PDAF - The Parallel Data Assimilation Framework: Experiences with Kalman Filtering

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Overview

PDAF in the context of Kalman filters

Parallel performance of PDAF

Data Assimilation

Estimate system state (atmosphere, ocean, …) on the basis of a numerical model and measurements by combining both sources of information.

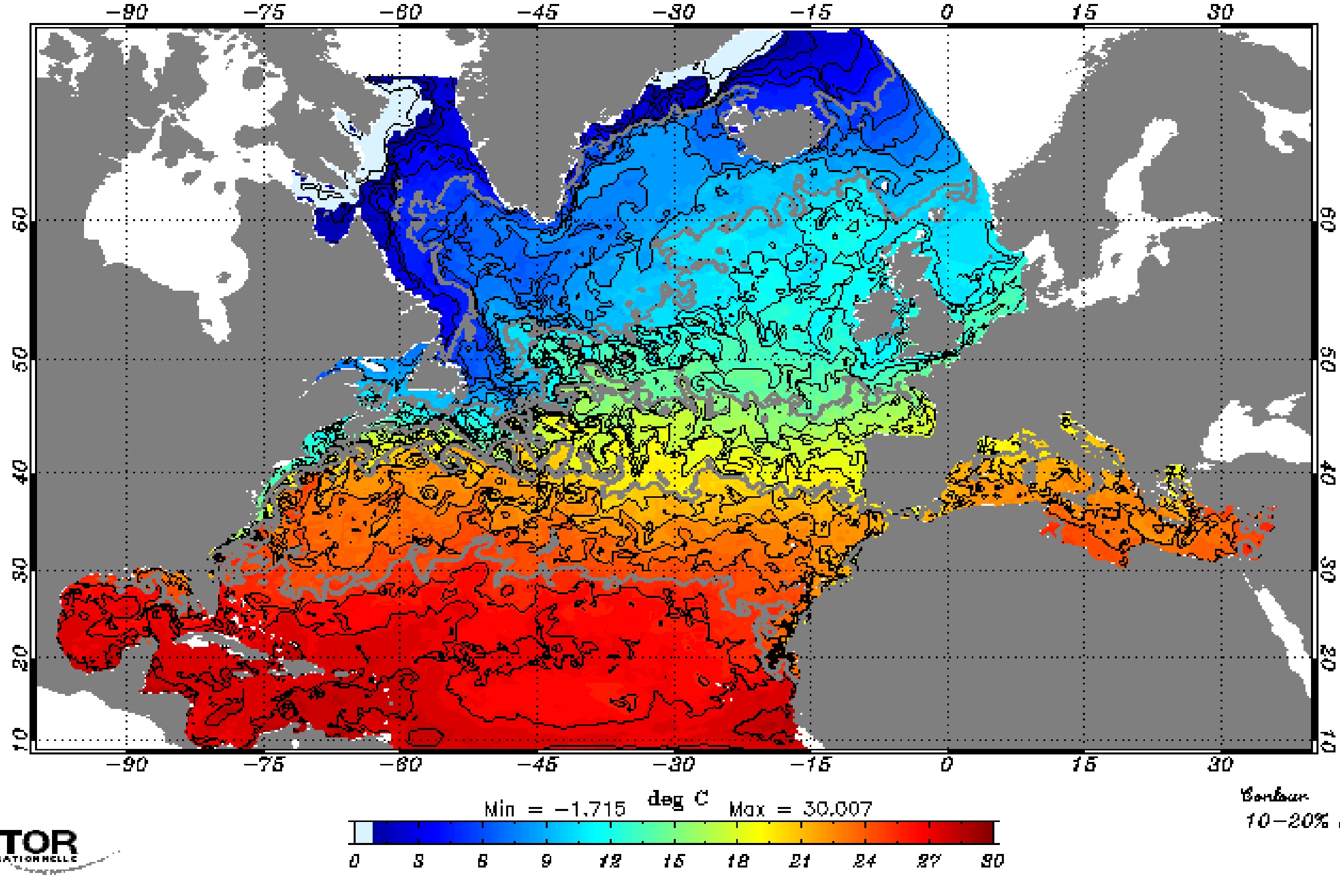
Filter ⇔ Smoother

Possible applications:

weather/climate forecasts
sensitivity studies

Data Assimilation

14-day forecast of ocean surface temperature



Ensemble-based Kalman filters

Initialization: Sample initial state and its error estimate by an ensemble of model states.

↓

Forecast: Evolve each ensemble member with the non-linear (stochastic) model.

↓

Analysis: Apply update step of the Kalman filter to ensemble mean or all ensemble states. Error estimate given by ensemble statistics.

↓

Re-Initialization: Transform state ensemble to exactly represent updated error statistics.

Computational and Practical Issues

- Huge amount of memory required
  (model fields and ensemble matrix)
- Huge requirement of computing time
  (ensemble integrations)
- Natural parallelism of ensemble integration exists
  - but needs to be implemented
- Existing models often not prepared for data
  assimilation

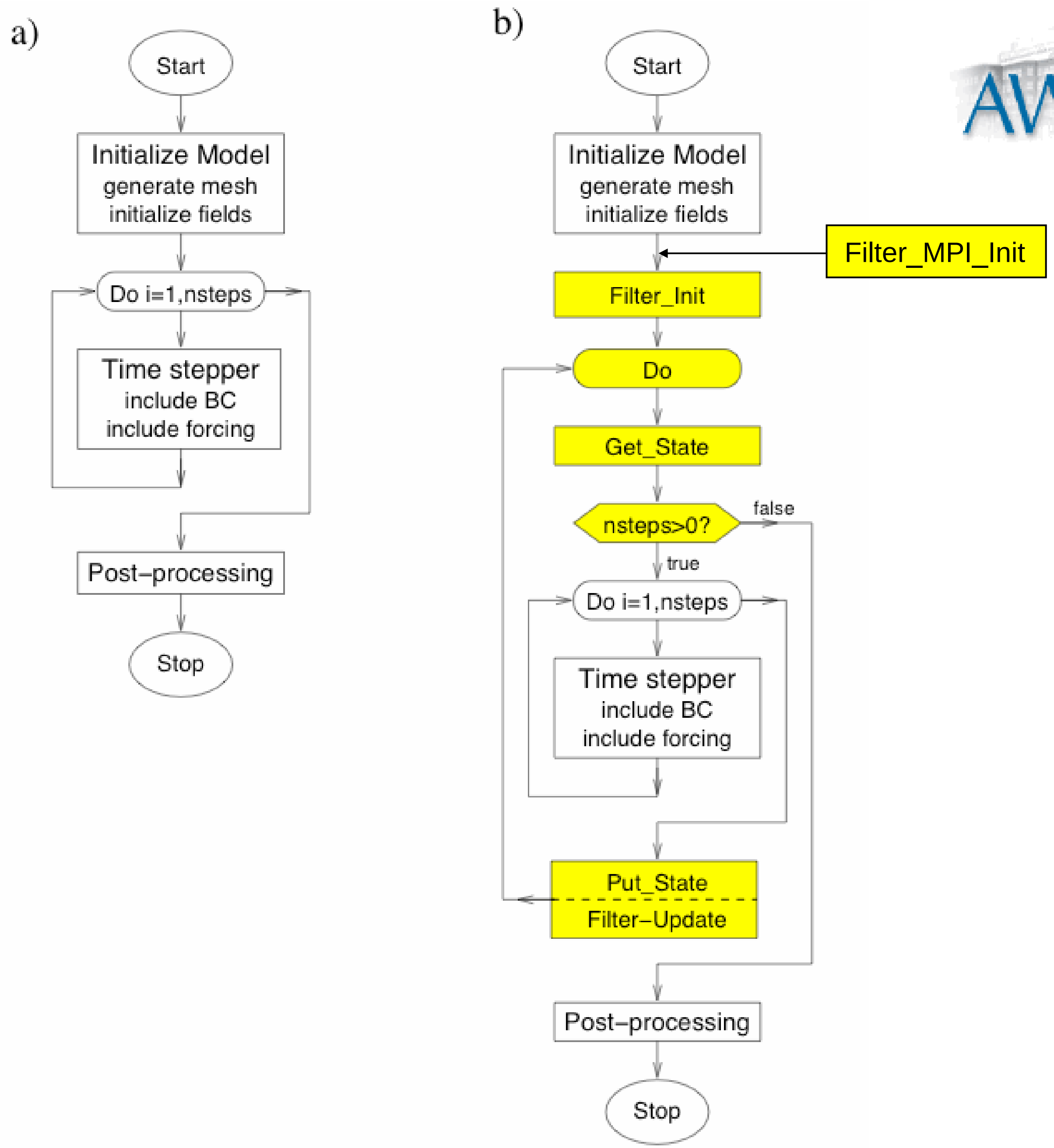
PDAF: Considerations for Implementation

Logical separation of problem

Model		Filter		Observations
initialization	state vector	Initialization	state vector	obs. vector
time integration	time	analysis	obs. vector	obs. operator
post processing		re-initialization		obs. error

Further considerations

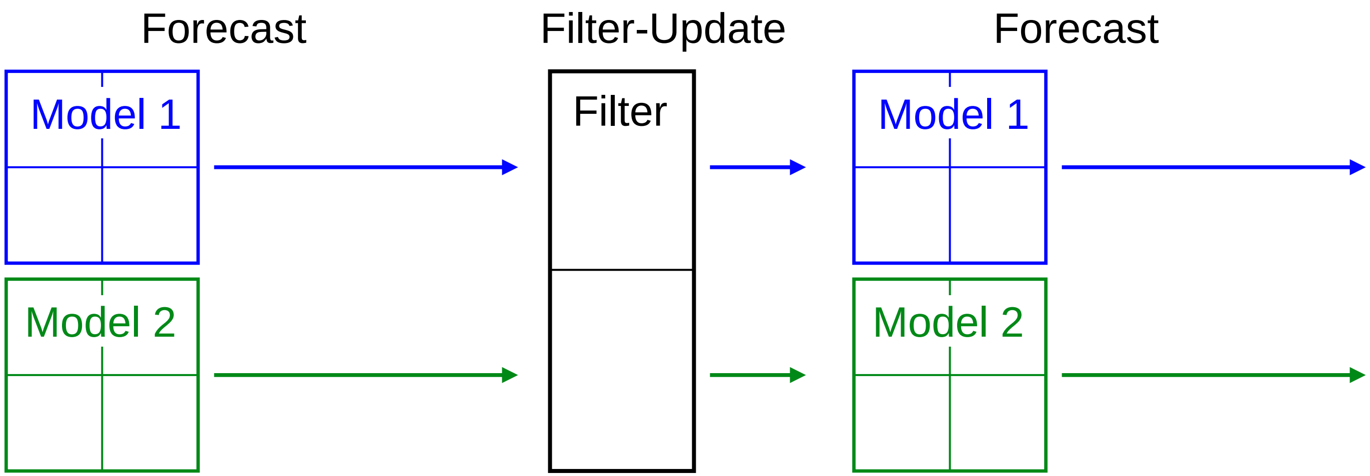
- Combination of filter with model with minimal changes to model code
- Control of assimilation program coming from model
- Simple switching between different filters and data sets
- Complete parallelism in model, filter, and framework


a)
Start
Initialize Model
generate mesh
initialize fields
Do i=1,nsteps
Time stepper
include BC
include forcing
Post–processing
Stop
b)
Start
Initialize Model
generate mesh
initialize fields
Filter_MPI_Init
Filter_Init
Do
Get_State
nsteps>0?
false
true
Do i=1,nsteps
Time stepper
include BC
include forcing
Put_State
Filter–Update
Post–processing
Stop

PDAF interface structure

- User-supplied routines for
  - field transformations between model and filter
  - observation-related operations
  - filter post-step
- Defined calling interface for
  - calls of framework routines
  - calls to user-supplied routines
- Interface independent of filter (almost)

2-level Parallelism



parallelization variants

distribute operations

different processes for model and filter update

Filter update with model processes

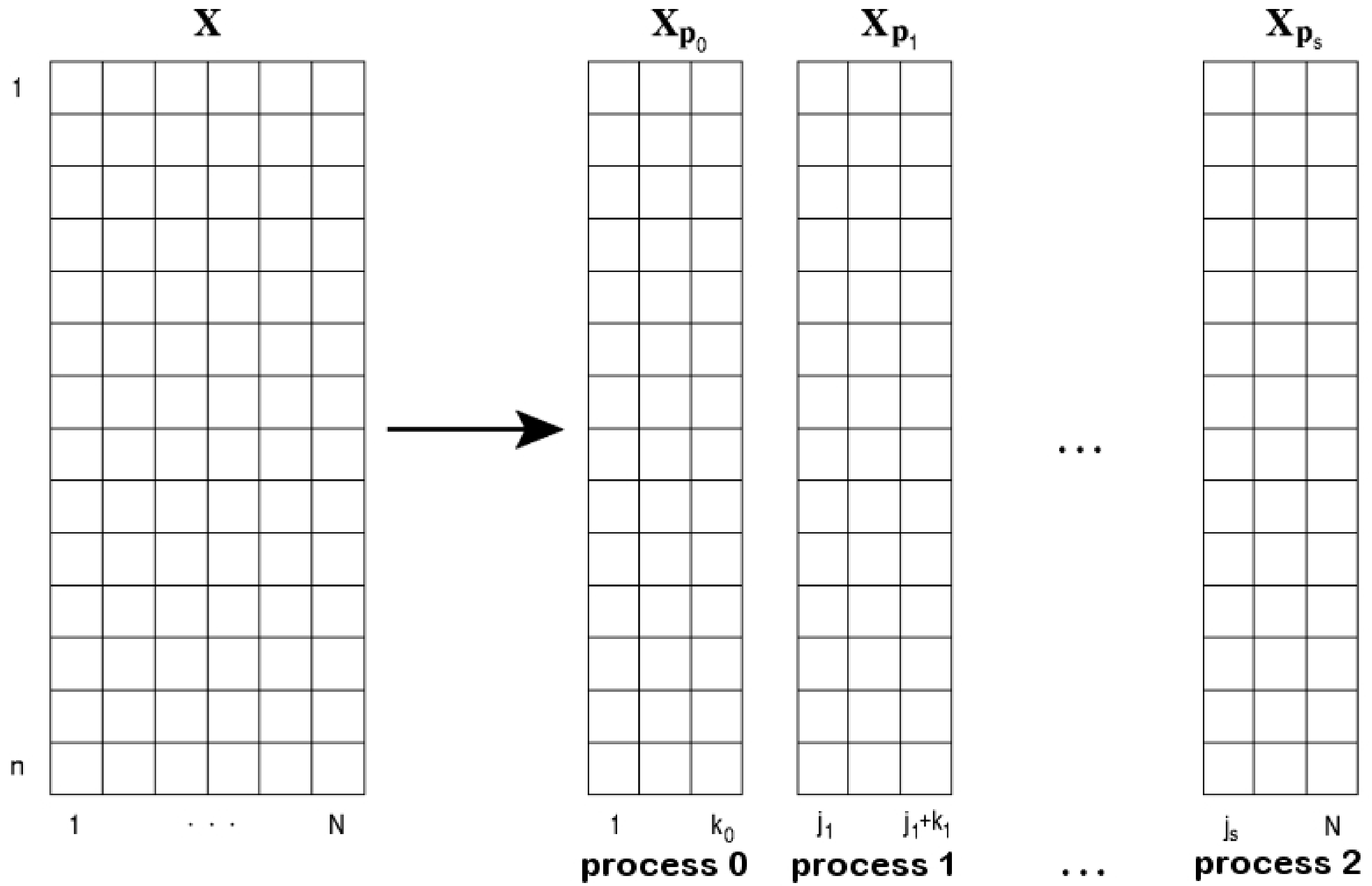
parallel filter update

distribute ensemble matrix

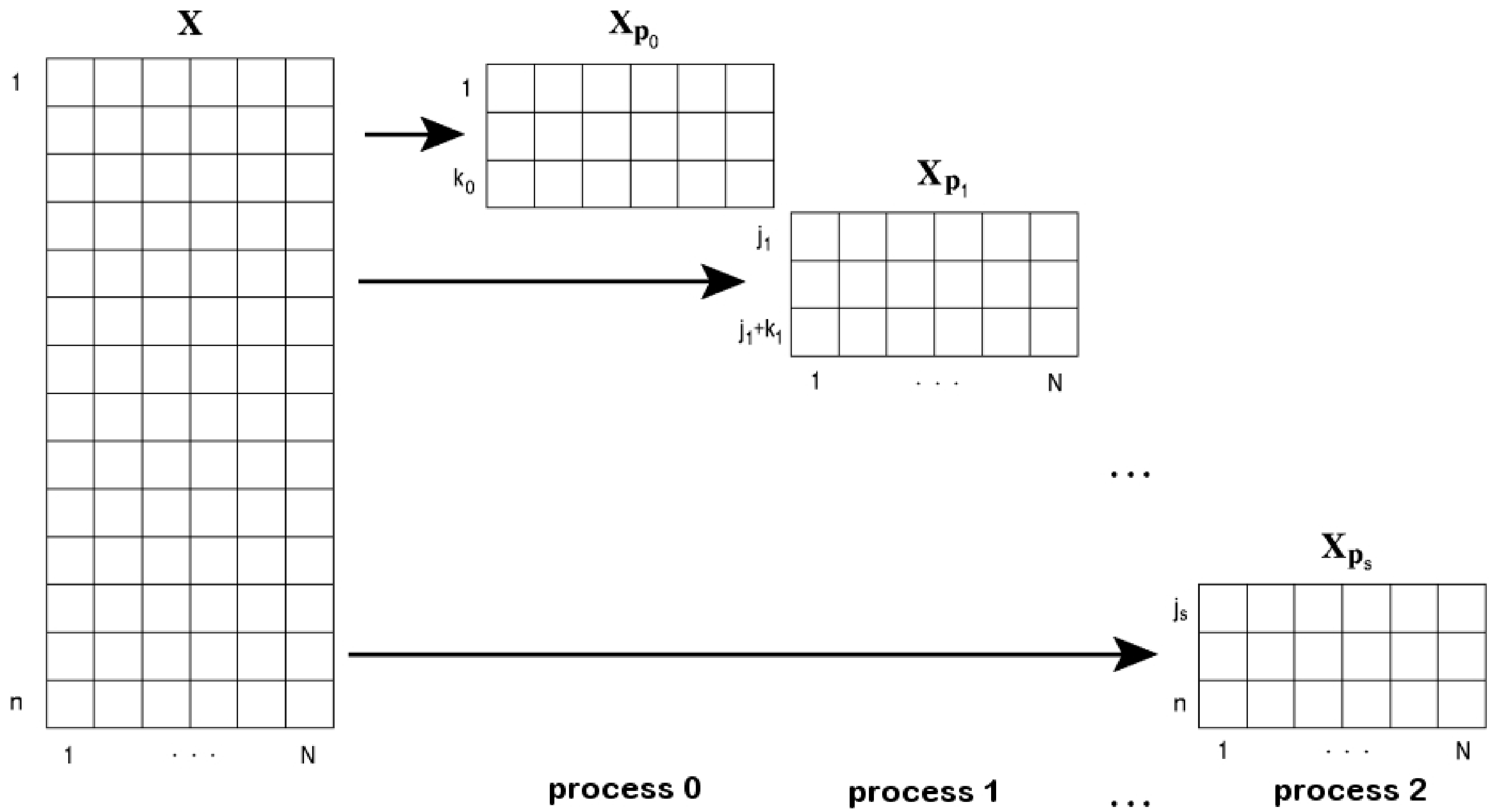
mode decomposition

domain decomposition

Mode decomposition



Domain decomposition



MPI parallelization

- Distribute model integrations
- Distribute filter update step

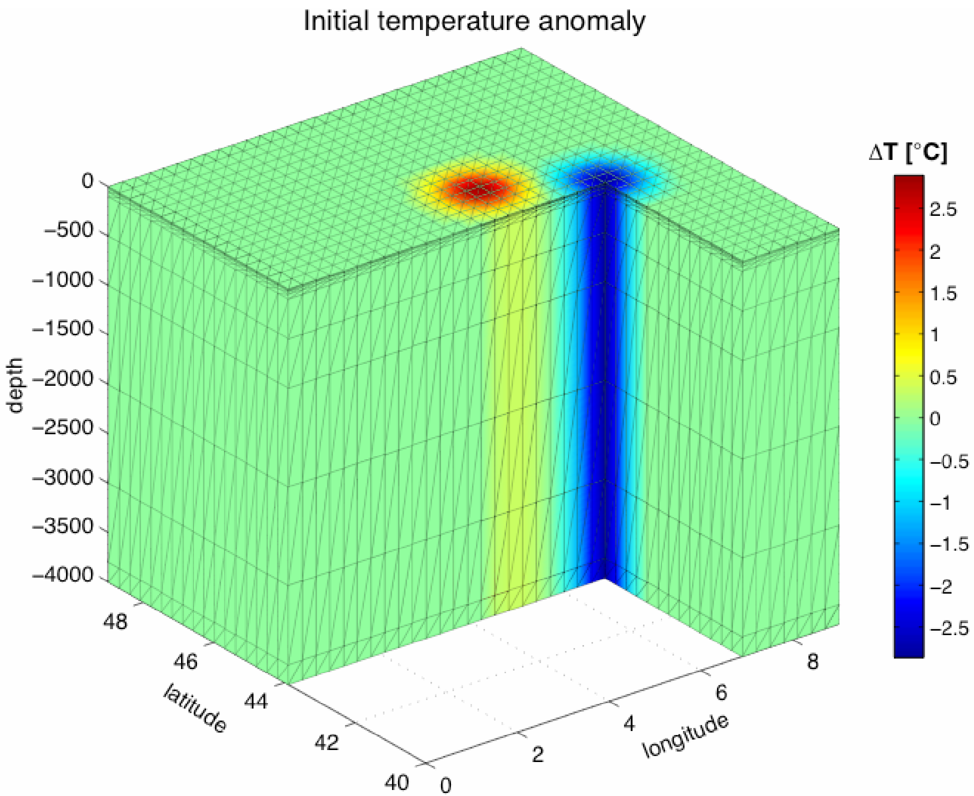
- 3 communicators
  - *Comm_Model*: model tasks
  - *Comm_Filter*: filter processes
  - *Comm_Couple*: communication between model and filter

Current KF algorithms in PDAF

- Ensemble Kalman filter (EnKF, Evensen, 1994)
  - widely used
  - fully nonlinear error forecast
- SEEK filter (Pham et al., 1997)
  - explicit low-rank (error-subspace) formulation
  - linearized error forecast
- SEIK filter (Pham et al., 1997)
  - combination of strengths of EnKF and SEEK

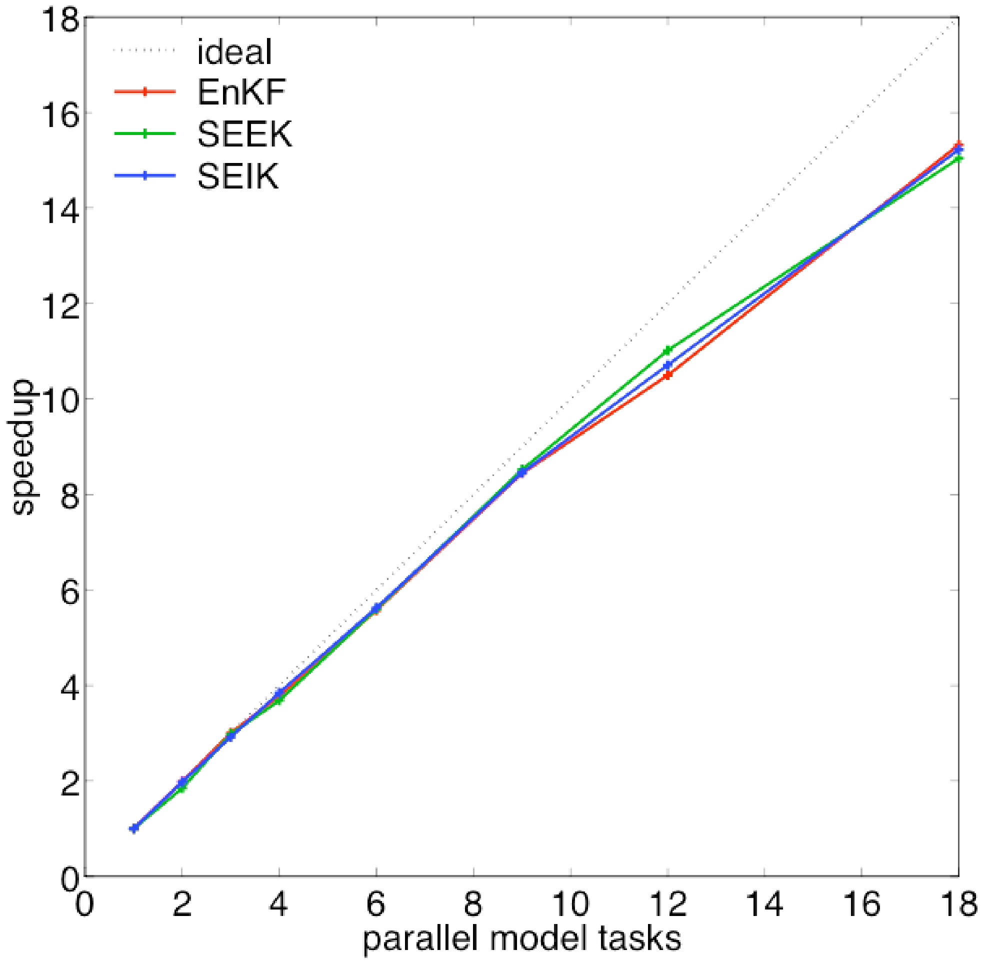
3D box experiment

- finite element model FEOM
- 31x31 grid points, 11 layers
- nonlinear problem: interacting baroclinic Rossby waves
- Assimilate sea surface height each 2.5 days over 40 days



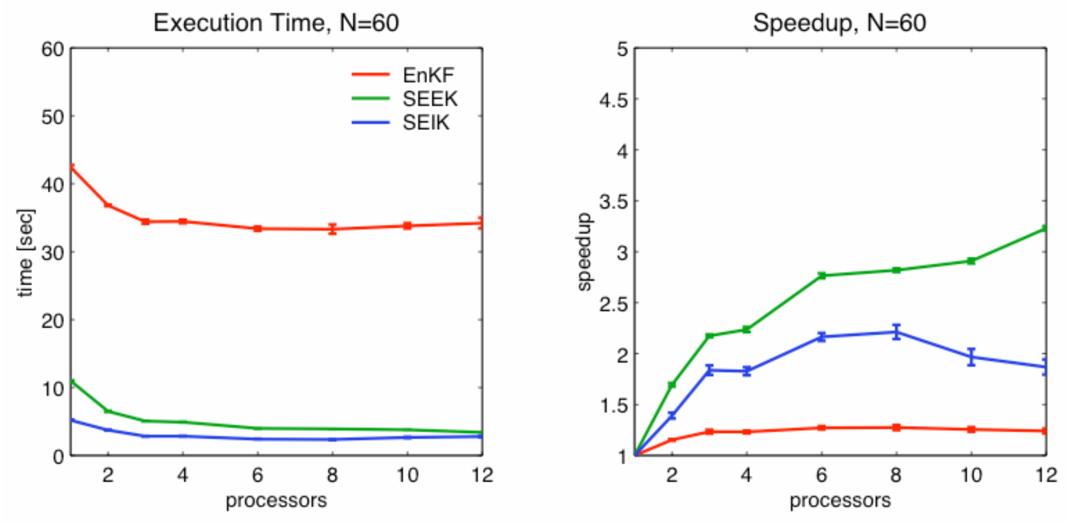
(FEOM: Danilov et al., Ocean Modeling, 2004)

Speedup of PDAF

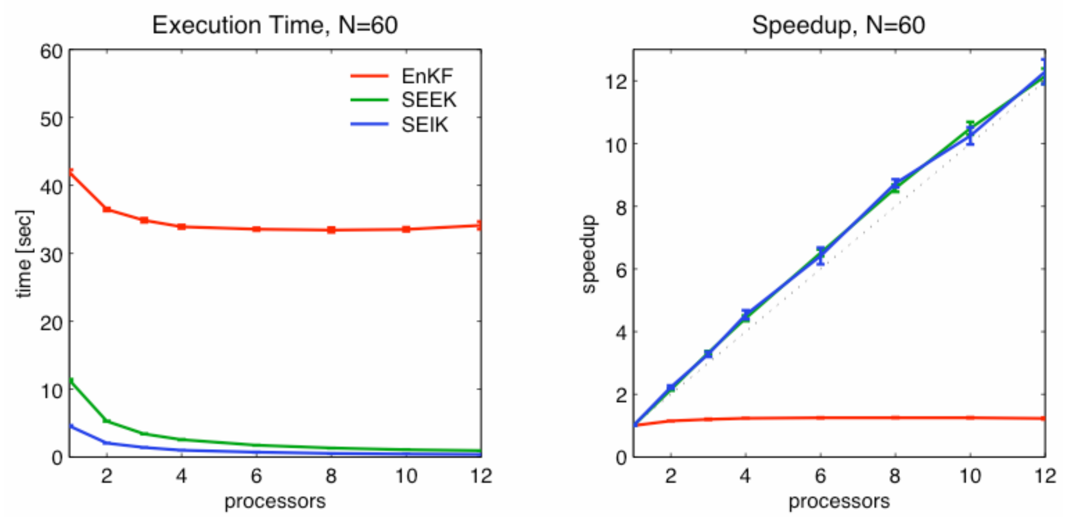


Parallel Efficiency of Filter Update

Mode decomposition



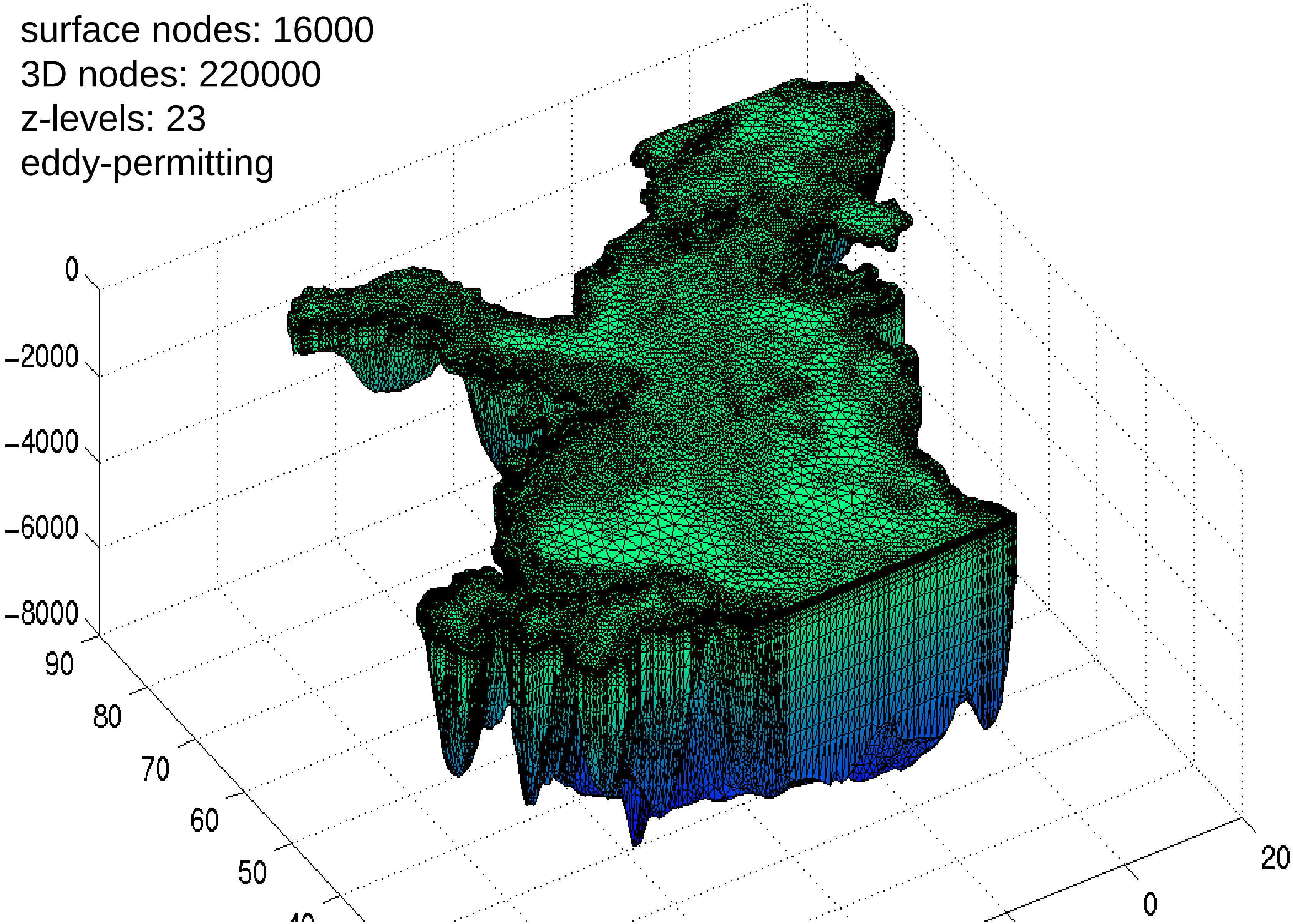
Domain decomposition



(ens. size = 10)

Further Example: FEOM North Atlantic

surface nodes: 16000
3D nodes: 220000
z-levels: 23
eddy-permitting



Summary

- Parallel Data Assimilation Framework PDAF
  - Simplified implementation of assimilation systems
  - Flexibility: Different assimilation algorithms and data configurations within one executable
  - Full utilization of parallelism
  - High parallel efficiency

Future directions

- Extensions of PDAF
  - more advanced filters (localization, adaptivity)
  - smoother algorithms
- Data assimilation applications (oceanography)
  - FEOM
    - stability of North Atlantic circulation
  - OPA-Model (with C. Böning, IFM-Geomar, Kiel)
    - large-scale circulation interannual to decadal

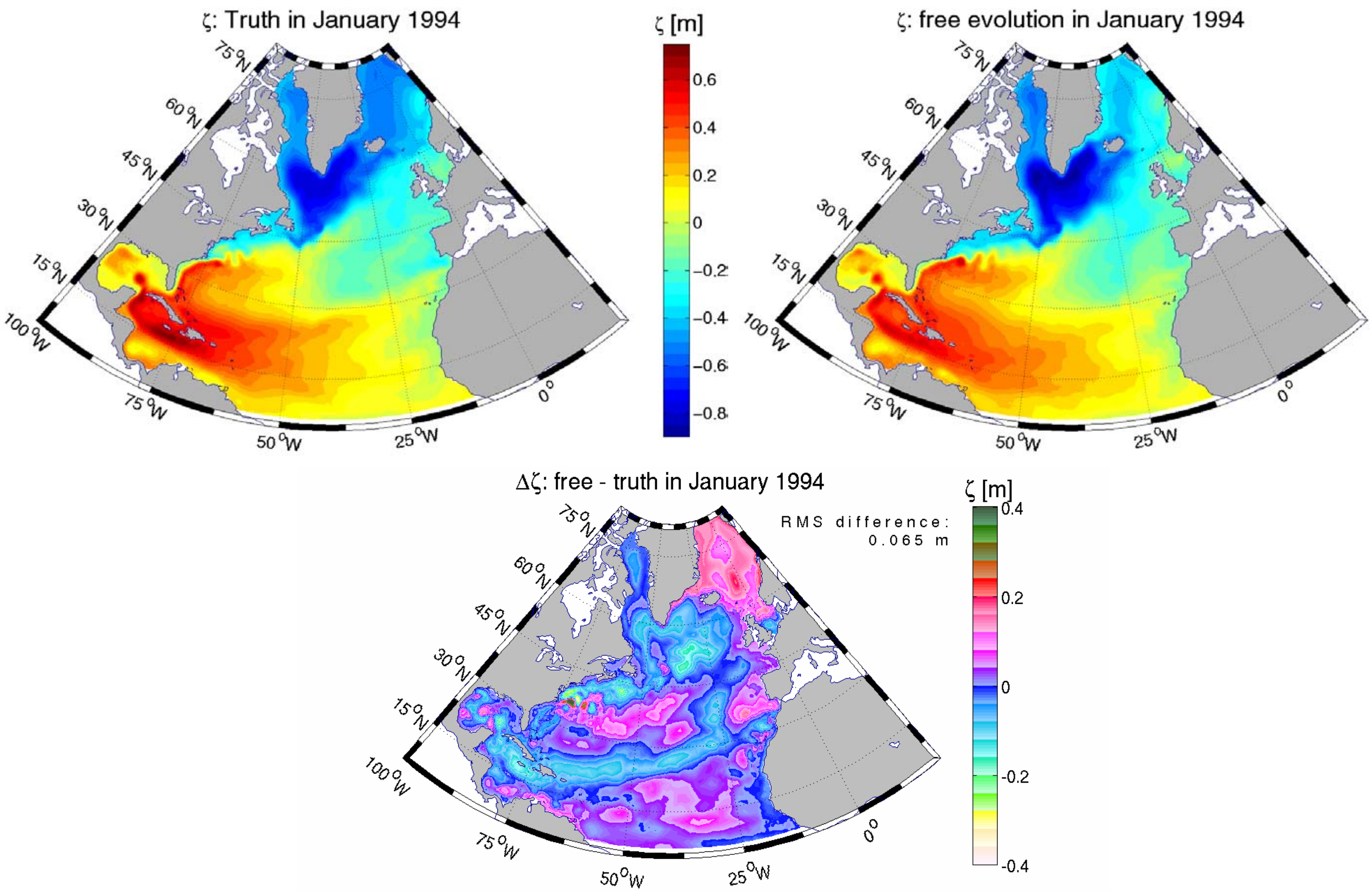
Application: FEOM North Atlantic

- 3D primitive equation model
- finite-element discretization

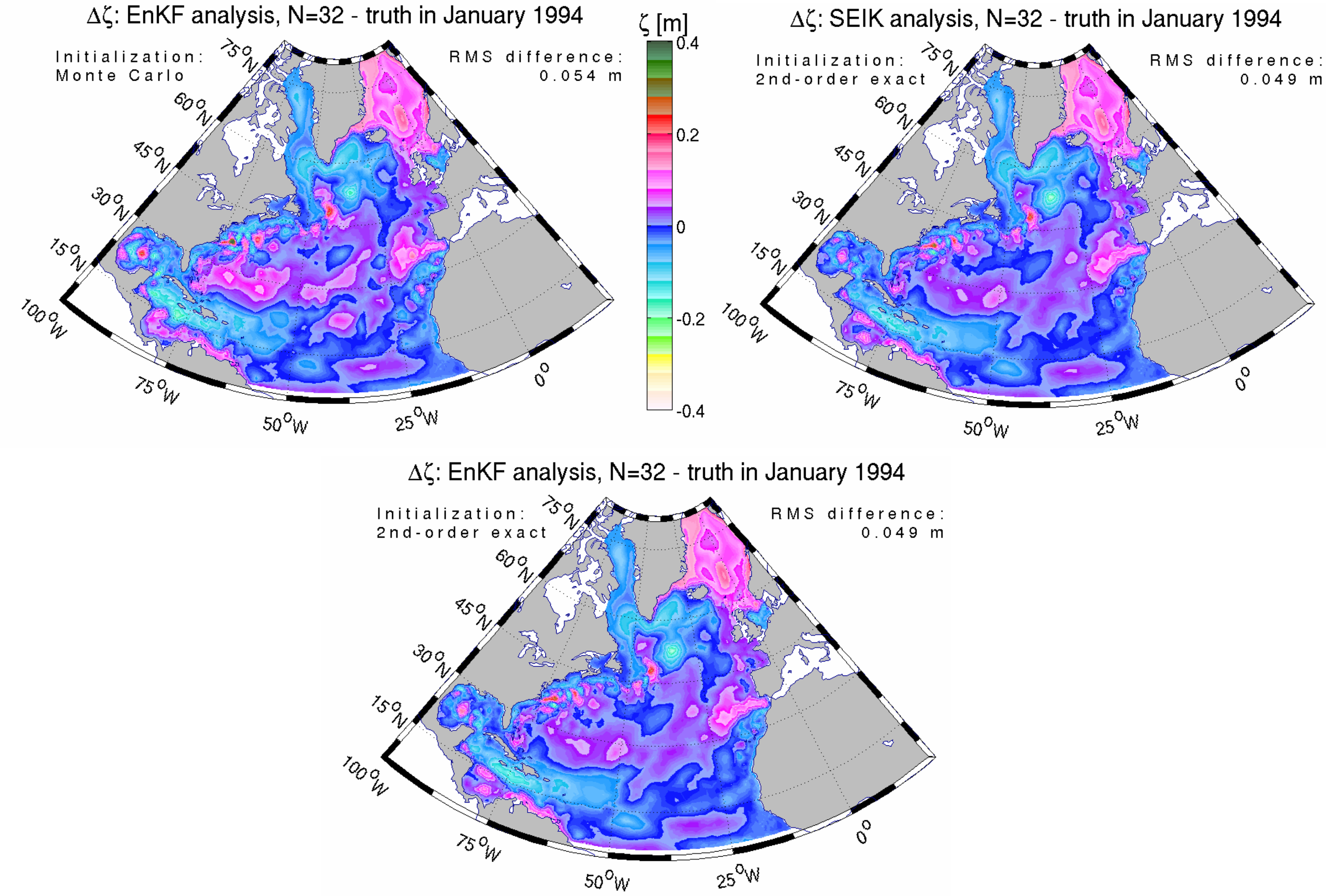
Filter Experiments:

- Assimilate synthetic observations of sea surface height ζ
- Covariance matrix estimated from 9-year model trajectory starting from January 1991 initialized from climatology
- Initial state estimate from perpetual 1990 model spin-up
- analysis steps: initial time & after 1 month of model integration
- No model error; forgetting factor 0.8 for both filters

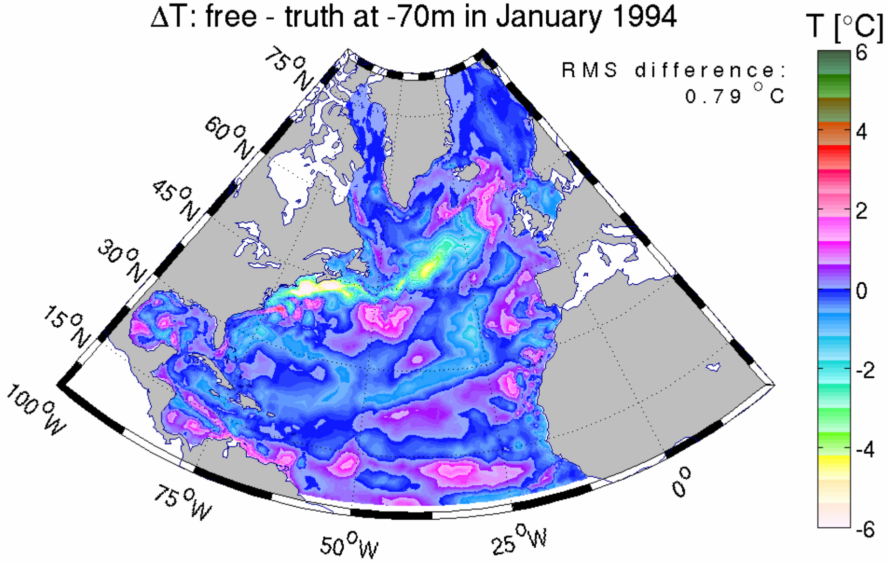
Modeled Sea Surface Height

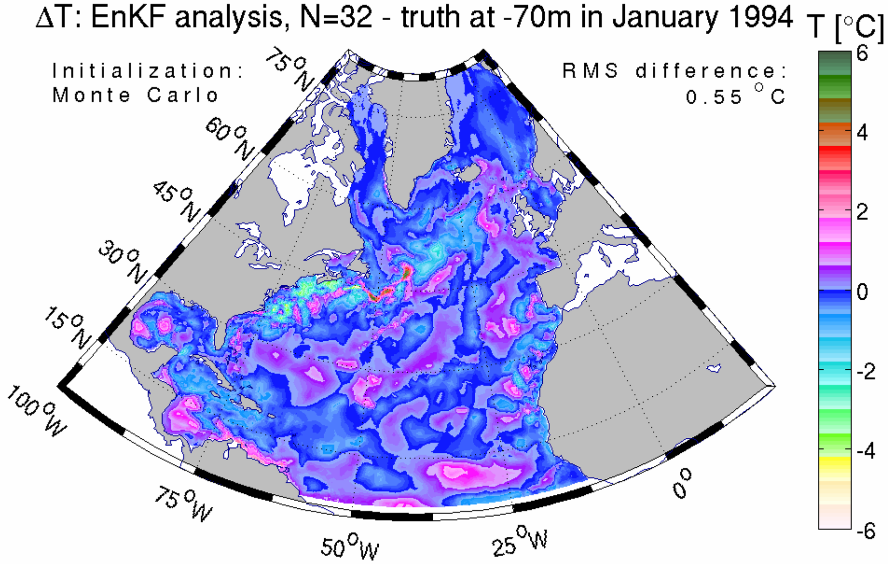


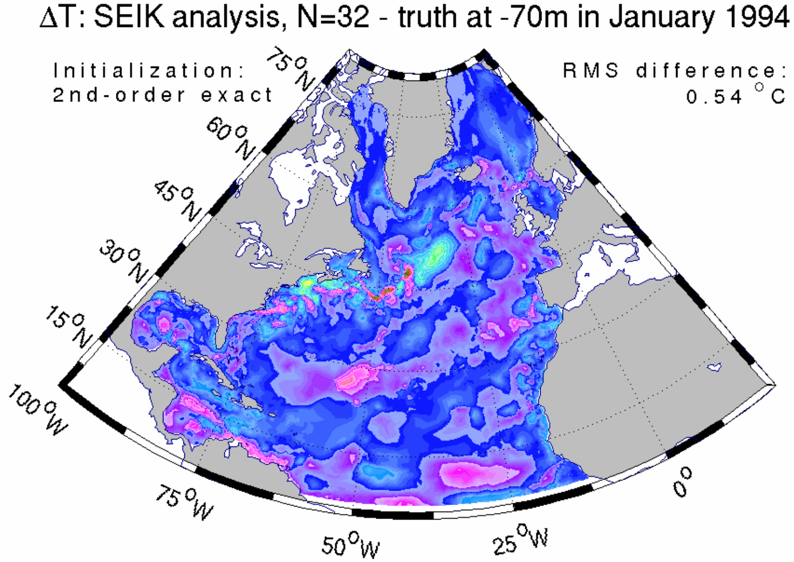
Estimated Sea Surface Height



Estimated Temperature at -70m







Comparsion of Computation Times

- Ensemble size 32; 8 concurrent model integrations

Model integrations: 34000s

Filter update:

Filter	Time
EnKF	4600s
SEIK	10s