Bjerknes Centre for Climate Research

Norwegian Earth System Model (NorESM) preparing for CMIP6

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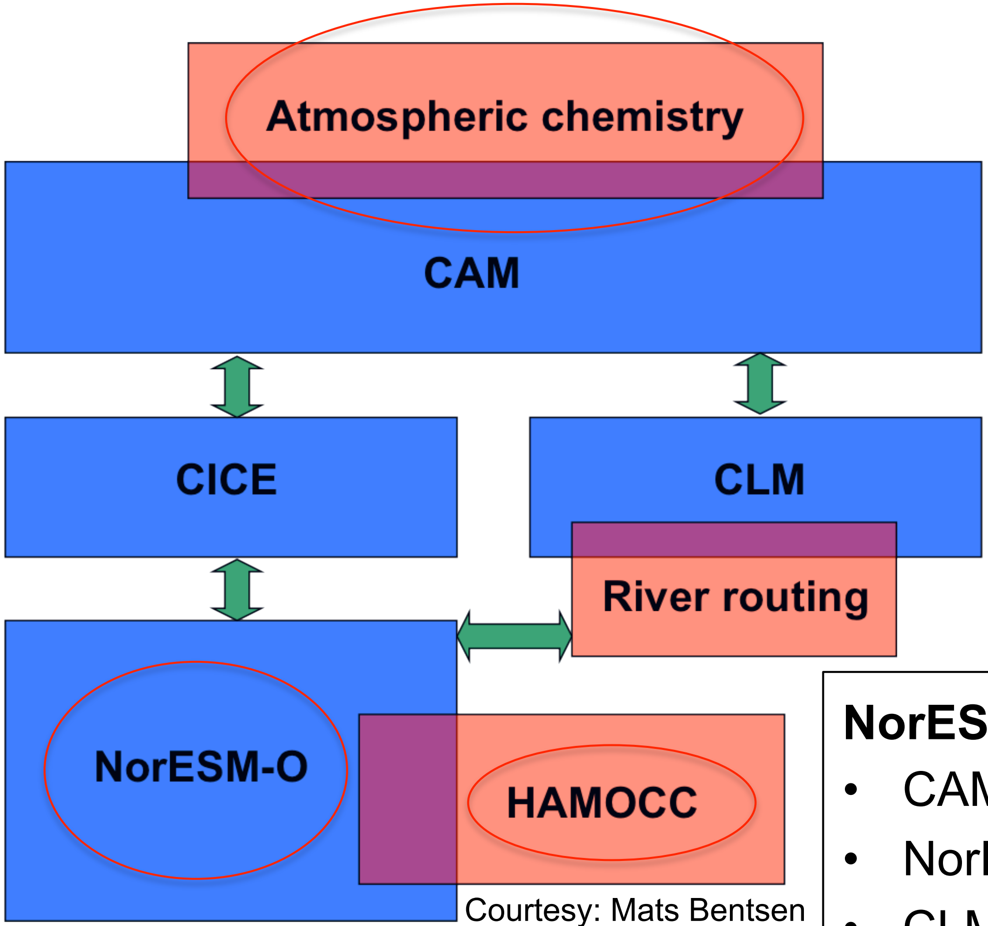
Norwegian Earth System Model



Courtesy: Mats Bentsen

Components in blue communicate through a coupling component.

Components in red are subroutines of blue components.

Variant of CESM with key modifications

1. Aerosol life cycle and cloud interaction from Oslo (CAM-OSLO)
2. Isopycnic coordinate ocean model (NorESM-O) based on MICOM
3. Hamburg Ocean Carbon Cycle biogeochemistry model (HAMOCC) adapted to isopycnic coordinates
4. Ensemble Kalman-filter assimilation adapted to isopycnic coordinates

NorESM1-M (Bentsen et al. 2012, Iversen et al. 2012)

- CAM4-Oslo (1.9x2.5, L26)
- NorESM-O (1deg gx1-grid, L53)
- CLM4, CICE4, CPL7 as in CCSM4

CMIP5

NorESM1-ME (Tjiputra et al. 2012)

- based on CESM1 and includes HAMOCC
- otherwise same as NorESM1-M

Development history

CAM5-Oslo (in progress)

CAM4-Oslo (Kirkevåg et al. 2013)

CAM3-Oslo (Seland et al. 2008)

CCM3-Oslo (Iversen & Seland 2002, Kirkevåg & Iversen 2002)

ECMWF-offline aerosol (Seland & Iversen 1999)

NorESM2 based on CESM2 (in progr.) **CMIP6**

NorESM1-ME based on CESM1 (Tjiputra et al. 2012) CMIP5

NorESM1-M based on CCSM4 (Bentsen et al. 2012) CMIP5

NorESM2-O/OC (in progress)

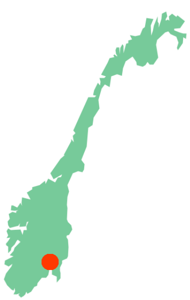
NorESM-O (Bentsen 2012)

MICOM/HAMOCC/LPJ coupled to ARPEGE/IFS (BCM-C, Tjiputra 2010)

MICOM coupled to ARPEGE/IFS (Bergen climate model - BCM, Furevik et al. 2003) CMIP3

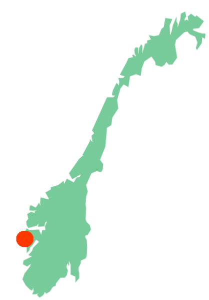
aerosol-cloud processes development in Oslo

ocean physics, dynamics and biogeochemistry in Bergen



Norwegian Climate Prediction Model (NorCPM) = NorESM + EnKF assimilation CMIP6 DCPP (Counillon et al. 2015, Wang et al. 2015)

assimilation in Bergen



Why have a Norwegian ESM?

Merits

- stimulates activity and collaboration on national level
- fosters local expertise that is key to inform stake-holders and public
- allows optimisation for regions and processes of national interest
- provides infrastructure for assessing the importance and utility of new process knowledge in regional and global context
- provides infrastructure for integrating new process knowledge
- strengthens international visibility and attracts international scientists
- makes your institute attractive partner in international projects

Challenges

- demanding to maintain a state-of-the-art system
- have to ensure uniqueness of model system to justify its development
- proprietary issues need to be clarified: branding/naming of model, giving appropriate credit to parent model (CESM genology – Knutti et al. 2013)
- should feed developments back into parent model (two-way exchange) but this requires harmonization of source code + enough manpower

Why have a Norwegian ESM?

- over 50 NorESM users and growing
- model used in 39 national projects with total budget of 50 mill USD
- model used in 26 international projects with total budget of 130 mill USD
- CMIP5 output from NorESM1 used in ~500 peer-reviewed publications

What defines NorESM?

CAM-Oslo

What

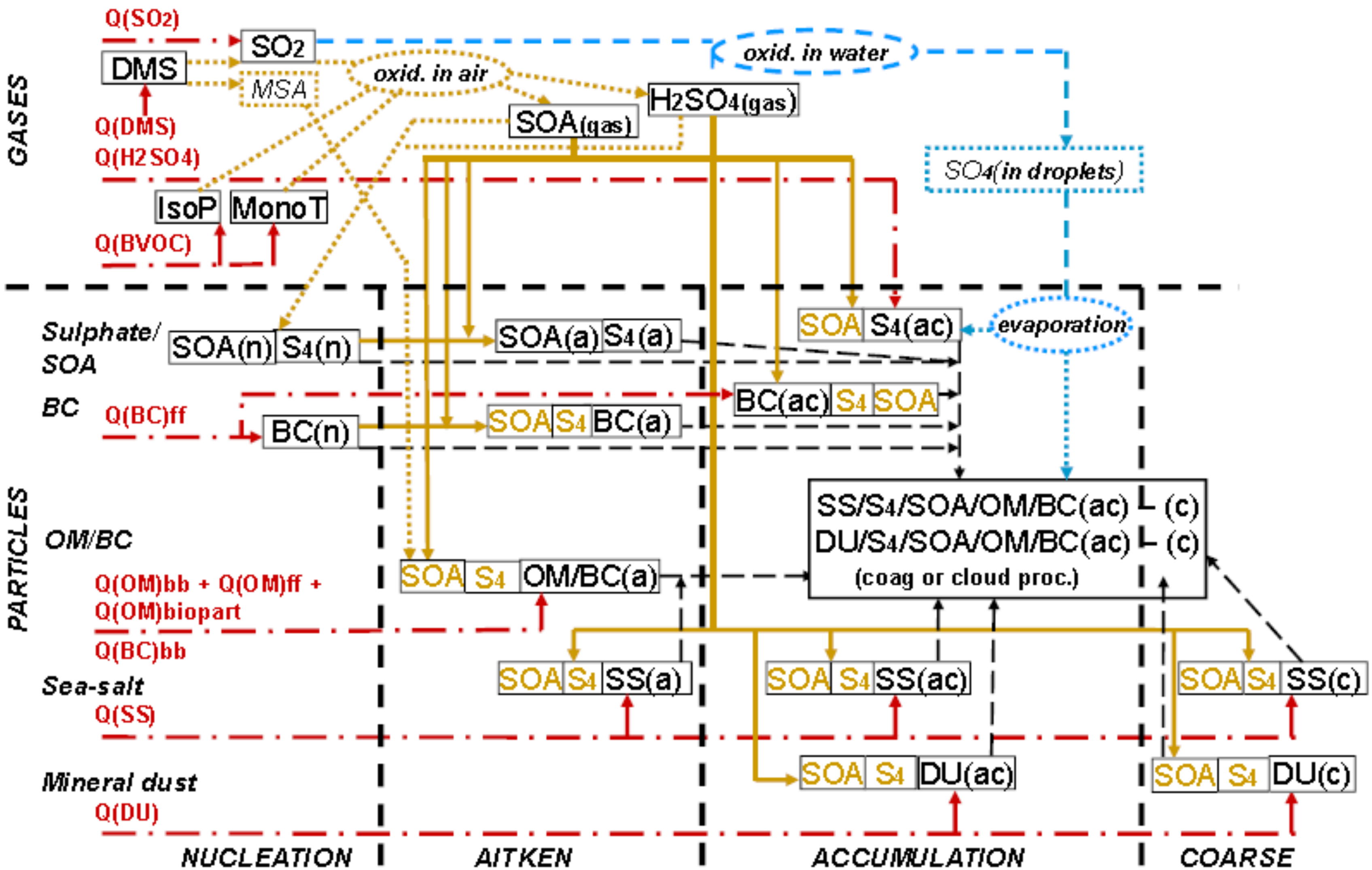
- schemes for aerosol chemistry, aerosol physics and interaction with clouds that are developed in Oslo
- alternative to modal aerosol module (MAM) in CAM5

Key features

- chemical comp.: dust, sea salt, black carbon, sulphate, organic matter, H2O
- 20 aerosol mixtures + precursors SO2 and DMS = 22 active tracers
- 4 size modes: nucleation, Aitken, accumulation, coarse
- calculates log-normal size distributions with changing median and log-std
- uses tabulated optical properties (e.g. single scattering, asymmetry factor, extinction coefficient) that are pre-calculated for a wide range of input values
- direct and indirect aerosol effects (no indirect effects in standard CAM4)

CAM-Oslo

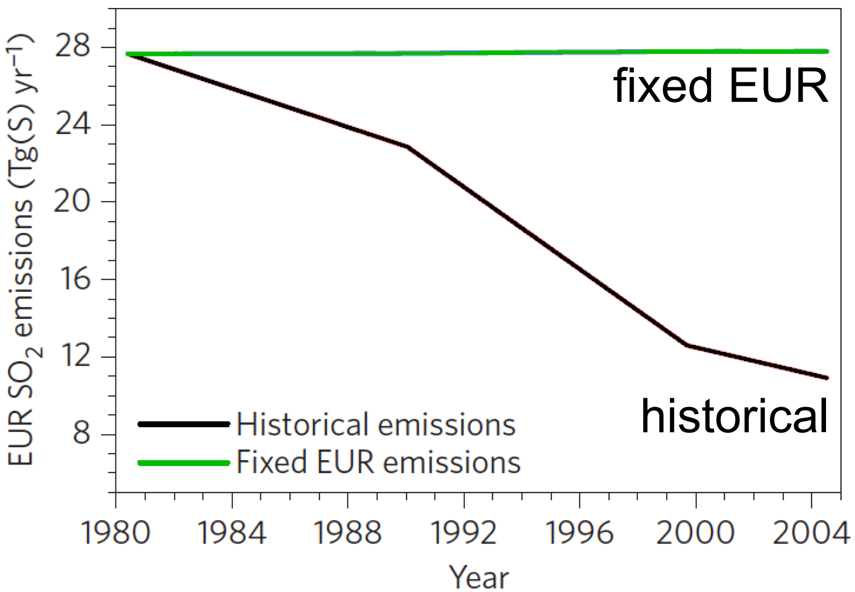
Comprehensive description of aerosol life cycles and cloud interactions



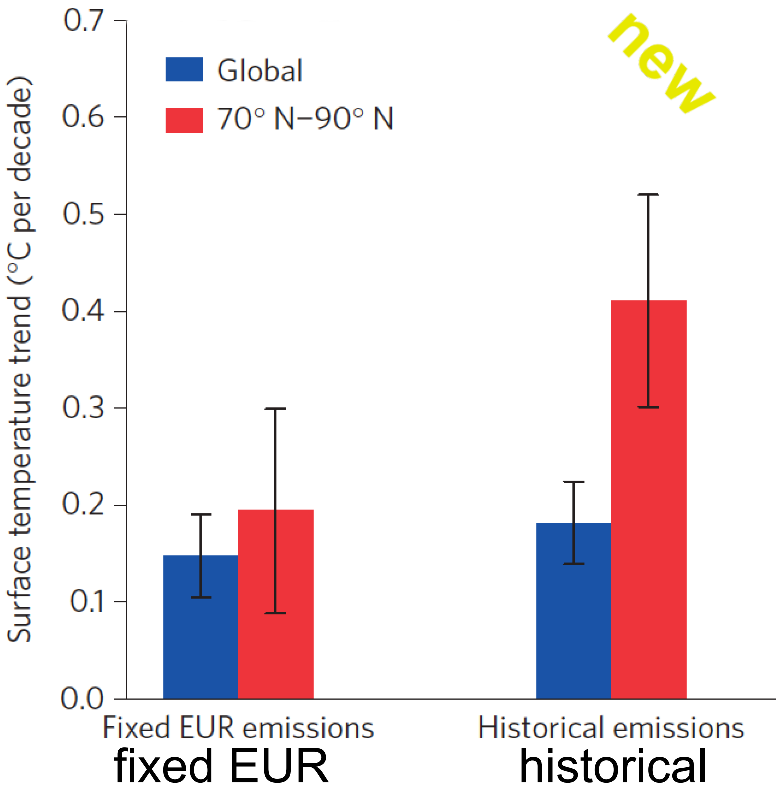
Kirkevåg et al. 2013, GMD

CAM-Oslo

Research focus – aerosol and cloud processes in high-latitude regions



Navarro et al. 2016, Nature Geoscience
using an updated version of NorESM1-M



Recent reduction in European SO2 emissions contributed to Arctic amplification of global warming

CAM-Oslo

Research focus – climate sensitivity to anthropogenic aerosol emissions

Effective radiative forcing (present day – pre-industrial aerosol emissions) new

ERF (W/m^2) decomposition	CAM4-Oslo	CAM5-Oslo	CAM5 MAM3	CAM5 MAM7	CAM5 MAM7-aging	IPCC AR5
SW ARI	-0.10	-0.07	-0.02 ± 0.01	0.00 ± 0.01	0.08	-0.45 (-0.95 to 0.05)
LW ARI	–	0.03	–	–	–	
SW ACI	-0.91	-0.97	-1.99	-2.00	-2.01	-0.45 (-1.20 to 0.0)
LW ACI	0.01	-0.02	0.54	0.46	0.27	
ARI & ACI	-1.00	-1.03	-1.47 ± 0.11	-1.54 ± 0.06	-1.66	-0.9 (-1.9 to -0.1)
Reference	Kirkevåg et al. (2013)	--	Ghan et al. (2012)	Ghan et al. (2012)	Ghan et al. (2012)	Myhre et al. (2013)

ARI=direct effect ACI=indirect effects

Courtesy: Alf Kirkevåg

Total EFR ~50% higher in CAM-MAM than in CAM-OSLO

CAM-Oslo

NorESM2 CMIP6 developments

- new sea spray emission parametrization (Salter et al. 2015)
- explicit particle formation from biogenic precursors (Makkonen et al. 2014)
- interactive DMS and marine primary organic matter *(will show results later)*
- interactive aerosol – ice nucleation (based on Wang et al. 2014)
- Nitrate aerosols under development for use in AerChemMIP

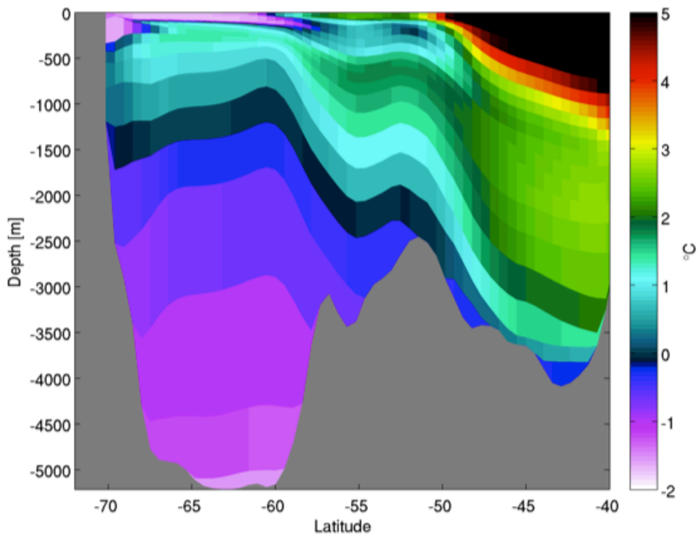
NorESM ocean component (NorESM-O)

What

- based on the Miami Isopycnic Coordinate Ocean Model (MICOM)
- further developed at the Bjerknes Centre in Bergen
- earlier version used as ocean component of the Bergen Climate Model (BCM)

Key features

- natural representation of motion (overflows, thermohaline circulation, potential vorticity) as water tends to follow surfaces of constant density
- spurious diapycnal mixing is minimized -> (nearly) closed energy budget
- accurate conservation and transformation of water mass and tracer properties



Meridional T section through Southern Ocean

Research focus

- water mass transformation and exchanges in the North Atlantic and Arctic
- climate variability and trends on decadal-to-centennial time scales
- ocean heat uptake and vertical redistribution -> climate sensitivity & sea level
- ice sheet – ocean interactions

NorESM ocean component (NorESM-O) – dynamical core

- **Mass conserving** formulation (non-Boussinesq).
- **Leap-frog** and forward-backward time-stepping for the baroclinic and barotropic mode, respectively.
- **Arakawa C-grid** horizontal discretization.
- Momentum equations formulated in vector invariant form and solved with a **potential vorticity/enstrophy conserving** scheme (Sadourny, 1975).
- Layer thickness and tracer **advection by incremental remapping** (Dukowicz and Baumgardner, 2000).
- Accurate vertical integration of the **in situ density in the evaluation of the pressure gradient** force.

- computationally efficient
- good conservation of properties
- leap-frog replaced in future

NorESM ocean component (NorESM-O) – physics

Surface bulk mixed layer

- The depth (detrainment/entrainment) is estimated with a Kraus-Turner type turbulent kinetic energy TKE model (Oberhuber, 1993).
- Extended with a parameterization of restratification by submesoscale eddies (Fox-Kemper et al., 2008).

Eddy mixing

- The parameterization of thickness (Gent and McWilliams (GM), 1990) and isopycnal eddy diffusivities follows the diagnostic version of the eddy closure of Eden and Greatbatch (2008).
- **The eddy diffusivities are reduced when the grid resolves the first baroclinic Rossby radius**.

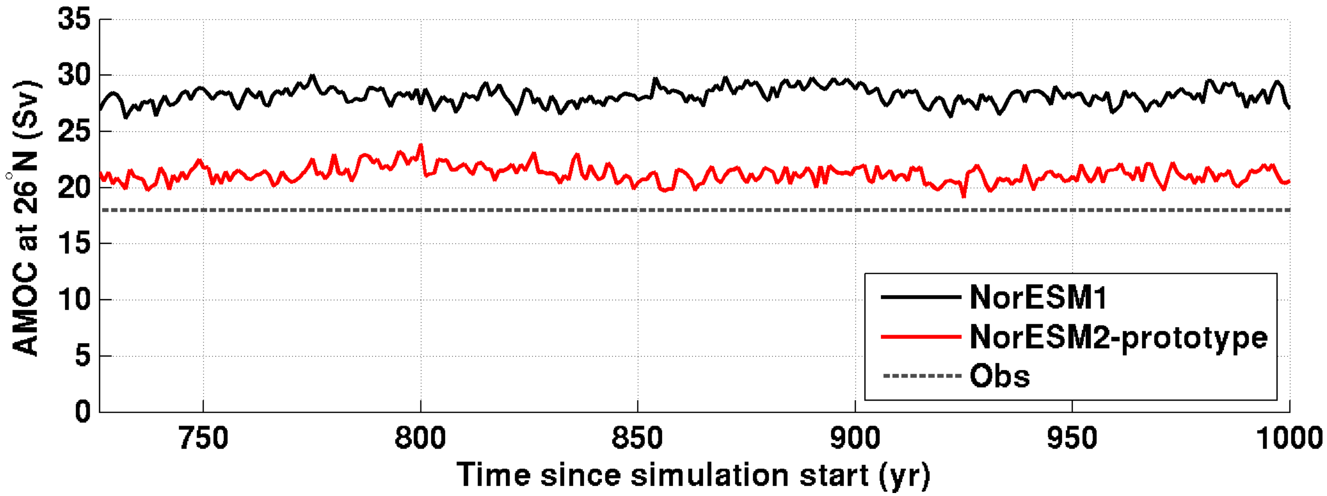
Diapycnal mixing

- Background diffusivity is vertically constant but with a latitude dependence following Gregg et al. (2003).
- Shear driven mixing follows Large et al. (1994) but with increased maximum allowable mixing near the ocean bottom to provide sufficient mixing downstream of overflows.
- Mixing driven by energy extracted from the mean flow by bottom drag.
- Tidally driven mixing according to Simmons et al. (2004).

NorESM ocean component (NorESM-O)

Atlantic meriodional overturning circulation much improved

new



Problem

- positive bias in subtropical surface salinities (mirrored by negative bias at intermediate levels)
- ➢ increased salt advection to subpolar North Atlantic
- ➢ increased dense water formation leading to intensification of AMOC

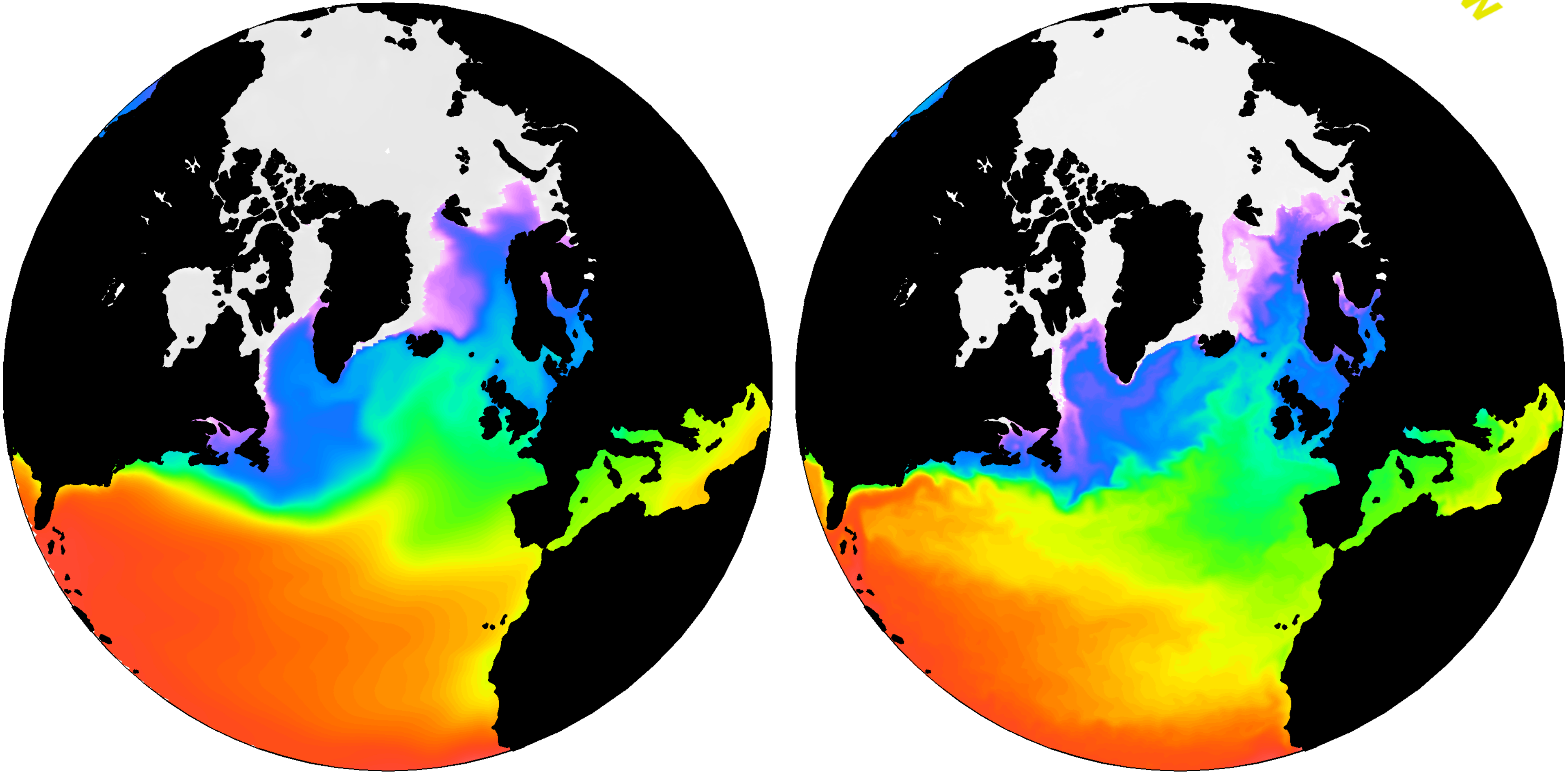
Solution – revised implementation of GM eddy mixing

- old formulation: layer interface smoothing, only active below mixed layer
- new formulation: true Gent-McWilliams implementation, extending to surface

NorESM ocean component (NorESM-O)

Horizontal resolution increased from 1° in NorESM1 to ¼° in NorESM2

new



- indications of reduced SST biases in ¼° configuration
- SST fronts sharper in ¼°; important for 1° atmospheric response?
- more realistic exchange between North Atlantic and subpolar seas

HAMburg Ocean Carbon Cycle model (HAMOCC)

What

- biogeochemistry module coupled to physical ocean component of NorESM

Key features

- formulation in isopycnic coordinate framework unique
- advanced representation of sediment interactions

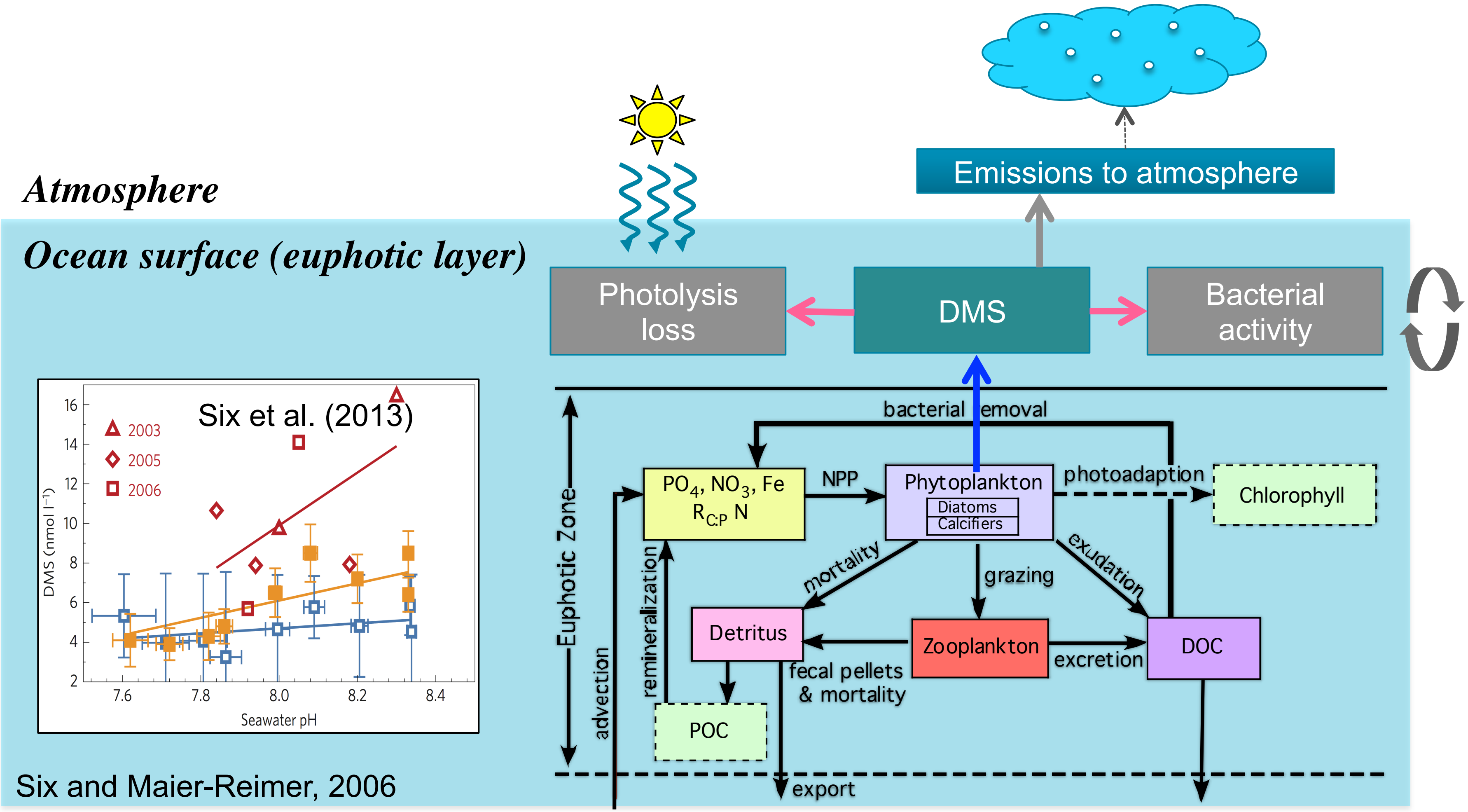
Research focus

- uncertainties in future ocean carbon uptake
- compatible GHG emission for atmospheric CO2 trajectories (Jones et al. 2013, J. Clim.)
- biogeochemical atmosphere–ocean interactions (DMS and N2O emissions, iron flux with dust)
- constraining ocean ventilation/mixing with help of biogeochemical tracers

HAMburg Ocean Carbon Cycle model (HAMOCC)

Marine DMS cycle included with PH dependency

new



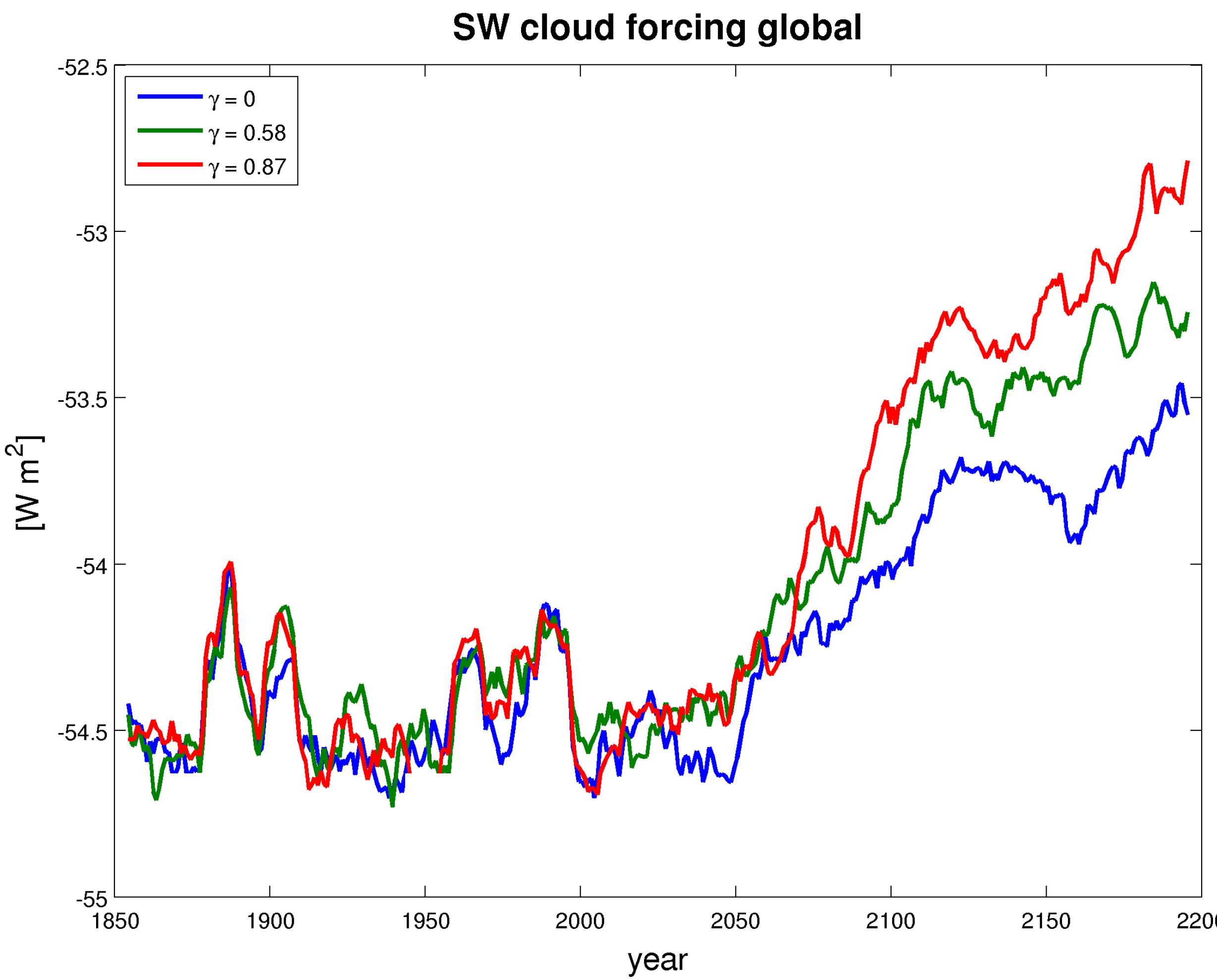
Courtesy: Jerry Tjiputra

Acidification leads to future decrease in DMS production

HAMburg Ocean Carbon Cycle model (HAMOCC)

Marine DMS included in HAMOCC with PH dependency

new

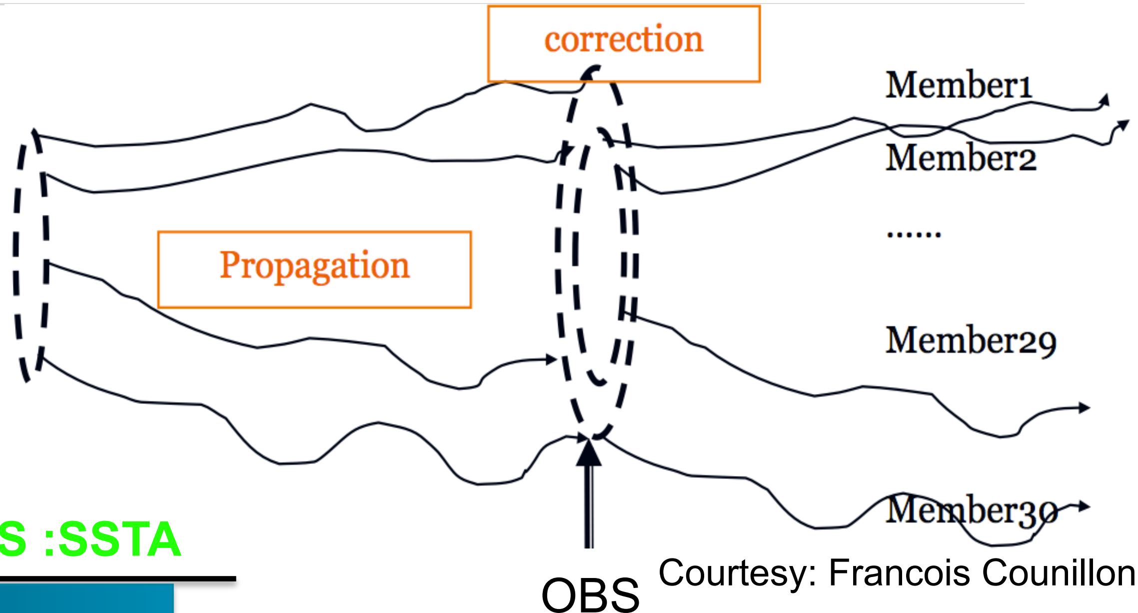


Courtesy:
Jörg Schwinger

Up to 0.5 W global SW cloud forcing using RCP8.5 scenario

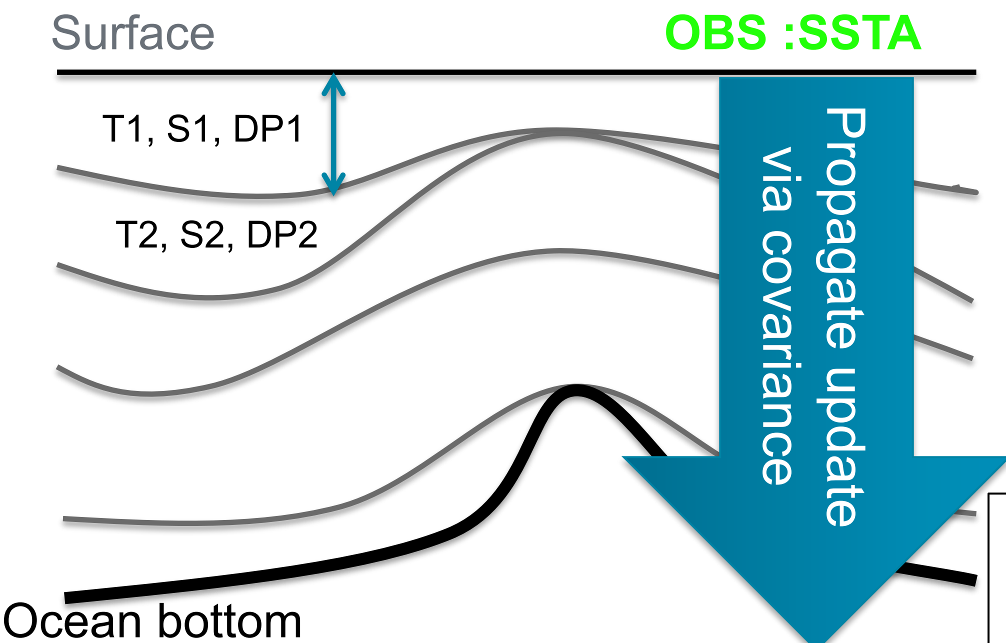
Ensemble Kalman filter assimilation in isopycnic coordinates

1. We use dynamical covariance



Courtesy: Francois Counillon

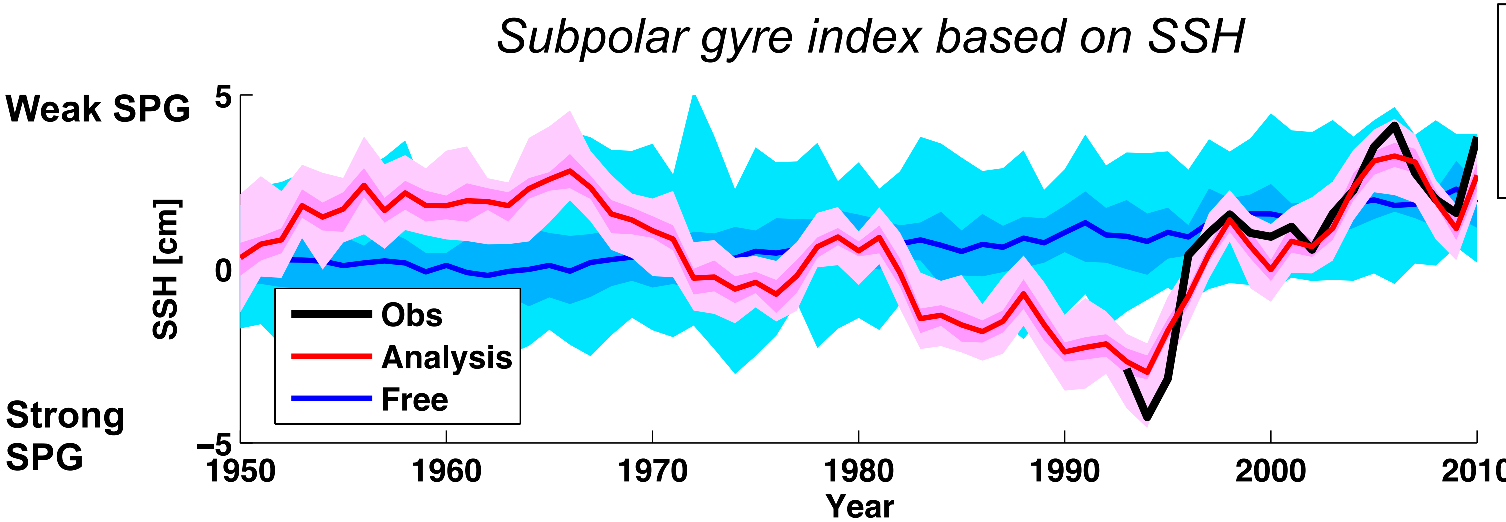
2. Covariance are constructed in isopycnal coordinate



Courtesy: Noel Keenlyside

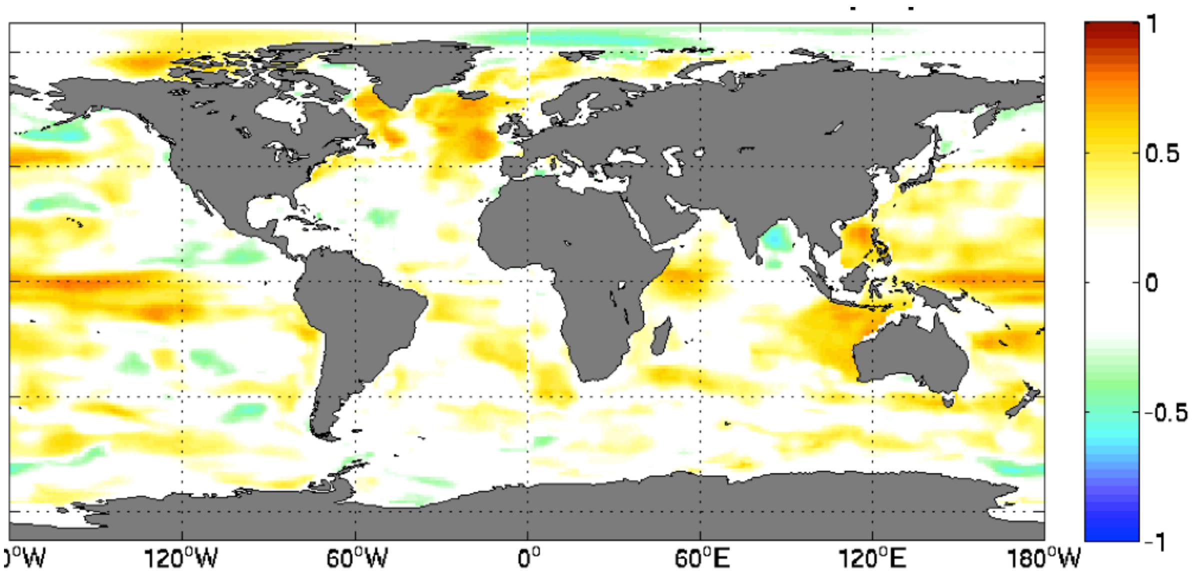
split into density compensated T/S update and **layer thickness (density stratification) update-> efficient synchronisation of dynamics**

Ensemble Kalman filter assimilation in isopycnic coordinates



Assimilated observations: **SST only**

new



Correlation with 0-200m Salt Content, EN4 objective analysis, yearly

EnKF assimilation contraints variability of unobserved variables

Courtesy: Francois Counillon

Preparing for CMIP6

NorESM1 vs NorESM2

		NorESM1 (CMIP5)	NorESM2 (CMIP6)
CESM version		CCSM4/CESM1	CESM2
ATMOSPHERE	CAM version	CAM4	CAM5.5
	Deep convection	Zhang-McFarlane (1995)	Zhang-McFarlane (1995)
	Shallow convection	Hack (1994)	CLUBB?
	PBL	Bretherton and Park (2009)	CLUBB?
	Microphysics	Rasch and Kristjánsson (1998)	Gettelman and Morrison (MG2; 2015)
	Aerosols	CAM4-Oslo	CAM5-Oslo
LAND	CLM version	CLM4	CLM5
	River routing	RTM	MOSART
OCEAN		NorESM1-O	NorESM2-O
SEA ICE		CICE4	CICE5

we try to stay close to CESM2 to 1) help attribution of climate differences and 2) facilitate future upgrades

NorESM2 resolutions and CMIP6 contributions

NorESM2-		HH	MH	MM	LM
RESOLUTION	Atmos. – Land	H: 0.23°x0.31°	**M: 0.9°x1.25°**	M: 0.9°x1.25°	**L: 1.9°x2.5°**
RESOLUTION	Ocean - Sea-Ice	H: 0.25°	**H: 0.25°**	M: 1°	**M: 1°**
PROCESSES	Atmos. Chem.	Simplified	**Simplified**	Simplified	**Simplified + full**
PROCESSES	Ocean BGC.	TBD	**TBD**	ON	**ON**
CMIP-DECK + CMIP6 Hist		(from MH)	**ALL**	ALL	**ALL**
MIPs		HighResMIP	**AerChemMIP CFMIP, RFMIP DAMIP, OMIP ScenarioMIP**	AerChemMIP CFMIP, RFMIP DAMIP, OMIP ScenarioMIP	**AerChemMIP CFMIP, DAMIP DCPP, LS3MIP LUMIP, OMIP PMIP, RFMIP ScenarioMIP VolMIP**
Comment		experimental ver., depends on EU PRACE resources	**flagship, cutting edge version**	fallback version if MH not realisable	**affordable version for ensemble and long runs**

CAN WE DO IT?

Courtesy: Trond Iversen

CMIP6 simulation plan – two scenarios

High (stretch goal) scenario

- use medium-high resolution configuration (MH: 1° atm, 1/4° ocn), including ocean biogeochemistry
- complete MH and ML production by end of 2017 and HH by fall 2018

Low (minimum) scenario

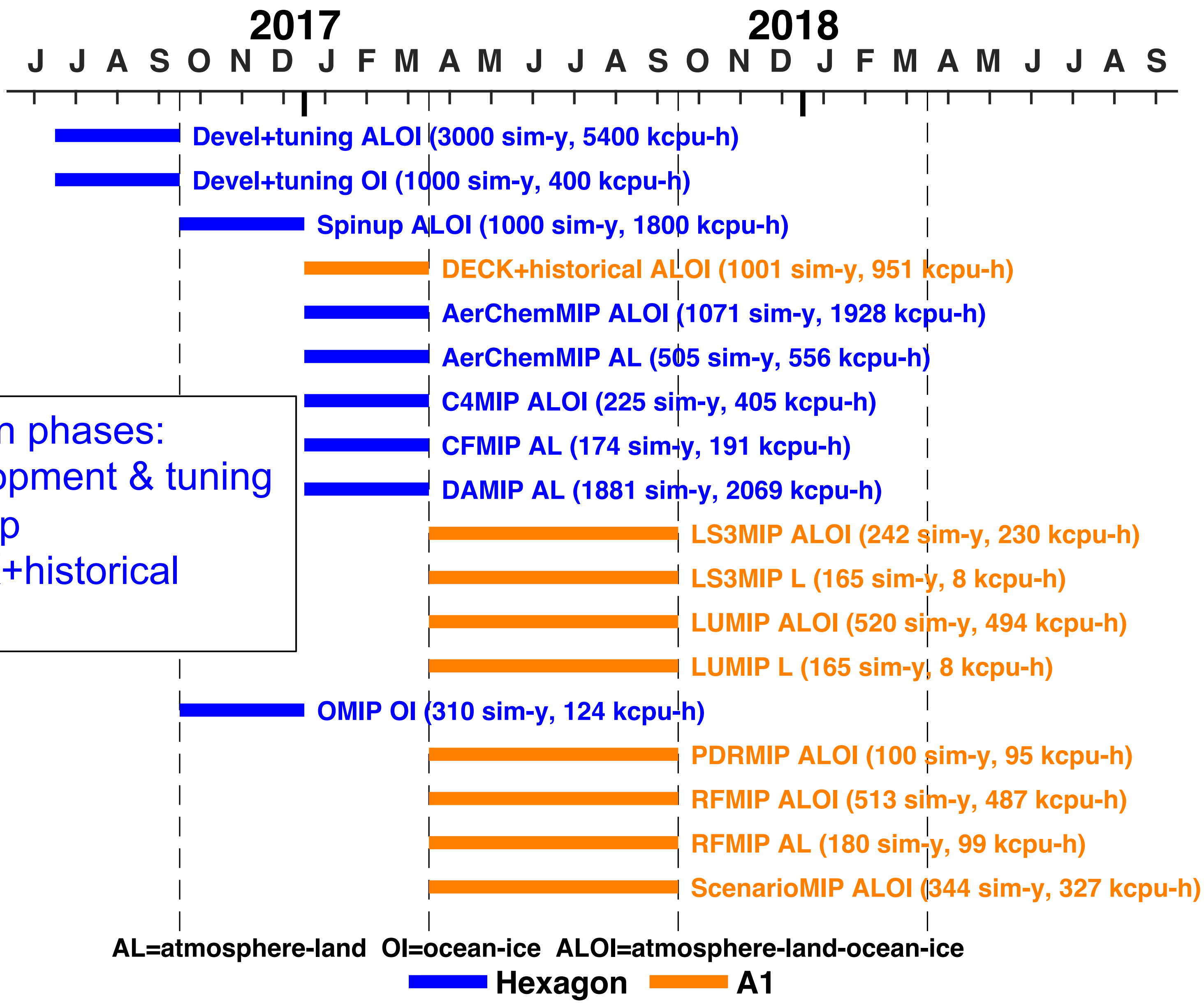
- use medium-medium resolution (MM: 1° atm, 1° ocn) instead of MH
- use 1° and 1/4° ocn for OMIP but without ocean biogeochemistry
- no high-high (HH) configuration
- otherwise same as high scenario

we are already 3-6 months behind schedule

CMIP6 simulation plan – information gathered in xml-sheets

MIP	Years	Model	Components	Machine	Start	End
Devel+tuning	3000	LM	ALOI	Hexagon	01.07.2016	01.10.2016
Devel+tuning	500	LM	OI	Hexagon	01.07.2016	01.01.2017
Spinup	800	LM	ALOI	Hexagon	01.10.2016	01.01.2017
DECK+historical	1001	LM	ALOI	A1	01.01.2017	01.04.2017
AerChemMIP	505	LM	AL	Hexagon	01.01.2017	01.04.2017
AerChemMIP	1071	LM	ALOI	Hexagon	01.01.2017	01.04.2017
C4MIP	225	LM	ALOI	Hexagon	01.01.2017	01.04.2017
CFMIP	174	LM	AL	Hexagon	01.01.2017	01.04.2017
DAMIP	1881	LM	AL	Hexagon	01.01.2017	01.04.2017
LS3MIP	165	LM	L	Vilje	01.04.2017	01.10.2017
LS3MIP	242	LM	ALOI	Vilje	01.04.2017	01.10.2017
LUMIP	165	LM	L	Vilje	01.04.2017	01.10.2017
LUMIP	520	LM	ALOI	Vilje	01.04.2017	01.10.2017
OMIP	310	LM	OI	Hexagon	01.01.2017	01.04.2017
PDRMIP	100	LM	ALOI	Vilje	01.04.2017	01.10.2017
RFMIP	180	LM	AL	Vilje	01.04.2017	01.10.2017
RFMIP	513	LM	ALOI	Vilje	01.04.2017	01.10.2017
ScenarioMIP	344	LM	ALOI	Vilje	01.04.2017	01.10.2017

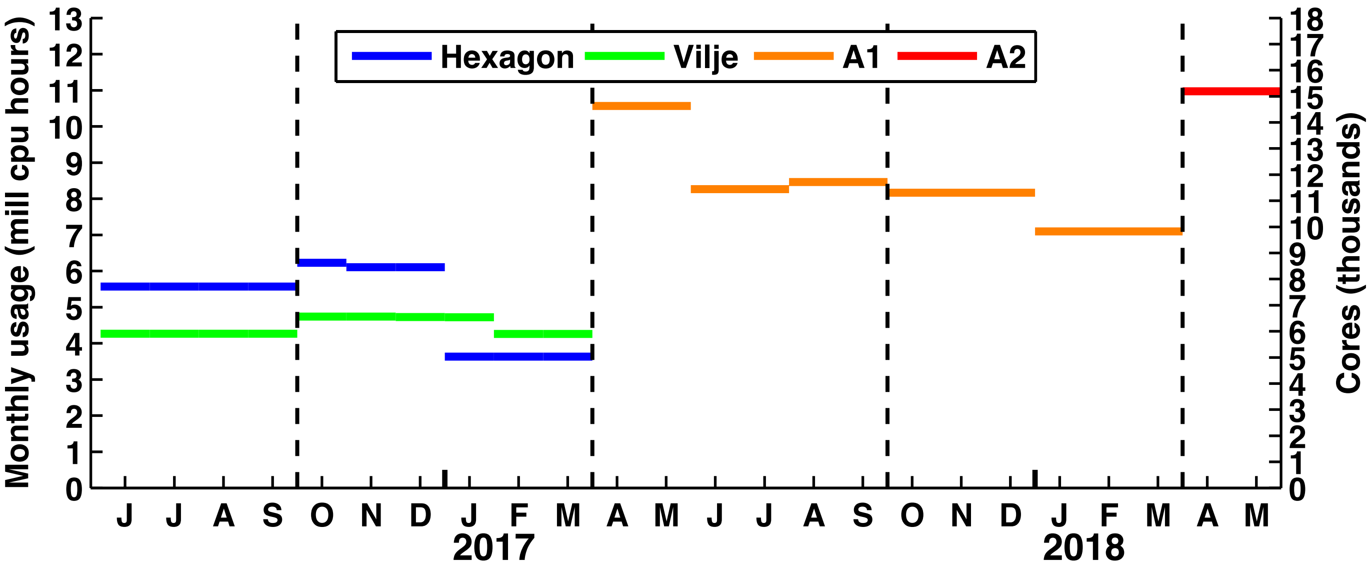
CMIP6 simulation plan – plotted simulation time-line for ML



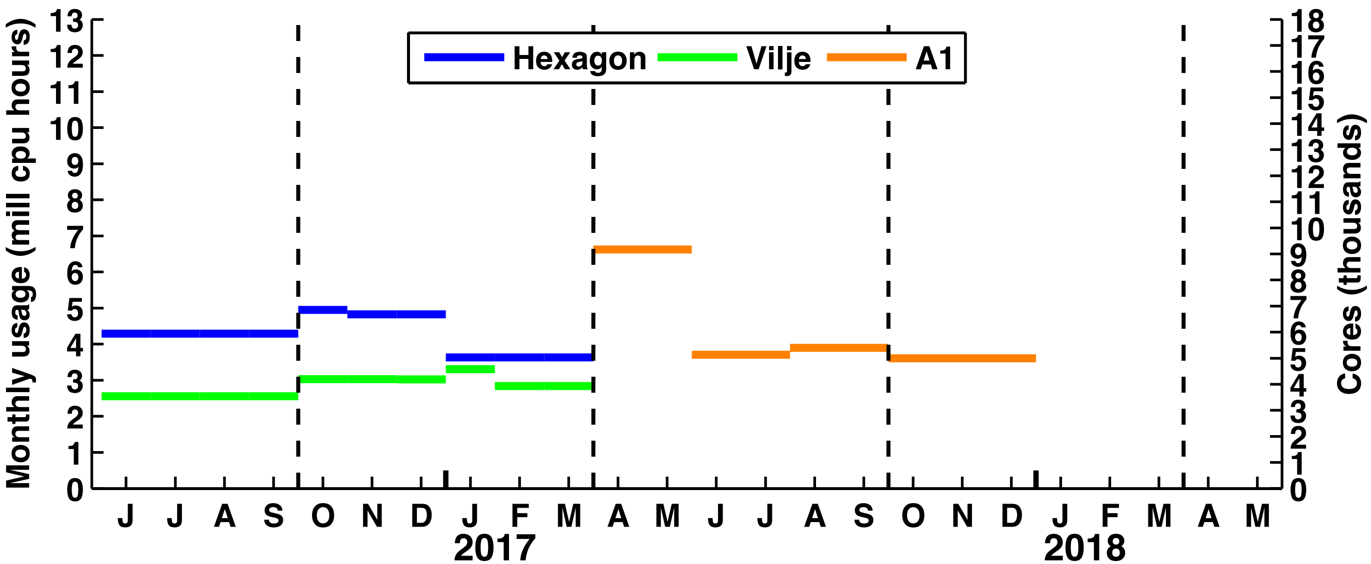
Simulation phases:

1. development & tuning
2. spin-up
3. DECK+historical
4. MIPs

CMIP6 simulation plan – monthly cpu usage



High scenario = 220 mill hours total



Low scenario = 110 mill hours total

100-200 mill hours excluding DCPP

~0.5 PB post-processed output

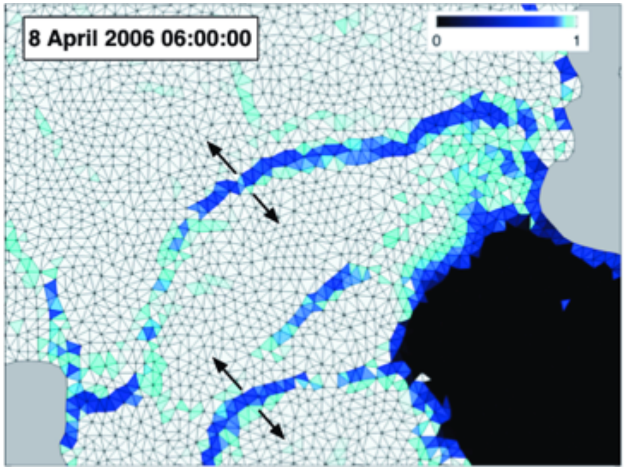
Plans beyond CMIP6 (NorESM3)

Atmosphere

- increased vertical resolution in stratosphere
- coupled (atmosphere-land-ice-ocean) assimilation

Ocean

- increased frequency of surface coupling
- increased vertical resolution in mixed layer
- replace virtual salt flux with mass fw flux
- representation of ice shelf-ocean interactions



Courtesy: Pierre Rampal

Lagrangian sea ice model (neXtSIM developed in Bergen)

- elastic-viscous-plast (EVP) rheology replaced by elasto brittle (EB) rheology
- ice mobility increased for thin ice (not captured by CMIP5 models)
- ice flow – wave interaction