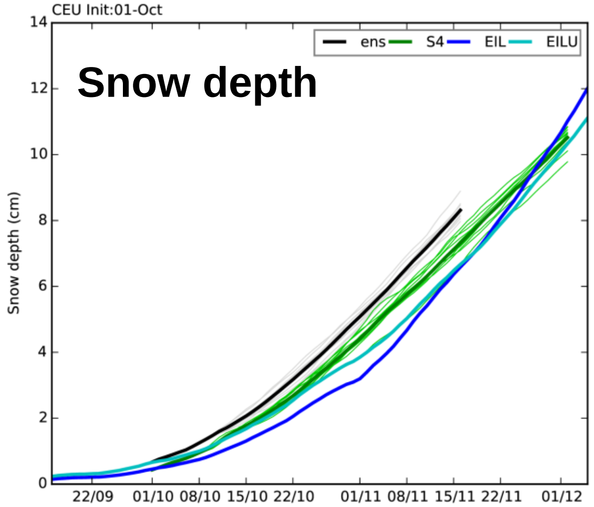
Interactive Multisensor Snow and Ice Mapping System (IMS, NIC 2008) 1997-present daily 24 km

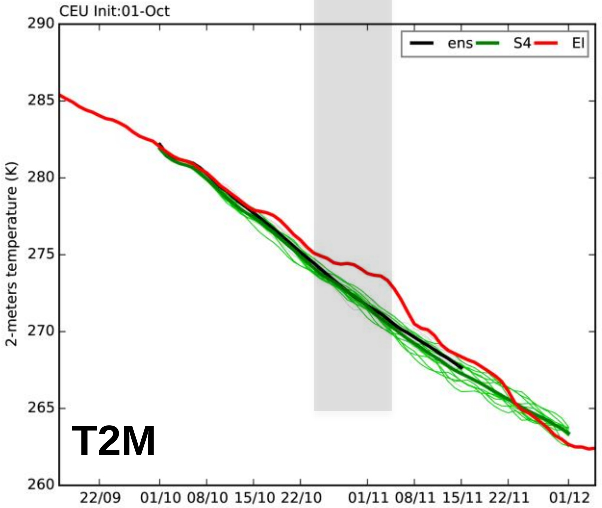
ENS / S4 evaluation



1st October forecasts (1997-2014)







ENS : Operational ensemble
S4: Operational seasonal forecasts
IMS(SCF) ERAI(T2M)
EIL
EILU

- Despite the differences in model version/resolution ENS & S4 have a similar mean climate, in particular for T2M. For SFC & snow depth the differences in the initial conditions EILU(ENS) and EIL(S4) remain during the forecast;
- IMS suggests a reduction of the SCF advance in end of October only partially captured by reanalysis.
- The SCF plateau in the end of October is consistent with a plateau of T2M;

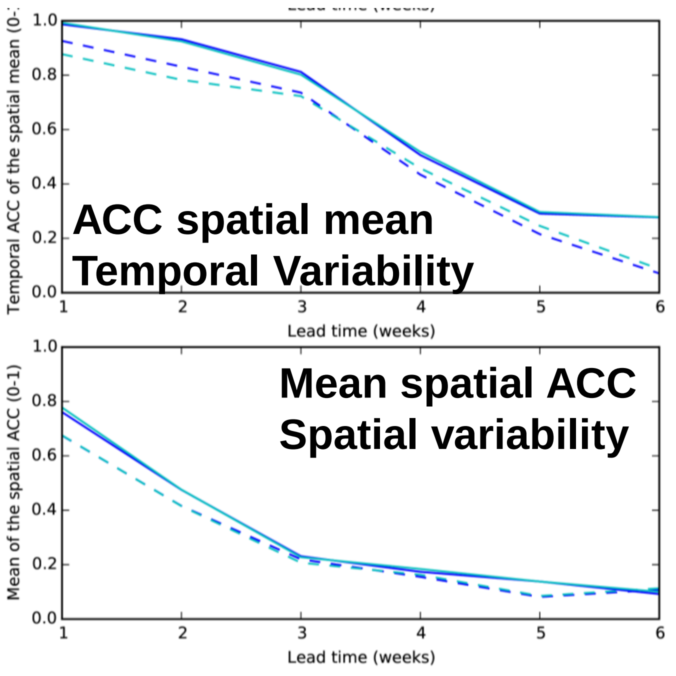
ENS / S4 evaluation

1st October forecasts (1997-2014)

Solid lines: ENS
Dashed lines : S4
Verified with EIL
Verified with EILU

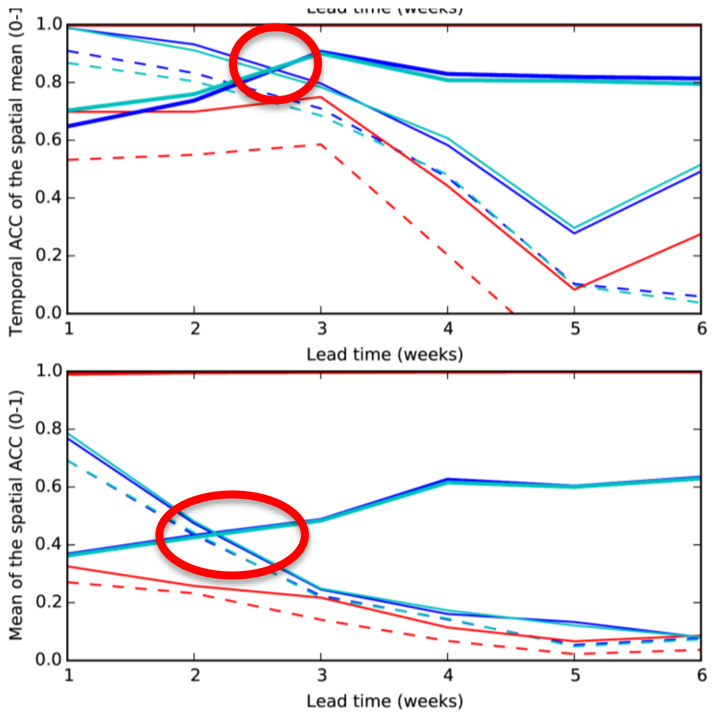
Verified with IMS
EIL vs IMS (thick)
EILU vs IMS (thick)

Snow depth



Lead time (weeks)

Snow cover fraction



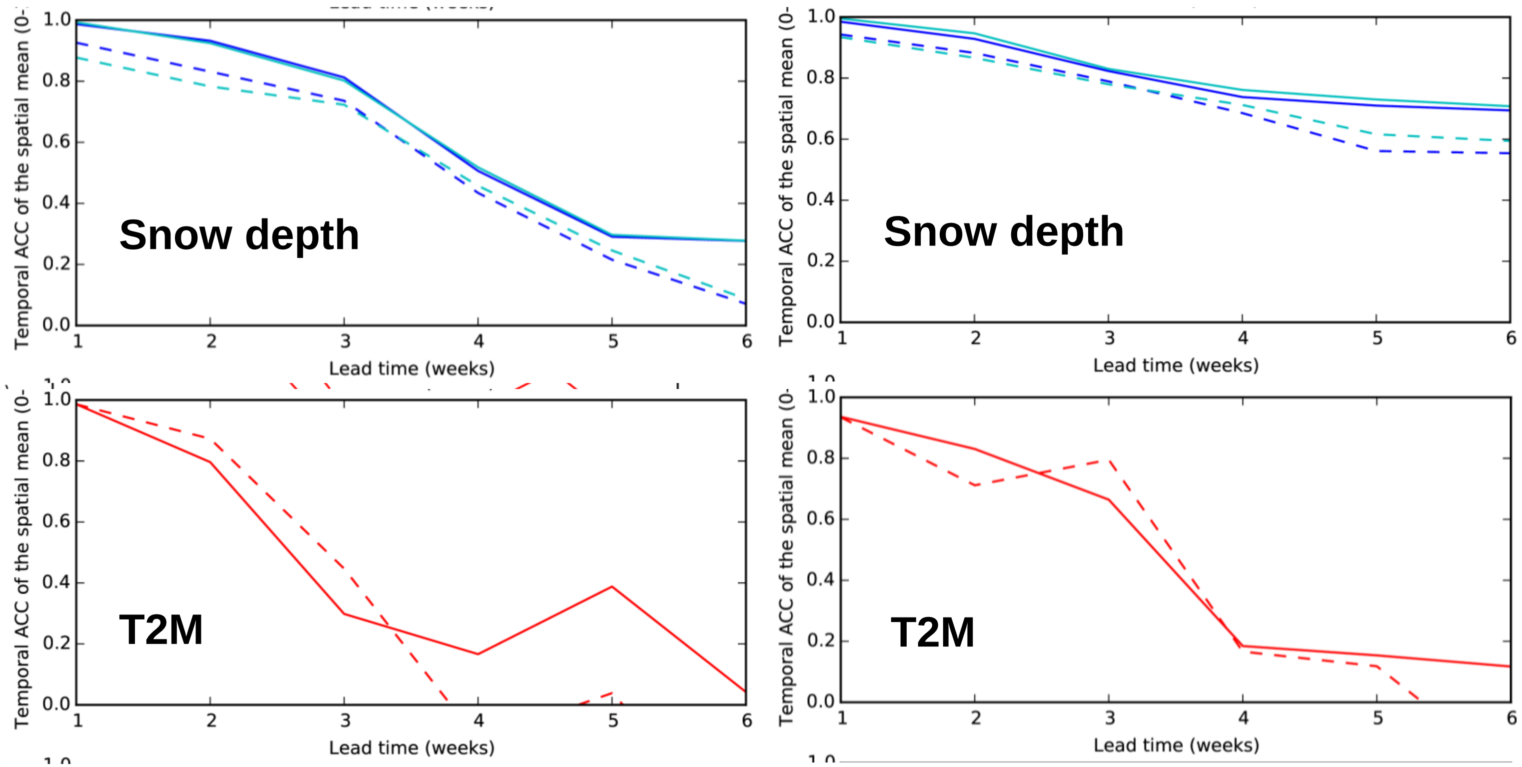
- Good error spread relationship (not show);
- Verifying against EIL/EILU gives similar results although the different initial conditions;
- ENS scores are consistently higher than S4 – is it resolution ? Model?;
- "**ENS/S4 vs reanalysis**" drop below "**reanalysis vs IMS**" between week 2 and 3: atmospheric variability/predictability dominates over initial conditions;

ENS / S4 evaluation

Solid lines: ENS
Dashed lines : S4
Verified with EIL
Verified with EILU
Verified with EI

ACC spatial mean
Temporal Variability

1st October forecasts (1997-2014) **1st November (1997-2014)**



- November scores of Snow depth (snow mass & SFC) are higher:
    - + snow == + memory;
- ENS/S4 scores of T2M are similar and are higher for the November starting dates, in particular at week 3
    - Could it be due to the snow memory effect ?

Final remarks & Future

- **Most of the studies focus on Eurasian snow cover during the accumulation period: strong evidences of the role of initial conditions & persistence of anomalies in the hemispheric circulation;**
- **During spring there less studies and the main impact seems to be local, except for the Himalayan-Tibetan Plateau and the Indian Summer Monsoon;**

- **Current ECMWF model & land reanalysis compare favourably with in-situ & satellite observations;**
- **The current sub-seasonal forecasts of snow fields are skilful up to week 3: higher snow cover fraction provides higher long-term predictability: memory effects.**

- **Future changes in the model:**
  - Testing of a multi-layer snow scheme (improved snow-atmosphere coupling)
  - Try to revise the snow albedo & snow cover fraction parameterizations (local feedbacks)
- **Consistent (time & with the forecast system) reanalysis are paramount:**
  - Provide initial conditions for the re-forecasts & verification of forecast snow fields;
  - To be used in idealized experiments (e.g. nudging snow fields to assess the potential predictability of a perfect snow)
  - Surface only simulations improved ERA-Interim but lack assimilation : upcoming ERA5 is important;
  - How to deal with changes in the model / DA : more frequent updates of ERAs ? Land Data Assimilation?

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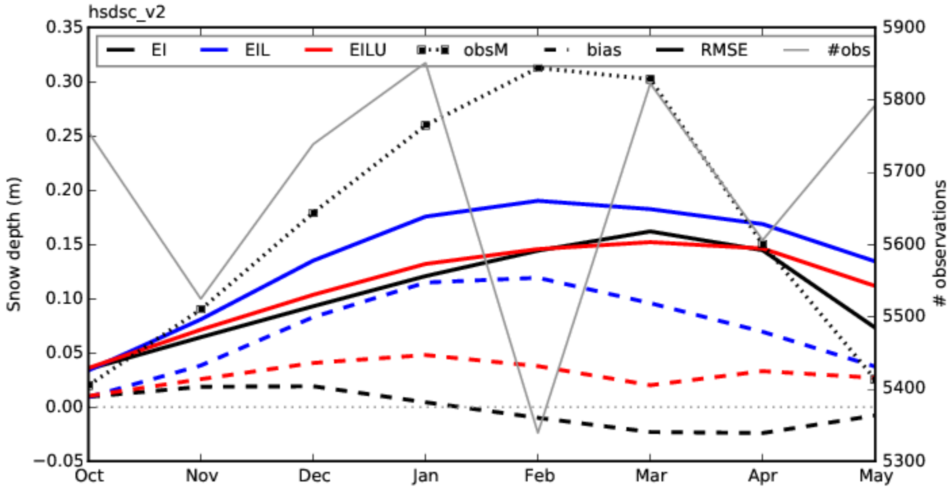
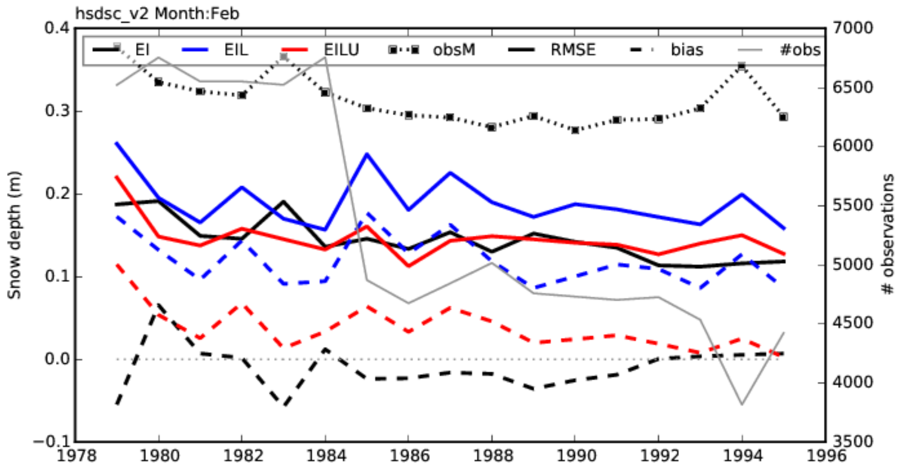
Extra material

Reanalysis evaluation: snow depth

HSDSD 1979-1995 mean annual cycle snow depth



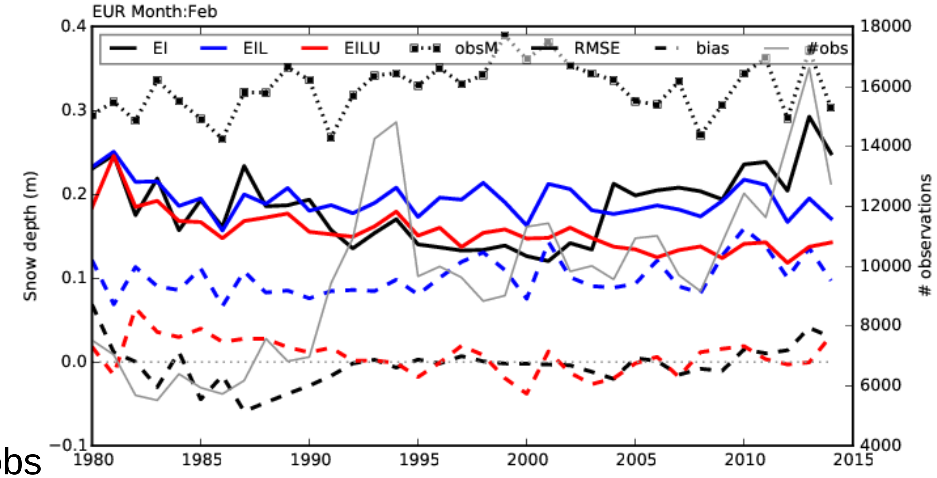
HSDSD 1979-1995 February



EI
EIL
EILU
Solid: RMSE
Dashed: Bias
Grey: # obs
Dots : mean obs

Global Historical Climatology Network – Daily (GHCN, Menne et al., 2012)

GHCN 1980-2014 February



- Consistent results between GHCN & HSDSD, but GHCN does not contain zero snow information;
- EI RMSEs increased from 2004 onwards due to several issues in the assimilation of satellite data.

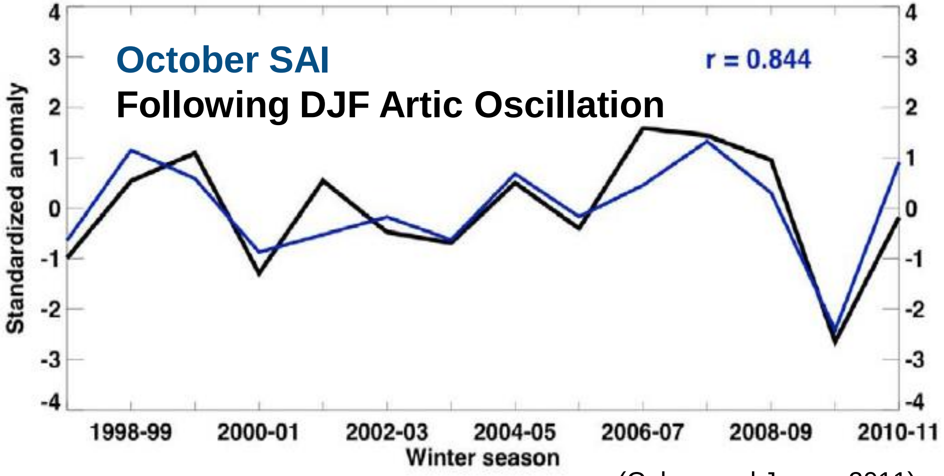
Historical Soviet Daily Snow Depth (HSDSD, Armstrong 1999): Daily snow depth in 284 stations, 1881-1995.

Overview of the data used

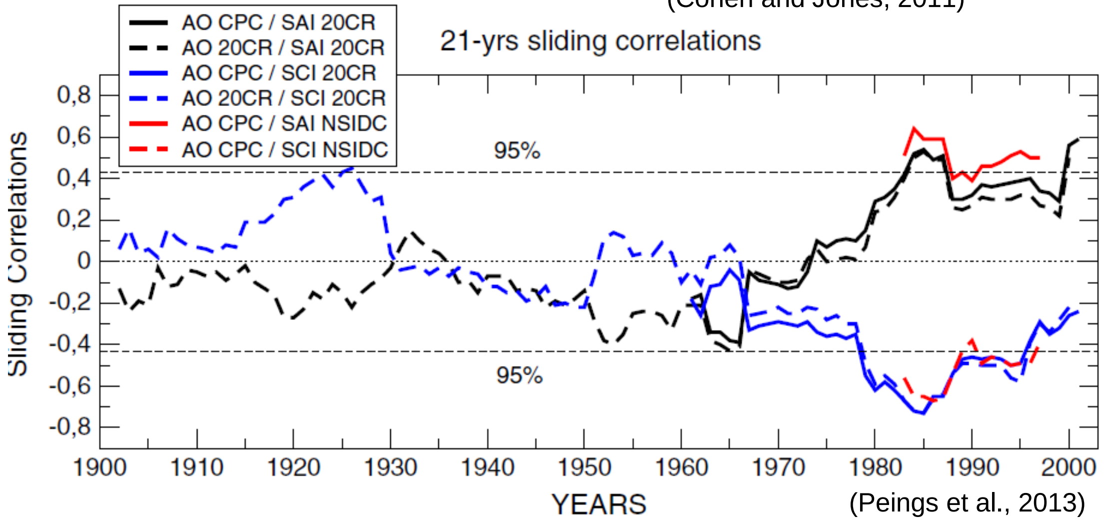
- Observations:
  - Interactive Multisensor Snow and Ice Mapping System (**IMS**, NIC 2008) 1997-present daily 24 km
  - Historical Soviet Daily Snow Depth (**HSDSD**, Armstrong 1999): Daily snow depth in 284 stations, 1881-1995. Consistent quality control – report zero snow depth.
  - Global Historical Climatology Network – Daily (**GHCN**, Menne et al., 2012) daily, thousands of stations globally – most of the synop station do not report zero snow depth.
- Simulations:
  - Reanalysis:
    - ERA-Interim: **EI**
    - ERA-Interim/Land (Balsamo 2015) : **EIL** - used by the seasonal forecasts;
    - ERA-Interim/Land Uncorrected : **EILU –** (no GPCP precipitation correction): used by the ensemble reforecasts;
  - Sub-seasonal forecasts:
    - **ENS**: operational ENS, 20 years of reforecasts & 11 ensemble members for 45 days lead time; Initialized with **EILU**
    - **S4**: seasonal forecasts system 4: reforecasts since 1980, 30/51 ensemble members; Initialized with **EIL**
- **Evaluation period: 1997-2014 (overlap of satellite snow cover). Focus on Eurasia.**

Snow advance index:

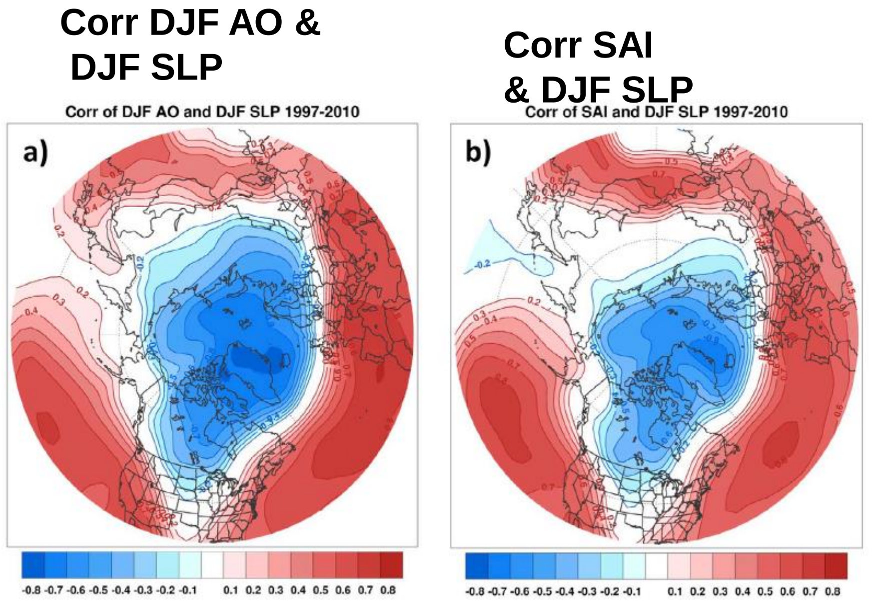
- Snow advance index: regression coefficient of the least square fit of the daily Eurasian snow cover extend equatorward of 60°N calculated for the month of October (Cohen and Jones, 2011)



(Cohen and Jones, 2011)



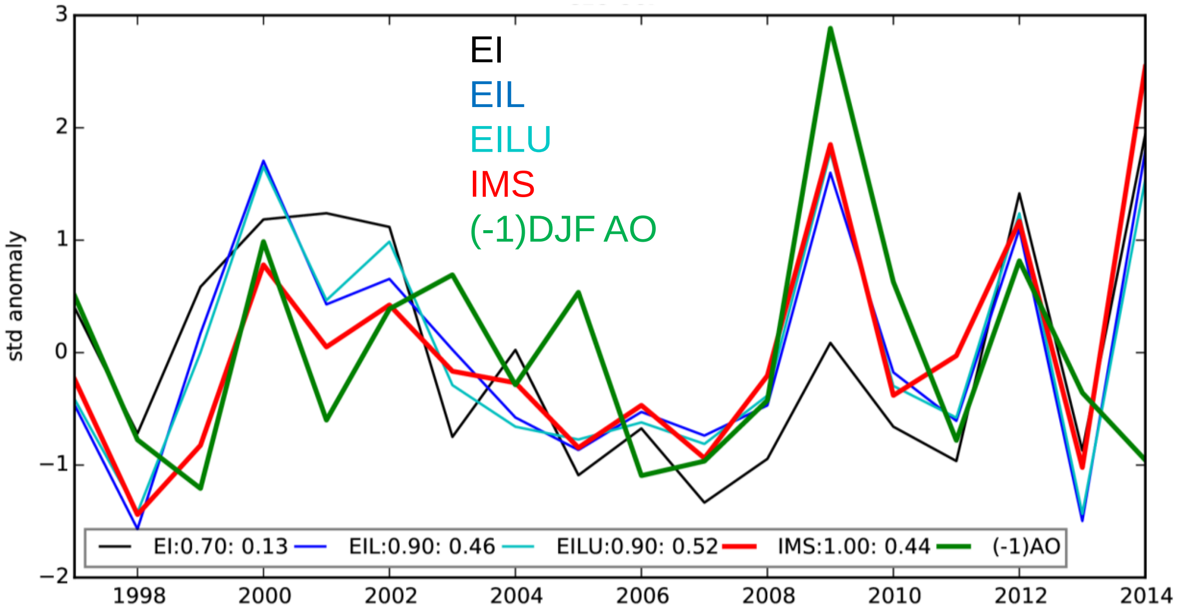
(Peings et al., 2013)



(Cohen and Jones, 2011)

- SAI 1997-2010 explains a large part of the winter AO variability: Is the AO predictable (Cohen and Jones, 2011) ?
- But, this relation is not stationary in the 20th century (Peings et al., 2013).

Reanalysis evaluation: October snow advance index & DJF AO



Correlations:

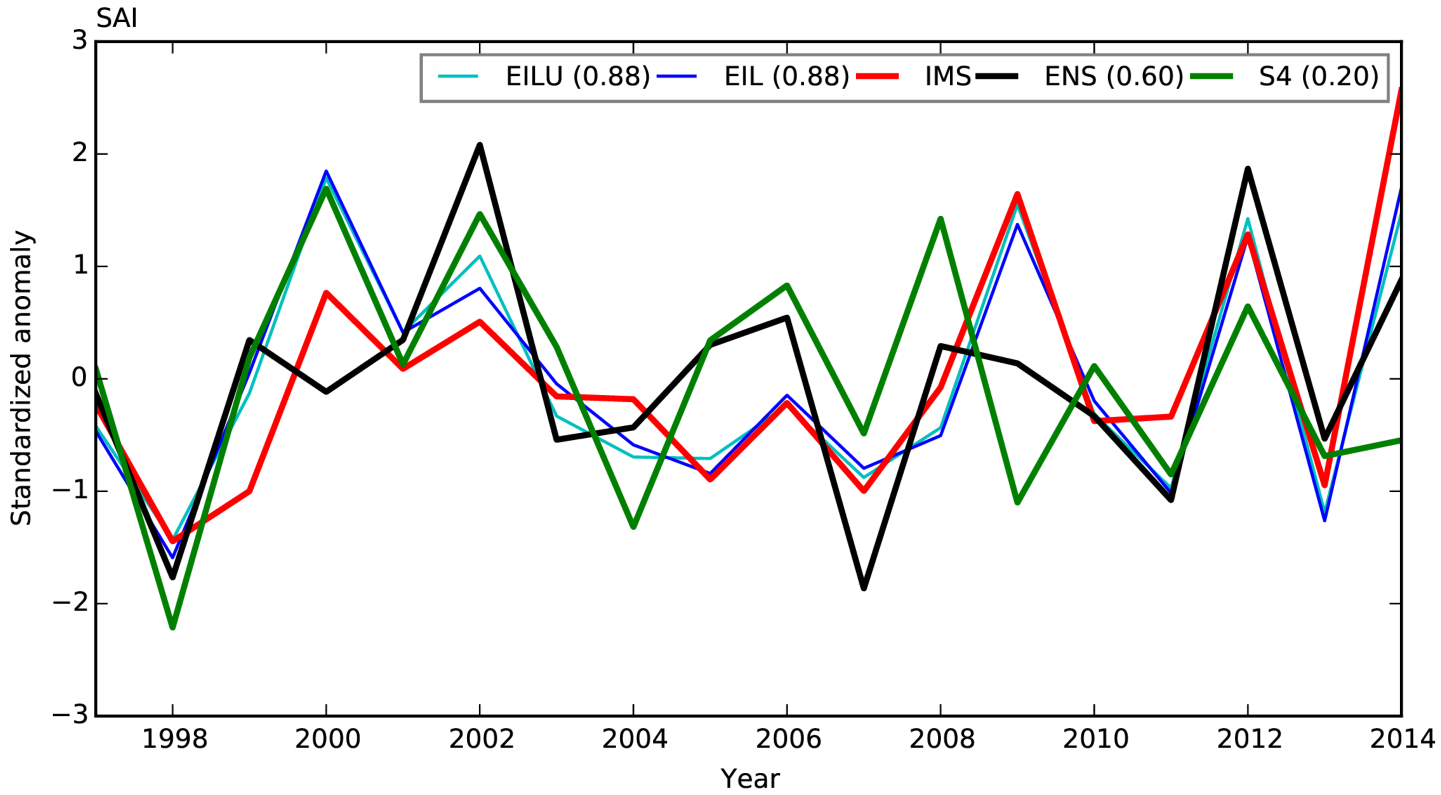
	1997-2010 (14 yeas)		1997-2014 (18 years)	
	SAI (vs IMS)	**SAI vs AO**	**SAI (vs IMS)**	**SAI vs AO**
EI	0.51	0.17	0.70	0.13
EIL	0.89	0.63	0.90	0.46
EILU	0.91	0.66	0.90	0.52
IMS	-	**0.80**	-	**0.44**

- The relation between the October SAI and the following winter Artic Oscillation is not consistent in the last 18 years;
- The 2014 winter is the main responsible ? Peings 2013 suggested the modulation of QBO but in 2014 there was also a negative QBO.
- As for the SCF, EIL/EILU SAI is very close to the satellite data.

- The current snow scheme is able to represent the observed climate and variability when forced by a realistic forcing (ERA-Interim);

ENS / S4 evaluation

1st October forecasts: October Snow advance index



EIL vs IMS: 0.88
EILU vs IMS: 0.88
ENS vs IMS: 0.60
S4 vs IMS: 0.2

- Only 18 years but there is a consistent signal in ENS:
  - Consistent with higher scores of SCF in ENS;
  - Why:
    - Model ? Resolution ? Initial conditions ?
- ENS predicted the high 2014 advance while S4 did not: Why ?