Coupled sea-ice-atmosphere variability and predictions

Steffen Tietsche

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ECMWF Predictability Training Course 2023

ECMWF

Outline

1. Sea-ice basics
2. Sea-ice variability and predictability
3. Atmospheric impact

Sea-ice basics

What is sea ice?

The Endurance crushed by sea ice
in the Weddell Sea, Nov 1915

- Sea water freezes at about -1.8C to form sea ice at the surface
- Covers ~12% of world ocean, up to ~5m thick
- Very dynamic, wide variety of ice types and features
- Moved and deformed by winds, currents and internal forces

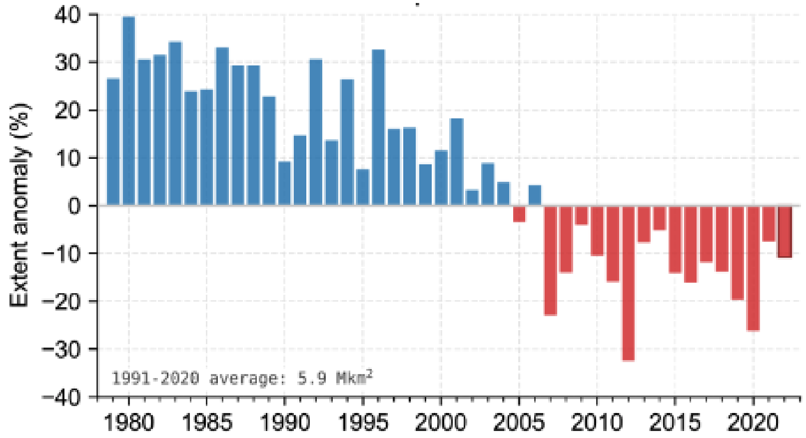
Fun and educating to read:

South! The Story of Shackleton's Last Expedition 1914-1917
by Sir Ernest Shackleton

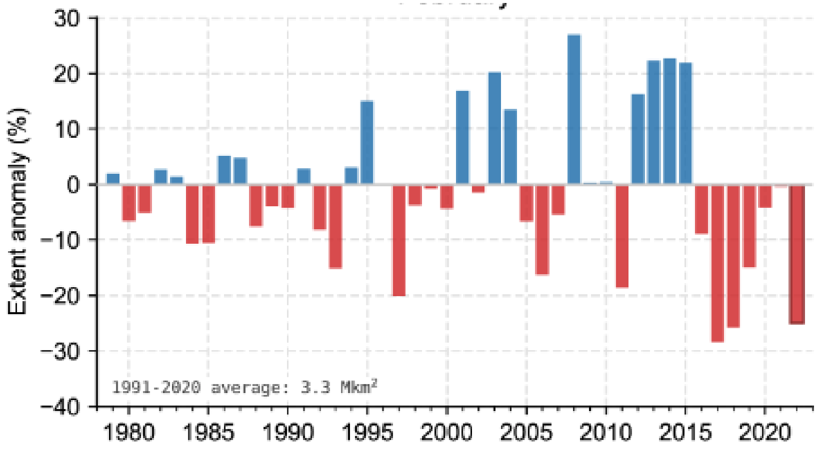
Wreck of the Endurance,
discovered on 5 March 2022

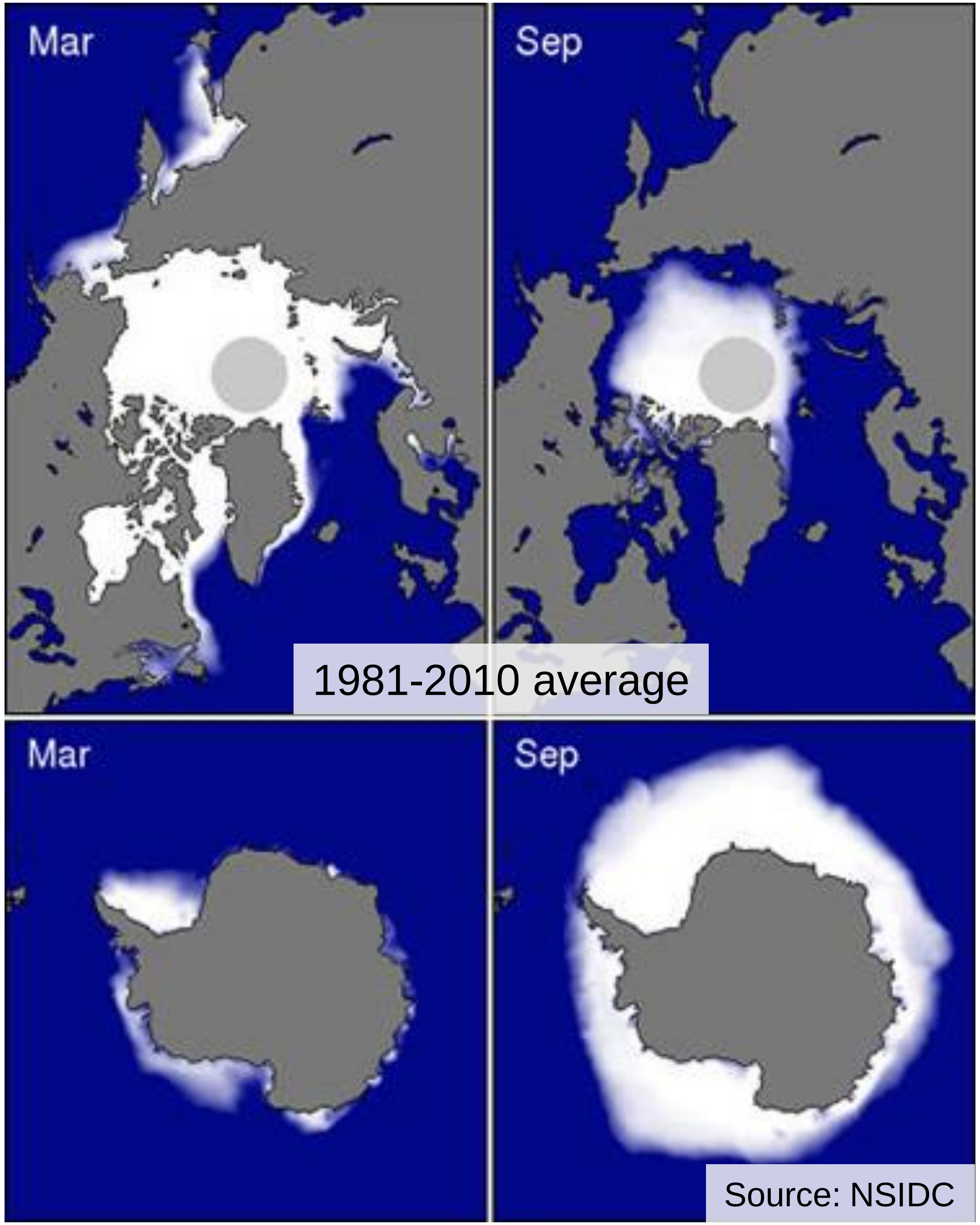
Sea ice occurrence and climate trends

September Arctic monthly sea ice extent anomalies



February Antarctic monthly sea ice extent anomalies





Sea ice in the Earth System

- Air-sea fluxes are radically changed in the presence of sea ice:
  - *Albedo*: incoming solar radiation is mostly *reflected* by sea ice, but mostly *absorbed* by sea water
  - *Surface temperature and heat fluxes*:
    - winter – prevent heat transfer from warm ocean to cold atmosphere
    - summer – prevent surface warming until all ice has melted
  - Suppression of *evaporation* from sea water which impacts atmospheric moisture and clouds
  - Suppression of wind-induced *mixing* and up-/downwelling of sea water

- Moving store of latent heat and freshwater

- A very simplified but useful picture:
  1. Sea ice *is preconditioned* by slowly-evolving state of the upper ocean waters
  2. Sea ice *integrates* fast atmospheric forcing in a non-trivial manner

Consistent modelling and prediction of these complex interactions requires a physical sea-ice model

Sea-ice modelling 101

Dynamic equations

$$\partial_t h_m = -\nabla \cdot (h_m \boldsymbol{v}) + S_h$$

Continuity equation for ice mass

$$\partial_t C = -\nabla \cdot (C \boldsymbol{v}) + S_C$$

Continuity equation for ice area

S_h, S_c : **thermodynamics** (a.k.a. sea-ice **physics**)

$$\partial_t \boldsymbol{v} = -f(\boldsymbol{k} \times \boldsymbol{v}) - g\nabla\zeta + \frac{\boldsymbol{\tau}_a}{\rho_i h_m} + \frac{\boldsymbol{\tau}_o}{\rho_i h_m} + \nabla \cdot \boldsymbol{\sigma}.$$

Momentum equation

In today's weather and climate models, sea ice modelled as a 2D non-Newtonian fluid
→ mostly okay for scales > 10km, but clearly inappropriate below that

Parametrisations of important small-scale processes exist, but often have not made their way into operational models, e.g.

- melt ponds
- state-dependent atmospheric and oceanic drag coefficient
- subgrid-scale thickness distribution
- anisotropic rheology
- floe-size distribution

Sea ice complexity

Sea-ice variability and predictability

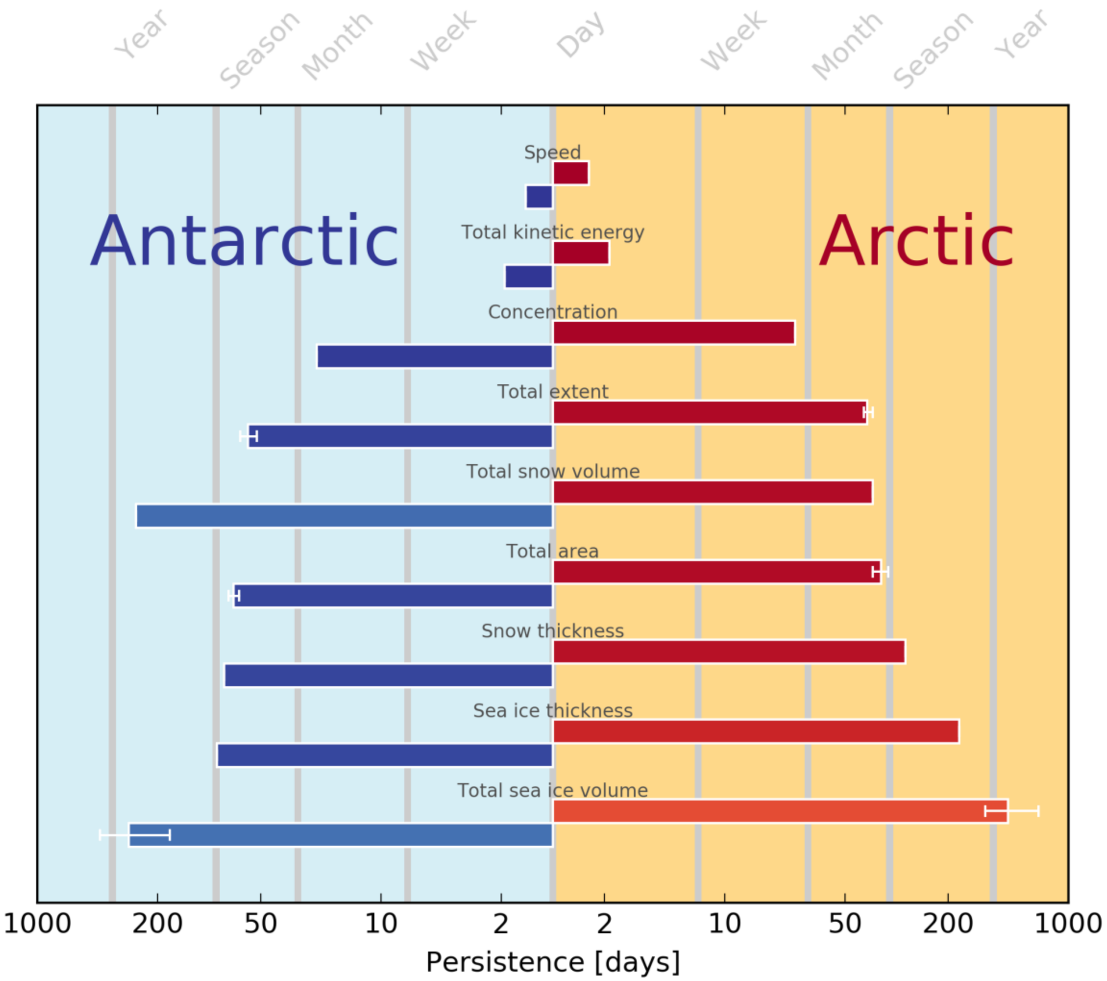
Why include sea ice in predictions?

- Critical environmental factor for mariners, local communities and wildlife
- Fast direct impact on atmosphere:
  strong regionally, potential for moderate remote impact
- Interacts with ocean circulation (heat fluxes, salinity, momentum transfer),
  → influences atmospheric predictions at longer lead times

Immediate impact (hours)	Delayed impact (days to seasons)
Surface cooling from albedo effect	Advection
Suppression of atmosphere-ocean heat fluxes	Timing of melt from ice thickness
Suppression of wind mixing in upper ocean	Melting: fresh water export

Sea-ice time scales relevant for weather and climate prediction

persistence of sea ice properties



Chevallier et al. 2019

Large-scale sea-ice changes take weeks or even years
→ potential source of atmospheric predictability

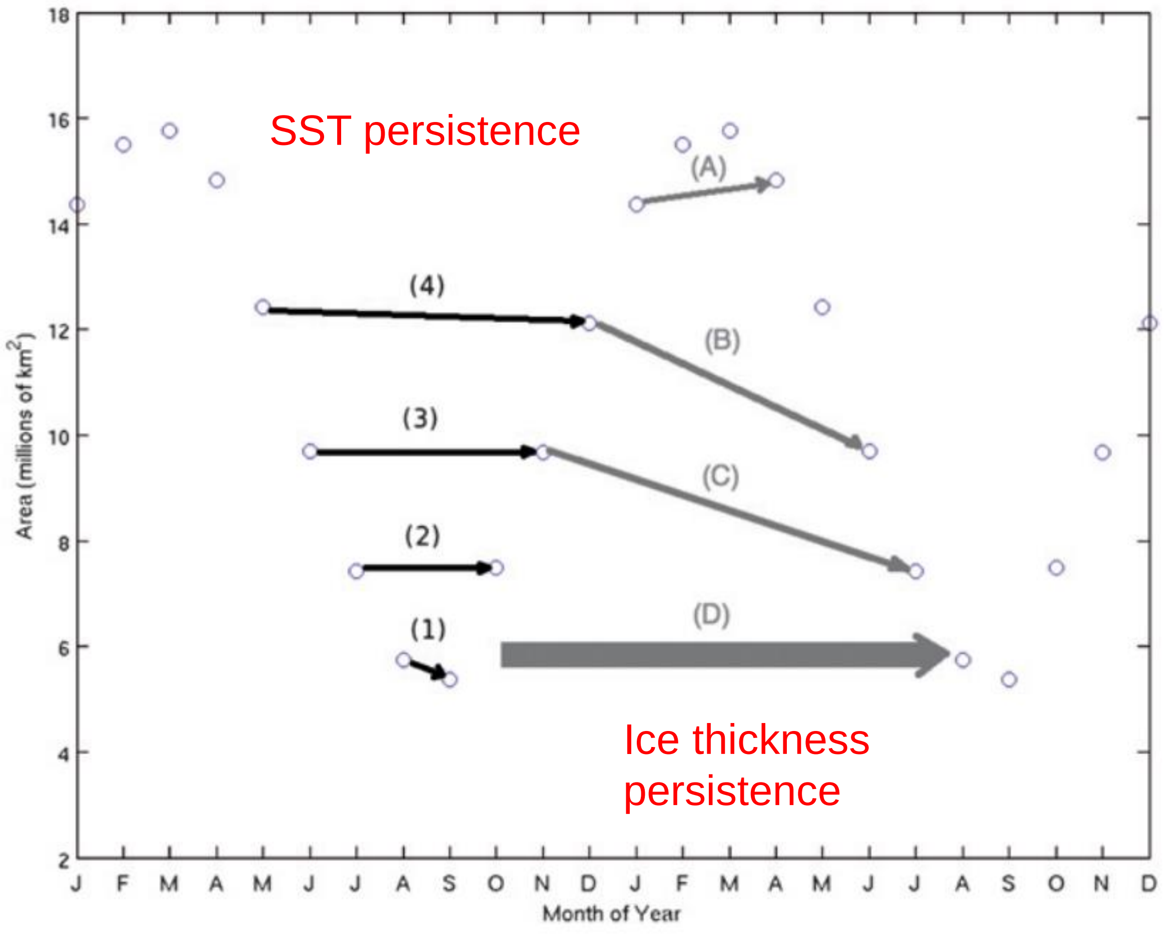
Mechanisms for sea-ice predictability

- Persistence
- Re-emergence of anomalies connected with seasonal cycle
- Medium- to extended-range: interaction with atmospheric modes of variability (e.g. NAO, blocking, MJO)
- Seasonal to decadal: interaction with slow modes of variability (e.g. AMOC and deep water formation, ENSO)

See Guemas et al. (2014) for an overview

Re-emergence of seasonal sea-ice predictability

arrows between months whose anomalies are well correlated



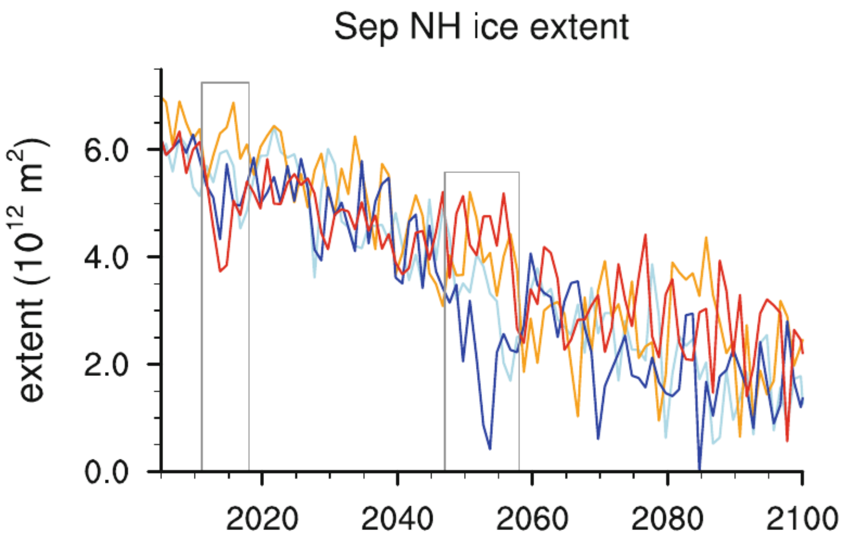
Transfer of persistence memory between sea-ice cover and

a) SST over summer
b) sea ice thickness over winter

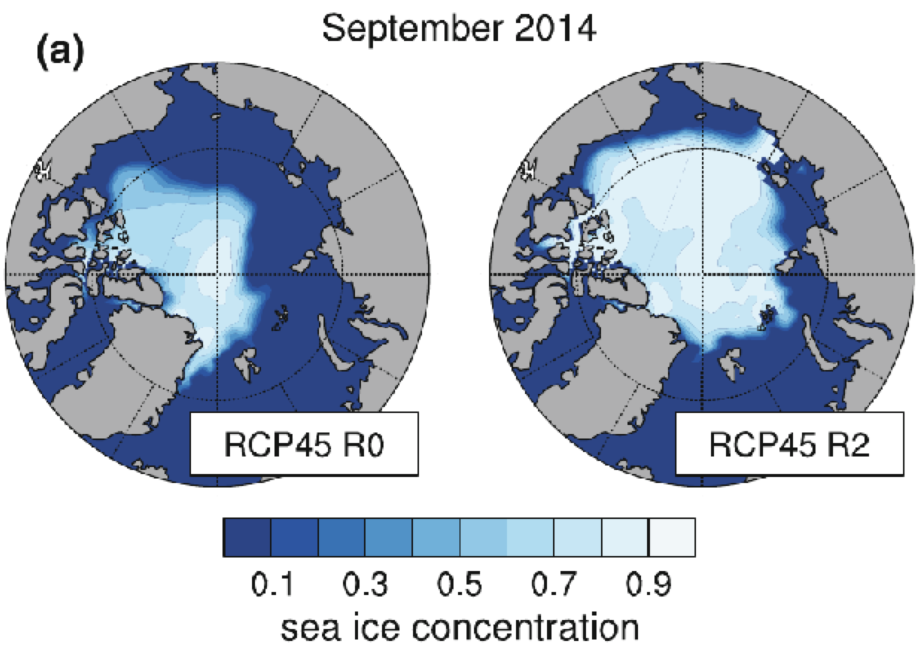
→ months with similar sea-ice extent tend to have similar anomalies

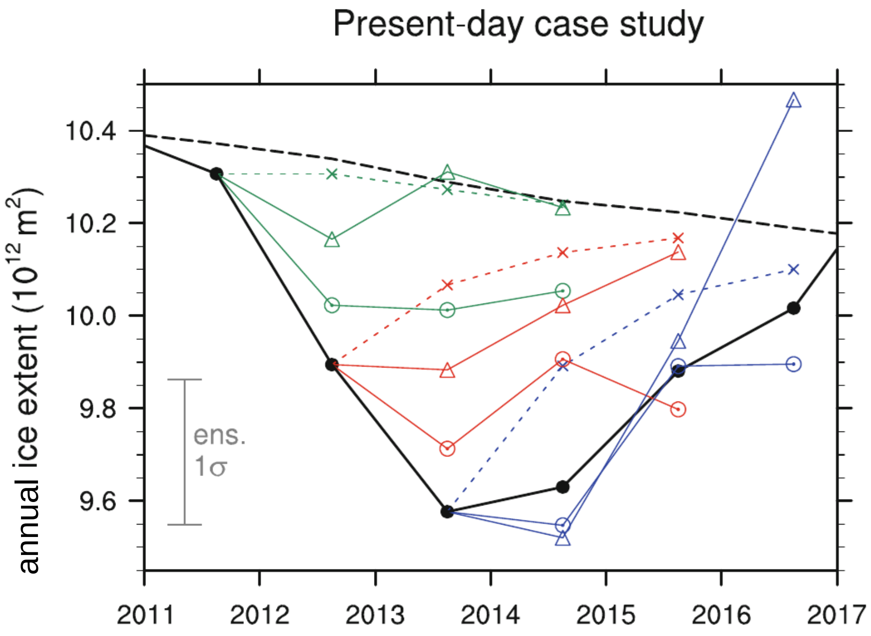
Blanchard-Wrigglesworth et al (2011)

Decadal predictability of sea-ice changes?

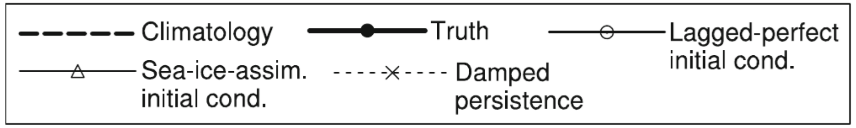


Initial-condition ensemble of CMIP5 projections with MPI-ESM





Idealized predictability experiments suggest inherent predictability for months or even years ahead.

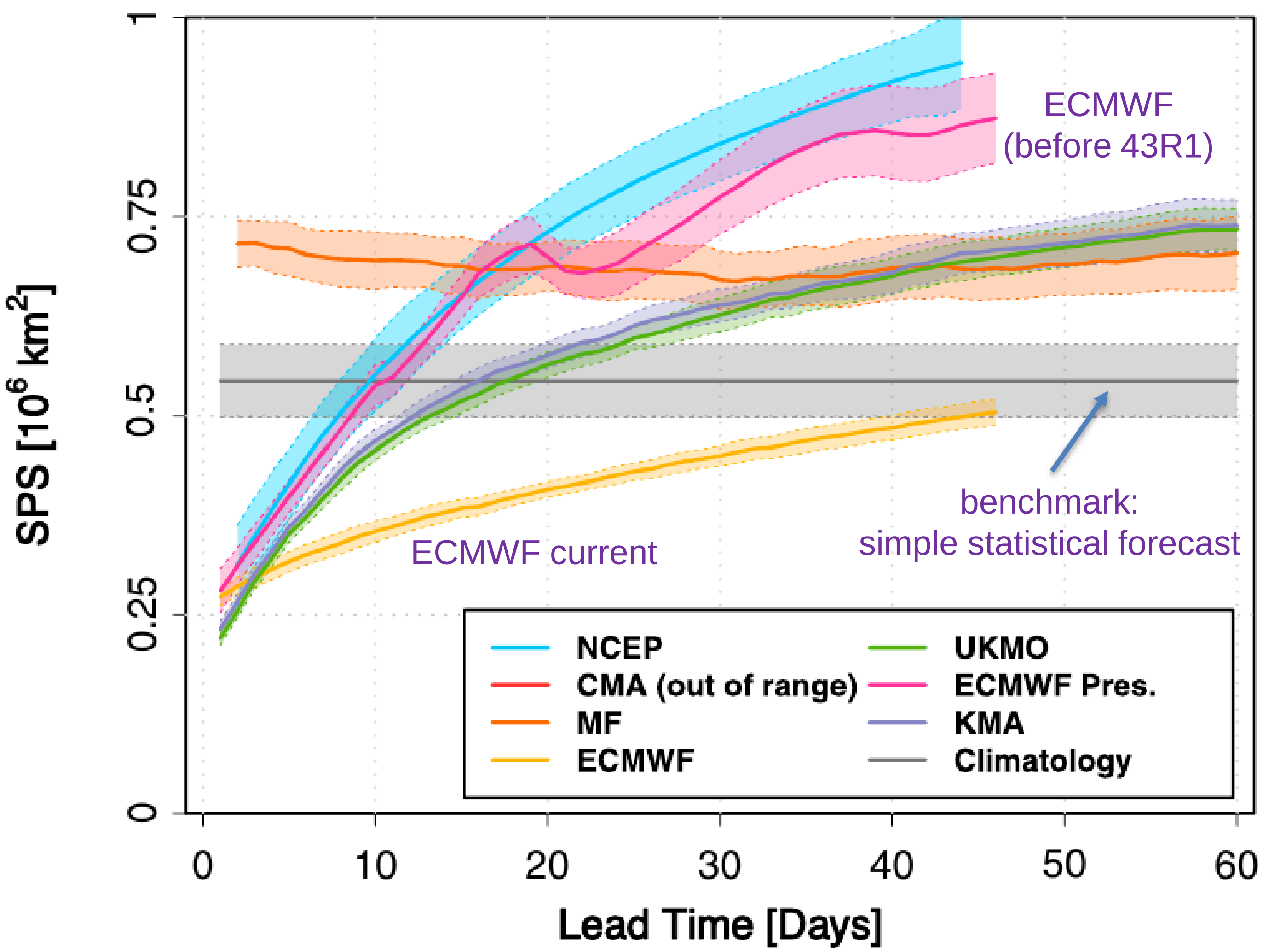


Tietsche et al. (2013)

Sea ice modelling in ECMWF forecasts

- **OCEAN4** (until 2016/7, before 43R1):
  - Medium and extended-range forecasts:
    persisted from initial conditions for 10 days, then relaxation to climatology
  - Seasonal forecasts: prescribed as a sample of previous 5 years
- **OCEAN5** (current operations): fully prognostic sea ice
  - Sea-ice model LIM2 (NEMO3.4) at ~20km resolution
  - Clear forecast improvements in for sea-ice cover and surface air temperatures around the ice edge
- **OCEAN6** (2024/5): sea-ice model SI3 (NEMO4)
  - Major model improvements, such as subgrid-scale sea ice thickness distribution and prognostic salinity
  - Improved assimilation of sea ice concentration leading to better initial conditions
  - Large improvements in winter-time performance

Extended-range forecast skill for Arctic sea ice from the S2S database



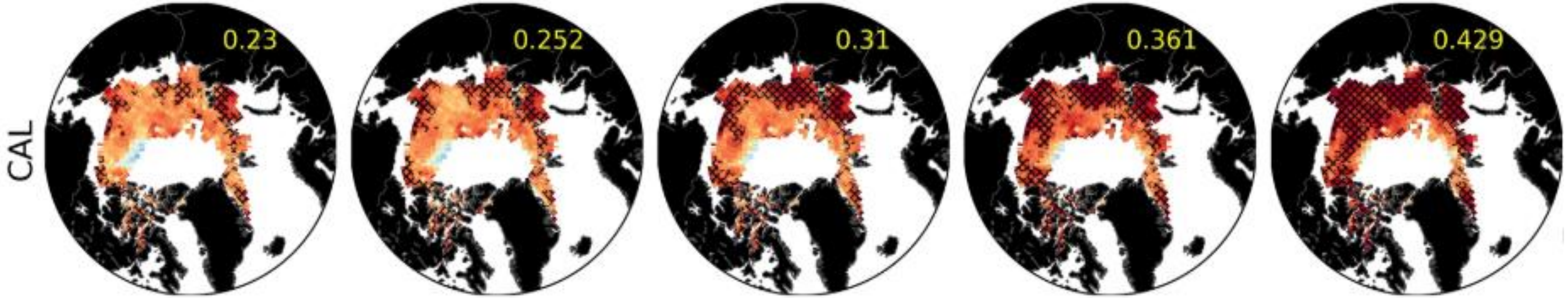
Sub-seasonal skill *up to 6 weeks* in currently operational sub-seasonal forecasts

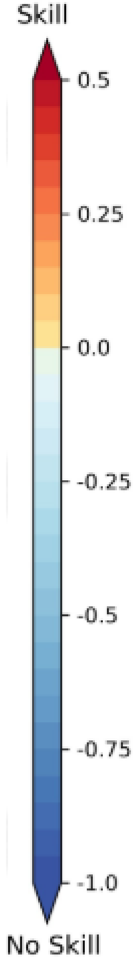
Zampieri et al., GRL 2018

Seasonal forecast skill

C3S multi-model skill (CRPSS) for September sea-ice area w.r.t. trend-adjusted climatology

Initialized from *1 Apr* *1 May* *1 Jun* *1 Jul* *1 Aug*





Dirksen et al. (2019)

Currently operational seasonal forecasts have substantial skill for sea-ice cover several months ahead.

Current challenges in sea-ice predictions

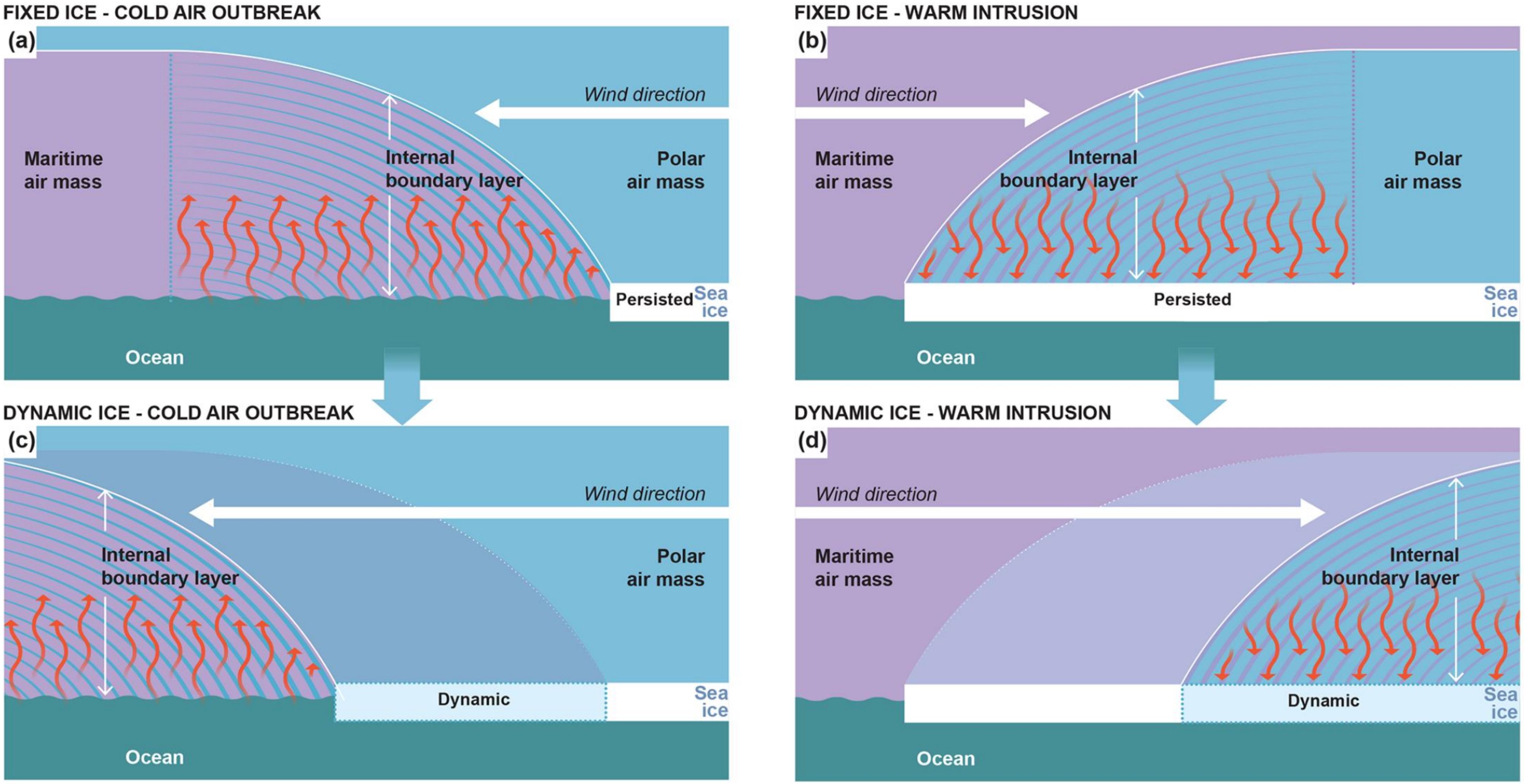
- **Initialization**: currently relies mostly on observations of sea-ice *concentration*, but memory resides in *sea-ice thickness* and *upper-ocean stratification*

- **Missing physics**: subgrid-scale variability of sea ice poorly represented, hence heavy reliance on well-tuned parameterisations

- **Model biases**: dominate especially at seasonal lead times, careful postprocessing needed to extract maximum information from forecast

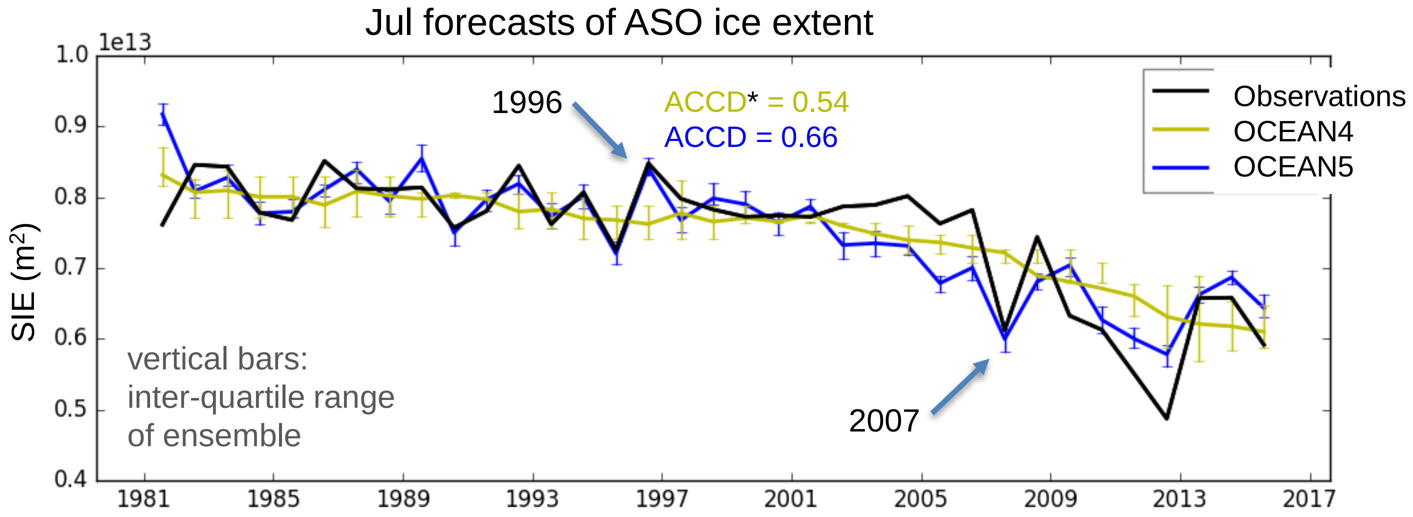
Atmospheric impact

Near-surface atmospheric impact in weather predictions

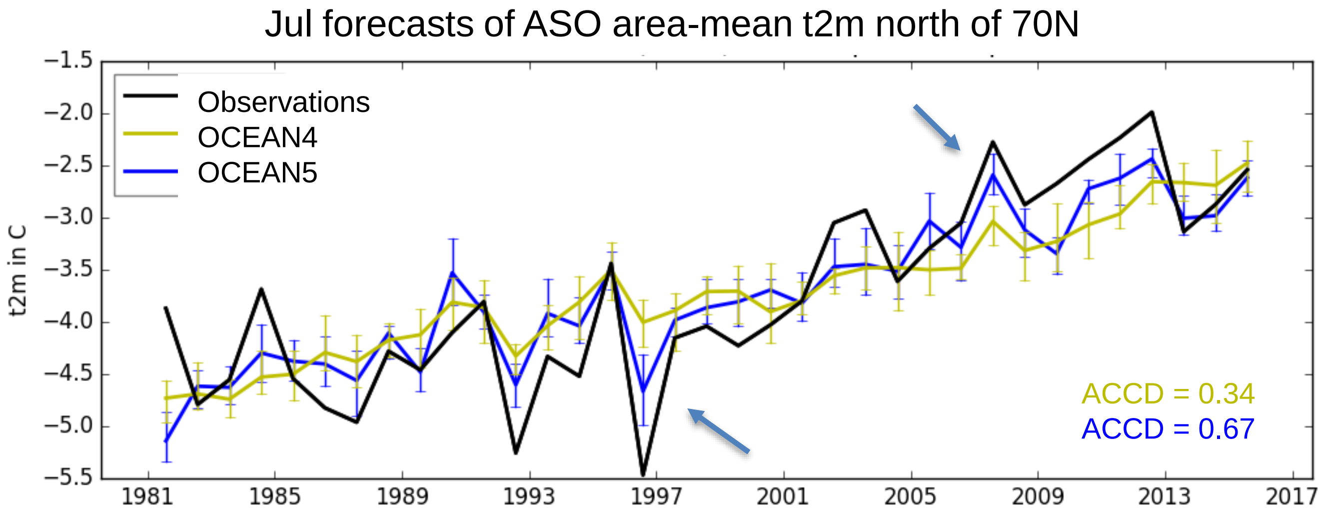


Day et al. (2022)

Summer Arctic surface air temperature and sea ice: SEAS5 forecasts



Good skill in seasonal forecasts of seasonal sea-ice minimum in OCEAN5/SEAS5, much improved than statistical forecast in OCEAN4/SEAS4



Associated with skill in seasonal forecasts of average surface temperatures north of 70N

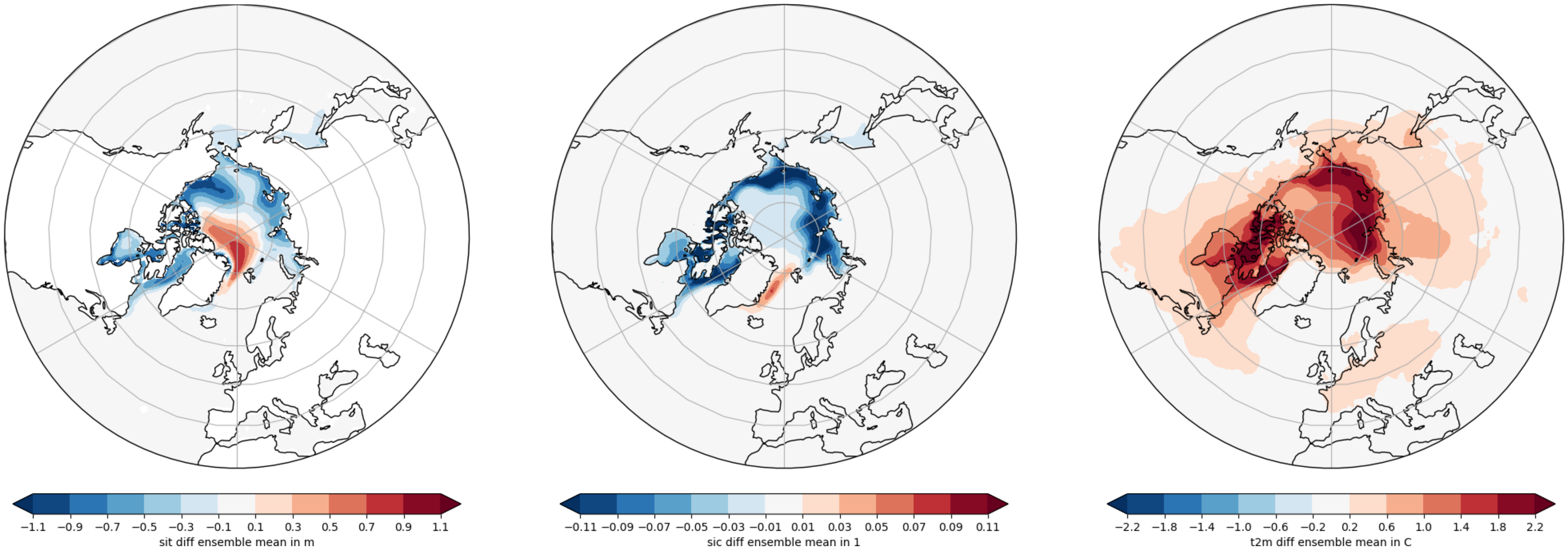
* ACCD: anomaly correlation of detrended time series

Initialization of spring sea-ice thickness impacts surface surface temperatures

SIT difference in initial conditions (Mar-Jun)

SIC difference after six months (Sep-Dec)

t2m difference after six months (Sep-Dec)



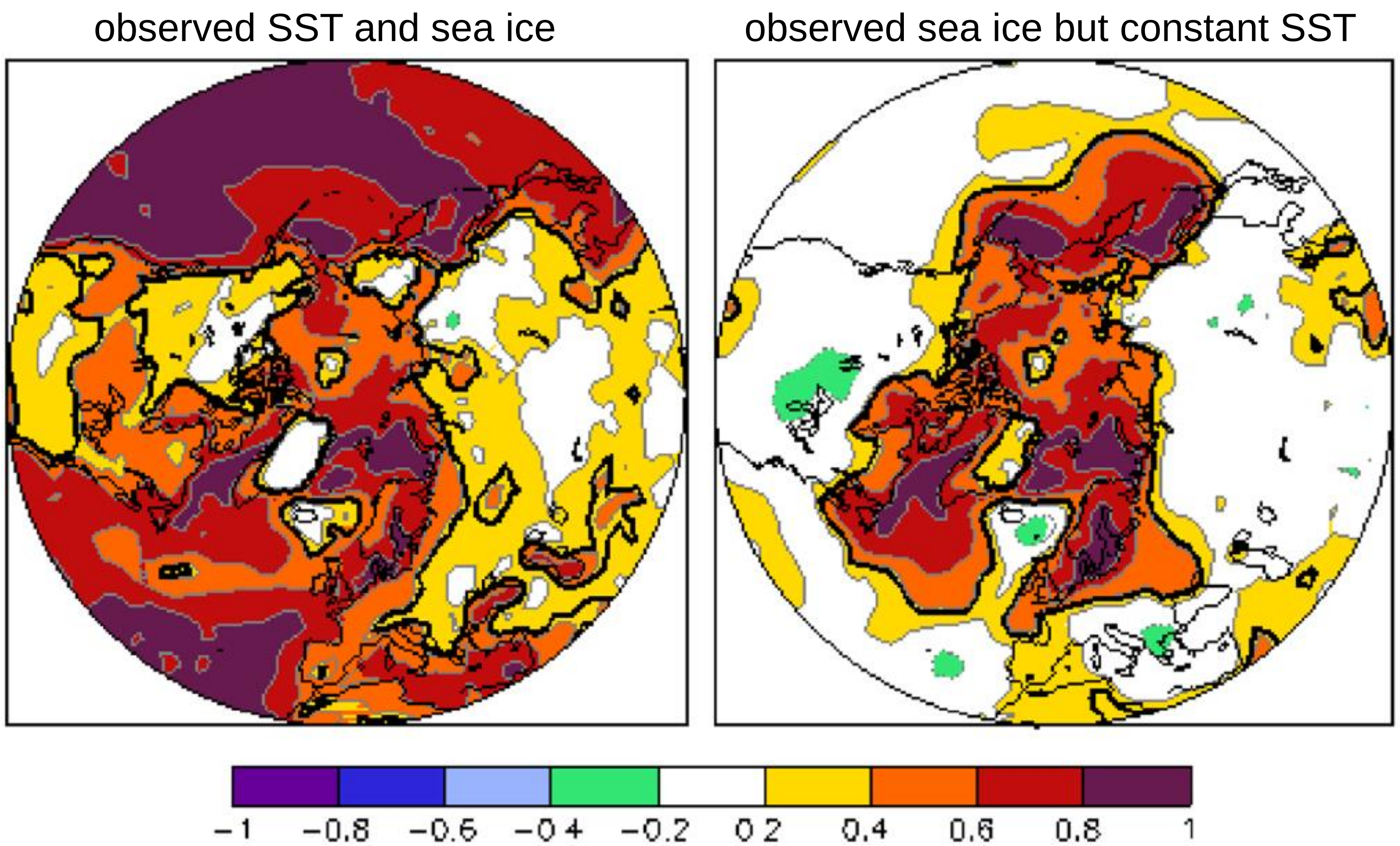
Numerical experiments with ORAS5/SEAS5:
winter-time only CS2SMOS initialization *reduces seasonal ice thickness* by up to 1m

- ice concentration *reduced throughout melt season* and into next autumn/winter
- *Higher* near-*surface temperatures*, with some impact on mid-latitudes (= improved forecast climate)

Balan-Sarojini et al. (2021)

Winter impact of sea ice on winter surface air temperature

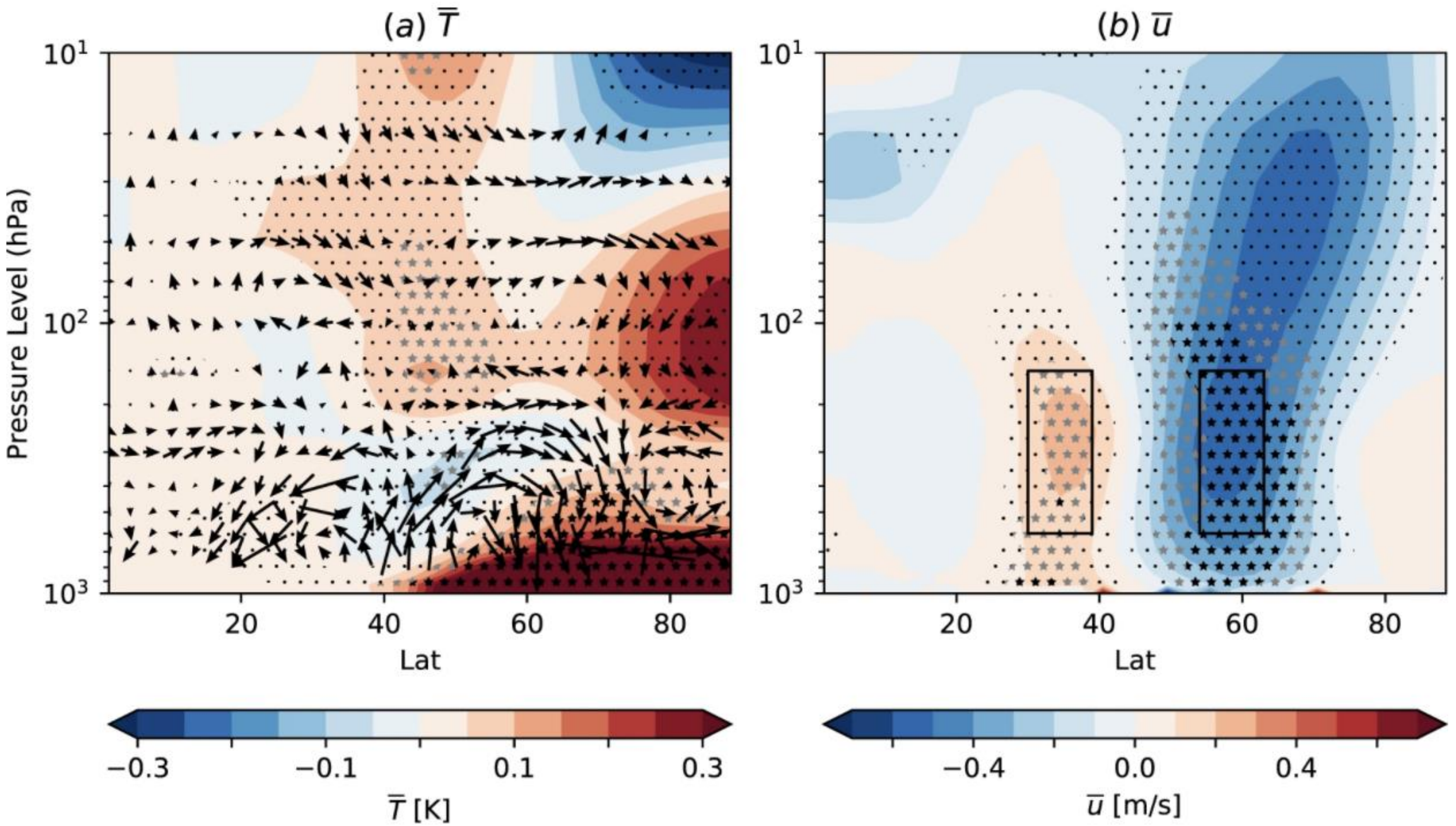
Correlation of DJF SAT with reanalysis in atmosphere-only simulations (1982-2014):



Koenigk et al. (2019)

Sea-ice impact on surface air temperature over parts of Europe, North Atlantic and North Pacific

Mean atmospheric circulation response to Arctic sea-ice loss



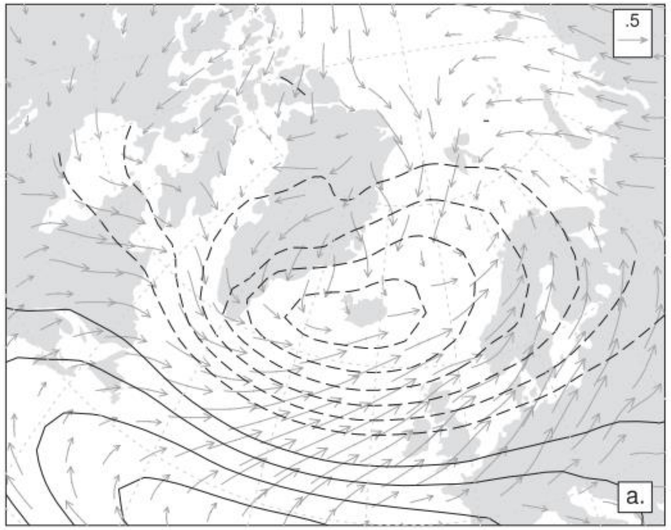
Multi-model response in zonal-mean temperature and zonal wind to sea ice changes for a 2C warmer climate

Smith et al. (2022)

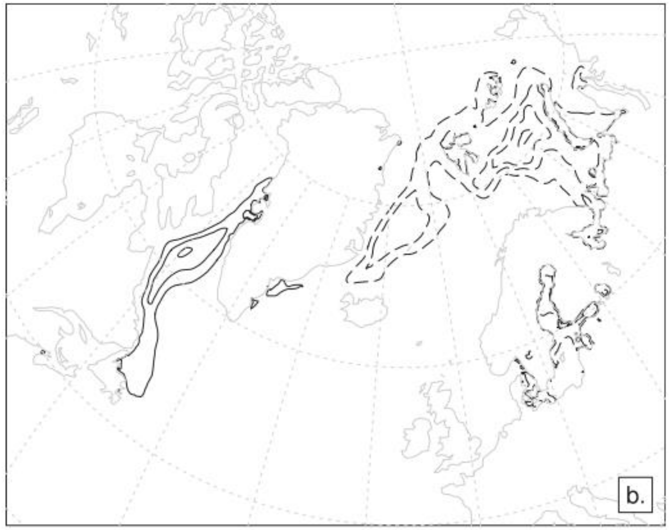
Models suggest a weakening of mid-latitude westerlies in response to reduced sea-ice cover
But: response is weak, and difficult to verify in observational record

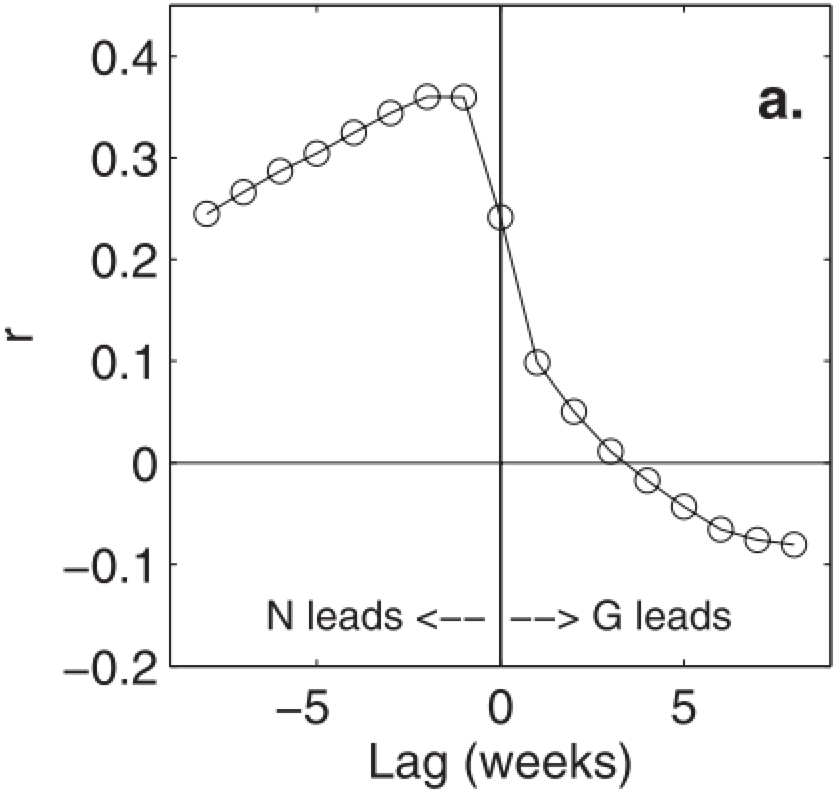
Coupled variability: NAO and Atlantic sea ice dipole

NAO EOF (N)



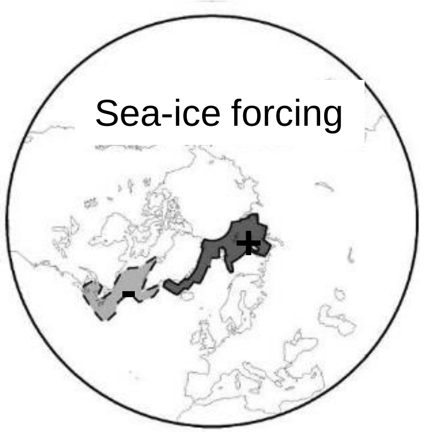
Sea-ice EOF (G)





Strong et al (2009)

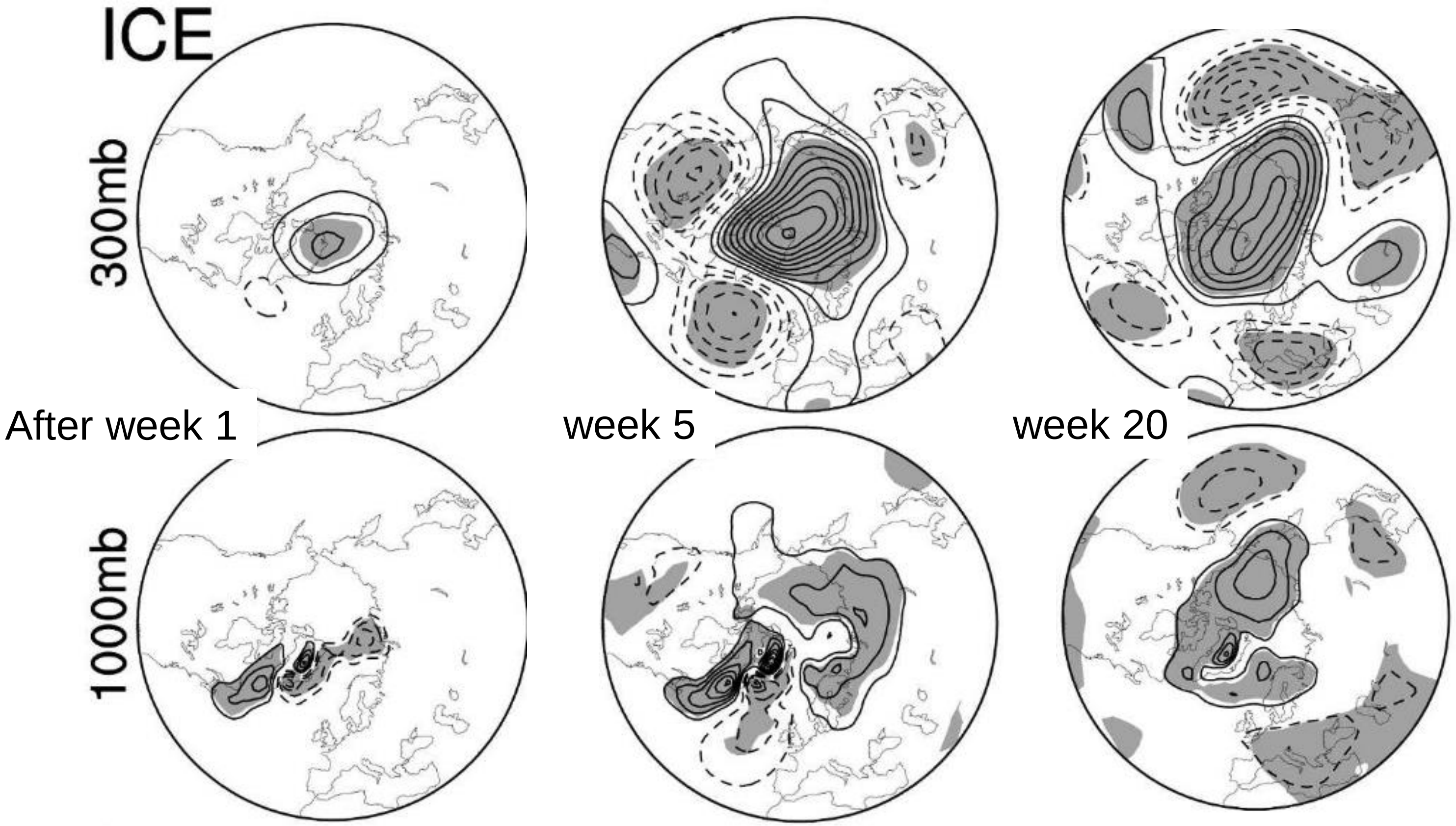
Correlation between *observed* weekly means of NAO and Atlantic sea ice
→ mostly caused by NAO forcing sea ice
→ detectable (but weak) feedback of sea-ice on NAO



Atmosphere circulation response to Atlantic sea ice forcing

Deser et al. (2007)

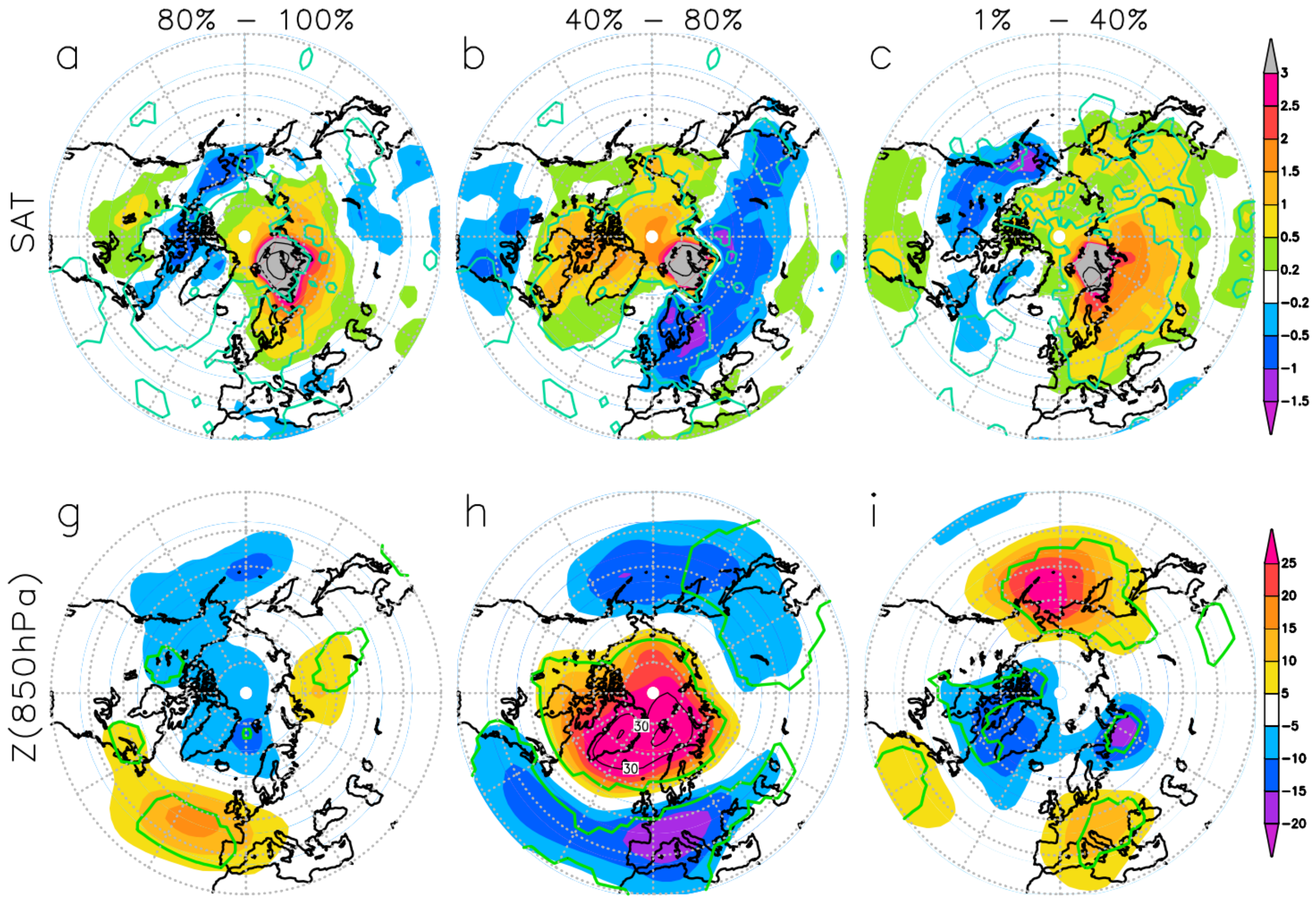
geopotential height response (ci=10m)



- *Numerical experiments* forcing the atmosphere with the dominant mode of sea-ice variability & climate change in the NH
- Initial baroclinic response (2-3 weeks)
- Equilibrium response (>2 months) barotropic and resembles NAO-NAM

→ **Remote sea-ice impact depends on time scales considered**

Reduced Barents Sea ice → cold Eurasian winters?

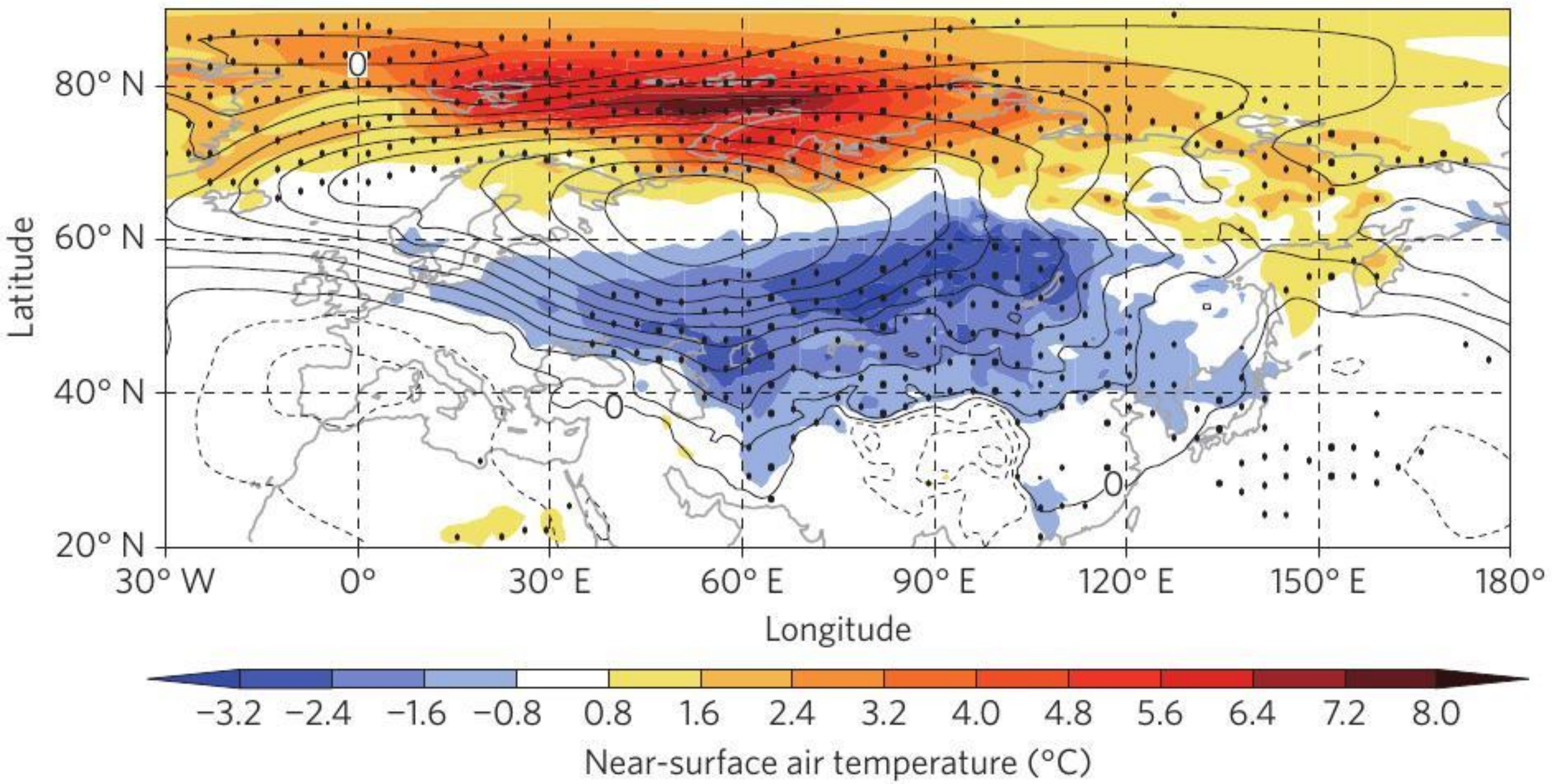


Petoukhov et al. (2010): *Numerical experiments* forcing atmosphere by reducing sea-ice concentration

Can cause *cold or warm* Eurasian winters, depending on the *size* of the reduction

→ Remote sea-ice impact *non-linear* (and *state-dependent)*
Overland et al (2016)

Does Arctic sea-ice loss cause cold Eurasian winters?



Composite of DJF 2m temperature difference between years with low and high sea-ice cover in the Barents and Kara Seas (ERA-Interim 1979-2013)

Mori et al. (2014)

Blackport et al. (2019) argue that this is co-incidence rather than causation: anomalous atmospheric circulation drives both sea ice loss and severe mid-latitude winters

Arctic-mid-latitude linkages – a few thoughts

- Plenty of potential mechanisms are being proposed in the last 10 years
- Episodical strong linkages evident (e.g. "Polar Vortex" and U.S. winter cold extremes)
- However, robust generic statements hard to come by
  - Mid-latitude variability high, especially in winter
  - Signal strength is moderate at best, many other factors at play
  - Observational records are short
  - Results often model-dependent
  - Time scale of anomalies matter (synoptic – s2s – climate change)

→ Ongoing debate, much less consensus than e.g. for ENSO or MJO teleconnections

→ Important to identify constraints and assumptions whenever linkages are reported

Summary

- Sea-ice modelling essential for predicting air-sea interactions at high latitudes
- Slow time scales of sea ice = potential source of predictive skill for sub-seasonal to seasonal (s2s) atmospheric predictions
- Latest generation of operational models have skill in predicting sea ice at s2s range, with obvious potential for improvement (e.g. thickness initialization)
- Sea ice presence strongly imprints on regional atmospheric vertical structure and circulation
- Broad spectrum of linkages to mid-latitude weather and climate in a changing climate

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