

Coupled sea-ice-atmosphere variability and predictions

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20th October 2026

ECMWF Predictability Training Course 2026



Outline

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

Sea-ice basics

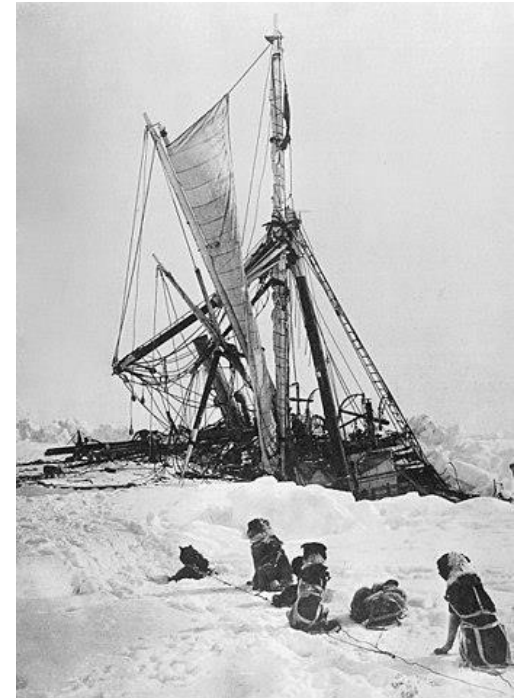
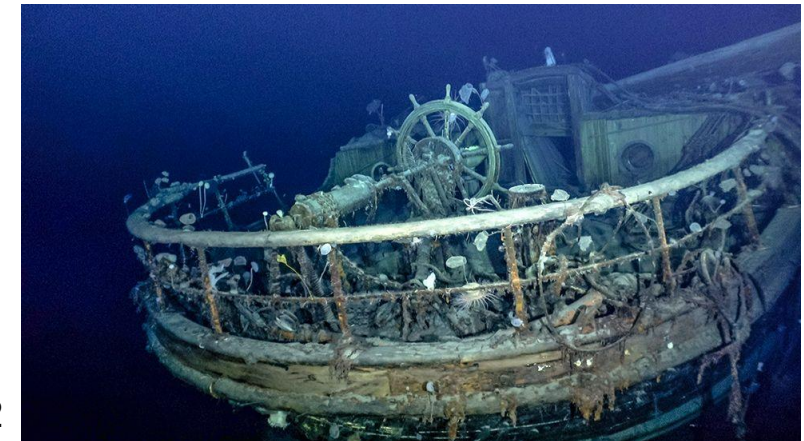
What is sea ice?

- Sea water freezes at about -1.8°C 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:

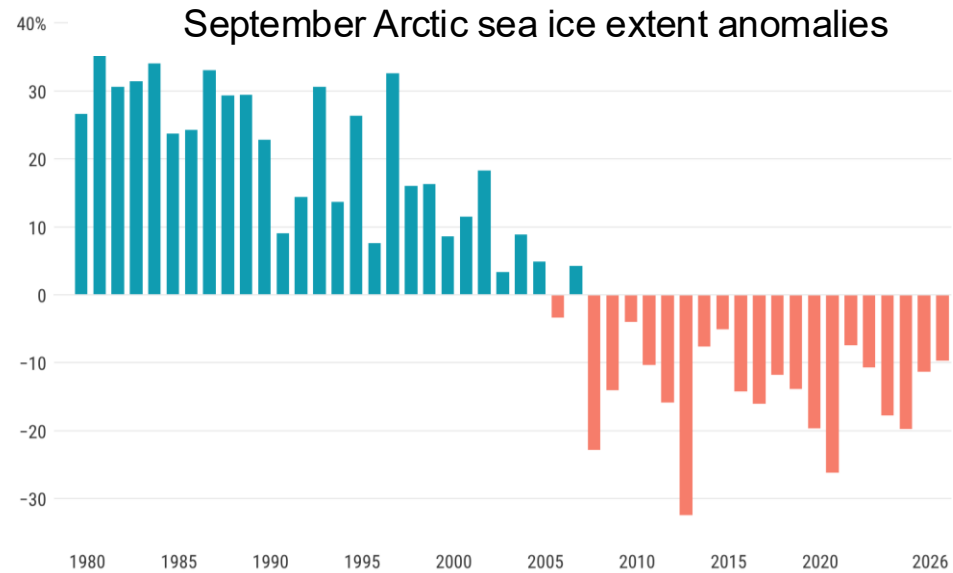
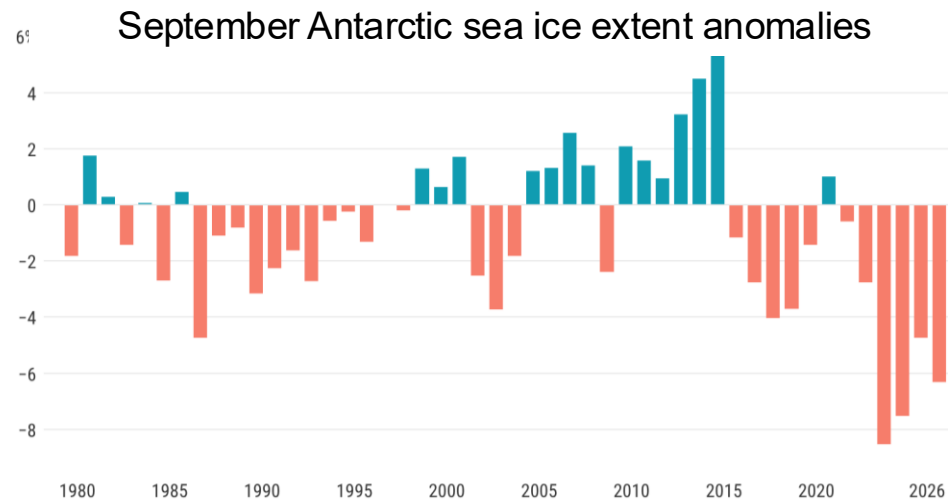
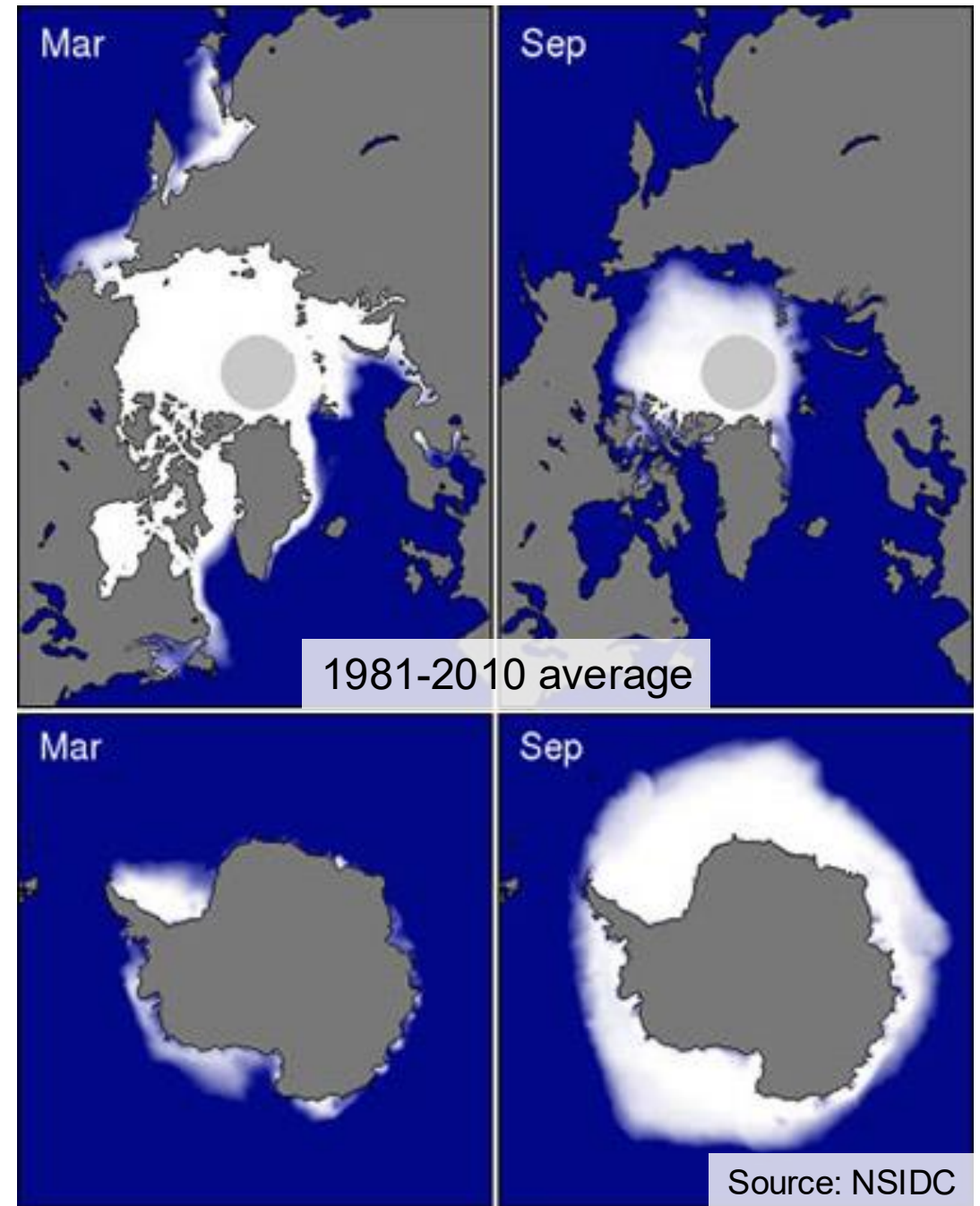
*South! The Story of Shackleton's Last Expedition 1914-1917
by Sir Ernest Shackleton*

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



Wreck of the Endurance,
discovered on 5 March 2022

Sea ice occurrence and climate trends



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*

(Physics-based) sea-ice modelling 101

Dynamic equations

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

Continuity equation for ice mass

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

Continuity equation for ice area

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

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

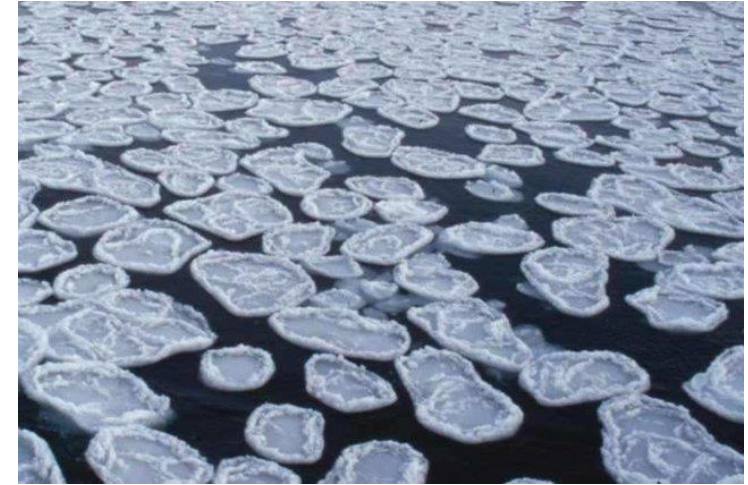
Momentum equation

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



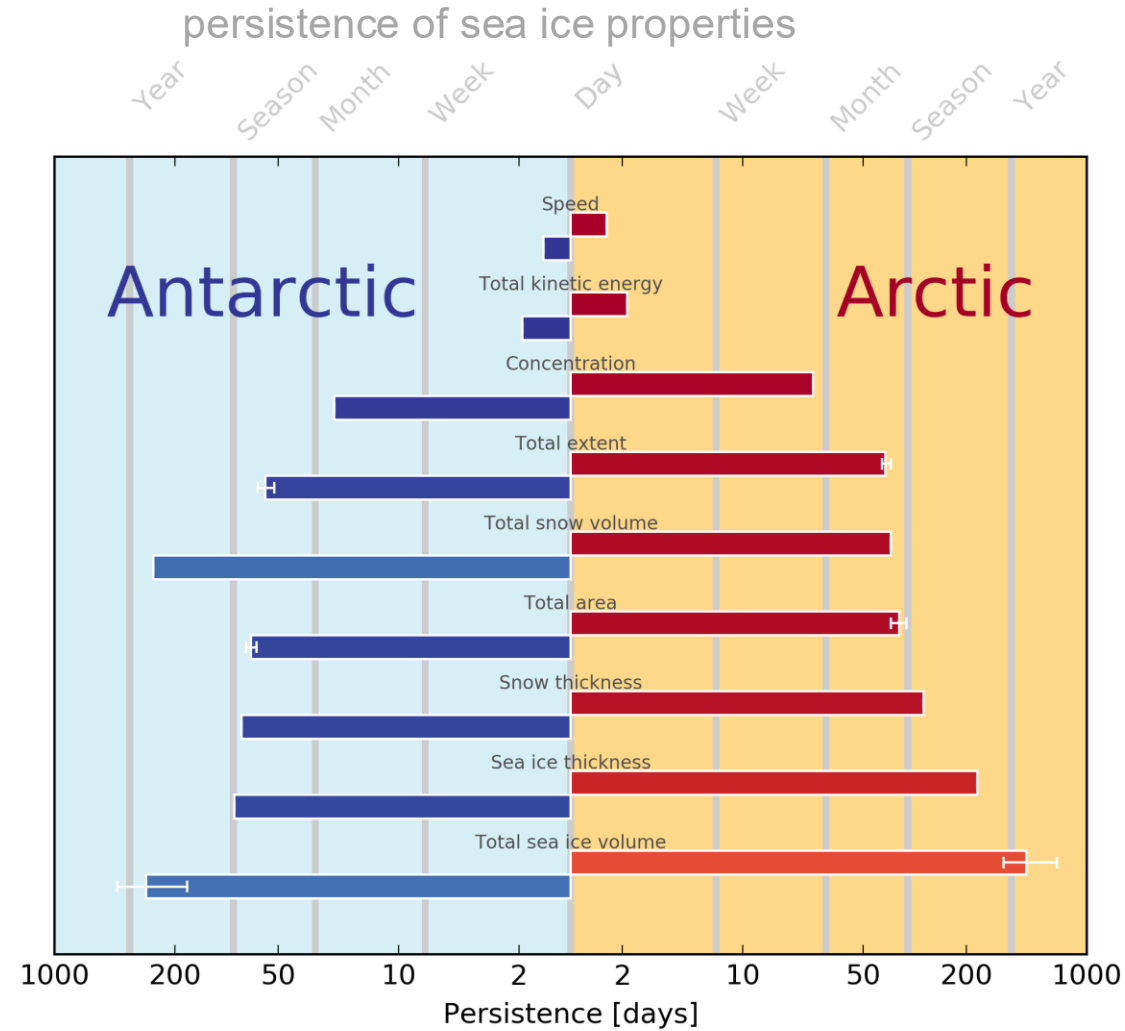
Sea-ice variability and predictability

Why include sea ice in predictions?

- Critical environmental factor for mariners, local communities and wildlife
- Fast direct impact on local lower atmosphere
- Potential to impact atmospheric circulation in mid-latitudes
- 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: freshwater export

Sea-ice time scales relevant for weather and climate prediction



Chevallier et al. 2019

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

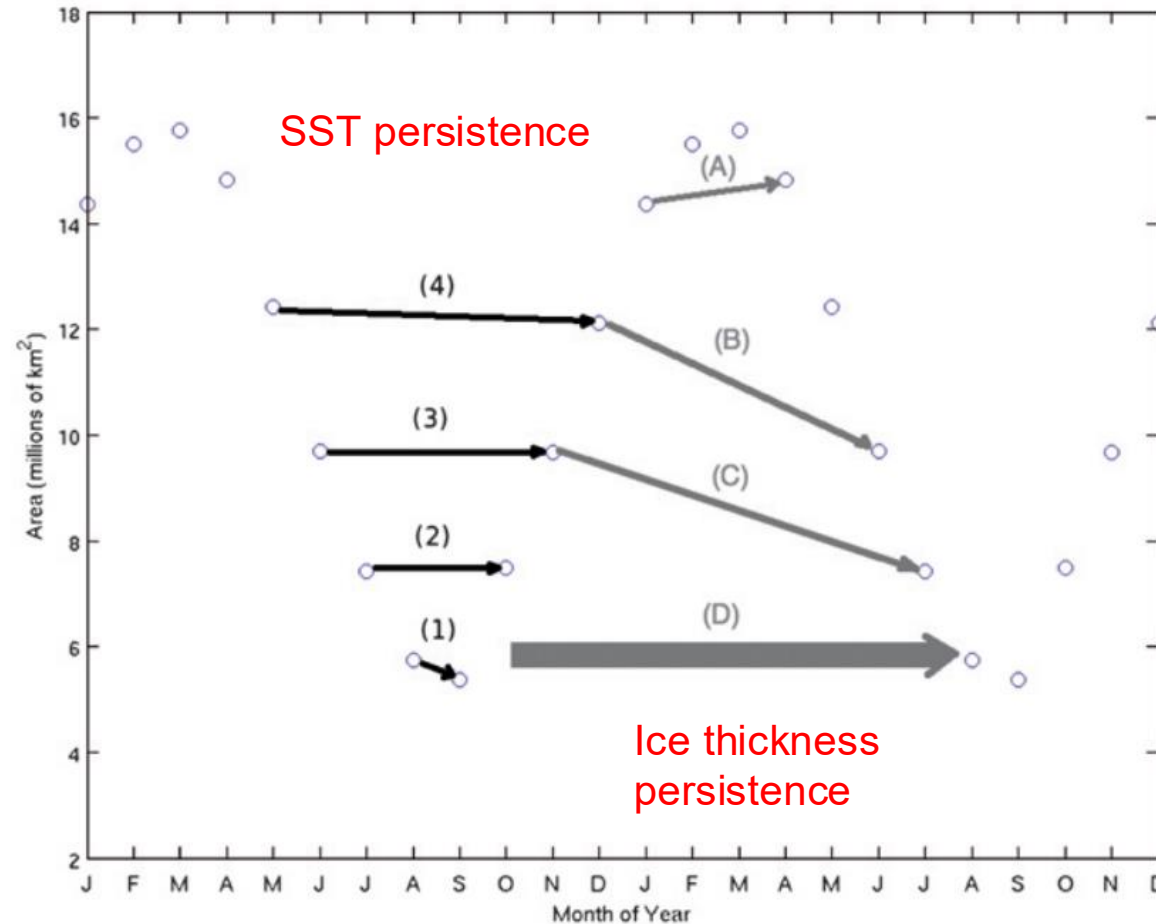
Mechanisms for sea-ice predictability

- Persistence
- Re-emergence of anomalies connected with seasonal cycle
- Medium- to extended-range: interaction with atmospheric modes of variability (e.g. NAO and blocking)
- 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

Strong seasonality of sea ice processes and predictability

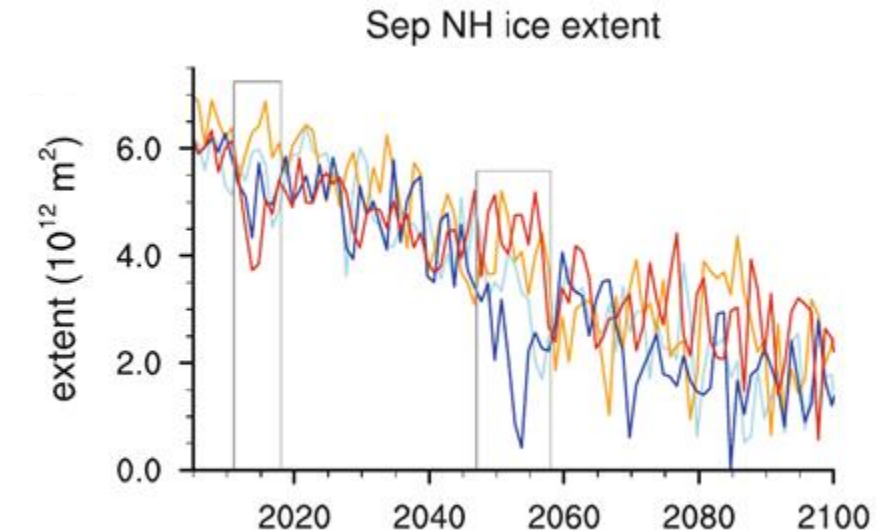
arrows between months whose anomalies are well correlated



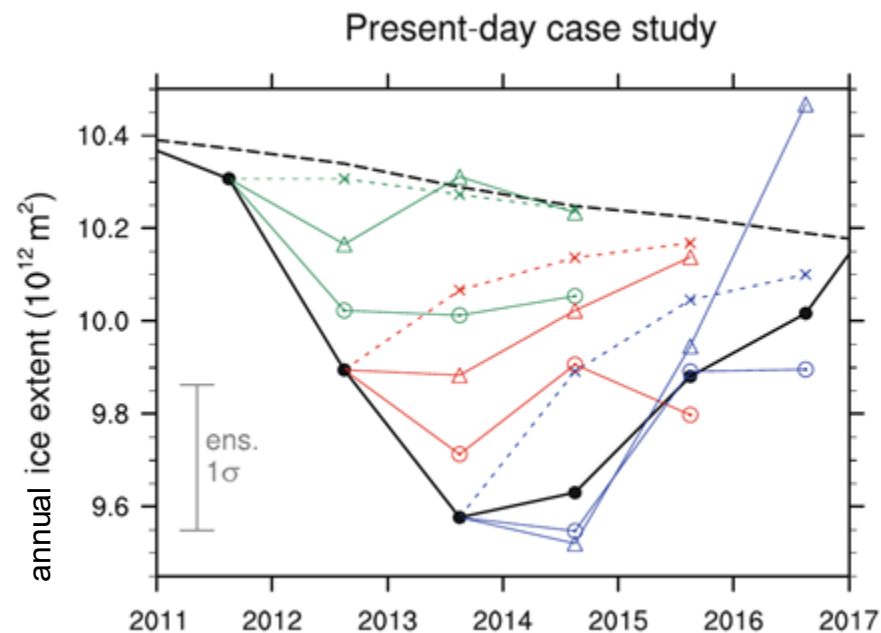
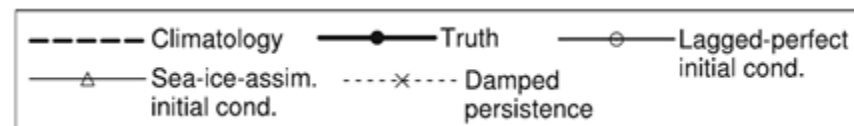
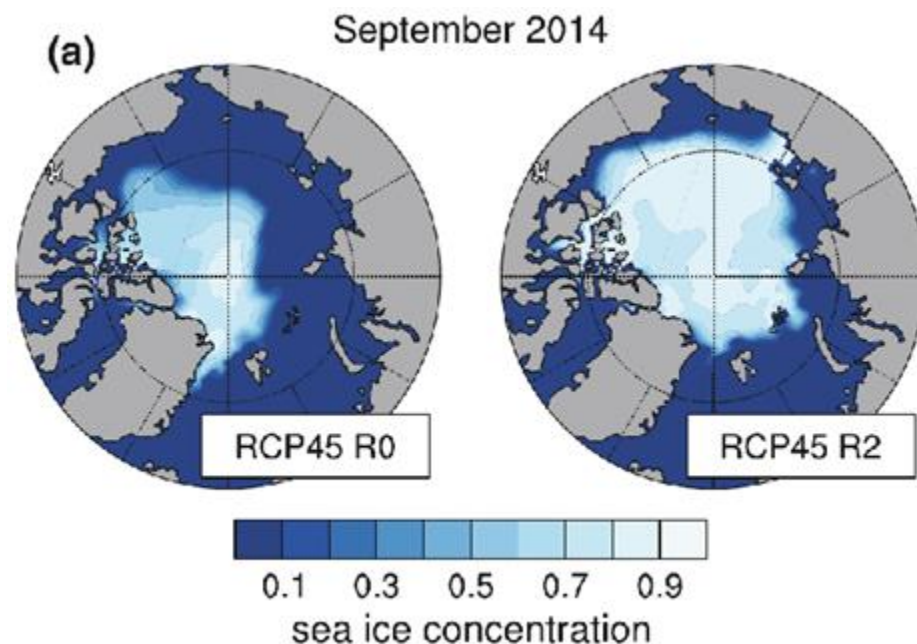
Transfer of persistence memory between sea-ice cover and
a) SST over summer
b) sea ice thickness over winter

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

Decadal predictability of sea-ice changes?



Initial-condition ensemble
of CMIP5 projections
with MPI-ESM



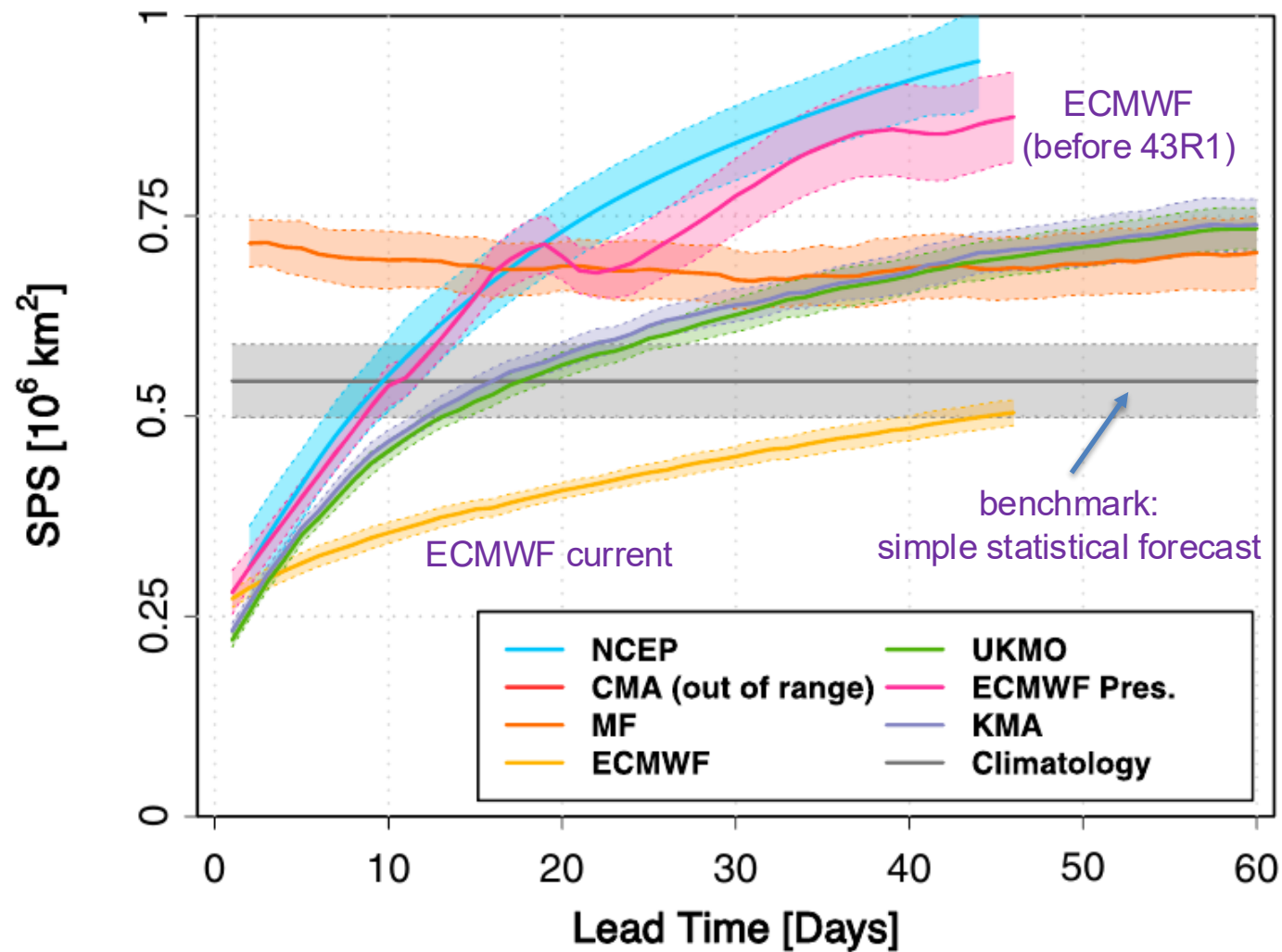
Idealized predictability experiments suggest inherent predictability for months or even years ahead.

Tietsche et al. (2013)

Sea ice modelling in ECMWF forecasts

- **OCEAN4** (until 2016, 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** (2016 - 2026): 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** (since 2026): 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
- **AIFS-Ocean ?**
 - data-driven ocean/sea ice forecasts trained on OCEAN6

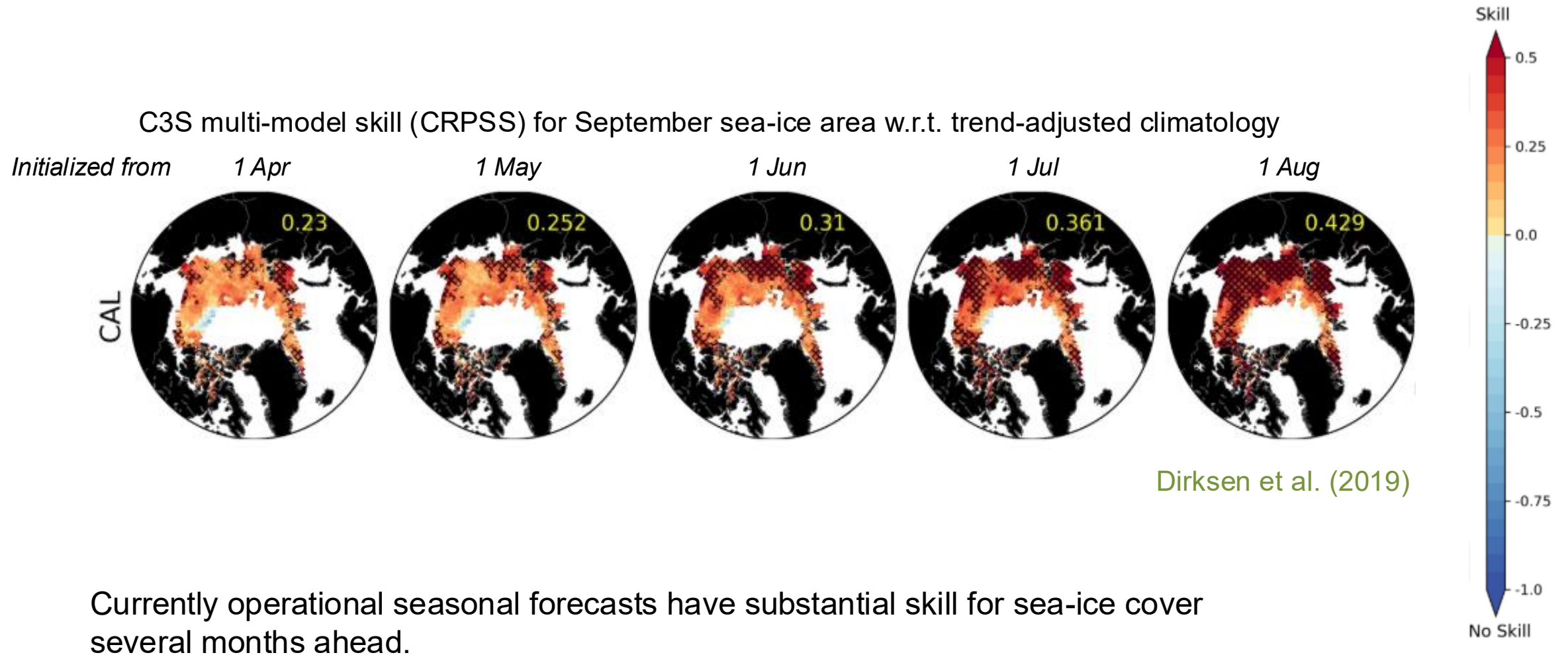
Extended-range forecast skill for Arctic sea ice from the S2S database



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

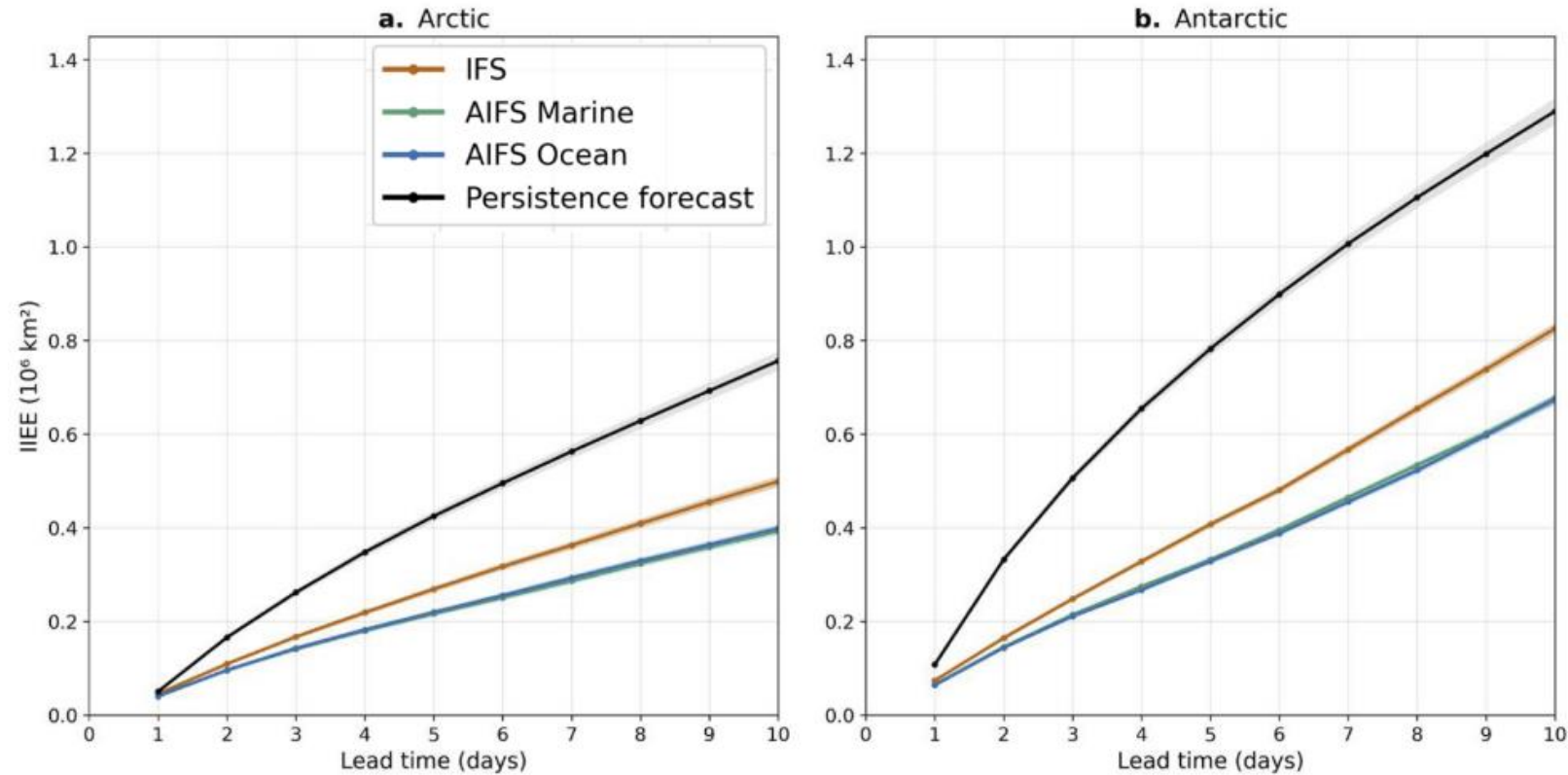
Zampieri et al., GRL 2018

Seasonal forecast skill



Data-driven sea ice forecasts with AIFS

Integrated Ice Edge Error (IIEE)
Verification window: 2023-06-15 to 2023-12-15 · Daily forecasts



> 10% improvement
over OCEAN5 forecasts

Hahner, Zampieri, et al. (2026)

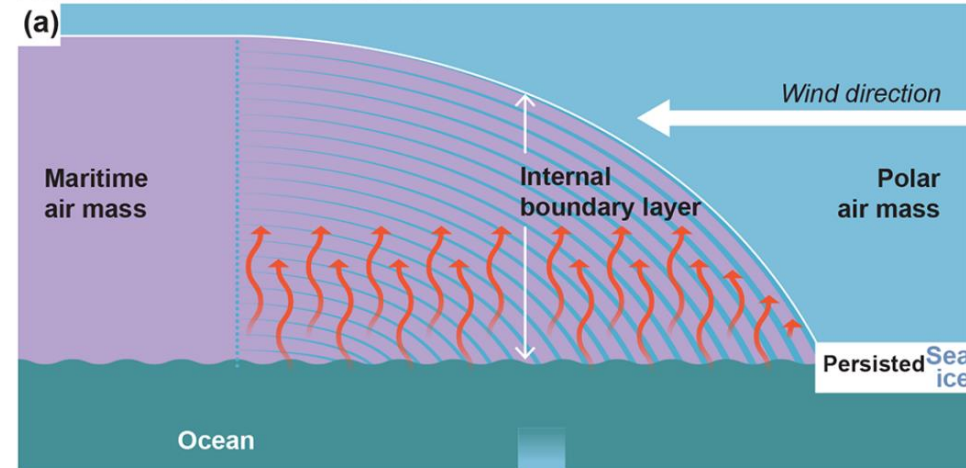
Current challenges in sea-ice predictions

- **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

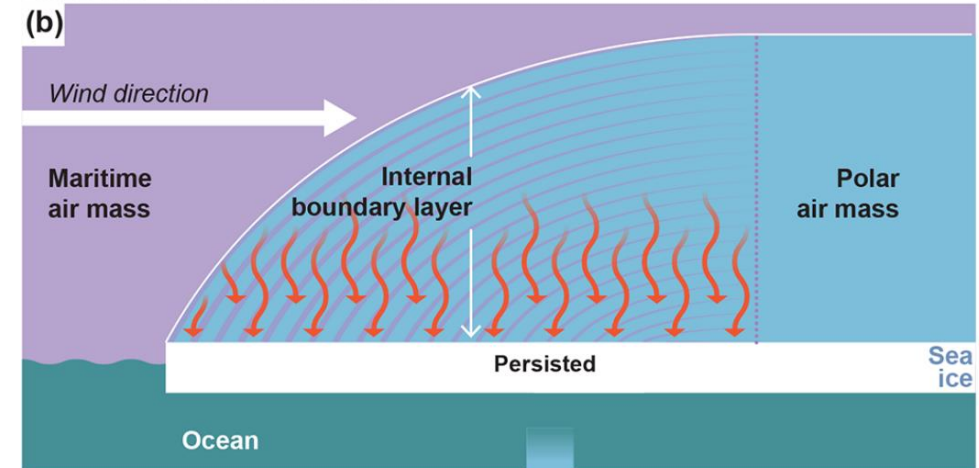
Atmospheric impact

Near-surface atmospheric impact in weather predictions

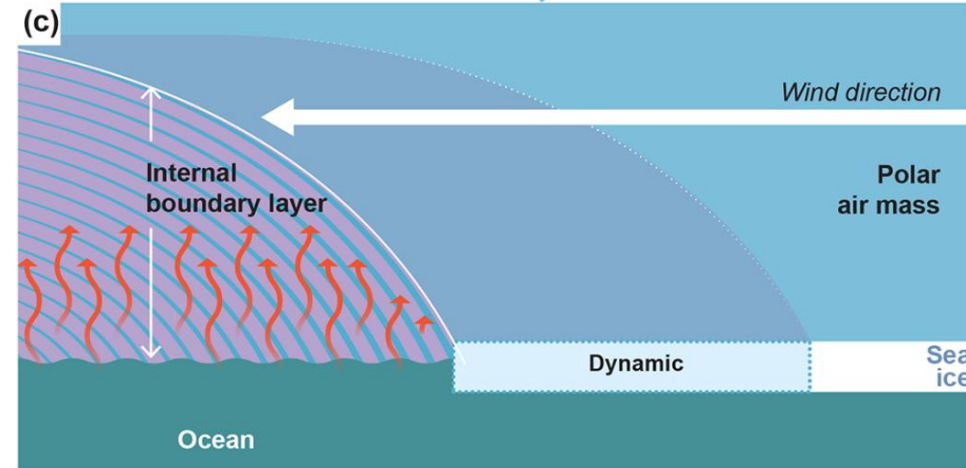
FIXED ICE - COLD AIR OUTBREAK



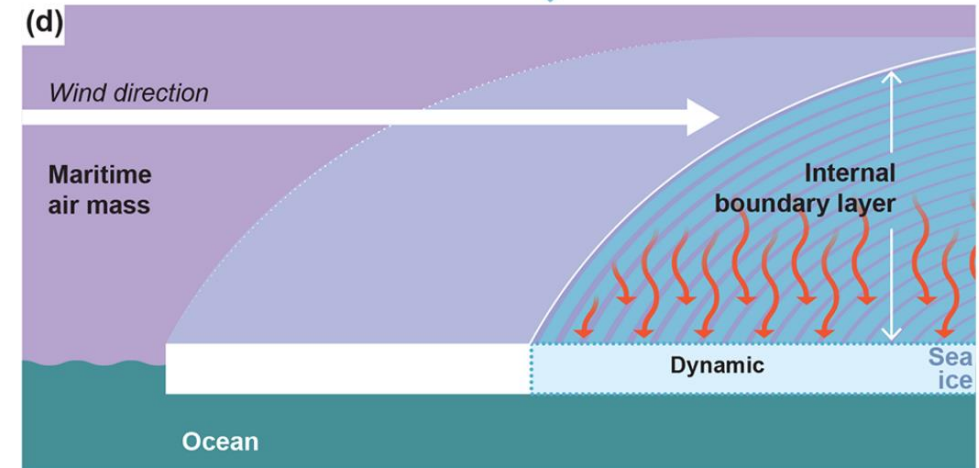
FIXED ICE - WARM INTRUSION



DYNAMIC ICE - COLD AIR OUTBREAK

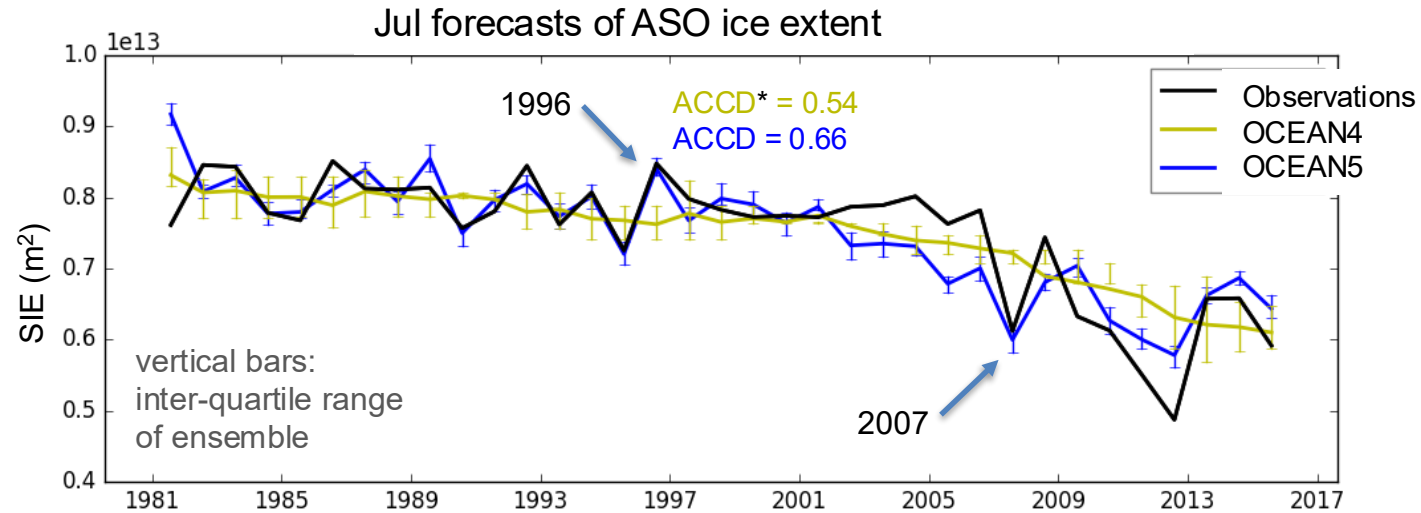


DYNAMIC ICE - WARM INTRUSION

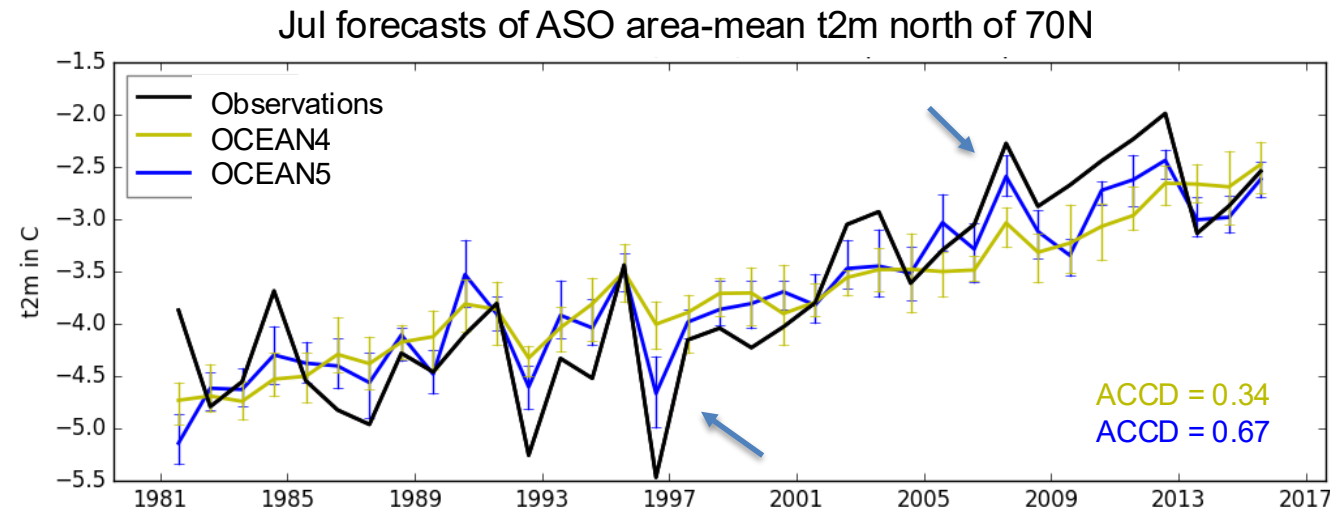


Day et al. (2022)

Summer Arctic surface air temperature and sea ice: seasonal forecasts



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

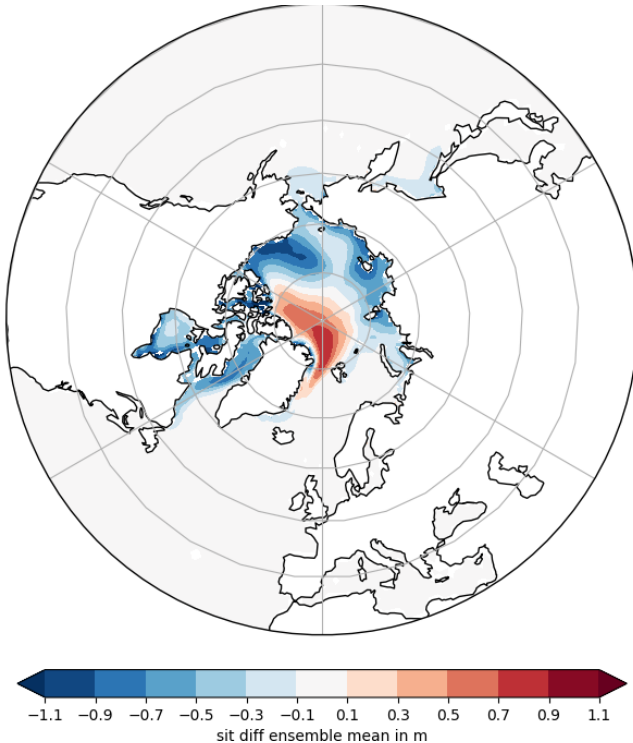


Associated with skill in seasonal forecasts of average surface temperatures north of 70N

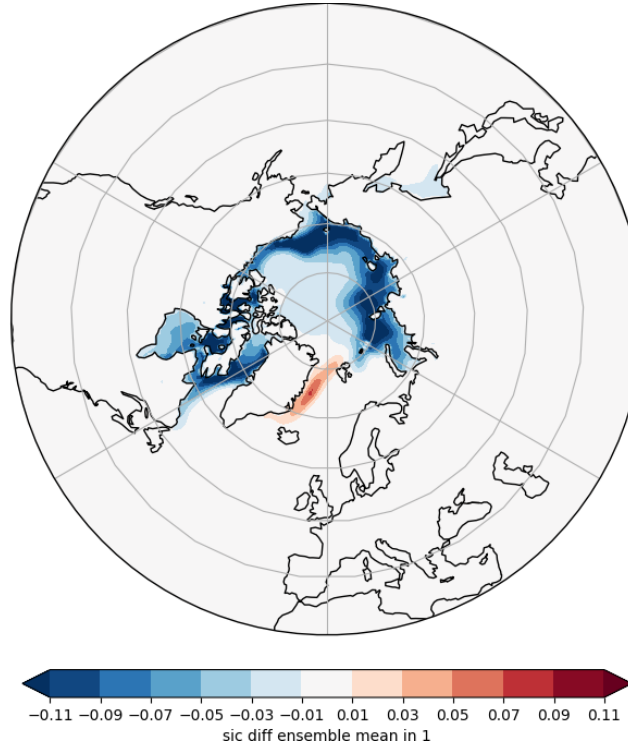
* ACCD: anomaly correlation of detrended time series

Spring sea-ice thickness impacts autumn surface temperatures

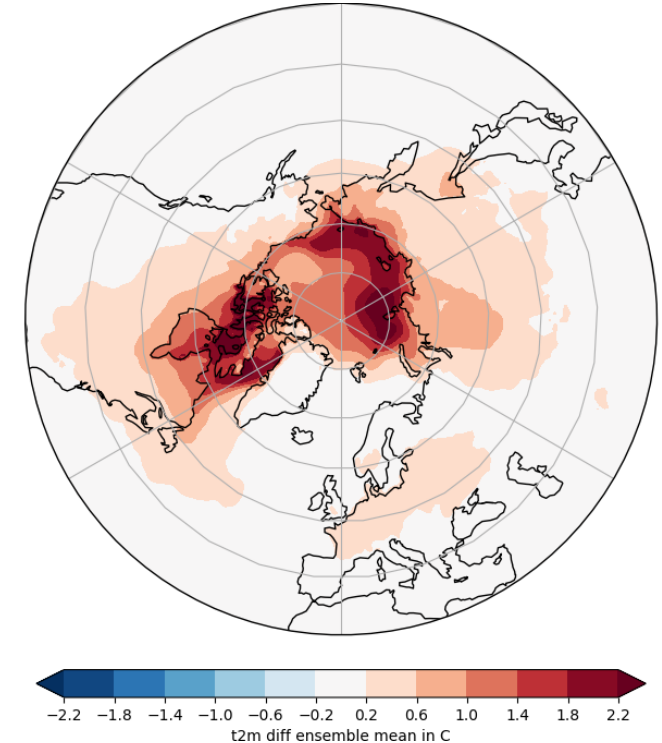
SIT difference in initial conditions
(Mar-Jun)



SIC difference after six months
(Sep-Dec)



t2m difference after six months
(Sep-Dec)



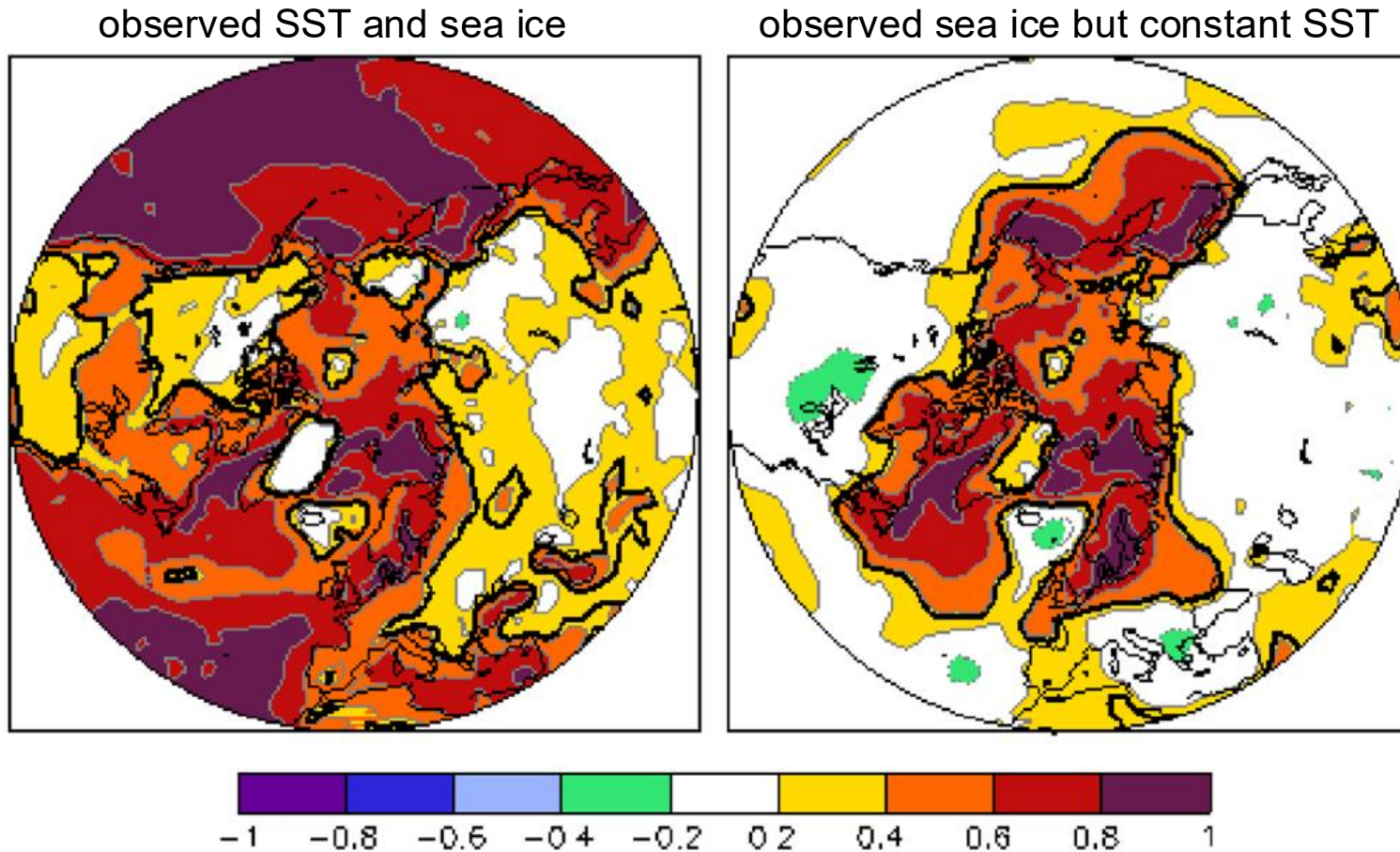
Numerical experiments with ORAS5/SEAS5:

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)

Winter impact of sea ice on winter surface air temperature

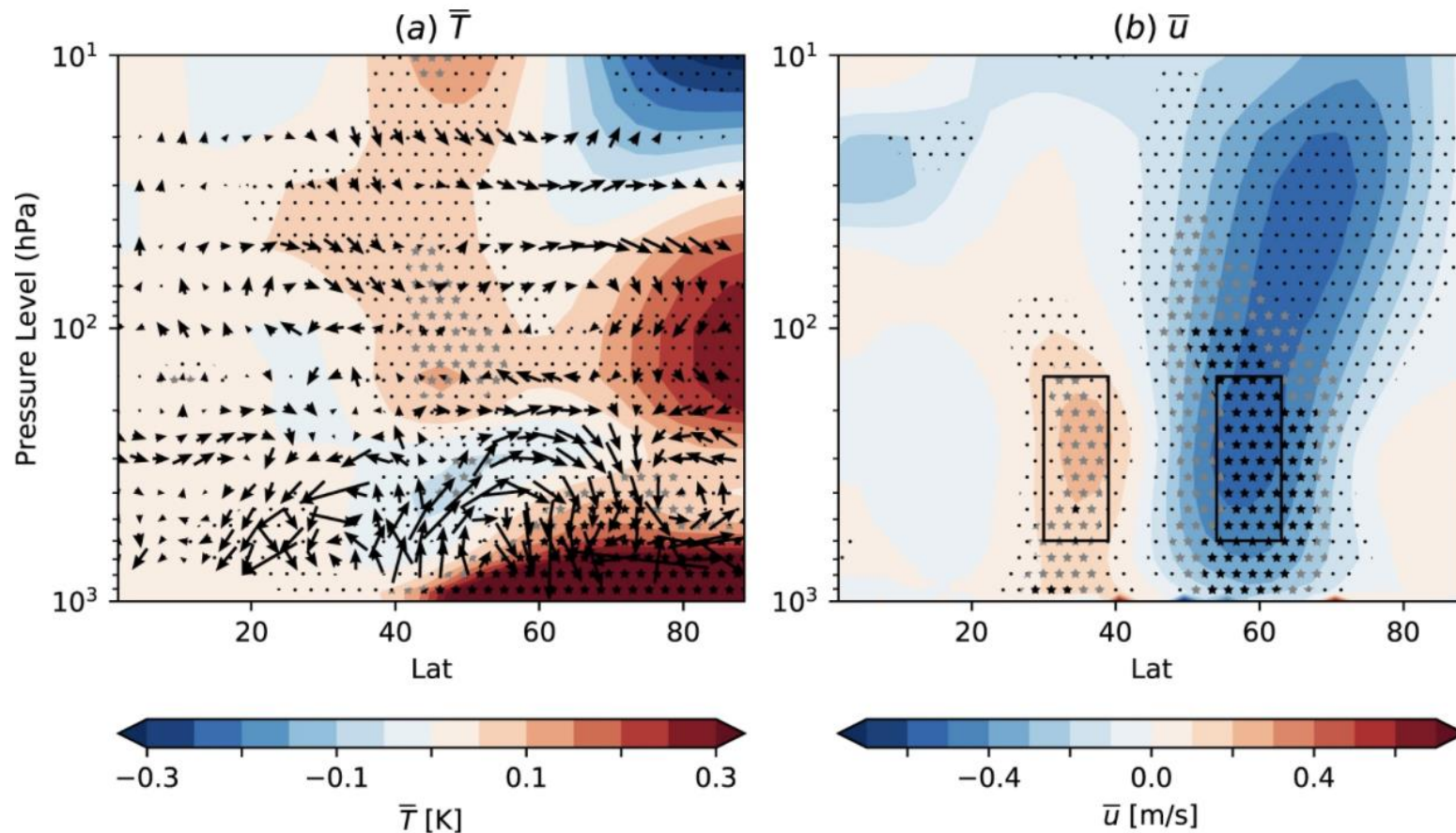
Correlation of DJF SAT with reanalysis in atmosphere-only simulations (1982-2014):



Koenigk et al. (2019)

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

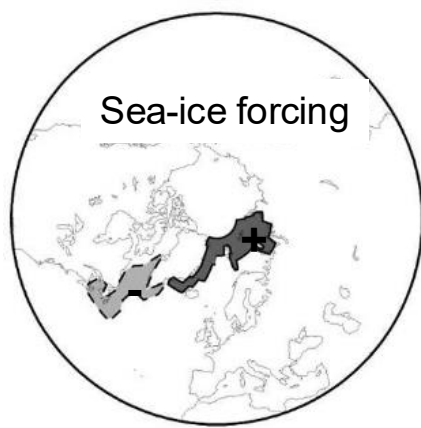
Mean atmospheric circulation response to Arctic sea-ice loss



Multi-model response in zonal-mean temperature and zonal wind to sea ice changes for a 2C warmer climate (CMIP6 PAMIP experiments)

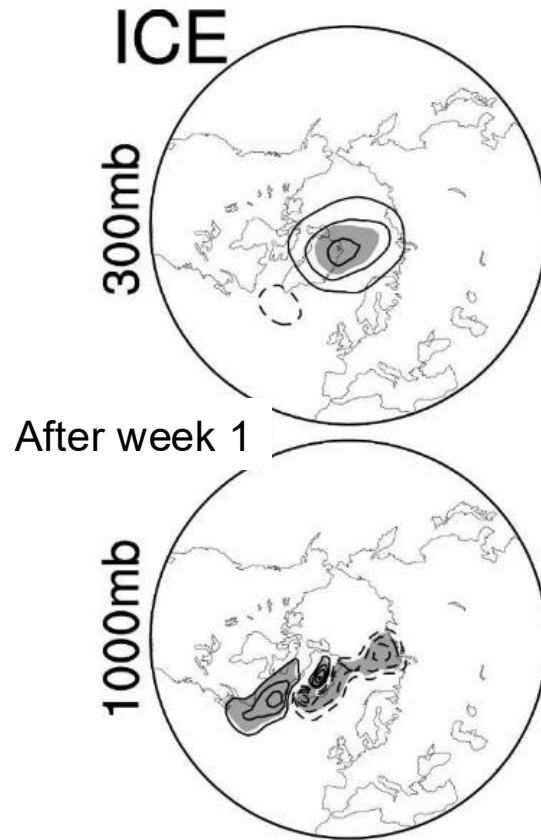
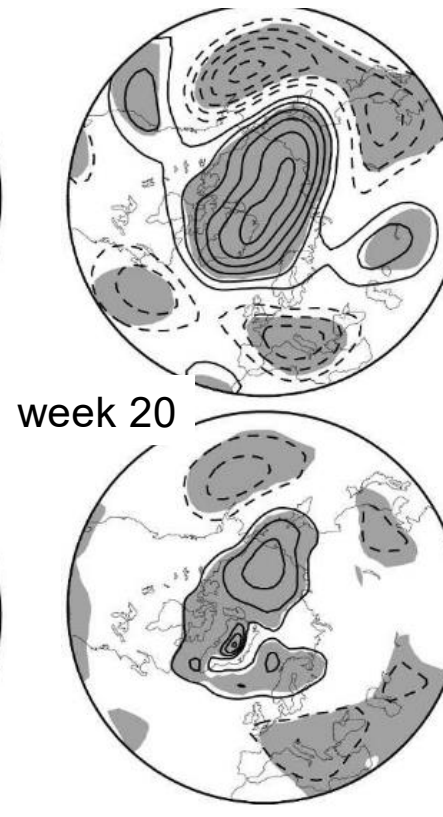
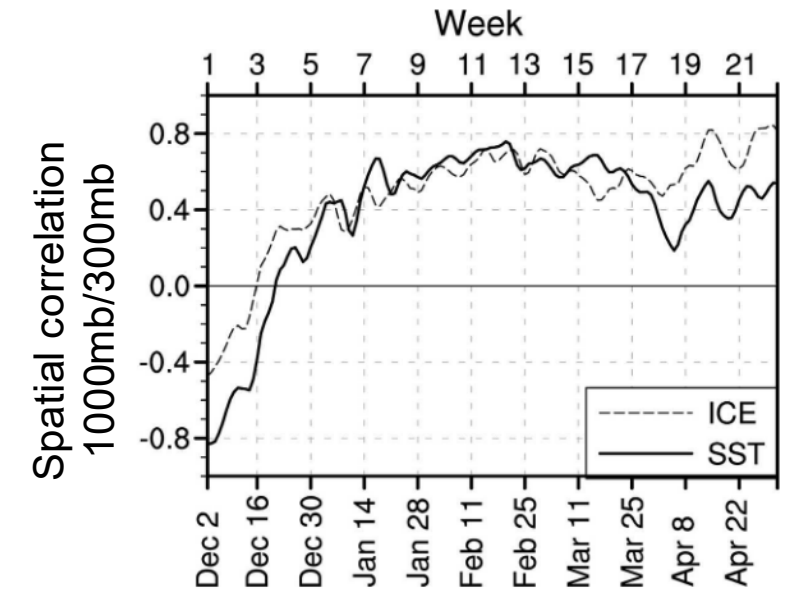
Smith et al. (2022)

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



Caveat I: atmospheric impact is time-scale dependent

geopotential height response (ci=10m)

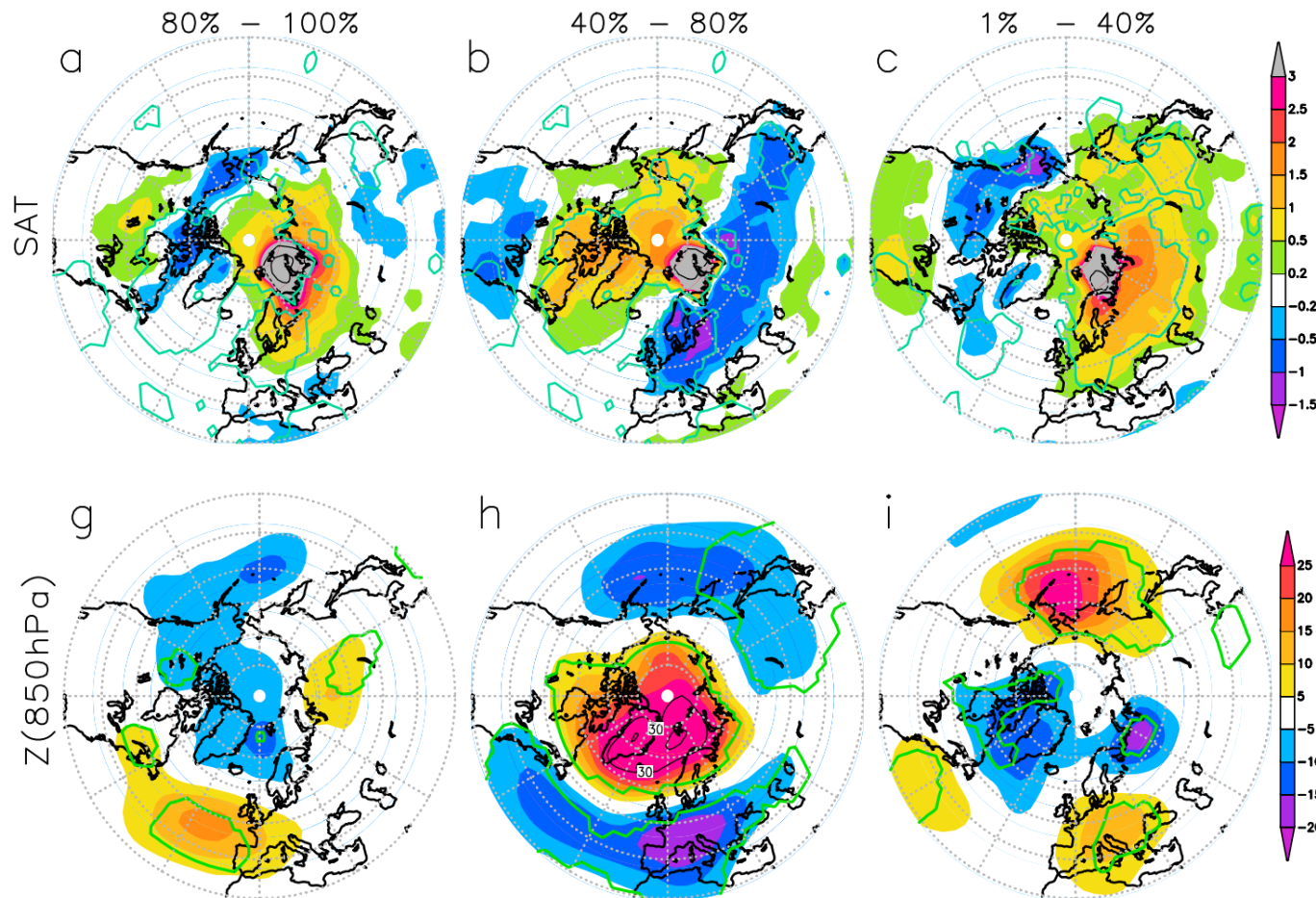
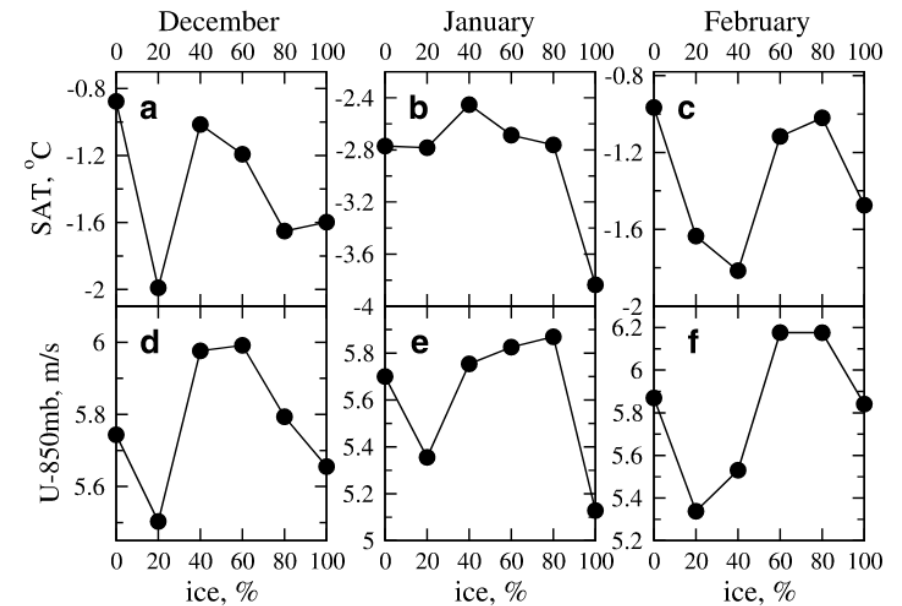


- *Numerical experiments* forcing the atmosphere with the dominant mode of sea-ice variability & climate change in the NH
- *Fast response*: local and baroclinic
- *Equilibrium response*: hemispheric and barotropic

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

Deser et al. (2007)

Caveat II: atmospheric impact is non-linear

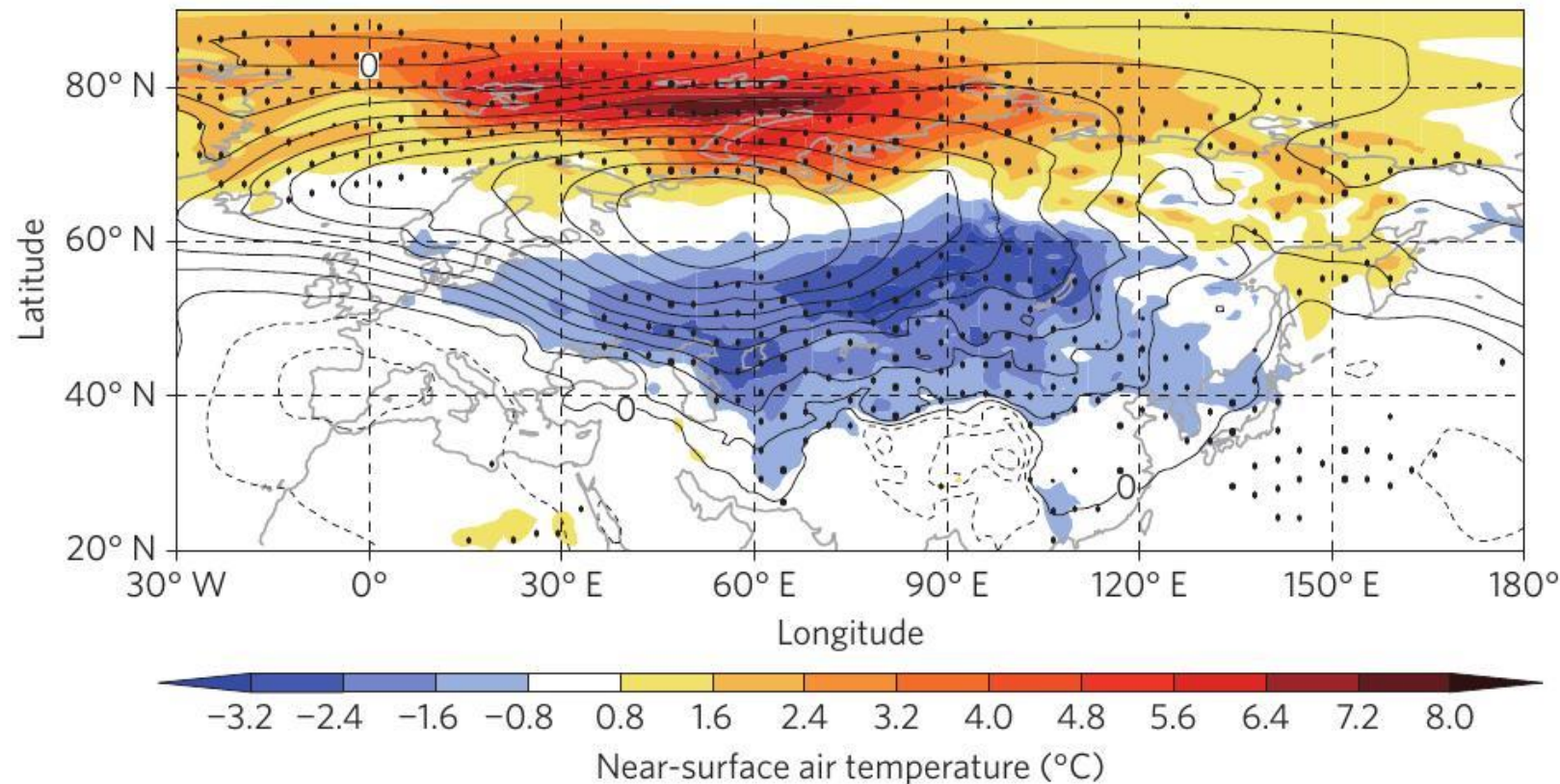


Petoukhov et al. (2010):
Numerical experiments forcing atmosphere
with reduced sea ice in Barents Sea

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)

The link between Barents/Kara sea ice and cold Eurasian winters



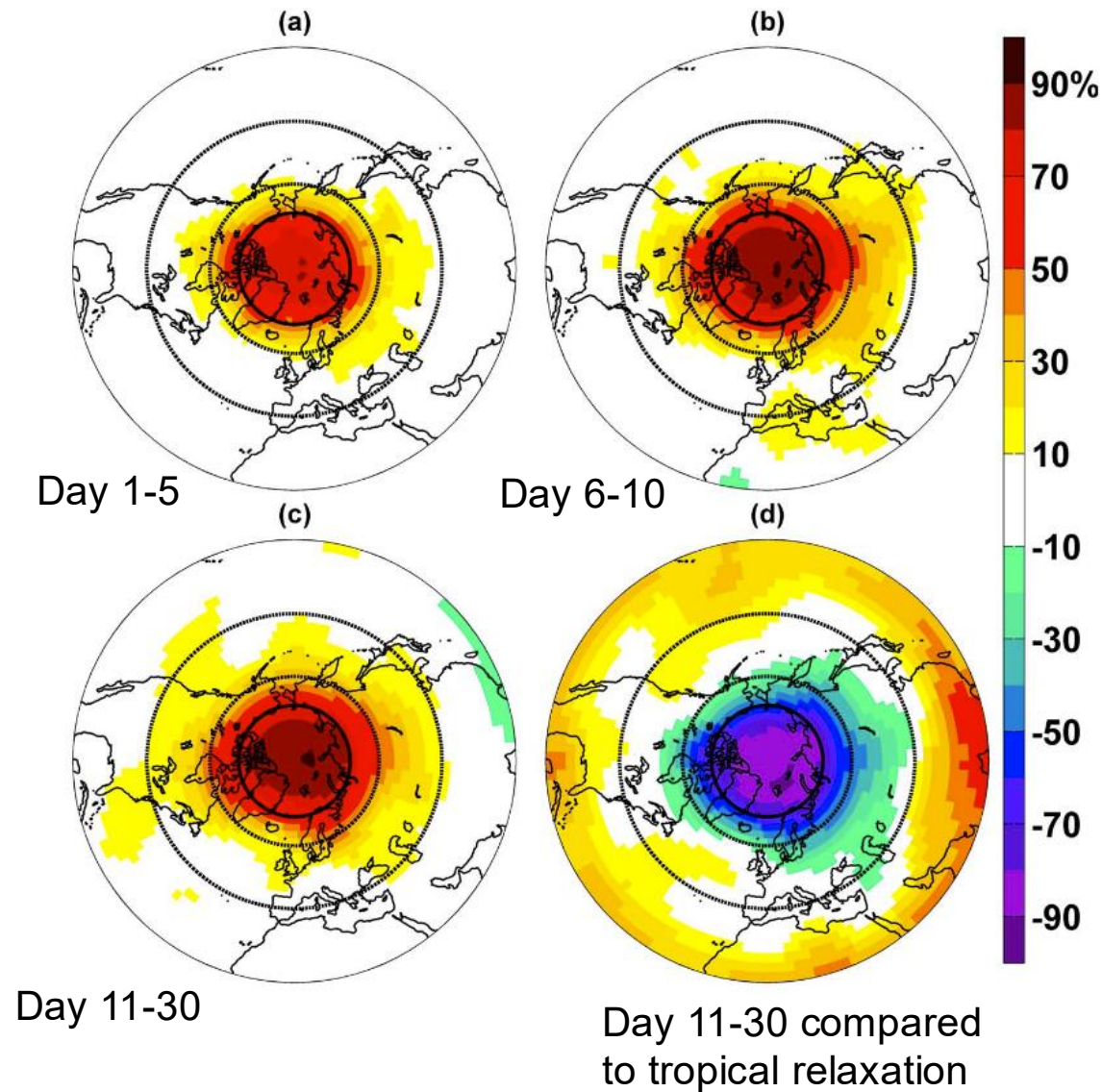
Composite of DJF 2m temperature difference between years with low and high sea-ice cover in the Barents and Kara Seas (1979-2013)

→ Ural blocking favouring cold-air advection over Eurasia

Mori et al. (2014)

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

Arctic atmosphere impact on mid-latitude predictions

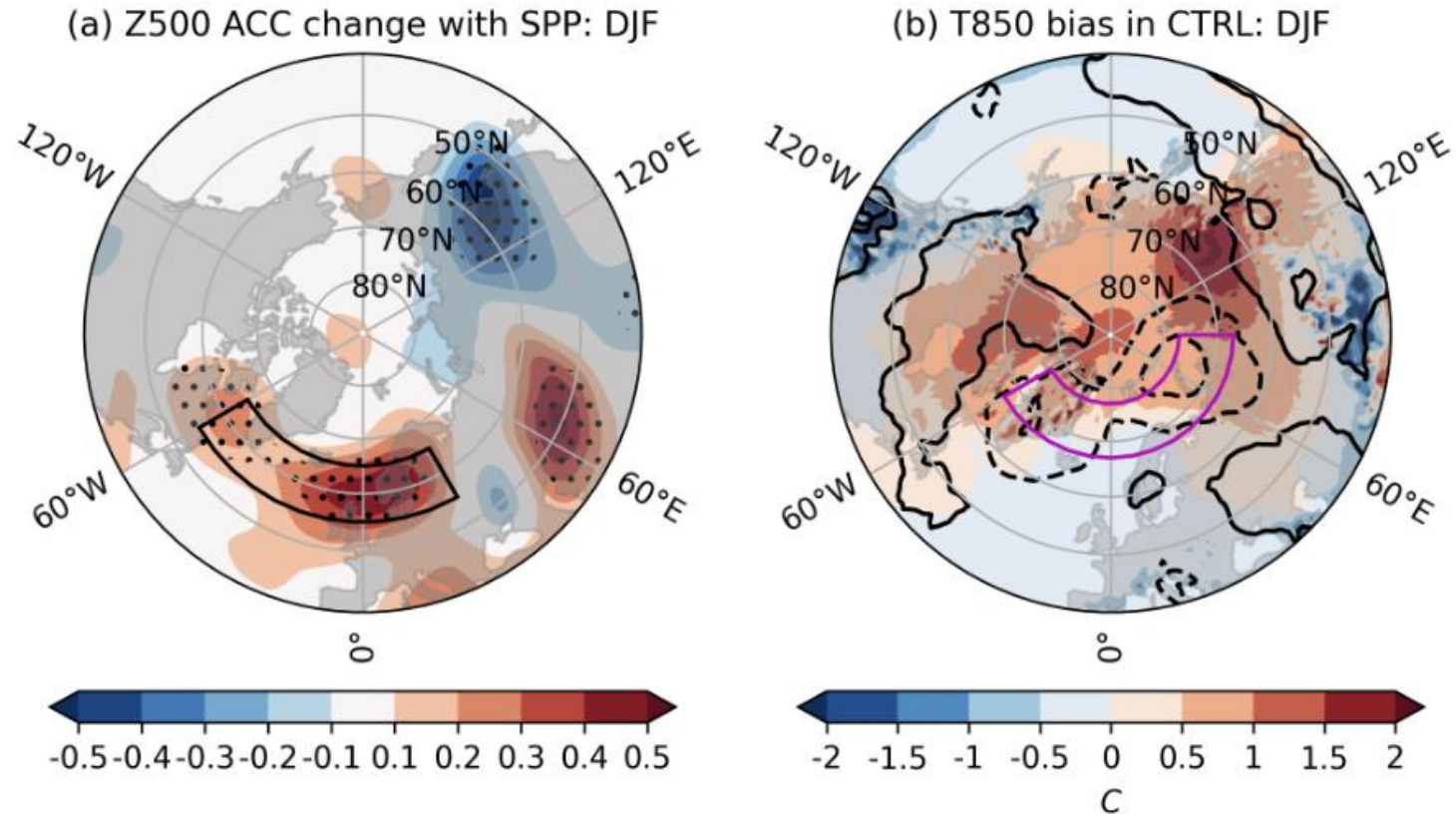


Relative reduction of z500 RMSE in winter forecasts achieved by Arctic atmosphere relaxation (*full column*)

→ Especially over mid-latitude Eurasia, strong linkages to the Arctic

Jung et al. (2014)

ECMWF seasonal forecast developments: even small changes in sea ice can affect NAO forecasts



Experimenting with stochastic perturbed sea ice parameters (SPP):

slight (unintended) mean state change around North Atlantic ice edge

→ changes to the modelled storm track and improved NAO predictions

[Strommen et al. \(2026\)](#)

Sea ice atmospheric impact in a nutshell

1. Strong and fast impact on lower atmosphere
2. Multifaceted circulation response via
 - Changes to baroclinity
 - Vertical waves and stratosphere-troposphere coupling
3. Robustness and generality of statements limited by
 - Dependence on time scale and background state; nonlinearity
 - Difficulties to infer causality
 - signal to noise ratio (need long observational records and/or large ensembles)
 - Deficiencies in weather and climate models
4. Cold Eurasian winters closely linked to sea ice loss in Barents/Kara Seas

Some take away messages

- 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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