Southern Ocean variability over the last centuries in coupled data assimilation experiments with particle filtering

Hugues Goosse, Violette Zunz
Université catholique de Louvain, Belgium

Toulouse, October 20, 2016
International workshop on coupled data assimilation
Sea ice changes over the last decades

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

Observed trend in sea ice concentration over the period 1978-2010 (data from NSIDC)
Among the members of the CMIP5 ensemble, only a few display a positive trend in sea ice extent.

### 1979–2005 JAS sea ice extent trend range

- **BCC-CSM1.1(3)**
- **CanESM2(5)**
- **CCSM4(6)**
- **CNRM-CM5(10)**
- **CSIRO-Mk3.6.0(10)**
- **FGOALS-s2(3)**
- **GFDL-CM3(5)**
- **GISS-E2-R(5)**
- **HadCM3(10)**
- **IPSL-CM5A-LR(4)**
- **MIROC4h(3)**
- **MIROC–ESM(3)**
- **MPI–ESM–LR(3)**
- **MRI–CGCM3(3)**
- **NorESM1–M(3)**

**Trend in sea ice extent (10^3 km^2/decade)**
Models suggest a large temperature increase in Antarctica over the 20th century while the warming is much weaker in reconstructions.

Annual mean surface temperature averaged over Antarctica simulated by five climate models following the PMIP3-CMIP5 protocol over the past 300 years and PAGES2k reconstruction for the same period (PAGES2k-PMIP3 working group, 2015).
Insights gained through data assimilation

Methods

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).

200 years of simulation on a single core in one day
Simulation over the last 150 years constrained by HadCRUT3 dataset

Data constrain: surface temperature (HadCRUT3)
Assimilation step: 3 months (Time averaged observations)
Method: nudging Particle Filter (96 simulations)

Data coverage:
- The dark grey area represents the model grid boxes for which observations are available since 1960
- 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.

Zunz and Goosse, 2015
Simulation over the last 150 years constrained by HadCRUT3 dataset

Yearly mean surface air temperature anomalies with regard to 1961–1990, averaged over the area south of 30°S.
Ensemble mean of yearly mean sea ice extent anomalies with regard to 1980–2009 (10^6 km^2) in the Southern Ocean

Simulation over the last 150 years constrained by HadCRUT3 dataset

In response to the forcing, the decreasing trend is relatively constant. The simulation with data assimilation shows a large shift between the 1960’s and the 1980’s.
“Predicting” trends over the last 30 years

Simulations initialized in 1980 from an ensemble of 96 simulations with the EMIC LOVECLIM using a nudging Particle Filter. No data constraint is applied after 1979.

1980–2009 trend in annual mean sea ice extent

Non-initialized hindcast

Initialized hindcast (STD)
‘Predicting’ trends over the last 30 years

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

Trend in annual mean sea ice concentration 1980-2009

Trend in annual mean sea ice concentration (yr$^{-1}$) – 1980-2009

Zunz and Goosse 2015
Simulations over the last centuries constrained by PAGES2k continental-scale reconstructions

Data constrain: surface temperature in 7 continental regions
Assimilation step: 1 year
Method: Particle Filter Importance Resampling (96 simulations)
Simulations over the last centuries constrained by PAGES2k continental-scale reconstructions

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

Smoothed time series of simulated temperatures and Pages2k reconstructions for two continent-scale regions

Temperature (K)

Arctic

Antarctica

Reconstruction

Simulations without data assimilation (ensemble mean)

Simulations with data assimilation

Goosse 2016
Influence of ocean dynamics

Atmosphere-ocean heat flux anomaly (in W m$^{-2}$) averaged over the period 850-1050

![Graph showing heat flux anomaly across different latitudes with and without data assimilation.](image-url)
Particle filtering is an interesting tool for coupled data assimilation on long time scales.

The ocean has potentially played a large role in the increase in sea ice extent over the last decades.

A strong incompatibility exists between simulated warming in Antarctica over the 20th century and reconstructions.
‘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

with additional freshwater flux during the hindcast

without additional freshwater flux during the hindcast (STD)

Zunz and Goosse 2015
Comparison of temperature changes in various latitude bands

Simulations without data assimilation (ensemble mean)

Simulations with data assimilation

Normalized Temperature

Time

80°S
45°S
80°N
Annual mean sea ice concentration

Trends of sea ice concentration over the period 1979-2009

Trend in annual mean sea ice concentration (yr$^{-1}$) – 1980-2009
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)

Zunz and Goosse 2015
Model-data comparison at the regional scale

Smoothed time series of simulated temperatures and Pages2k reconstructions for two continent-scale regions

Year CE

CSIRO-Mk3L-1-2 / piControl
COSMOS1-1 / CTL segment 1
COSMOS1-2 / CTL segment 2
COSMOS1-3 / CTL segment 3
COSMOS1-4
CCSM4 / piControl
CESM / piControl
GISS-E2-R-1 / piControl
GISS-E2-R-2
GISS-E2-R-3
GISS-E2-R-4
HadCM3 / piControl
IPSL-CM5A-LR / piControl
MPI-ESM-P / piControl
Reconstruction uncertainty
Role of atmospheric dynamics

Spatial distribution of the geopotential height anomaly at 800 hPa (in m\(^2\)s\(^{-2}\)) in a simulation with data assimilation