How can we improve the prediction of decadal trends in Antarctic sea ice extent ?

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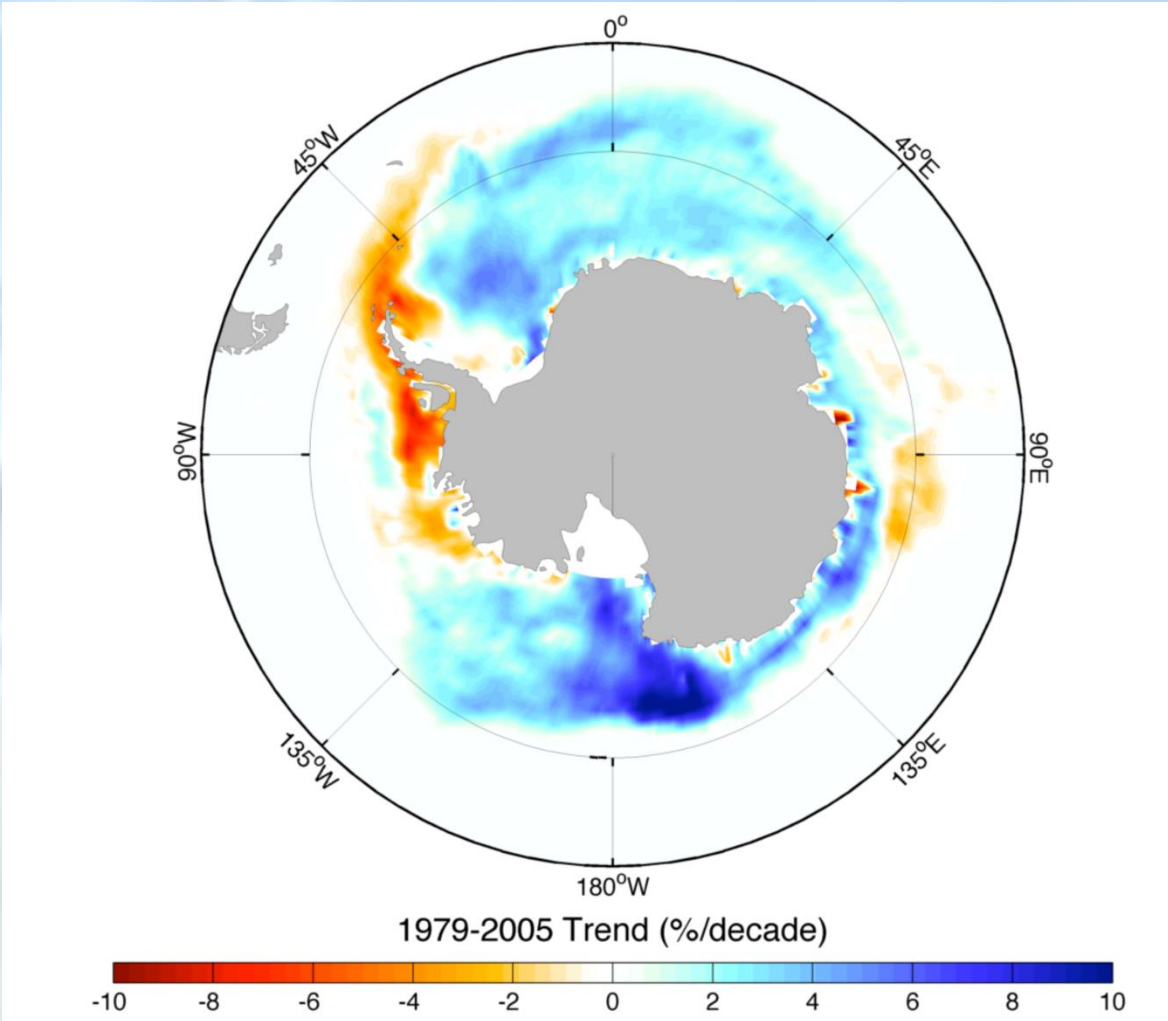
Sea ice changes over the last decades

Observed trend in sea ice concentration over the period 1978-2010 (data from NSIDC)



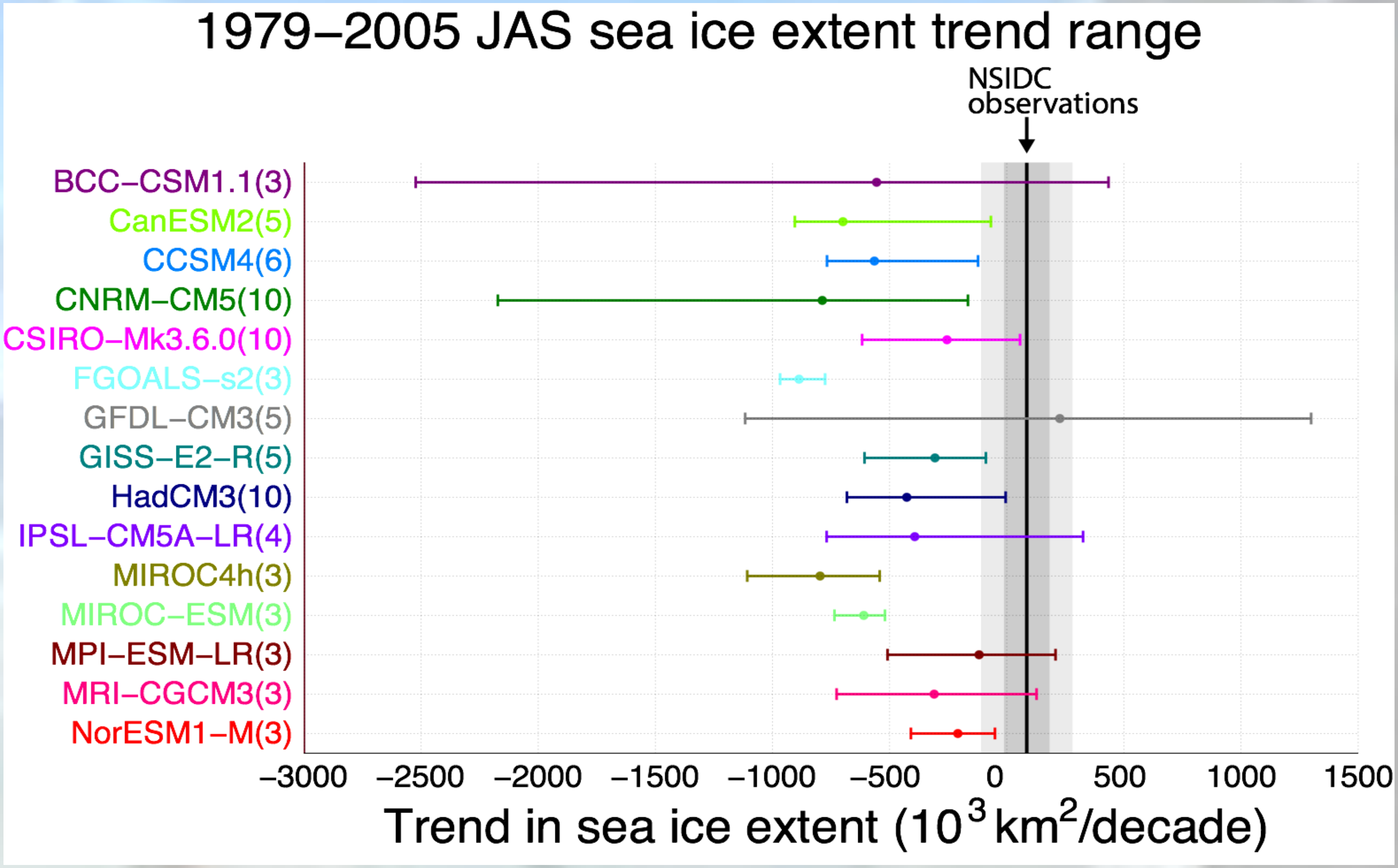
Satellite observations indicate a **significant positive sea ice extent trend** of 1.7 $10^5 \pm 2\ 10^4$ km^2 per decade in the Southern Ocean for the period November 1978–December 2010, (Cavalieri and Parkinson, 2012).

What is the origin of this trend ?

Are models able to reproduce it ?

Sea ice changes over the last decades

Among the members of the CMIP5 ensemble,
only a few display a positive trend in sea ice extent.



Sea ice changes over the last decades

•The simulated trends are marginally compatible with the observed trend.

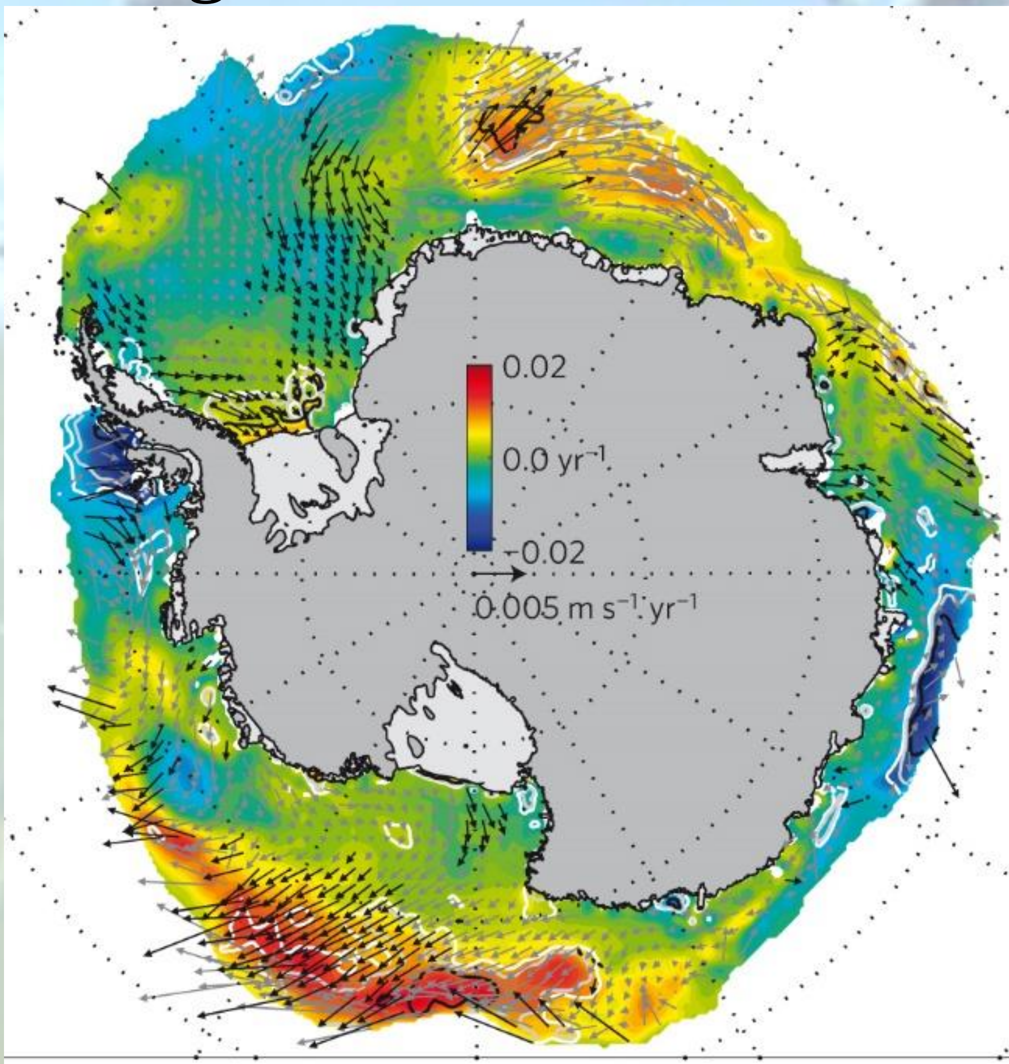
•Forced response: decreasing trend for the ensemble mean

•Strong contribution of internal variability ?

The conclusions based on model results must be taken with caution because of the large biases in the Southern Ocean.

Mechanisms responsible for the trend

Changes in ice concentration are linked to wind-driven changes in ice motion

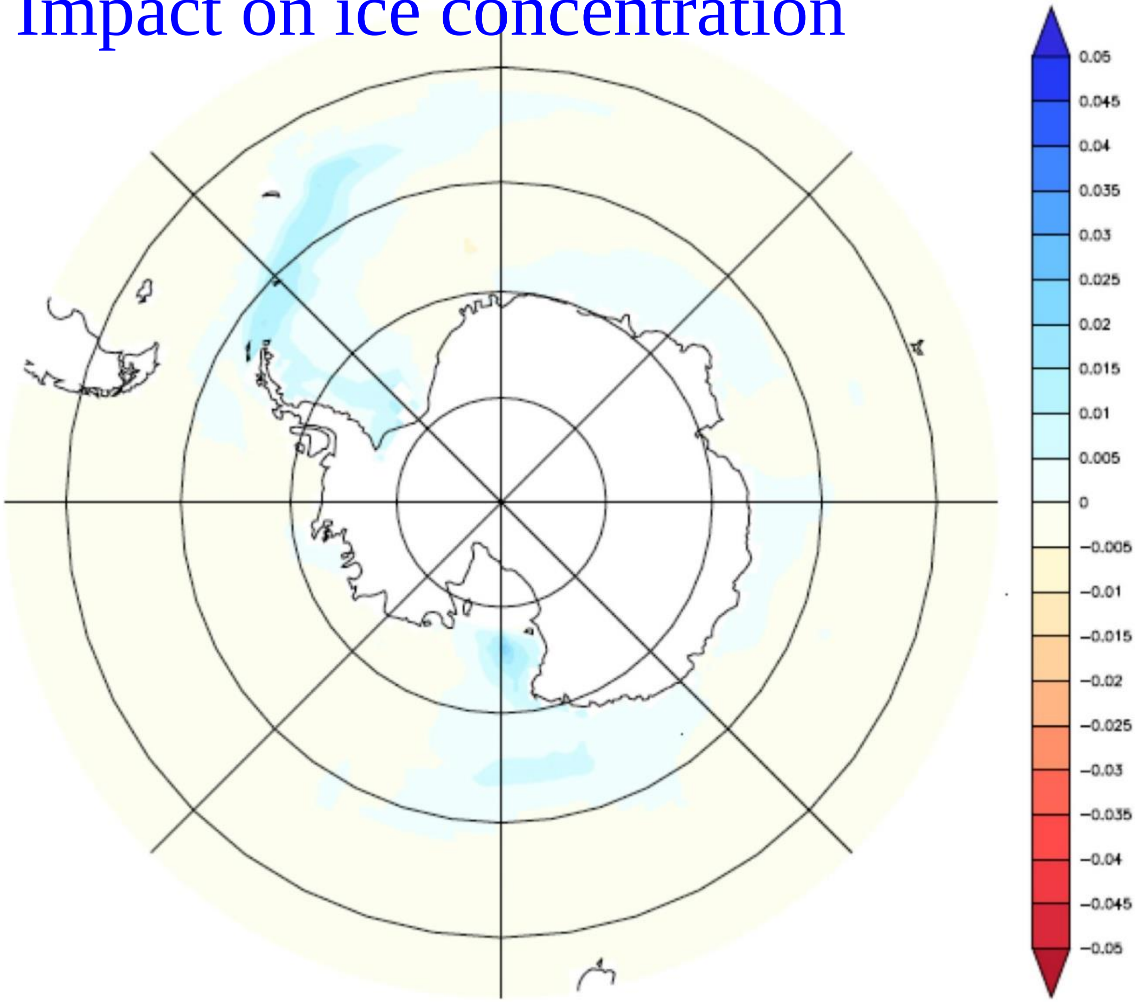


Autumn (April–June) ice-motion trend vectors over 1992–2010 overlaid on ice-concentration trends (Holland and Kwok, 2012).

Mechanisms responsible for the trend

Additional “forcing” : meltwater input

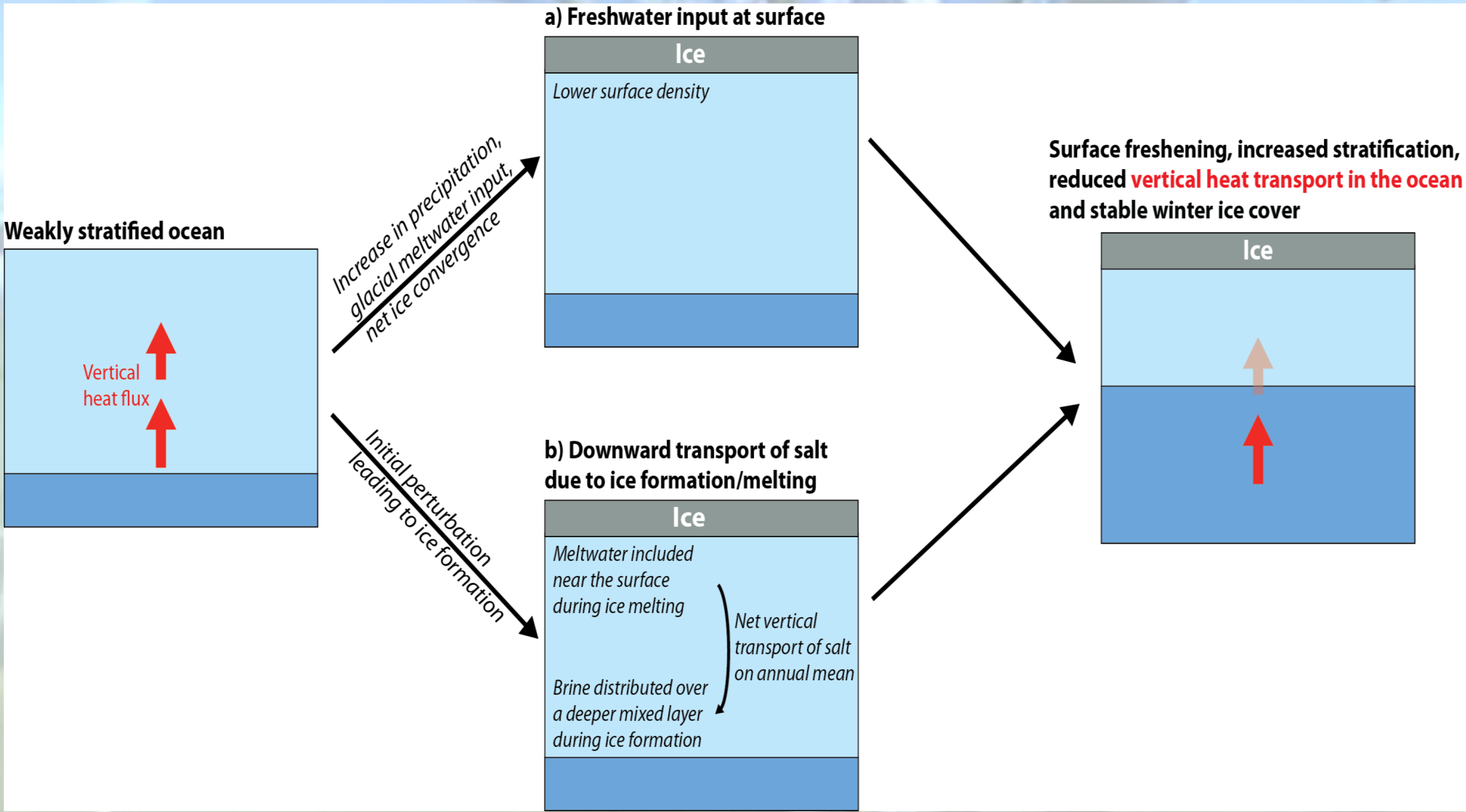
Impact on ice concentration



Spatial distribution of the annual mean change in sea ice fraction difference between an increased meltwater sensitivity experiment and the control run in EC-Earth (Bintanja et al., 2013).

Mechanisms responsible for the trend

Key role of ice-ocean interactions



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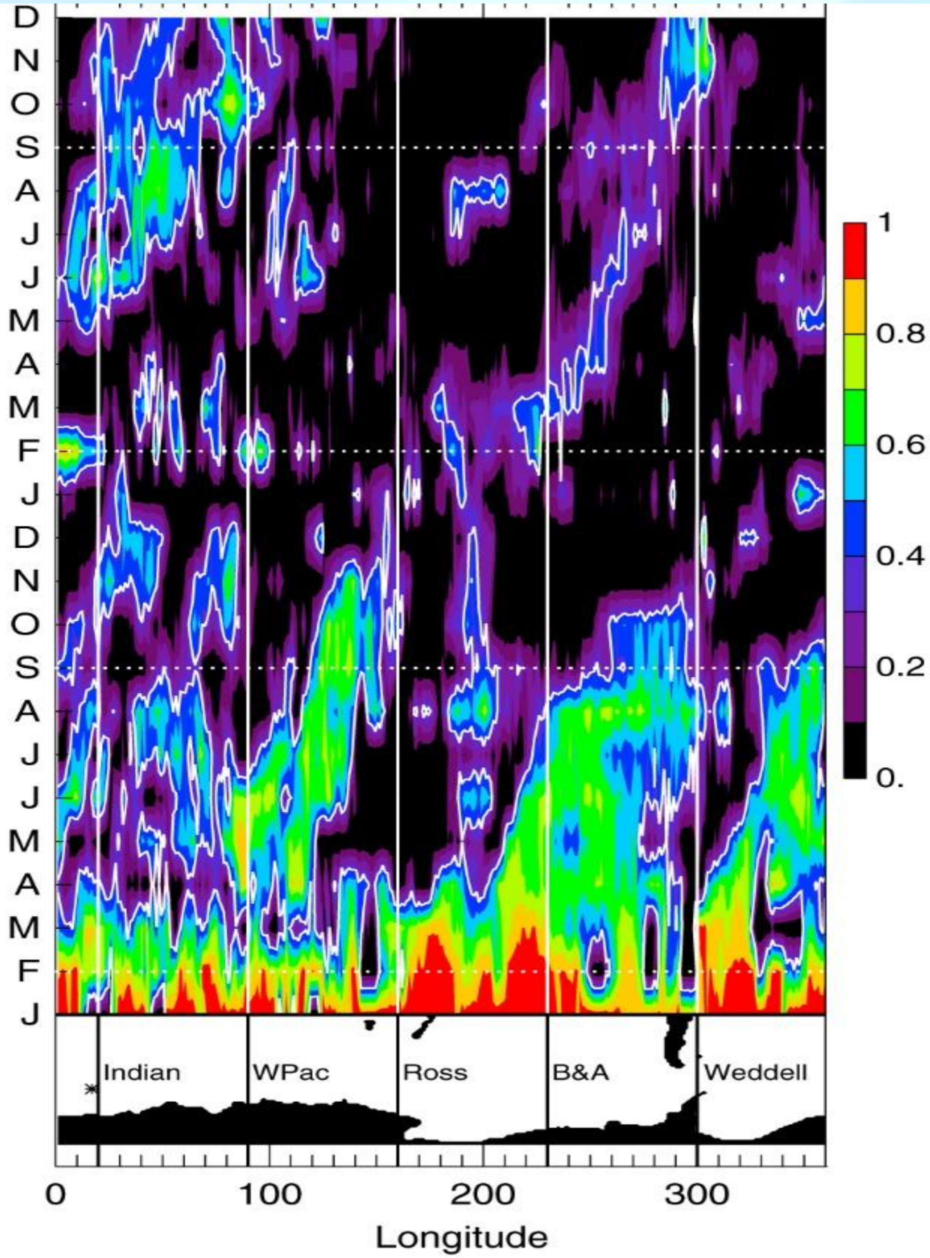
Predicting interannual variations

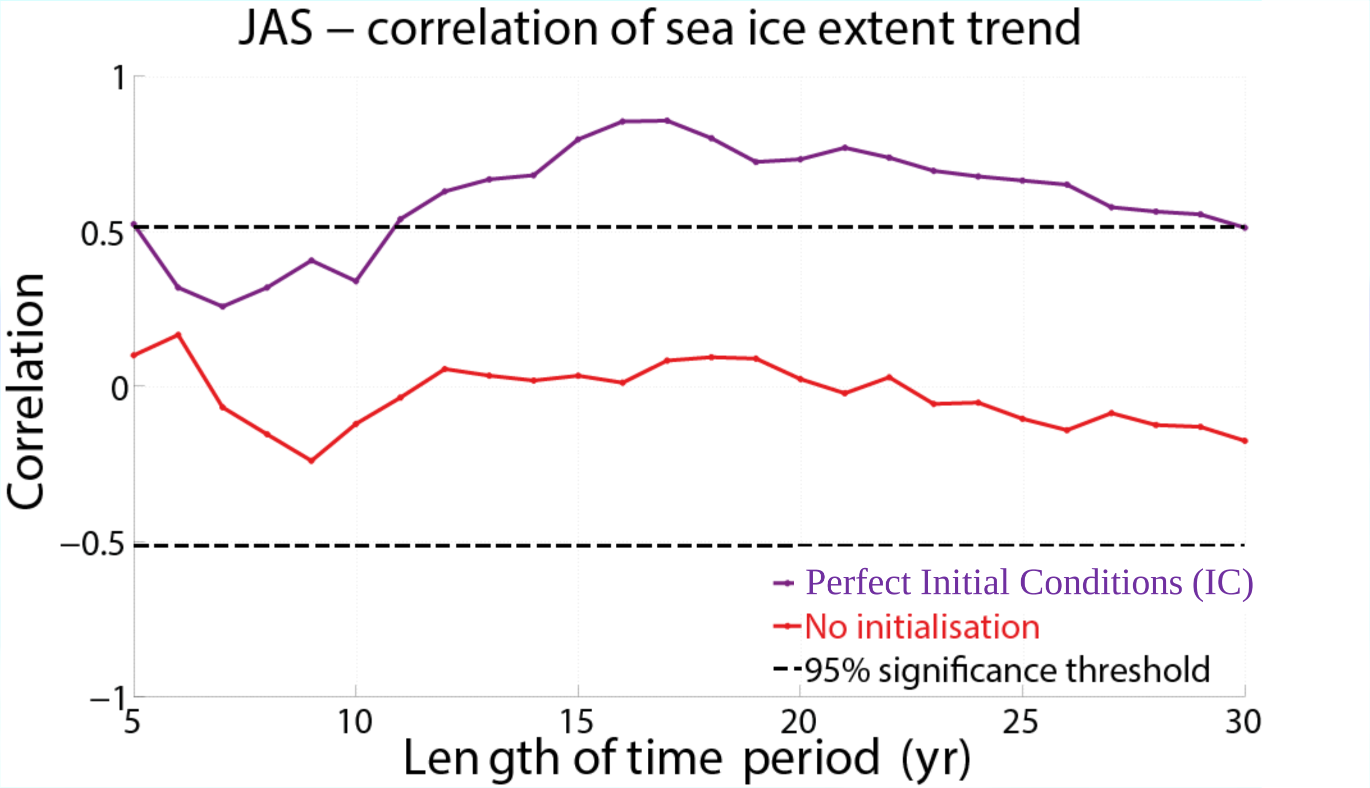


Potential predictability of the ice edge location in experiments performed with CCSM3 (Holland et al., 2003).

Predicting decadal trends

Predictions initialized from pseudo observations with the EMIC LOVECLIM

Correlation between the trend in winter sea ice extent in hindcasts and pseudo-observations



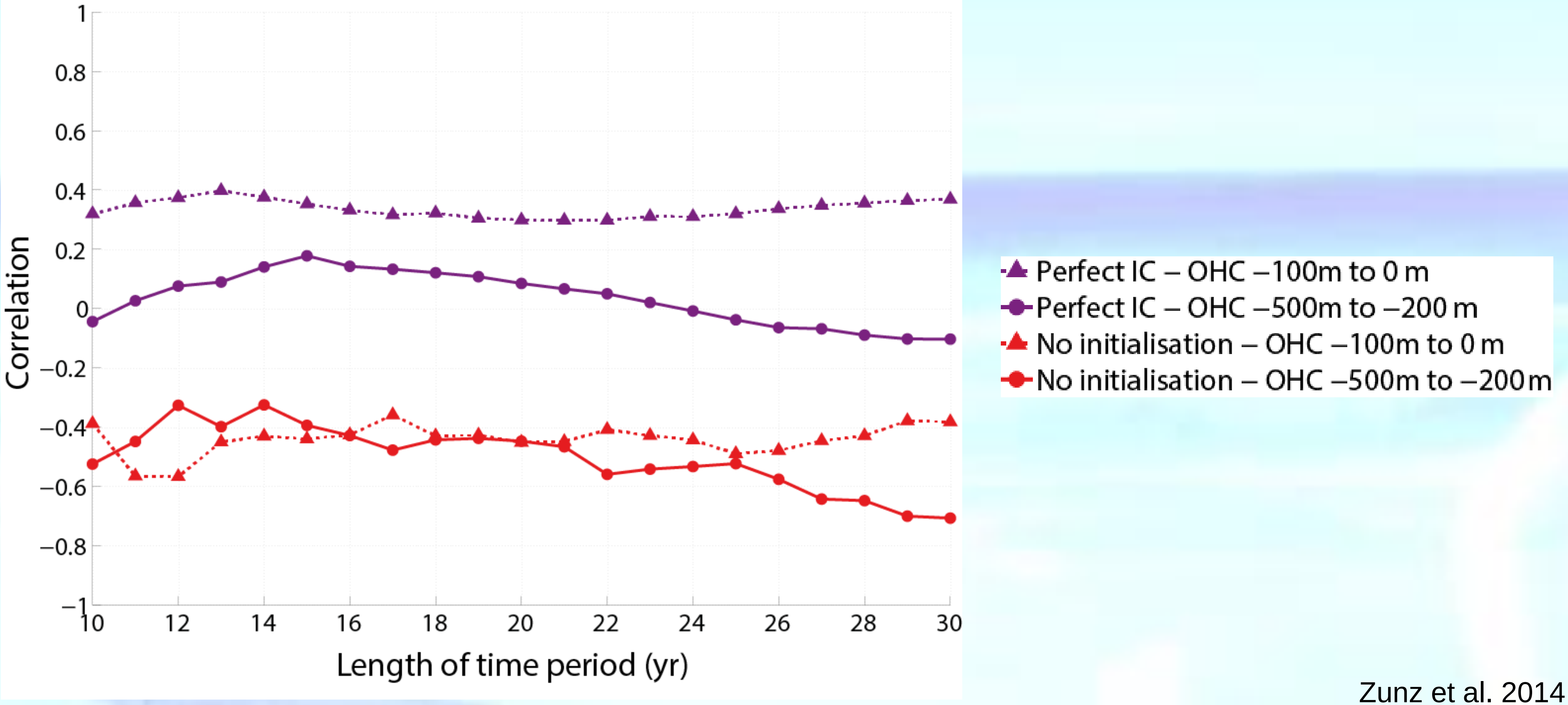
Statistically significant correlation for the 10- to 30-year trend.

Zunz et al. 2014

Predicting decadal trends

Predictions initialized from pseudo observations: skill comes from ocean initialization.

Correlation between the trend in sea ice extent in JAS from hindcasts and the ocean heat content (OHC) in the last year before the beginning of the hindcasts in pseudo-observations



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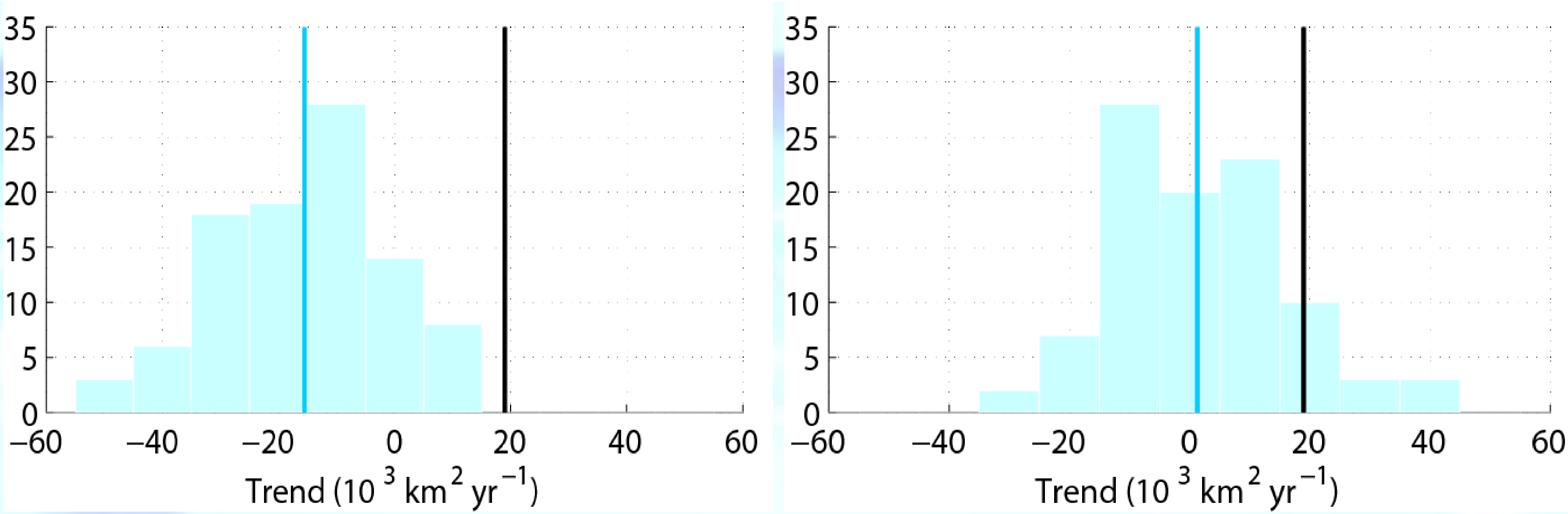
Predicting trends over the last 30 years

Simulations initialized from an ensemble of 96 simulations with LOVECLIM using a nudging Particle Filter

1980–2009 trend in annual mean sea ice extent

Non-initialized hindcast — Initialized hindcast (STD)



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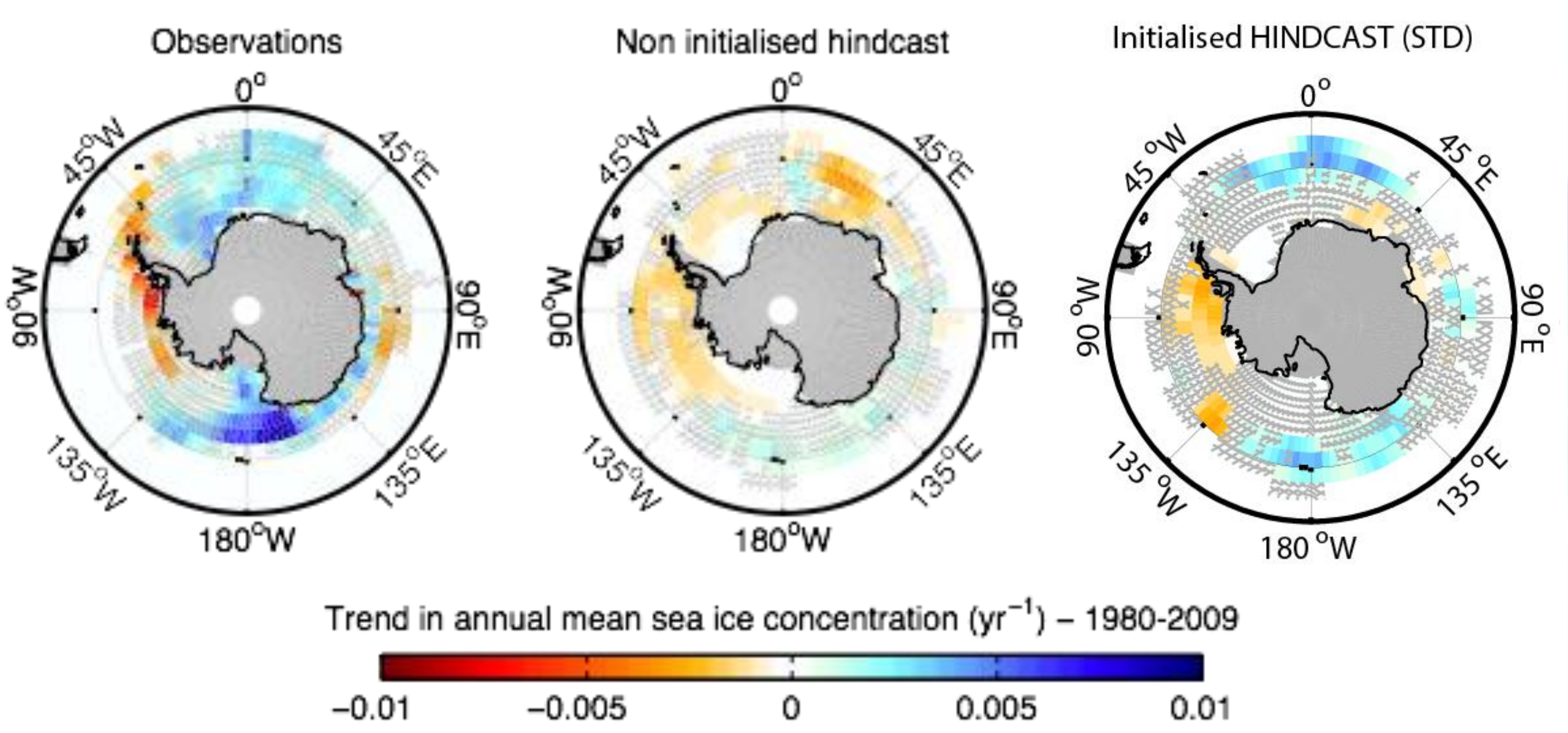
Trend in annual mean sea ice concentration 1980-2009



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Predicting trends over the last 30 years

Simulations initialized from an ensemble of 96 simulations with LOVECLIM using a nudging Particle Filter

Including a (diagnosed) freshwater input is needed to obtain adequate initial conditions but not required during the hindcast.

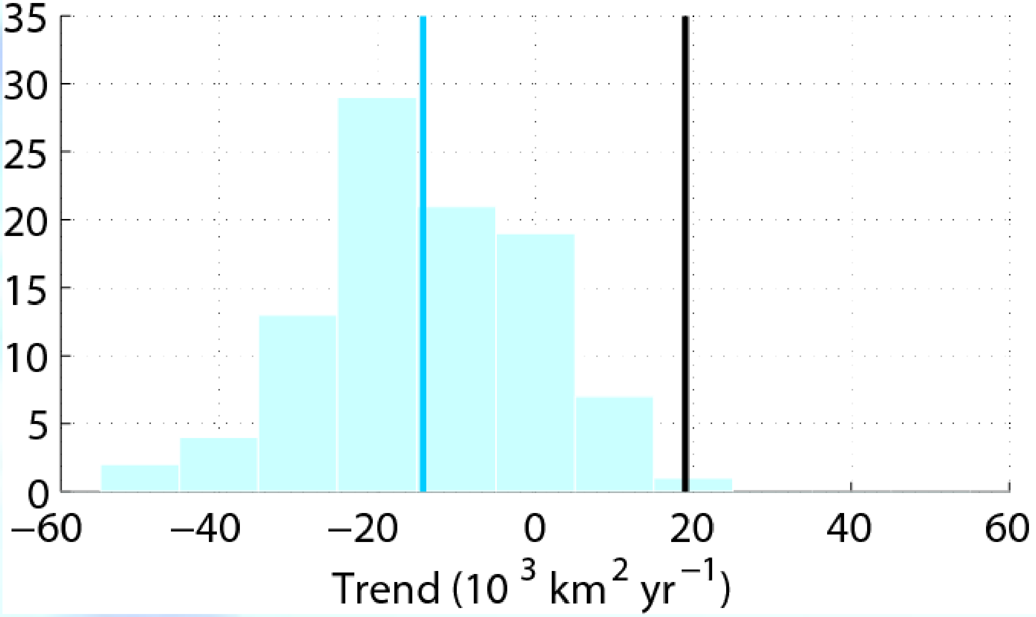
Zunz and Goosse 2014

Predicting trends over the last 30 years

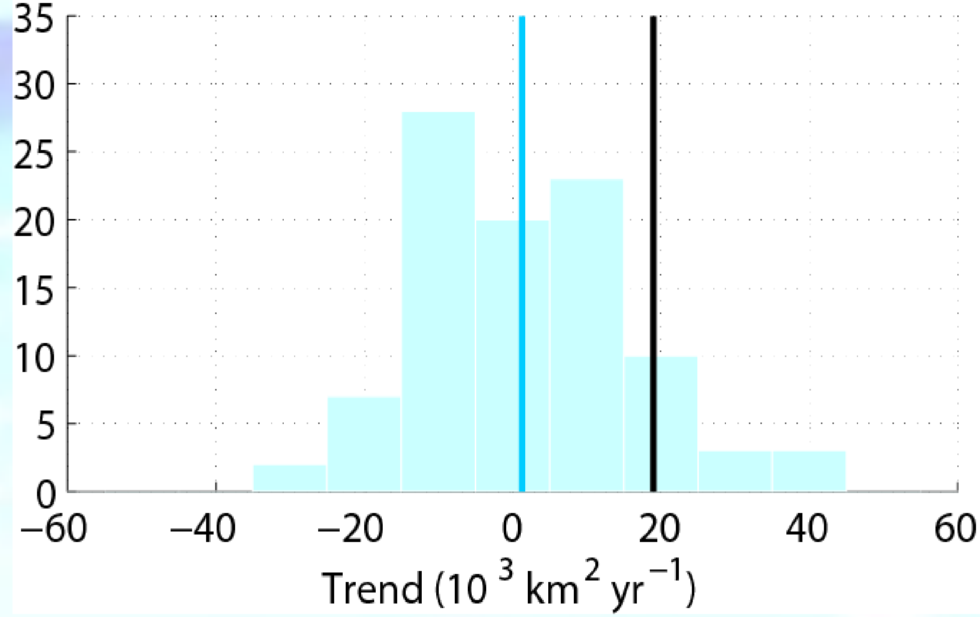
Simulations initialized from an ensemble of 96 simulations with LOVECLIM using a nudging Particle Filter

1980–2009 trend in annual mean sea ice extent in hindcasts initialized from a simulation with data assimilation

without perturbation of the freshwater flux before 1980



with a perturbation of the freshwater flux before 1980 (STD)



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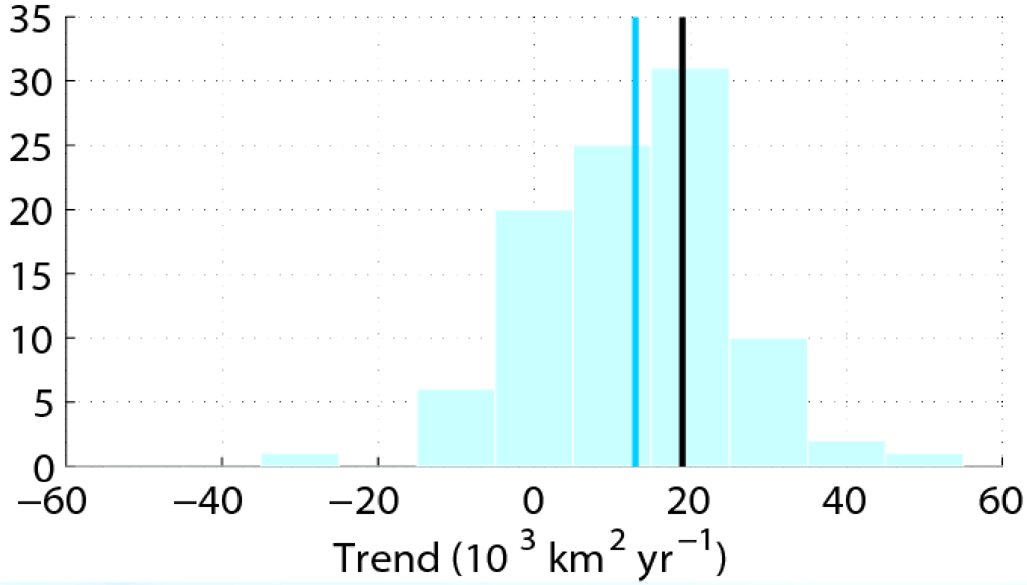
Predicting trends over the last 30 years

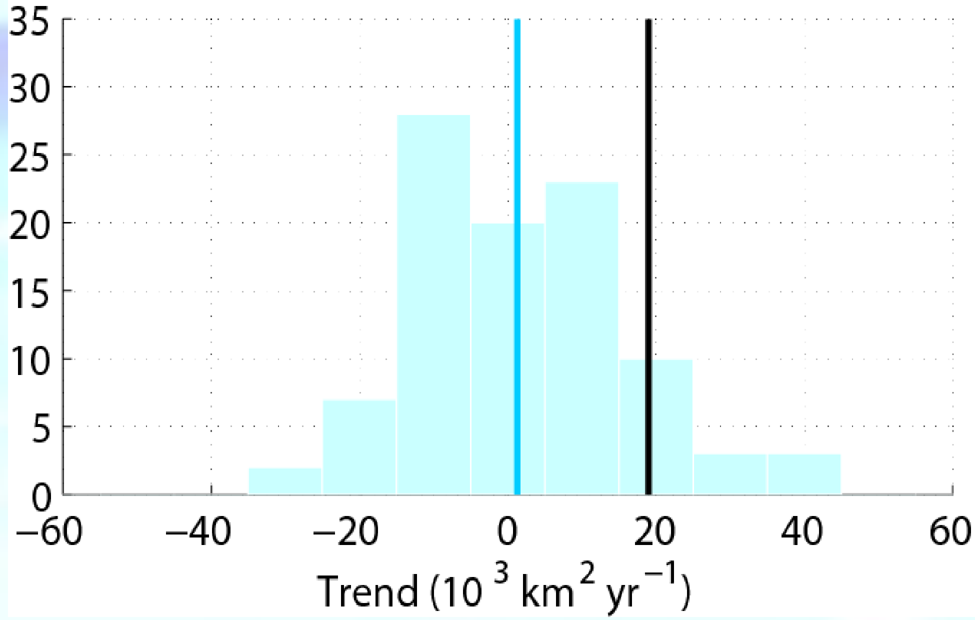
Simulations initialized from an ensemble of 96 simulations with the EMIC LOVECLIM using a nudging Particle Filter

1980–2009 trend in annual mean sea ice extent in hindcasts initialized from a simulation with DA including freshwater perturbation

with additional freshwater flux during the hindcast



without additional freshwater flux during the hindcast (STD)



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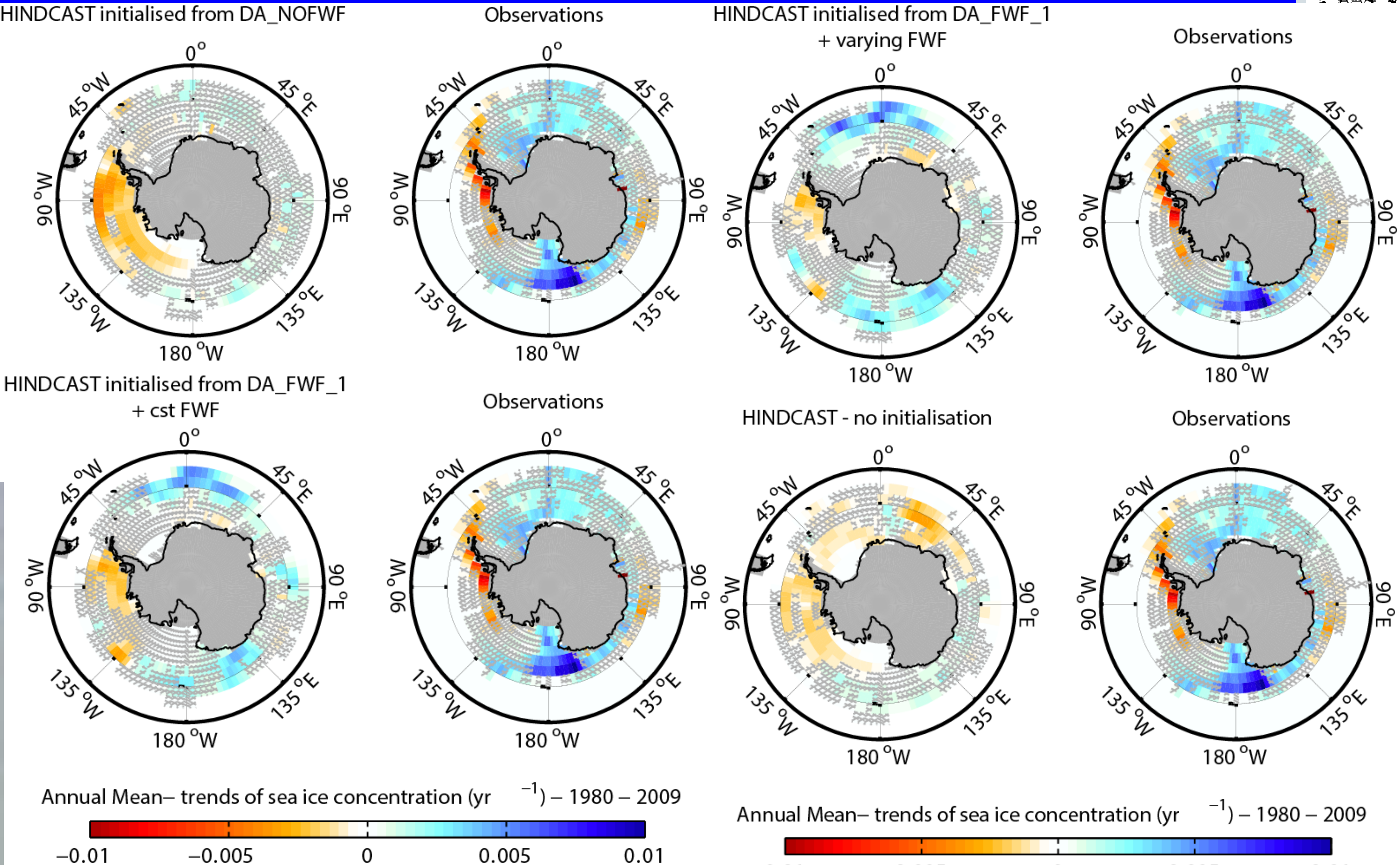
Conclusions

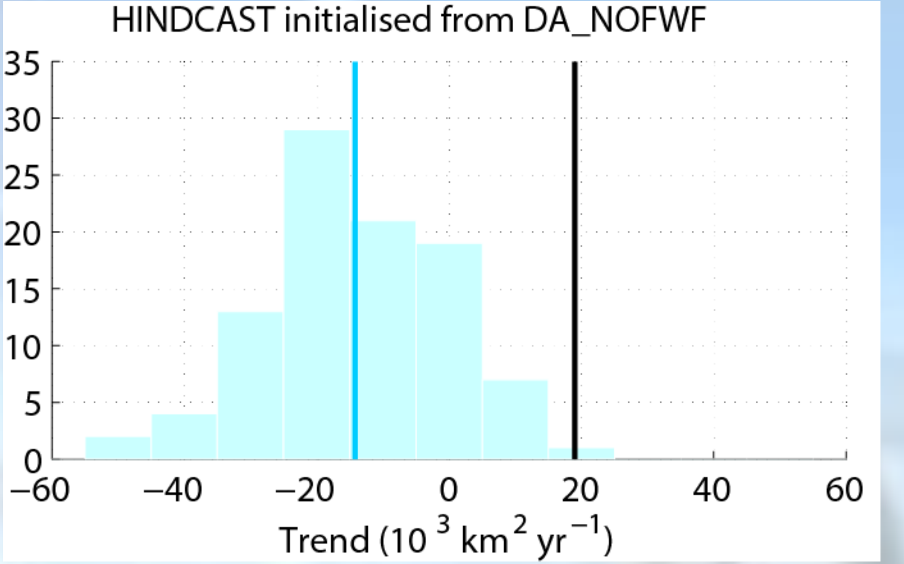
How can we improve the prediction of decadal trends in Antarctic sea ice extent ?

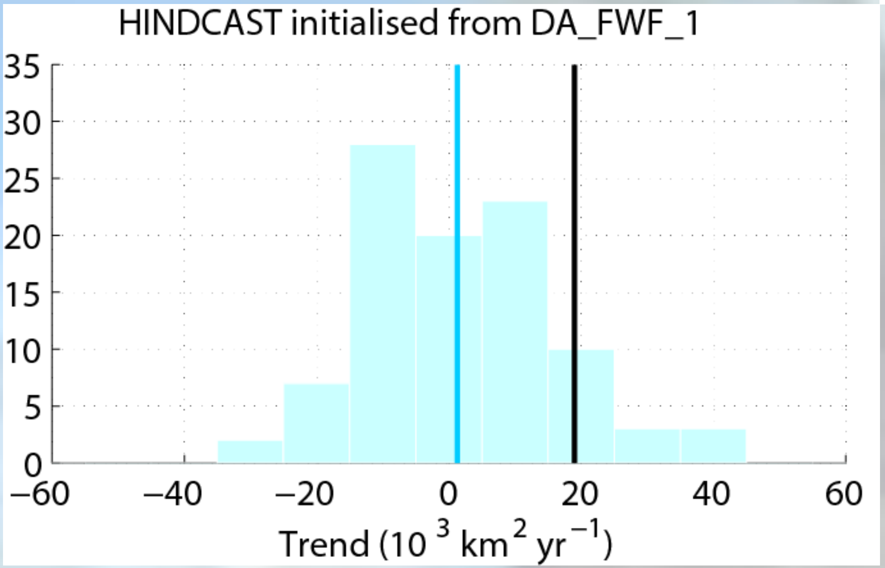
- Predict the meltwater input ?
- Initialize adequately the surface and intermediate layers in the Southern Ocean.

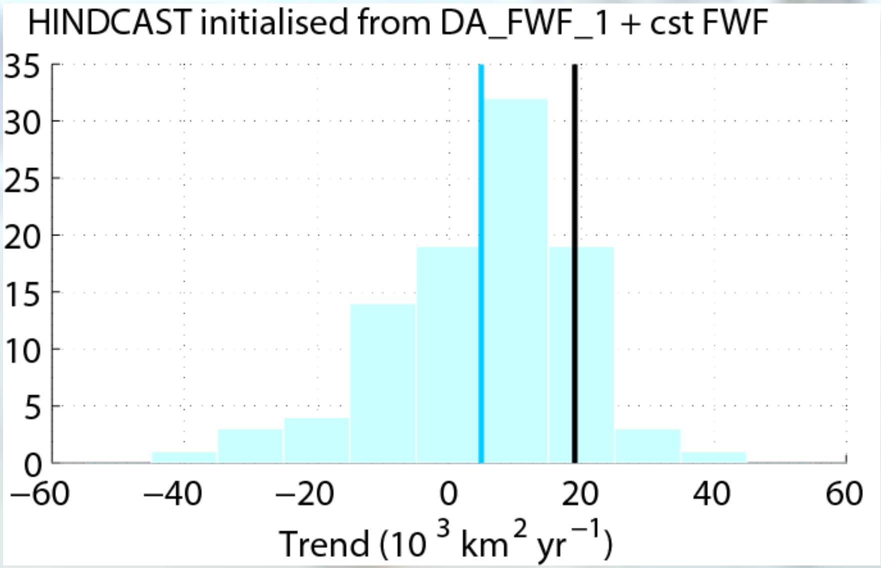
Hindcast trend

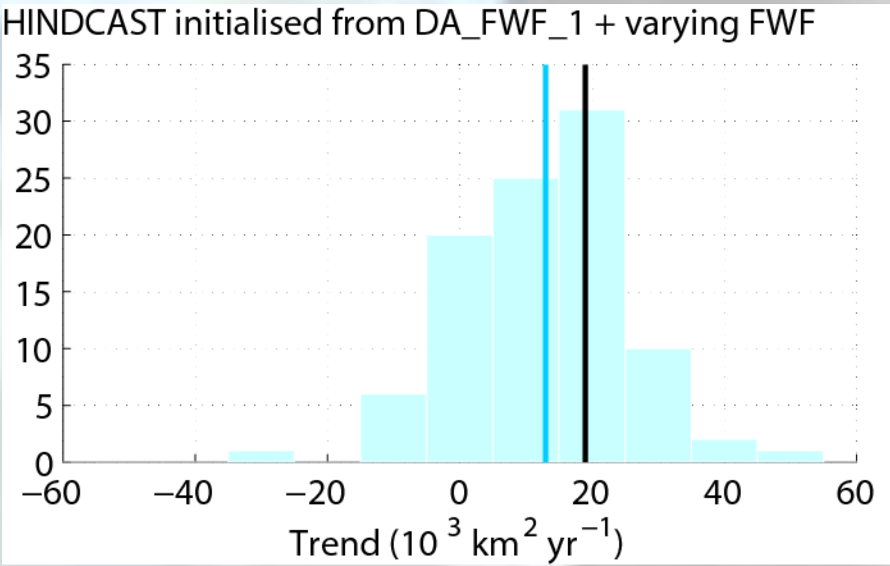


Hindcast trend









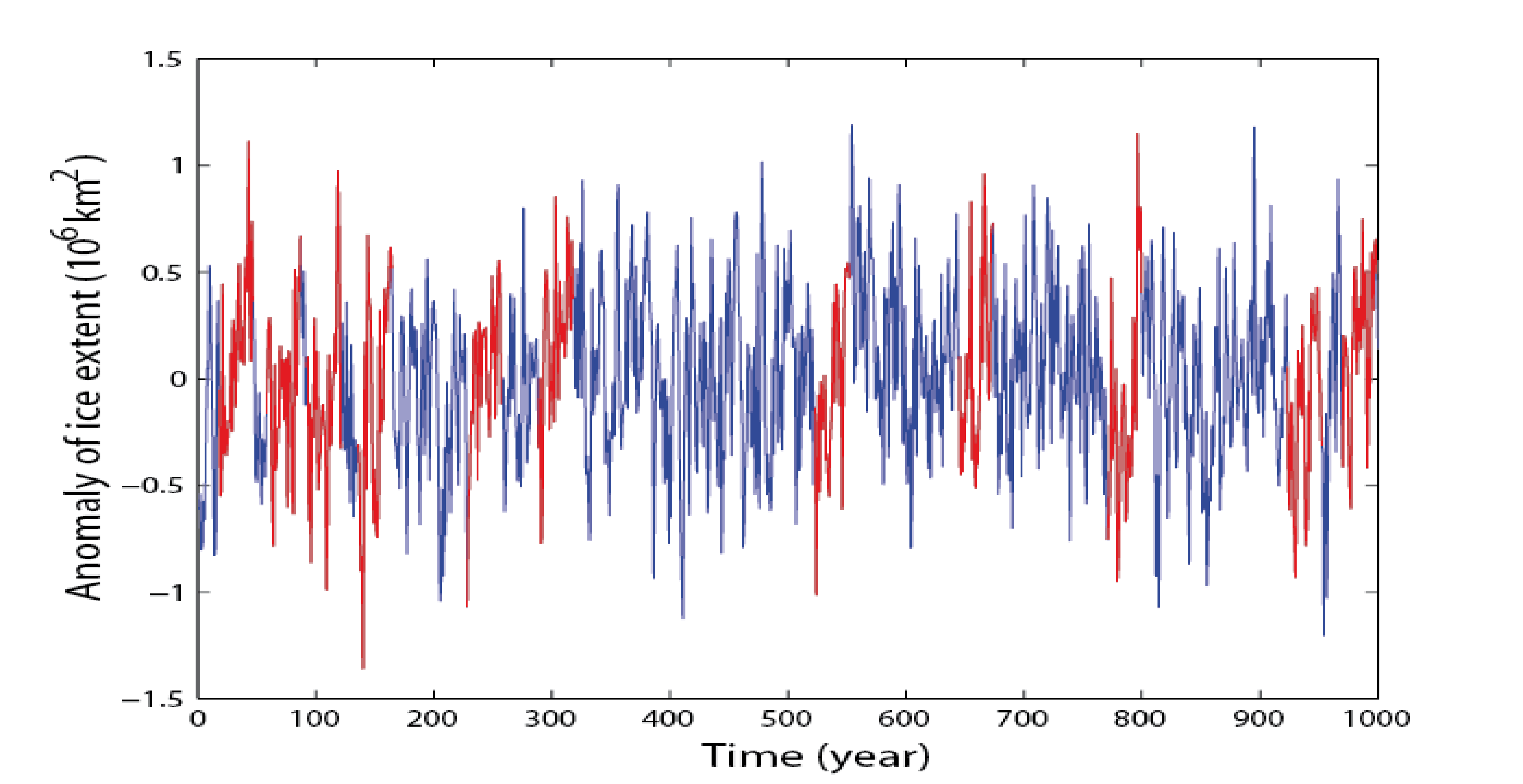
Hindcast trend

Prediction OK starting in 1980. Skill right initial state

+ comment role freshwater flux ?

Role of ice-ocean feedback in sea ice extent trend

Periods of large increase in sea ice extent in a control experiment performed with the EMIC LOVECLIM



Time series of the anomaly of annual mean sea ice extent in a long control run performed with LOVECLIM. The 11 periods characterised by an increase at a rate larger than 10^5 km^2 per decade during 30 years in each month of the year are in red.

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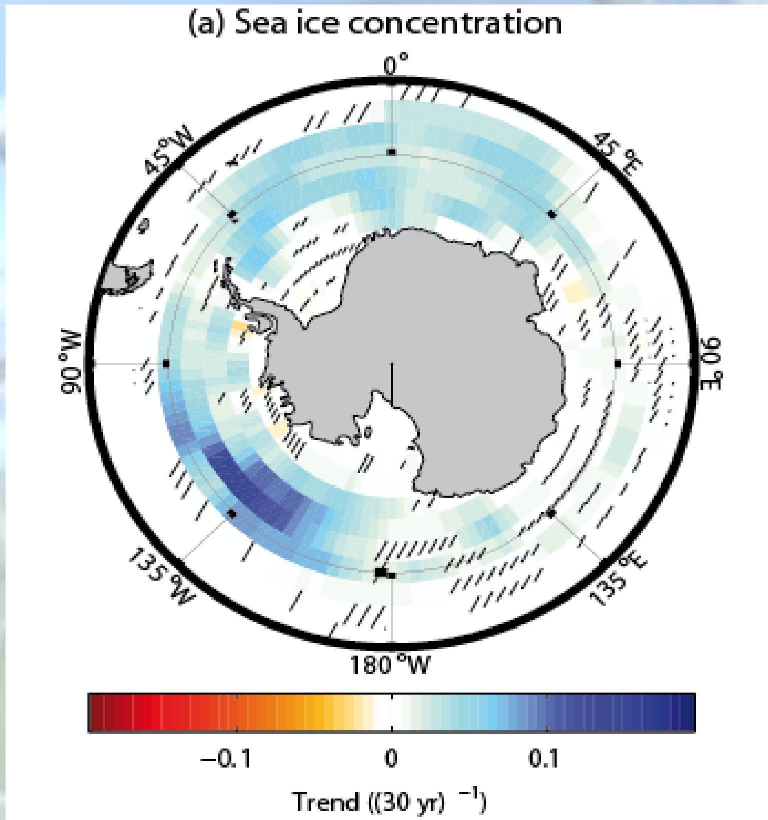
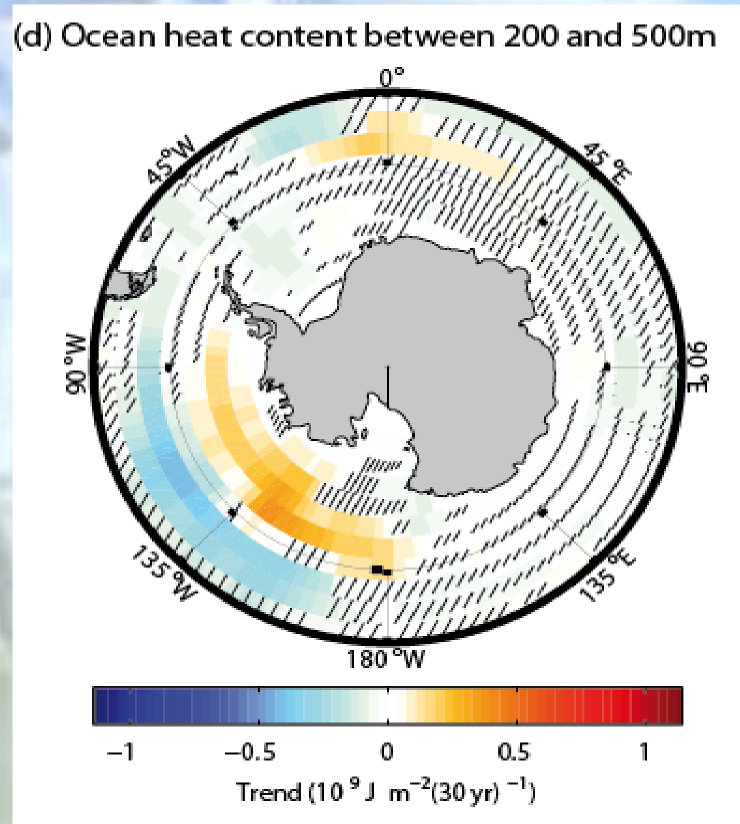
Role of ice-ocean feedback in sea ice extent trend

Periods of large increase in sea ice extent in a control experiment





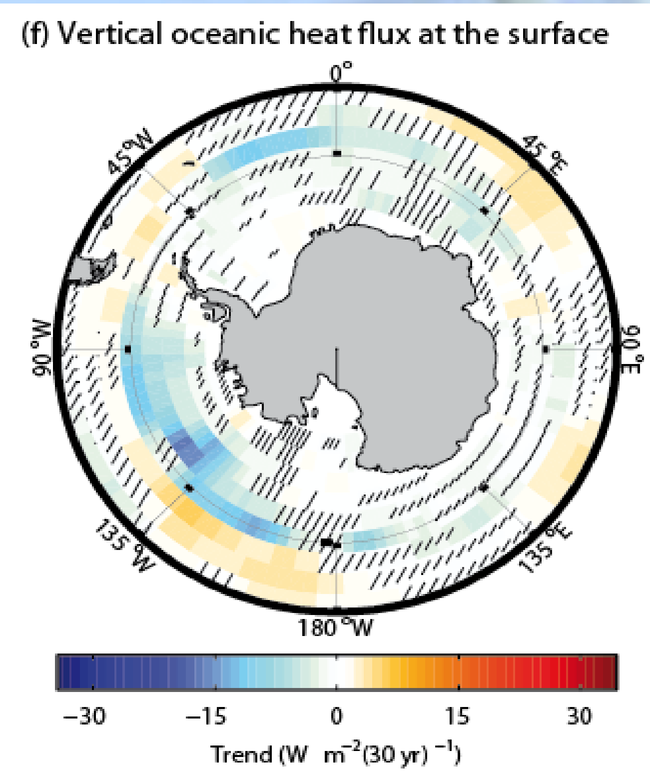
Trends in annual means averaged over the 11 periods showing a large increase in Antarctic sea ice extent scaled to represent the 30 year changes of ice concentration and ocean heat content in the layer between 200 and 500 m (Jm^{-2})

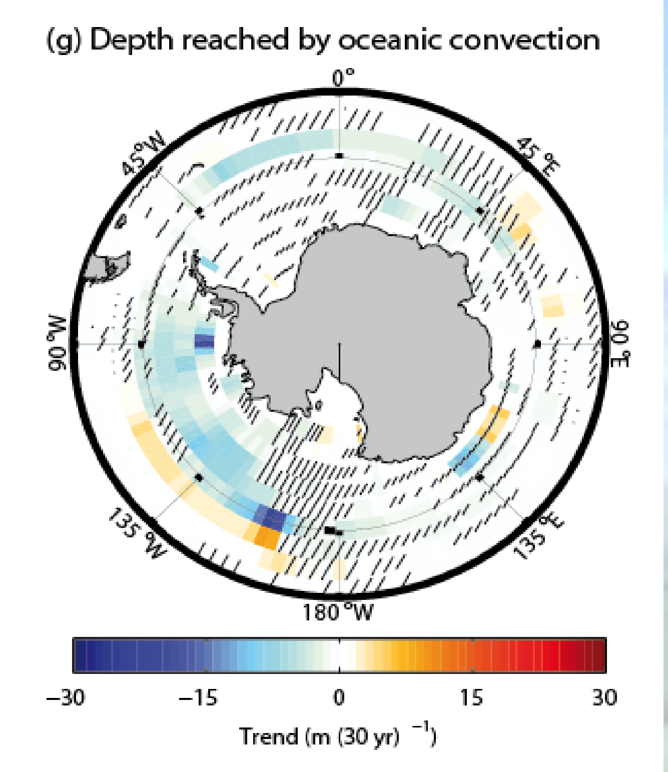
The increase in ice extent is associated with a larger heat content at intermediate depth.

Goosse and Zunz., 2013

Role of ice-ocean feedback in sea ice extent trend

Periods of large increase in sea ice extent in a control experiment





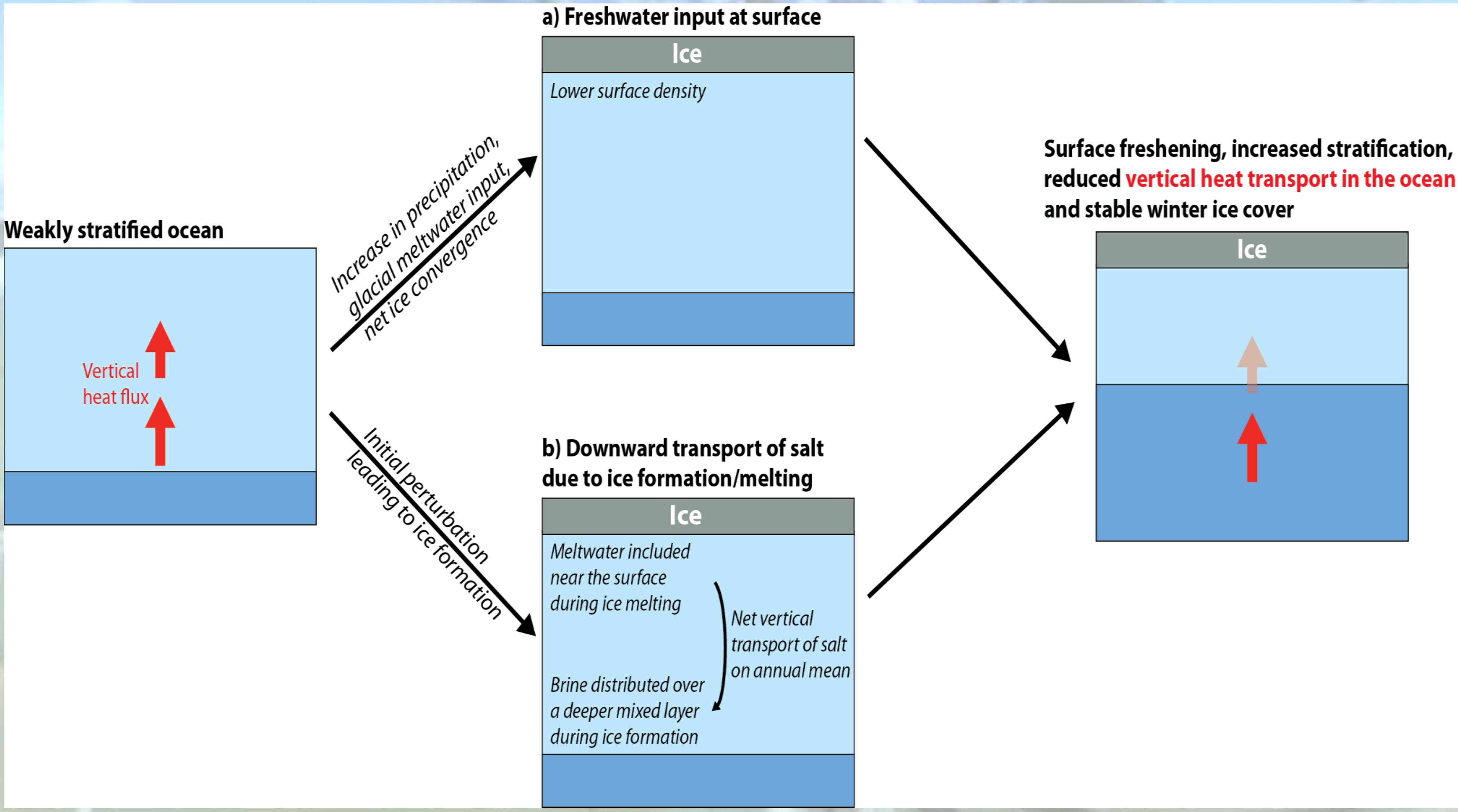
Trends in annual means averaged over the 11 periods showing a large increase in Antarctic sea ice extent scaled to represent the 30 year changes of the vertical oceanic heat flux at the ocean surface (positive upward, W m^{-2}) and of the depth reached by oceanic convection (m).

The larger heat content at intermediate depth is associated with a lower upward heat flux in the ocean and shallower mixed layer depths.

Goosse and Zunz., 2013

Role of ice-ocean feedback in sea ice extent trend

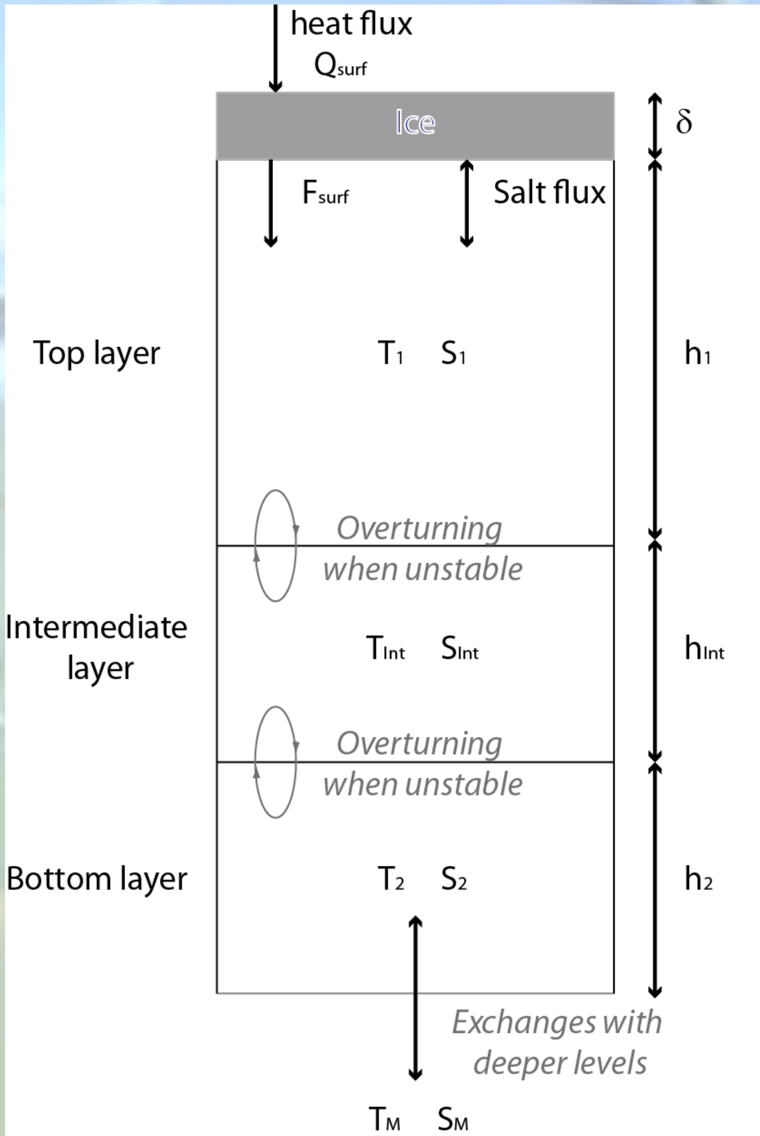
Schematic representation of the stabilization of the Southern Ocean by sea ice processes



Goosse and Zunz., 2013

Role of ice-ocean feedback in sea ice extent trend

A simple model to illustrate the role of the downward transport of salt due to the cycle of ice formation and melting



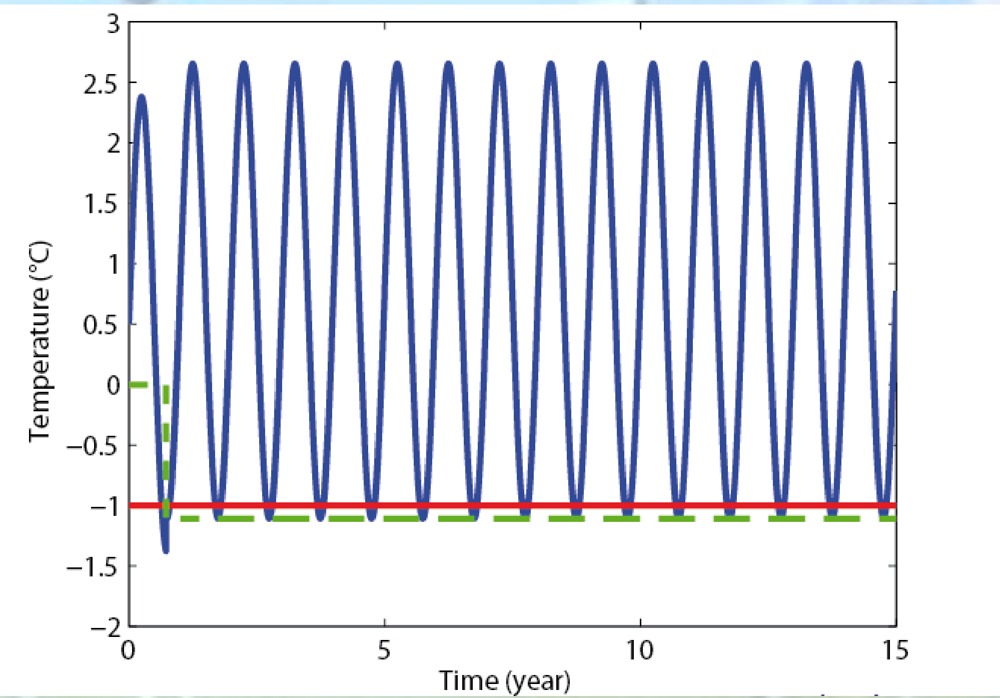
Schematic representation of the three-level model displaying the dominant processes included and the state variables.

Goosse and Zunz., 2013

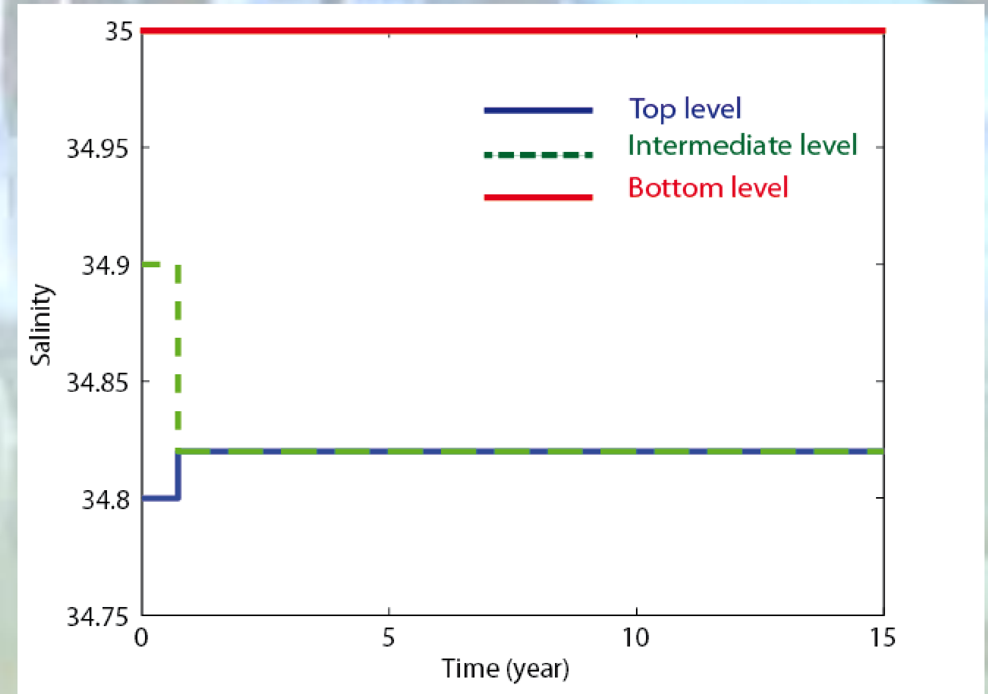
Role of ice-ocean feedback in sea ice extent trend

A stable situation of the simple model without ice formation

Temperature



Salinity



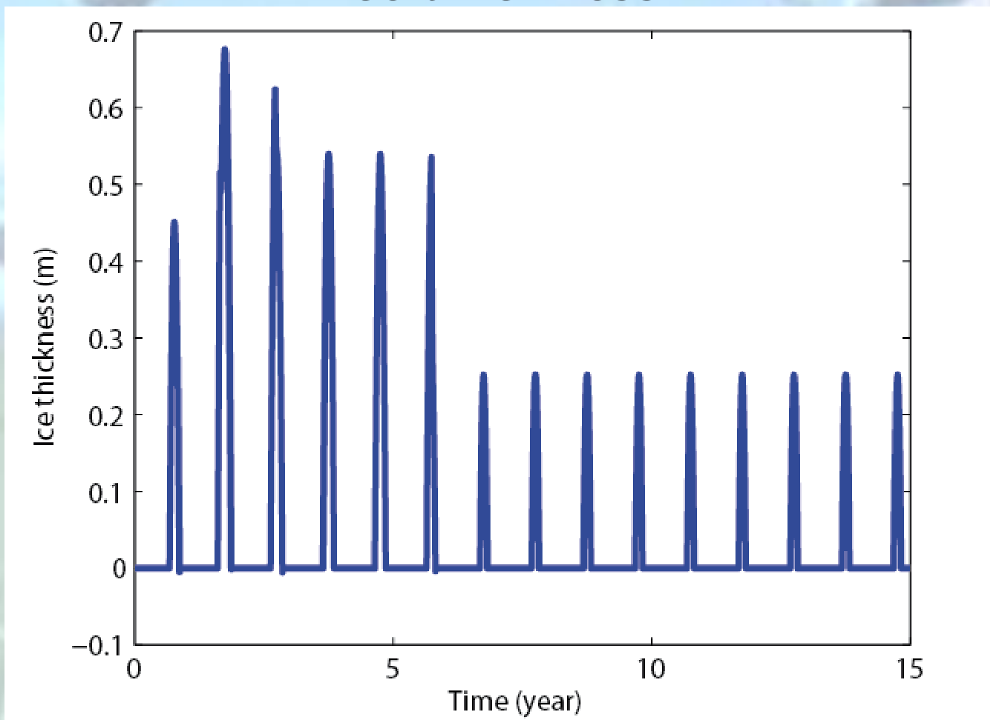
Temperature (°C) and salinity in an experiment performed with the three-level model initialized from a weakly stratified state. The value of the top level is in blue, the intermediate level in green and the bottom one is in red. In this configuration, the top two levels interact every winter and no ice is formed.

Goosse and Zunz., 2013

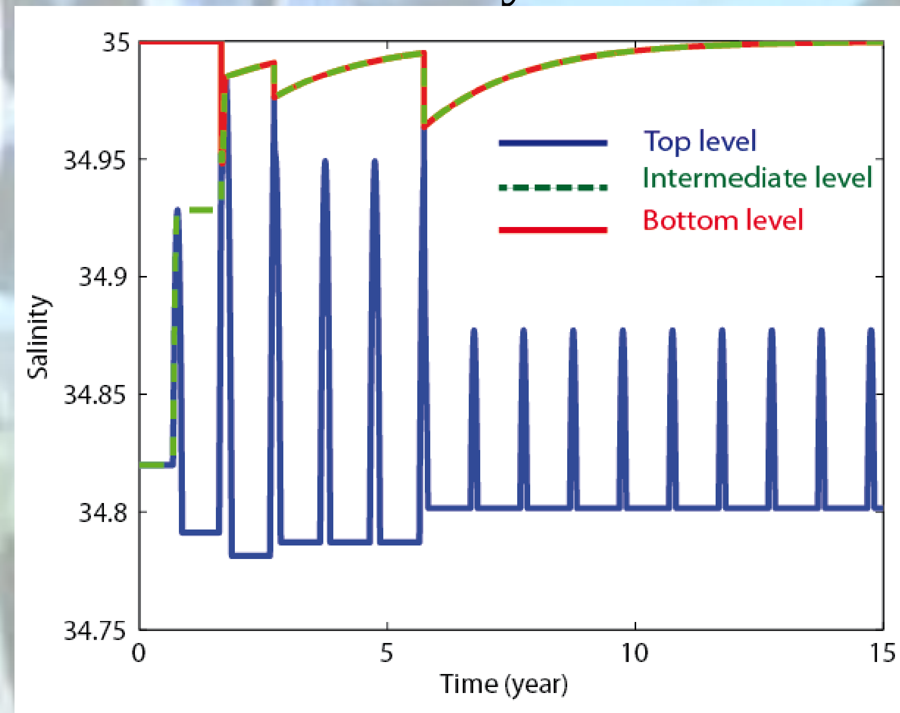
Role of ice-ocean feedback in sea ice extent trend

Formation of a stable sea ice cover in winter in response to a perturbation

Ice thickness



Salinity



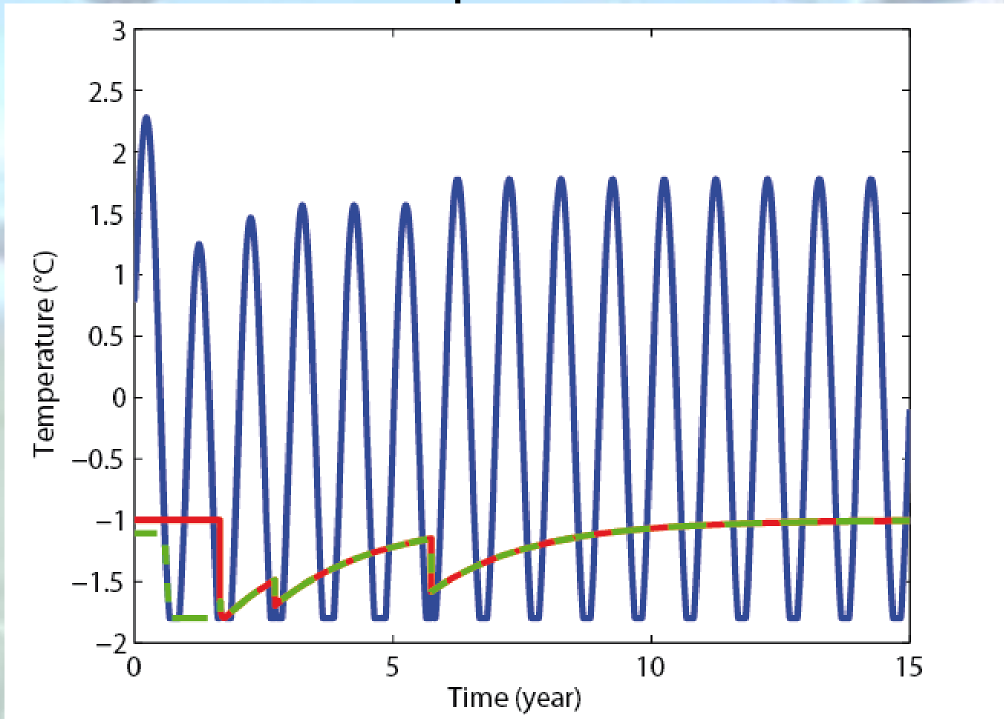
Ice thickness and salinity, in the three-level model in response to a reduction of the surface heat flux during the first year. The value of the top level is in blue, the intermediate level is in green, and the bottom one is in red. Because of the perturbation, strong sea ice formation initially destabilizes the water column but the downward transport of salt out of the top level finally leads to a stable water column during all the seasons after 7 years.

Goosse and Zunz., 2013

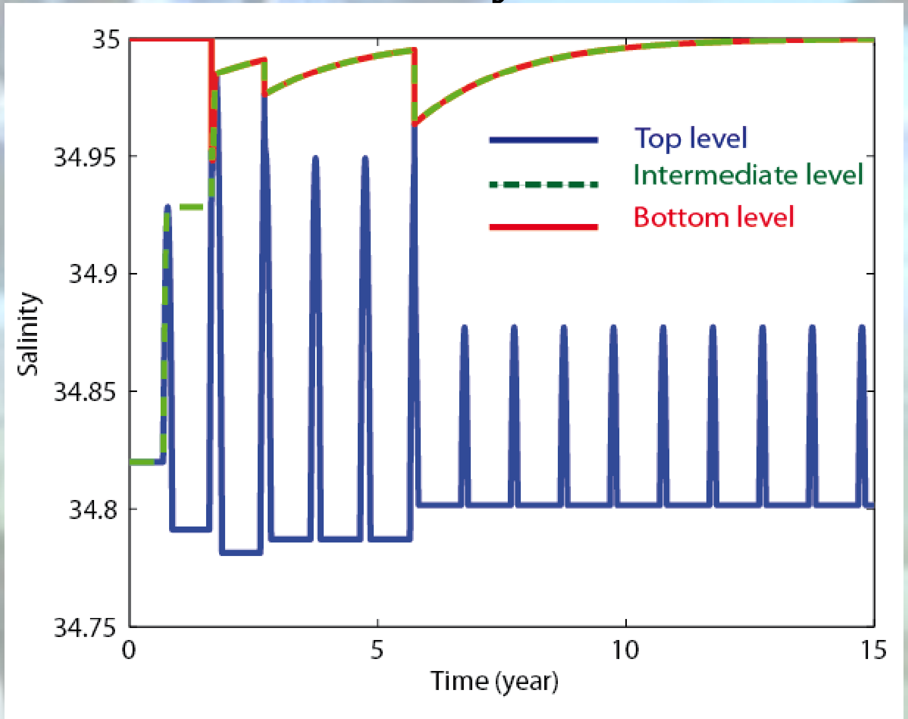
Role of ice-ocean feedback in sea ice extent trend

Formation of a stable sea ice cover in winter in response to a perturbation

Temperature



Salinity



Temperature (°C) and salinity, in the three-level model in response to a reduction of the surface heat flux during the first year. The value of the top level is in blue, the intermediate level is in green, and the bottom one is in red. Because of the perturbation, strong sea ice formation initially destabilizes the water column but the downward transport of salt out of the top level finally leads to a stable water column during all the seasons after 7 years.

Goosse and Zunz., 2013

Predictability of sea ice extent trend

If the ocean is playing such a large role in decadal variability of the sea ice cover, does it bring some predictability of the trend in sea ice extent ?

1st step: test with LOVECLIM in an idealised framework

Experimental setup

- Hindcast = 96-member ensemble simulations.
- One hindcast launched every 5 years between 1900 and 1990.
- Hindcast initialised from
  - perfect initial conditions;
  - a state that does not take into account any pseudo-observations;
  - various simulations with data assimilation, assimilating dense or sparse pseudo-observations of surface air temperature.

Zunz et al. 2014

Predictability of sea ice extent trend

If the ocean is playing such a large role in decadal variability of the sea ice cover, does it bring some predictability of the trend in sea ice extent ?

1st step: test with LOVECLIM in an idealised framework

Data assimilation methods tested with LOVECLIM

- a nudging technique;
- a particle filter with sequential importance resampling (PF);
- a nudging proposal particle filter (NPPF)

= PF + nudging.

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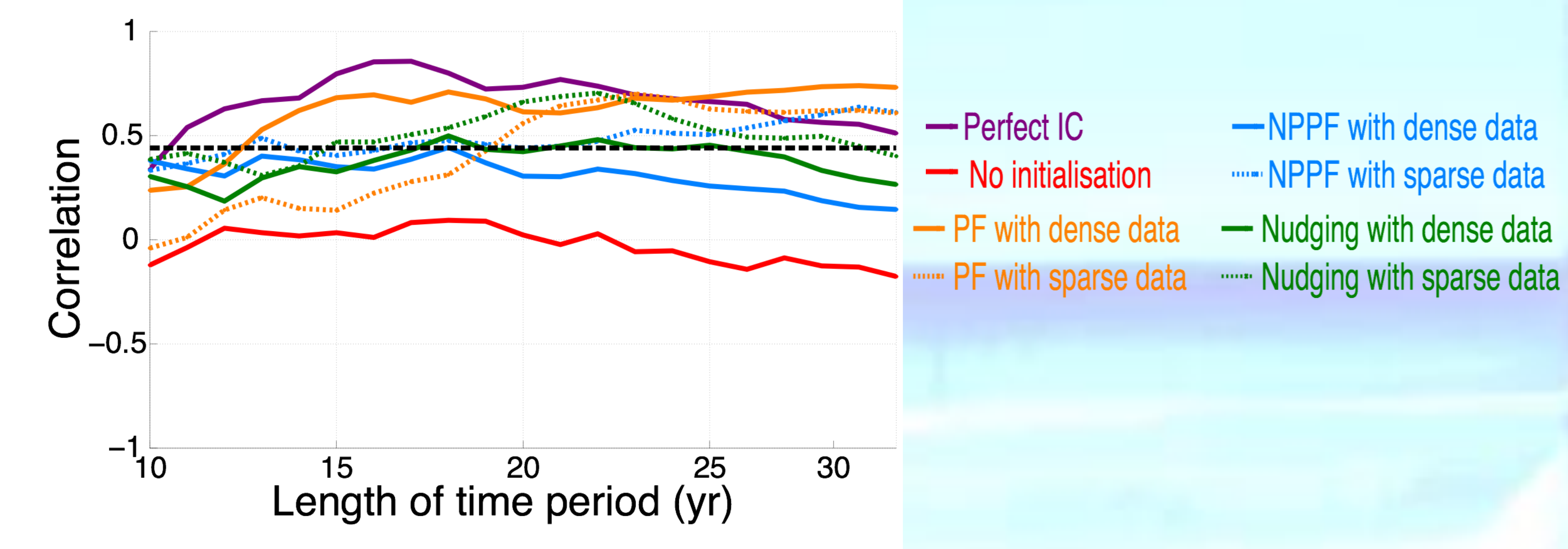
Predictability of sea ice extent trend

1st step: test with LOVECLIM in an idealised framework

Correlation between the trend in winter sea ice extent in hindcasts and pseudo-observations



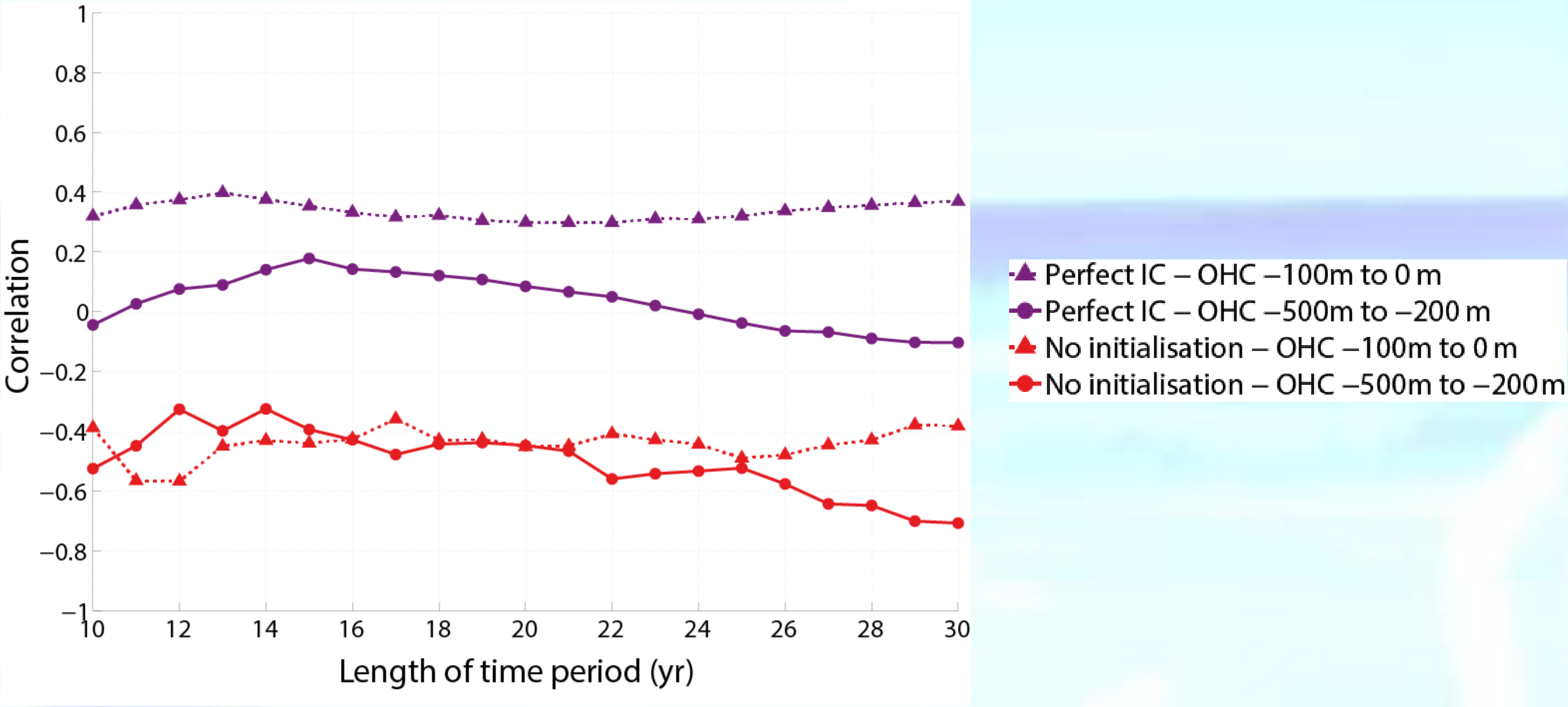
- Statistically significant correlation for the 10- to 30-year trend.
- Clear improvement of the correlation achieved thanks to the initialisation with pseudo-observations.

Zunz et al. 2014

Predictability of sea ice extent trend

1st step: test with LOVECLIM in an idealised framework

Correlation between the trend in sea ice extent in JAS from hindcasts and the ocean heat content (OHC) in the last year before the beginning of the hindcasts in pseudo-observations



Zunz et al. 2014

Predictability of sea ice extent trend

2nd step: realistic framework

- Use of actual observations for both the initialisation of simulation (through data assimilation) and for the evaluation of the skill.
- The initialisation of CMIP5 models with observations, mainly thanks to a nudging technique, does not systematically improve the simulated trend in sea ice extent over the period 1981-2009.
- What about a more sophisticated initialisation method?

Experimental design of the LOVECLIM simulations.

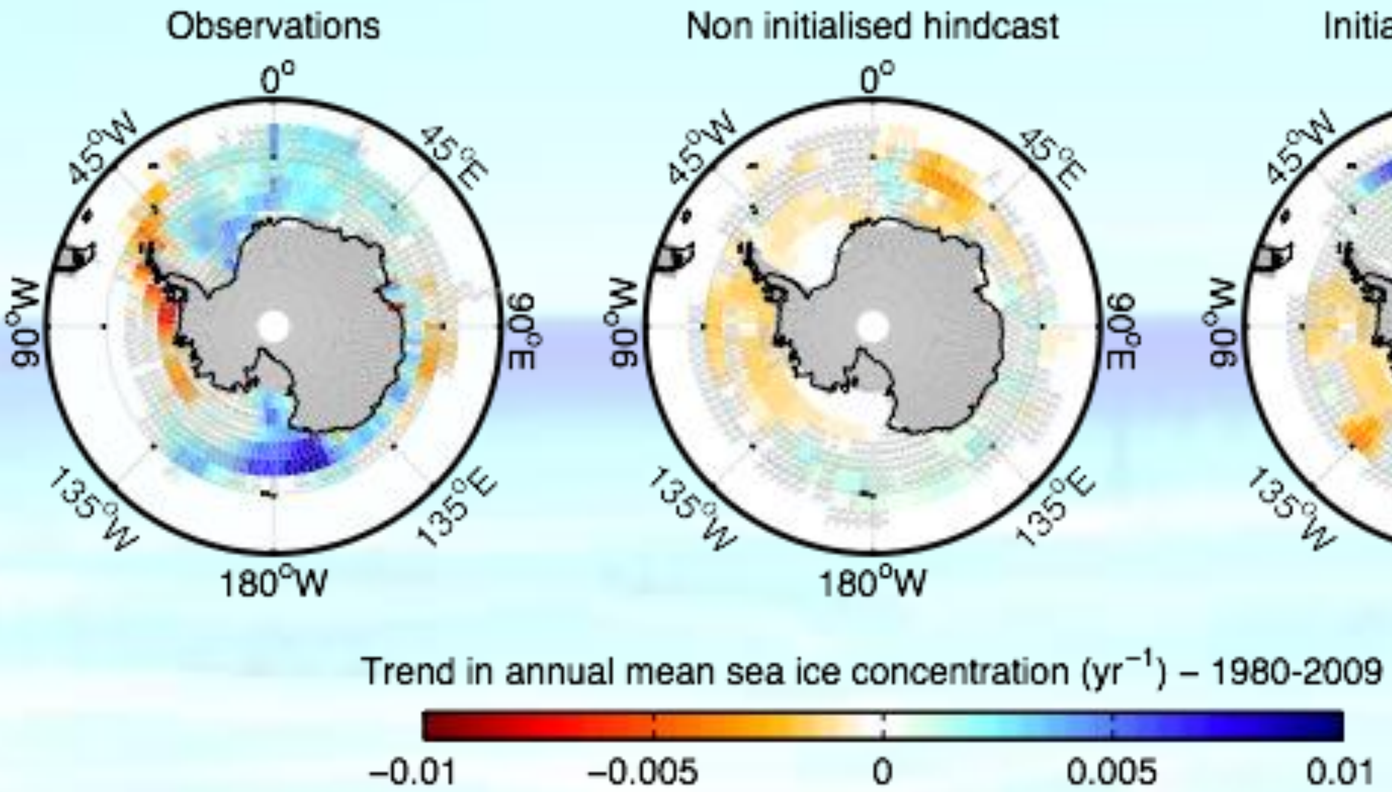
- Initialised from the simulation with NPPF including an additional random freshwater flux.
- An additional freshwater flux of similar amplitude has to be included in the hindcast simulation to ensure the consistency between the experimental design of the initialised hindcast and the one of the simulation with DA.

Zunz and Goosse, 2014

Predictability of sea ice extent trend

2nd step: realistic framework

Trend in annual mean sea ice concentration 1980-2009

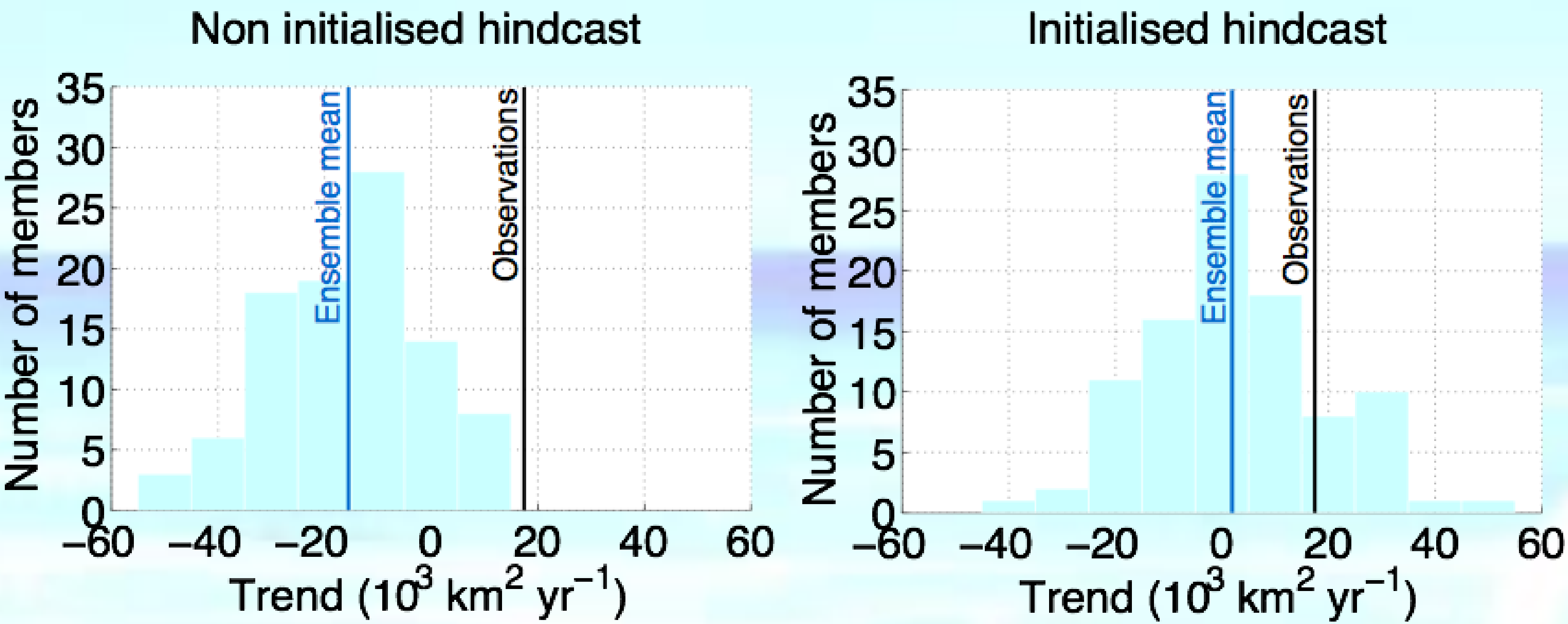


Zunz and Goosse, 2014

Predictability of sea ice extent trend

2nd step: realistic framework

1980–2009 trend in annual mean sea ice extent



Zunz and Goosse, 2014

Conclusions

♦ The **observed increase** in ice extent in the Southern Ocean over the last decades is (marginally) compatible with the **internal variability** of model.

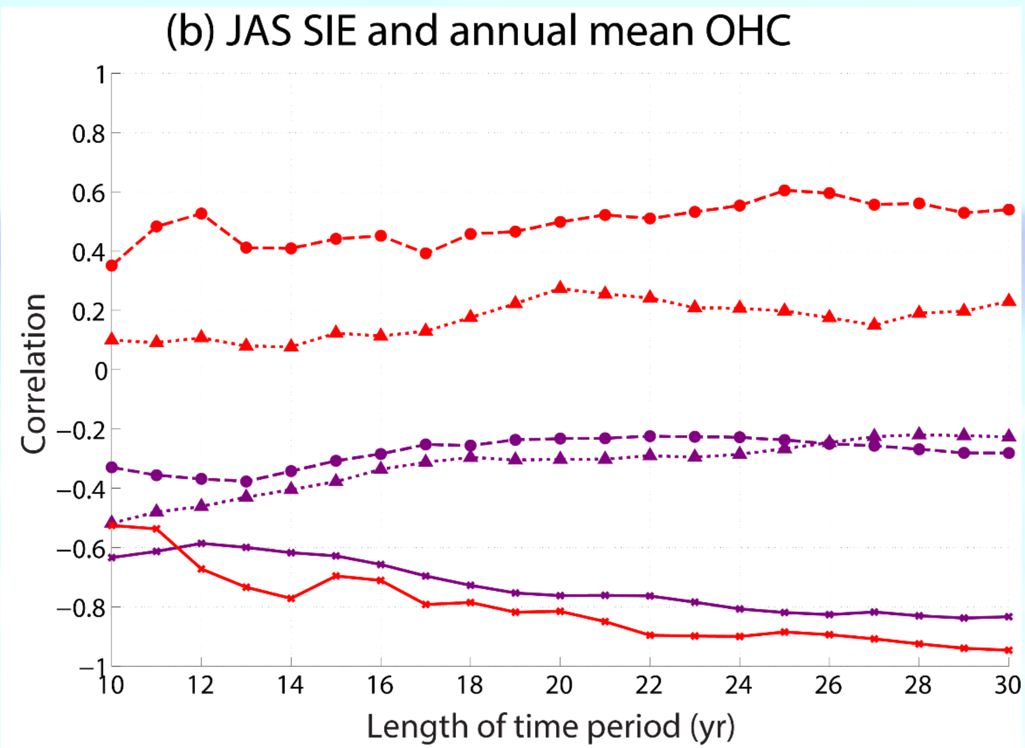
♦ **Ice-ocean feedbacks** control to a large extent the magnitude of the decadal trends in the Antarctic sea ice extent.

♦ The **multi-decadal trends in sea ice extent** might be **predicted** if the prediction simulations are adequately initialised and if the experimental setup is consistent. However, these results have to be considered **with caution** since they are based on **idealised experiment** and the **only 30-yr time period** for which reliable observations of the sea ice are available.

Predictability of sea ice extent trend

1st step: test with LOVECLIM in an idealised framework

Correlation between the trend in sea ice extent (SIE) and oceanic heat content (OHC).



Perfect Init | No Init

Correlation between the trend in JAS SIE and the SIE the year preceding the initialisation

Correlation between the trend in annual mean OHC and the OHC the year preceding the initialisation

Correlation between the trend in JAS SIE and the trends in annual mean OHC

Why not correl trend in SIE and initial OHC?
Surface (0-100) et 200-500 ?

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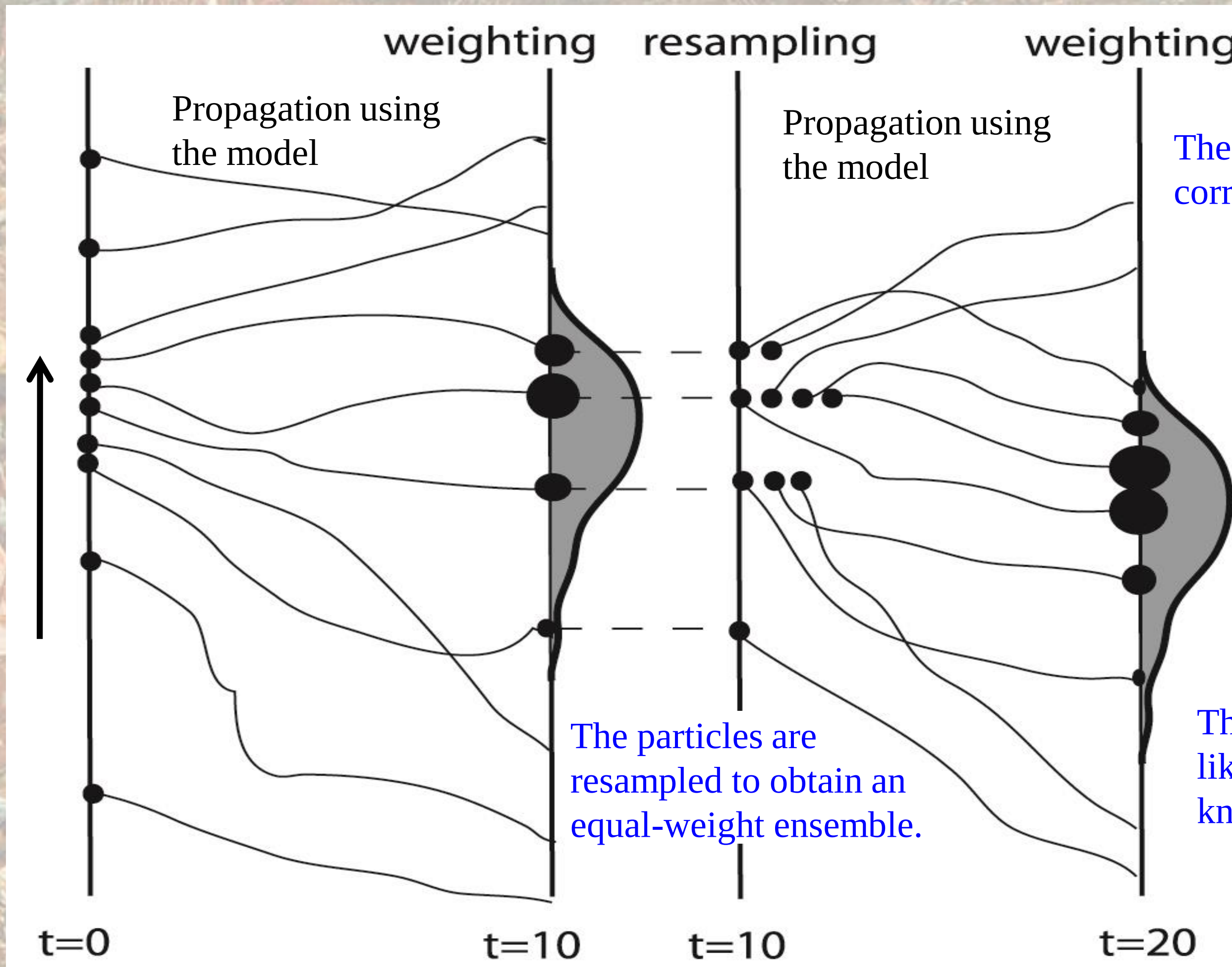
Method :Particle filter with resampling

Model states



The weight of each particle corresponds to the size of the bullets.

The weight is proportional to the likelihood of the model state, knowing the observations.

Time

The observations are available at a time interval of 10 time units in the example.

Adapted from van Leeuwen 2010

Method :Particle filter with resampling

Assuming a Gaussian likelihood, the weights w_i of the each particle is derived from:

$$w_i = \frac{\exp\left[-0.5\left(d - H\left(\psi_i\right)\right)^T \mathbf{C}^{-1}\left(d - H\left(\psi_i\right)\right)\right]}{\sum_{i=1}^{n} \exp\left[-0.5\left(d - H\left(\psi_i\right)\right)^T \mathbf{C}^{-1}\left(d - H\left(\psi_i\right)\right)\right]}$$

where d is the vector including all the observations

ψ_i is the model state vector

C is the error covariance matrix

H is the observation operator.

The error covariance matrix C describes the properties of the discrepancy between the model variables and the observations. It includes a component corresponding to an instrumentation error and a component corresponding to a representativeness error.

Method :Particle filter with resampling

Potential problems:

- Degenerative filter: only a few (one) particles get a significant weight

- “Divergent filter” or ‘biased filter’: even the best particles are not close to the target.

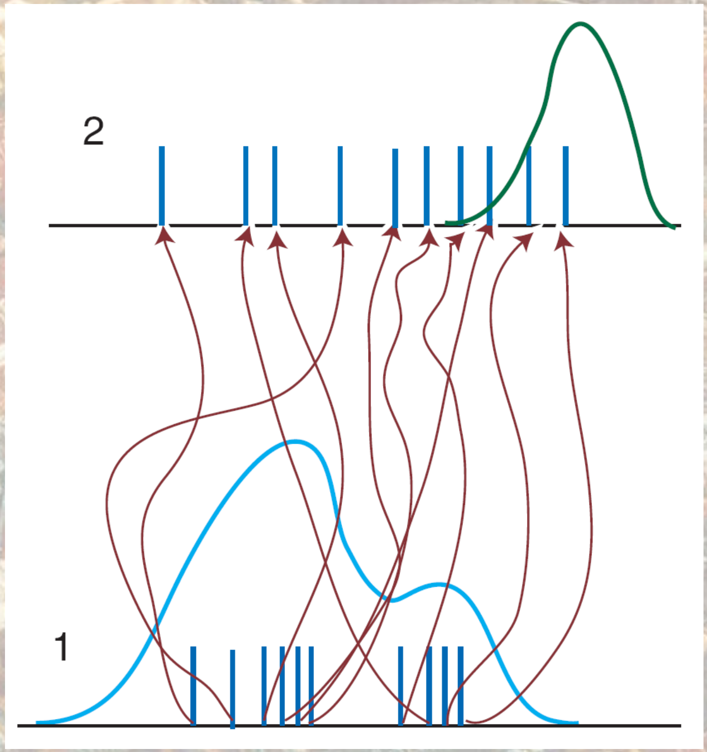
- The predictability of the system is low at seasonal to interannual timescales

Only a few degrees of freedom can be reconstructed using a reasonable number of particles.

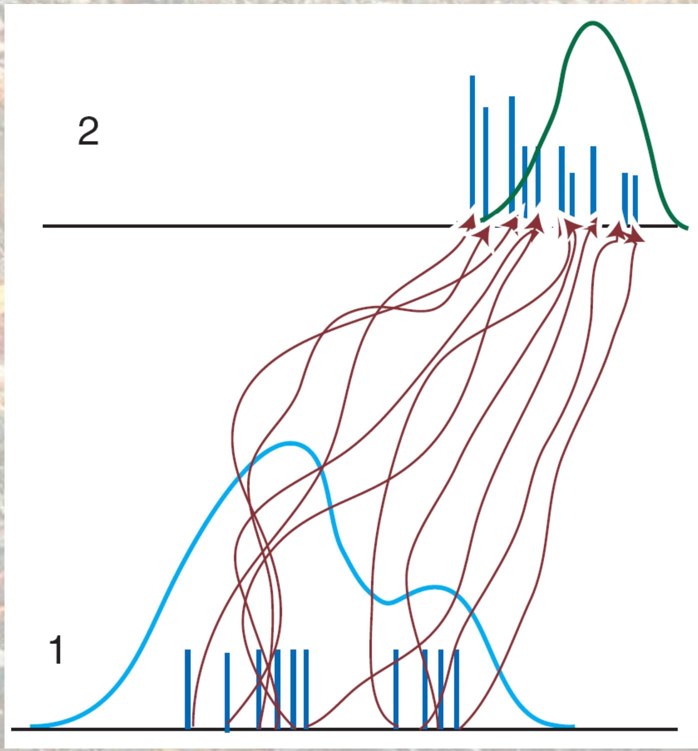
Nudging proposal particle filter

Nudging is widely used in GCMs for initializing predictions.

Particle filter with sequential importance resampling (SIR)

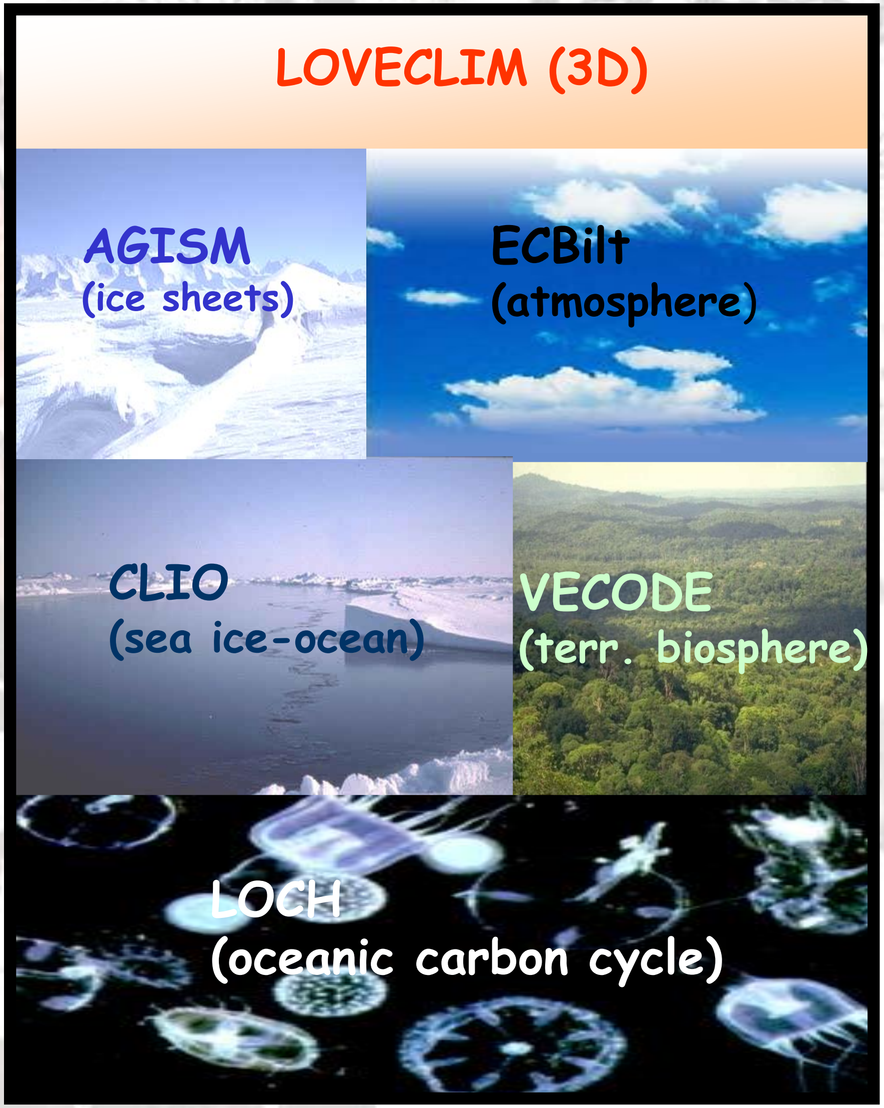


Nudging proposal particle filter (NPPF)



From P.J. van Leeuwen 2010

Description of LOVECLIM



ECBilt (Opsteegh et al., 1998)
Quasi-geostrophic atmospheric model (prescribed cloudiness; T21, L3).

CLIO (Goosse and Fichefet, 1999)
Ocean general circulation model coupled to a thermodynamic-dynamic sea ice model (3 x 3, L20).

VECODE (Brovkin et al., 2002)
Reduced-form model of the vegetation dynamics and of the terrestrial carbon cycle (same resolution as ECBilt).

LOCH (Mouchet and François, 1996)
Comprehensive oceanic carbon cycle model (same resolution as CLIO).

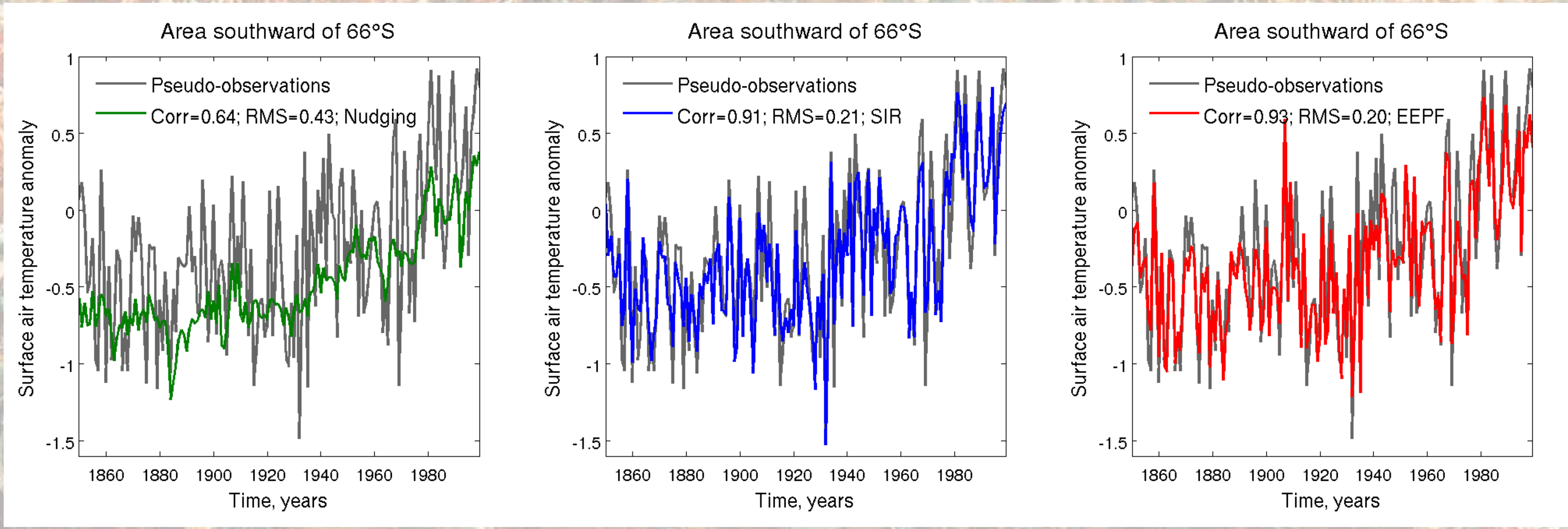
AGISM (Huybrechts, 2002)
Thermomechanical model of the ice sheet flow + visco-elastic bedrock model + model of the mass balance at the ice-atmosphere and ice-ocean interfaces (10 km x 10 km, L31).

Experiments using pseudo-observations

- ❑ Only pseudo-observations of surface temperature are used to constrain model results.
- ❑ Nudging is applied only above the ocean.

Surface air temperature averaged over the area southward of 66°S

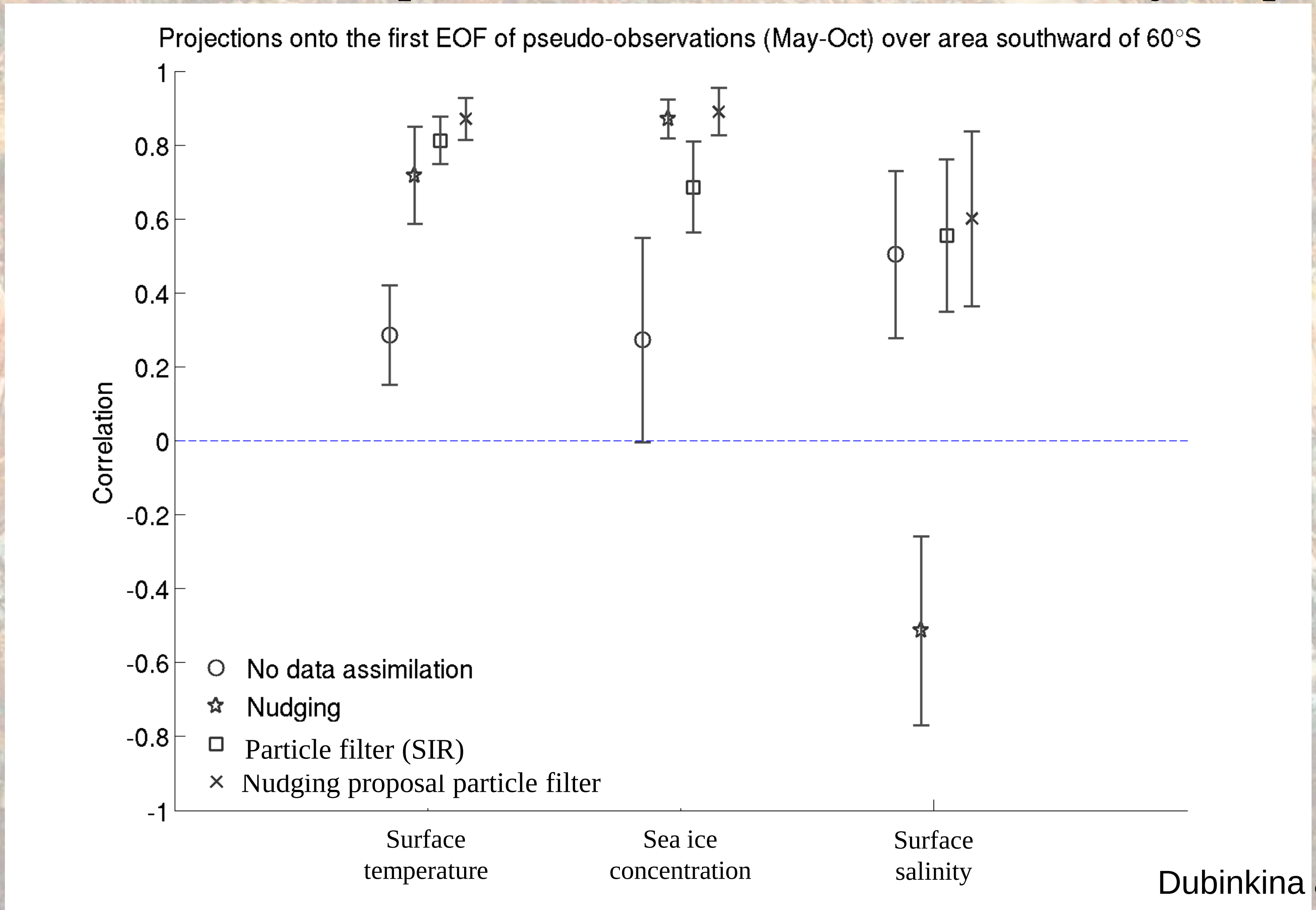
Nudging | Particle filter (SIR) | Nudging proposal particle filter



Dubinkina and Goosse 2013

Experiments using pseudo-observations

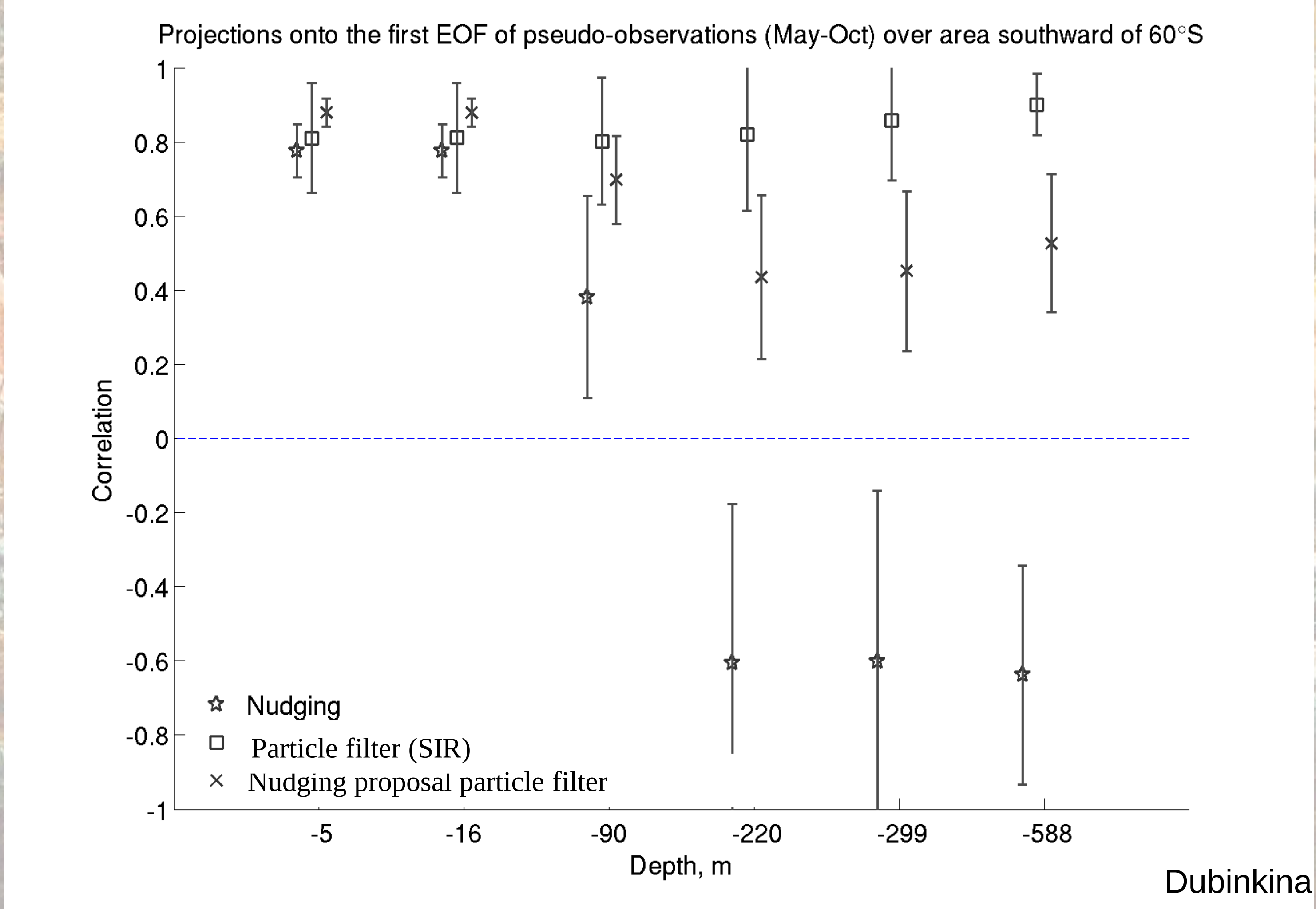
Correlations between the first principal components of the pseudo-observations and projections of the model simulations onto the corresponding first empirical orthogonal functions of the pseudo-observations over six 21-year periods.



Dubinkina and Goosse 2013

Experiments using pseudo-observations

Correlations between the first principal components of the pseudo-observations and model simulations for ocean temperature as a function of depth.



Dubinkina and Goosse 2013

Particle filter

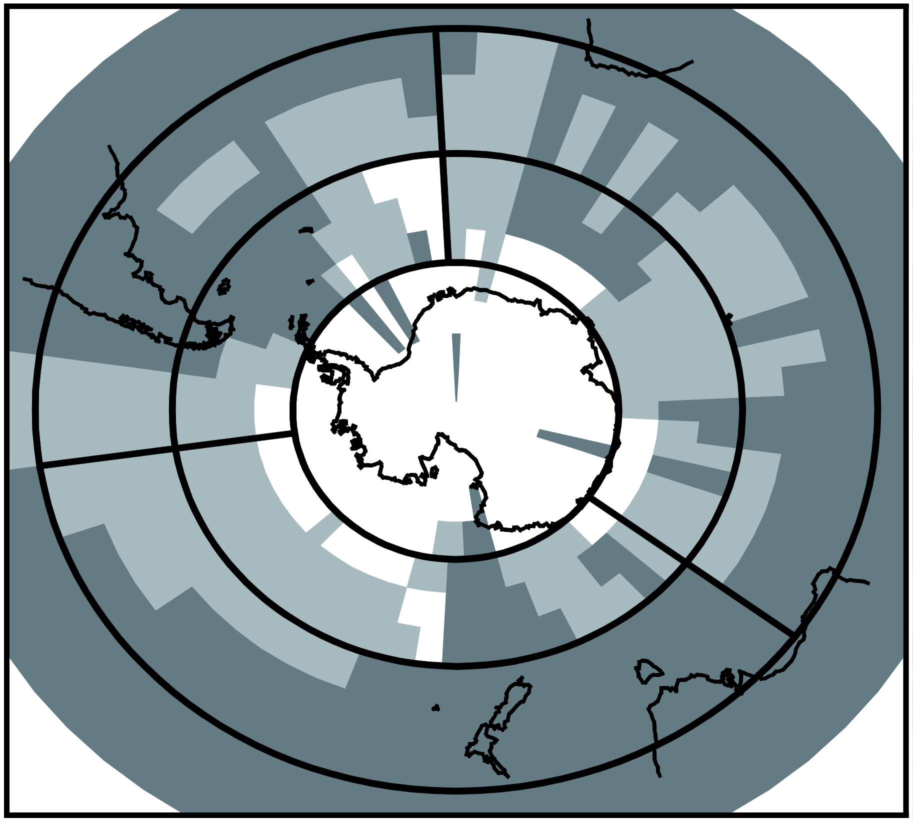
Advantages

- The particle filter respects the dynamics of the system. This is not the case for simpler methods such as nudging.

- It is possible to combine the advantages of the particle filter with the ones of other methods (nudging, EnKF, etc) in order to have good results using a reasonably small number of particles.

Simulation over the last 150 years constrained by HadCRUT3 dataset

The only data used is the surface temperature



Data coverage:
The dark grey area represents the model grid boxes for which observations are available since 1960 while the light grey area represents the model grid boxes for which observations are available since 1980. No data is available in the white grid boxes.

Goosse et al., 2009

Conclusions

♦ It is **possible to constrain a model** to follow, at large scale, observations over the 20th century in the Southern Ocean.

♦ The **particle filter** as implemented here provides a relatively weak constrain.

- **Advantage**: the model dynamics is respected
- **Disadvantage**: the model-data agreement is not always perfect if you do not use a very large number of particles.

♦ **Ice-ocean feedback** control to a large extent (?) the magnitude of the decadal trends in the Antarctic sea ice extent