Coupled sea-ice-atmosphere variability and predictions

Steffen Tietsche

5th November 2024

ECMWF Predictability Training Course 2024

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

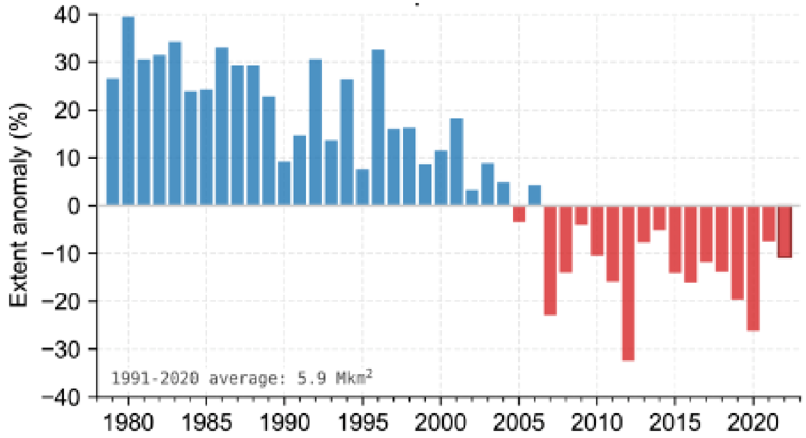
Fun and educating to read:

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

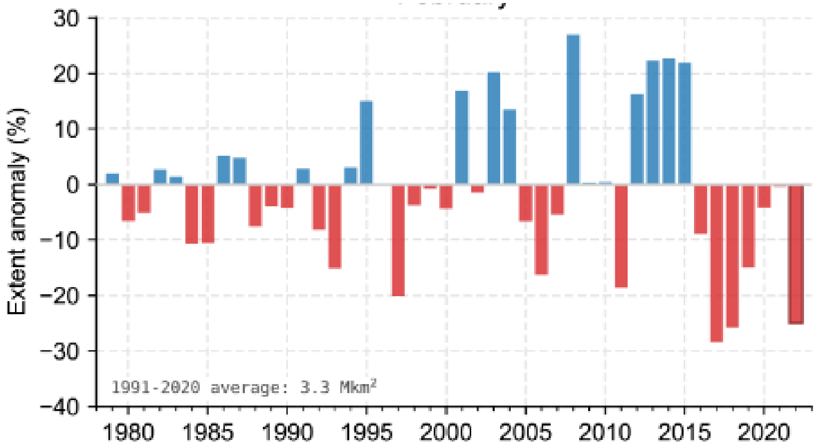
Wreck of the Endurance,
discovered on 5 March 2022

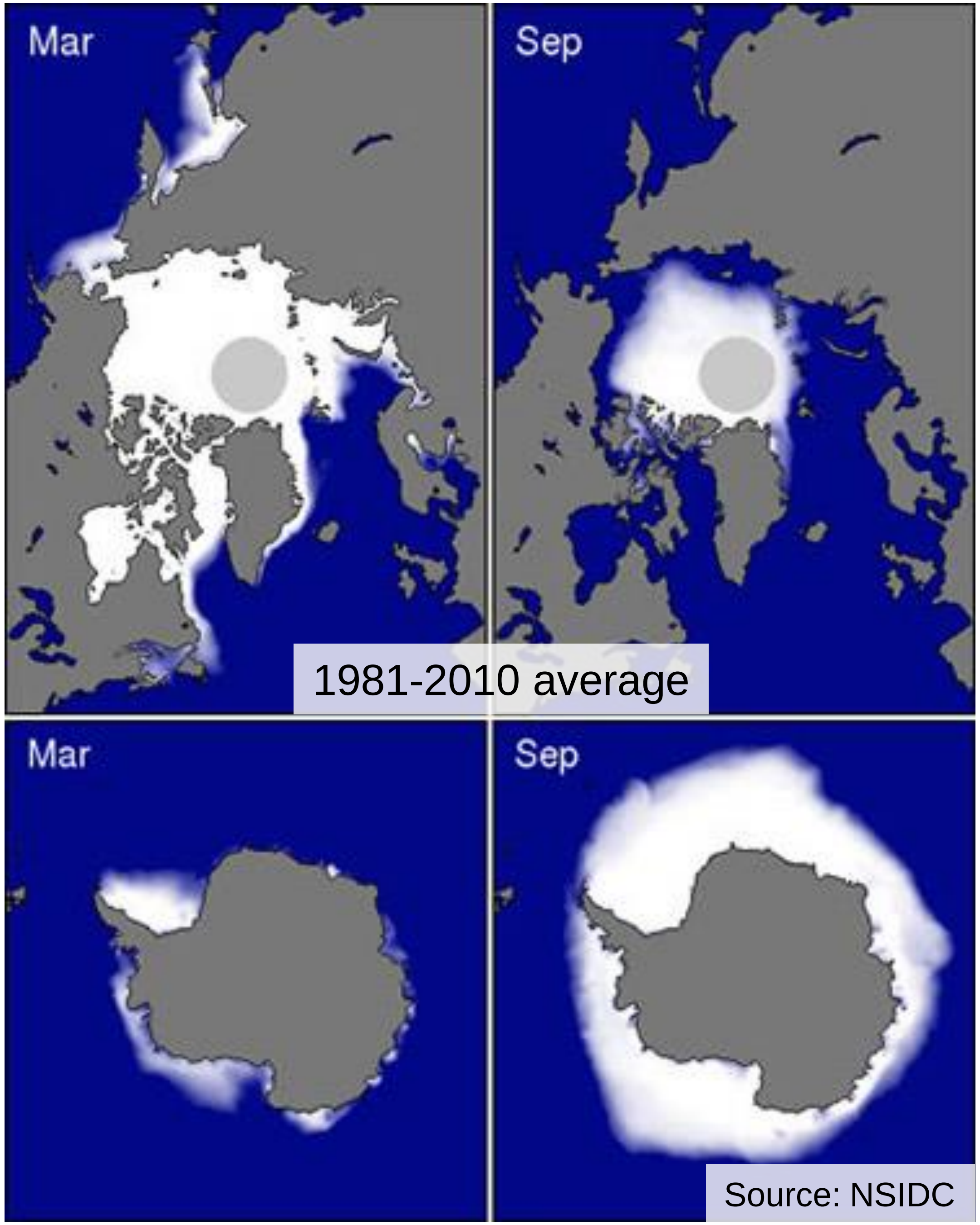
Sea ice occurrence and climate trends

September Arctic monthly sea ice extent anomalies



February Antarctic monthly sea ice extent anomalies





1981-2010 average

Source: NSIDC

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

$$\partial_{\mathrm{t}} h_{\mathrm{m}} = -\nabla \cdot (h_{\mathrm{m}} \boldsymbol{v}) + S_h$$

Continuity equation for ice mass

$$\partial_{\mathrm{t}} C = -\nabla \cdot (C \boldsymbol{v}) + S_C$$

Continuity equation for ice area

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

$$\partial_{\mathrm{t}} \boldsymbol{v} = -f\,(\boldsymbol{k} \times \boldsymbol{v}) - g\nabla\zeta + \frac{\boldsymbol{\tau}_{\mathrm{a}}}{\rho_{\mathrm{i}} h_{\mathrm{m}}} + \frac{\boldsymbol{\tau}_{\mathrm{o}}}{\rho_{\mathrm{i}} h_{\mathrm{m}}} + \nabla \cdot \boldsymbol{\sigma}\,.$$

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

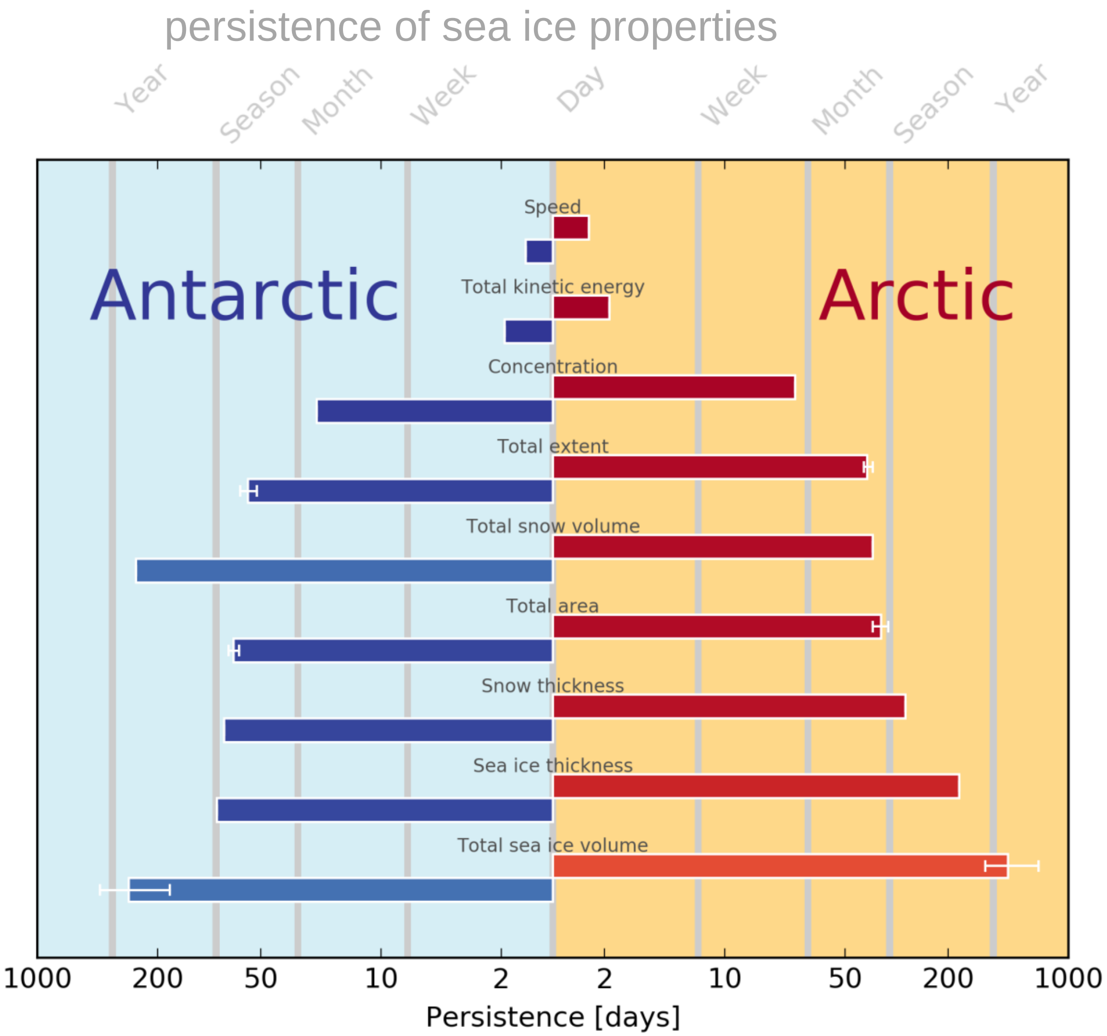
Sea-ice variability and predictability

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: fresh water 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

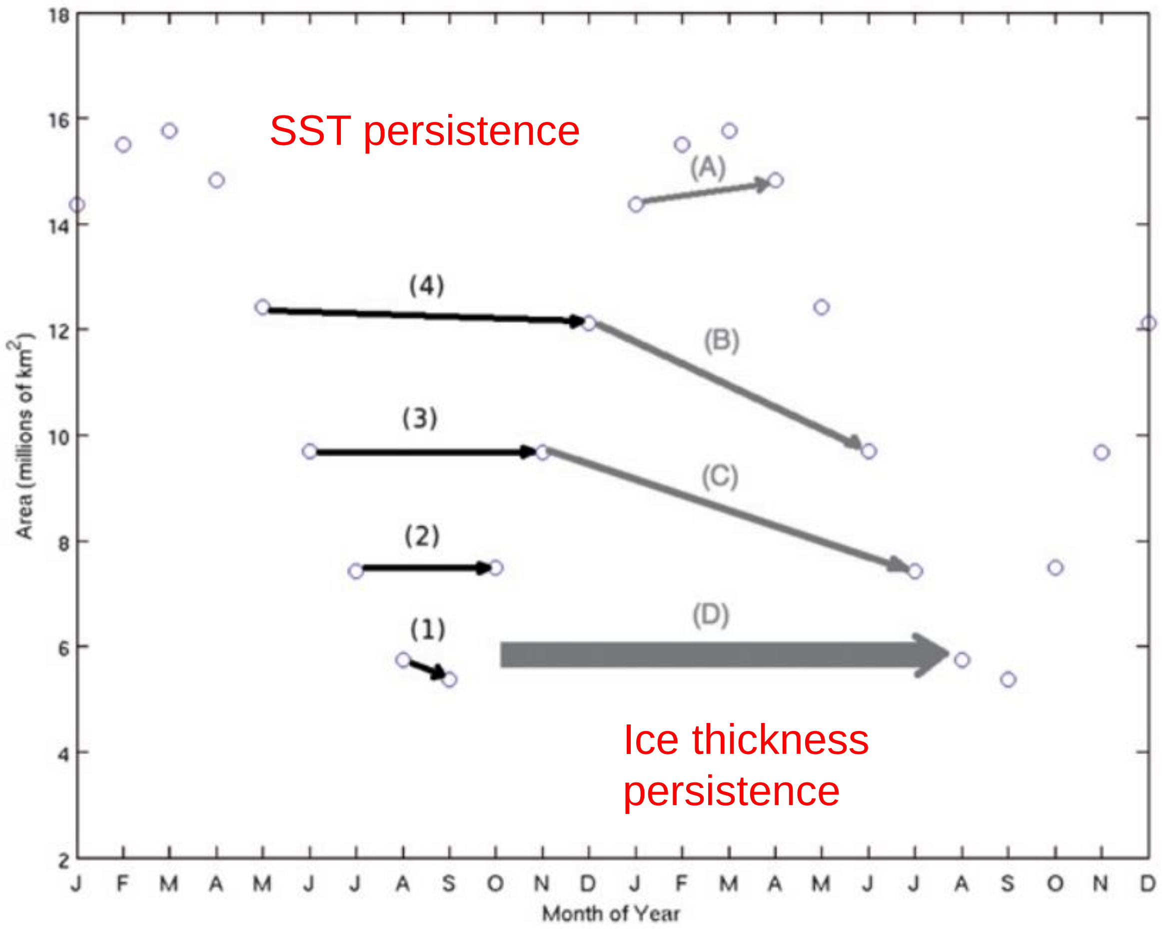
Mechanisms for sea-ice predictability

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

Strong seasonality of sea ice processes and predictability

arrows between months whose anomalies are well correlated



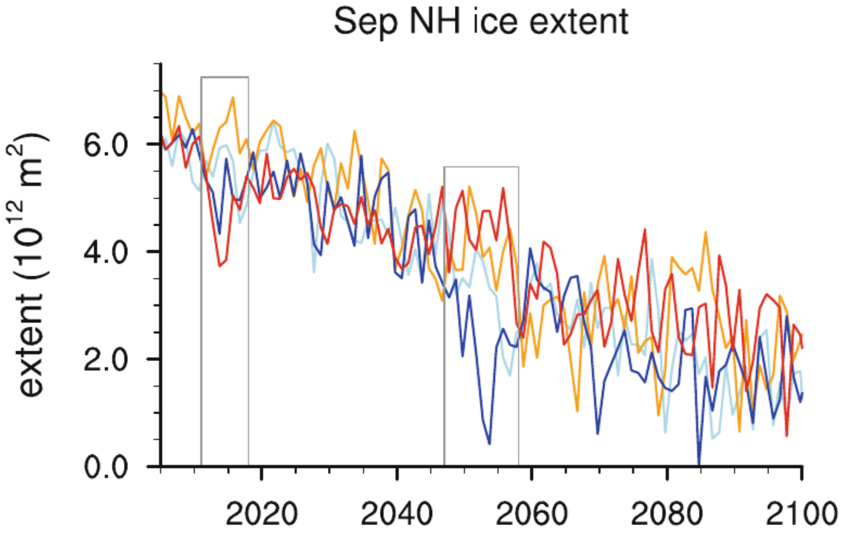
Transfer of persistence memory between sea-ice cover and

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

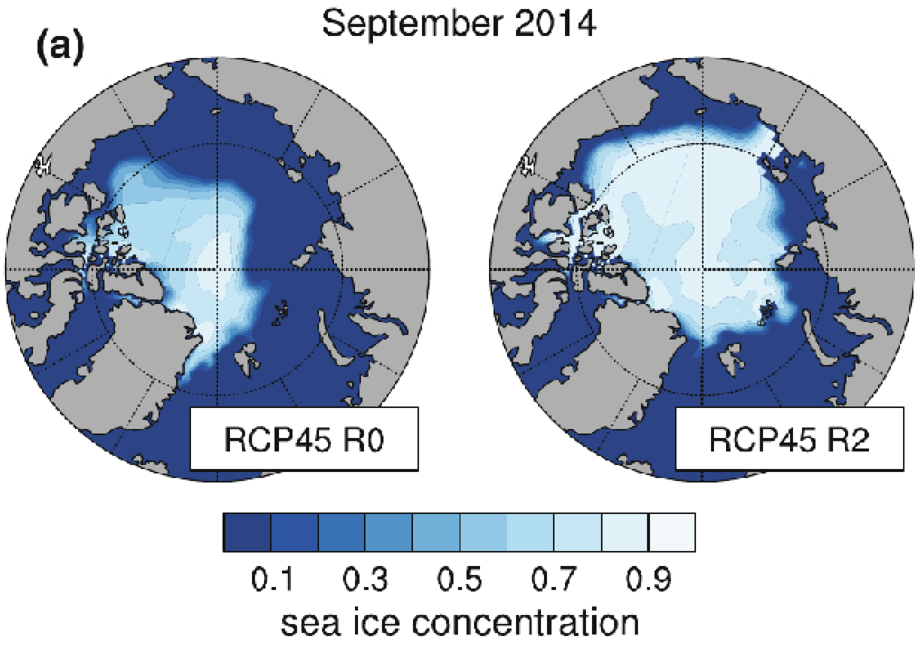
→ months with similar sea-ice extent tend to have similar anomalies

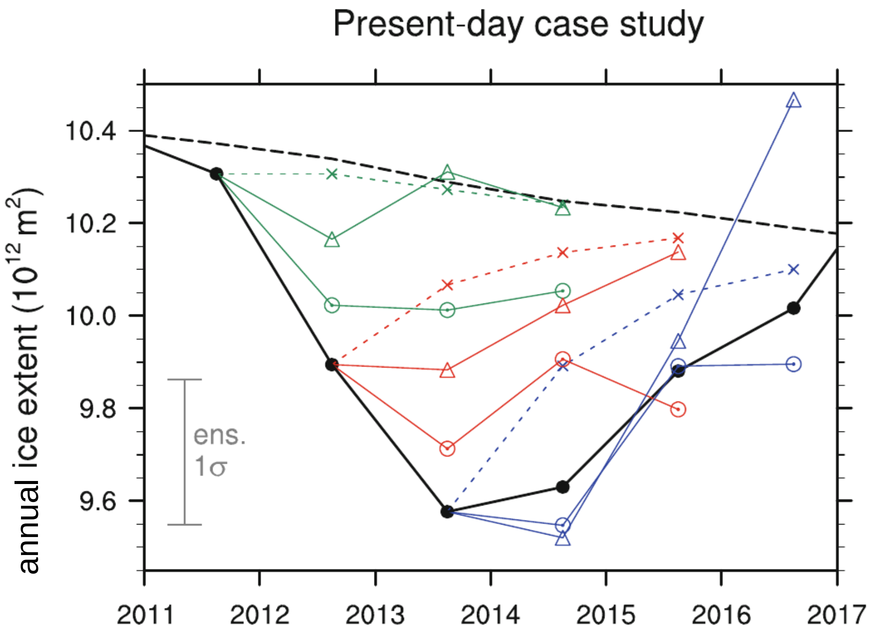
Blanchard-Wrigglesworth et al (2011)

Decadal predictability of sea-ice changes?



Initial-condition ensemble of CMIP5 projections with MPI-ESM





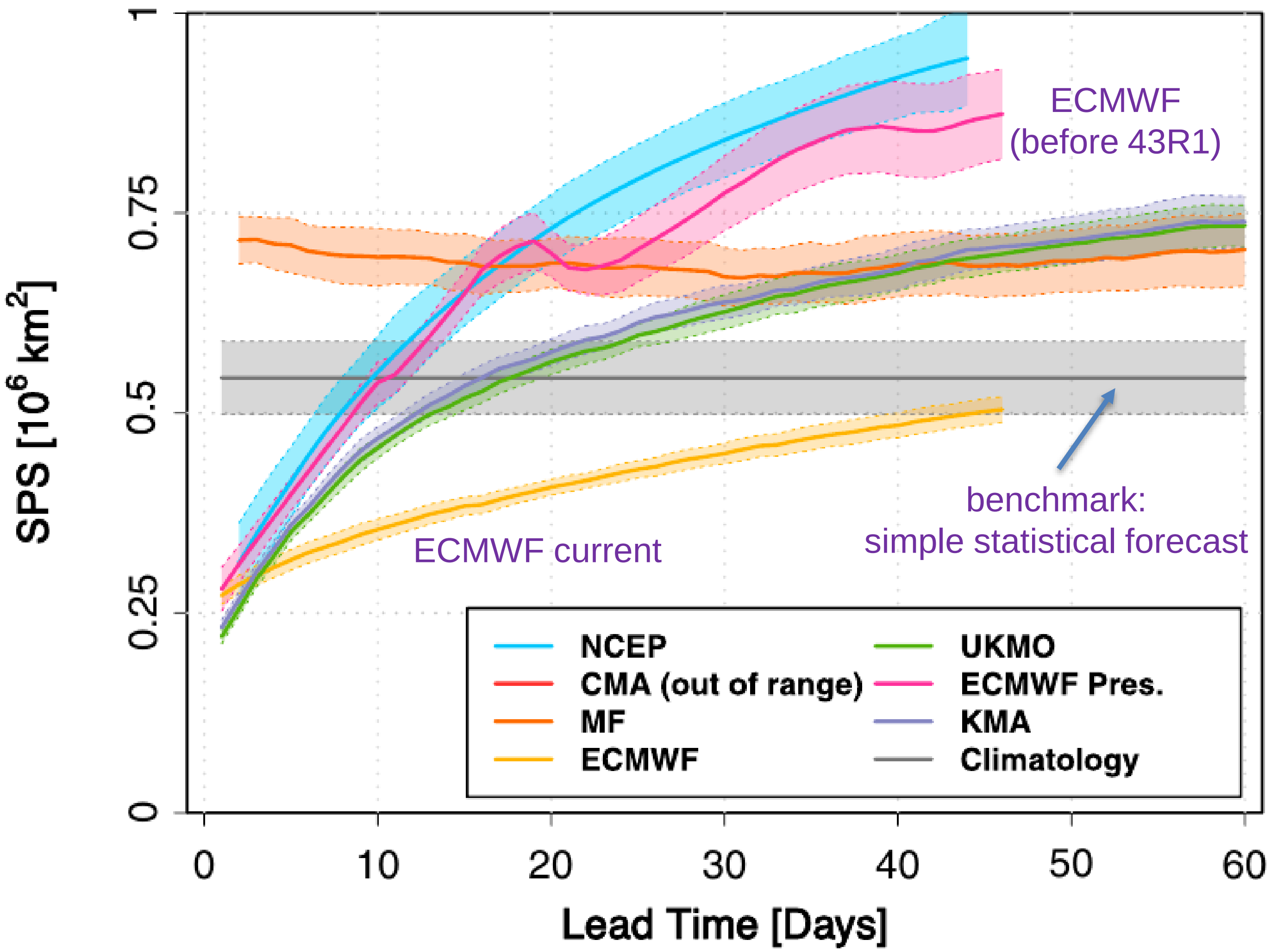
Idealized predictability experiments suggest inherent predictability for months or even years ahead.

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** (2025): 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

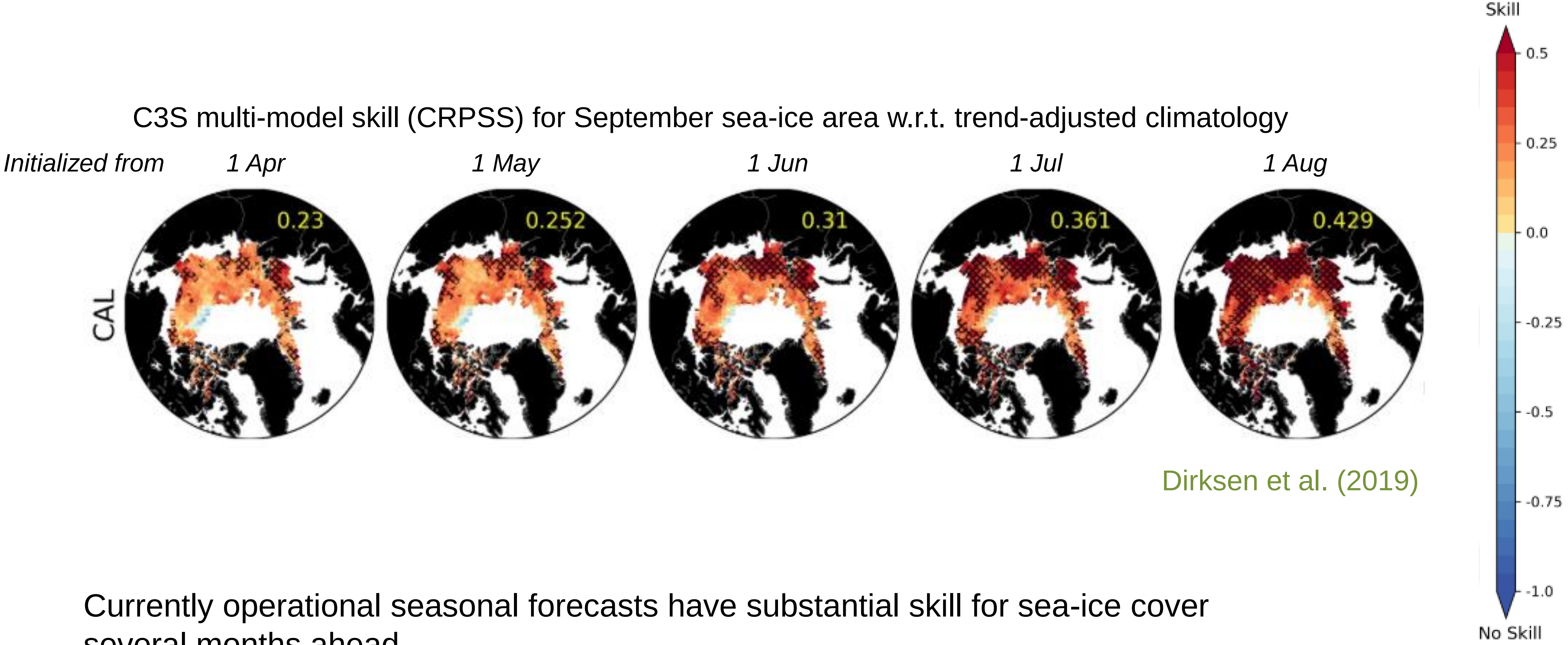


Sub-seasonal skill *up to 6 weeks* in currently operational sub-seasonal forecasts

Zampieri et al., GRL 2018

Seasonal forecast skill

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



Dirksen et al. (2019)

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

Current challenges in sea-ice predictions

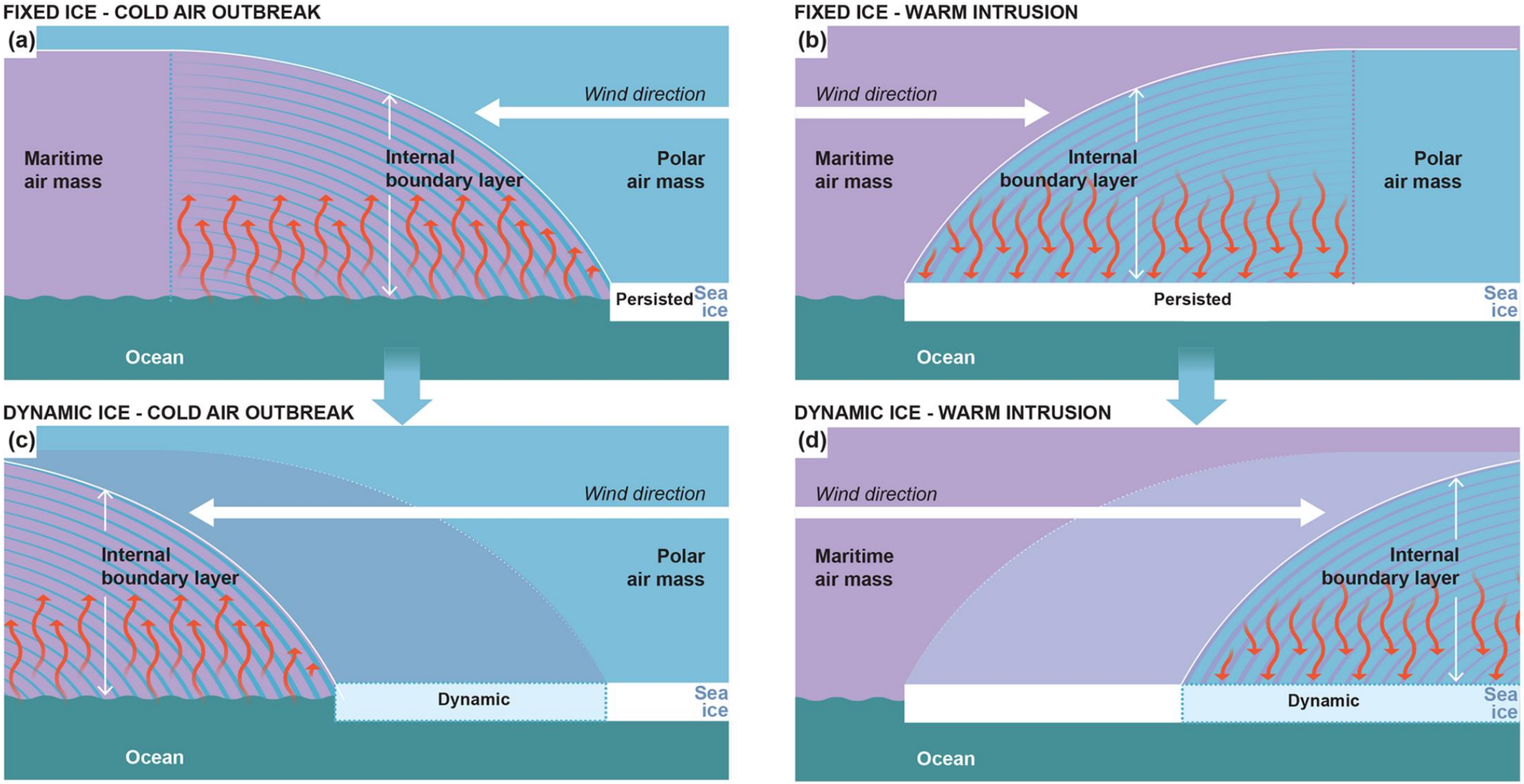
- **Initialization**: currently relies mostly on observations of sea-ice *concentration*, but memory resides in *sea-ice thickness* and *upper-ocean stratification*

- **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

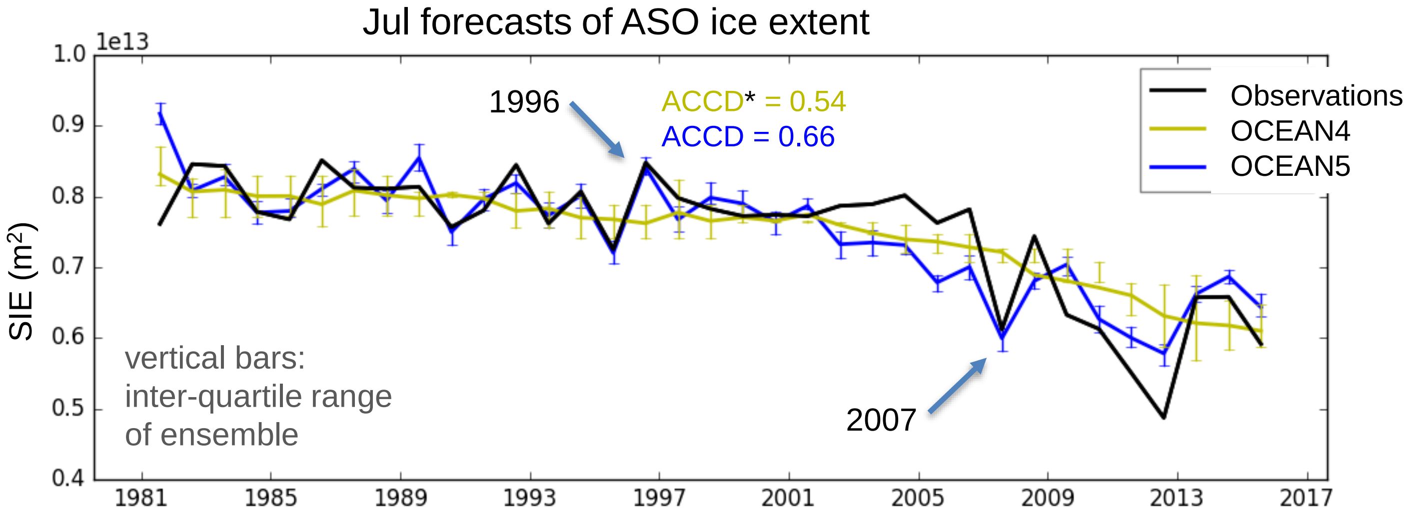
Atmospheric impact

Near-surface atmospheric impact in weather predictions



Day et al. (2022)

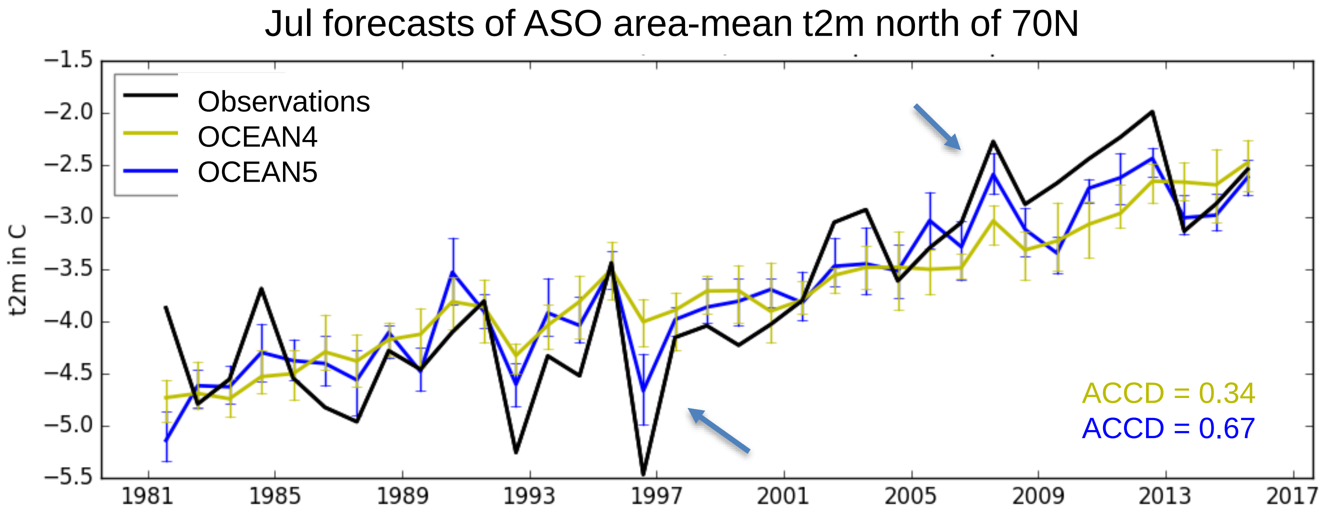
Summer Arctic surface air temperature and sea ice: seasonal forecasts


Jul forecasts of ASO ice extent

ACCD* = 0.54
ACCD = 0.66

vertical bars:
inter-quartile range
of ensemble

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


Jul forecasts of ASO area-mean t2m north of 70N

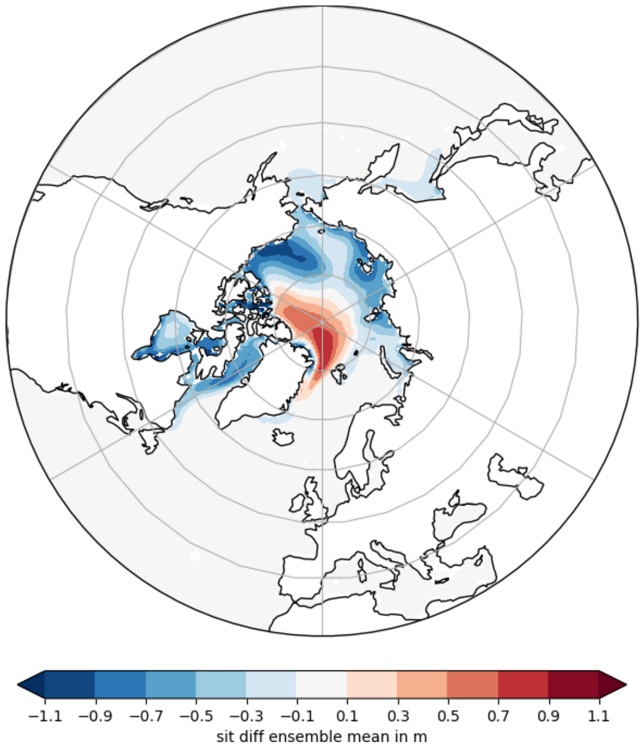
ACCD = 0.34
ACCD = 0.67

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

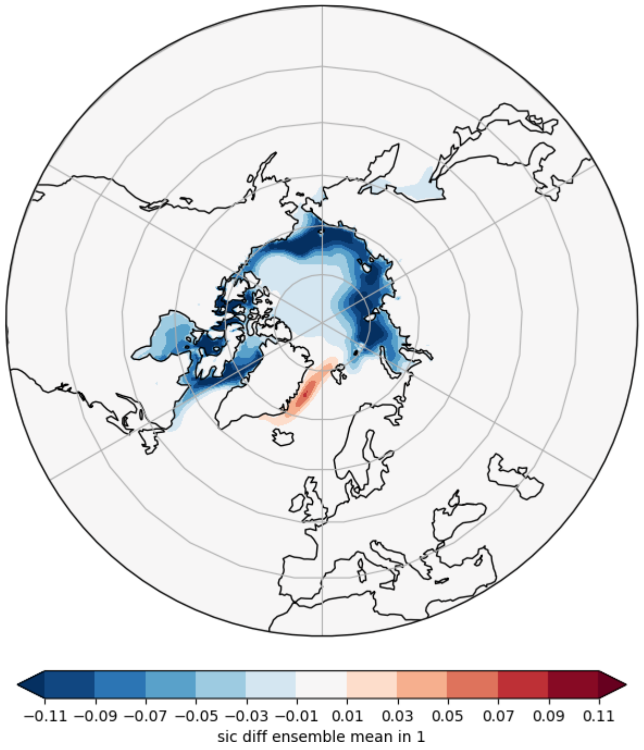
* ACCD: anomaly correlation of detrended time series

Spring sea-ice thickness impacts autumn surface temperatures

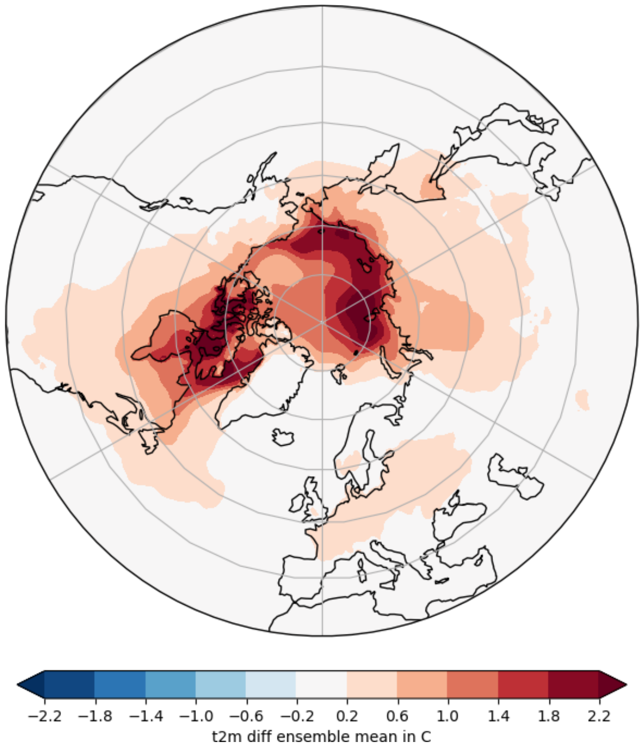
SIT difference in initial conditions
(Mar-Jun)



SIC difference after six months
(Sep-Dec)



t2m difference after six months
(Sep-Dec)



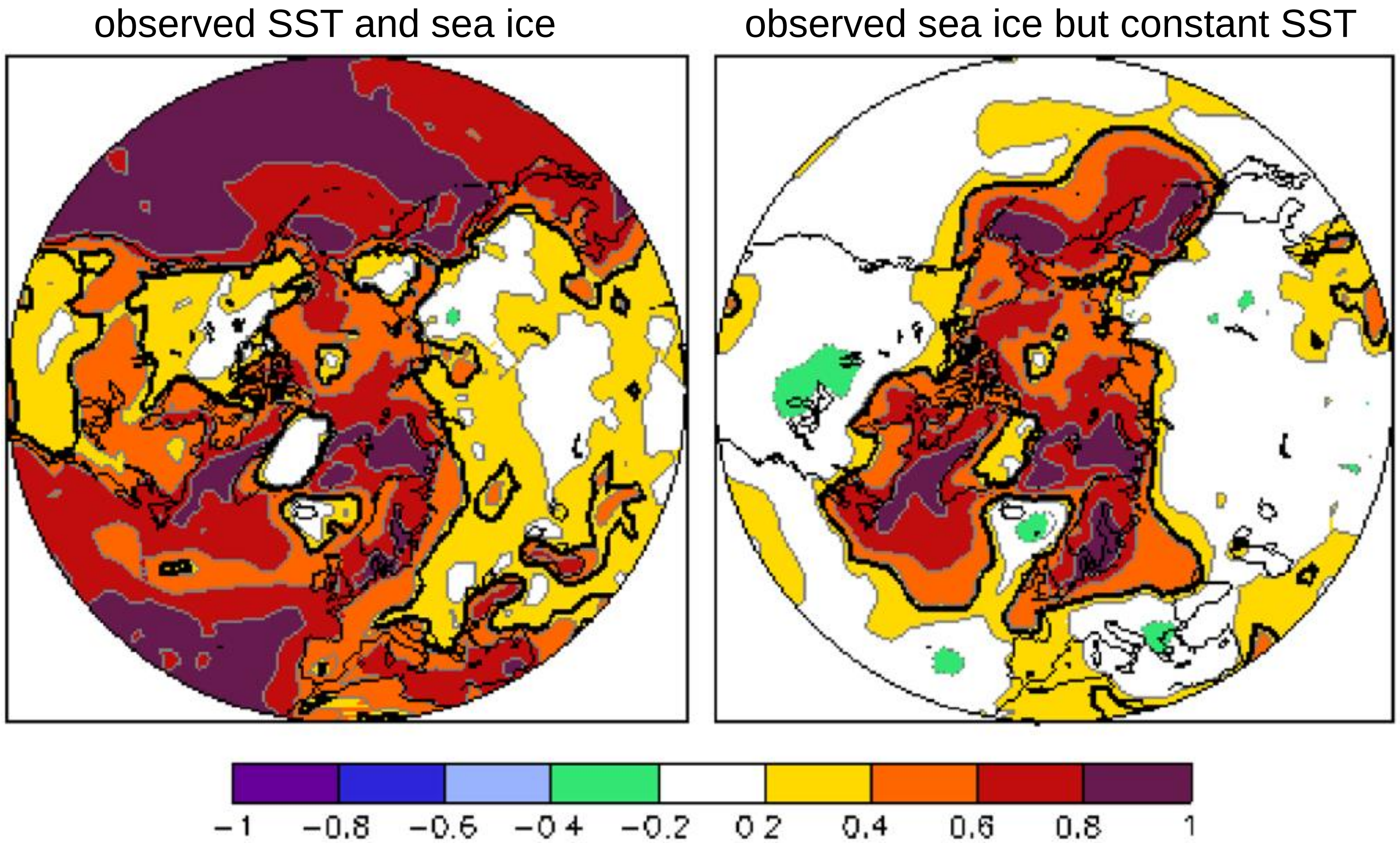
Numerical experiments with ORAS5/SEAS5:
winter-time only CS2SMOS initialization *reduces seasonal ice thickness* by up to 1m

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

Balan-Sarojini et al. (2021)

Winter impact of sea ice on winter surface air temperature

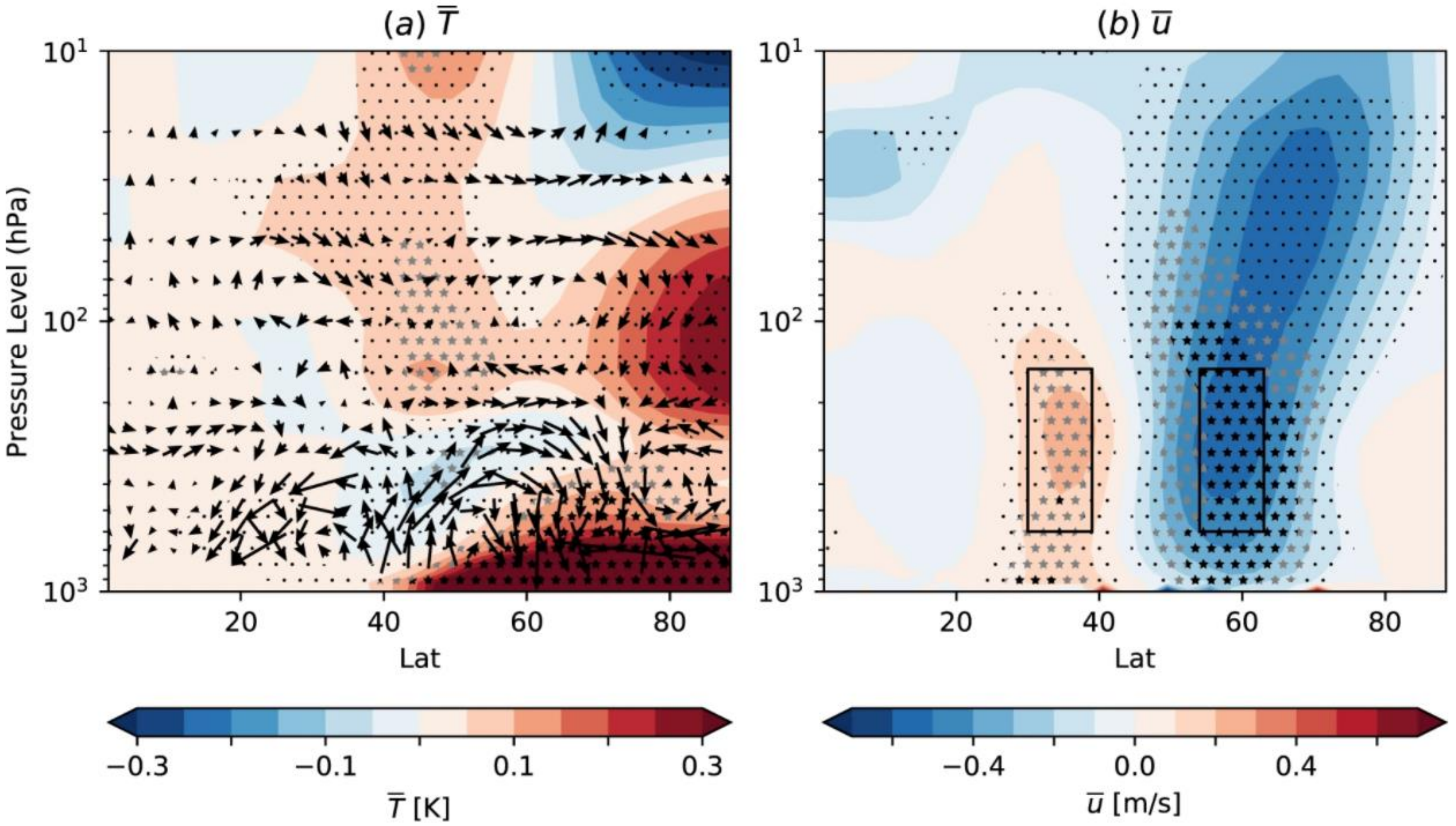
Correlation of DJF SAT with reanalysis in atmosphere-only simulations (1982-2014):



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



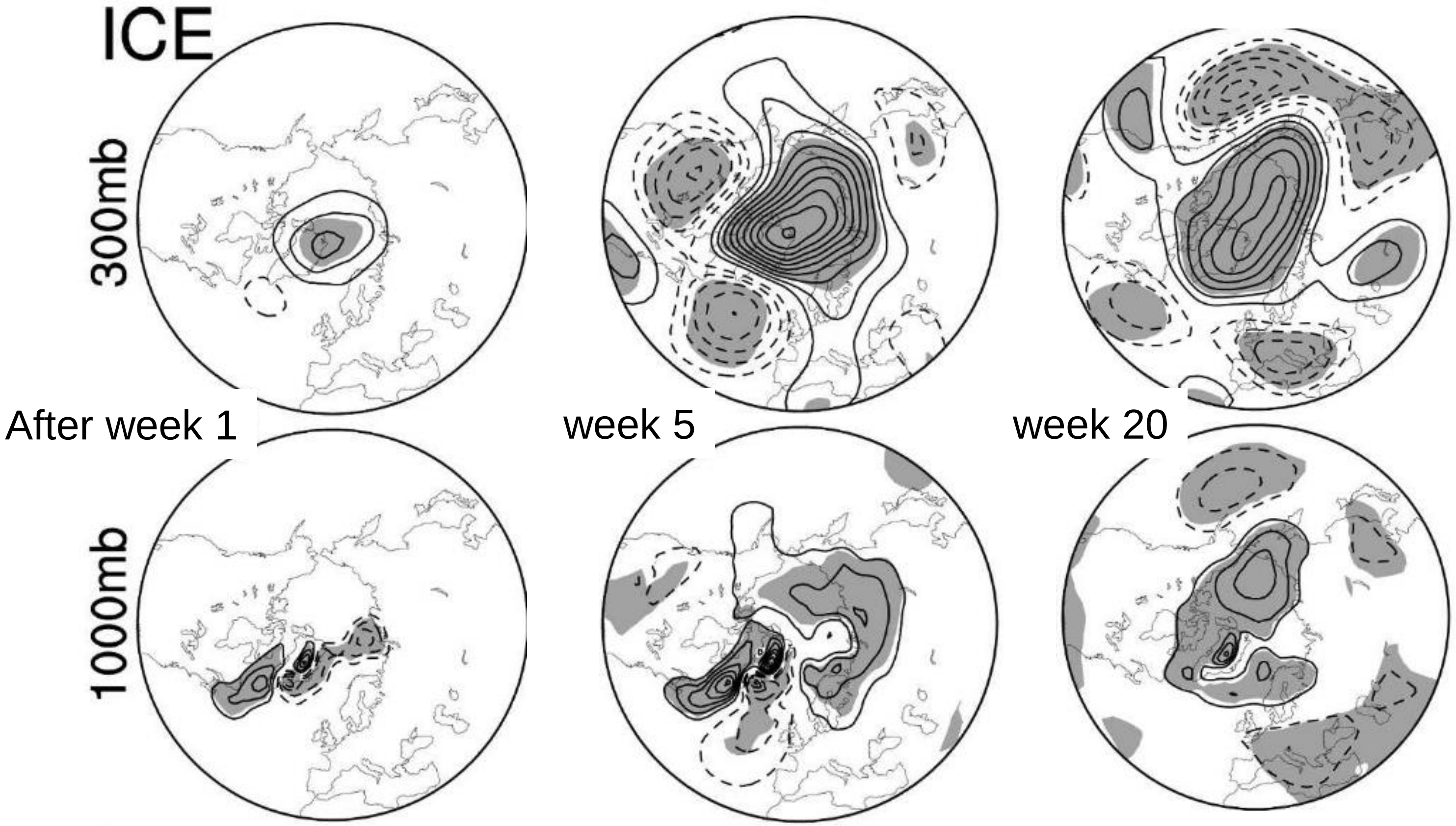
Multi-model response in zonal-mean temperature and zonal wind to sea ice changes for a 2C warmer climate (CMIP6 PAMIP experiments)

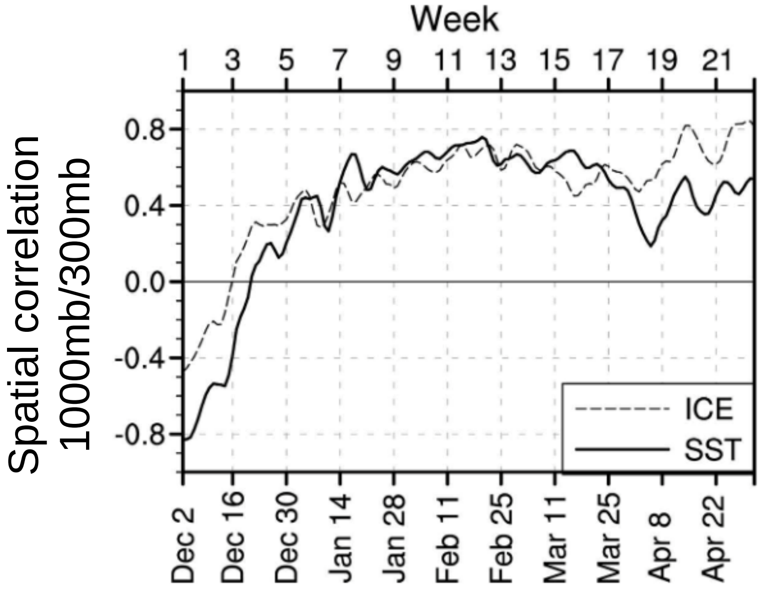
Smith et al. (2022)

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)



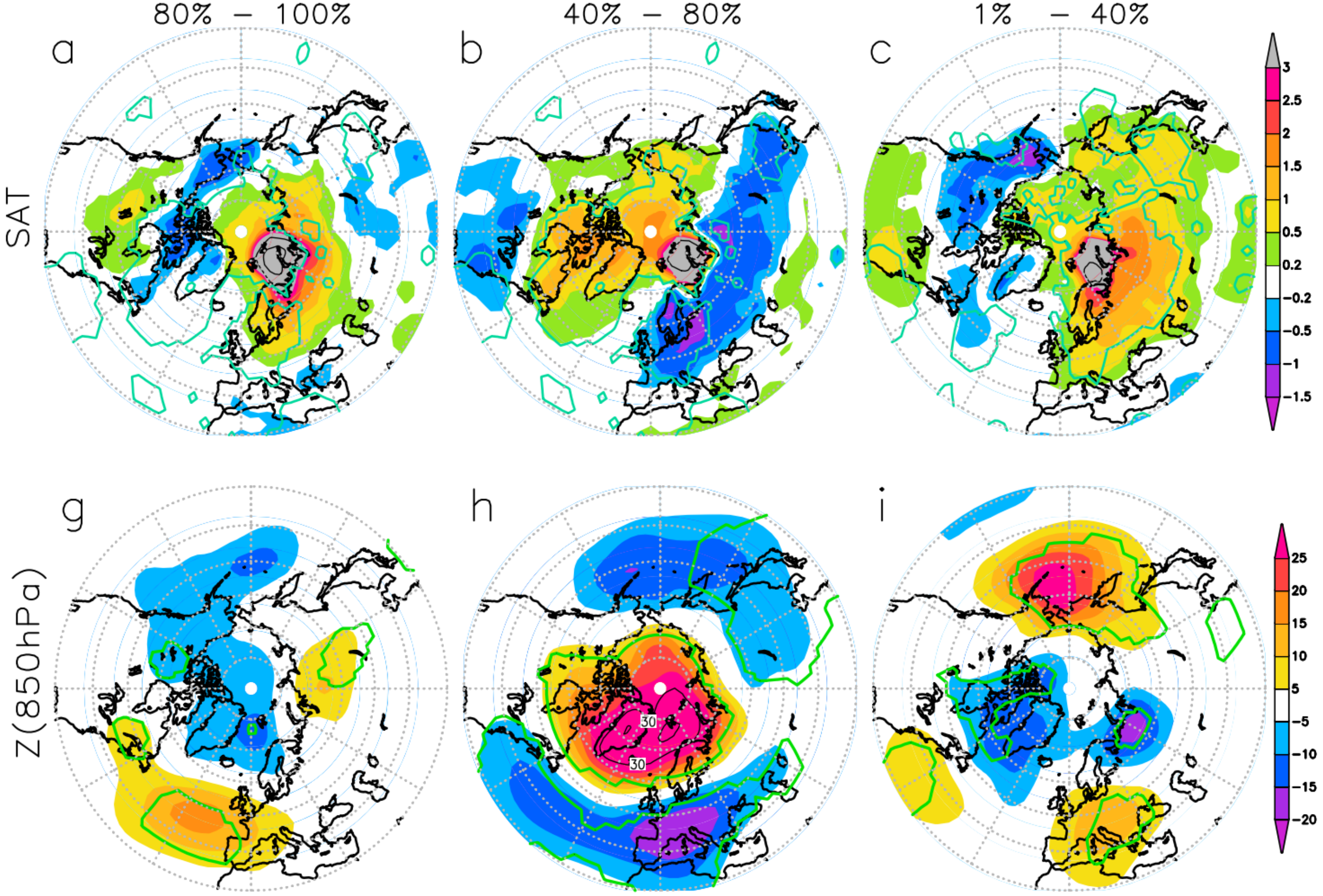


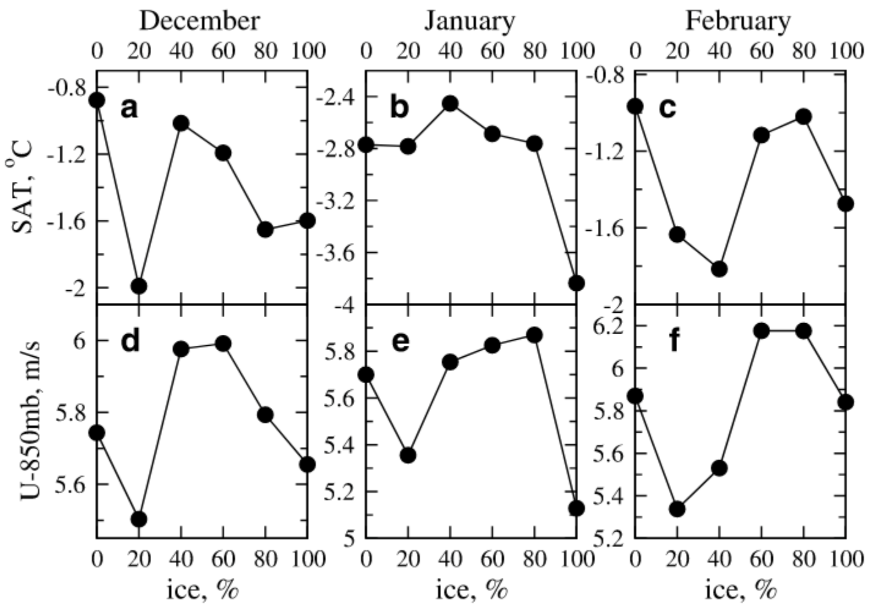
- *Numerical experiments* forcing the atmosphere with the dominant mode of sea-ice variability & climate change in the NH
- *Fast response*: local and baroclinic
- *Equilibrium response*: hemispheric and barotropic

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

Deser et al. (2007)

Caveat II: atmospheric impact is non-linear



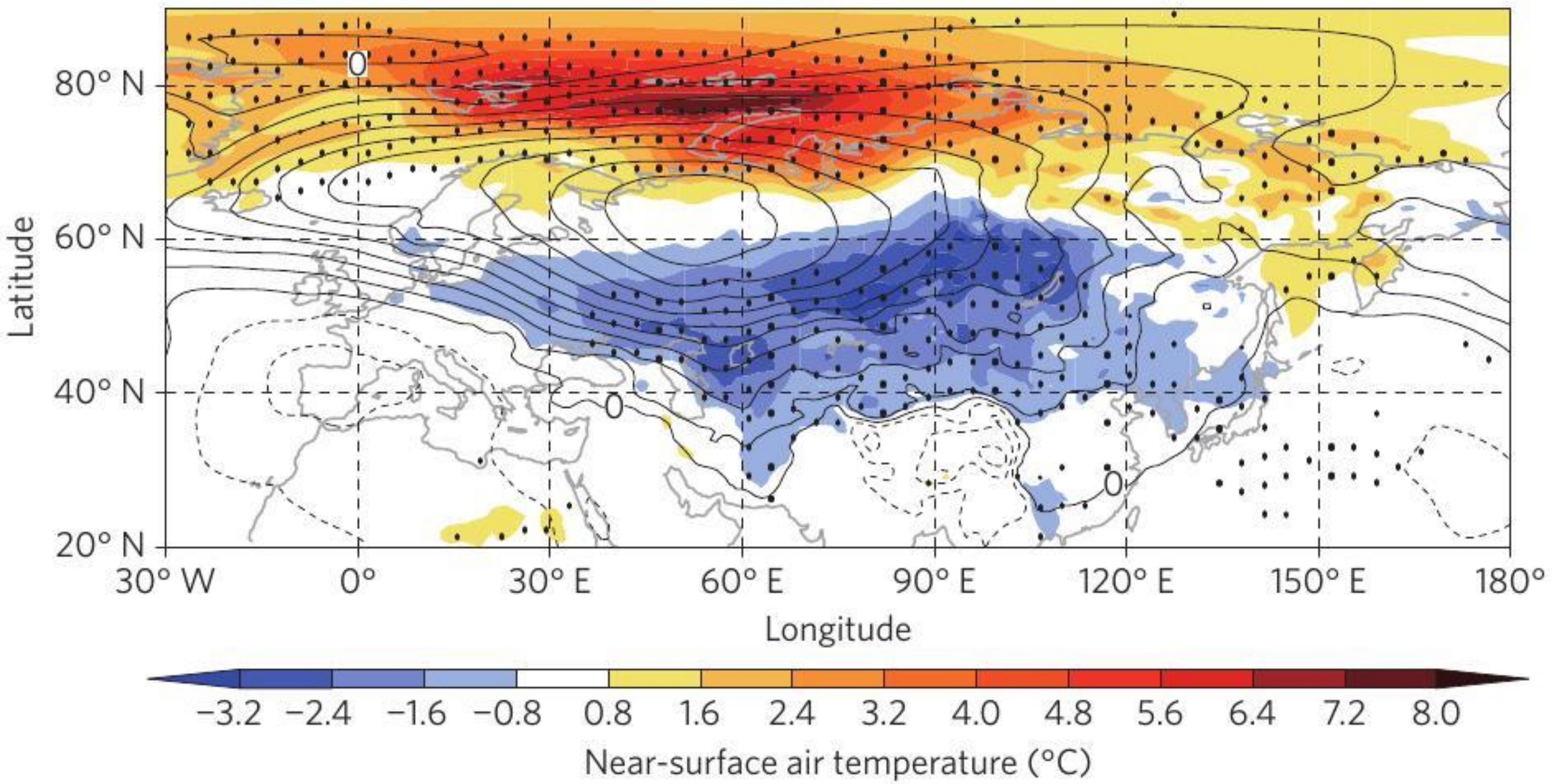


Petoukhov et al. (2010):
Numerical experiments forcing atmosphere with reduced sea ice in Barents Sea

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



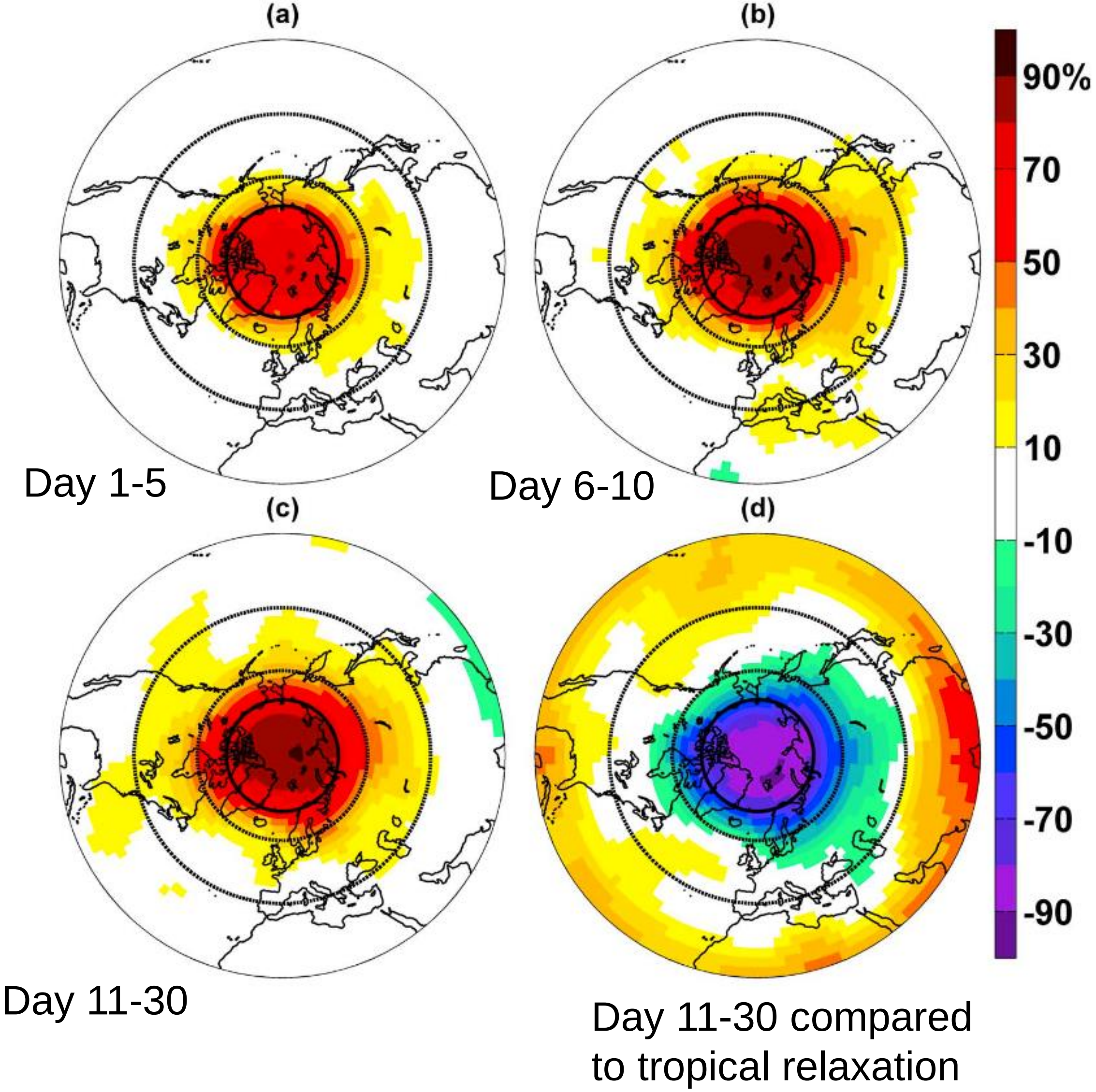
Composite of DJF 2m temperature difference between years with low and high sea-ice cover in the Barents and Kara Seas (1979-2013)

→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



Day 1-5

Day 6-10

Day 11-30

Day 11-30 compared to tropical relaxation

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)

Sea ice atmospheric impact in a nutshell

1. Strong and fast impact on lower atmosphere (local heating)
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

References

- Balan-Sarojini, B., Tietsche, S., Mayer, M., Balmaseda, M., Zuo, H., De Rosnay, P., Stockdale, T., & Vitart, F. (2021). Year-round impact of winter sea ice thickness observations on seasonal forecasts. *Cryosphere*, *15*(1), 325–344. https://doi.org/10.5194/tc-15-325-2021
- Blackport, R., Screen, J. A., van der Wiel, K., & Bintanja, R. (2019). Minimal influence of reduced Arctic sea ice on coincident cold winters in mid-latitudes. Nature Climate Change, 9(9), 697–704. https://doi.org/10.1038/s41558-019-0551-4
- Blanchard-Wrigglesworth, E., Armour, K. C., Bitz, C. M., & DeWeaver, E. (2011). Persistence and inherent predictability of Arctic sea ice in a GCM ensemble and observations. J. Climate, 24(1), 231–250. https://doi.org/10.1175/2010JCLI3775.1
- Chevallier, M., Massonnet, F., Goessling, H., Guémas, V., & Jung, T. (2019). The Role of Sea Ice in Sub-seasonal Predictability. In Sub-Seasonal to Seasonal Prediction (pp. 201–221). Elsevier. https://doi.org/10.1016/B978-0-12-811714-9.00010-3
- Day, J. J., S. Keeley, G. Arduini, L. Magnusson, K. Mogensen, M. Rodwell, I. Sandu, and S. Tietsche, 2022: Benefits and challenges of dynamic sea ice for weather forecasts. *Weather and Climate Dynamics*, **3**, 713–731, https://doi.org/10.5194/WCD-3-713-2022.
- Deser, C., Tomas, R. A., & Peng, S. (2007). The transient atmospheric circulation response to North Atlantic SST and sea ice anomalies. *Journal of Climate*, *20*(18), 4751–4767. https://doi.org/10.1175/JCLI4278.1
- Dirkson, A., Denis, B., & Merryfield, W. J. (2019). A Multimodel Approach for Improving Seasonal Probabilistic Forecasts of Regional Arctic Sea Ice. Geophysical Research Letters, 46(19), 10844–10853. https://doi.org/10.1029/2019GL083831
- Jung, T., M. A. Kasper, T. Semmler, and S. Serrar, 2014: Arctic influence on subseasonal mid-latitude Prediction. *Geophysical Research Letters*, **41**, 3676–3680, https://doi.org/10.1002/2014GL059961.
- Guemas, V., Blanchard-Wrigglesworth, E., Chevallier, M., Day, J. J., Déqué, M., Doblas-Reyes, F. J., … Tietsche, S. (2014). A review on Arctic sea-ice predictability and prediction on seasonal to decadal time-scales. Quarterly Journal of the Royal Meteorological Society, 142(695), n/a-n/a. https://doi.org/10.1002/qj.2401
- Smith, D. M., Eade, R., Andrews, M. B., Ayres, H., Clark, A., Chripko, S., Deser, C., Dunstone, N. J., García-Serrano, J., Gastineau, G., Graff, L. S., Hardiman, S. C., He, B., Hermanson, L., Jung, T., Knight, J., Levine, X., Magnusdottir, G., Manzini, E., … Walsh, A. (2022). Robust but weak winter atmospheric circulation response to future Arctic sea ice loss. *Nature Communications 2022 13:1*, *13*(1), 1–15. https://doi.org/10.1038/s41467-022-28283-y
- Koenigk, T., Gao, Y., Gastineau, G., Keenlyside, N., Nakamura, T., Ogawa, F., … Yang, S. (2019). Impact of Arctic sea ice variations on winter temperature anomalies in northern hemispheric land areas. Climate Dynamics, 52(5–6), 3111–3137. https://doi.org/10.1007/s00382-018-4305-1
- Mori, M., Watanabe, M., Shiogama, H., Inoue, J., & Kimoto, M. (2014). Robust Arctic sea-ice influence on the frequent Eurasian cold winters in past decades. Nature Geoscience, 7(12), 869–873. https://doi.org/10.1038/ngeo2277
- Overland, J. E., Dethloff, K., Francis, J. A., Hall, R. J., Hanna, E., Kim, S. J., Screen, J. A., Shepherd, T. G., & Vihma, T. (2016). Nonlinear response of mid-latitude weather to the changing Arctic. In *Nature Climate Change* (Vol. 6, Issue 11, pp. 992–999). Nature Publishing Group. https://doi.org/10.1038/nclimate3121
- Petoukhov, V., & Semenov, V. A. (2010). A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents. *Journal of Geophysical Research*, *115*(D21), D21111. https://doi.org/10.1029/2009JD013568
- Strong, C., Magnusdottir, G., & Stern, H. (2009). Observed Feedback between Winter Sea Ice and the North Atlantic Oscillation. Journal of Climate, 22(22), 6021–6032. https://doi.org/10.1175/2009JCLI3100.1
- Tietsche, S., Notz, D., Jungclaus, J. H., & Marotzke, J. (2013). Predictability of large interannual Arctic sea-ice anomalies. Climate Dynamics, 41(9), 2511–2526. https://doi.org/10.1007/s00382-013-1698-8
- Zampieri, L., Goessling, H. F., & Jung, T. (2018). Bright Prospects for Arctic Sea Ice Prediction on Subseasonal Time Scales. Geophysical Research Letters, 45(18), 9731–9738. https://doi.org/10.1029/2018GL079394