Impact of snow on subseasonal-to-seasonal forecasts

Yvan J. Orsolini

NILU - Norwegian Institute for Air Research

and University of Bergen , Norway

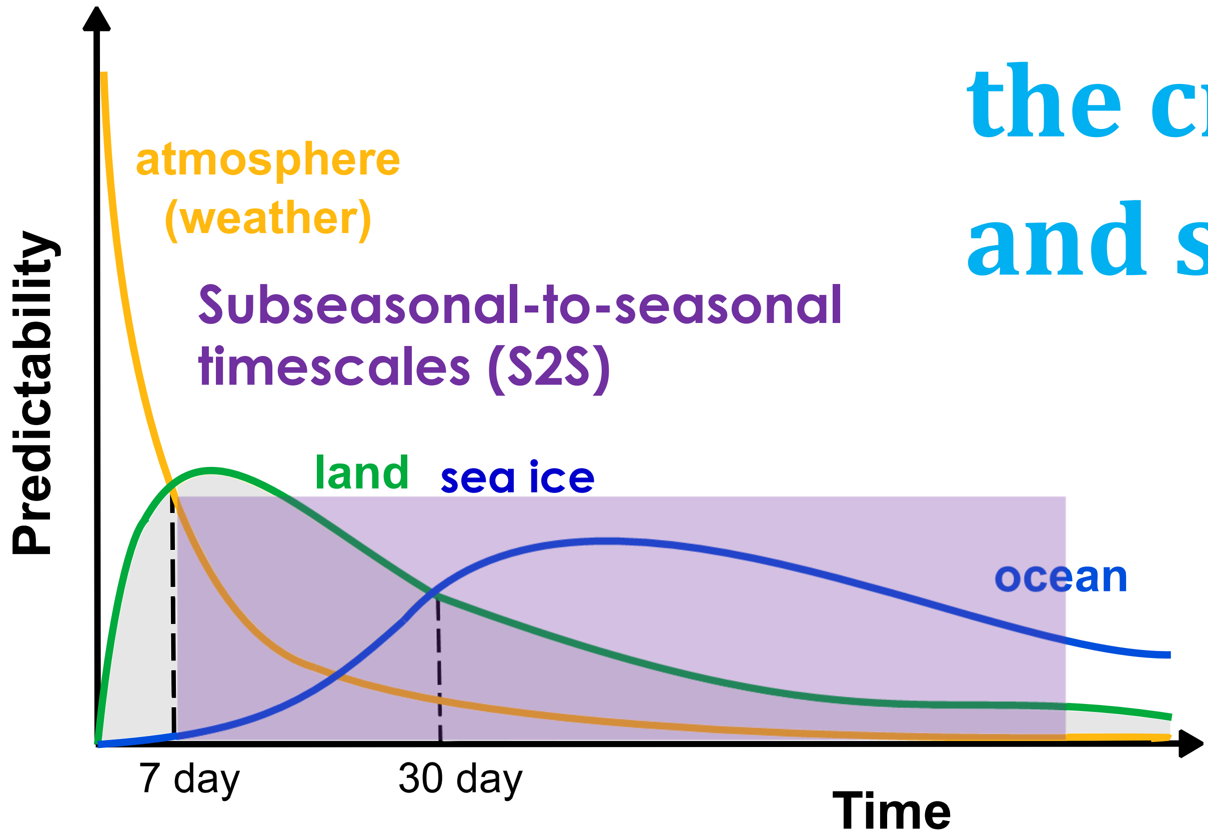
Collaborators: G. Balsamo, E. Dutra, A. Weisheimer, F. Vitart (ECMWF, UK), Fei LI (NILU, Norway)

NILU Norsk institutt for luftforskning

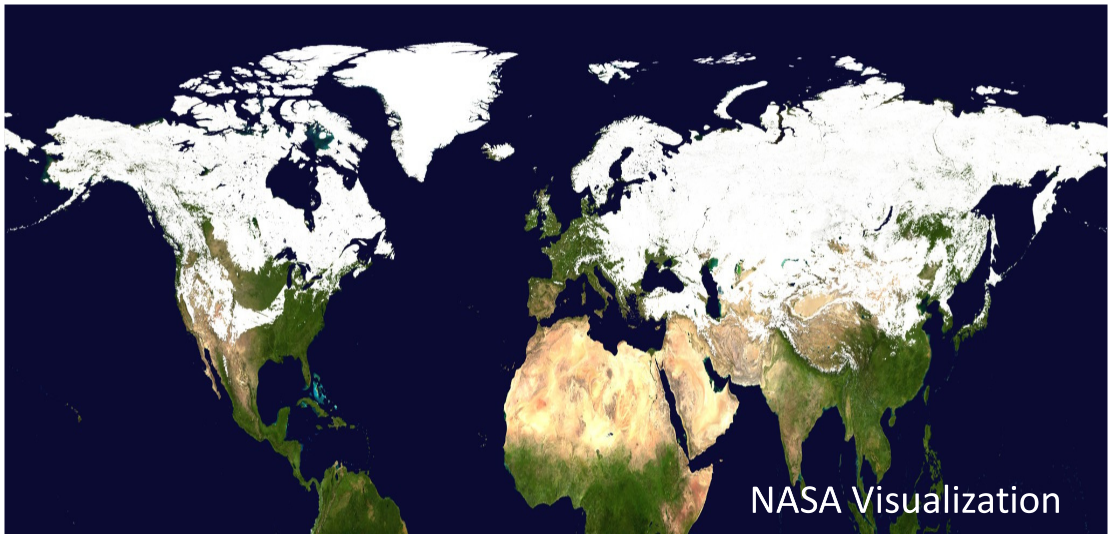
UNIVERSITAS BERGENSIS

Funded by Norwegian Research Council

Two components of the cryosphere : snow and sea ice

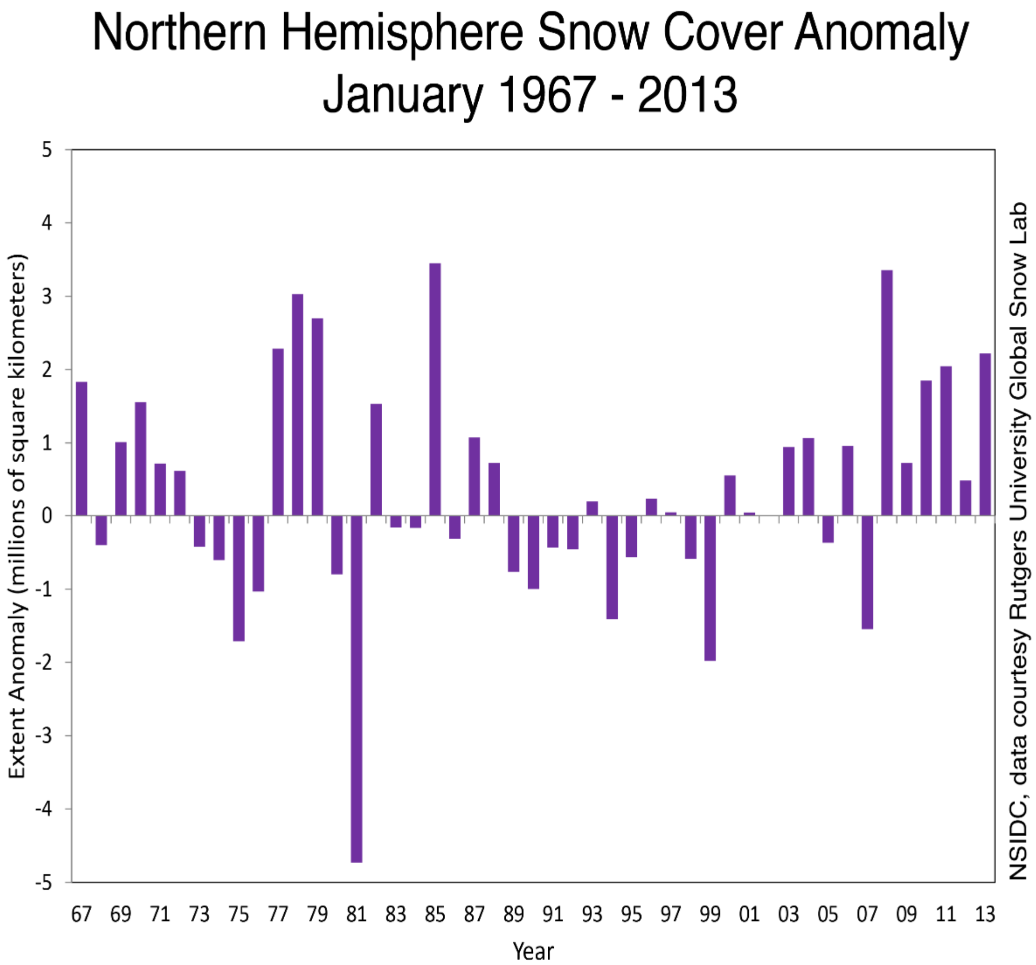


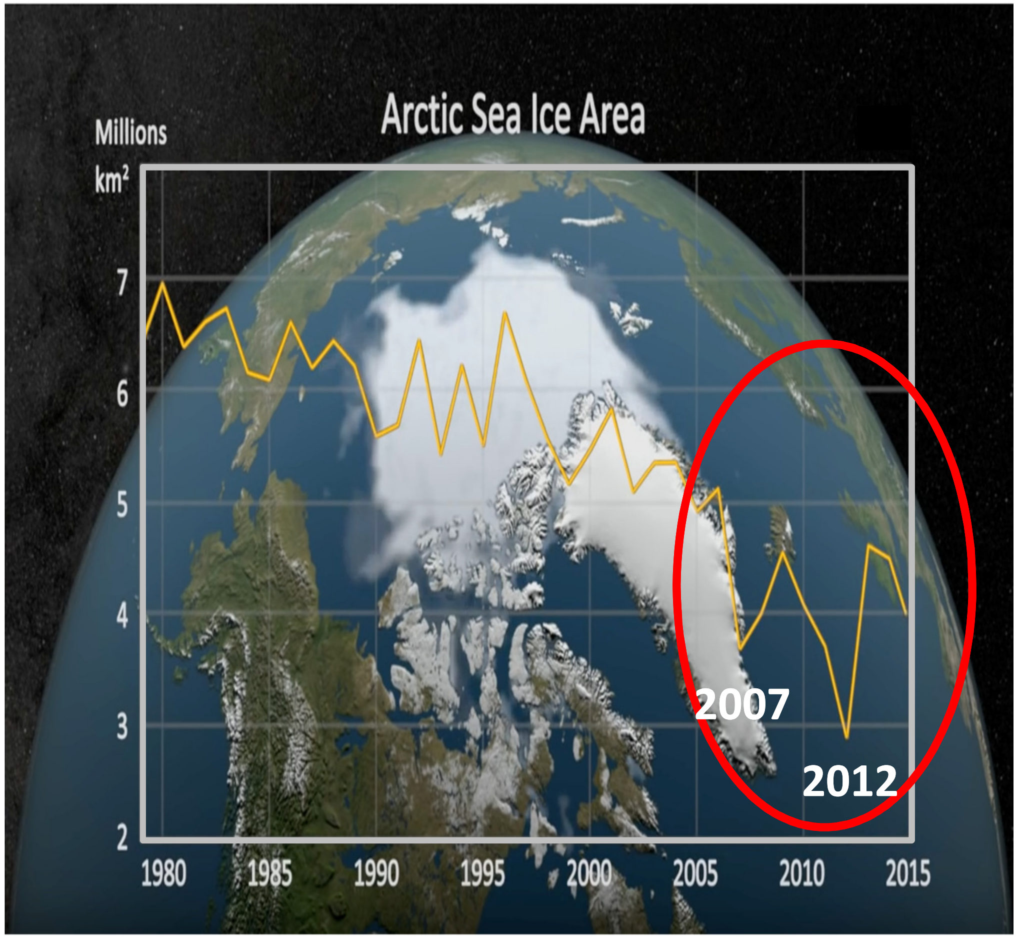
- Large inter-annual variability
- Interest in tapping on these slowly varying components for S2S prediction



Snow/Sea Ice interannual variability

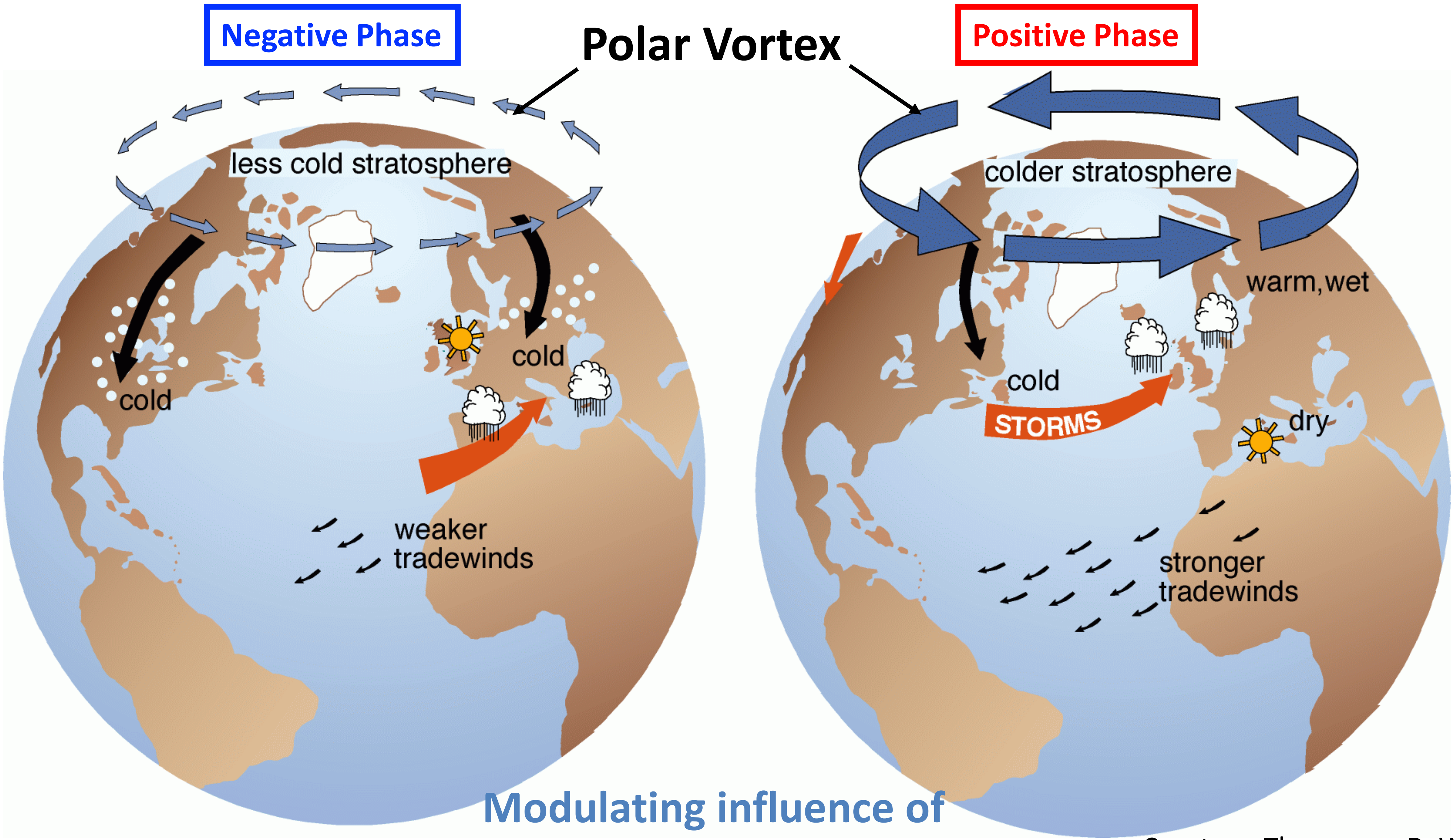
- **Local effect on surface temperature (direct)**
- **Coupling to large-scale circulation (indirect)**





Source: NASA Satellite

Arctic Oscillation (North Atlantic Oscillation) : key mode of wintertime variability of the Climate System

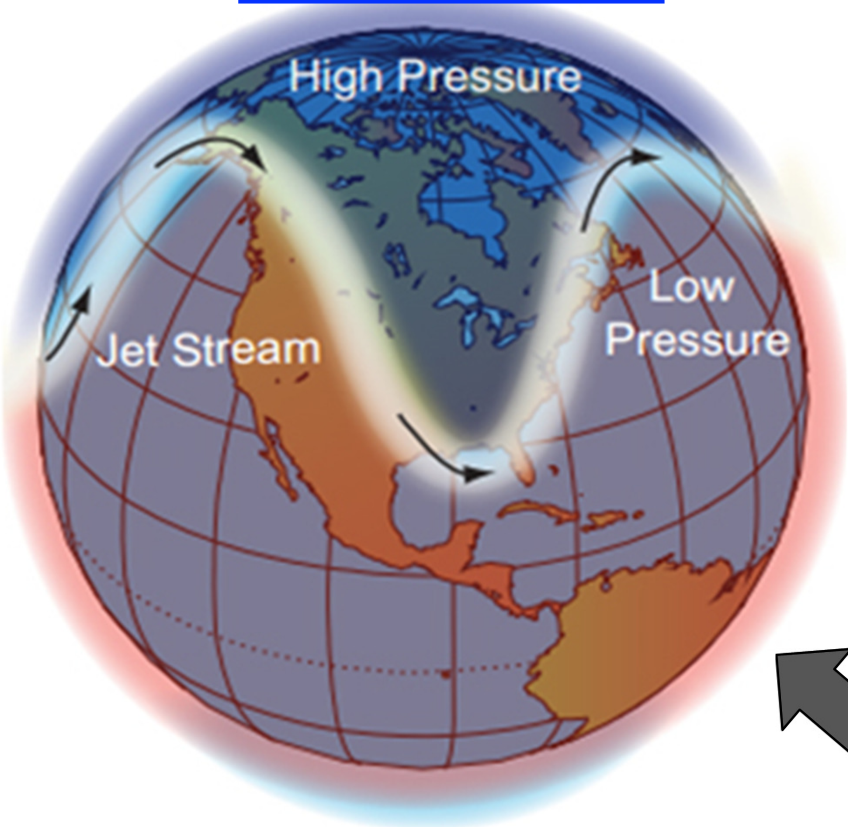


Modulating influence of cryosphere (snow/sea ice) ?

Courtesy: Thompson, D. W.
Colorado State University

Stratosphere is implicated in response to sea ice and snow variability

Negative AO Phase



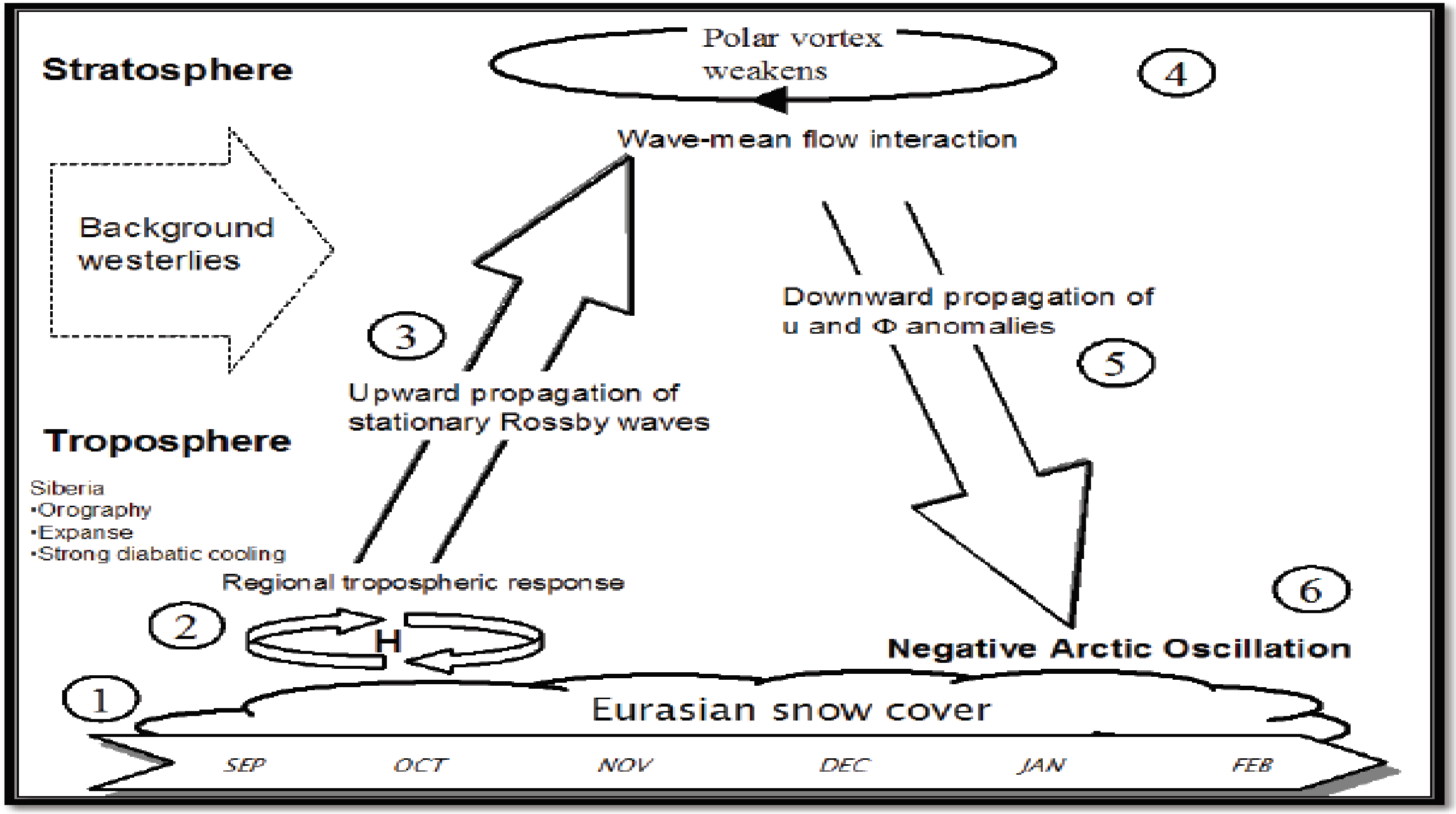
High Eurasian snow anomalies

Barents-Kara Seas Ice Loss

Impact of autumn Eurasian snow cover on NAO/AO

- ❑ modulates planetary waves propagating upward into the stratosphere, & the intensity of the polar vortex, with a lagged surface impact at high latitudes (e.g., AO) resulting from downward descent of stratosphere-troposphere interactions
- ❑ modulates planetary wave trains propagating horizontally, downstream of Eurasia over the North Pacific

(e.g. Cohen et al., Nature Geos 2007, 2014; Orsolini and Kvamstø, JGR 2009,…)

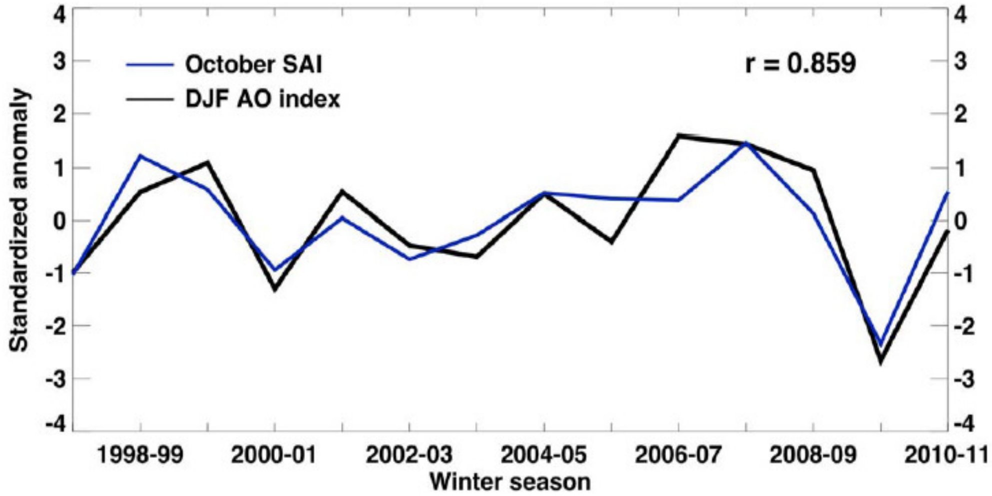


- ✓ Observations

Atmospheric re-analyses and satellite data for snow cover

- ✓ Model simulations

Observed link between October Eurasian snow cover and AO



corr: 0.86

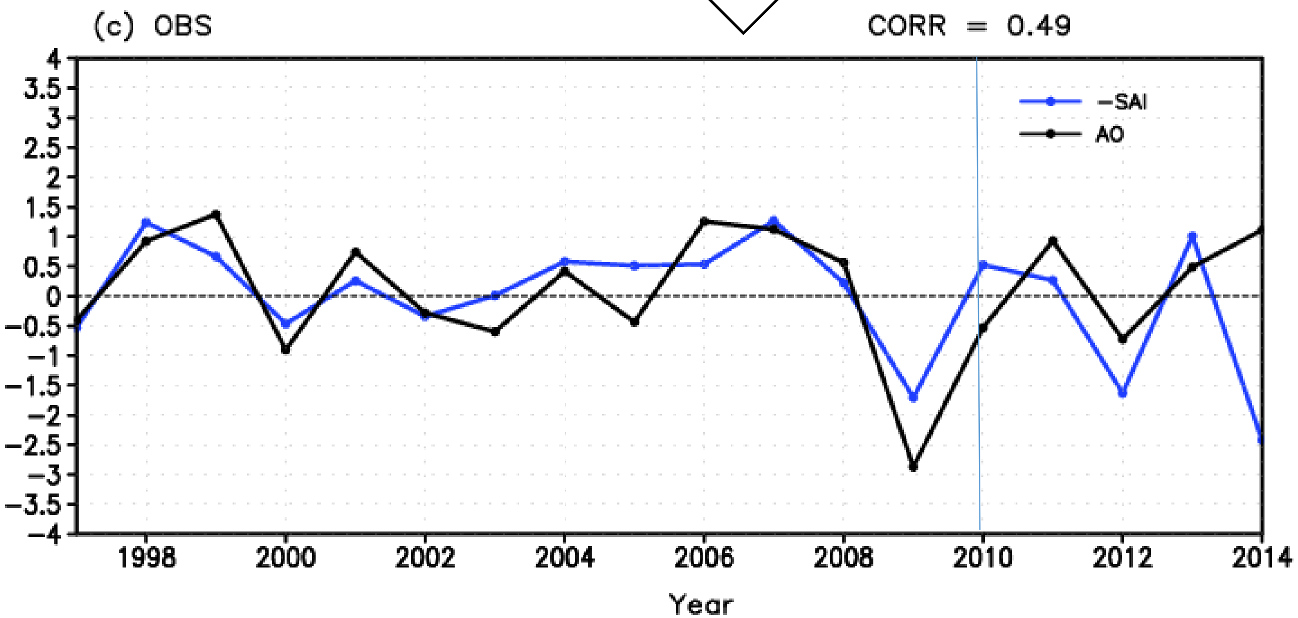
OCT SNOW → Winter-mean AO

LONG LAG

OCT snow cover advance index
vs winter (DJF) AO
OCT : first snow, high interannual variability

e.g. Cohen (2011)

corr:0.49

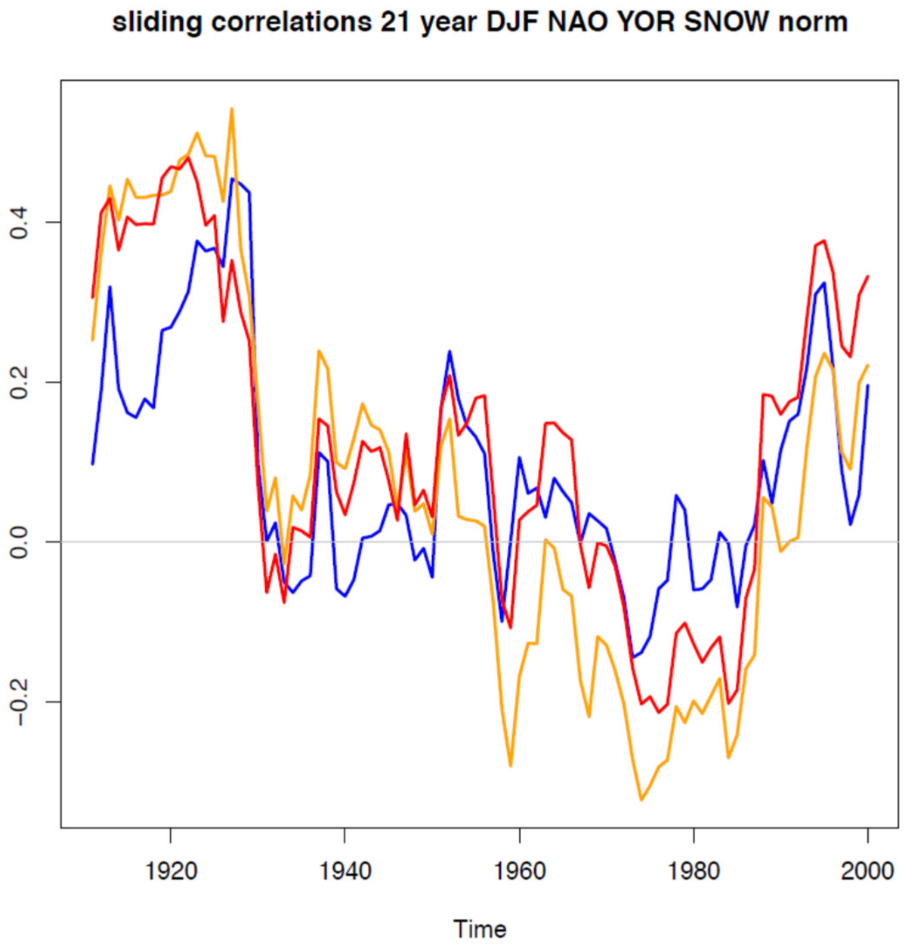


→ Questions the robustness of the snow/AO link

Before considering long lag, we need to better understand the sub-seasonal response of atmosphere to snow forcing

Figure courtesy of SH Kim and J-H Jeong, KOPRI

Non-Stationarity of snow/AO link in climate re-analyses



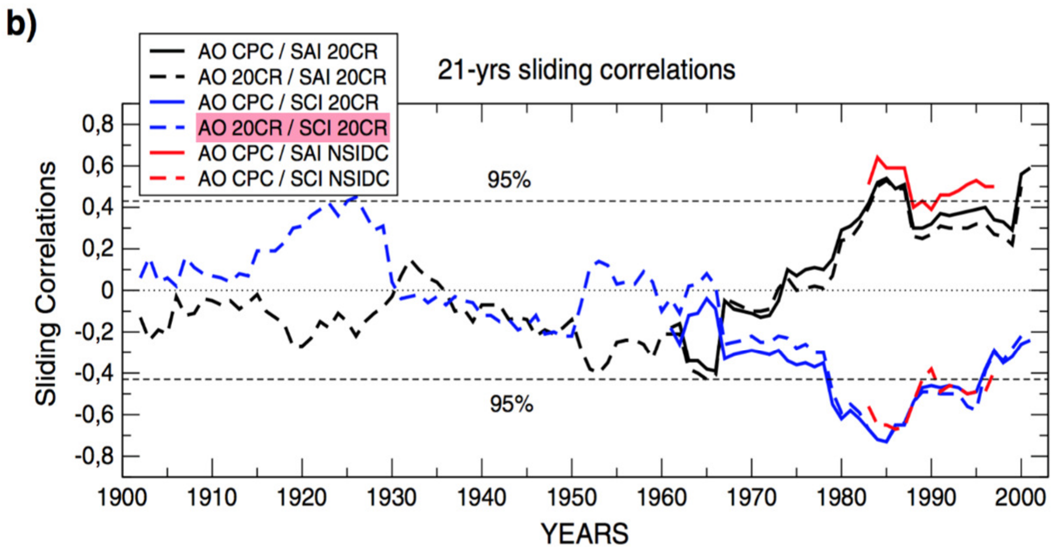
20CR (NOAA)

ERA20C (ECMWF)

CERA20C (ECMWF)

Wegmann, Orsolini et al, in prep.

Sliding snow / AO Correlations over 20th Century



- **Non-stationarity : correlation even reversed in early 20th Century**

Peings et al, GRL, 2015

Eurasian snow /NAO link in climate models

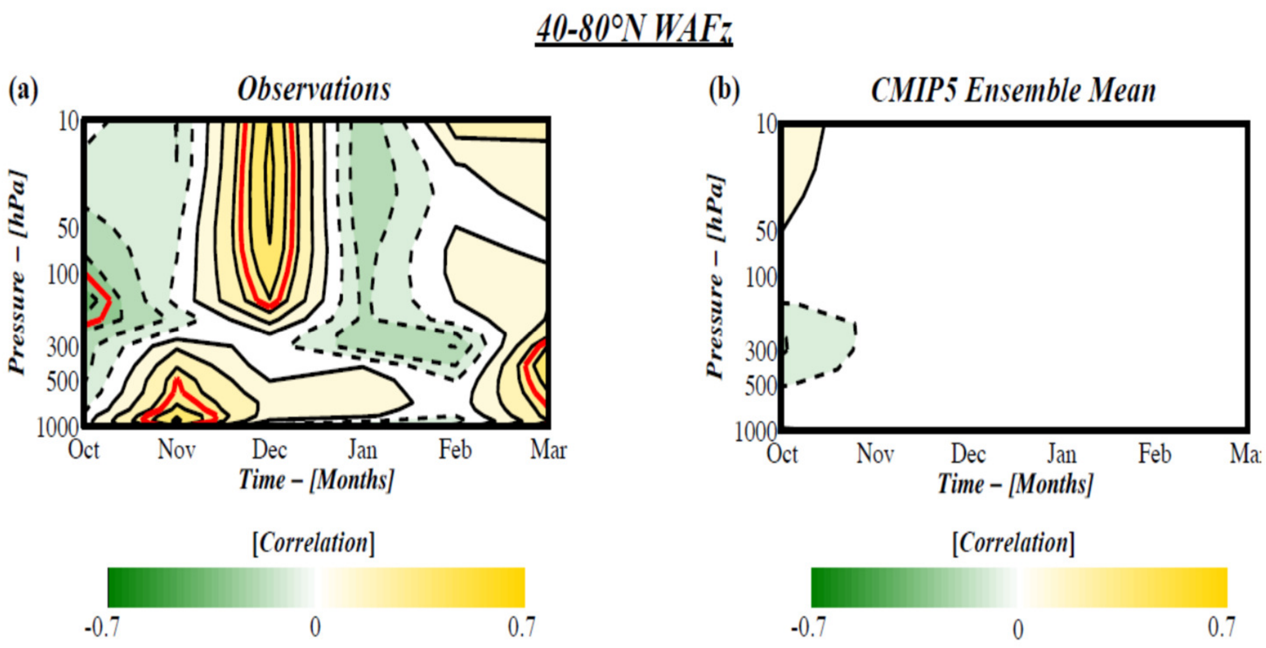
(see Henderson et al., Nature 2018 for review)

- Climate models (e.g. CMIP5) do not capture link between OCT snow cover and winter-mean AO (caveat : how robust is this link?)

- Climate models lack inter-annual autumn snow variability

- Overall issue that climate models are under-responsive to surface forcings

- Deficient PW interaction with the stratospheric jet



Correlation WAFz and October snow cover

Furtado et al., Clim. Dyn, 2015)

Physical Mechanisms of snow/atmosphere coupling

(see Henderson et al., Nature 2018 for review)

- ❑ **Short-wave albedo feedback : snow-covered land has high albedo**

- ❑ **Thermodynamical feedback : heavy snowpack provides insulating layer, decoupling lower atmosphere from soil below**

- ❑ **Hydrological feedback : heavy snowpack provides larger melt water in spring, carrying the signal into soil moisture**

Implications of snow/AO link for predictability

- **Forecast or climate models do respond to (strong) imposed snow cover variability (Jeong et al., 2013; Orsolini et al., ClimDyn 2013)**

- **Actual predictability experiments : coupled ocean-atmosphere forecasts with realistic initialisation (atmosphere, ocean, land incl. snow)**

1)

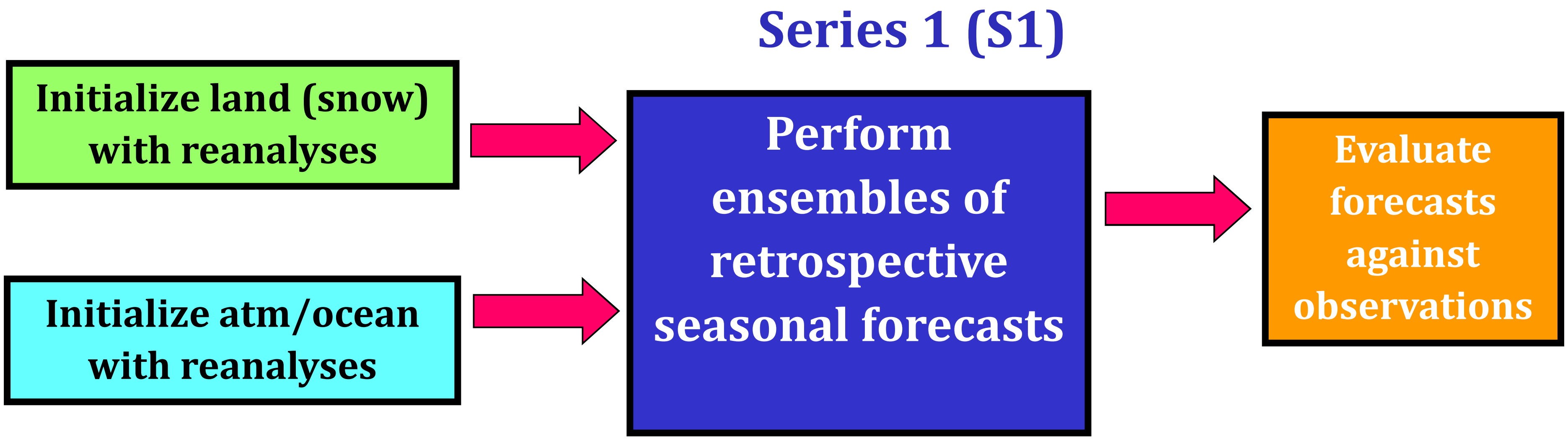
- **Experiments with the ECMWF seasonal prediction model**
- **Case study of the very cold winter 2009/10 in Europe and USA**

Most negative NAO in winter (DJF) in 145-Year Record

2)

- **Norwegian Climate Prediction Model (NorCPM)**
- **Longer 32-year period (1985-2016)**

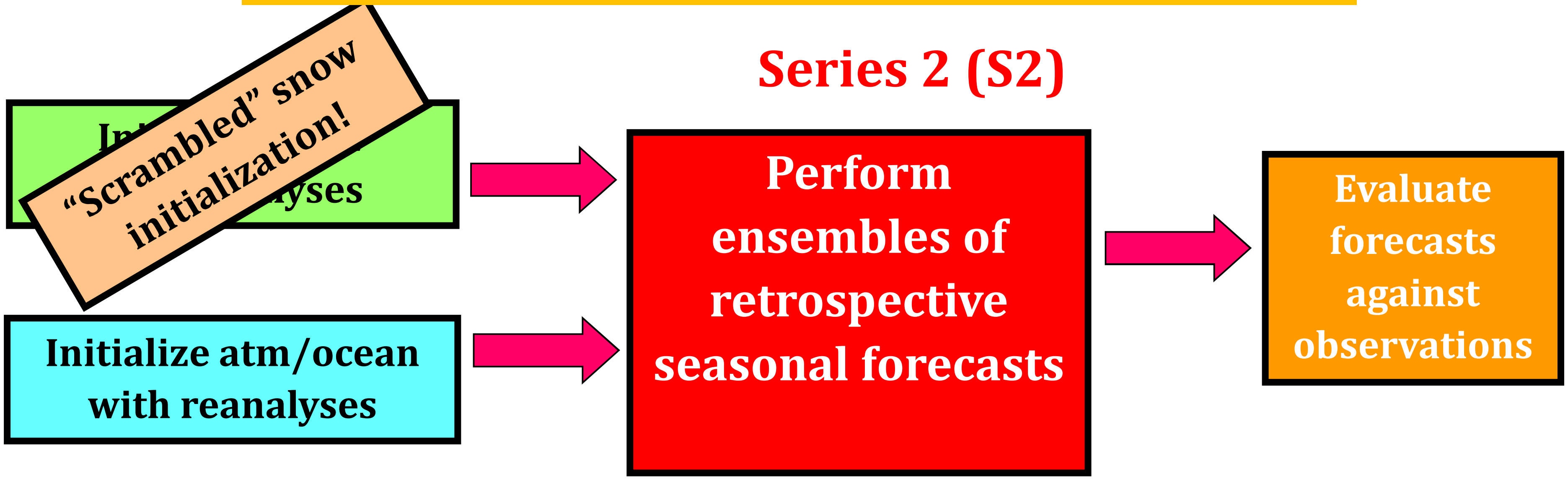
A first ensemble of S2S forecasts with accurate snow initialisation



Following GLACE approach for soil moisture impact (Koster et al. 2004; 2010)

A second ensemble of seasonal forecasts with ”scrambled” snow initialisation

Series 2 (S2)



Following GLACE soil moisture approach (Koster et al. 2004; 2010)

Forecast skill increment in surface temperature : evaluation against re-analyses

Forecast skill obtain in experiment using realistic snow initialization (SERIES 1)

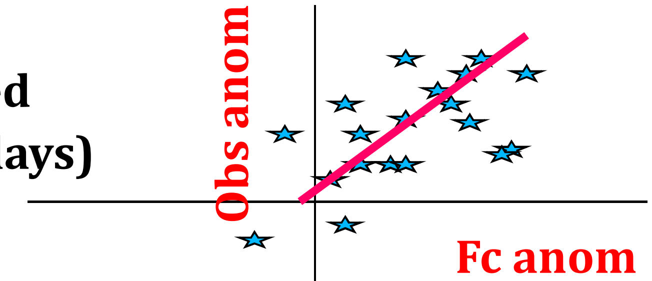
−

Forecast skill obtained in (scrambled) snow experiments (SERIES 2)

=

Forecast skill increment due to snow initialization

Lead fixed (e.g. 30 days)



★ **Ensemble-mean forecasts**

Skill measure : r^2 (correlation coefficient sqr)

Following GLACE approach (Koster et al. 2004; 2010)

”SNOWGLACE” experiments with ECMWF seasonal prediction system (not with operational system S4)

- **High horizontal resolution (T255) coupled ocean-atmosphere model (IFS HOPE V4)**
- **State-of-the-art ensemble prediction system atmospheric model:** 36R1, 62L, (low) top at 5hPa
- **land surface module is HTESSEL improved hydrology**
- **improved 1-layer snow scheme Dutra (2011)**
- **<u>High horizontal</u> resolution is same as ERAINT re-analyses**

Orsolini, Y.J., Senan, R., Vitart, F., Weisheimer, A., Balsamo, G., Doblas-Reyes F., Influence of the Eurasian snow on the negative North Atlantic Oscillation in subseasonal forecasts of the cold winter 2009/10, Clim. Dyn., vol47, 3, 1325–1334, (2016)

Series 1 (S1)

- 12-member ensemble
- atmospheric / oceanic / land

  initialisation
- forecast length : 2-month
- Start date: DEC 1, 2009
- 2009

•realistic snow initialisation *(ERAINT)*

Series 2 (S2)

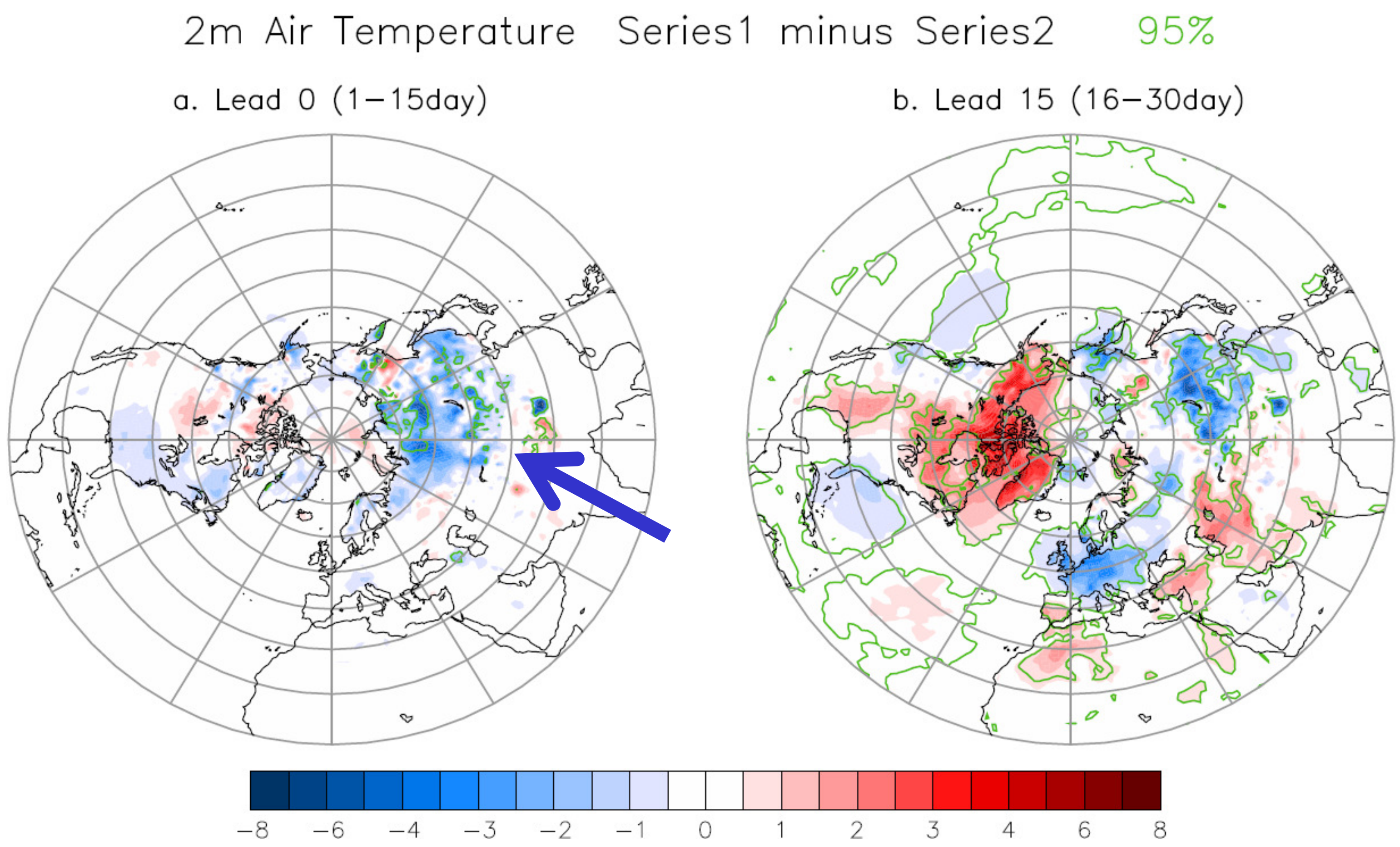
identical , <u>but</u>

• "low snow" taken from earlier start dates in fall, and other years

Anomaly field : ensemble-mean difference (Series 1 – Series 2) in 15-day averaged sub-periods (day 1-15, day 16-30, ...)

Ens (S1 – S2) is a (high minus low) snow composite difference

Sensitivity to high snow : surface temperature differences



ensemble-mean

High snow – Low snow

DEC 1, 2009

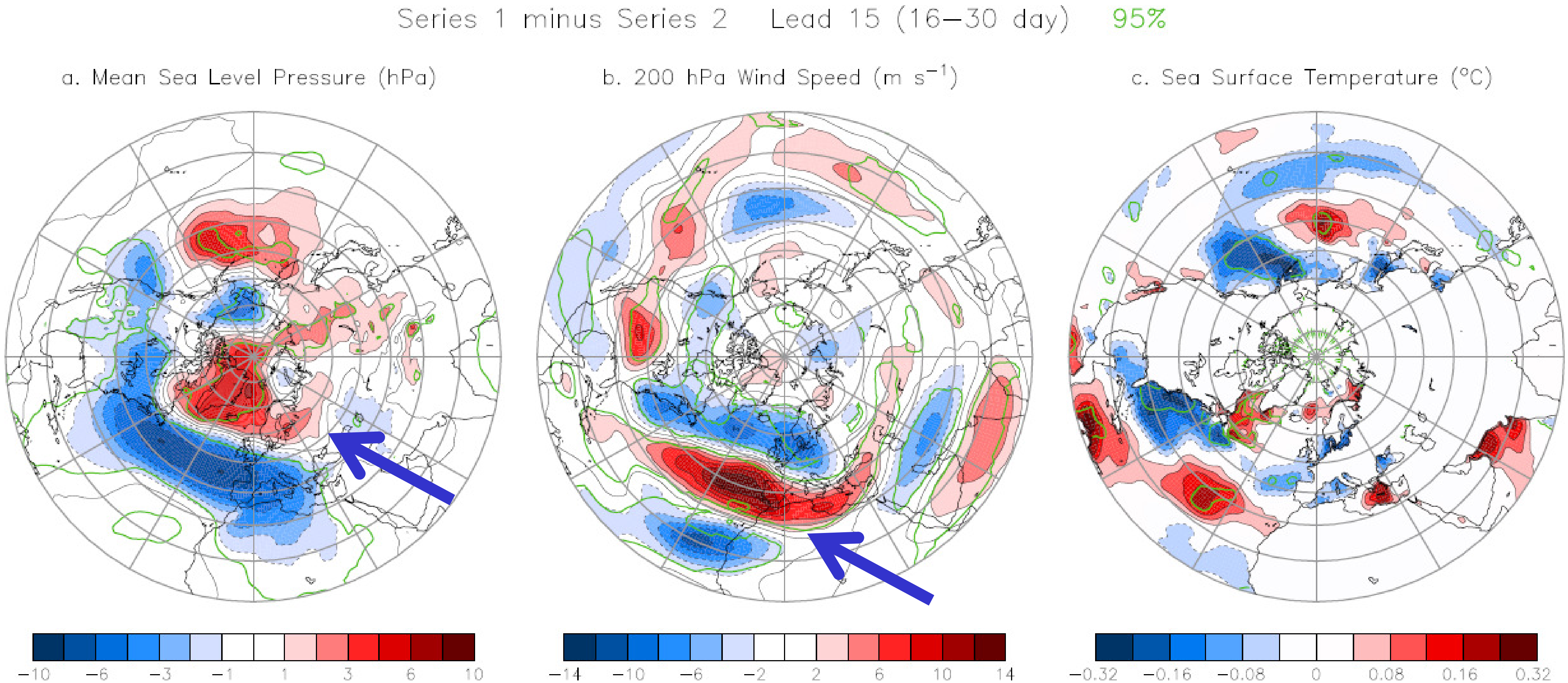
start date

Presence of thick snow pack → colder surface temperature initially (up to 6K) over Eurasia.

Afterwards, quadrupole pattern across ATL, typical of negative NAO → cold Europe and NE America.

+ Cold anomaly over Far East

Sensitivity to high snow : Sea level pressure, wind speed (200 hPa), SST differences



ensemble-mean

High snow – Low snow

15-day lead (16-30 days))

differences between High snow minus Low Snow initialisation :

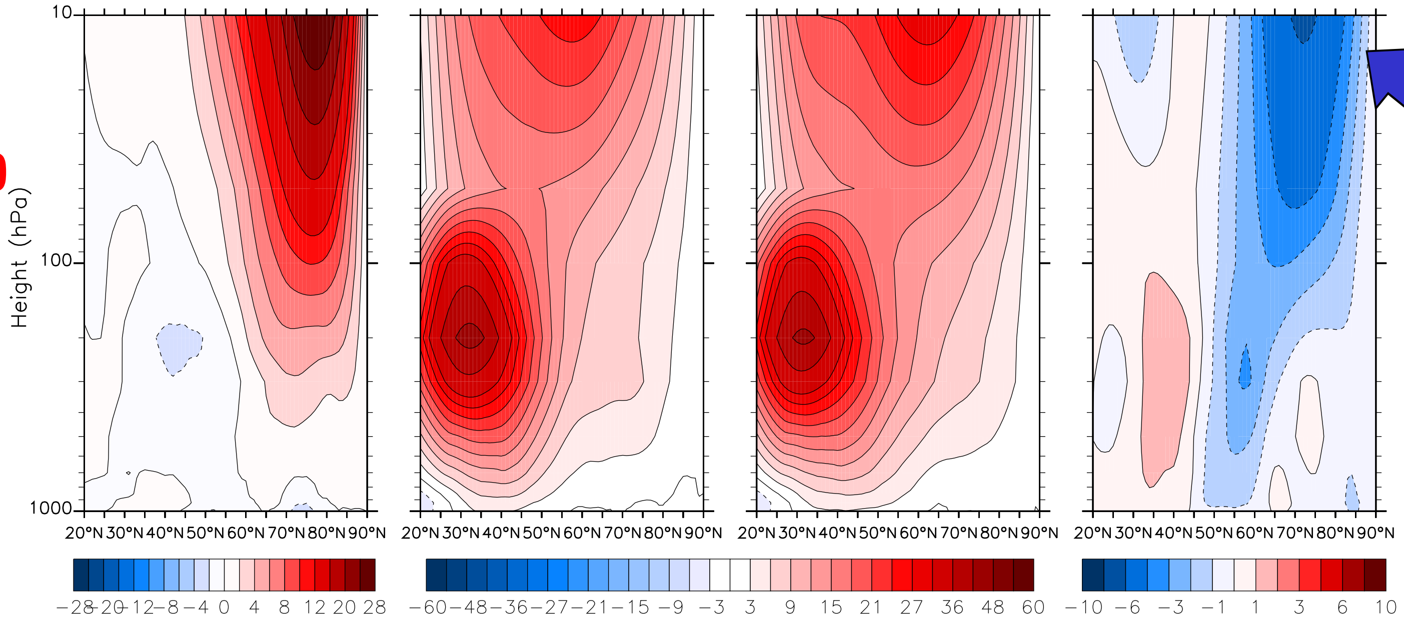
→ more negative NAO

As seen in SLP meridional dipole, jet stream displaced further south, SST tripole.

ROLE OF STRATOSPHERE

High snow – low snow | High snow | Low snow | High snow – low snow

Quasi-stationary v-heat flux (v*T*)



Zonal-mean U cross- sections *(z-lat)*

ensemble-mean

15-day lead

Forecasts with high snow : enhanced heat flux

→ Stratospheric vortex deceleration:

→ Fast response (1-2 weeks) to stratospheric change over N.ATL. (NAO neg)

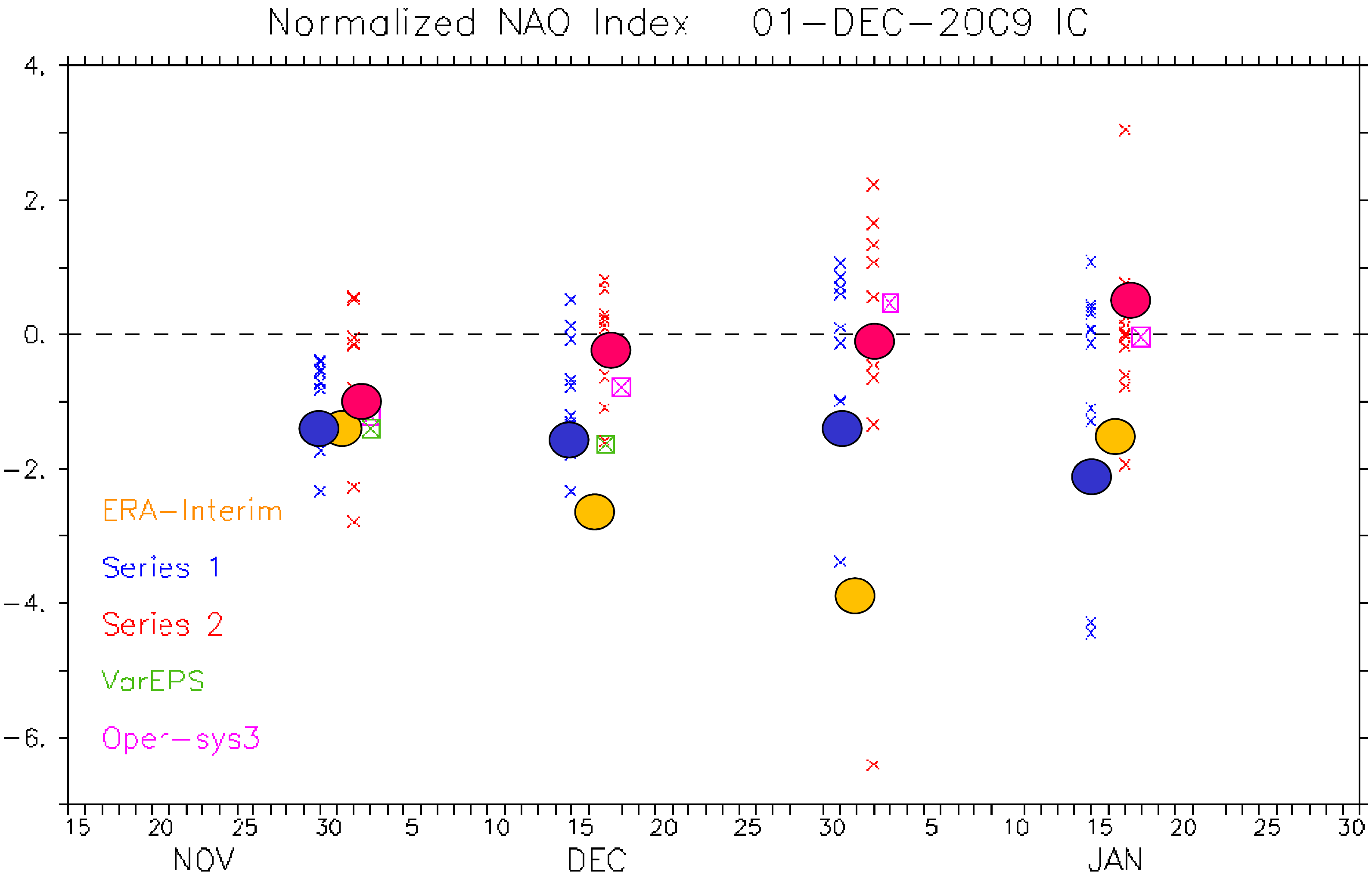
Normalised NAO index

(based on anomaly of SLP difference; years *2004-2010*)

- Series1 has more negative <ensemble> NAO index than Series2, closer to re-analyses. (T255)
- VAREPS: oper. monthly forecasts, at variable resolution

(nearly identical to our SNOWGLACE runs) (T255)

- Operational (S3) (T159)



→ Snow initialisation (high snow) contributes to maintaining negative NAO

→ one of the factors influencing negative NAO phase, not main driver

Implications of snow/AO link for predictability

- **actual predictability experiments : coupled ocean-atmosphere forecasts with realistic initialisation (atmosphere, ocean, land incl. Snow)**

- **Norwegian Climate Prediction Model (NorCPM)**
- **Coupled atmosphere-ocean model (NCAR WACCM + MICOM)**
- **Two-month forecasts over a 32-year period (1985-2016)**
- **Start date in NOV 1 (NOV, DEC forecasts)**

Initialisation

✓**Land**: **CLM**; the initial and boundary data is taken from an off-line run driven by NCEP reanalysis.

✓**Ocean & sea ice**: **NorCPM reanalyses**; SST anomaly and temperature and salinity profiles are monthly assimilated into the ocean component.

✓**Atmosphere**: nudging **WACCM** (for 2-week period) towards the ERA-Interim reanalysis.

Period

✓Ten of 3-month ensemble forecasts, started on every 1st November in the years 1980–2010.

Twin experiments

✓**Series 1**: realistic initialisation of snow variables based on CLM/NCEP.

✓**Series 2**: as in Series 1, but with "scrambled" snow initial conditions from an alternate year.

i.e., snow perturbations representative of inter-annual variability

Verification datasets

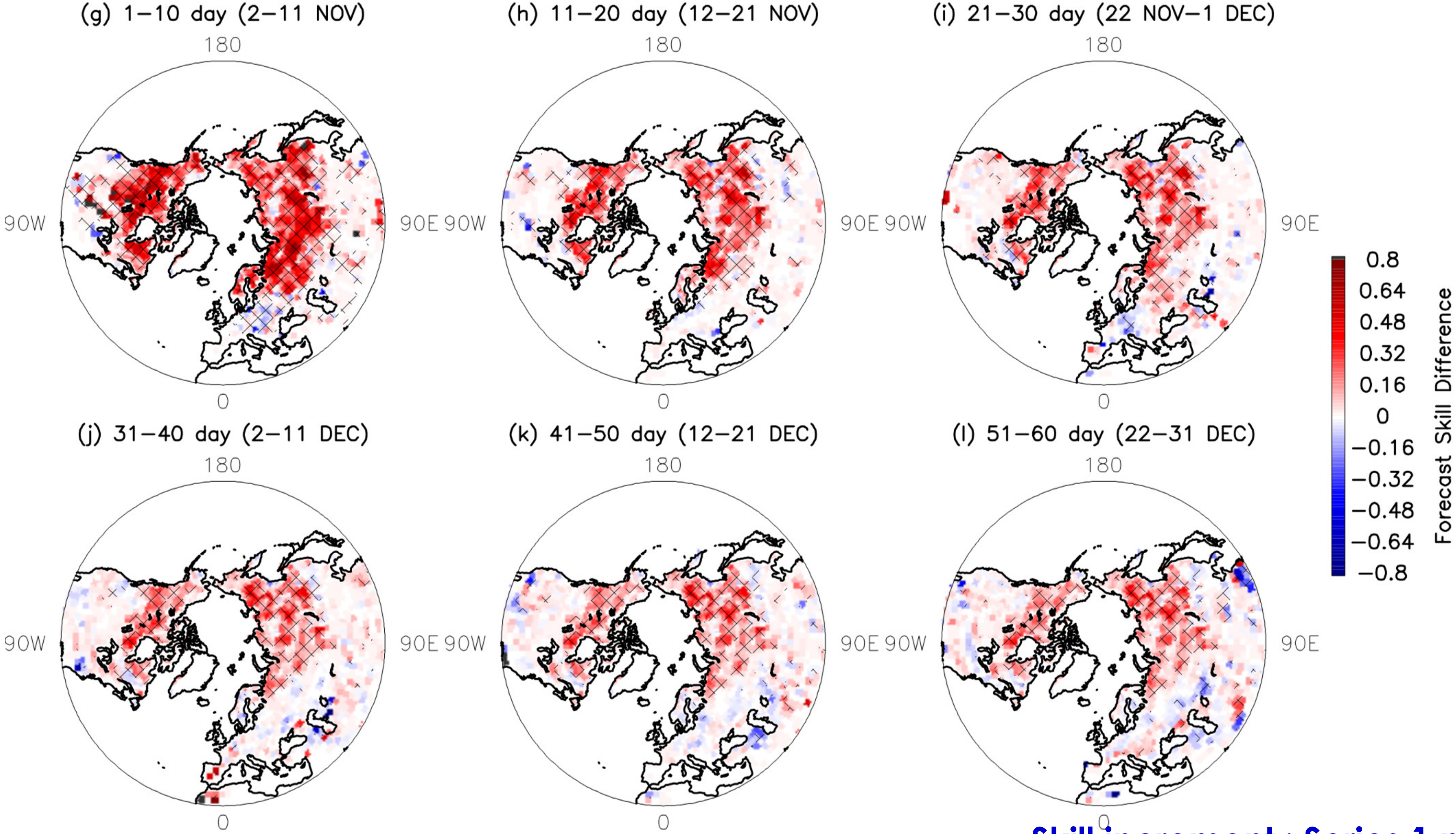
✓ ERA-Interim land (snow) [uncorrected version]

✓ ERA-Interim (temperature)

Ensemble of retrospective S2S winter forecasts (1985-2016) with Norwegian Climate Prediction Model (NorCPM)

Snow water equivalent

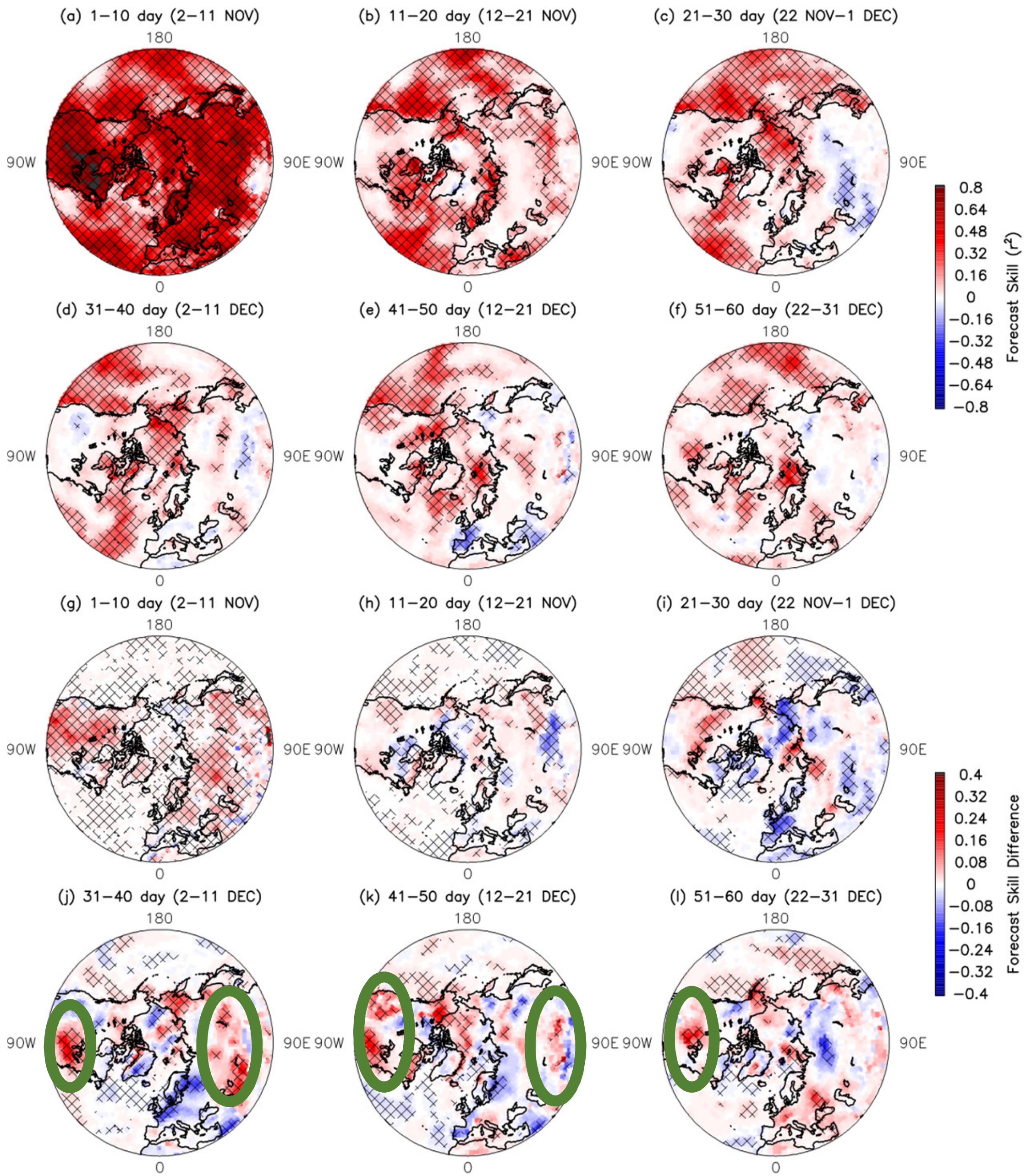
6 lead times (0-day to 50-day) ; start date : NOV 1



Large skill increment (up to 0.8) incl. at long leads:
Accurate snow initialisation improves snow forecast…

Skill increment : Series 1 minus Series 2
(gain from realistic vs. degraded snow initialisation)

Ensemble of retrospective S2S winter forecasts (1985-2016) with Norwegian Climate Prediction Model (NorCPM) : role of snow initialisation



Skill: Series 1
(realistic initialisation)

2m Air Temperature
6 lead times (0-day to 50-day) ; start date : NOV 1

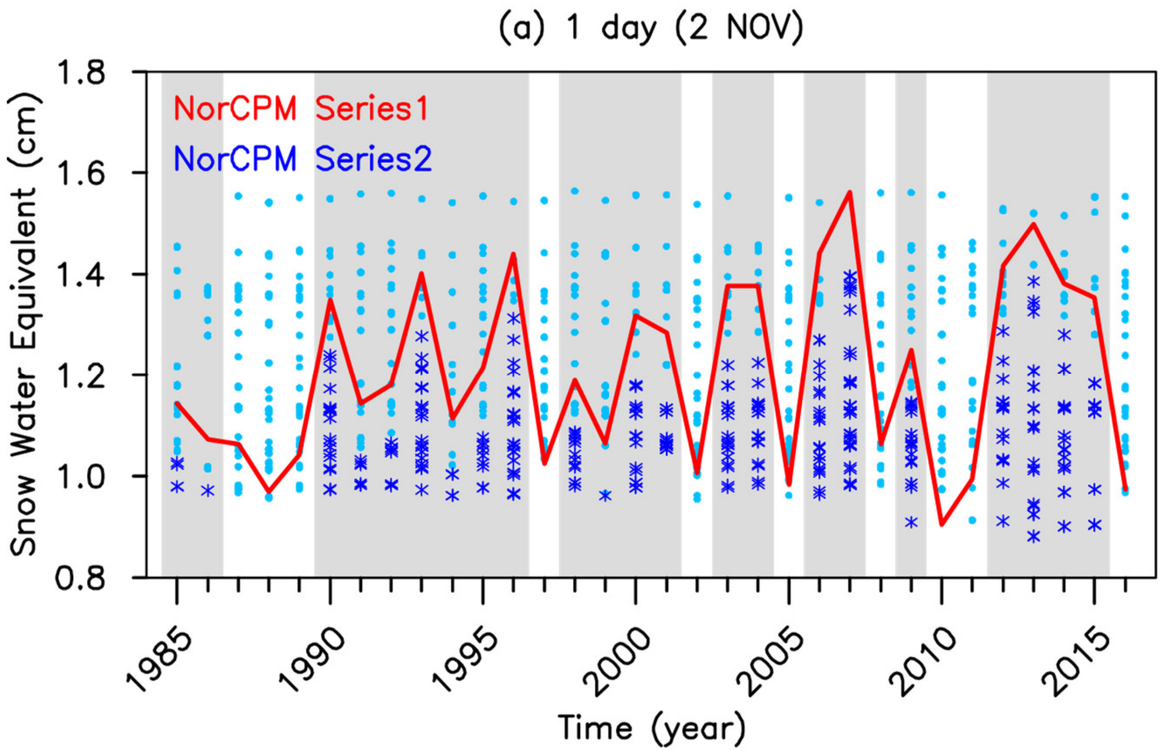
Skill increment : Series 1 minus Series 2
(gain from realistic vs. degraded snow initialisation)

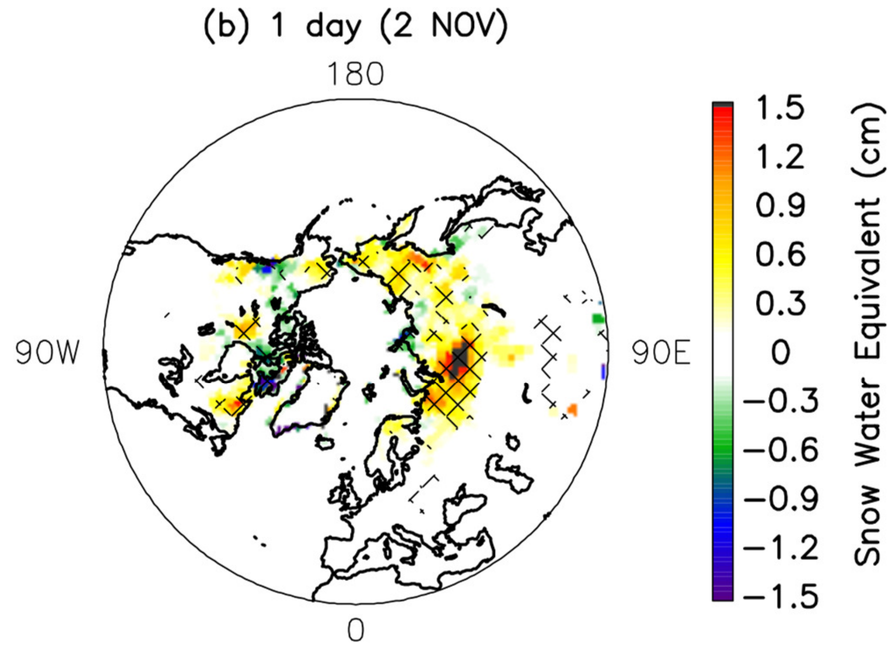
Moderate skill increment (0.3-0.4) at southern edge of continental snowpacks at long leads (analogous to soil moisture – Koster 2010)

Region of high snow variability

Composite of high versus low initial snow

Initial Eurasian Snow for each year



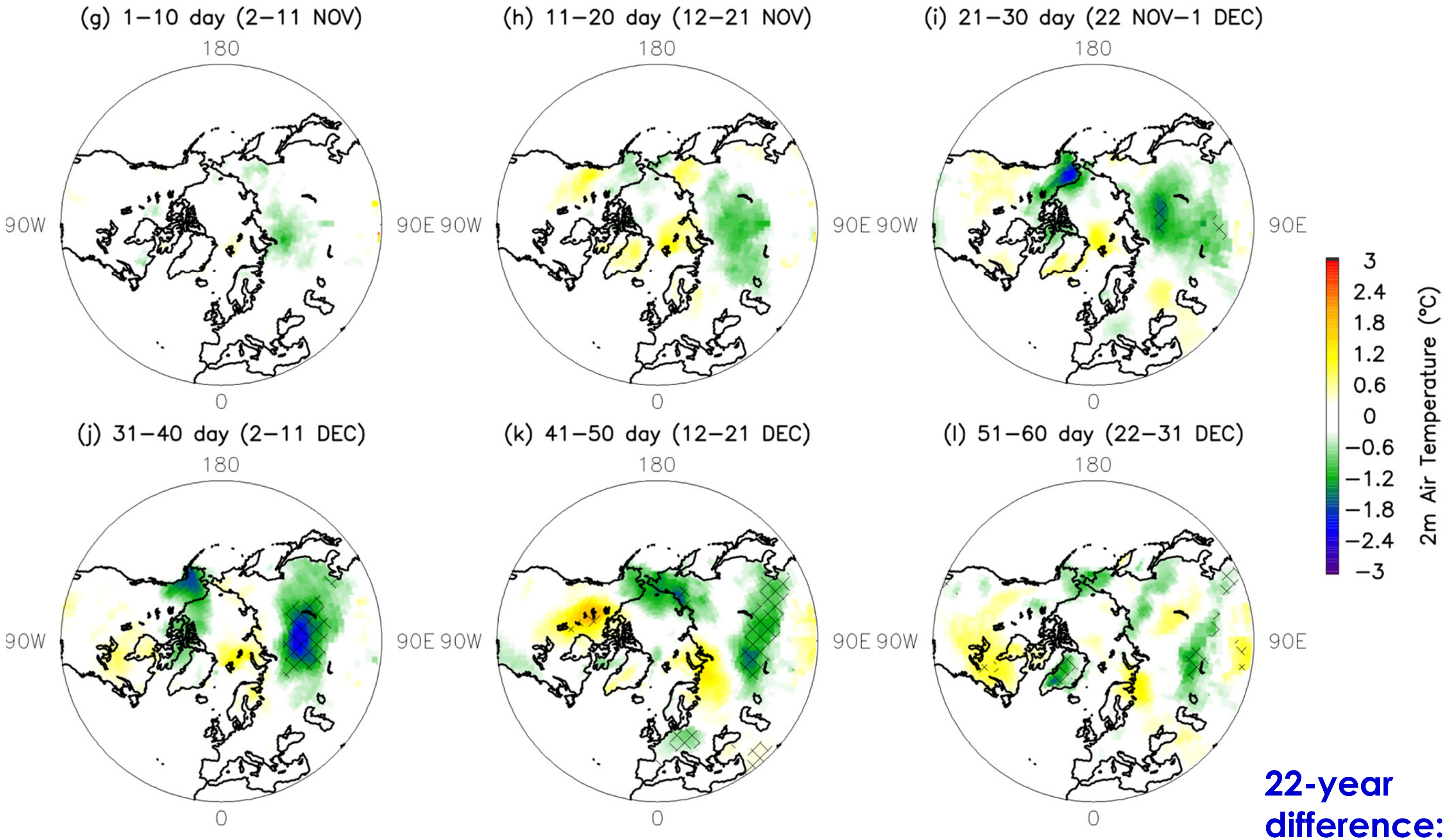


Series 1: **30-member ensemble-mean (red curve)**
Series 2: **members with higher (skyblue dots) or lower (blue crosses) SWE** than Series 1, based on -0.5 standard deviation.

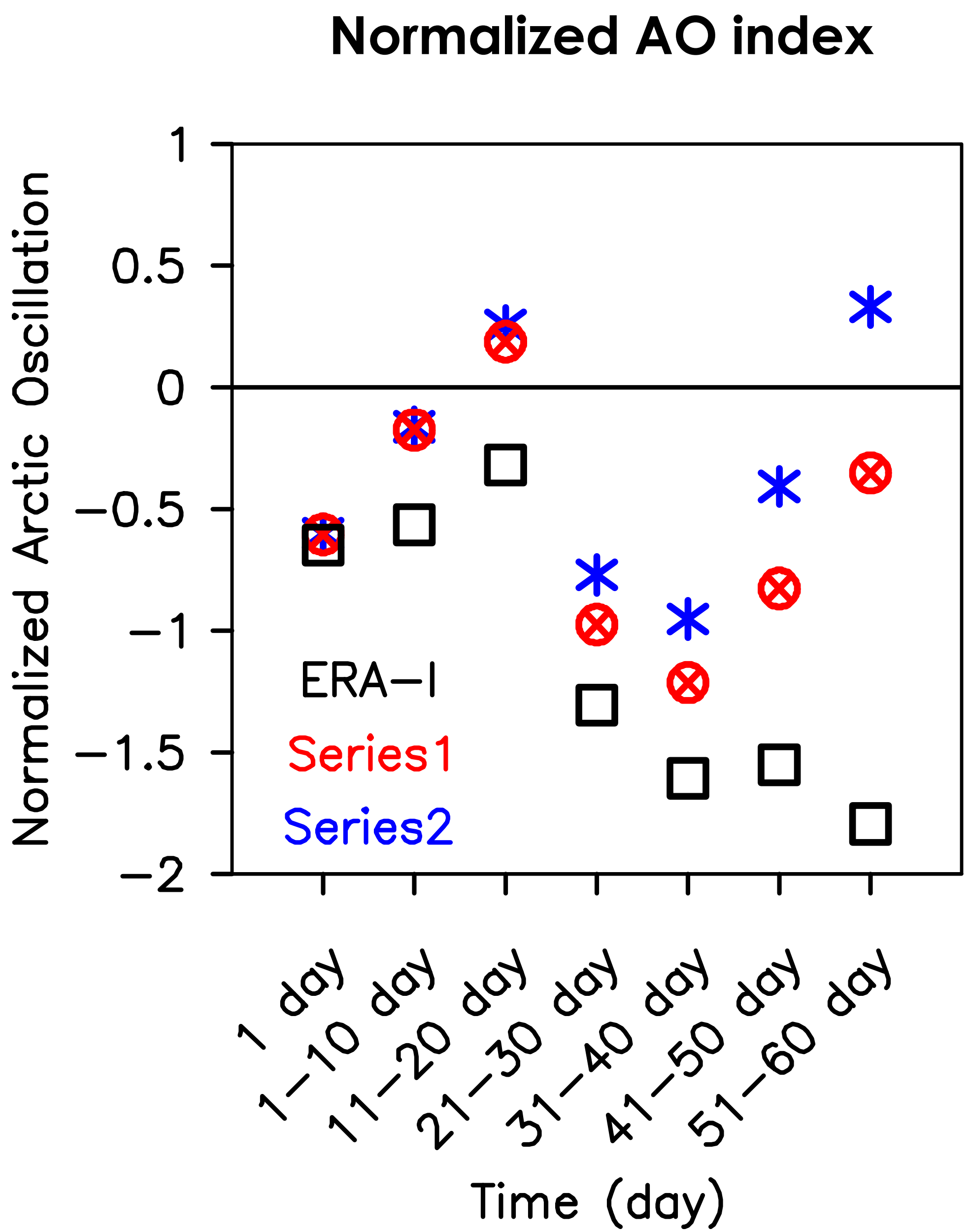
22-year initial difference: Series 1 minus conditionally sampled Series 2

Composite of high versus low initial snow

2m Air Temperature	6 lead times (0-day to 50-day) ; start date : NOV 1



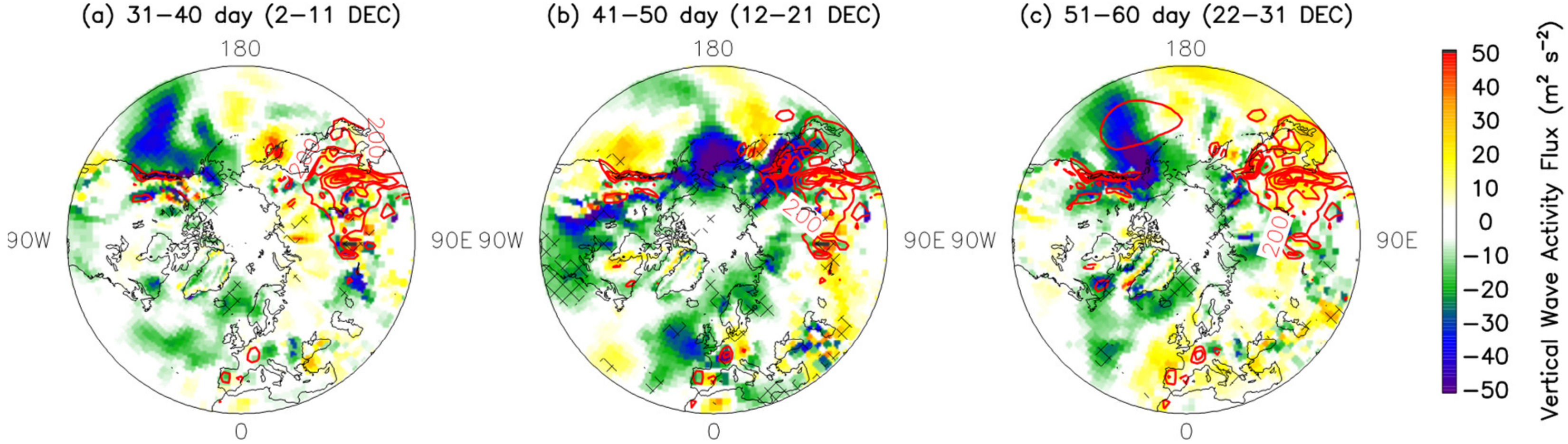
22-year difference: Series 1 minus conditionally sampled Series 2

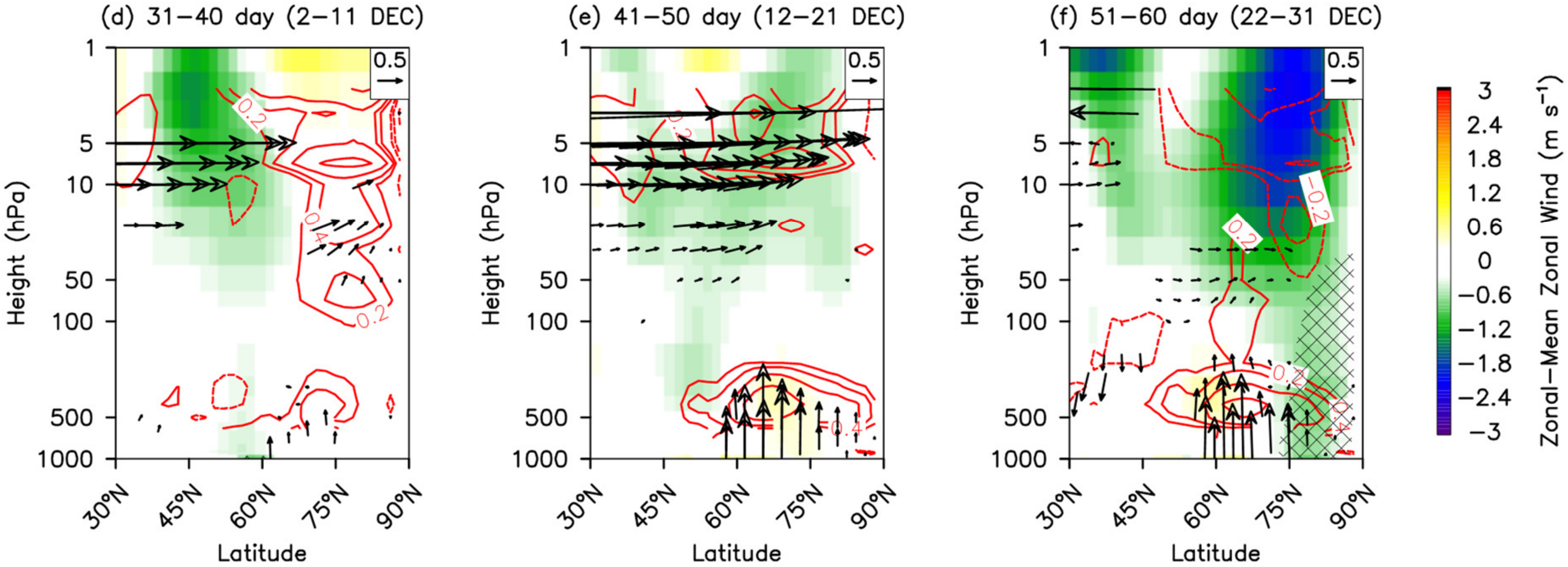


- The AO is more negative in the forecasts with high initial snow than low snow
- Possibly by the same stratospheric coupling mechanism

7-negative AO-year difference: Series 1 minus conditionally sampled Series 2

500-hPa Vertical wave activity flux





22-year difference: Series 1 minus conditionally sampled Series 2

Zonally-mean zonal wind (shaded), E-P flux (vectors) and its divergence (contours)

Summary of dedicated model experiments

- Heavy snowpack has initial cooling effect on lower atmosphere
- Presence of thick snowpack over Eurasia maintains the initial negative NAO
- Coupling to the stratosphere
- Snow acts a feedback (not the main driver of winter NAO/AO)

Prediction aspects

- Snow accurate initialisation improves snow forecast skill
- Moderate but "patchy" skill increments in surface temperature in the transition regions at the southern edge of snow-covered land at long lead times.
- "Cold spots" where snow-atmosphere coupling operate (needs to be verified in multi-model framework)
- Analogous results to "Hot spots" with soil moisture-atmosphere coupling, with same limitations

PUBLICATIONS

Orsolini, Y.J., Senan, R., Balsamo, G., Doblas-Reyes, F.J., Vitart, F, Weisheimer, A., Carrasco, A., and Benestad, R.E. Impact of snow initialization on sub-seasonal forecasts, Climate Dynamics, 41:1969-1982, (2013)

Senan, R., Orsolini, Y.J., Weisheimer A., Vitart, F., Balsamo, G., Stockdale, T., Dutra, E., Doblas-Reyes, F., D. Basang, Impact of springtime Himalayan-Tibetan Plateau snowpack on the onset of the Indian summer monsoon in coupled seasonal forecasts, Clim. Dyn., Vol. 47, Issue 9, pp 2709–2725, doi:10.1007/s00382-016-2993-y. (2016)

Orsolini, Y.J., Senan, R., Vitart, F., Weisheimer, A., Balsamo, G., Doblas-Reyes F., Influence of the Eurasian snow on the negative North Atlantic Oscillation in subseasonal forecasts of the cold winter 2009/10, Clim. Dyn., vol47, 3, 1325–1334, (2016)

F. Li, Y. Orsolini, N. Keenlyside, M.-L. Shen, F. Counillon, Y. Wang, Impact of snow initialisation in subseasonal-to-seasonal winter forecasts with the Norwegian Climate Prediction Model , submitted to JGR special issue on Bridging Weather and Climate: Subseasonal-to-Seasonal (S2S) Prediction, submitted April 29, 2019

RESERVE SLIDES

Linking Eurasian snow and Arctic sea ice

❑ **LOW ARCTIC SEA ICE (late summer/early autumn)→ HIGH SNOW (autumn over Eurasia) :**

- **some statistical evidence for link between low sea ice in autumn and winter snowfall**

(Liu et al, PNAS 2012)

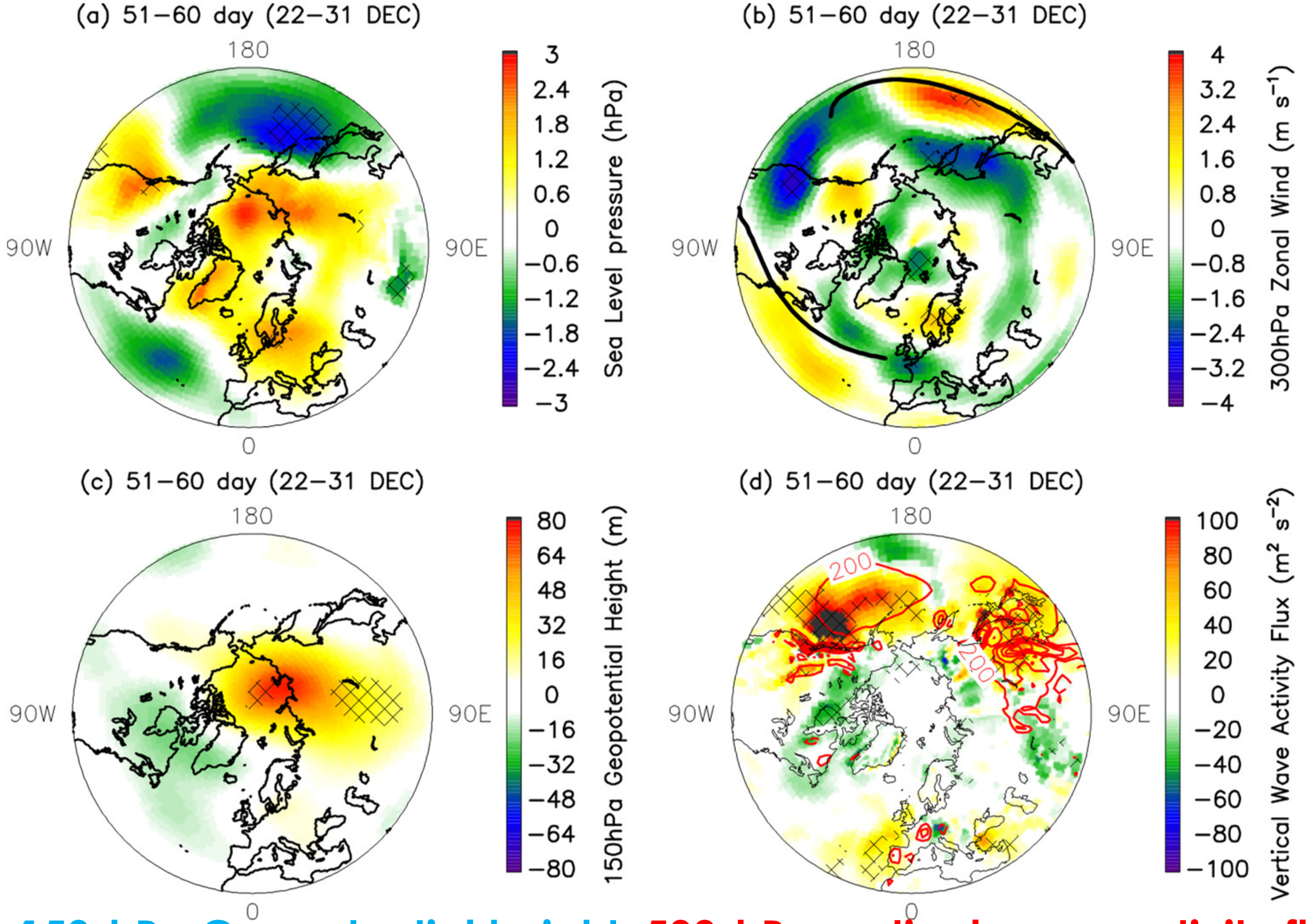
- **Evidence from Lagrangian studies linking moisture transport from an ice-free Barents-Kara Sea to increased snowfall and snow depth over Southwestern Siberia**

(but not continent-wide)

Wegmann, Orsolini, Jaiser, Rinke, Dethloff et al., Arctic moisture source for Eurasian snow cover variations in autumn (Env. Res. Lett. - 2015)

Sea level pressure

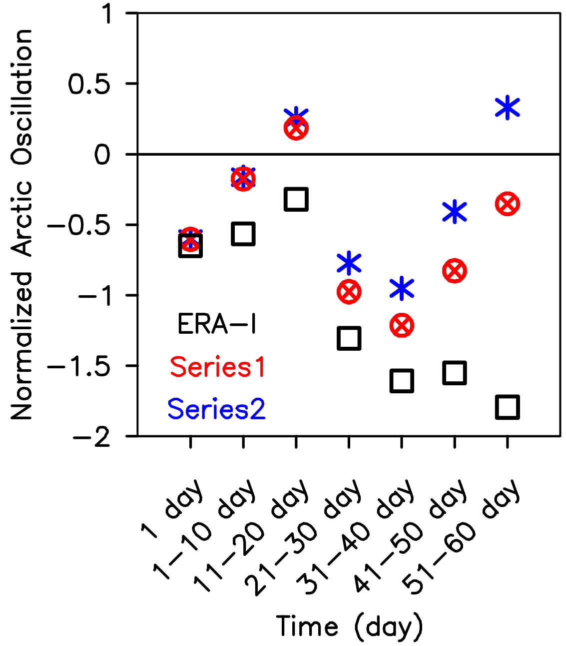
300-hPa zonal wind



150-hPa Geopotential height

500-hPa vertical wave activity flux

Normalized AO index



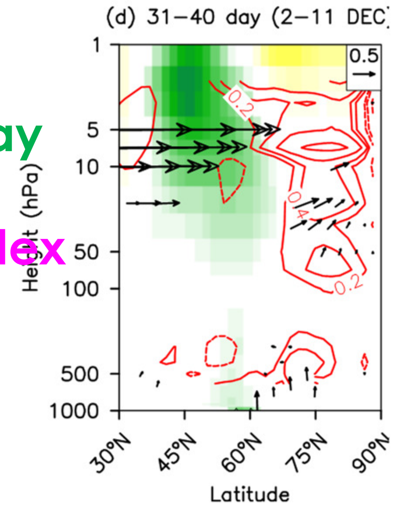
7-negative AO-year difference: Series 1 minus conditionally sampled Series 2

1) Modelled surface temperature is strongly impacted by the presence of snow and high Eurasian snow is related to **enhanced wave activity fluxes**;

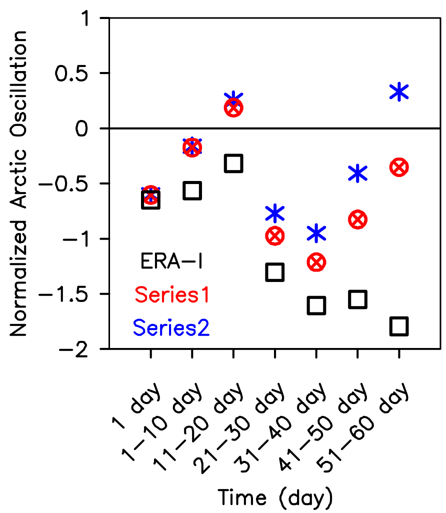
2) Realistic snow **initialisation** favors the maintenance of **the negative Arctic Oscillation** though a land surface–stratosphere connection;

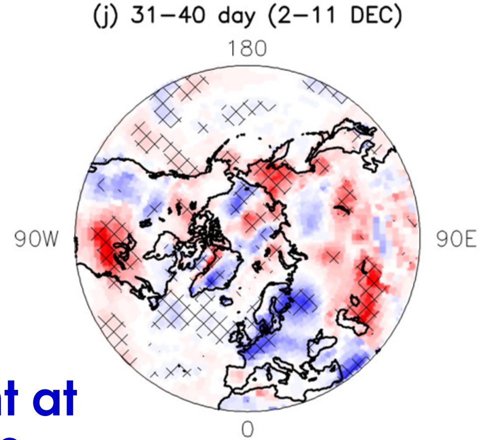
3) It leads to skill increments in **surface temperature** in the transition regions at the southern edge of snow-covered land at long lead times.

Series 1 & 2 difference at day 31–40



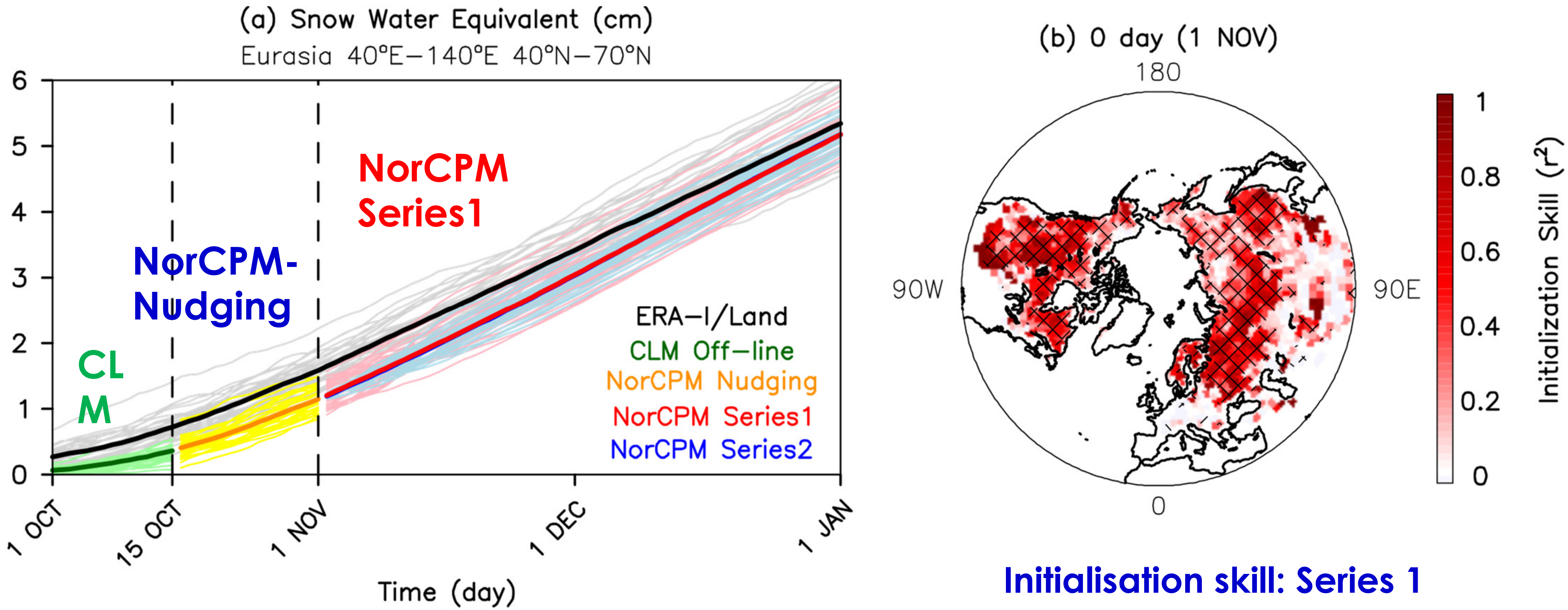
Normalized AO index





Skill increment at day 31–40

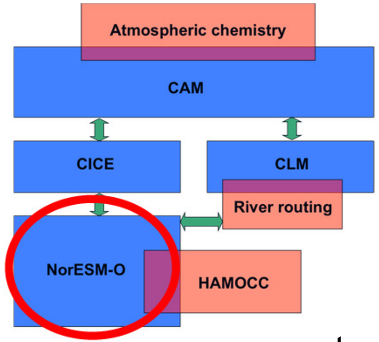
Snow water equivalent



Initialisation skill: Series 1

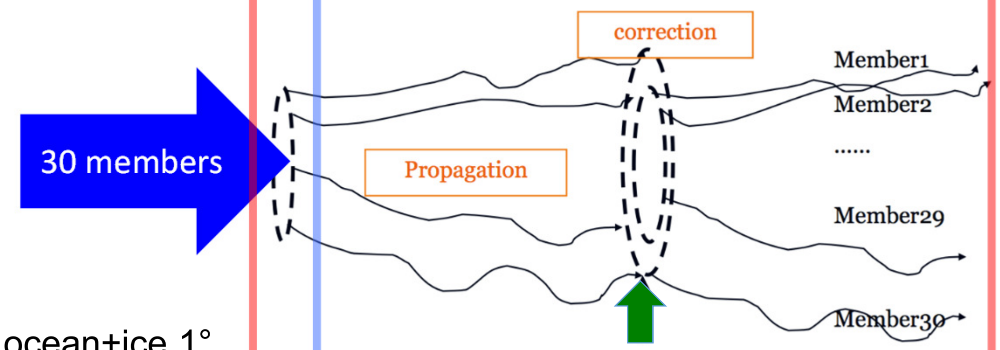
Norwegian Climate Prediction Model (NorCPM)

Earth System model (NorESM1-M)

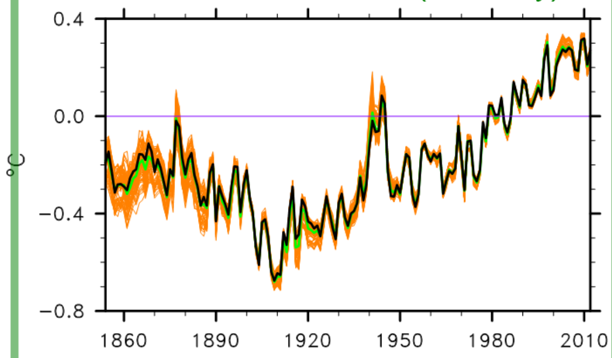


atm 2°; ocean+ice 1°

Data assimilation (EnKF)



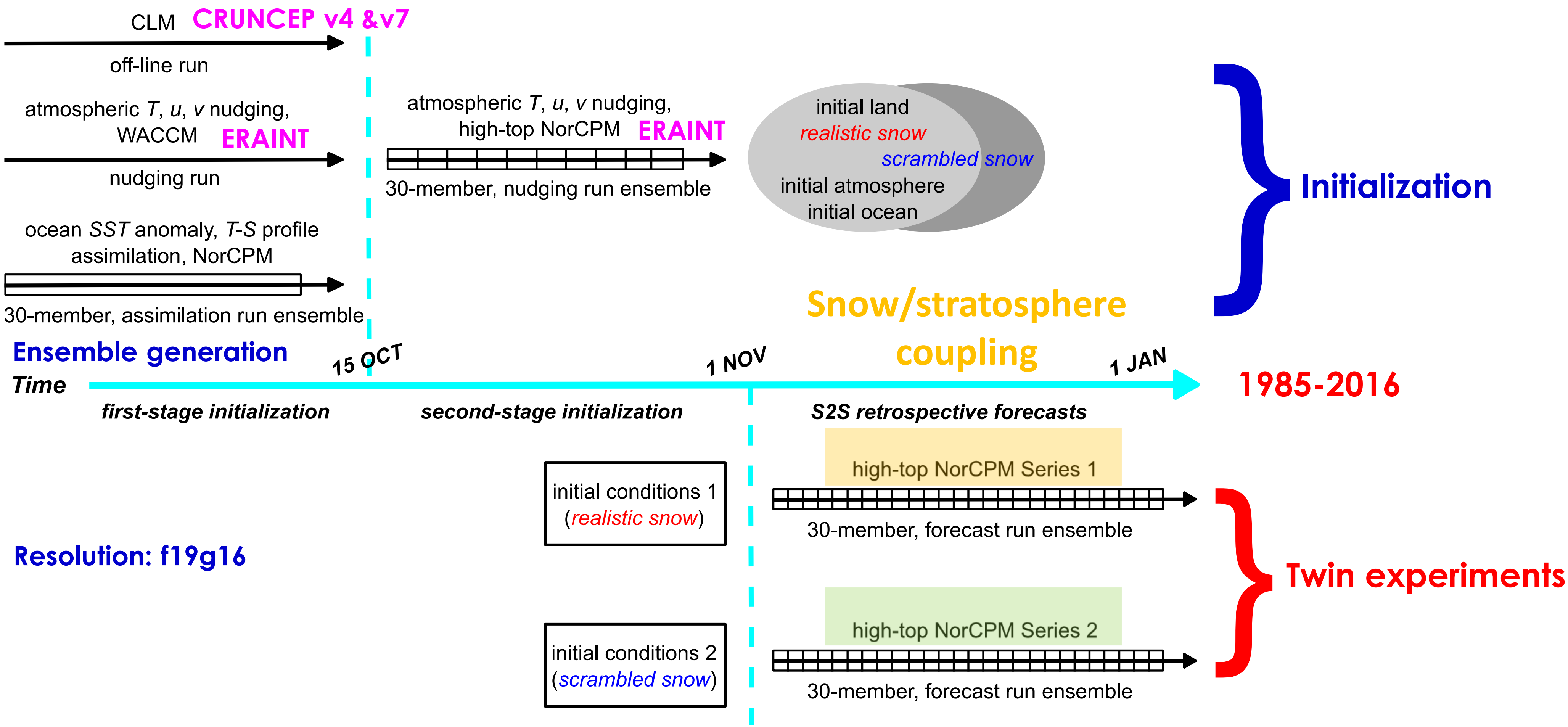
observations
HadISST2 anom (monthly)



Long-term reanalysis :1980–2017

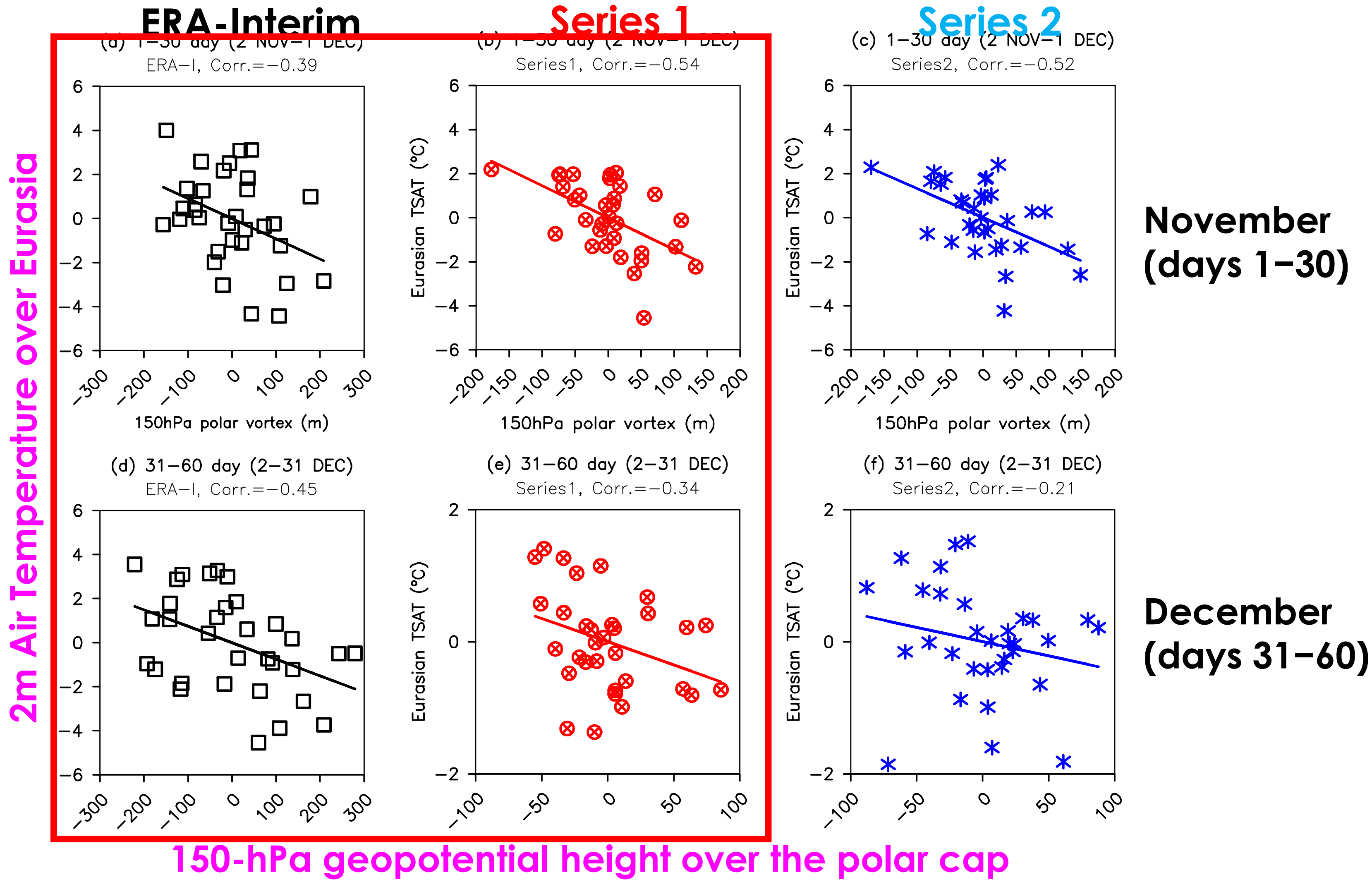
V1 system: SST anom + ocean Temp-Salinity profile

(Counillon et al., Tellus 2014 & 2016)

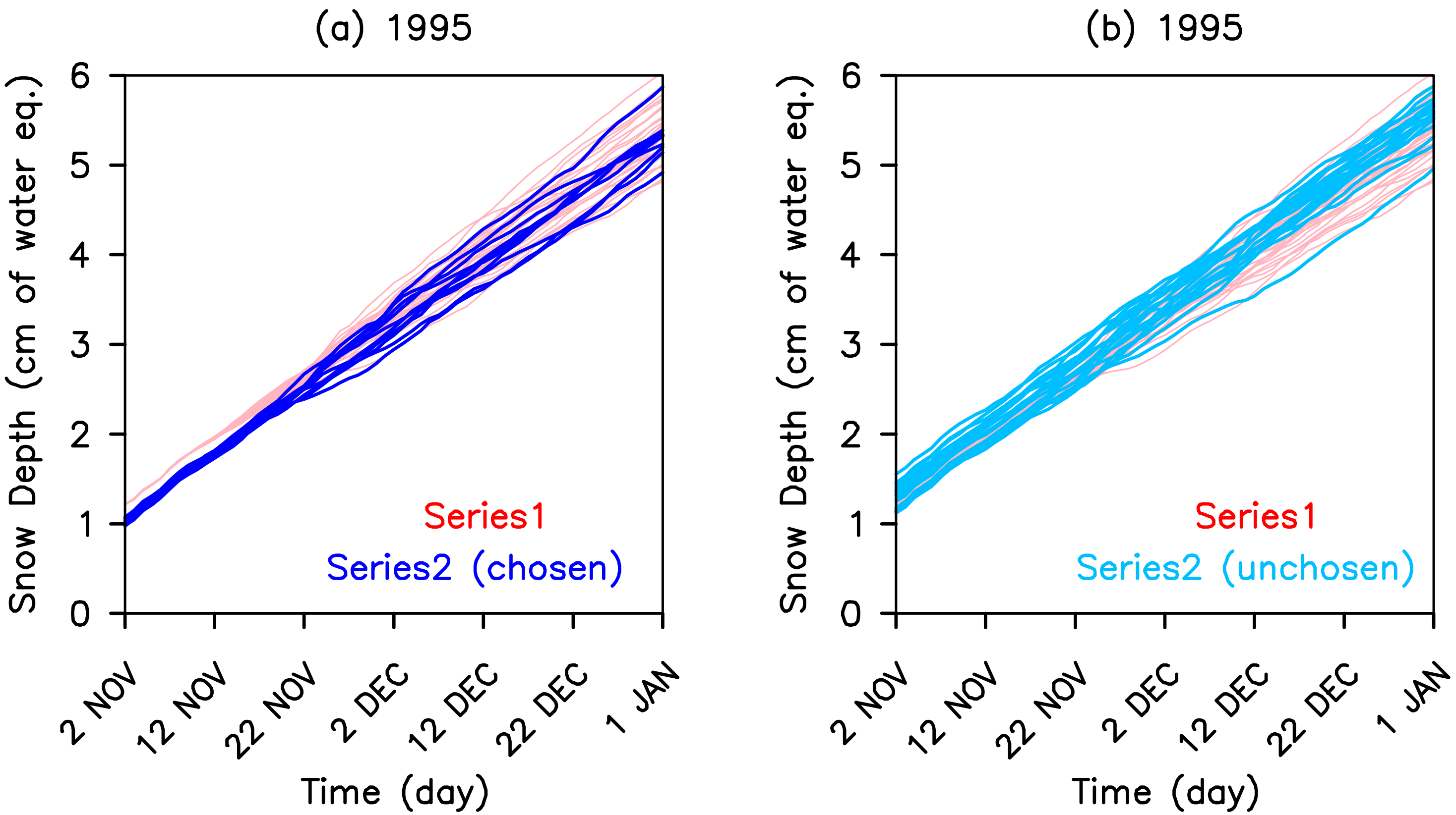


CLM CRUNCEP v4 &v7
off-line run
atmospheric T, u, v nudging,
WACCM ERAINT
nudging run
ocean SST anomaly, T-S profile
assimilation, NorCPM
30-member, assimilation run ensemble
atmospheric T, u, v nudging,
high-top NorCPM ERAINT
30-member, nudging run ensemble
initial land
realistic snow
scrambled snow
initial atmosphere
initial ocean
Initialization
Snow/stratosphere
coupling
Ensemble generation
Time
15 OCT
1 NOV
1 JAN
1985-2016
first-stage initialization
second-stage initialization
S2S retrospective forecasts
high-top NorCPM Series 1
initial conditions 1
(realistic snow)
30-member, forecast run ensemble
Resolution: f19g16
Twin experiments
high-top NorCPM Series 2
initial conditions 2
(scrambled snow)
30-member, forecast run ensemble

3.5. Relation between the stratospheric polar vortex and surface conditions



Example of evolution of SWE in the year 1995



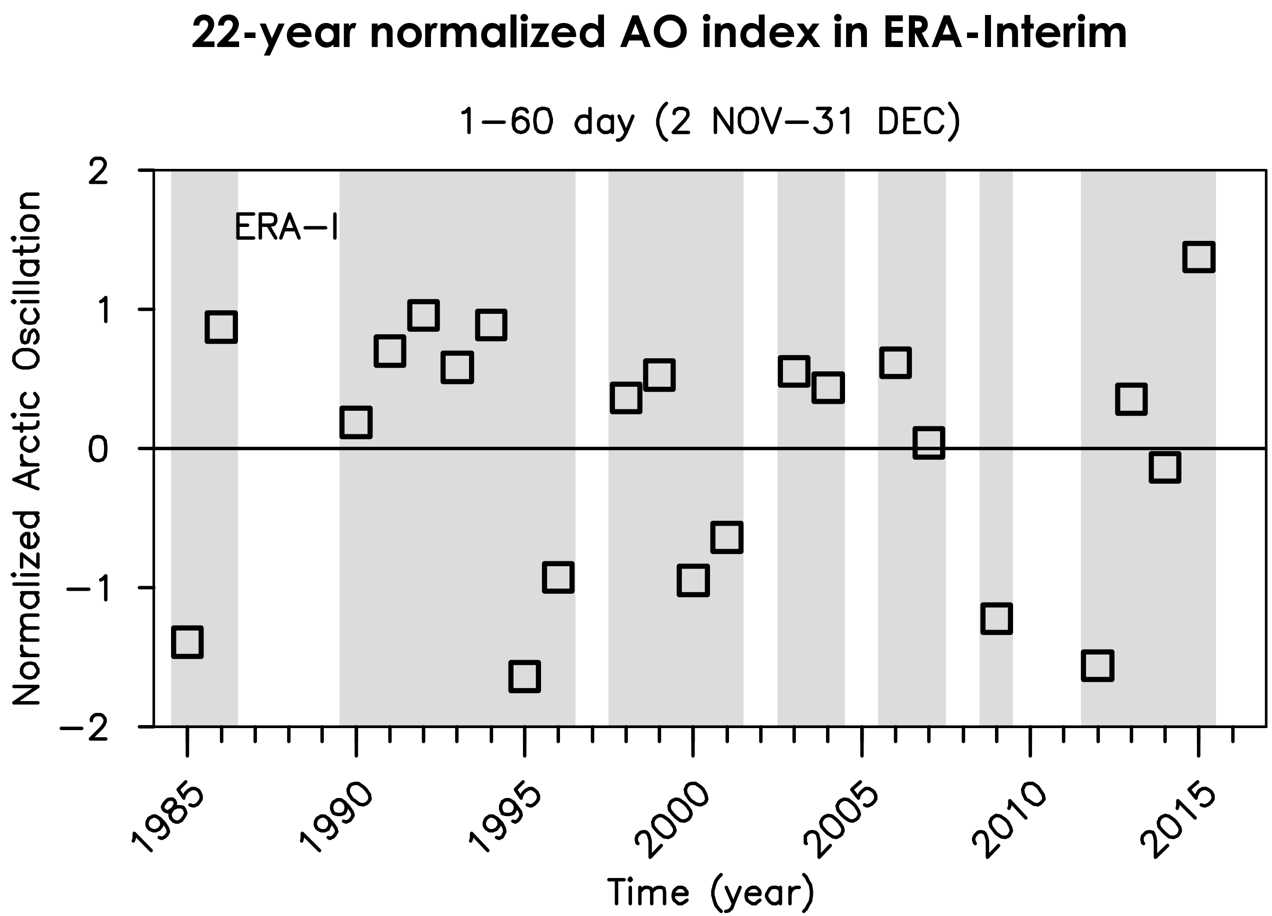
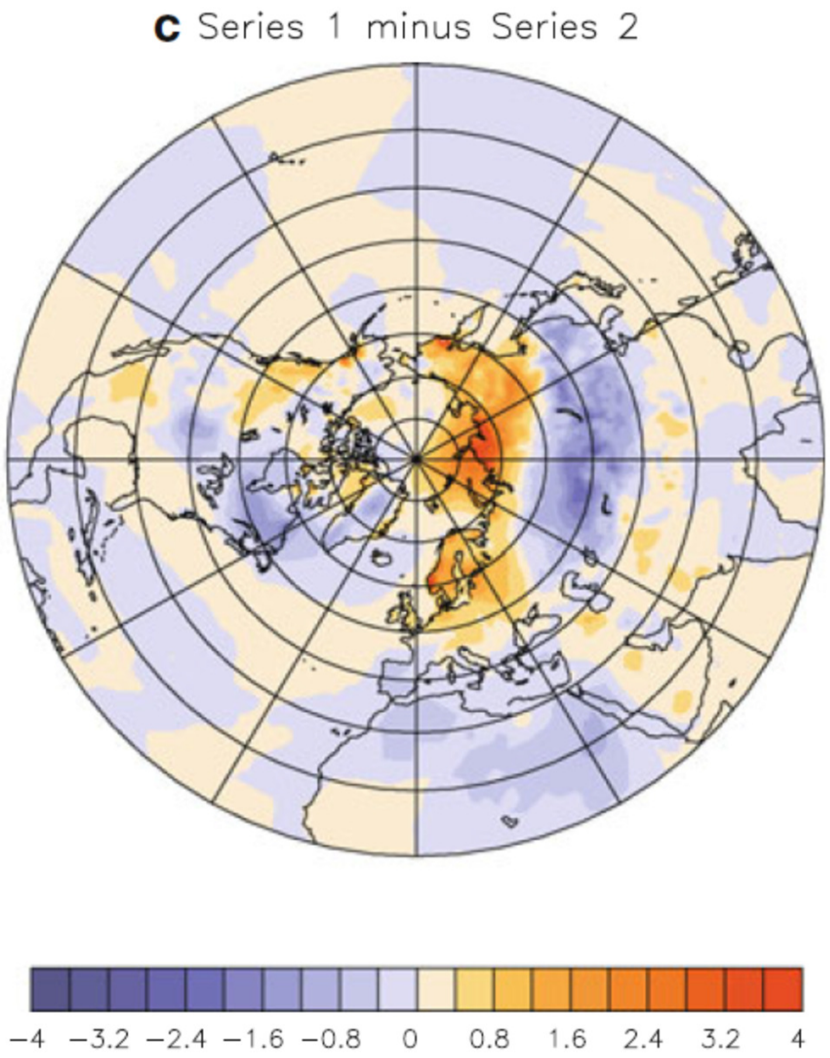

22-year normalized AO index in ERA-Interim
1−60 day (2 NOV−31 DEC)
ERA−I
Normalized Arctic Oscillation
2
1
0
−1
−2
1985
1990
1995
2000
2005
2010
2015
Time (year)

Table. The snow variables scrambled in Series 2

Name	Long-name	Units
SNLSNO	number of snow layers	unitless
SNOWDP	snow depth	m
frac_sno	fraction of ground covered by snow	0 to 1
DZSNO	snow layer thickness	m
ZSNO	snow layer depth	m
ZISNO	snow interface depth	m
H2OSNO	snow water	mm
H2OSOI_LIQ	liquid water (only in the snow layer)	kg/m^2
H2OSOI_ICE	ice lens (only in the snow layer)	kg/m^2
T_SOISNO	soil-snow temperature	K
snw_rds	snow layer effective radius	um
albsnd_hst	snow albedo (direct)	0 to 1
albsni_hst	snow albedo (diffuse)	0 to 1

Changing high-latitude cryosphere: warm Arctic-cold continents due to Eurasian snow



T_{2m} difference

Difference : High snow – Low snow 30-day lead

(2004-2010)

High Snow anomaly leads to:

Warm Arctic-Cold Eurasia pattern

(analogous to sea-ice impact)