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Earth Sciences Department
Climate Prediction Group

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

On the results of EOS-COST Polar Ocean Reanalysis Inter-comparison Project and the BSC sea ice reanalysis

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11th RES Users' Meeting & 6th HPC Advisory Council Conference
Santiago de Compostela, Spain
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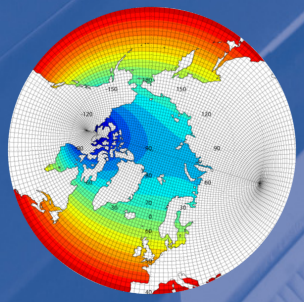

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→ Computer Sciences

→ **Earth Sciences**
- Atmospheric composition
- **Climate prediction**
- Earth System Services
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→ Life Sciences

→ Computer Applications

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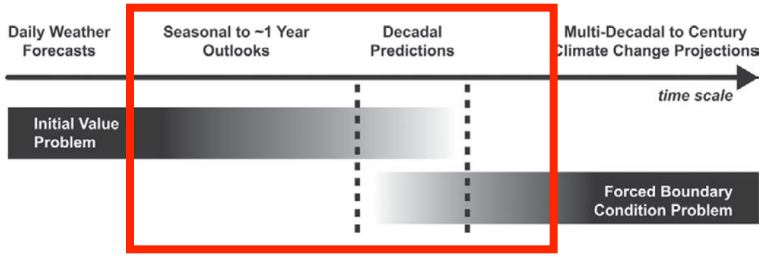
MareNostrum IV (housed in the former chapel Torre Girona) is the third most powerful supercomputer in Europe and the thirteenth in the world (165.888 processors processors with 11,1 Pflops peak performance)

→ Climate Prediction Group

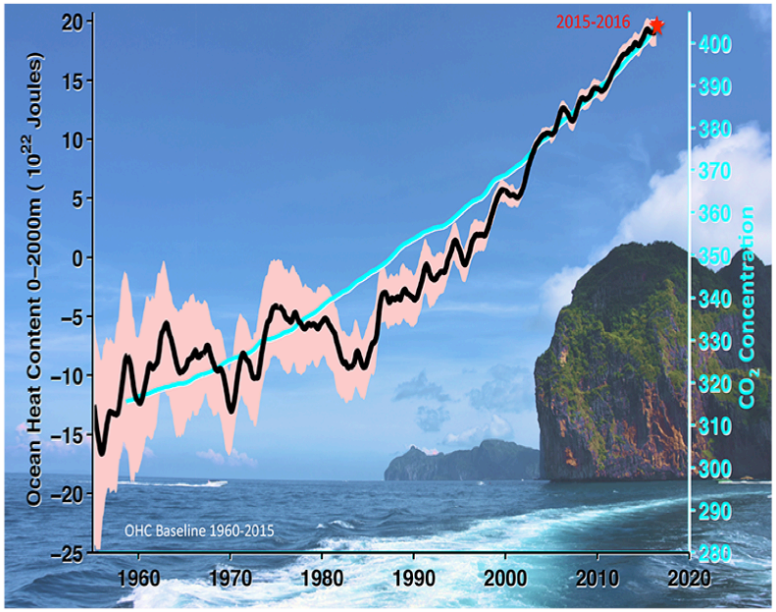


Focus on sub-seasonal to multi-decadal range of forecast horizons when memory of initial state (IC) and boundary forcing (BC) are both important

→ reanalyses/reconstructions critical for understanding climate evolution and IC

Polar ORA-IP

The global oceans are flywheel of the Earth's climate system critical on sub-seasonal to multi-decadal, and longer timescales
→ change of ocean heat content does not show surface global warming slowdown



Atmospheric reanalyses are established as invaluable tools for forecast as well as study of climate variability and change
→ Ocean and sea ice ReAnalyses (ORA) are similarly valuable source for climate prediction and understanding of climate dynamics

→ OCEAN STATE, SEA ICE, SNOW, AND SOIL MOISTURE

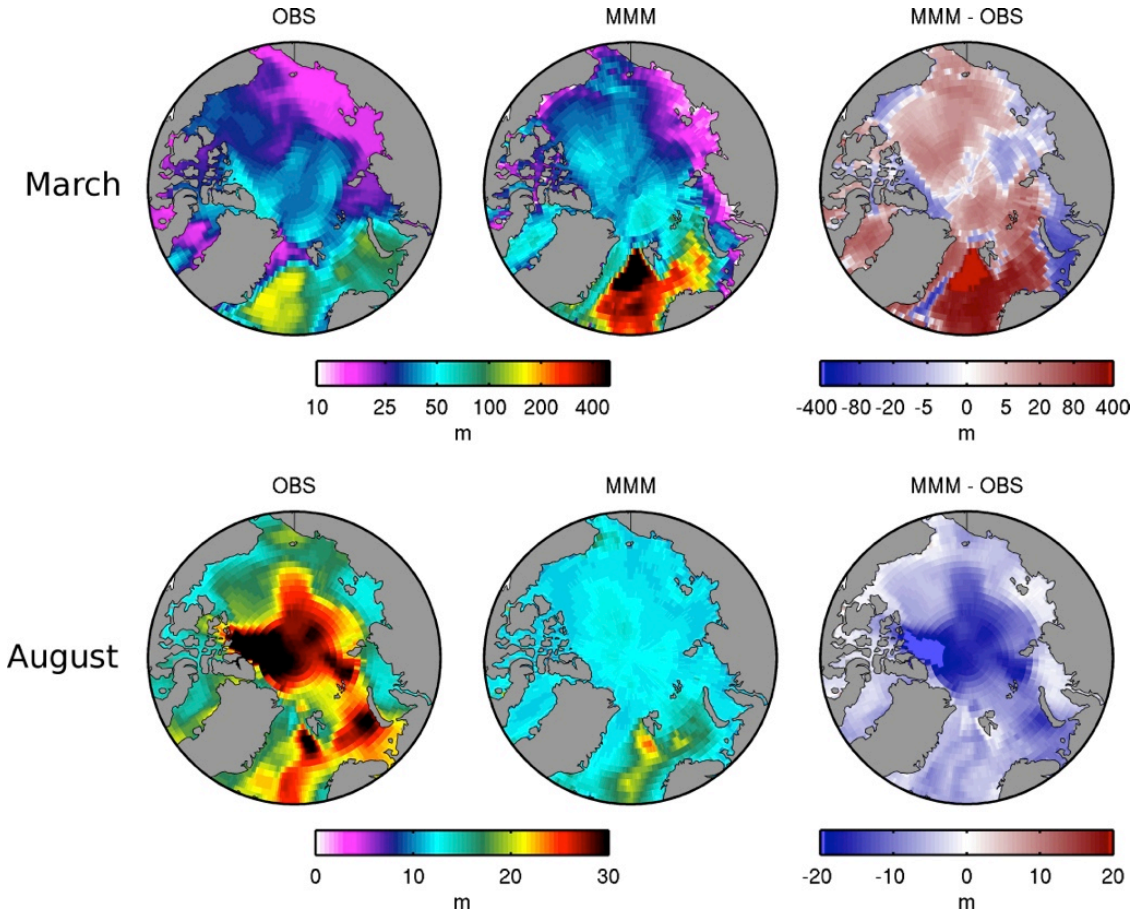
Global and regional ORA products are increasingly used in polar research, but their quality remains to be systematically assessed in high-latitude regions
→ the Polar ORA Intercomparison Project (ORA-IP) has been established within the framework of EOS-COST Action

→ here focus on ORAs elements critical for climate

ORAs included in Polar ORA-IP

Name	C-GLORS025v5	ECDA3	GECCO2	GLORYS2v4	GloSea5-GO5	MOVE-G2i	ORAP5	SODA3.3.1	TOPAZ4	UR025.4
Institution	CMCC	GFDL/NOAA	Hamburg University	Mercator Océan	UK MetOffice	MRI/JMA	ECMWF	University of Maryland	NERSC	University of Reading
Nominal horizontal resolution	0.25°	1°	1° × 1/3°	0.25°	0.25°	1° × 0.3 − 0.5°	0.25°	0.25°	12–16 km	0.25°
Vertical resolution	50 z-levels	50 z-levels	50 z-levels	75 z-levels	75 z-levels	52 z-levels	75 z-levels	50 z-levels	28 z-isopycnal layers	75 z-levels
Ocean–ice model	NEMO3.2 – LIM2	MOM4 – SIS	MITgcm	NEMO3.1 – LIM2	NEMO3.4 – CICE	MRI.COM3 – CICE4	NEMO3.4 – LIM2	MOM5 – SIS	HYCOM – EVP SI	NEMO3.2 – LIM2
Time period	1993–2013	1961–2012	1948–2014	1992–2015	1993–2012	1980–2012	1979–2012	1980–2015	1991–2013	1989–2010
Initialization	spinup	spinup	cold start	cold start	spinup	spinup	spinup	spinup	cold start	cold start
Source of atmospheric forcing data	ERA-Interim	coupled	NCEP RA1	ERA-Interim	ERA-Interim	JRA-55[1]	ERA-Interim	NASA MERRA2	ERA-Interim	ERA-Interim
Ocean restoring	Large scale bias correction to EN3v2a	fully coupled	None	T, S restoring towards EN4.1.1 for z>2000 m & lat < 60°N (τ=1 yr)	Surface Haney SSS restoring (-33.333 mm/d/PSU), 3D T/S to ENACT3 2004–2008 climatology (τ=1 yr)	Relaxing (by IAU) T/S to merged PHC3-WOA13 climatology	Relaxation to OSTIA/NOAA OIv2d SST	Restoring to mean T & S (τ=10 yrs). Relaxation to WOA SSS (τ=3 mths)	None	None
Sea-ice DA method	Nudging	None (SST)	None (SST)	reduced order KF	3DVAR	3DVAR	3DVAR-FGAT	None (SST)	EnKF	OI
Sea-ice DA variables	SIC	–	–	SIC	SIC, SIT	SIC	SIC	–	SIC, SIV	SIC
Sea-ice DA sources	NOAA OIv2d	–	–	CERSAT	OSISAFv2	MGDSST	OSTIA, NOAA OIv2d	–	OSISAF	OSISAF
Ocean DA method	3DVAR	EnKF	4DVAR (adjoint)	reduced order KF + 3DVAR large scale bias correction to in-situ T, S	3DVAR	3DVAR (τ=5 yrs)	3DVAR	OI	EnKF	OI
Ocean DA variables	T, S, SSH, SST	T, S, SST	T, S, SSH, SST	T, S, SSH, SST	T, S, SST, SSH	T, S, SSH, SST	T, S, SSH, SST	T, S, SST	T, S, SSH, SST	T, S, SSH, SST, SSS
Ocean DA sources	EN3v2a, AVISO	HadSST, OISST, WOD09, GT-SPP, Argo	EN3v2a, AVISO, GOCO, HadISST, AMSRE, WOA09	CMEMS, NOAA AVHRR	EN4, ICOADS, AVHRR, ATSR, AMSRE, AVISOv3	WOD13, GT-SPP, AVISO, MGDSST	EN3v2a, AVISO, OSTIA	WOD, ICOADS, AVHRR, Metosat SEVIRI	NOAA Reynolds, OSTIA, CLS, Damocles	EN3v2a

NH Mixed Layer Depth



Winter

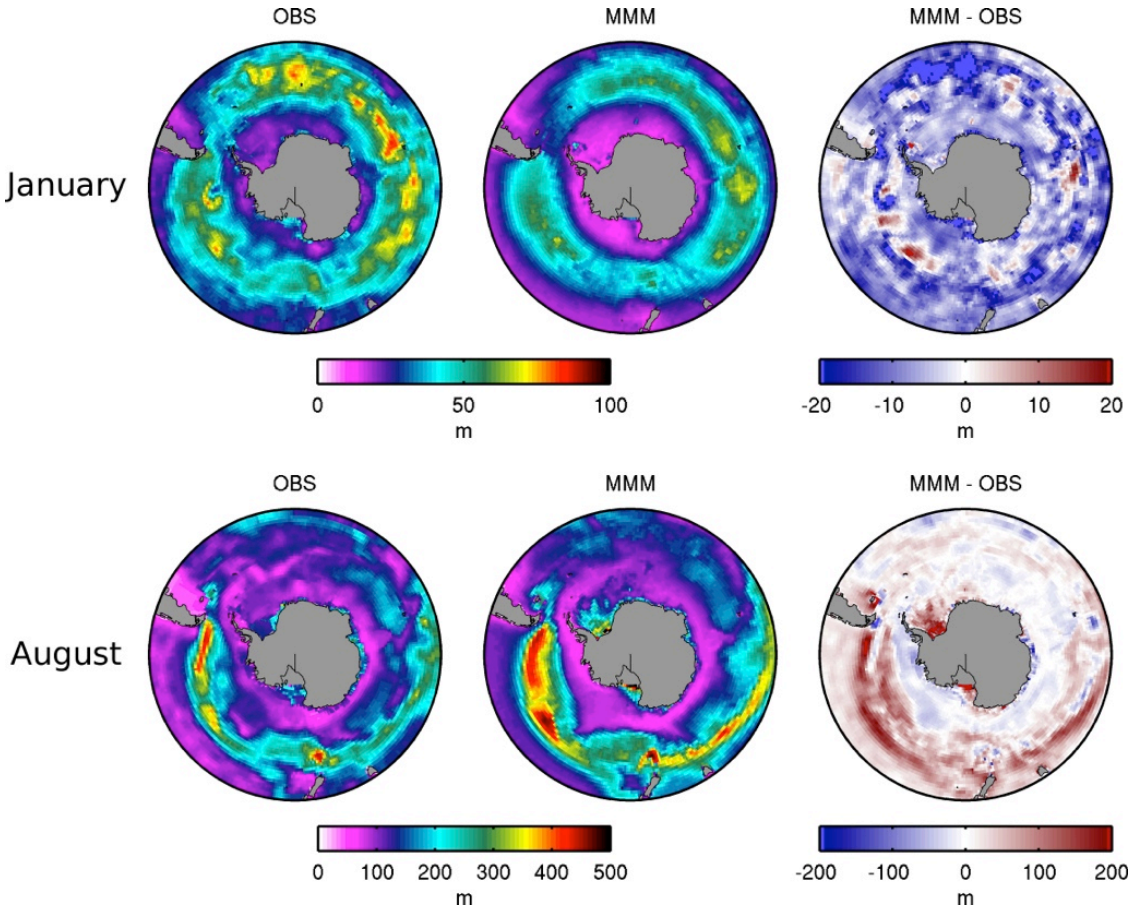
- observed pattern not well represented by MMM
- no uniform bias within the Arctic basin
- strong overestimation in all ORAs in the Barents Sea and south of Svalbard

Summer

- systematic under-estimation, especially under sea ice
- common bias in ocean models, whose cause is not clear

MLD criterion: 0.03 kg/m3 density threshold, reference at 10 m

SH Mixed Layer Depth



Summer

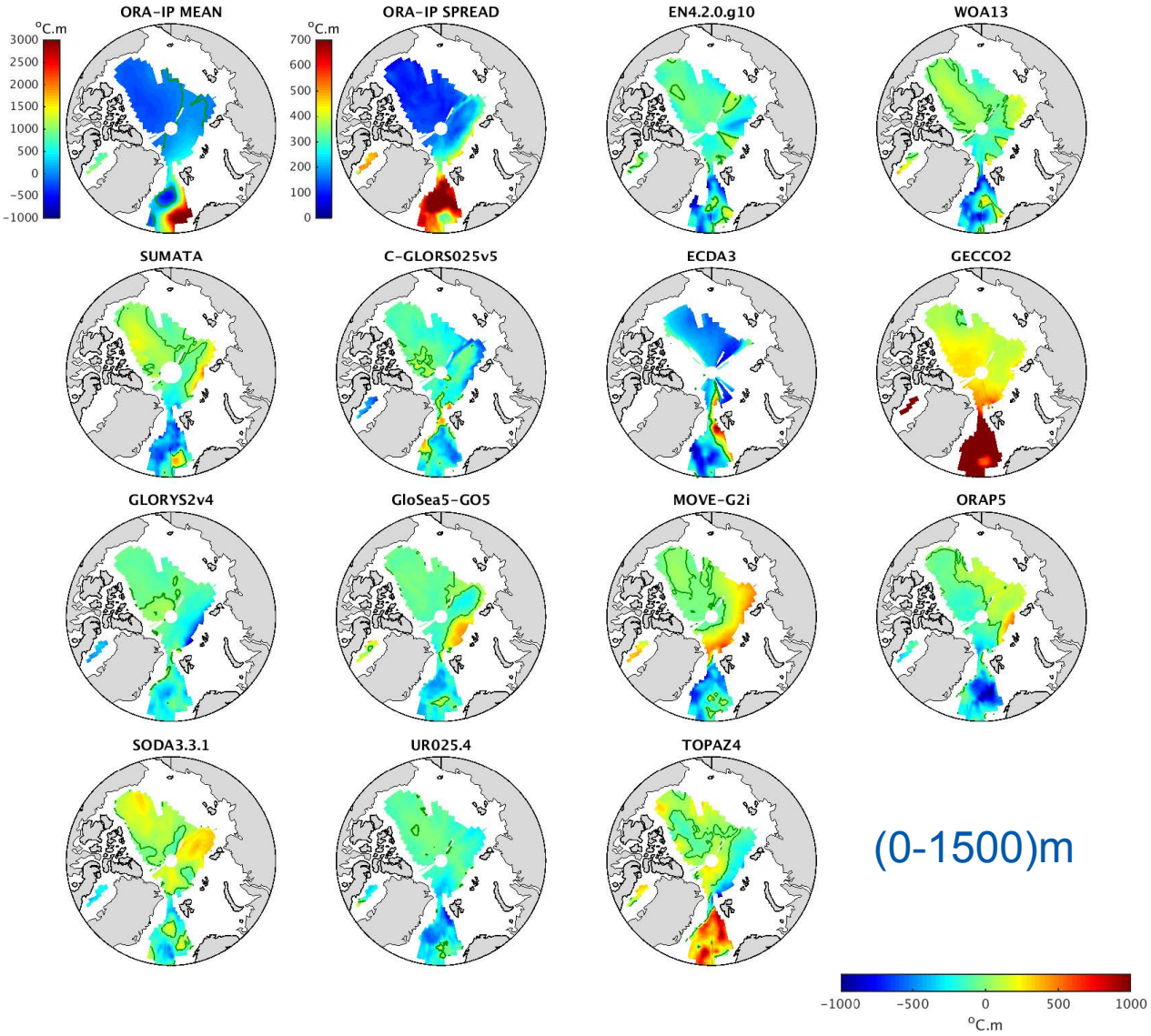
- underestimation south of the ACC in all but 2 ORAs
- relatively good representation of the band of deeper MLDs within the ACC

Winter

- overestimation of the deep MLDs north of the ACC in most ORAs
- underestimation along the coast of East Antarctica and overestimation in the Ross and Weddell Seas
- spurious deep convection in the Weddell Sea in 3 ORAs

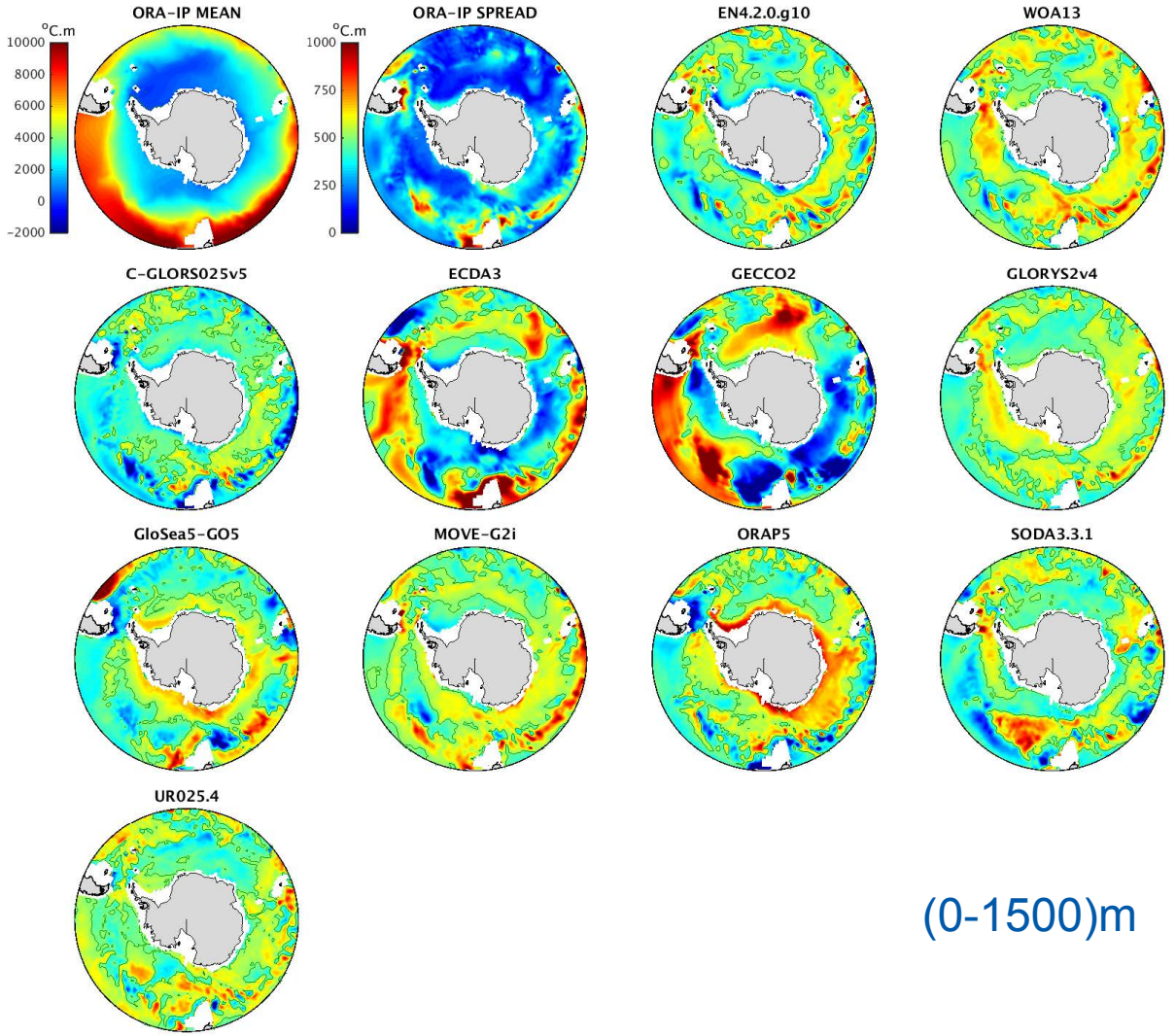
NH Ocean Heat Content

- ORA spread is largest in Norwegian Sea and Fram Strait
- GECCO2 is a warm outlier
- MOVE-G2i and SODA3.3.1 are warm outliers north of Fram Strait and in North Barents sea
- ECDA3 is a cold outlier
- Obs products appear a little warmer in the Beaufort Gyre and a little colder elsewhere than the ORA MMM



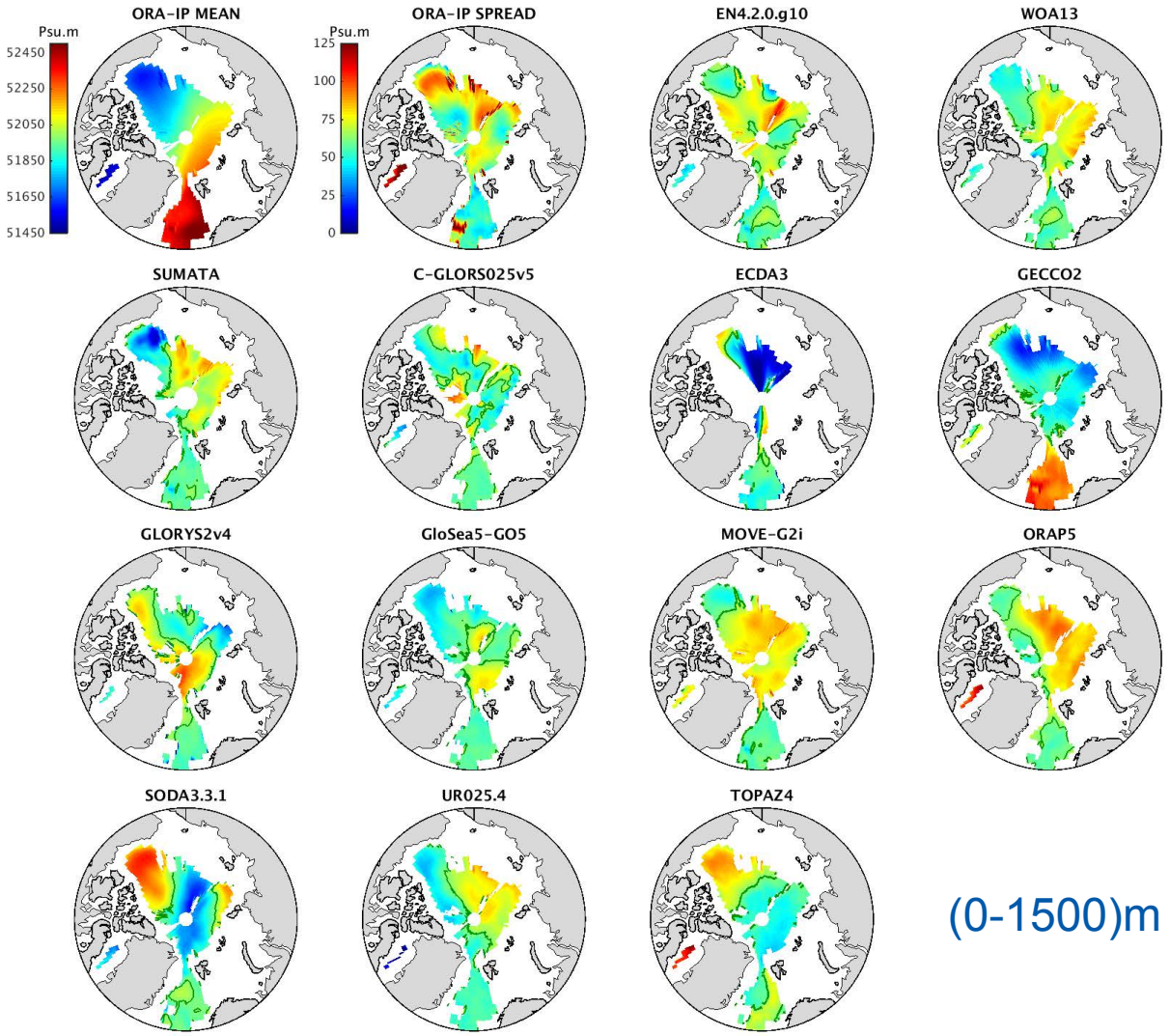
SH Ocean Heat Content

- ECDA3 and GECCO2 still show the largest anomalies, in this case both positive and negative.
- WOA13 is slightly warmer than EN4.2.0.g10
- Amplification of the anomalies in all products when compared to (0-100)m: It may reflect the larger disagreement in deeper levels.



NH Ocean Salinity Content

- ORA spread mainly stands out in the Pacific part of the Arctic basin
- Amerasian basin still has large discrepancies between different ORAs products
- Obs products appear to reasonably agree and suggest a freshier Beaufort Gyre, especially in the Sumata product



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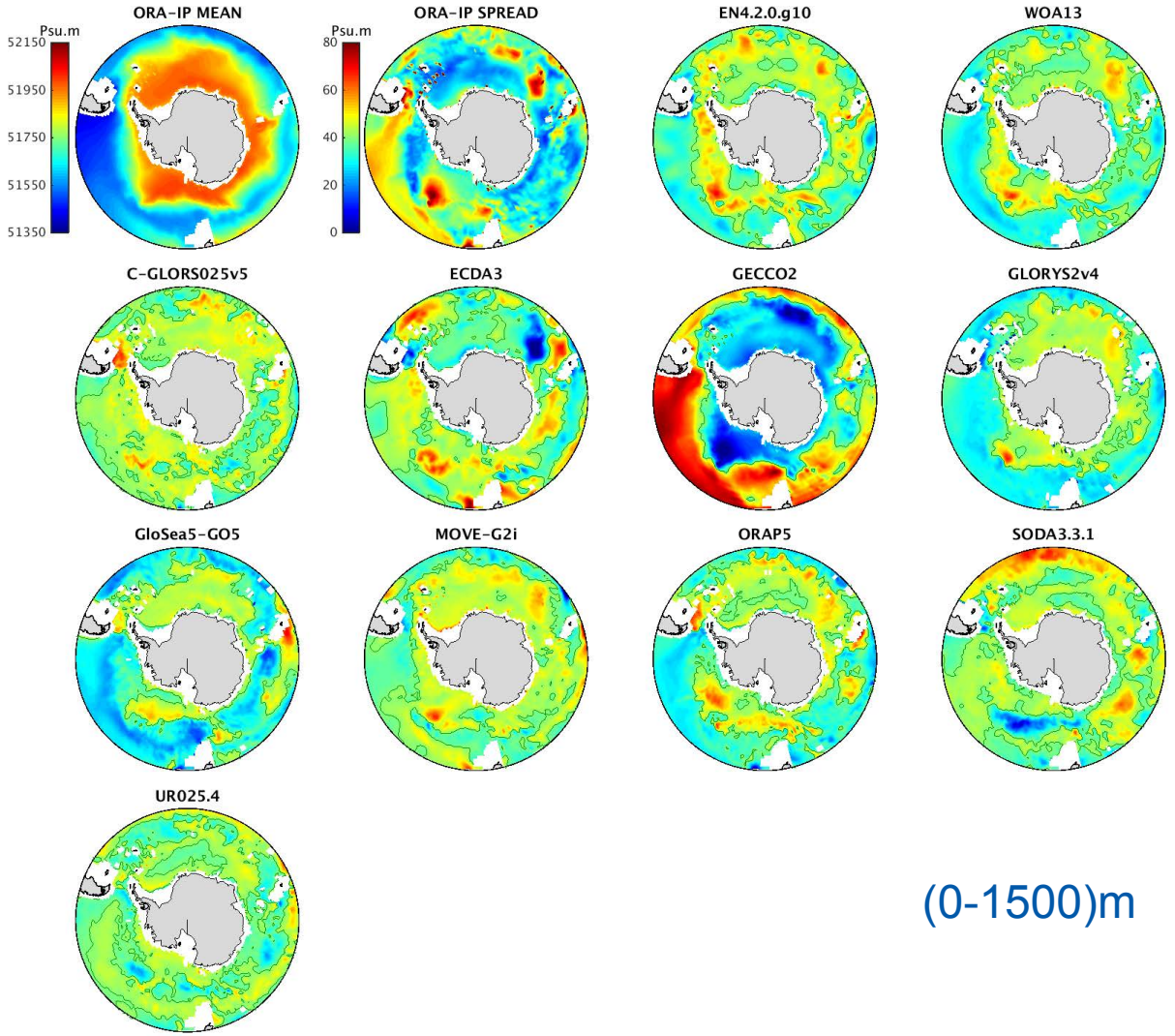
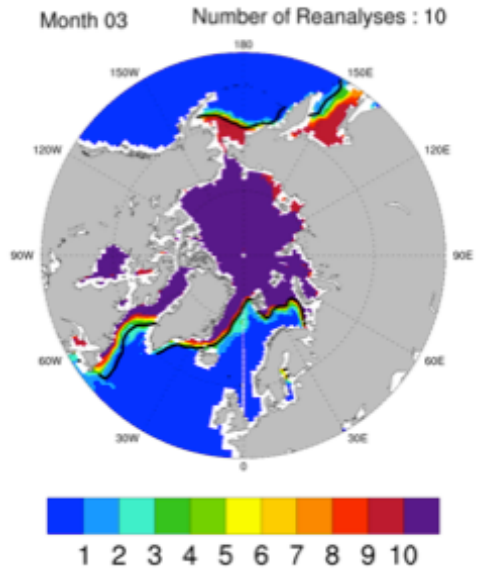
SH Ocean Salinity Content

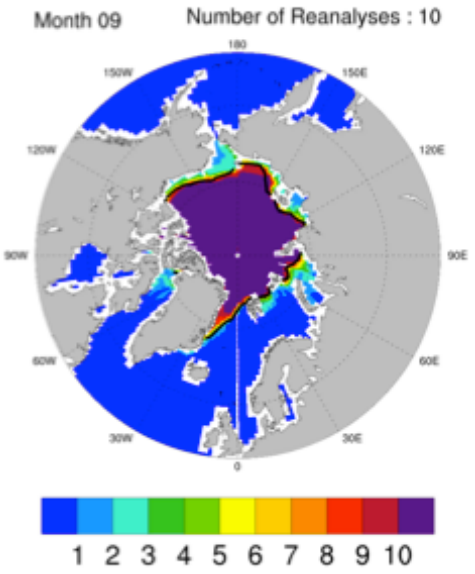
- GECCO2 stands out with very large anomalies.
- Increase of the anomalies relative to (0-100)m
- Good agreement between the obs products which are saltier than ORA-IP mean near Antarctic continent

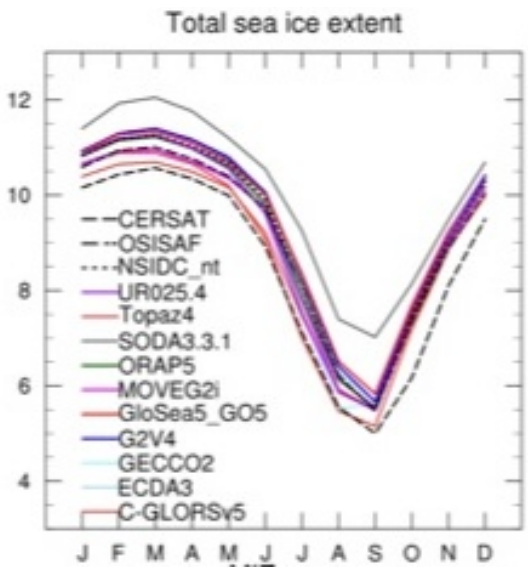


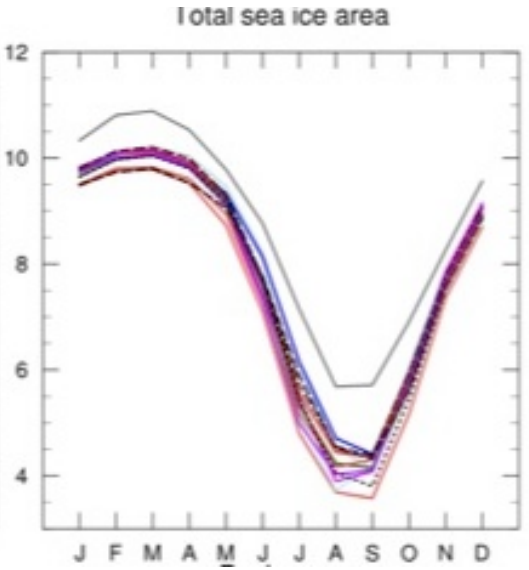
NH Sea Ice

- Overall agreement in the location of the ice edge in the Arctic Ocean and marginal regions
- Winter: biases in the Labrador Sea, the Greenland Sea, and the sea of Okhotsk
- Summer: underestimation east of Greenland Sea, overestimation in Kara +shelves
- Modeled seasonal cycle of SIA/SIE generally in phase with obs (min, max)
- Model spread comparable to that in observations (larger during winter)



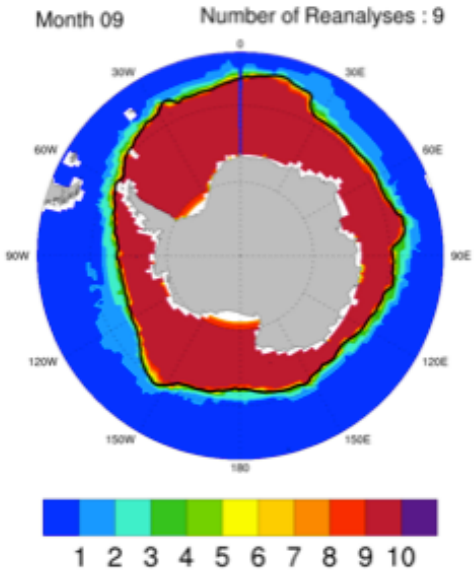


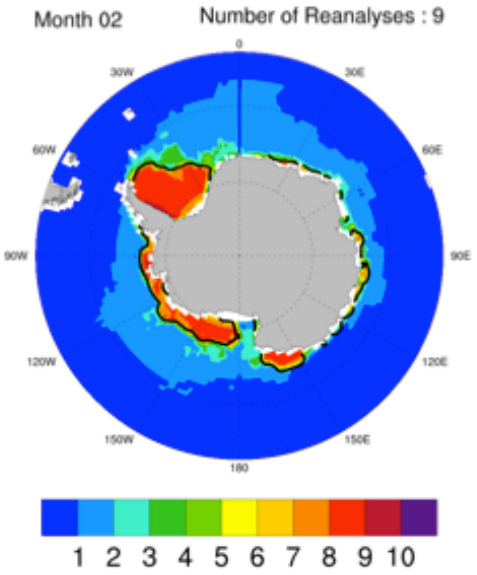


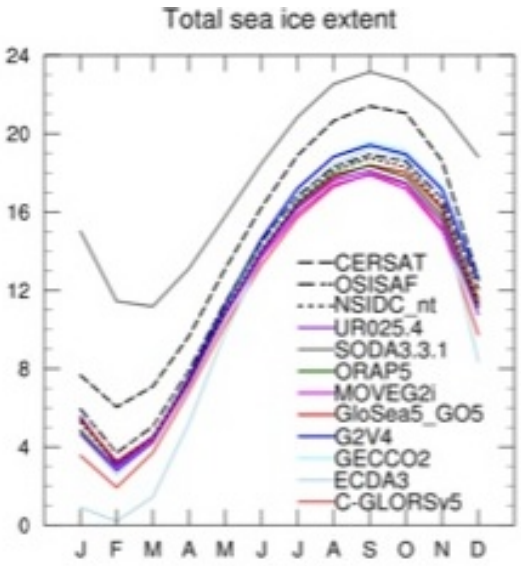


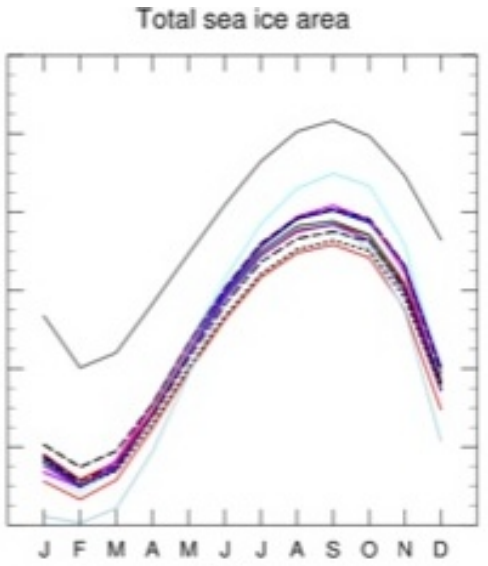
SH Sea Ice

- Overall agreement in the location of the ice edge
- Winter: few ORAs extend too far north
- Summer: SODA too persistent (outlier), ECDA too seasonal (ice free summer)
- Modelled seasonal cycle of SIA/SIE generally in phase with obs (min, max)
- ECDA has the widest seasonal cycle (low minimum and normal maximum)
- Larger spread during winter than in the summer
- Sea ice area overestimated during the winter



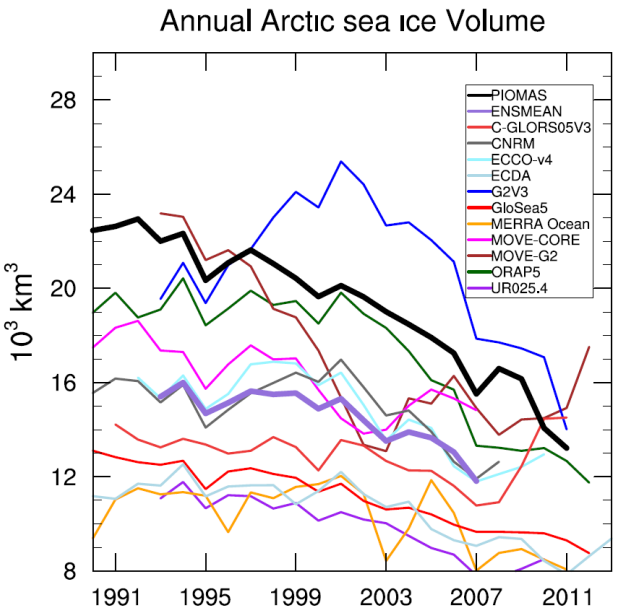






Limitations of current sea ice reanalyses

- The spread in sea ice cover is large in available ORAs
  - Representation/modeling of sea ice varies from model to model
  - Data assimilation algorithms are sometimes very basic (nudging/restoring)
  - The observational data assimilated are also subject to errors and biases
  - Not much is known about uncertainties within each model
- Arctic sea ice predictability is thought to stem in part from sea ice IC up to decadal time scales
  - A good representation of sea ice is a necessary condition for skillful forecasts



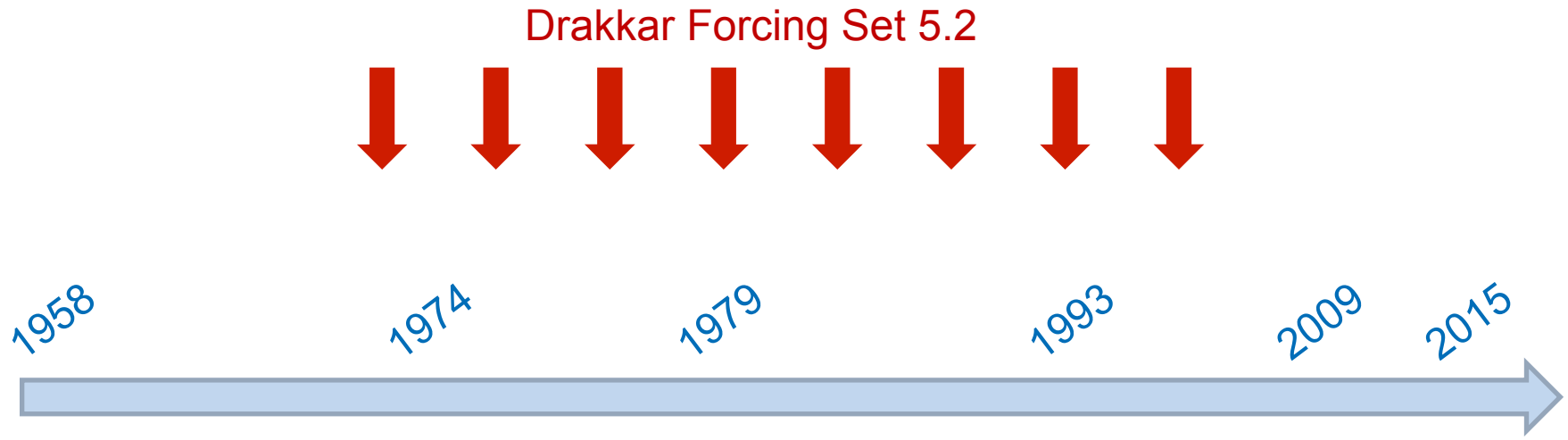
We propose an ensemble sea ice reanalysis conducted with a state-of-the-art ocean sea ice model assimilating high-quality observational data using an advanced data assimilation scheme

EnKF vs other data assimilation methods

	Nudging/erstoring	Variational (3D/4D Var)	Sequential methods (EnKF)	Particle filtering
Ease of implementation	Fair	Hard (coding adjoint)	Medium-Hard	Medium
CPU consumption	Low	Low-Medium	High (~20-50 members)	Very high (~100 members to avoid degenerate solution)
Needs changes in model code?	Yes (restoring term added to tendencies)	Yes (adjoint)	No	No
Physical consistency	Little (univariate)	Up to linear approximation	Up to linear approximation	Full consistency
Estimation of prior uncertainty	None	Static	Dynamic	Dynamic
Assumptions to reach optimality	Not defined as an optimization problem	Gaussian centered errors	Gaussian centered errors	None
Produces ensembles?	No	No	Yes (hence available as IC)	Yes (hence available as IC)

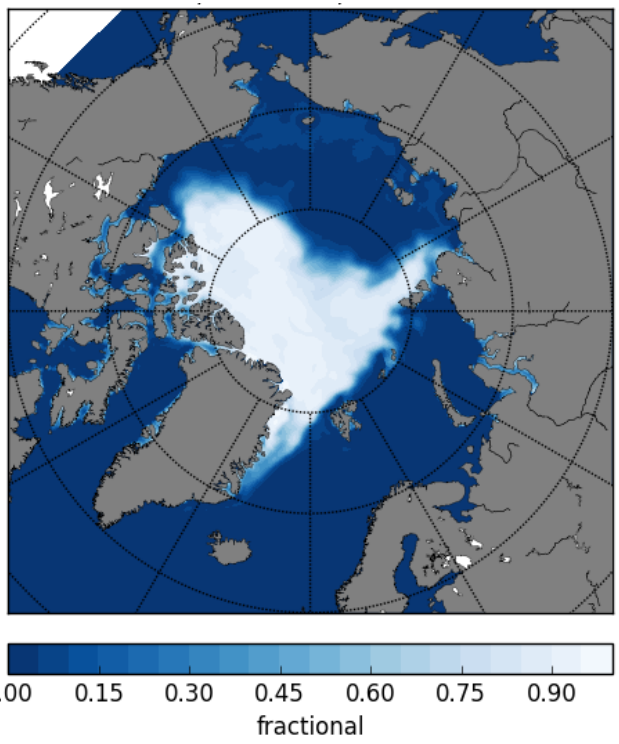
A Kalman Filter (KF) is a multivariate statistical method for state estimation by maximizing the posterior state distribution, given obs, assuming bias-free models, and obs and gaussian distribution of errors.

Numerical setup for EnKF sea ice reanalysis



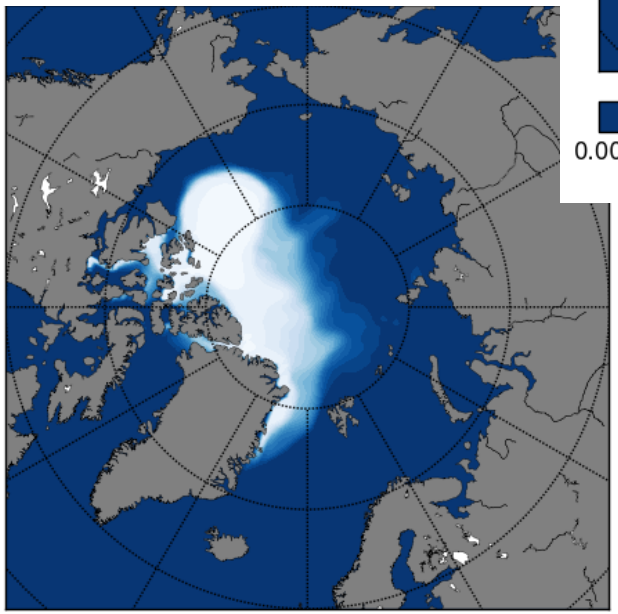
September 2007 monthly sea ice minimum

ESA-SIC-CCI obs, September 2007

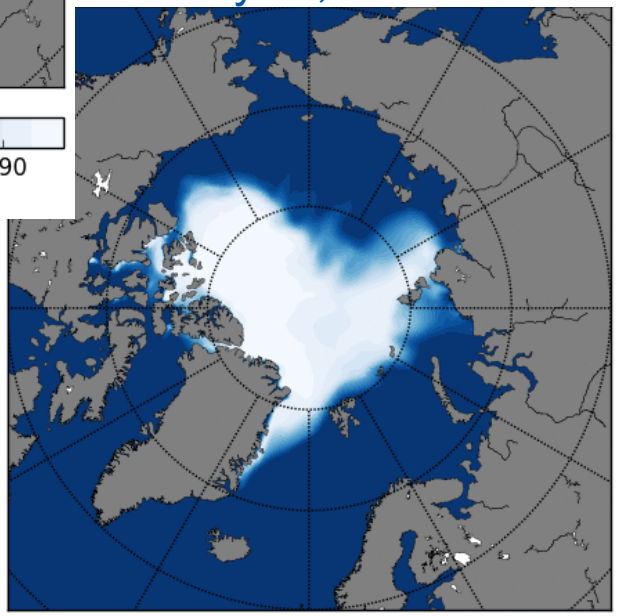


Substantial regional improvements

Model without EnKF

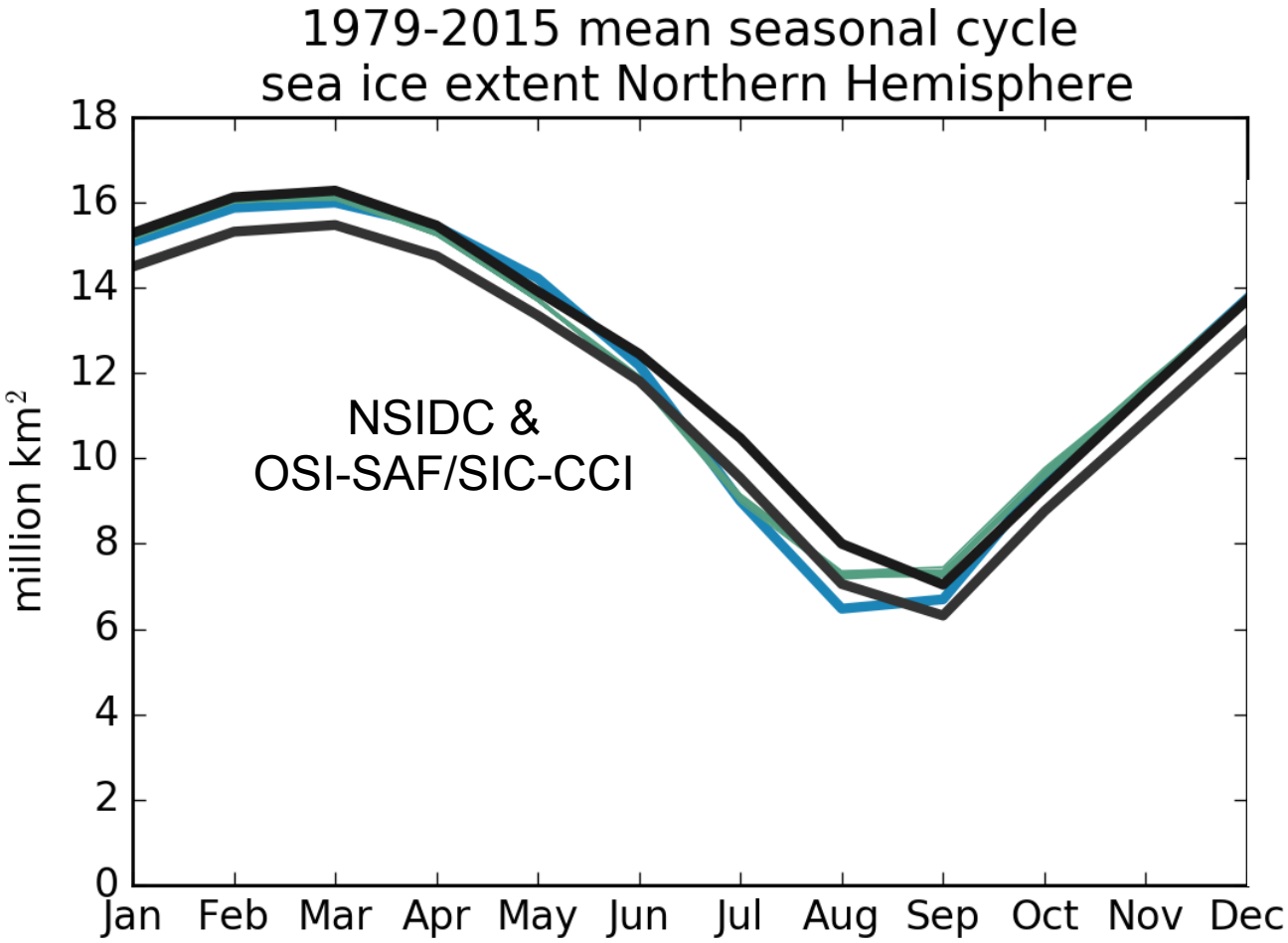


Reanalysis, 25 members



Seasonal cycle of the NH sea ice extent

Bear in mind that observational products are also uncertain!

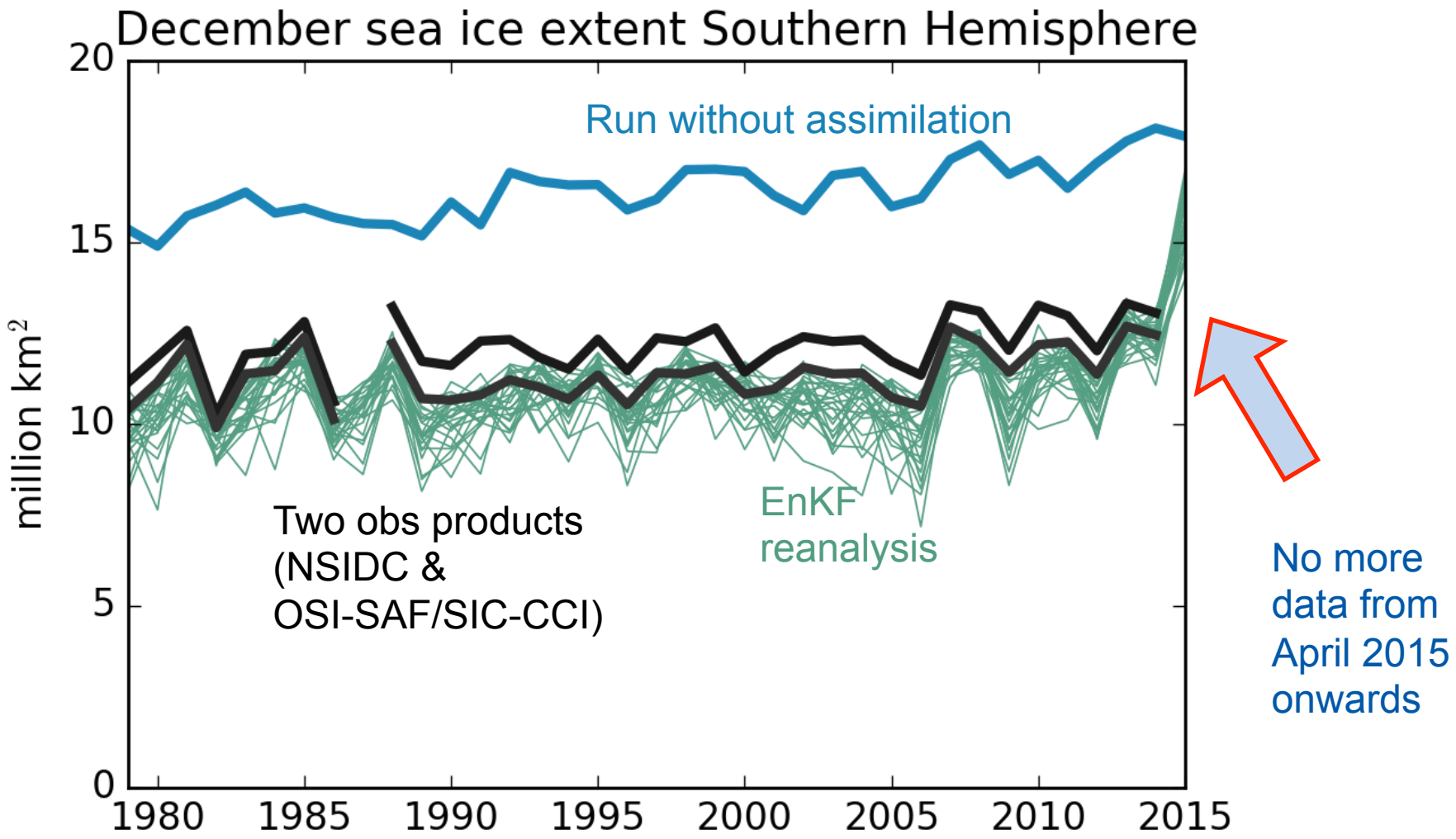


Free run

EnKF reanalysis

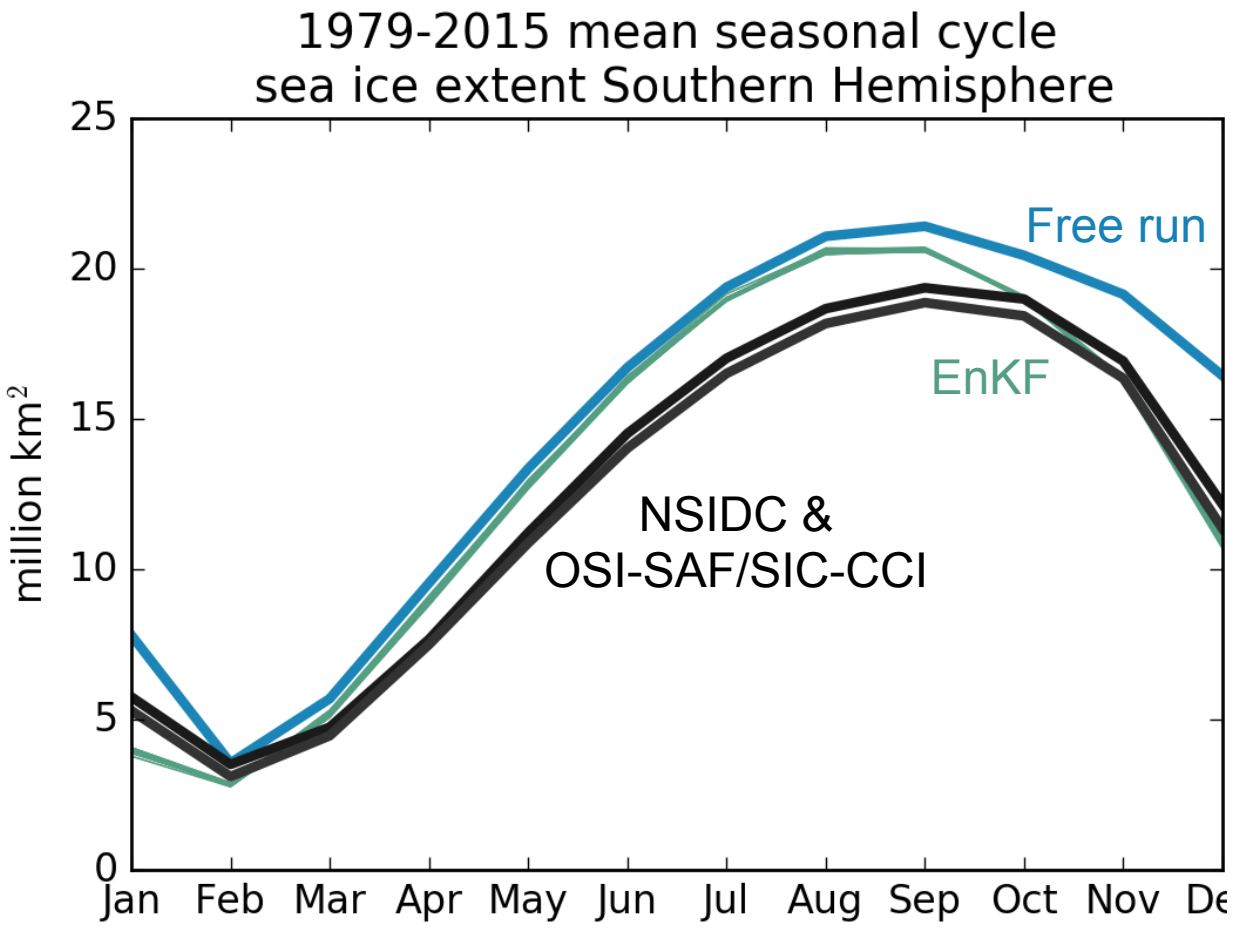
Subtle influence at pan-Arctic level

Impact of missing data

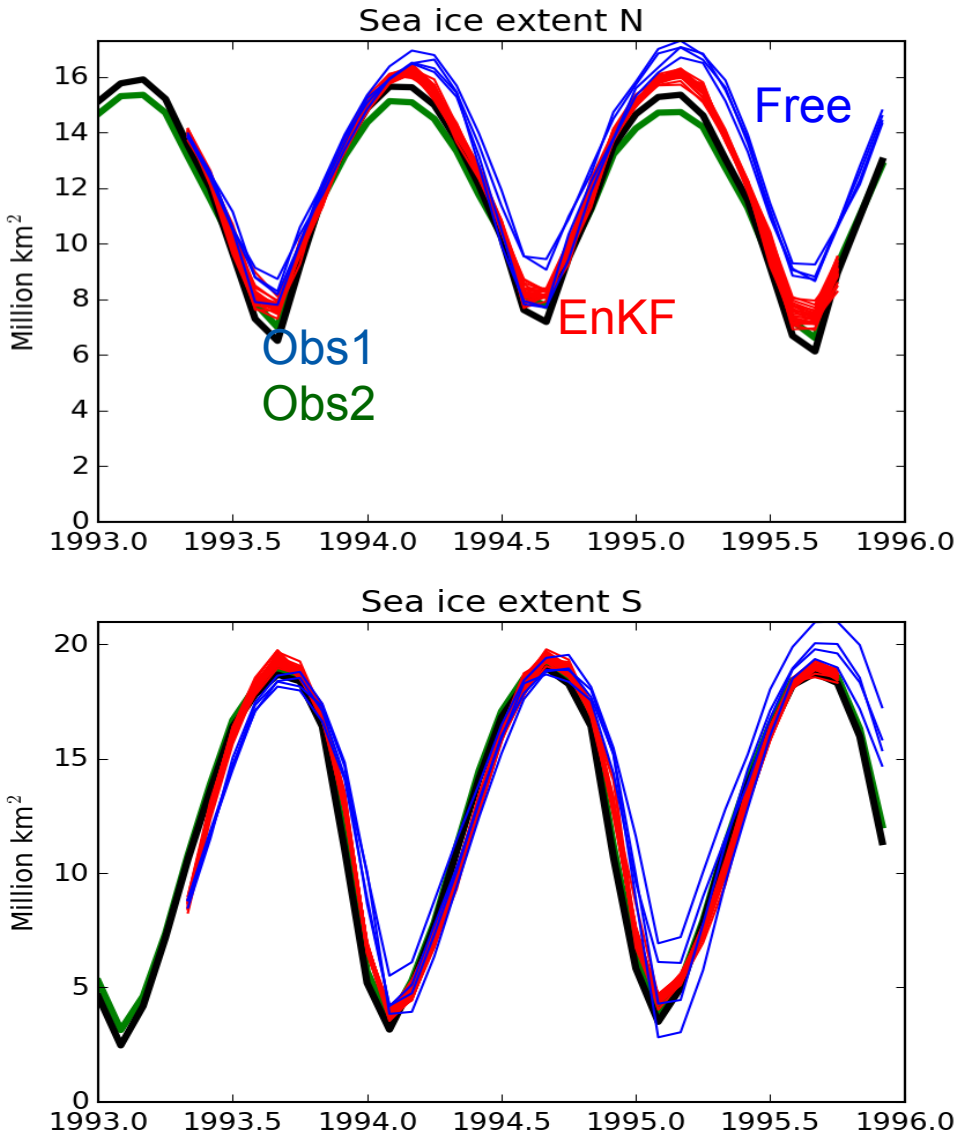


Seasonal cycle of the SH sea ice extent

Sea ice assimilation is mostly reducing melt biases, not growth biases in the Southern Ocean



Coupled EnKF sea ice reanalysis



NH SIE

SH SIE

A prototype coupled data assimilation scheme has been developed:

- SIC is assimilated monthly in EC-Earth3.2
- The EnKF provides a good constraint on sea ice extent

Summary and conclusions

Polar ORA-IP (community activity):

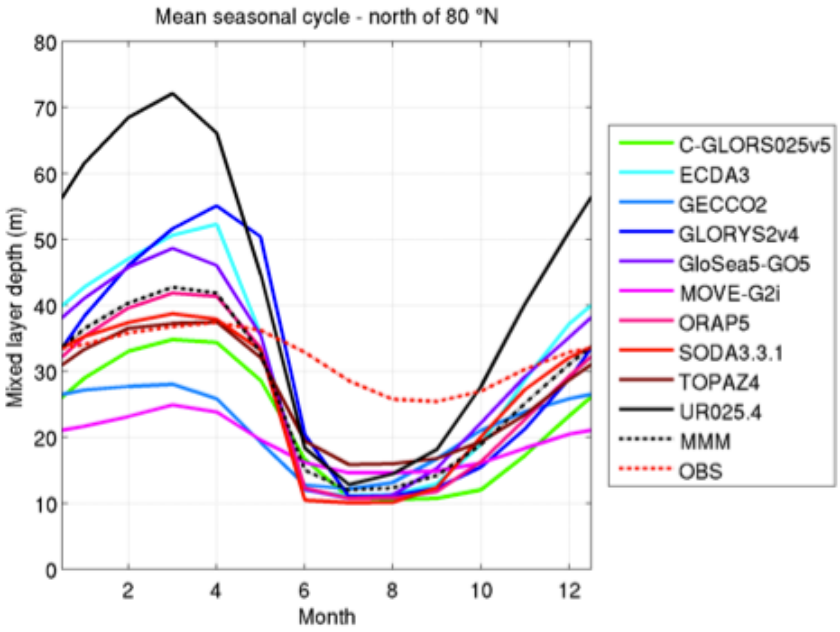
→ ORAs agree well on the location of sea ice edge in the Arctic and Southern Ocean, but sea ice concentration tends to be overestimated

→ ORAs have too shallow (deep) MLD in summer (winter) likely due to missing or crude parameterization of subgrid-scale processes

→ Ocean heat and salinity content in polar and subpolar regions show significant discrepancies with respect to obs datasets – such errors can have significant impact on the skill of initialized climate prediction

BSC activity:

→ EnKF data assimilation of sea ice concentration reduces sea-ice biases from regional to hemispheric scales



Thank you for your attention

Gracias por su atención
Preguntas, comentarios, ..

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