Ensemble based and implicit cross-correlations in coupled data assimilation

Patrick Laloyaux, Sergey Frolov (NRL), Benjamin Ménétrier (Météo-France) and Massimo Bonavita

ECMWF
EUROPEAN CENTRE FOR MEDIUM RANGE WEATHER FORECASTS

Earth system modelling at ECMWF

Atmosphere *Land* *Ocean* *Wave* *Sea ice*





To produce global numerical weather forecasts

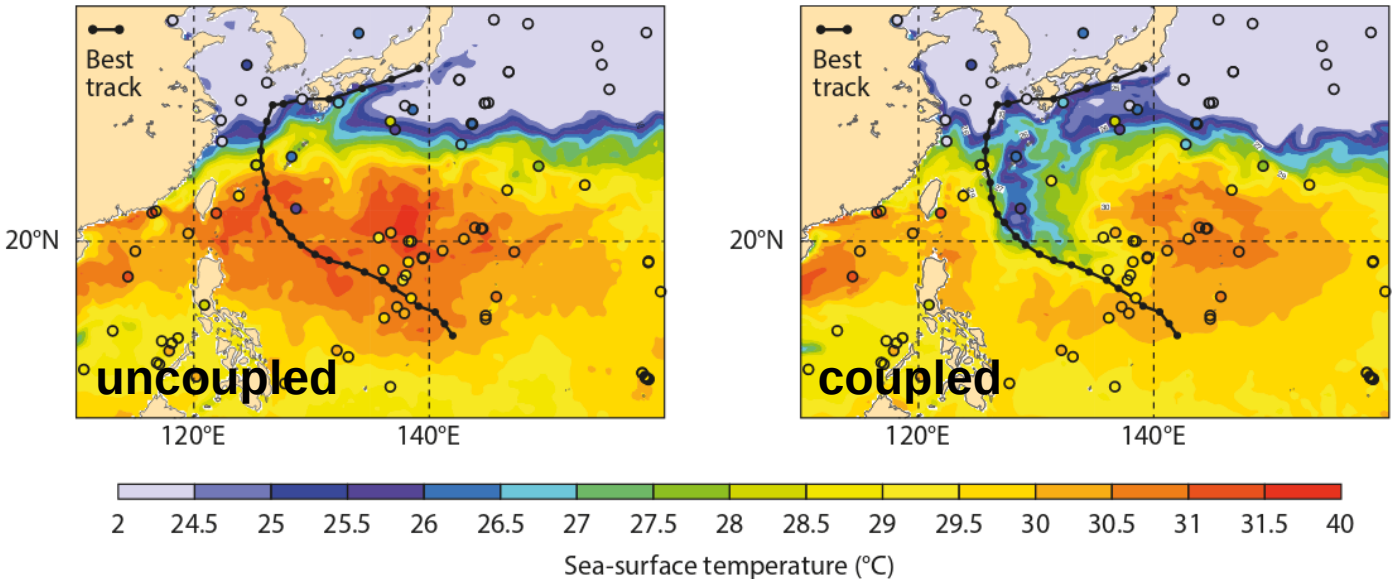
- medium-range (9km/0.25 degree resolution)
- monthly
- seasonal

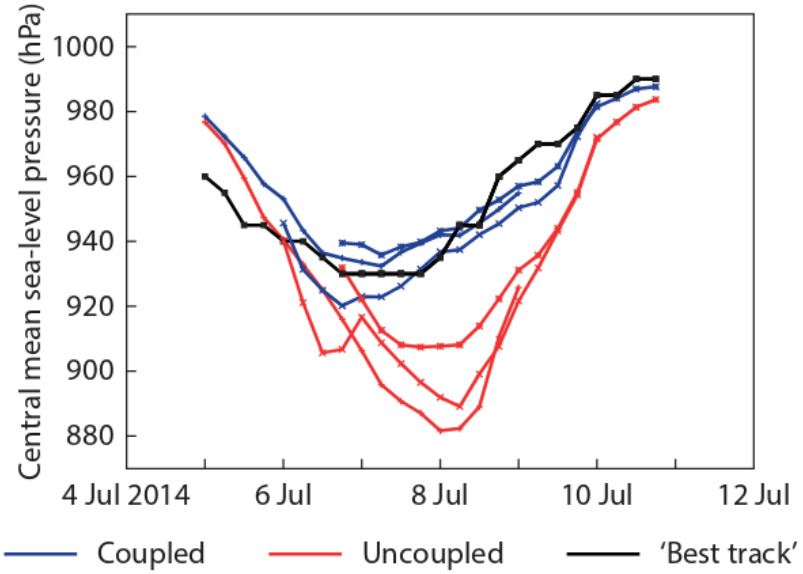
Complexity of the Earth system model has increased with time

- to improve the medium-range forecasts (better modelling of relevant processes)
- to extend the prediction horizon (monthly and seasonal)

Atmosphere-ocean coupling in medium-range forecasts

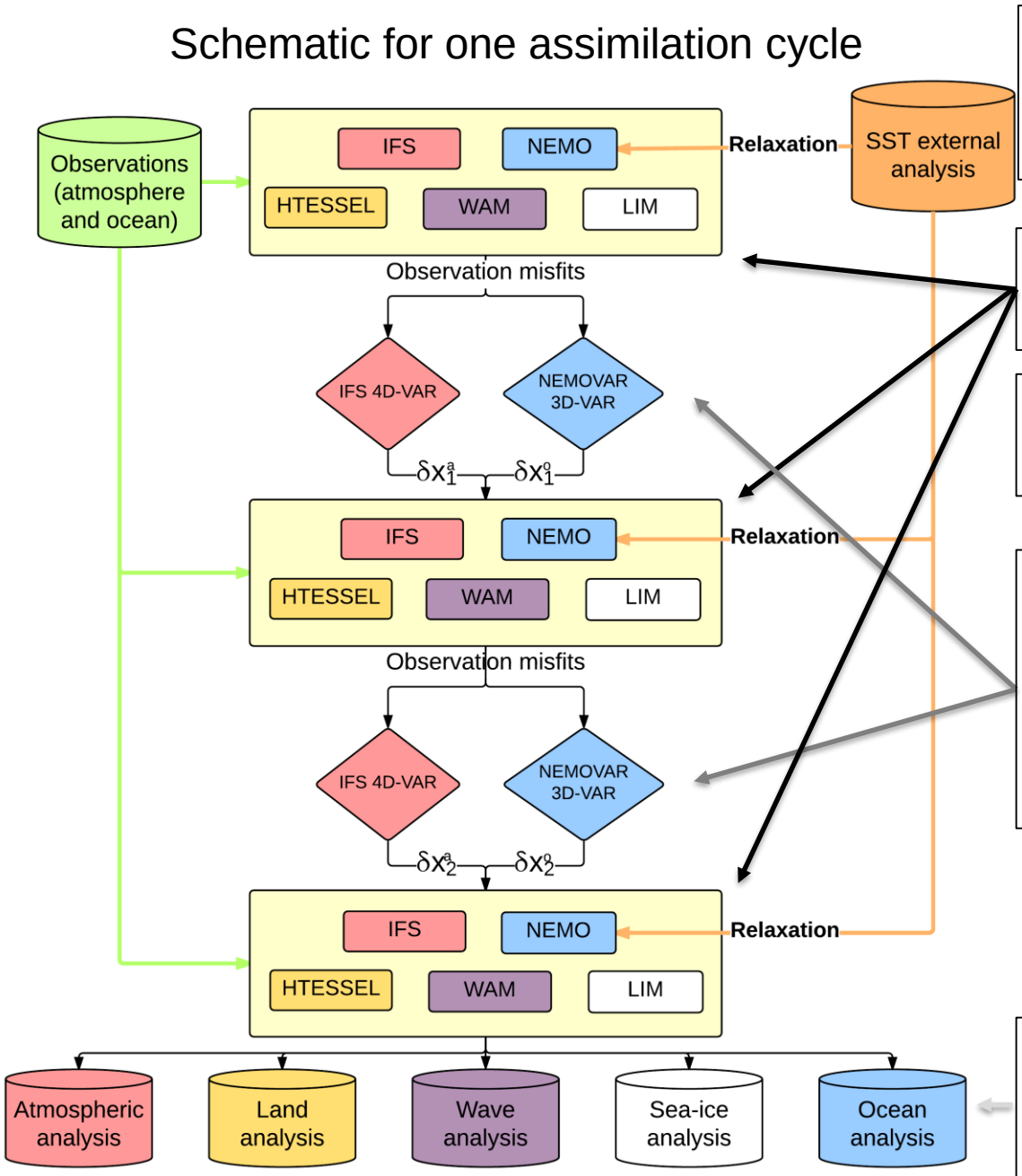
Tropical cyclone Neoguri





K Mogensen et al. ECMWF Newsletter No. 154

Coupled atmosphere-ocean assimilation system (CERA)



A common 24-hour window
Atmospheric/ocean obs assimilated simultaneously

Outer loop: coupled model computes observation misfits

SST computed in NEMO and constrained by relaxation

Inner loop: atmospheric and ocean increments are computed in parallel (separate background error, no coupled TLM and adjoint)

analysis dynamically consistent with respect to the coupled model

Coupled atmosphere-ocean assimilation system (CERA)

Iterative process where the ocean and the atmosphere converge towards a consistent coupled state

$$\begin{bmatrix} \mathrm{x}^0 \\ \mathrm{x}^0 \end{bmatrix} = \begin{bmatrix} \mathrm{x}^\mathrm{b} \\ \mathrm{x}^\mathrm{b} \end{bmatrix}$$

for k=0,1,... do

Compute observation departures

$$\begin{bmatrix} \delta\mathrm{y}^\mathrm{k} \\ \delta\mathrm{y}^\mathrm{k} \end{bmatrix} = \begin{bmatrix} \mathrm{y} \\ \mathrm{y} \end{bmatrix} - \begin{bmatrix} \mathcal{H} \\ \mathcal{H} \end{bmatrix} \mathcal{M}(\mathrm{x}^\mathrm{k}, \mathrm{x}^\mathrm{k})$$

Compute increments

$$\delta\mathrm{x}^\mathrm{k} = (\mathrm{x}^\mathrm{b} - \mathrm{x}^\mathrm{k}) + \mathrm{BH}^\mathrm{T}(\mathrm{HBH}^\mathrm{T} + \mathrm{R})^{-1}\delta\mathrm{y}^\mathrm{k}$$

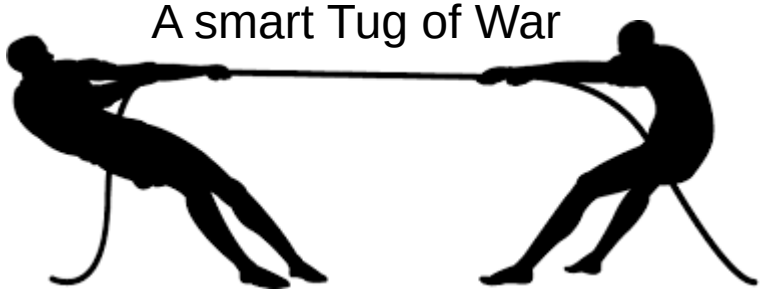
$$\delta\mathrm{x}^\mathrm{k} = (\mathrm{x}^\mathrm{b} - \mathrm{x}^\mathrm{k}) + \mathrm{BH}^\mathrm{T}(\mathrm{HBH}^\mathrm{T} + \mathrm{R})^{-1}\delta\mathrm{y}^\mathrm{k}$$

Update initial condition

$$\begin{bmatrix} \mathrm{x}^{\mathrm{k}+1} \\ \mathrm{x}^{\mathrm{k}+1} \end{bmatrix} = \begin{bmatrix} \mathrm{x}^\mathrm{k} \\ \mathrm{x}^\mathrm{k} \end{bmatrix} + \begin{bmatrix} \delta\mathrm{x}^\mathrm{k} \\ \delta\mathrm{x}^\mathrm{k} \end{bmatrix}$$

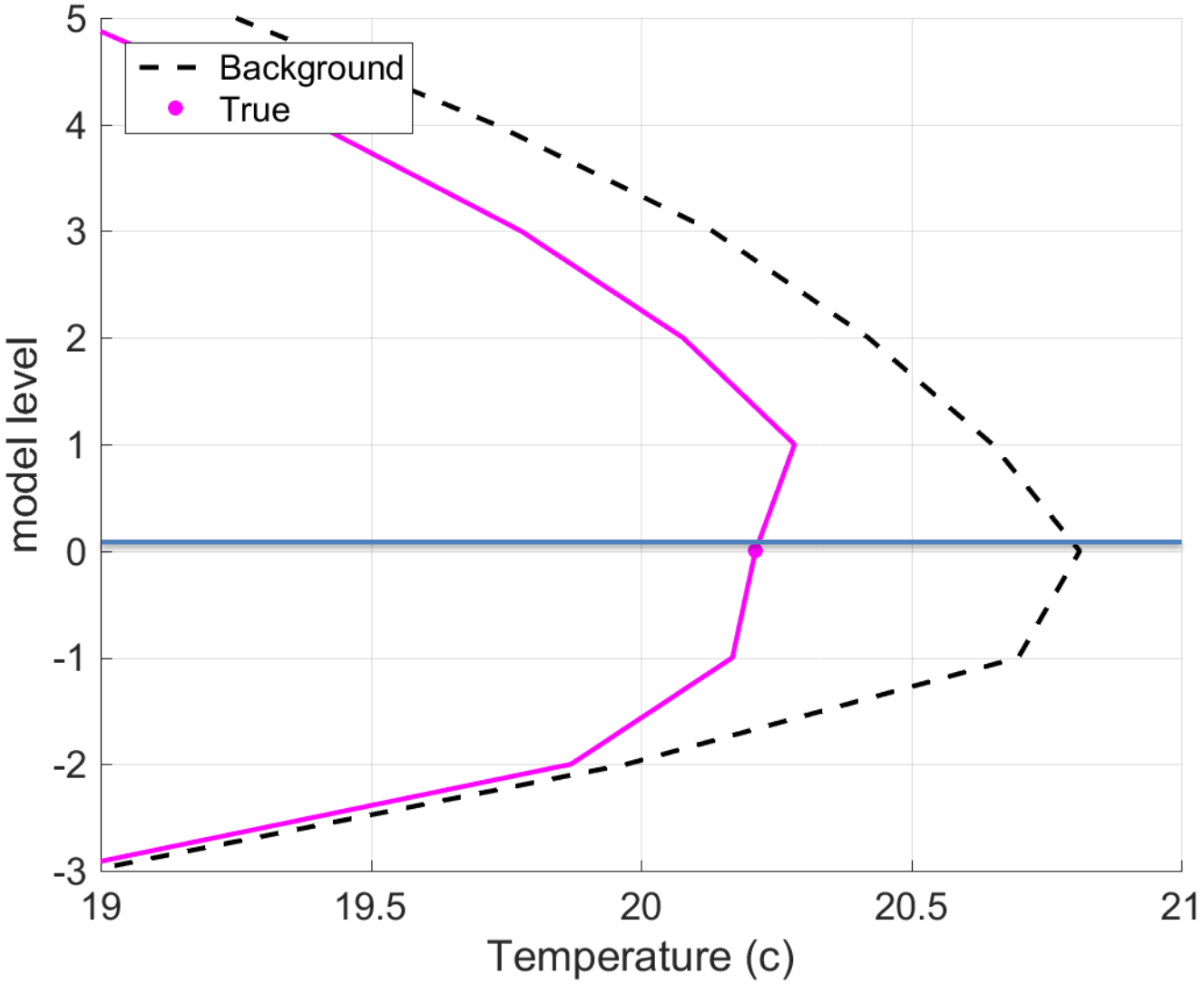
end

A smart Tug of War



separate background error to compute the atmospheric and the ocean increments

A single observation experiment (CERA)

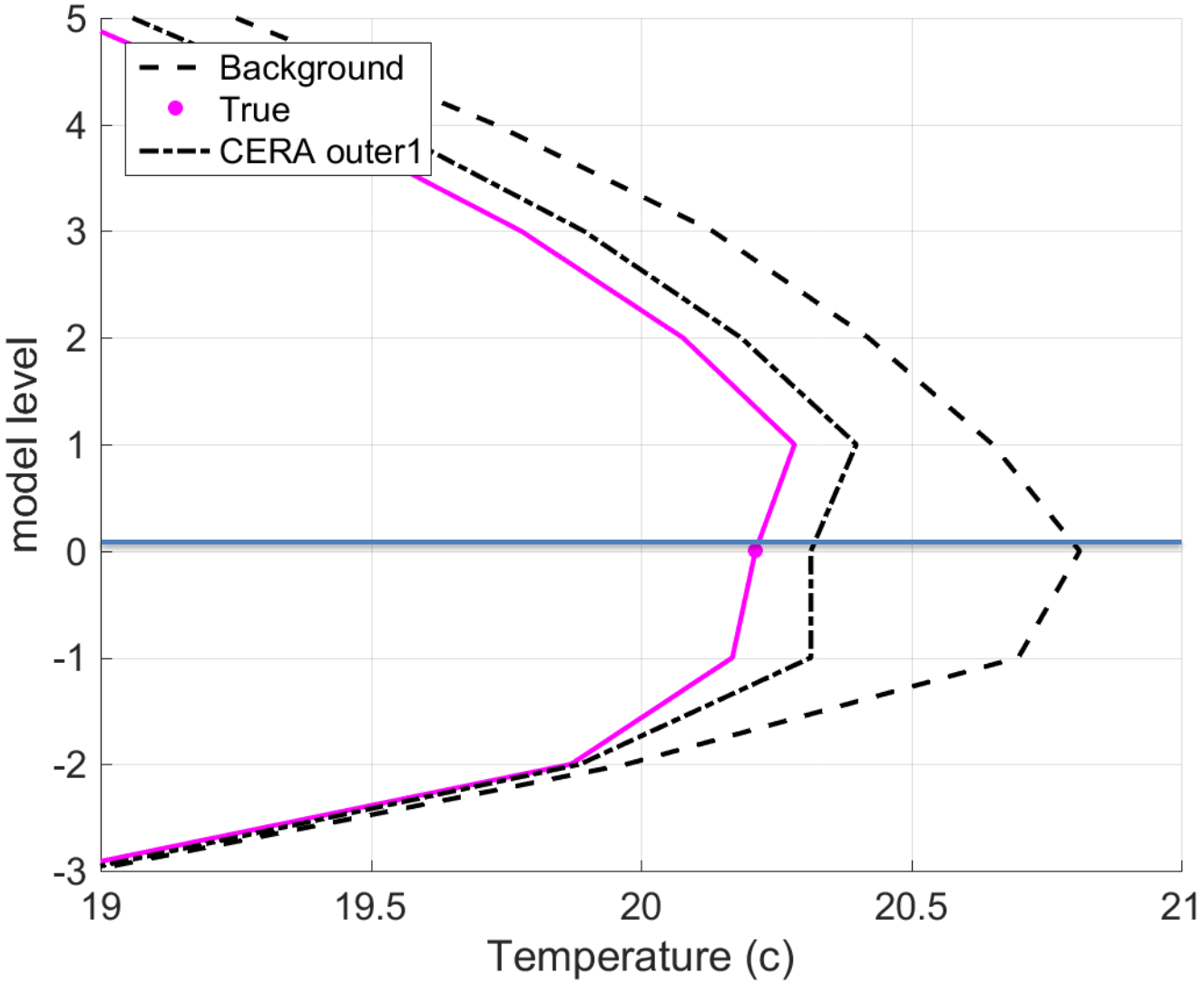


→ Ocean increment from the ocean observation is propagated in the atmosphere

→ CERA produces implicit cross-correlations using the physics of the coupled model

→ Several outer iteration to ensure a consistent coupled analysis

A single observation experiment (CERA)



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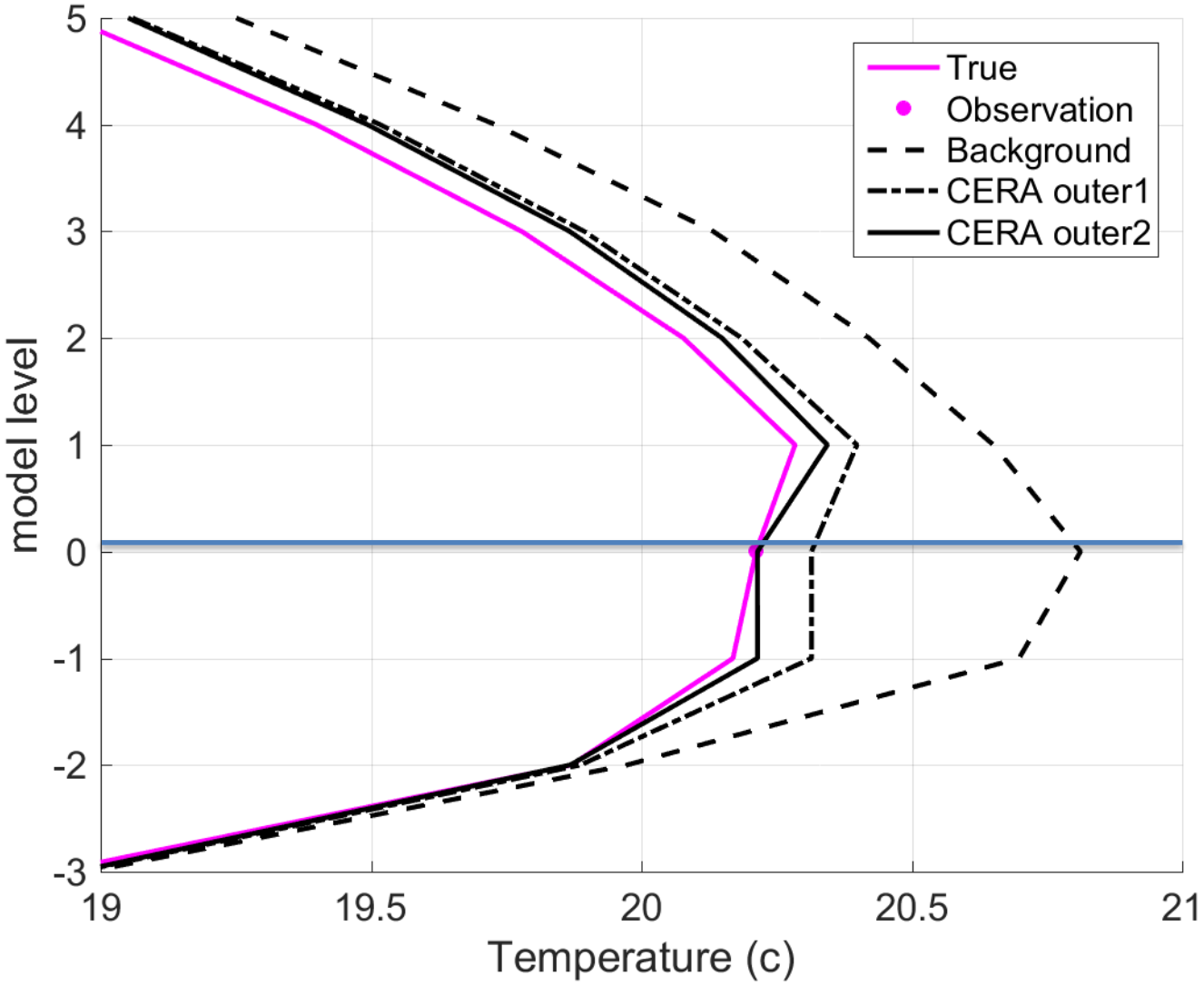


→ Ocean increment from the ocean observation is propagated in the atmosphere

→ CERA produces implicit cross-correlations using the physics of the coupled model

→ Several outer iteration to ensure a consistent coupled analysis

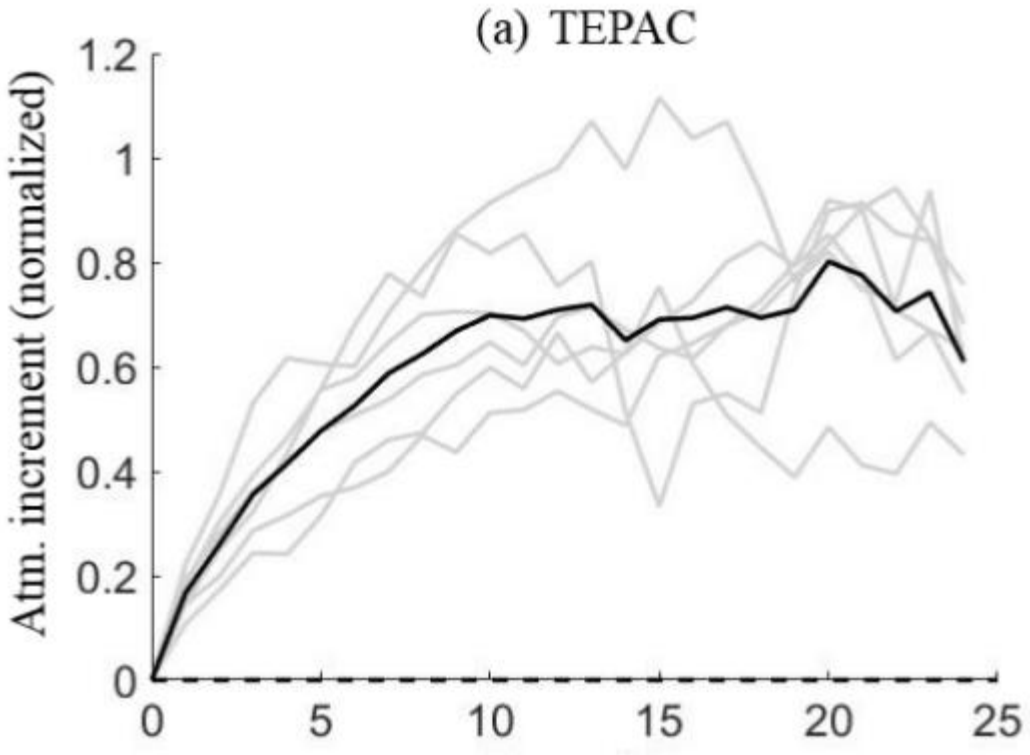
Atmosphere-ocean coupling in CERA

How fast the ocean temperature increment propagates in the atmosphere?

→ 18 single observation experiments (different locations and seasons)

→ depends on the location and the resolution

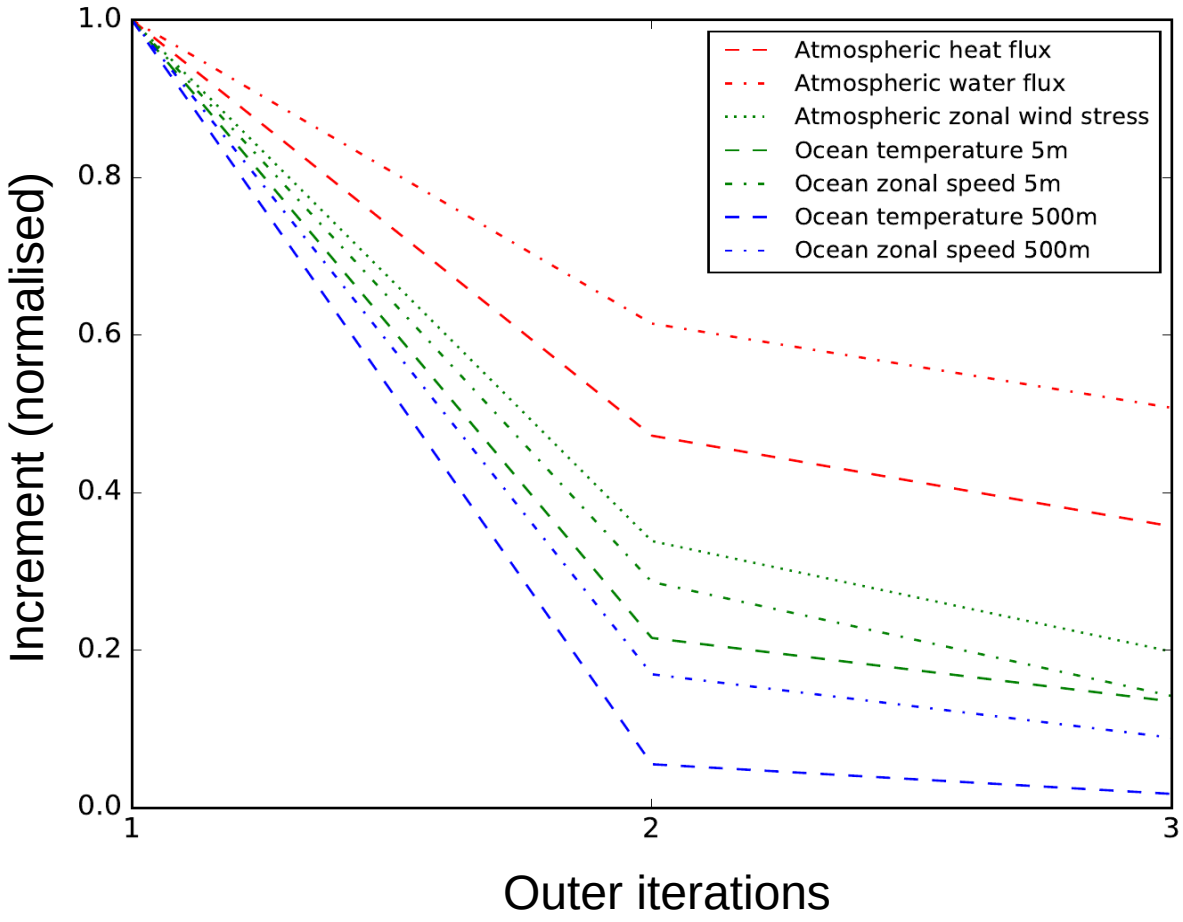
→ 6-12 hours in the tropical Pacific ocean



No cross-correlation at the initial time (separate background error)

Atmosphere-ocean coupling in CERA

How many outer iterations for convergence?



Assimilating only conventional surface and subsurface observations

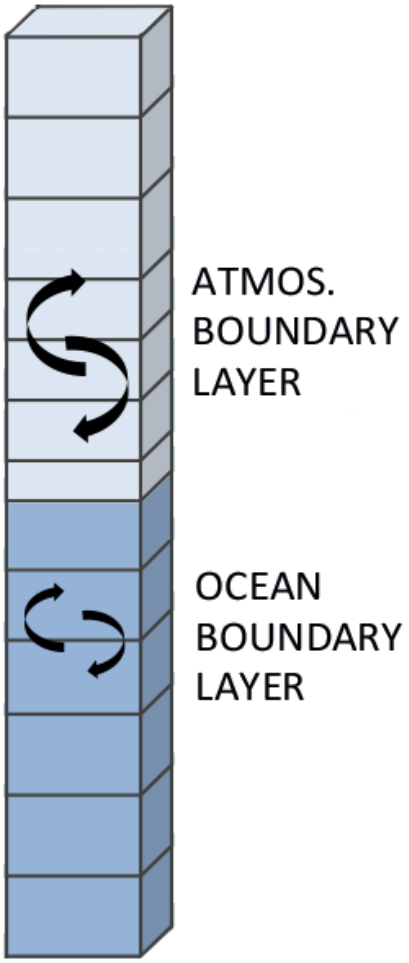
Speed of convergence is different for ocean fields, coupled fields and atmospheric fields

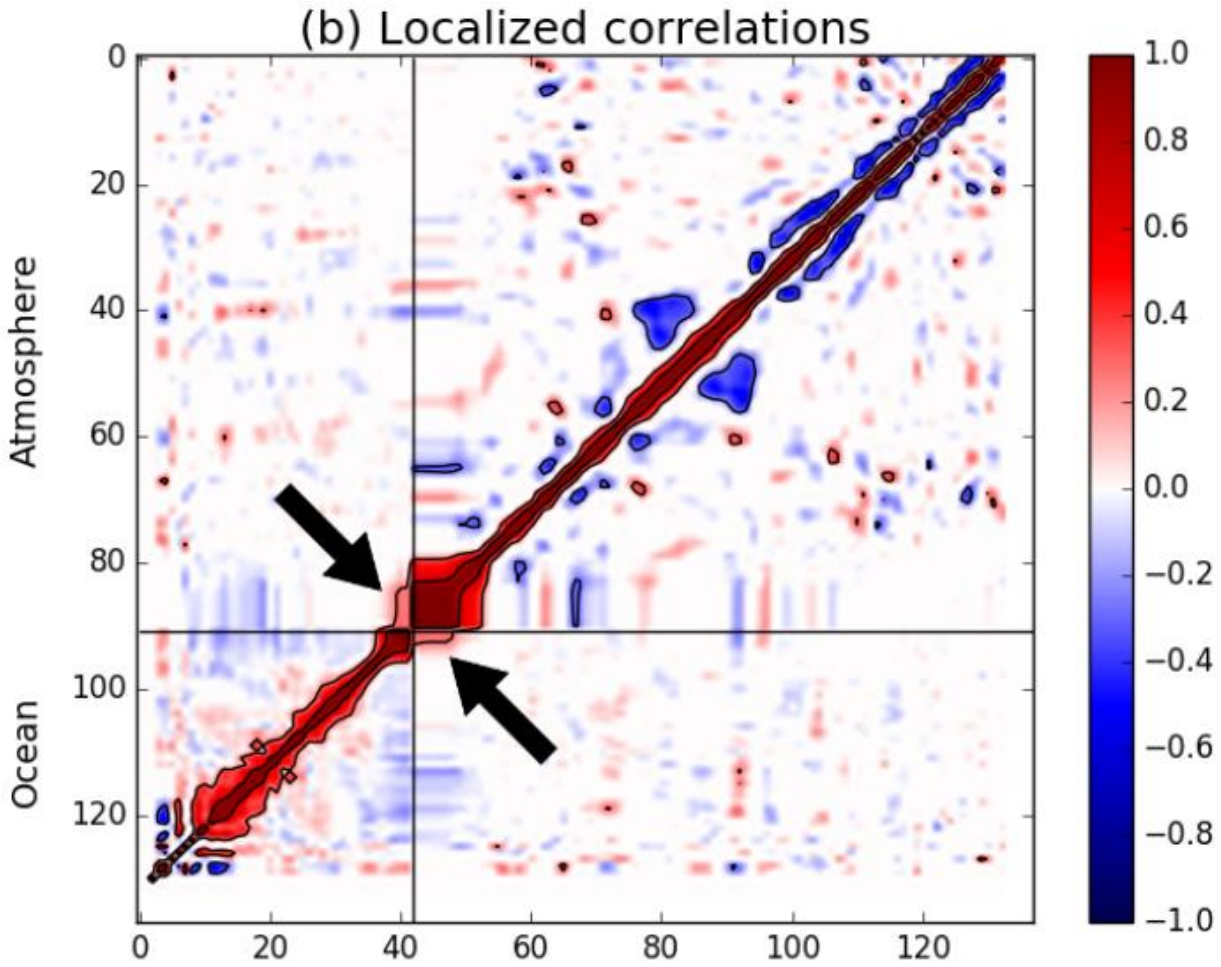
Explicit cross-correlations from coupled ensemble forecasts

→ 25-member coupled ensemble forecasts

→ Coupled temperature covariance on the 21st August 2005 (130W, 0N)

→ Localisation is needed (Menetrier et al.)





A coupled Kalman filter with explicit cross-correlation

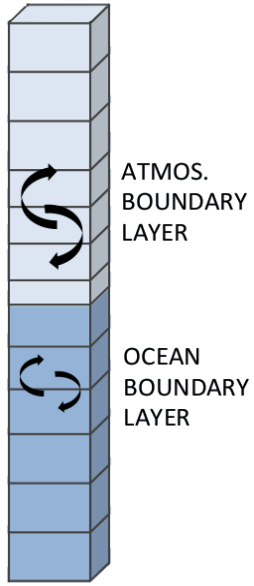
$$\begin{bmatrix} \mathrm{x}^{\mathrm{f}} \\ \mathrm{x}^{\mathrm{f}} \end{bmatrix} = \begin{bmatrix} \mathrm{x}^{\mathrm{b}} \\ \mathrm{x}^{\mathrm{b}} \end{bmatrix}$$

Compute observation departures

$$\begin{bmatrix} \delta\mathrm{y} \\ \delta\mathrm{y} \end{bmatrix} = \begin{bmatrix} \mathrm{y} \\ \mathrm{y} \end{bmatrix} - \begin{bmatrix} \mathcal{H} \\ \mathcal{H} \end{bmatrix} \mathcal{M}(\mathrm{x}^{\mathrm{k}}, \mathrm{x}^{\mathrm{k}})$$

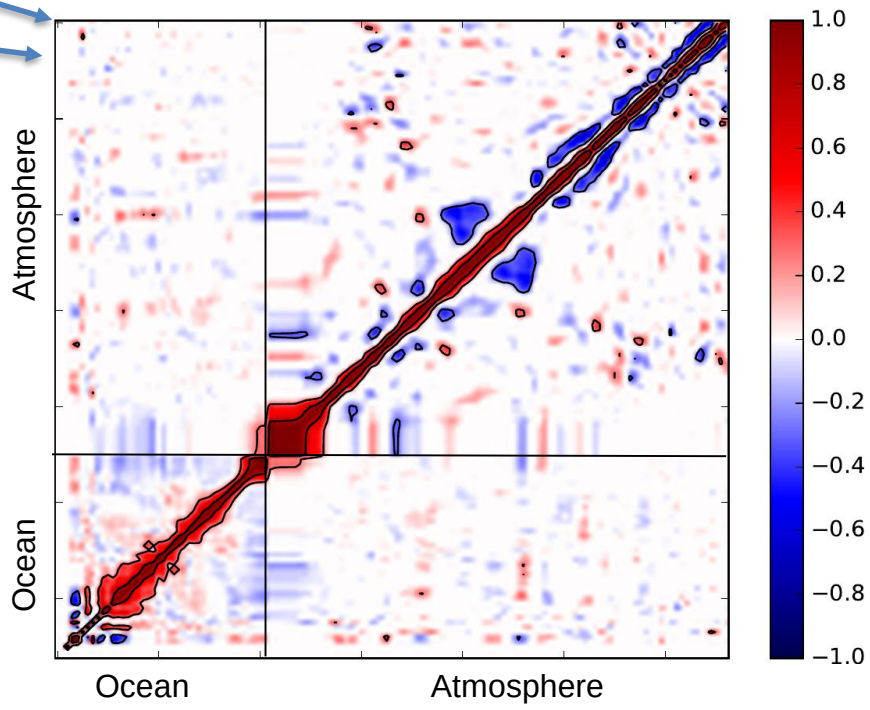
Compute analysis

$$\begin{bmatrix} \mathrm{x}^{\mathrm{a}} \\ \mathrm{x}^{\mathrm{a}} \end{bmatrix} = \begin{bmatrix} \mathrm{x}^{\mathrm{f}} \\ \mathrm{x}^{\mathrm{f}} \end{bmatrix} + \begin{bmatrix} \mathrm{B} & \mathrm{B} \\ \mathrm{B} & \mathrm{B} \end{bmatrix} [\mathrm{H}\ \mathrm{H}] \left(\begin{bmatrix} \mathrm{H} \\ \mathrm{H} \end{bmatrix} \begin{bmatrix} \mathrm{B} & \mathrm{B} \\ \mathrm{B} & \mathrm{B} \end{bmatrix} [\mathrm{H}\ \mathrm{H}] \right)^{-1} \begin{bmatrix} \delta\mathrm{y} \\ \delta\mathrm{y} \end{bmatrix}$$



The correction in the ocean and in the atmosphere is computed at the background time

B is only from ensemble, no climatologic/static part



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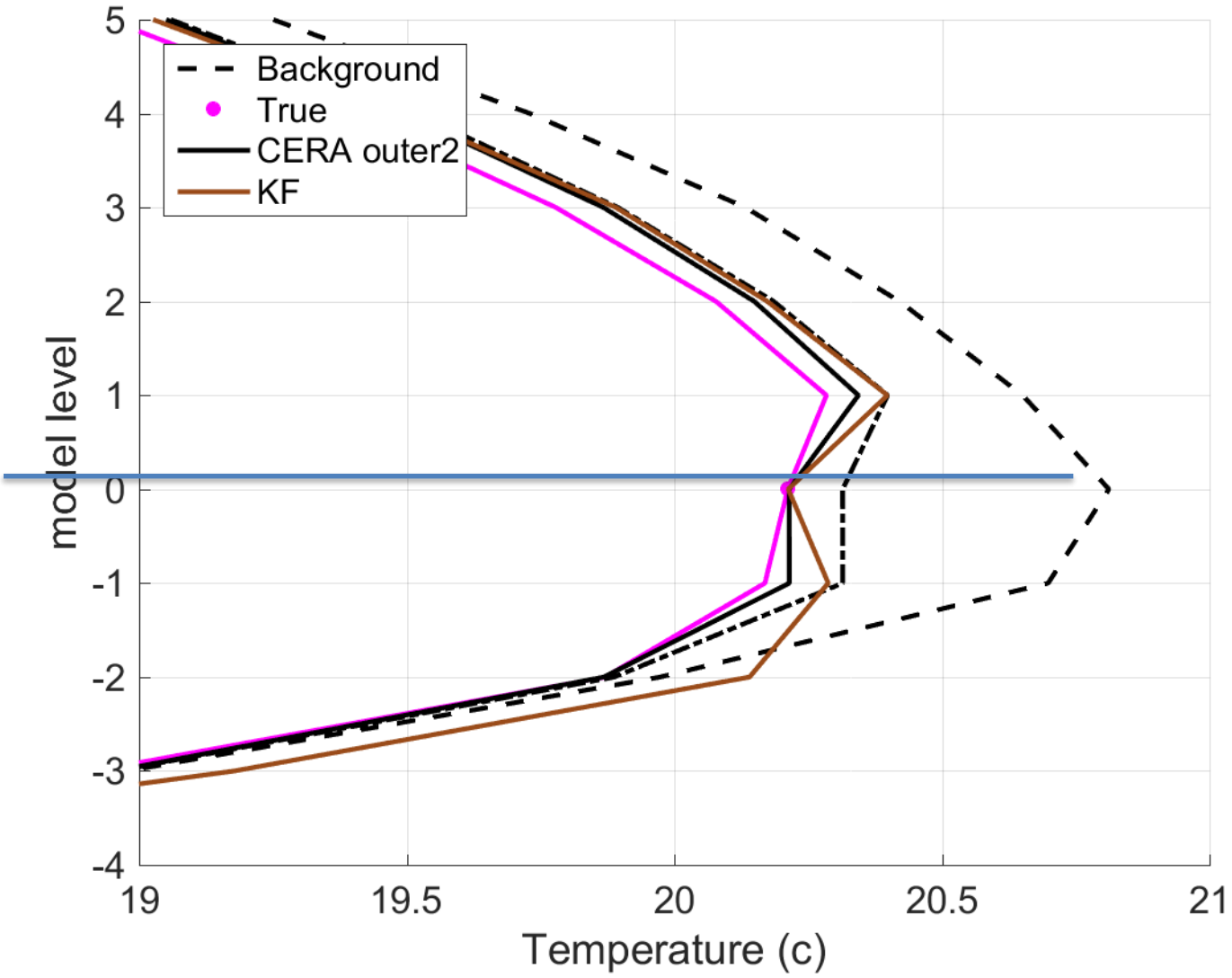
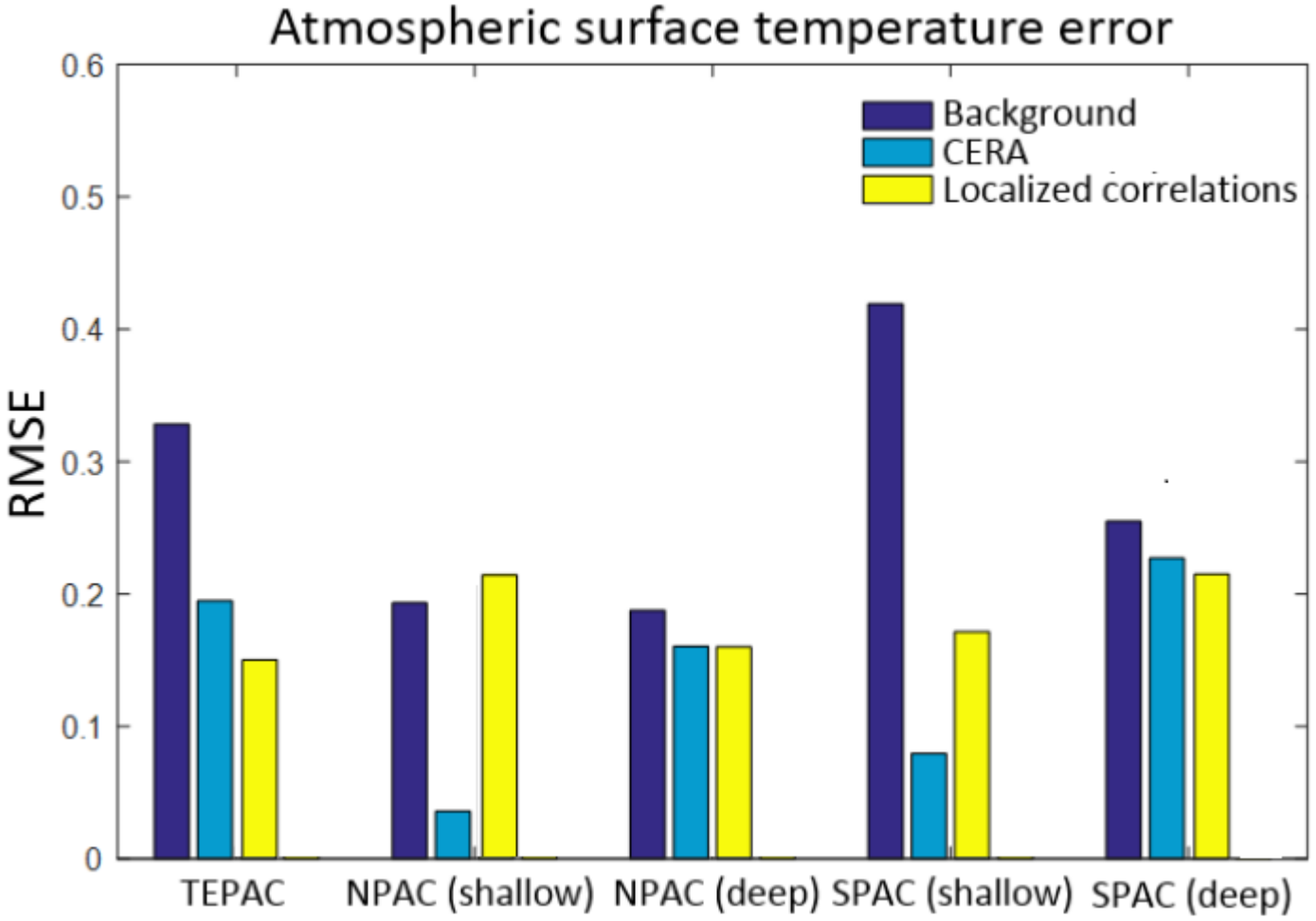


Comparison between implicit and explicit cross-correlation



→ Implicit and explicit cross-correlation reduce the error in the atmosphere

→ Performance depends on the mixed layer depth

Comparison between implicit and explicit cross-correlation

CERA

- ✓ Coupling based on the model physics
- ✓ Implementation recycling available blocks

- ✗ No cross-correlation at initial time
- ✗ Long assimilation window required

Ensemble-based

- ✓ Coupling based on the model physics
- ✓ Cross-correlation at initial time

- ✗ Localization required

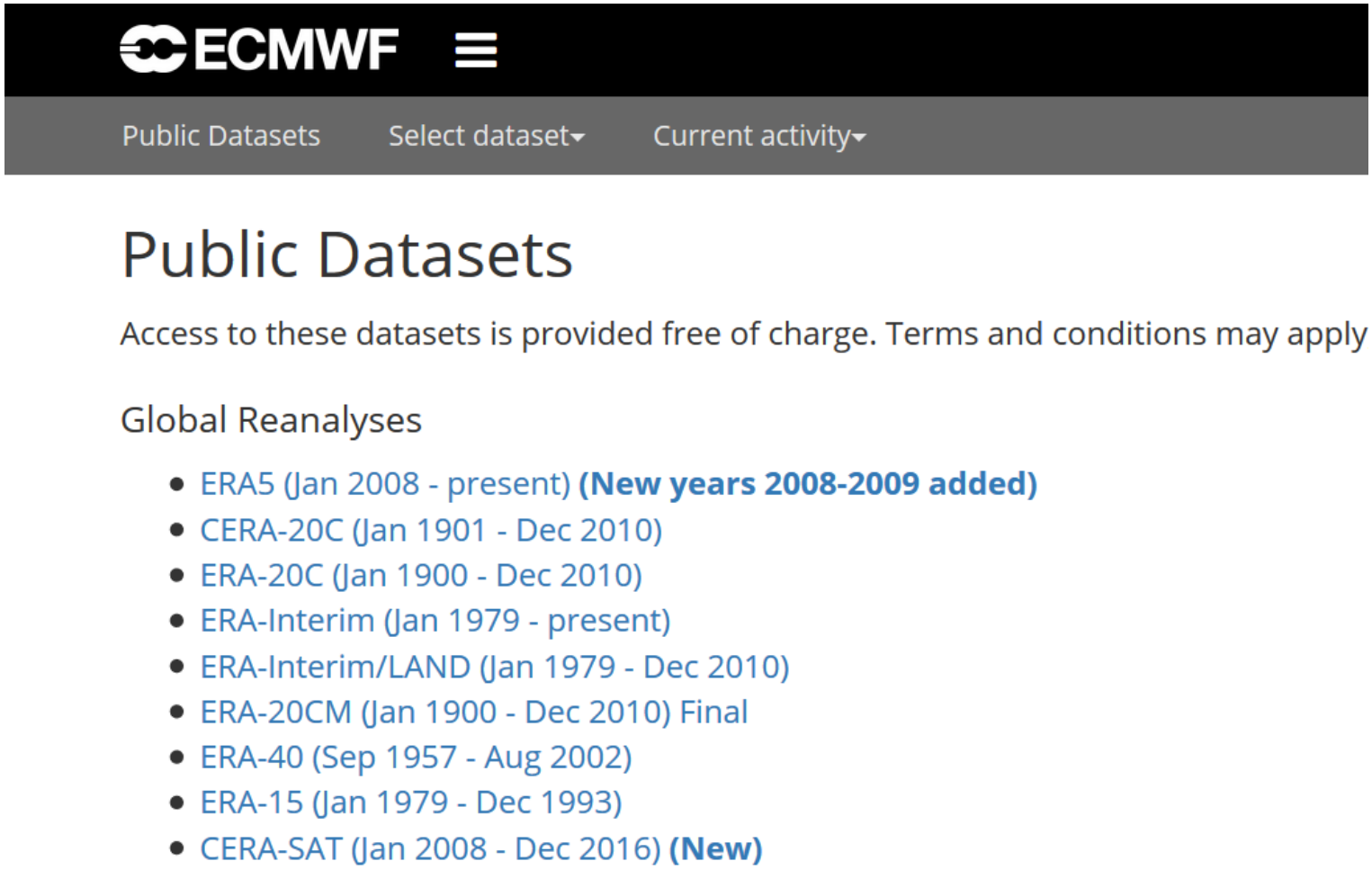
Hybrid method using an ensemble of CERA system with an hybrid background error should be investigated in the future

Great collaboration with NRL!

Coupled reanalyses

CERA-20C (1901-2010) and CERA-SAT(2008-2016) are available

http://apps.ecmwf.int/datasets/



Coupled reanalyses

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RESEARCH ARTICLE

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CERA-20C: A Coupled Reanalysis of the Twentieth Century

Patrick Laloyaux[1], Eric de Boisseson[1], Magdalena Balmaseda[1], Jean-Raymond Bidlot[1], Stefan Broennimann[2], Roberto Buizza[1], Per Dalhgren[1], Dick Dee[1], Leopold Haimberger[3], Hans Hersbach[1], Yuki Kosaka[4], Matthew Martin[5], Paul Poli[6], Nick Rayner[5], Elke Rustemeier[7], and Dinand Schepers[1]

[1]European Centre for Medium-Range Weather Forecasts, Reading, UK, [2]University of Bern, Bern, Switzerland, [3]University of Vienna, Wien, Austria, [4]Japan Meteorological Agency, Tokyo, Japan, [5]Met Office, Exeter, UK, [6]Meteo France, Paris, France, [7]Deutscher Wetterdienst, Offenbach, Germany

Key Points:

- CERA-20C reconstructs the past climate of the atmosphere, ocean, land, waves, and sea ice
- CERA-20C provides a 10 member ensemble of reanalyses to account for errors
- CERA-20C shows significant improvements in the troposphere,