Coupled Ensemble Data Assimilation with the Climate Model AWI-CM

Lars Nerger, Qi Tang, Longjiang Mu

Alfred Wegener Institute
Helmholtz Center for Polar and Marine Research
Bremerhaven, Germany

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Overview

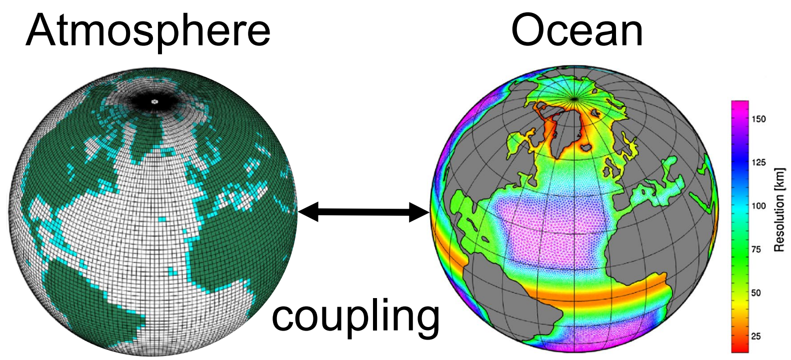
- Assimilation system: AWI-CM and PDAF
- Weakly-coupled assimilation into the ocean component
- Toward strongly coupled assimilation

Coupled Models and Coupled Data Assimilation

PDAF Parallel Data Assimilation Framework

Coupled models

- Several interconnected compartments, like
  - Atmosphere and ocean
  - Ocean physics and biogeochemistry (carbon, plankton, etc.)



Coupled data assimilation

- Assimilation into coupled models
  - **Weakly coupled**: separate assimilation in the compartments
  - **Strongly coupled**: joint assimilation of the compartments
    - Use cross-covariances between fields in compartments
  - Plus various “in between” possibilities …

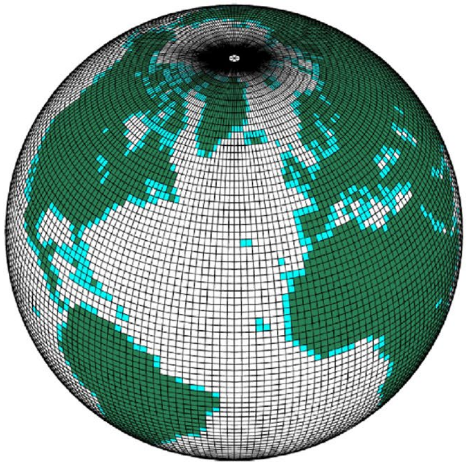
AWI

Assimilation System

AWI-CM-PDAF

Assimilation into coupled model: AWI-CM

Atmosphere

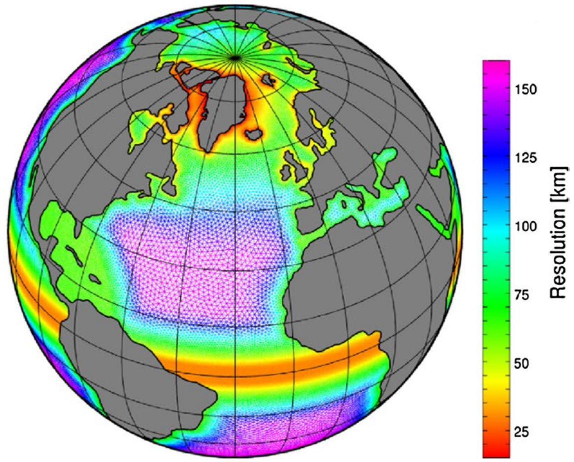


OASIS3-MCT

fluxes →

← ocean/ice state

Ocean



Atmosphere
- ECHAM6
- JSBACH land

Coupler library
OASIS3-MCT

Ocean
- FESOM
- includes sea ice

Two separate executables for atmosphere and ocean

Goal: Develop data assimilation methodology for cross-domain assimilation ("strongly-coupled")

AWI-CM: Sidorenko et al., Clim Dyn 44 (2015) 757

PDAF: A tool for data assimilation

PDAF Parallel Data Assimilation Framework

PDAF - Parallel Data Assimilation Framework

- a program library for ensemble data assimilation
- provides support for parallel ensemble forecasts
- provides filters and smoothers - fully-implemented & parallelized
  (EnKF, LETKF, LESTKF, NETF, PF … easy to add more)
- easily useable with (probably) any numerical model
  (coupled to e.g. NEMO, MITgcm, FESOM, HBM, MPI-ESM, SCHISM)
- run from laptops to supercomputers (Fortran, MPI & OpenMP)
- Usable for real assimilation applications and to study assimilation methods
- ~400 registered users; community contributions

Open source:
Code, documentation, and tutorial available at

http://pdaf.awi.de

L. Nerger, W. Hiller, Computers & Geosciences 55 (2013) 110-118

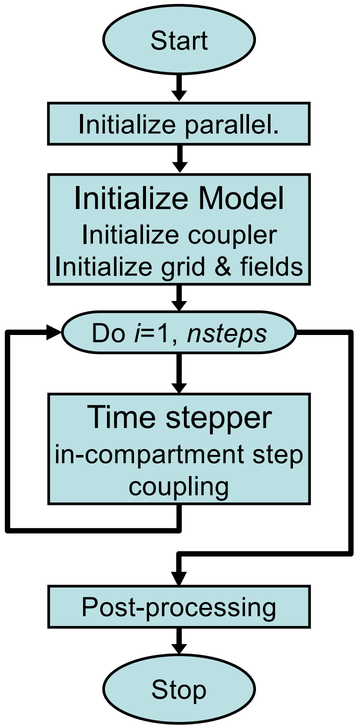
AWI

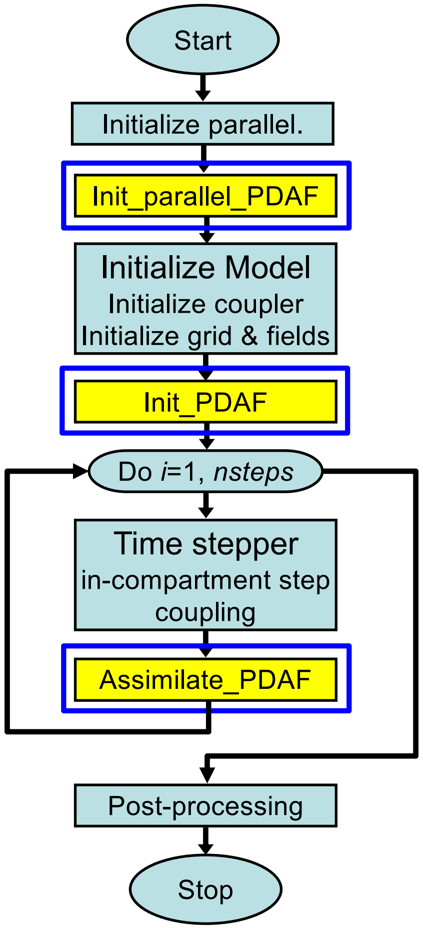
Augmenting a Model for Data Assimilation

Model

single or multiple executables

coupler might be separate program





Extension for data assimilation

plus:
Possible model-specific adaption

e.g. in NEMO or ECHAM: treat leap-frog time stepping

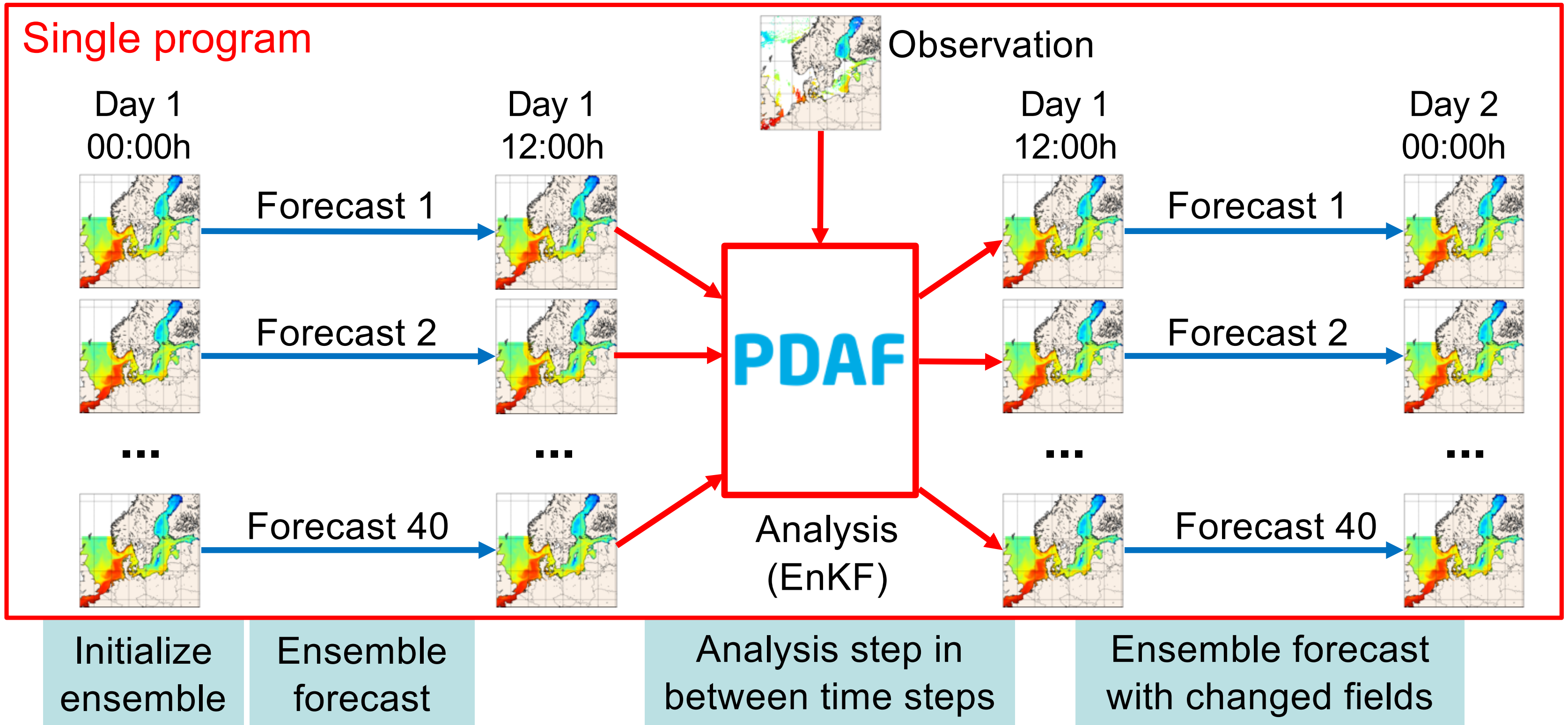
revised parallelization enables ensemble forecast

Assimilation-enabled Model

PDAF Parallel Data Assimilation Framework

Couple PDAF with model

- Modify model to simulate ensemble of model states
- Insert correction step (analysis) to be executed at prescribed interval
- Run model as usual, but with more processors and additional options



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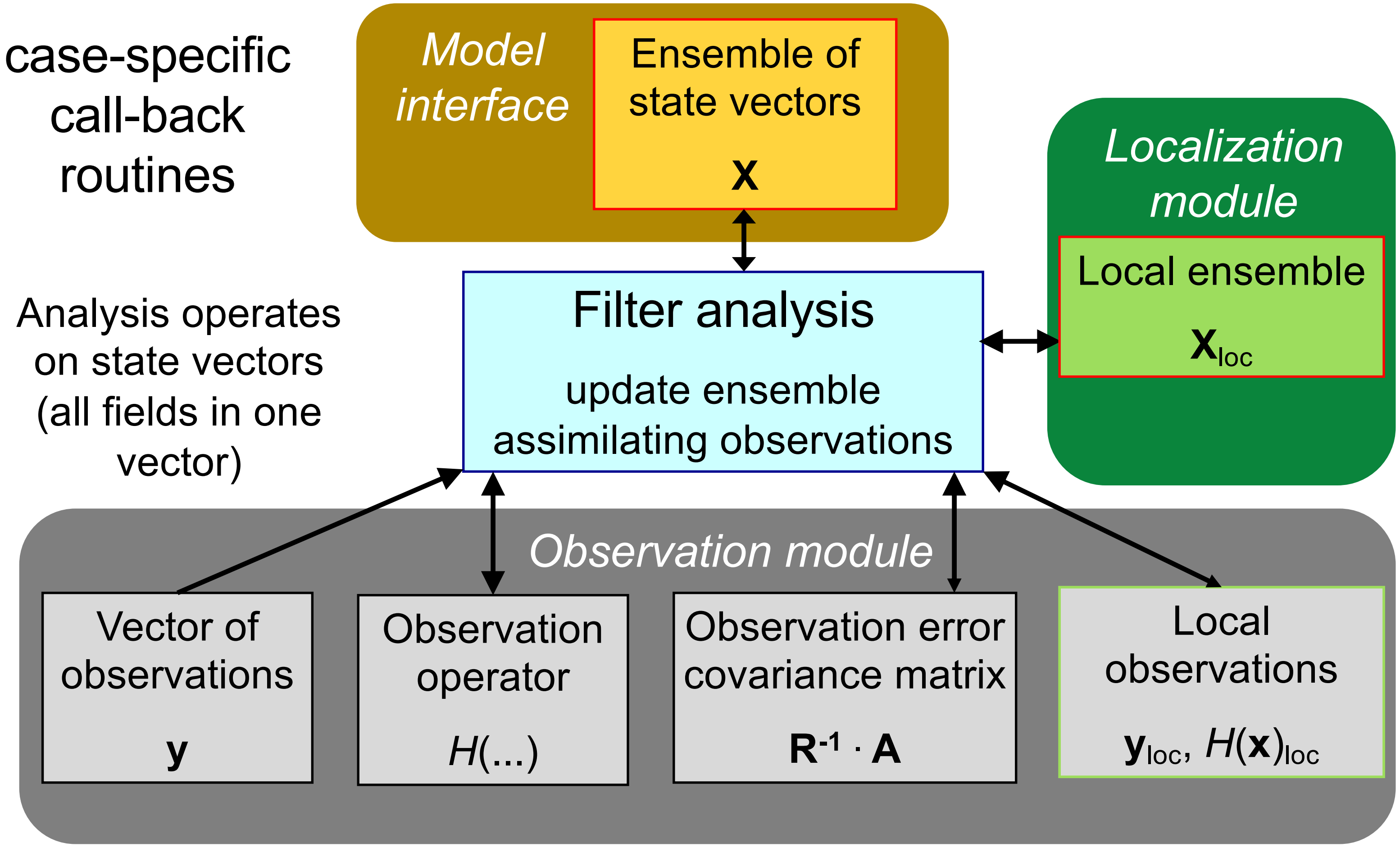
Ensemble Filter Analysis Step



Weakly-coupled Assimilation in Ocean

Data Assimilation Experiments

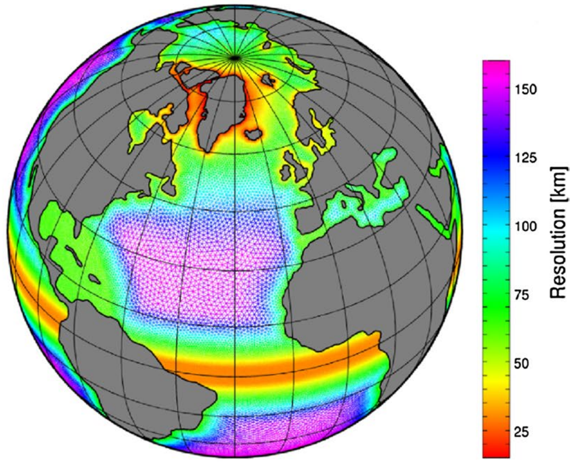
Model setup

- Global model
- ECHAM6: T63L47
- FESOM: resolution 30-160km

Data assimilation experiments

- Observations
  - Satellite SST
  - Profiles temperature & salinity
- Updated: ocean state (SSH, T, S, u, v, w)
- Assimilation method: Ensemble Kalman Filter (LESTKF)
- Ensemble size: 46
- Simulation period: year 2016, daily assimilation update
- Run time: 5.5h, fully parallelized using 12,000 processor cores

FESOM mesh resolution



Offline Coupling - Efficiency

Offline-coupling is simple to implement
but can be very ineffcient

Example:
Timing from atmosphere-ocean
coupled model (AWI-CM)
with daily analysis step:

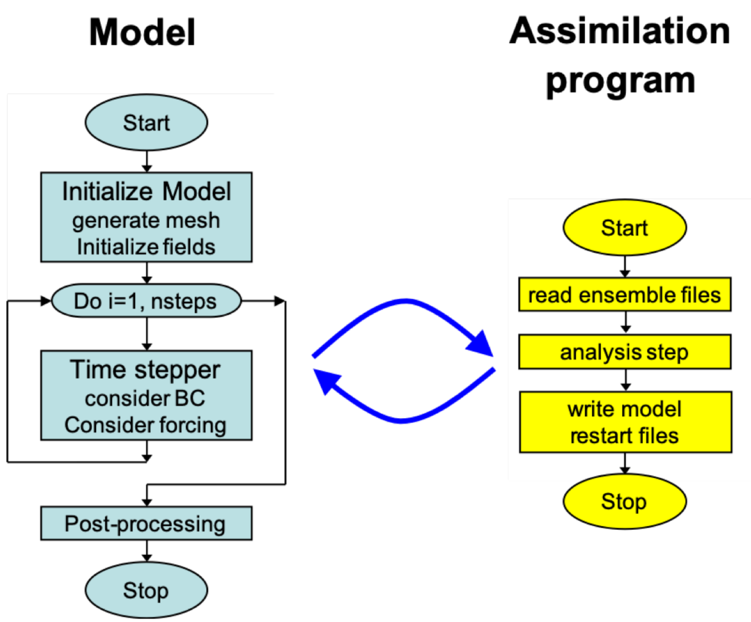
Model startup: 95 s
Integrate 1 day: 33 s
Model postprocessing: 14 s

overhead (model startup and model postprocessing)

Analysis step: 1 s

Restarting this model is ~3.5 times
more expensive than integrating 1 day

➜ avoid this for data assimilation

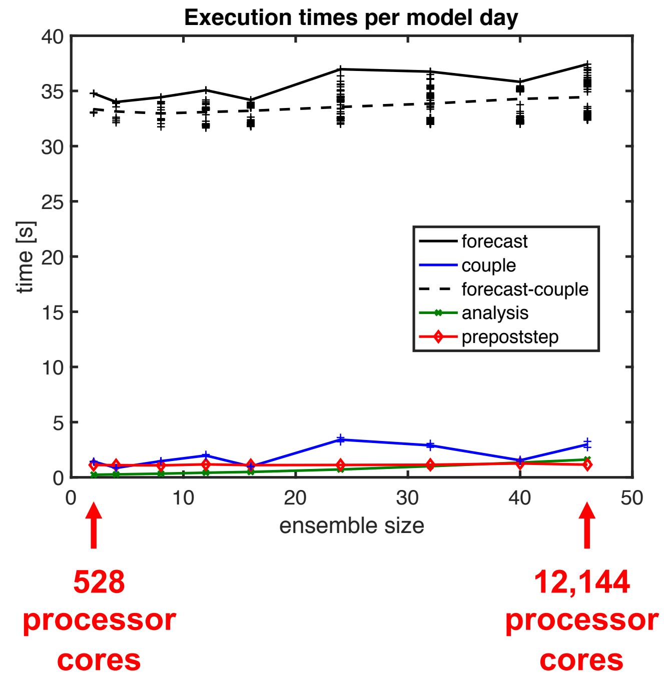


Execution times (weakly-coupled, DA only into ocean)

MPI-tasks

- ECHAM: 72
- FESOM: 192

- Increasing integration time with growing ensemble size (11%; more parallel communication; worse placement)
- some variability in integration time over ensemble tasks



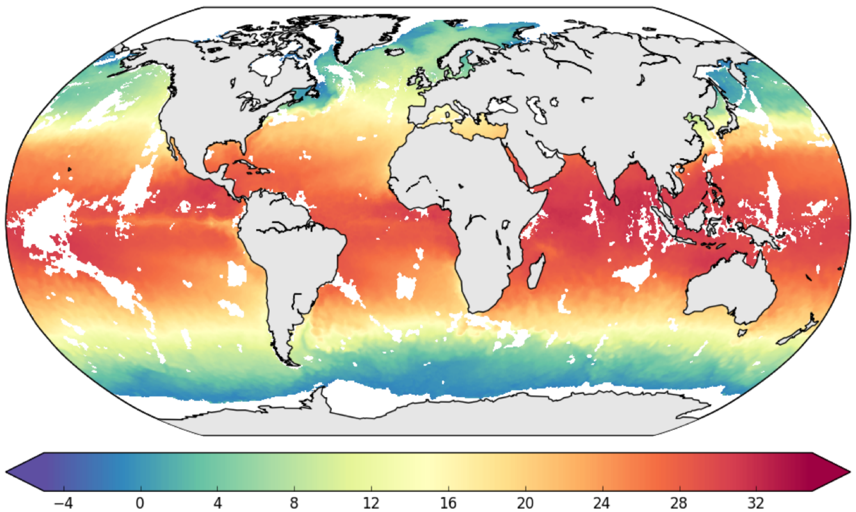
Important factors for good performance

- Need optimal distribution of programs over compute nodes/racks (here set up as ocean/atmosphere pairs)
- Avoid conflicts in IO (Best performance when each AWI-CM task runs in separate directory)

Nerger et al., GMDD (2019), doi:10.5194/gmd-2019-167

Assimilate sea surface temperature (SST)

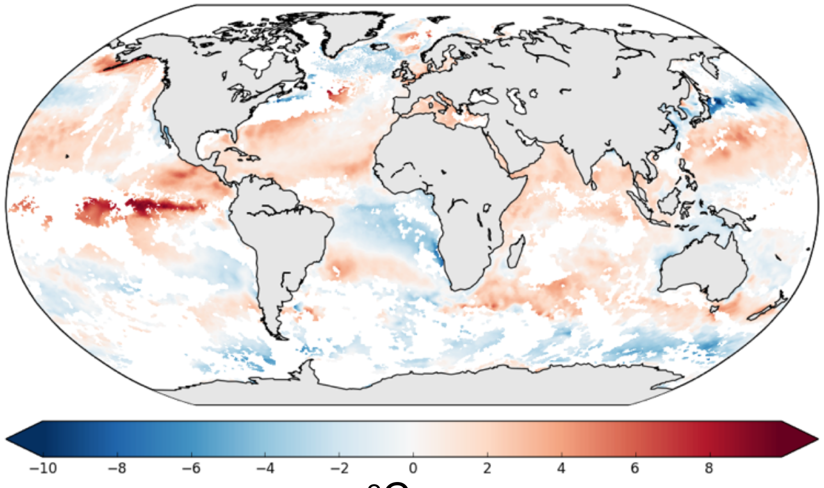
SST on Jan 1st, 2016



- Satellite sea surface temperature (level 3, EU Copernicus)
- Daily data
- Data gaps due to clouds
- Observation error: 0.8 °C
- Localization radius: 500 km

SST DA: Achieving stable assimilation

SST difference: observations-model



Coupled model only represents climate, not weather:
Large initial SST deviation up to 10°C

DA in this case is unstable!

For stabilization:

omit SST observations where

$|SST_{obs} - SST_{ens\_mean}| > 1.6\ ^{o}C$

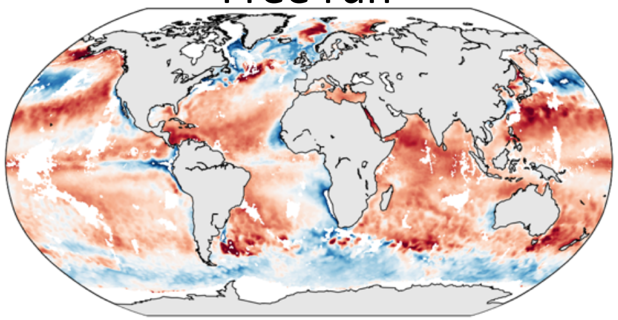
(30% initially, <5% after 2 months)

Further omit SST observations at grid points where model has ice
(mismatch between ice and no-ice conditions)

Assimilation of satellite SST: Effect on the ocean

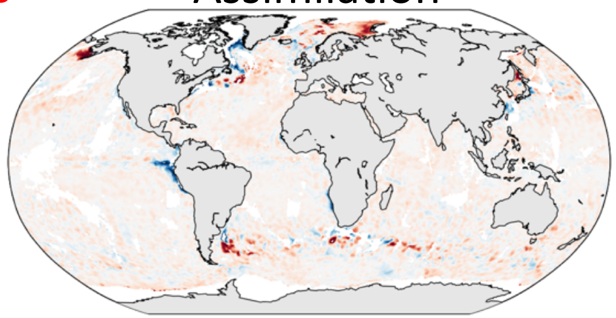
SST difference (obs-model): strong decrease of deviation

Free run



4/30/2016
Day 120

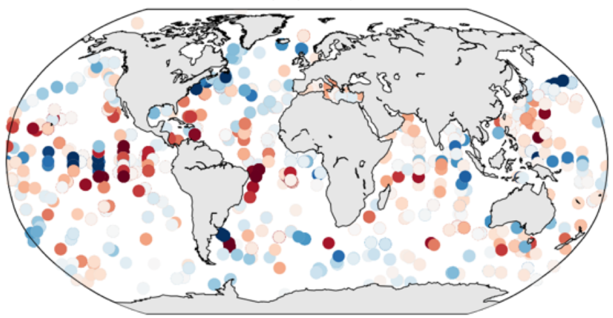
Assimilation



Necessary effect: dependent data

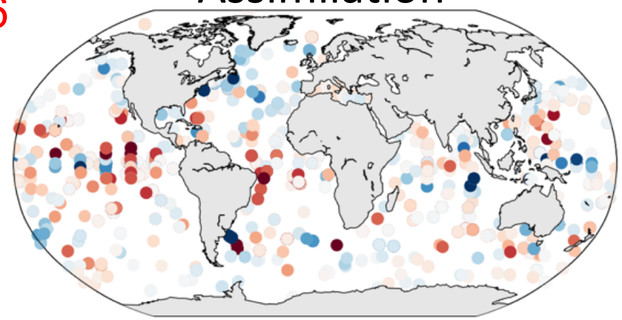
Subsurface temperature difference (obs-model); all model layers at profile locations

Free run

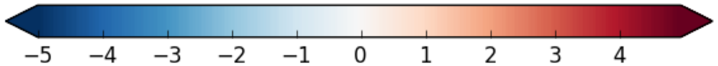


4/30/2016
Day 120

Assimilation



independent data



ESM Advanced Earth System Modelling Capacity

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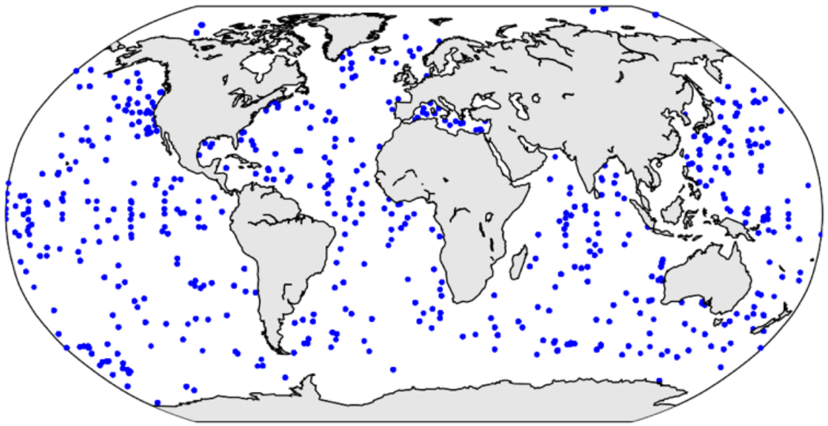
Assimilate subsurface observations: Profiles

Profile locations on Jan 1st, 2016

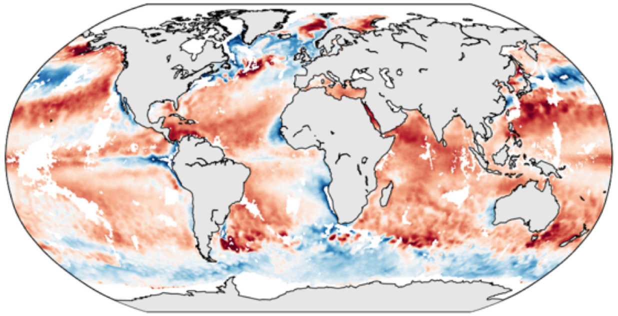


- Temperature and Salinity
- EN4 data from UK MetOffice
- Daily data
- Subsurface down to 5000m
- About 1000 profiles per day
- Observation errors
  - Temperature profiles: 0.8 °C
  - Salinity profiles: 0.5 psu
- Localization radius: 1000 km

Assimilation of Profiles: Effect on the ocean

SST difference (obs-model)

Free run



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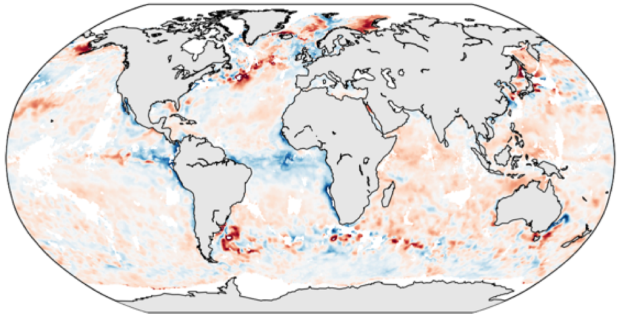
Day 120

Assimilation

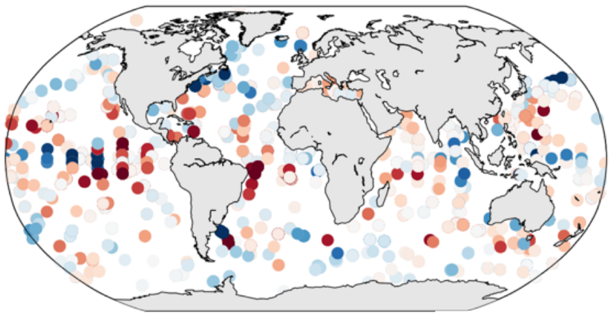


larger deviations than for SST assimilation

(independent data)

Subsurface temperature difference (obs-model); all the model layers at profile locations

Free run



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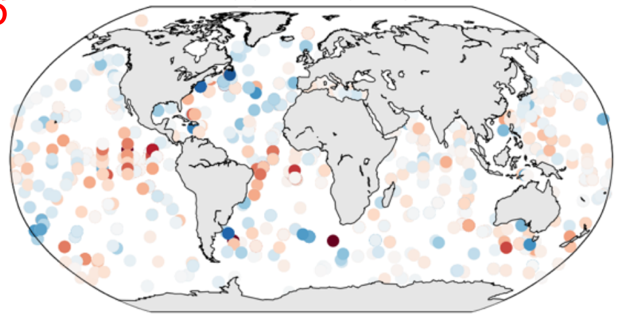
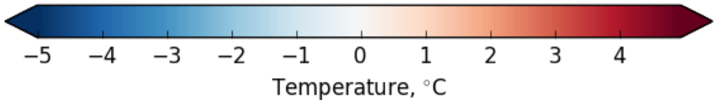
Assimilation



smaller deviations than for SST assimilation

(dependent data)

La



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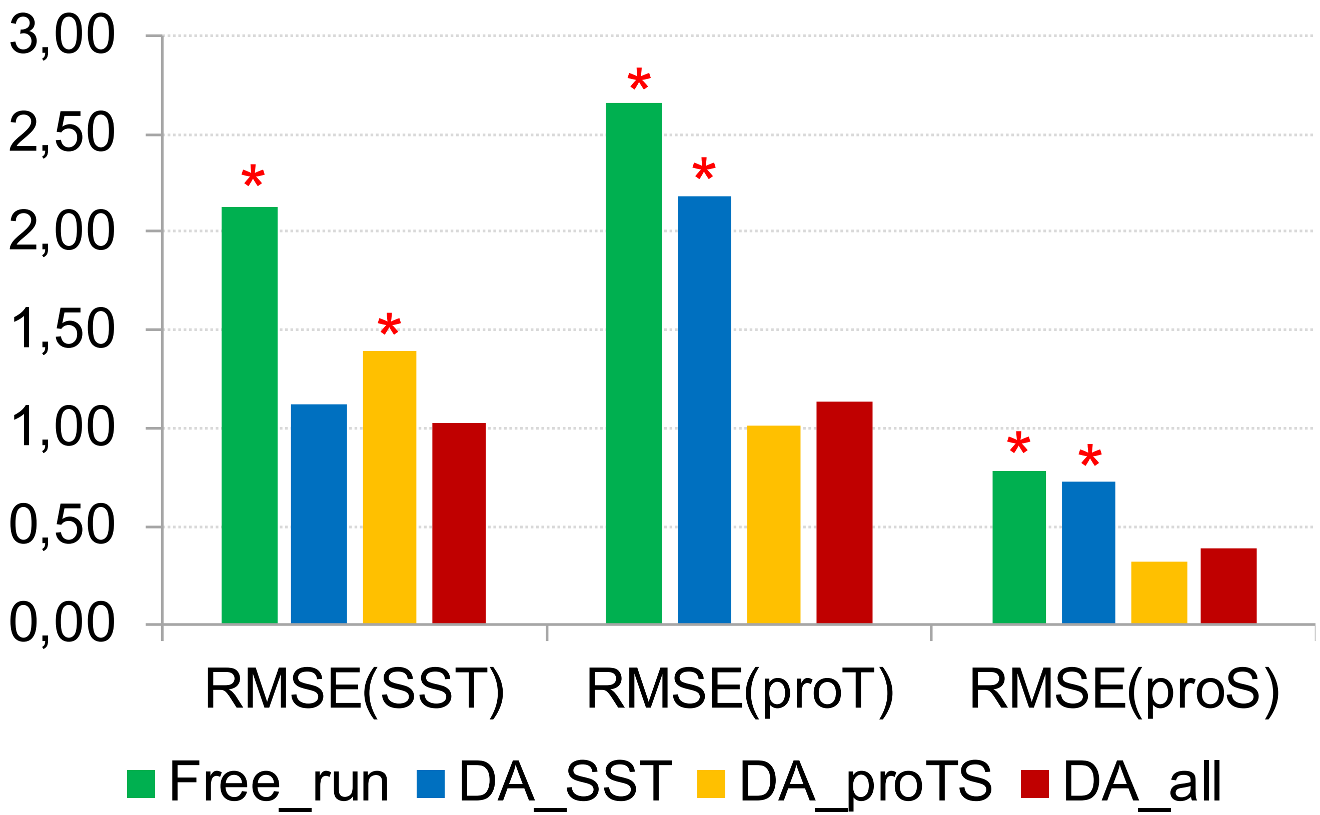
Assimilation effect: RMS errors



* Independent data

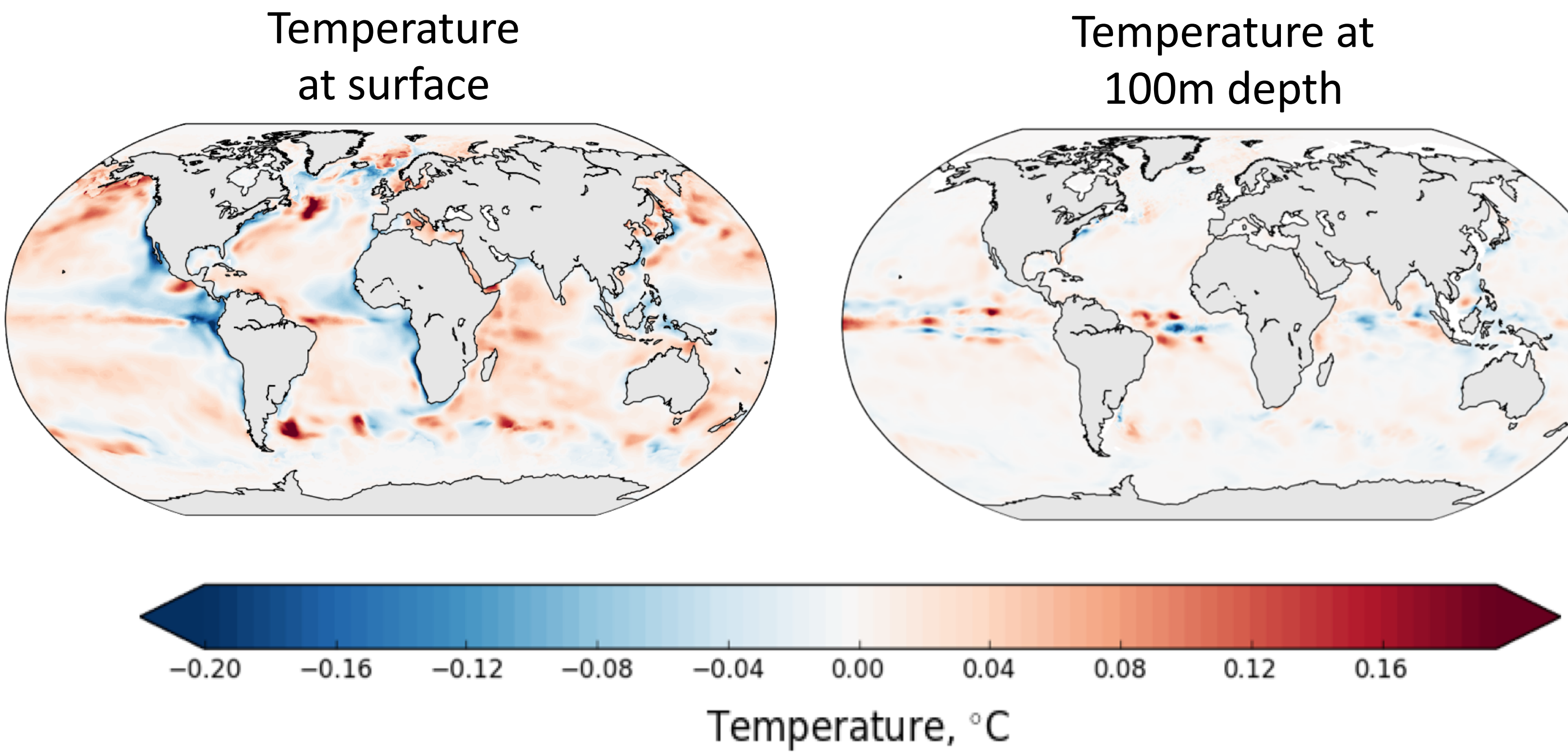
Overall lowest errors with combined assimilation

- But partly a compromise

Mean increments

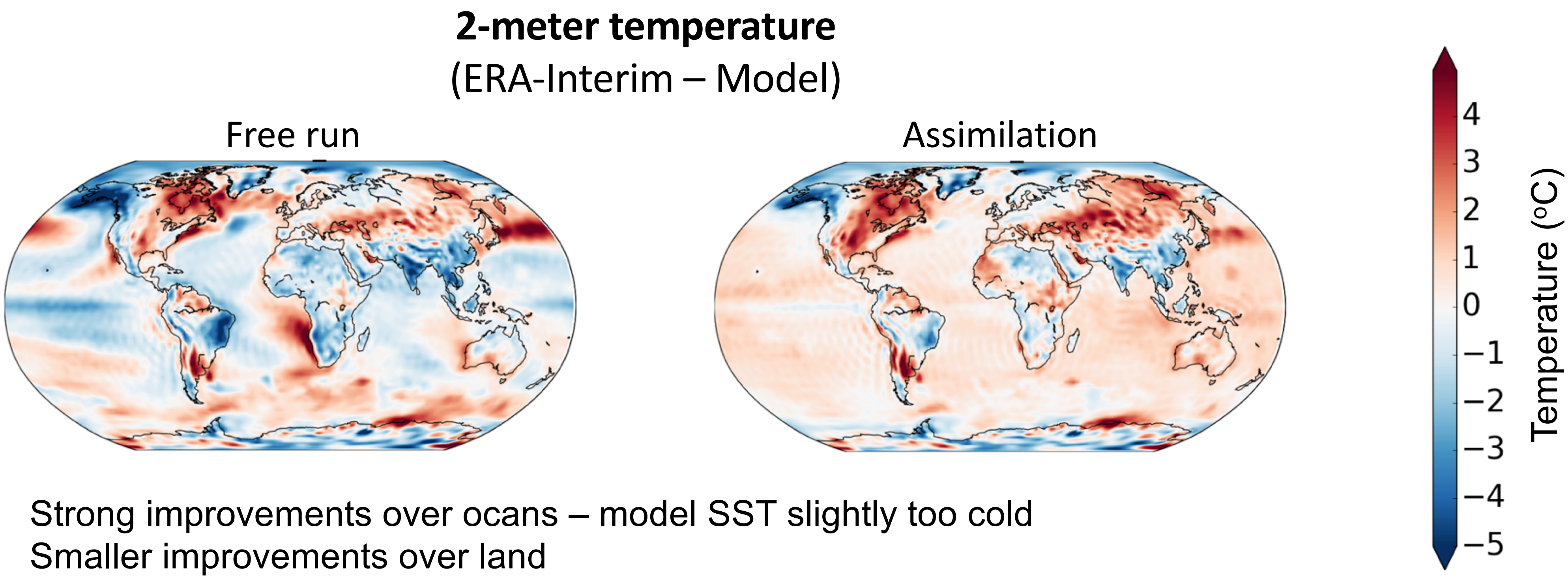
Mean increments (analysis – forecast) for days 61-366 (after DA spinup)

- non-zero values indicate regions with possible biases



Effect on Atmospheric State

- Compare to ERA-Interim
- mean over 2016

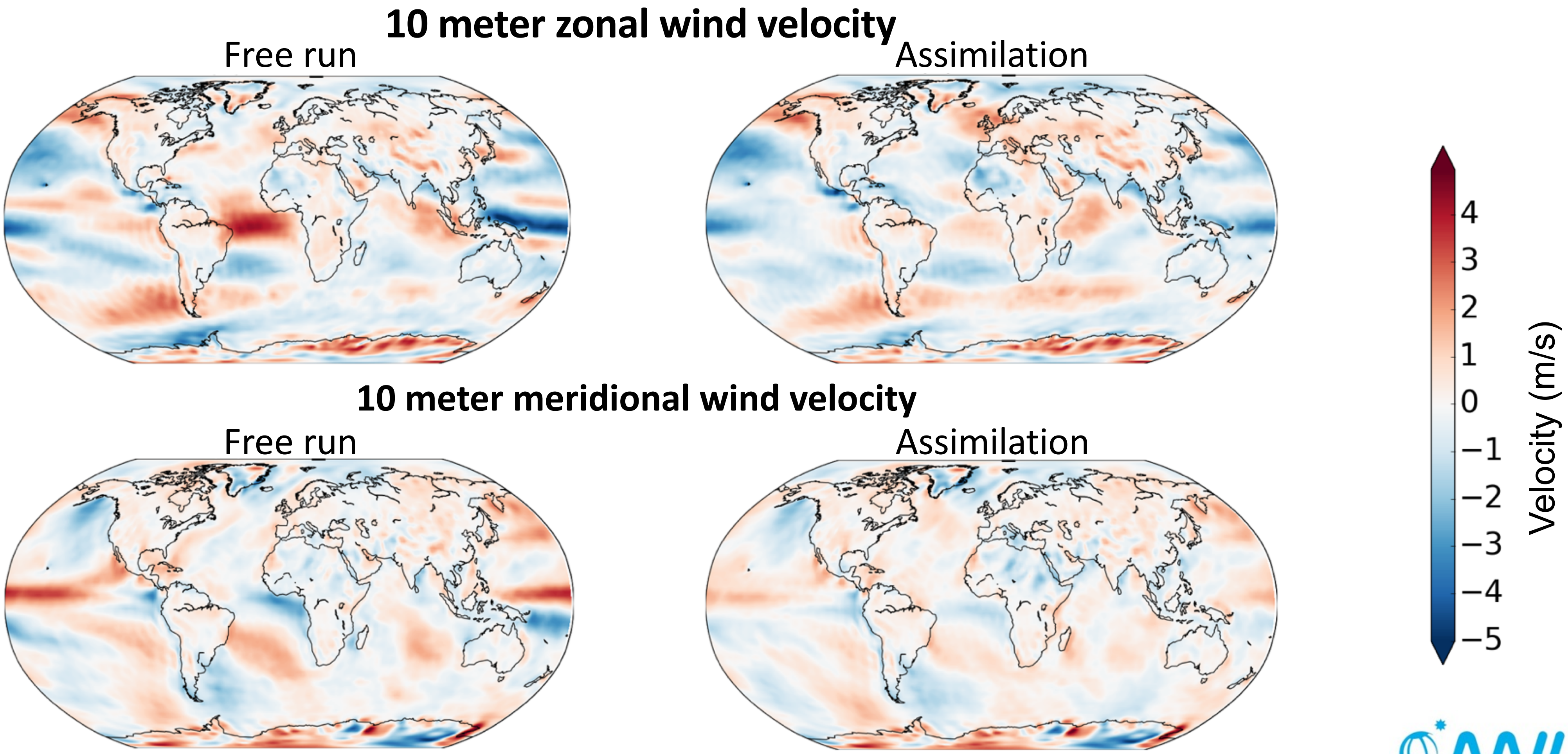


- Strong improvements over ocans – model SST slightly too cold
- Smaller improvements over land

Effect on Atmospheric State

ERA-Interim – Model (mean over 2016)

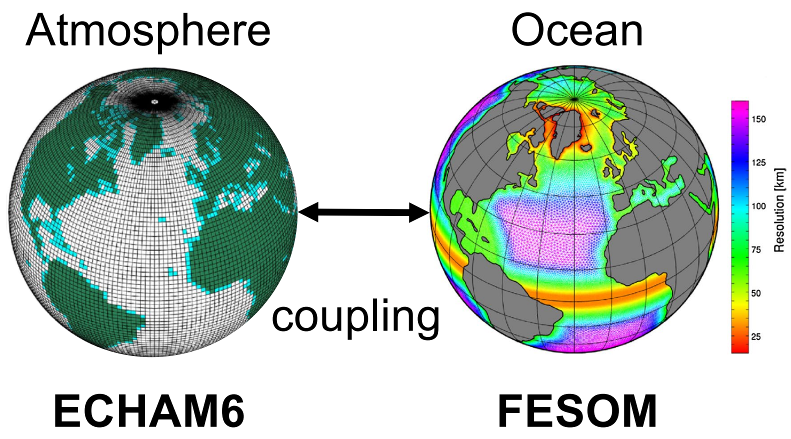
Assimilation generally positive



Toward Strongly-coupled Assimilation

Strongly Coupled Data Assimilation

- joint assimilation of the compartments
- First step: assimilation ocean observations into atmosphere
- Unfortunately, no results yet

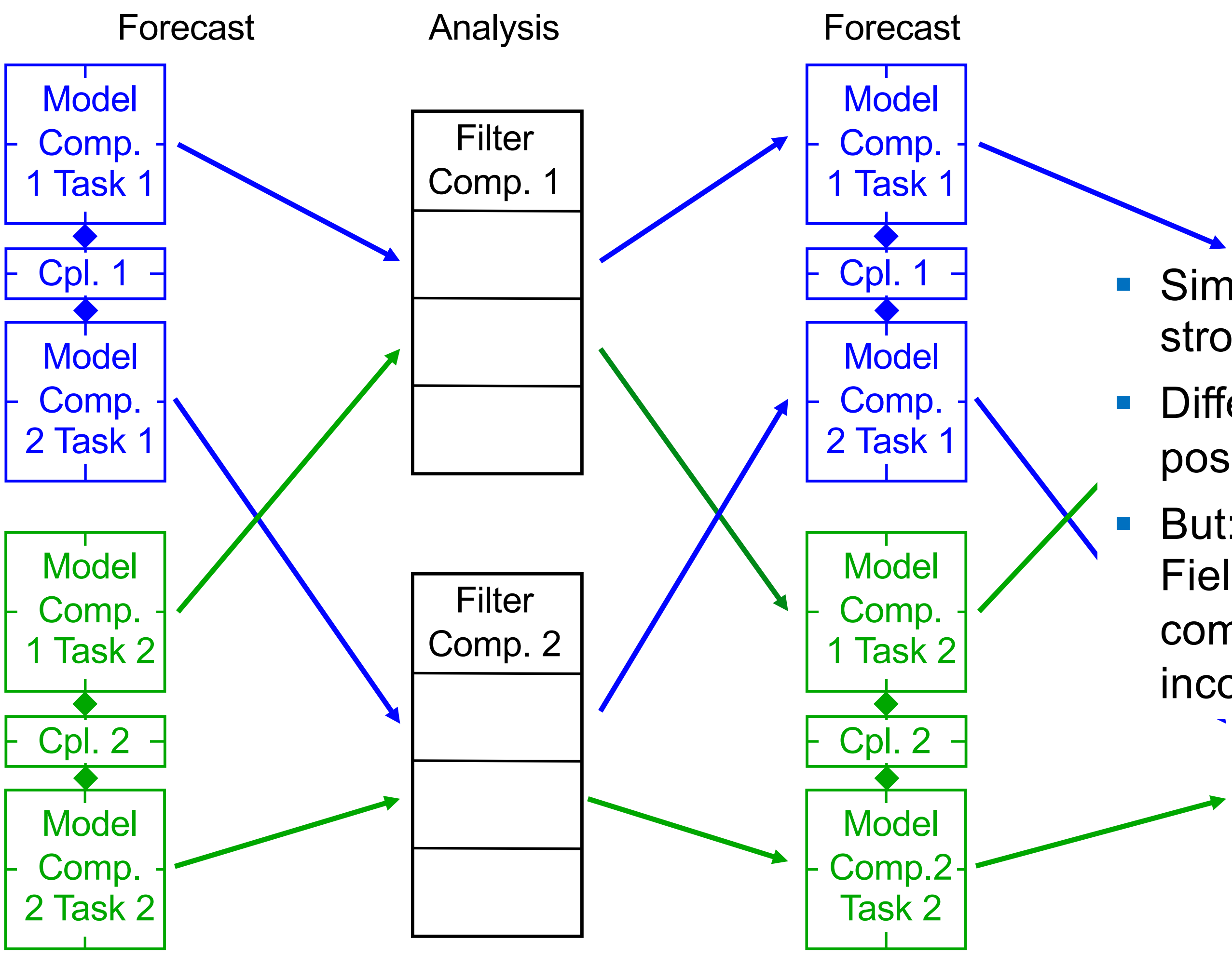


Technical Challenges:

- ECHAM is spectral model
  - Need fields in grid point space for localization (just identified the right place in the code; thank to ECHAM developers)
  - Need coordinate information in ECHAM (hidden in the code, but found it)

2 compartment system – weakly coupled DA

PDAF Parallel Data Assimilation Framework



- Simpler setup than strongly coupled
- Different DA methods possible
- But:
  Fields in different compartments can be inconsistent

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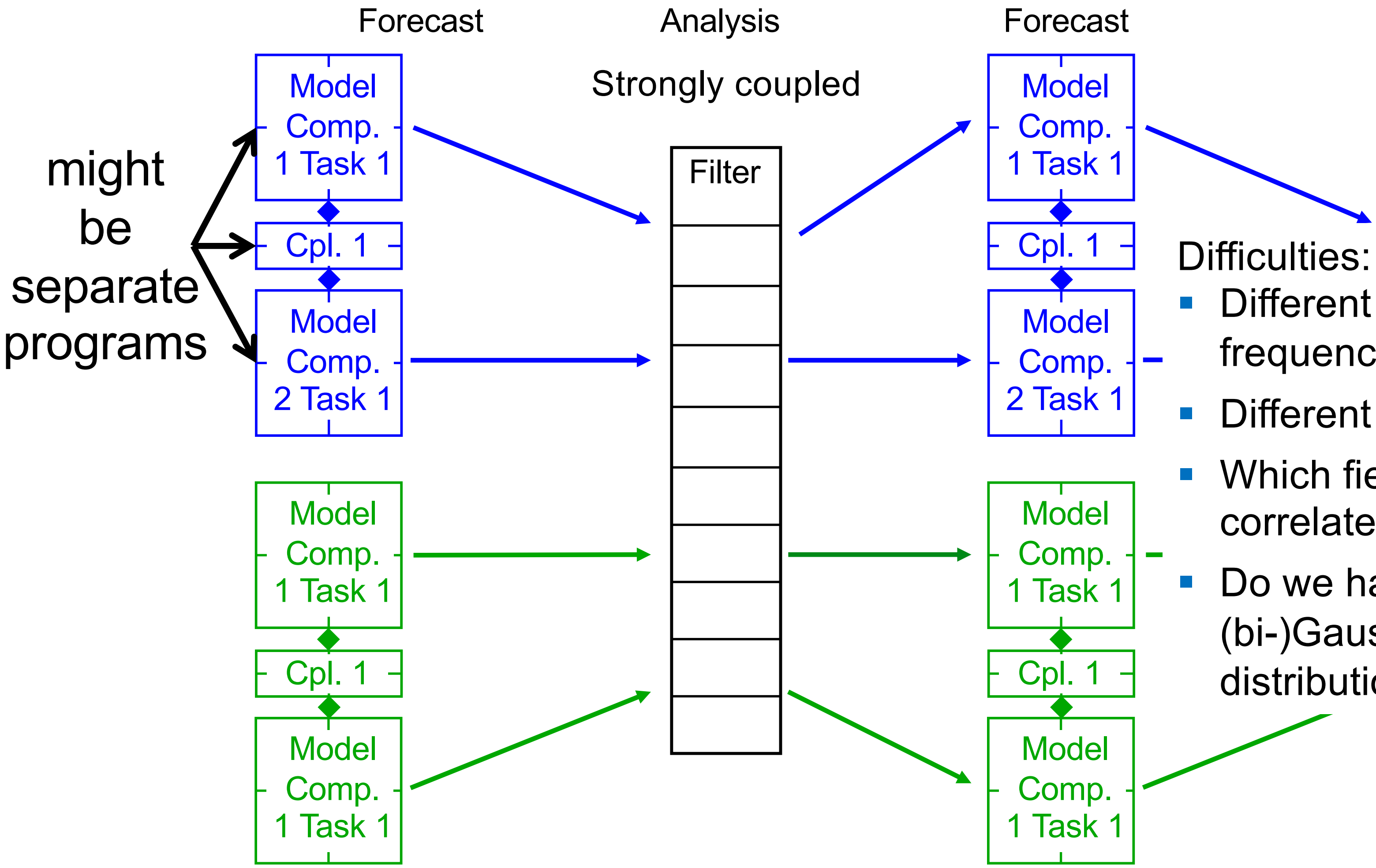
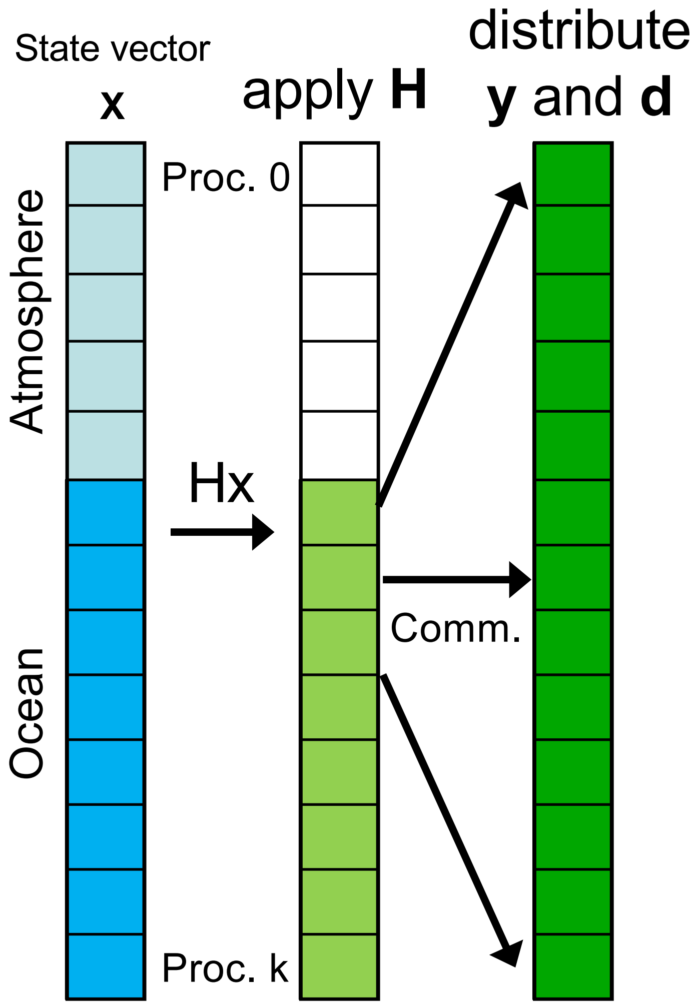
2 compartment system – strongly coupled DA



Difficulties:

- Different assimilation frequency
- Different time scales
- Which fields are correlated?
- Do we have (bi-)Gaussian distributions?

Strongly coupled: Parallelization of analysis step



We need innovation: **d** = **Hx** - **y**

Observation operator links different compartments

1. Compute part of **d** on process 'owning' the observation
2. Communicate **d** to processes for which observation is within localization radius

In PDAF:

achieved by changing the communicator for the filter processes (i.e. getting a joint state vector decomposed over the processes)

Summary

- Assimilation system of AWI-CM with PDAF for coupled DA
- Weakly coupled assimilation
  - Good effects of assimilation for ocean
  - Improvements in atmosphere
- Strongly coupled
  - Getting there
  - Technically not difficult for analysis step
  - ECHAM6 is tricky
- Further current work
  - Upgrade to FESOM2 (finite-volume) coupled to IFS

Lars.Nerger@awi.de