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Earth System Reanalysis and Model Improvements at UHH

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Content

- GECCO 3 (Armin)
- CESAM Coupled Assimilation
- New EU Project
- WCRP Assimilation Workshop

GECCO3 1948-2018 Ocean Synthesis

MODEL

- MITgcm ocean model coupled to a dynamic viscous-plastic sea ice model
- Grid and bathymetry are taken from the high-resolution (0.4˚) version of the MPI-ESM (Giogetta et al., 2013).
- Prior forcing derived via bulk formula from NCEP RA1 atmospheric state
- Initial condition state taken from end of one-year spinup from WOA13

METHOD

- Adjoint method (one window), smoothed adjoint model with simplified parameterizations

CONTROLS

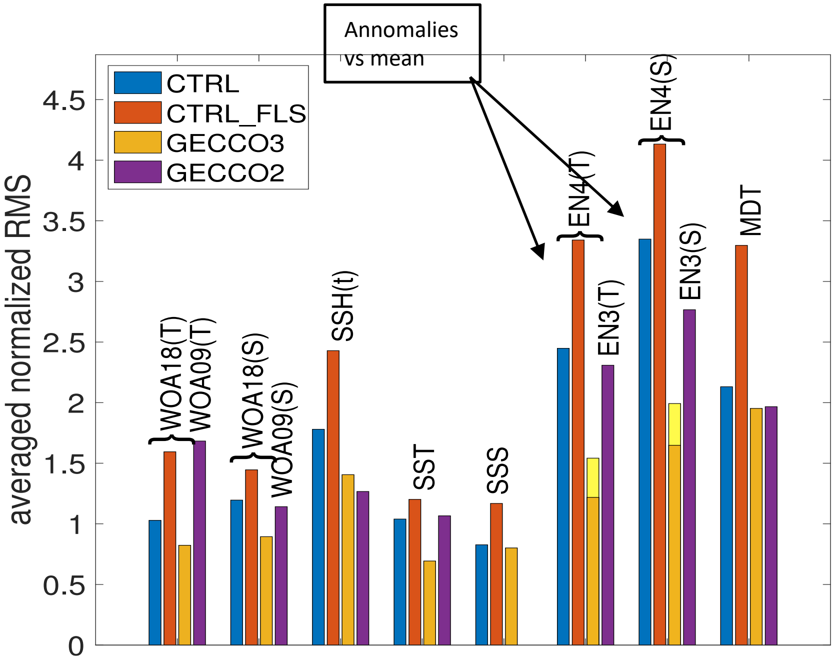
- Initial T/S., surface air temperature, humidity, precipitation, 10 m wind speeds, short wave heat flux 10d, isopycnal, thickness, and vertical diffusion and critical gradient Richardson number

DATA CONSTRAINTS

- Along track altimeter from Topex/Jason, ERS/Enivsat, GFO, C2
- MTD from the DTU10 mean sea surface minus GOCO05s geoid
- SST from HadISST
- T/S profiles from EN4.2.1
- T/S climatology from WOA18
- SSS from WOA18

GECCO3 1948-2018 Ocean Synthesis

- Different from GECCO2, which uses 5yr-long overlapping windows, GECCO3 uses **one window**
- The **convergence problem** over long windows (GECCO3first) is related to the instability to high latitude fresh water forcing (Bryan, 1986) and was solved by adding SSS relaxation.
- **Two syntheses**: GECCO3 uses 60-day and GECCO3S6m 180-day relaxation time scales.
- **Parameterized eddies** (CTRL) show better agreement with the data than what is resolved at 0.4° (CTRL_FLS)



GECCO4

- Hybrid version using GECCO3 adjoint linearized around a higher resolution forward model trajectorie similar to Köhl and Willebrand (2002)

GECCO3 1948-2018 Ocean Synthesis

TABLE 1 Configuration of the experiments

Experiment	Data assimilation	tracer advection scheme	Relaxation time-scale
GECCO3first	yes	centered with GM	no relaxation
GECCO3	yes	centered with GM	30 days
GECCO3S6m	yes	centered with GM	180 days
CTRL	none	centered with GM	30 days
CTRL_FLS	none	FLS without GM	30 days

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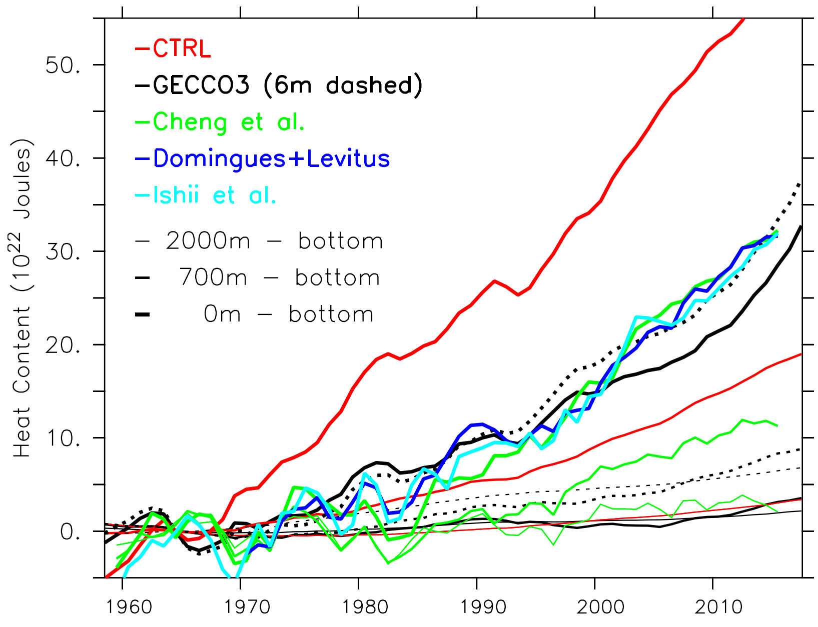
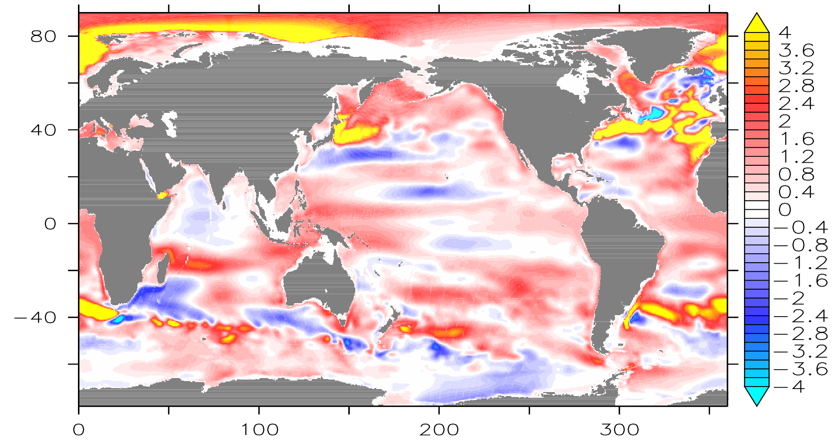
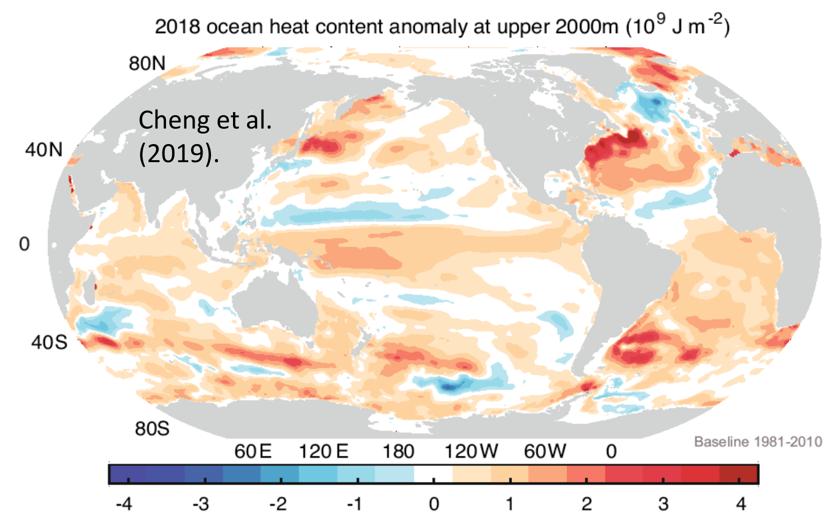
Global Heat Content



Global Heat content changes *in the three different depth categories in comparison to CEA. The anomalies with respect to 1960-1969. The curve Domingues+Levitus is added to the 2000m-to-bottom estimate by CEA to allow a comparison.*

GECCO3 2018 heat content anomaly of the upper 2000m relative to 1981-2010





The Future of Climate Modelling

WCRP's Core Project on Earth System Modelling and Observations (ESMO) organized a virtual workshop on "The Future of Climate Modelling", March 21-24, 2022.

Major outcomes:

- Significant model problems remain (missing processes, better resolution, better metrices and testing; improved output that is fit for purpose, …)
- Model improvements requires increased attention (and funding).
- **Requires close interaction between modeling and observations: enhancing the opportunity space**

How can we further improve climate model?

- Requires better merging of climate models with observations to perform a joint analysis (reanalysis/synthesis).
- Methodologically syntheses/reanalyses concerned with data assimilation, ML, AI.
- **Calls for a climate/Earth system reanalysis**

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Earth System Reanalysis

- Goal of an Earth system reanalysis (assimilation), similar to atmosphere and ocean reanalysis:

- Obtain a best possible (dynamical) description of the Earth system by combining all available data with the dynamics of a (circulation) model and use the results:
  - **Improve understanding** of climate variability, climate dynamics, and climate sensitivities.
  - **Improve climate forecasts** by merging coupled models with the **climate data base** (certainly relevant for SSH predictions).

- **Earth System Reanalysis/assimilation needs to preserve first principles** (Bengtsson et al., 2007).

Outlook on Climate Reanalysis

- Initial Earth system reanalyses started done by component and in ways that are practical. Might be OK with filters for initialization, but not for a dynamical description.

- Biggest (unique) **impact of climate data assimilation** might be in model improvements (online bias corrections) through parameter estimations and dynamically consistent descriptions using smoothers.

- **Requires adjoint models of ESM!!**

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DFG Project Earth^{RA}

Overall Goals

(1) Develop a dynamically consistent Earth System Reanalysis framework (AD tool development).

(2) Estimate coupled adjoint climate sensitivities and feedbacks.

(3) Apply toward bias improvements through dynamically consistent parameter optimizations

(4) Build on CESAM, but expand toward ICON climate model applications, or any other model.

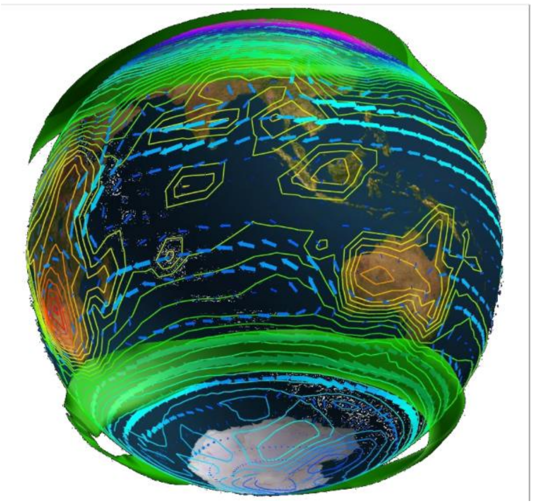
CESAM
Centre for Earth System Science
Earth System Assimilation Model

- **Intermediate complexity**

  low resolution, simplified processes for sea ice and

  land processes, hydrostatic approx., radiative transfer

- **Components**
  - **Ocean** general circulation model MITgcm
  - **Atmosphere** spectral general circulation model PlaSim
  - **Land surface and soil** parameterizations
  - **Sea ice** fraction climatology



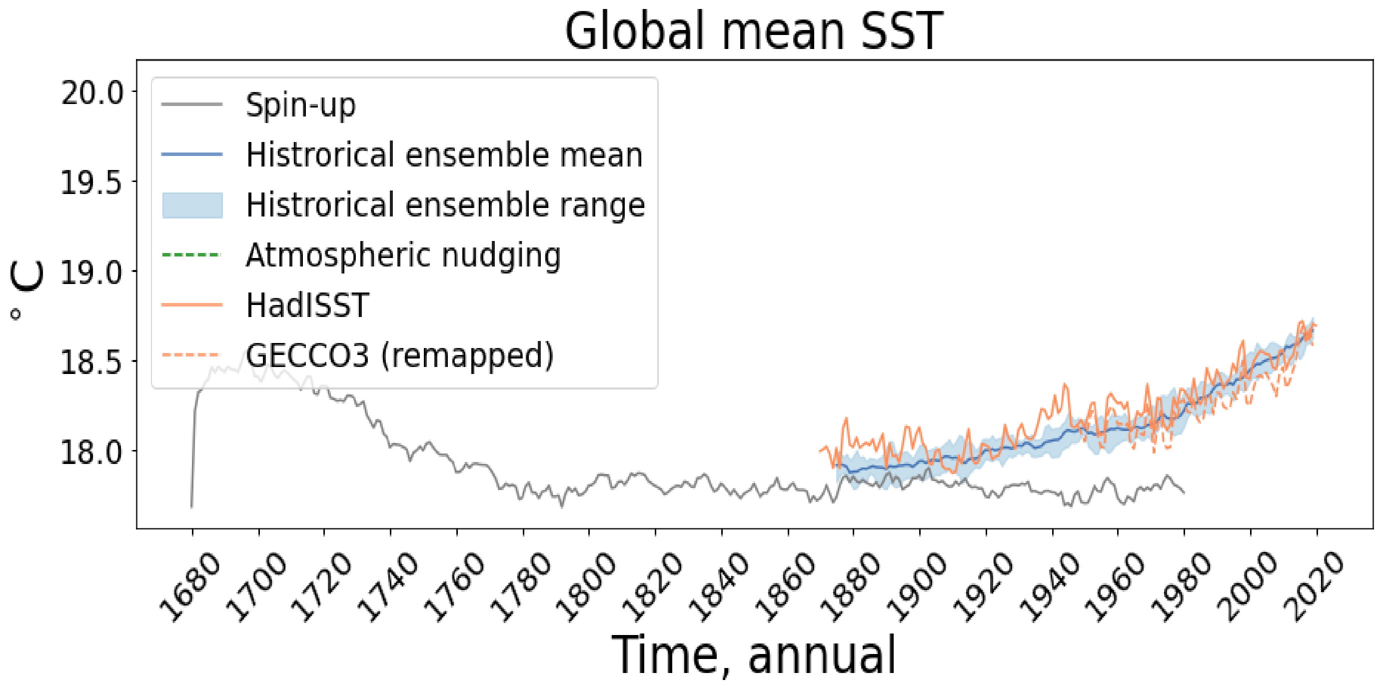
- **4D-VAR/adjoint** for coupled system (strongly coupled) from AD compiler
- **Source code available**

  www.cen.uni-hamburg.de/research/cen-models/cesam.html

(Stammer et al 2018)

CESAM performance for a standard set of historical climate simulations

The externally-forced trend is well represented in CESAM historical simulations



The model has necessary large-scale processes important for predictability at decadal timescales. However, CESAM variability is somewhat weaker in the ocean.

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CESAM Papers

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- Blessing, S., Kaminski, T., Lunkeit, F., Matei, I., Giering, R., Köhl, A., Scholze,M., Herrmann,P., Fraedrich,K., & Stammer, D. (2014). Testing variational estimation of process parameters and initial conditions of an earth system model. Tellus A: Dynamic Meteorology and Oceanography, 66(1), 22606
- Stammer, D., Koehl, A., Vlasenko, A., Matei, I., Lunkeit, F., Schubert, S. (2018). A pilot climate sensitivity study using the CEN coupled adjoint model (CESAM). Journal of Climate, 31, 2031-2056. https://doi.org/10.1175/JCLI-D-17-0183.1
- Lyu, G., Köhl, A., Matei, I., & Stammer, D. (2018). Adjoint-based climate model tuning: Application to the planet simulator. Journal of Advances in Modeling Earth Systems, 10(1), 207-222.
- Köhl, A., & Vlasenko, A. (2019). Seasonal prediction of northern European winter air temperatures from SST anomalies based on sensitivity estimates. Geophysical Research Letters, 46(11), 6109-6117.

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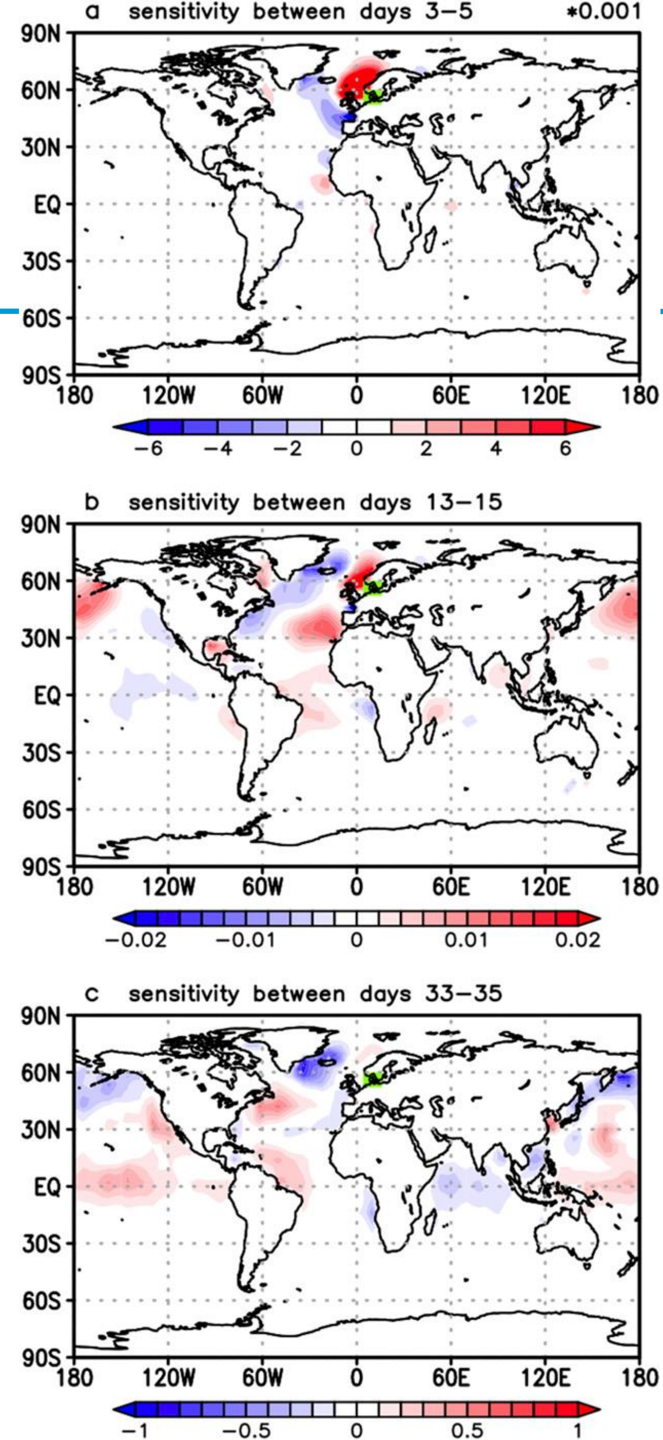
Initial sensitivity tests

CESAM Sensitivity of European temperature to SST anomalies over the Atlantic

(Stammer et al., 2018)



Initial model tuning tests

Adjoint-Based Climate Model Tuning: Application to the Planet Simulator

Guokun Lyu, Armin Köhl, Ion Matei, and Detlef Stammer, JAMES, 2018.

The adjoint method is used to calibrate the medium complexity climate model ''Planet Simulator'' through parameter estimation.

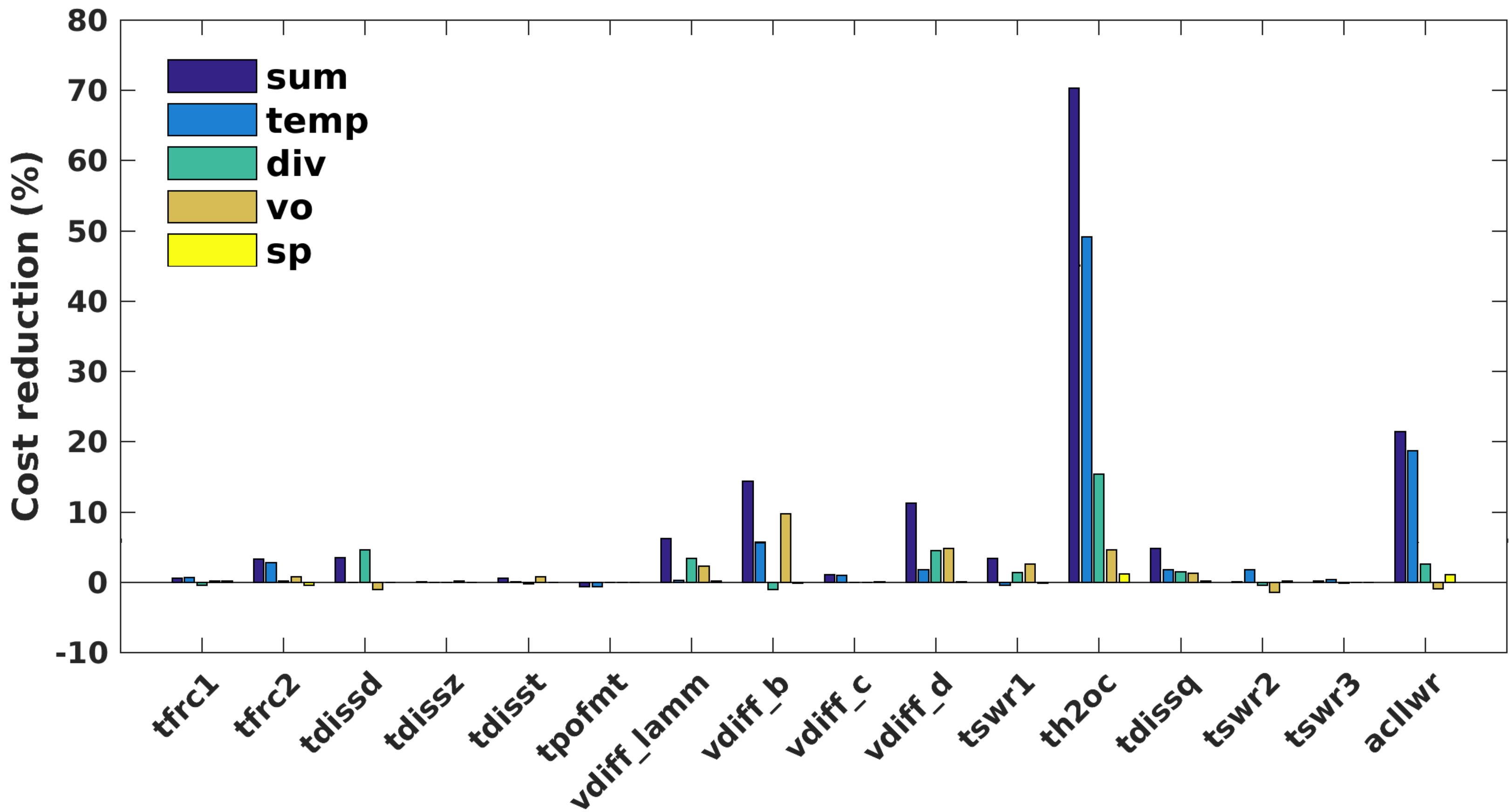
Chaos synchronization through nudging, required to overcome limits in the temporal assimilation window in the adjoint method, is employed successfully to reach this assimilation window length.

- Identical twin experiments demonstrate that this method **can retrieve default values of the control parameters** when using an assimilation window of the order of 2 months or longer.

- Results suggest a promising way for tuning uncertain parameters in nonlinear coupled climate models.

- **Optimized parameters improve the free model** simulation (without nudging terms) in a way simil21ar to that in the assimilation experiments.

When assimilating ERA-Interim reanalysis data into CESAM, the **observations of air temperature and the radiative fluxes were the most important data** for adjusting the control parameters.



Percentage reduction of the total cost and its components (see legend) from each control parameter (x axis). The bars indicate contribution of each parameter to total cost (sum), temperature cost (temp), divergence cost (div), vorticity cost (vo) and surface pressure cost (sp). From Lyu (2018).

- The global mean net longwave fluxes at the surface and at the top of the atmosphere are significantly improved by tuning two model parameters controlling the absorption of clouds and water vapor.

- The global mean net shortwave radiation at the surface is improved by optimizing three model parameters controlling cloud optical properties.

Earth^{RA} Work Packages

1 Coupled Climate Adjoint Model Development

- Improve the adjoint to the CESAM ESM using automatic differentiation tools;
- Advance assimilation approaches to deal with non-linearities and time-scales;
- Transfer the capabilities to the new ICON ESM.

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Earth^{RA} Work Packages

2 Sensitivity studies, parameter estimation and Earth System Reanalysis

- Climate adjoint sensitivity studies;
- Parameter estimations and model improvements through a climate reanalysis;
- Pilot Earth System Reanalysis

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Way Forward

- Earth System reanalyses will continue to develop and improve.
- Applications and use of results in terms of adjoint sensitivities and parameter estimation are spinning up.
- Initial activities toward bias correction is speeding up and more efforts toward initialization of climate forecasts through climate observations will emerging.
- A close collaboration with model developers is intended for use of parameter improvements and model correction.
- **Work with AD community to develop toolbox for modern code differentiation.**

Collaboration with MPI-MET

- Discussion ongoing about adjointing ICON code (B. Stevens)
- Invited AD developers to a workshop targeting on adjoining ICON
- Near term: have ad adjoint of ICON to replace CESAM

New EU AD and DA Development Project

HORIZON-CI5-2023-01-01-01: Further climate knowledge through advanced science and technologies for analyzing Earth observation and Earth system model

Project Goal:

1. Make AD tools available for modern programming codes.
2. Perform Earth system reanalysis and model improvement in support of IPCC and UNFCCC.

- Involved groups: UHH, FastOpt, Tapenade, RWTH-Aachen, TU Dresden, ECMWF, COPERNICUS, DWD, CNRS, NERSC, CNR, UUI.
- From the US: ARGON, U Texas

WCRP Workshop on
Improving climate models and projections using observation
MIT, Cambridge MA, USA
June 12 – 14, 2023

- Workshop is planned to take place between June 12 and June 14, 2023.

- The workshop will focus on data assimilation and artificial intelligence/machine learning (AI/ML) approaches in the context of Earth system reanalysis and climate model improvement.

- The workshop will be hosted by MIT in Cambridge, Massachusetts, and will be open but limited in number of participants.

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WCRP Workshop on
Improving climate models and projections using observation
MIT, Cambridge MA, USA
June 12 – 14, 2023

- The workshop will be organized 25 years after the inception of the ECCO assimilation effort at MIT.

- It will consist only of a plenary session featuring keynote talks on all aspects of future Earth system reanalysis and climate model improvements and related aspects of coupled data assimilation and machine learning techniques.

- As outcome a white paper is anticipated that will guide WCRPs efforts on coupled data assimilation and that can be used as input into WCRPs Open Science Conference, held in Kigali during Oct 23 – 27, 2023.

- The local hosts will be Raffael Ferrari, Chris Hill and Carl Wunsch.

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WCRP Open Science Conference 2023
Advancing climate science for a sustainable future
SAVE THE DATE
23-27 October 2023
Kigali Convention Centre
Kigali - Rwanda
WCRP
https://www.wcrp-climate.org/wcrp-osc23

WCRP OSC 2023

WORLD CLIMATE RESEARCH PROGRAMME

OPEN SCIENCE CONFERENCE

23 - 27 OCT 2023 | RWANDA

Thank You!