An Overview of Coupled data Assimilation Methods

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Coupled data assimilation

Coupled models (or in general Earth's system models) are numerical models that embed governing equations of physical processes, at different degree of accuracy/approximation/parametrization

Earth's system models are used in a variety of weather and climate-oriented applications:

- Reconstructions and/or reanalyses
- Prediction systems (short, medium, long, seasonal, decadal ranges)
- Climate simulations (with forcing from atmospheric gases composition)
- Future and scenario projections

As processes in nature (but not in models) are intrinsically coupled, so the observations are, in the sense that their measurements refer to coupled processes. It is natural to envisage coupled data assimilation for

- Better representation of coupled processes
- Better exploitation of observing networks

Coupled data assimilation

This concept applies to both short- (NWP) to long- (seasonal and decadal) ranges operational prediction systems, to extend predictive skills, and climate-oriented reconstructions (Earth's system reanalyses), to improve past weather events reconstructions and low-frequency variability.

We consider hereafter air-sea coupling only, most ideas can be applied to all other couplings

Uncoupled DA is still largely used (e.g. ocean reanalyses forced by atmospheric reanalyses, atmospheric composition reanalyses forced by atmospheric reanalyses, etc.) and will continue to be for a number of reasons (high-resolution target, historical and cultural reasons, computational costs, etc)

Generally coupled data assimilation is divided in:

Weakly Coupled data assimilation (WCDA)

Data assimilation is applied to each of the components of the coupled model independently, but the forecast (hence the background) is coupled.
An observation in one medium does NOT impact the coupled forecast initial conditions in another medium, but background fields for observation departures computation are coupled

Strongly Coupled data assimilation (SCDA)

Data assimilation is not applied independently, i.e. an observation in one medium impacts the coupled forecast initial conditions in another medium.

Keep in mind this definition of WCDA and SCDA is somehow subjective...

Weakly Coupled data assimilation

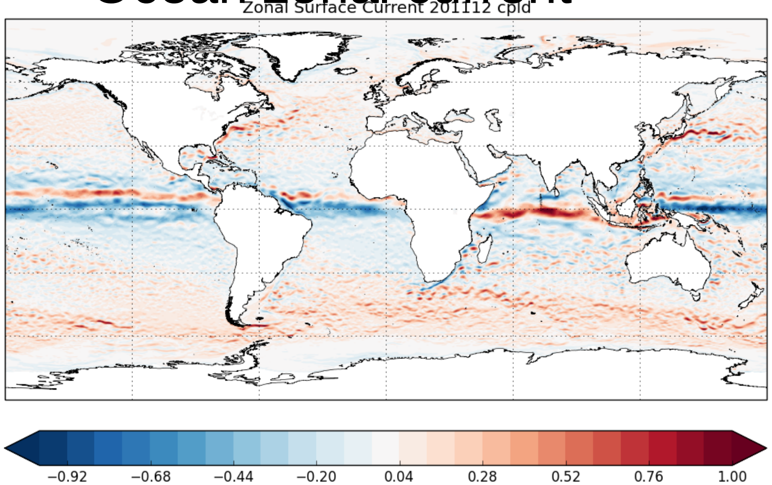
In uncoupled data assimilation some consistency between media may be achieved if interface data used are the same (e.g. SST for relaxation in the ocean and surface boundary conditions in the atmosphere)

Weakly Data assimilation is relatively easy to implement for operational centers already running long-term (seasonal, decadal) prediction systems

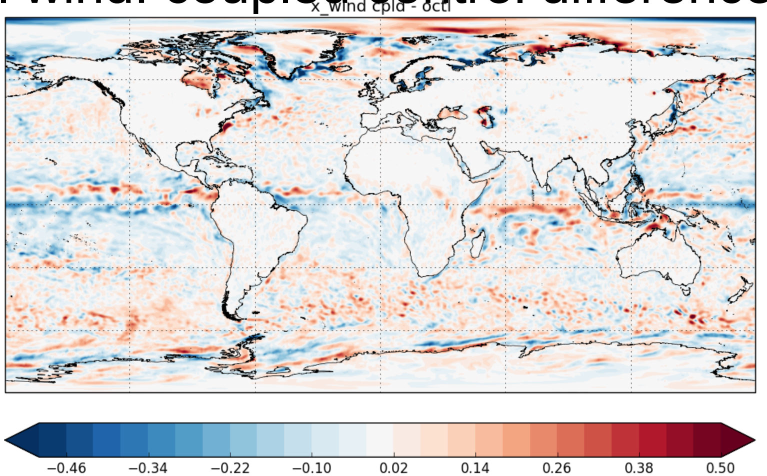
<u>The MetOffice Experience:</u> Weakly coupled ocean/sea-ice/atmosphere/land data assimilation system was developed in N216/ORCA025 (60km/25km) configuration and reported in Lea *et al.* (2015). It is a demonstration operational system

Future work, by ~2019, is to upgrade the resolution of the demonstration operational

Ocean zonal current



Zonal wind: coupled control difference



Issues remain: optimal time-window, diurnal cycle representation, treatment of geographical boundaries, initialization shocks and biases, etc.

Assessing a New Coupled Data Assimilation System Based on the Met Office Coupled Model, Lea, et al., MWR, 143, 2015

Strongly coupled data assimilation (SCDA)

Motivation: Weekly coupled DA proves successful in improving near-surface atmospheric parameters in both operational and reanalysis systems:

Why strongly coupled DA should lead to further improvements?

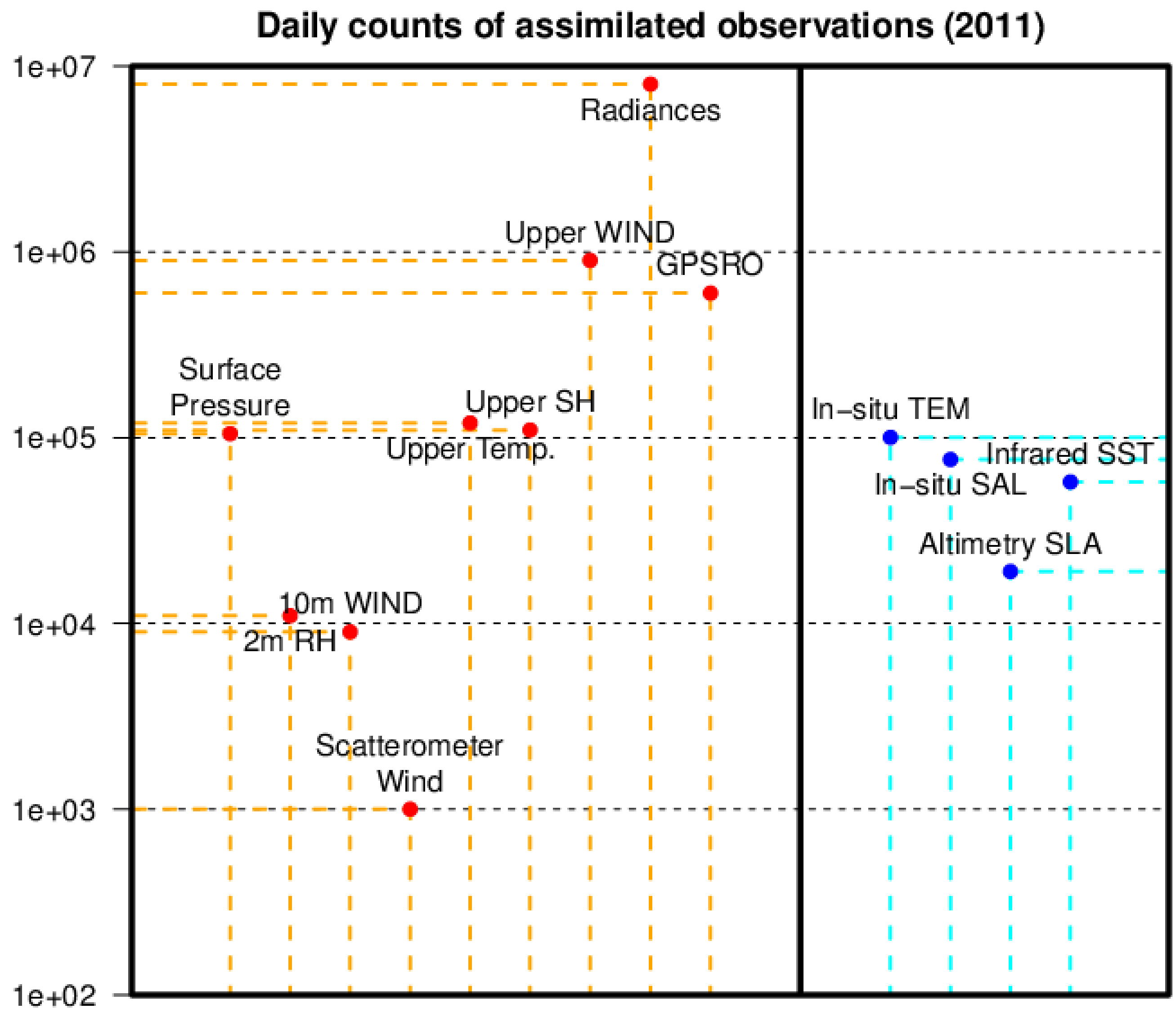
1] Observation synergy and inter-medium observation impact may alleviate observational deficiencies in a single medium

2] Observations whose operators depend on multiple media may further benefit from SCDA (e.g. RTMs for satellite channels sensitive to surface temperature and atmosphere)

3] Strongly coupled DA may also alleviate initialization shocks typical of weakly coupled DA systems, although different time scales of the errors in the two media are not straight-forward to treat.

4] Strongly coupled DA may improve the representation of intrinsically coupled processes and diagnostics (e.g. cyclogenesis, water and heat budgets, storm surges and many more)

Observation synergy



No of Single-level Observations

ECMWF ERA-Interim (Adapted from Dee et al., 2011)

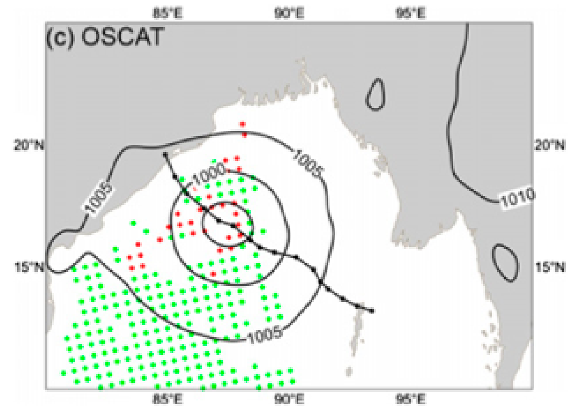
CMCC C-GLORS www.cmcc.it/c-glors

Observation synergy

Example from Laloyaux et al. (2016, MWR)

Case study:

Observing changes in ocean temperature due to the Cyclone Phailin passage (October 2013), in uncoupled and coupled system with/without assimilation of scatterometer data



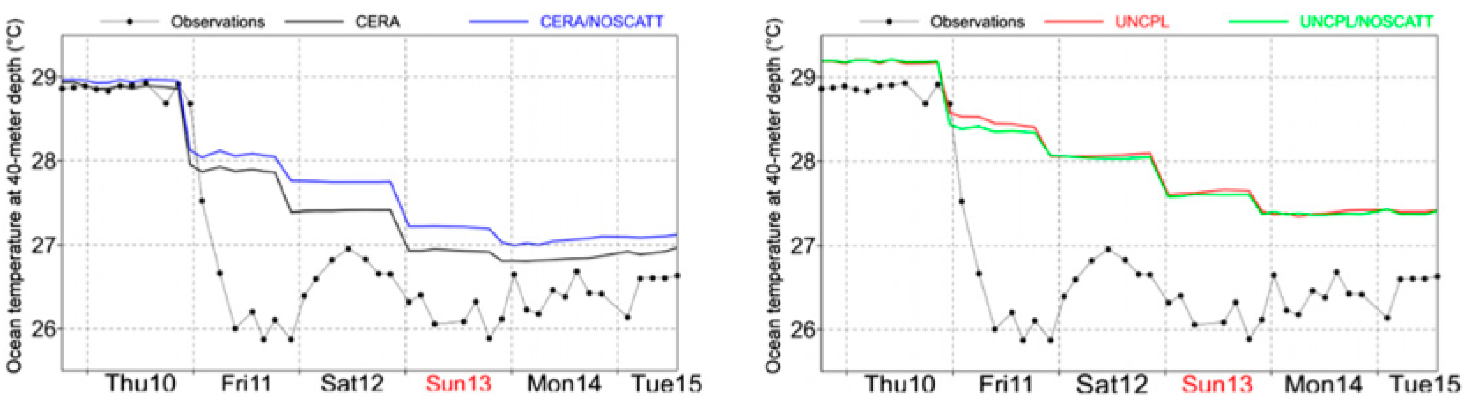
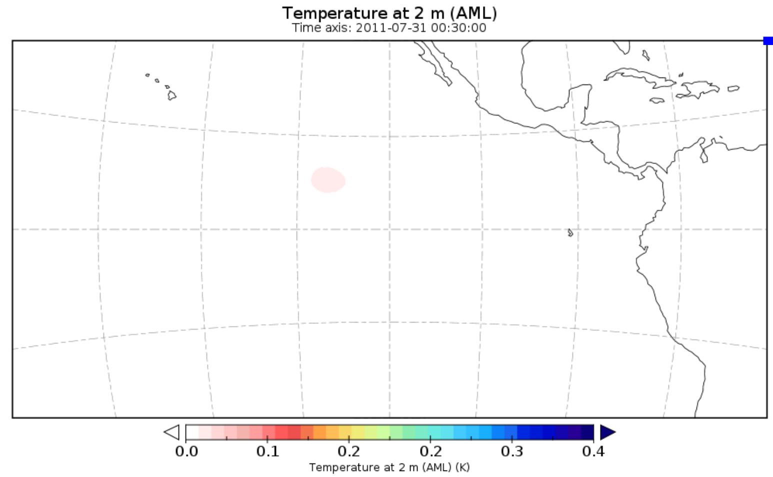


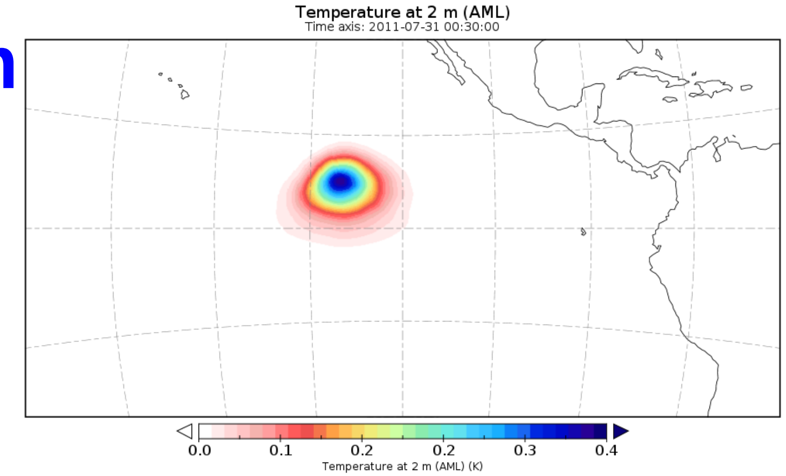
FIG. 13. Time series of ocean temperature observations at 40-m depth from the Argo float 2901335 (black stars). The temperature analyses produced by the (left) CERA and (right) UNCPL systems are plotted for the full and denial observational configurations.

Initialization shocks

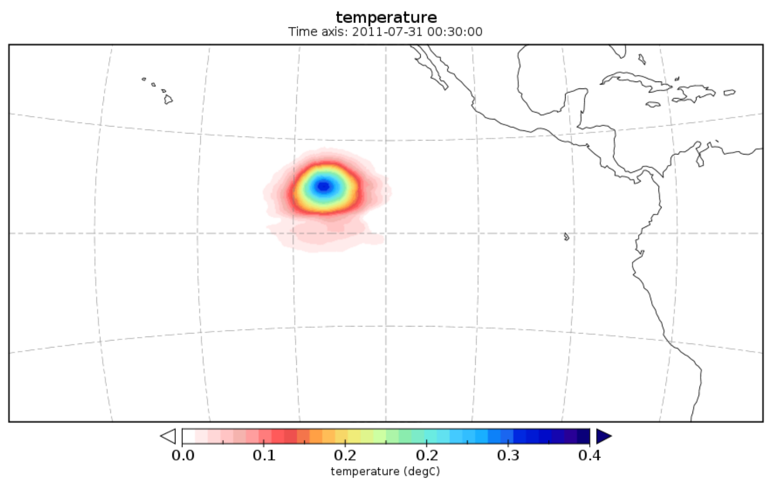
WEAKLY **STRONGLY** **+01h**

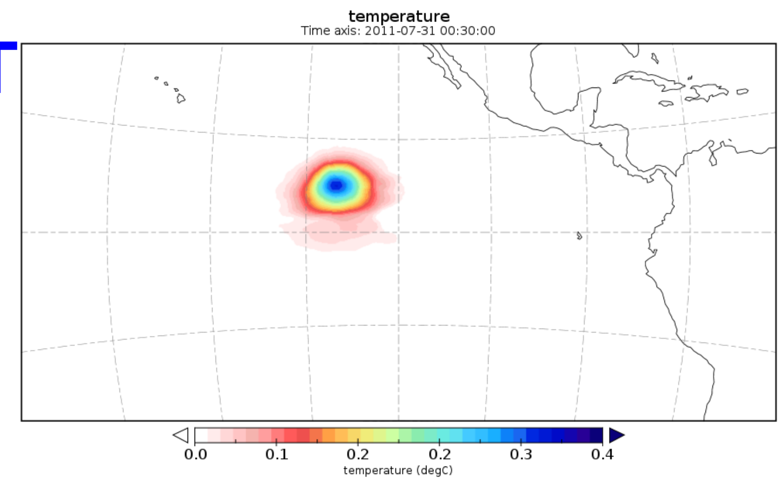
T2m





SST





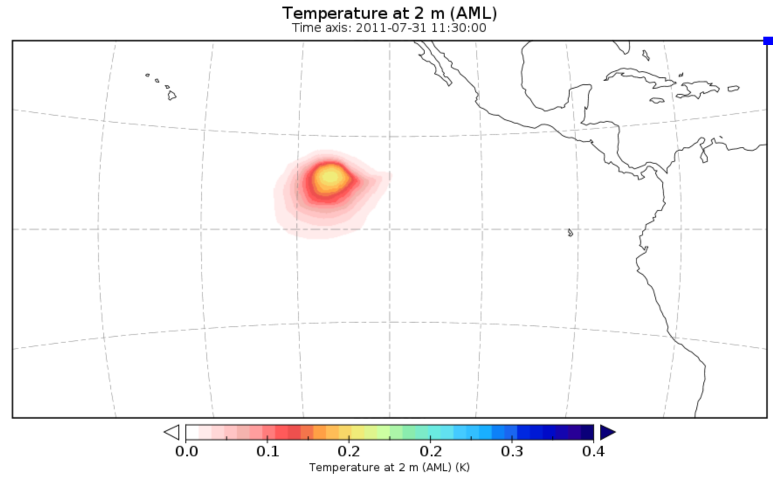
Initialization shocks

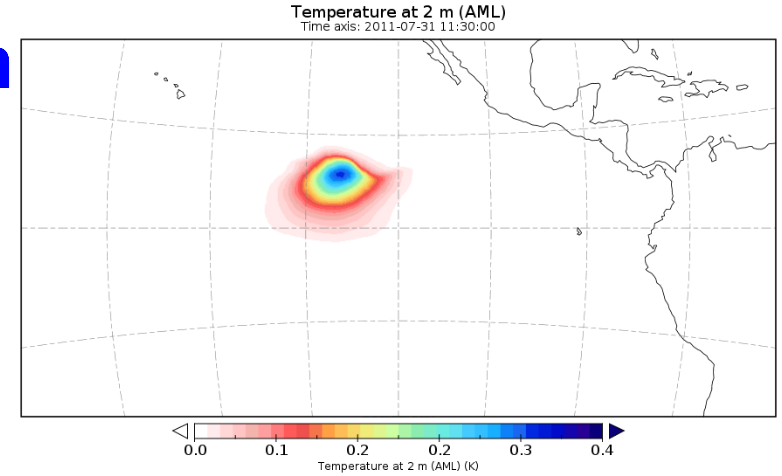
WEAKLY

STRONGLY

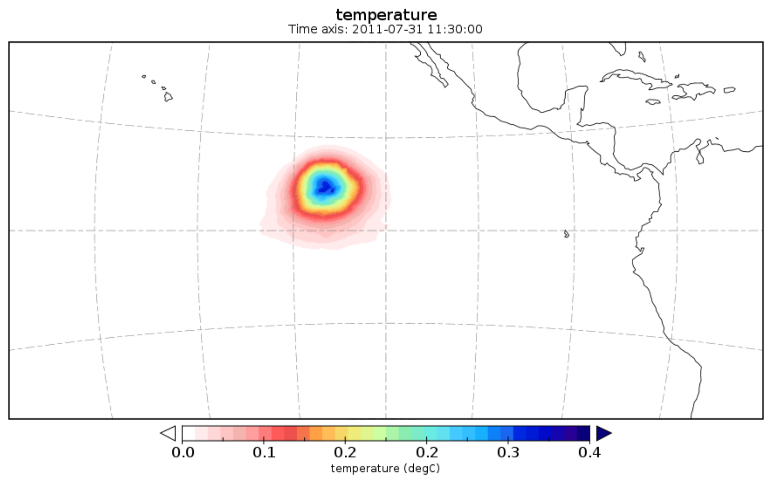
+12h

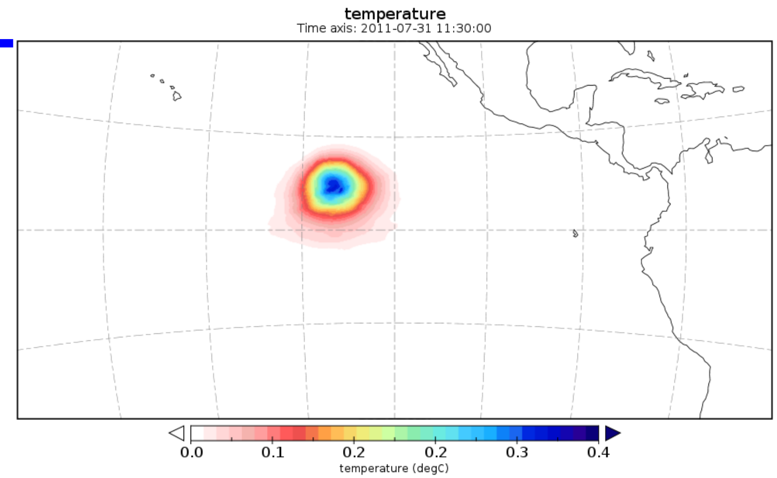
T2m





SST





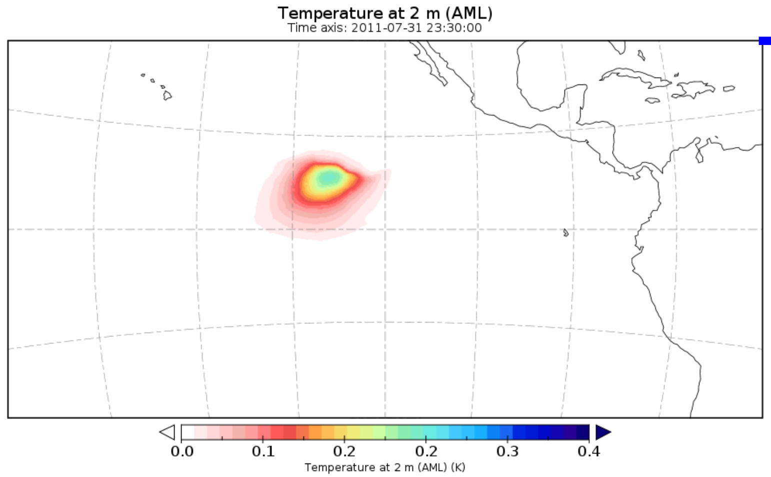
Initialization shocks

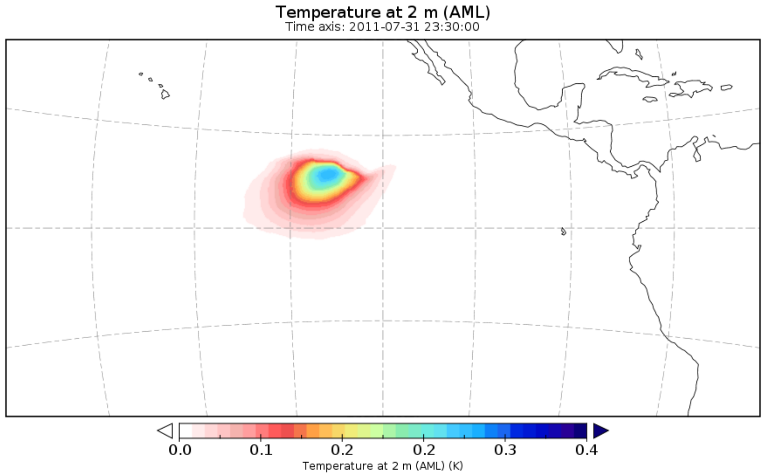
WEAKLY

STRONGLY

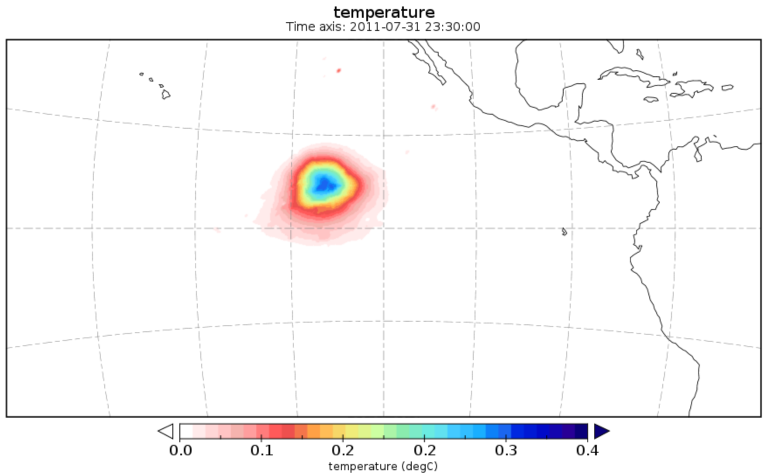
+24h

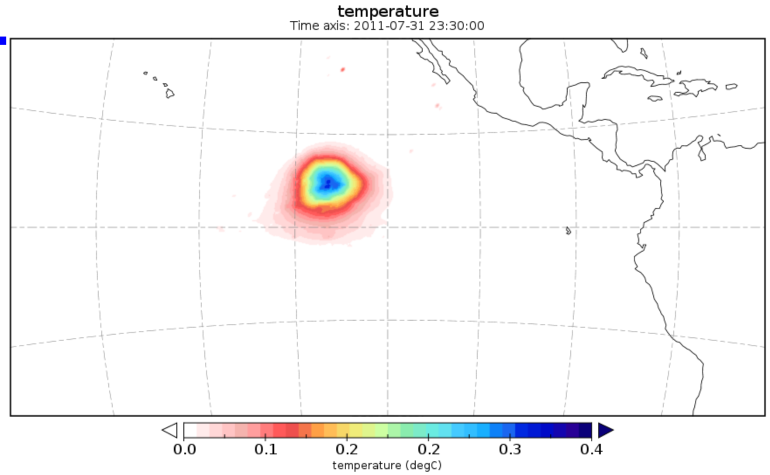
T2m





SST

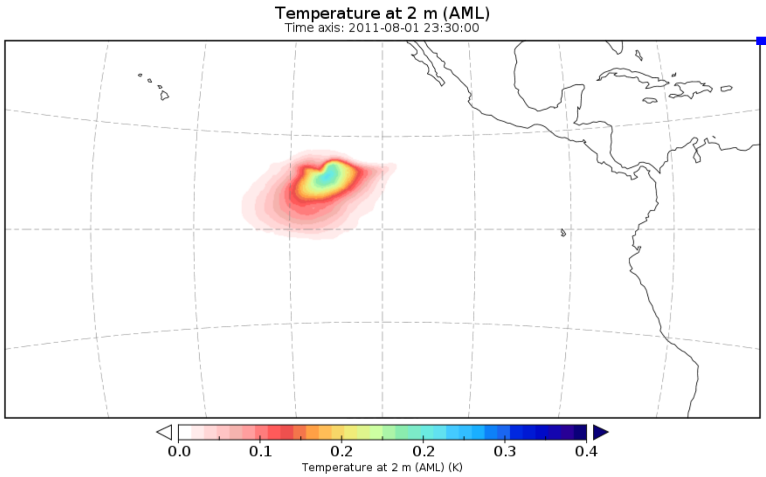


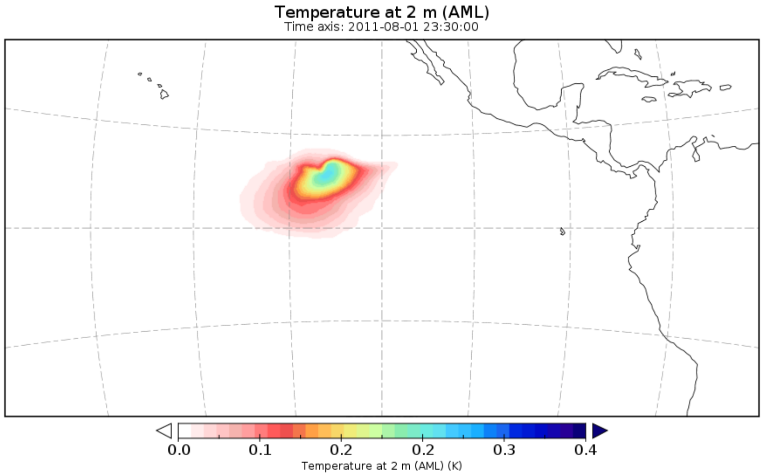


Initialization shocks

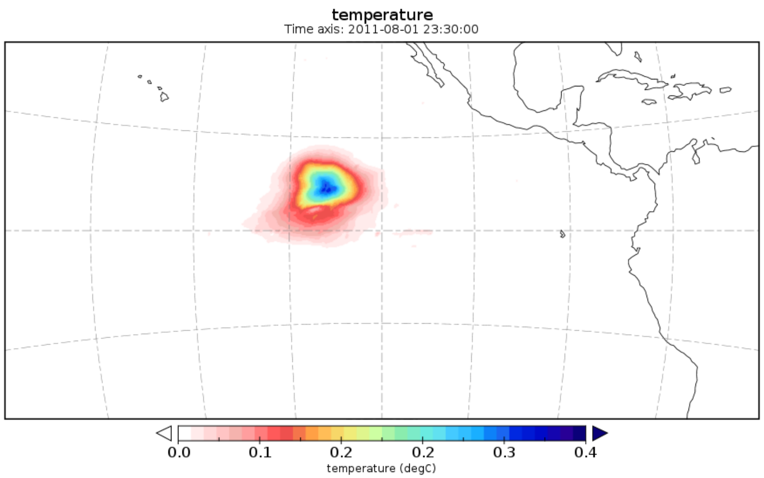
WEAKLY **STRONGLY** **+48h**

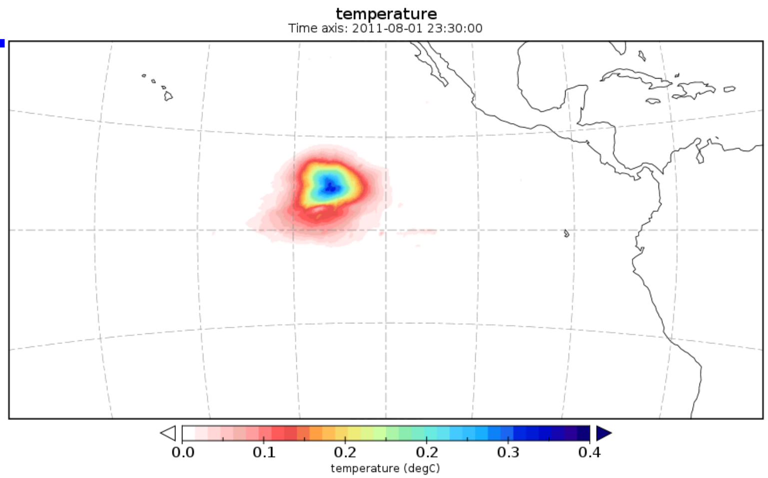
T2m



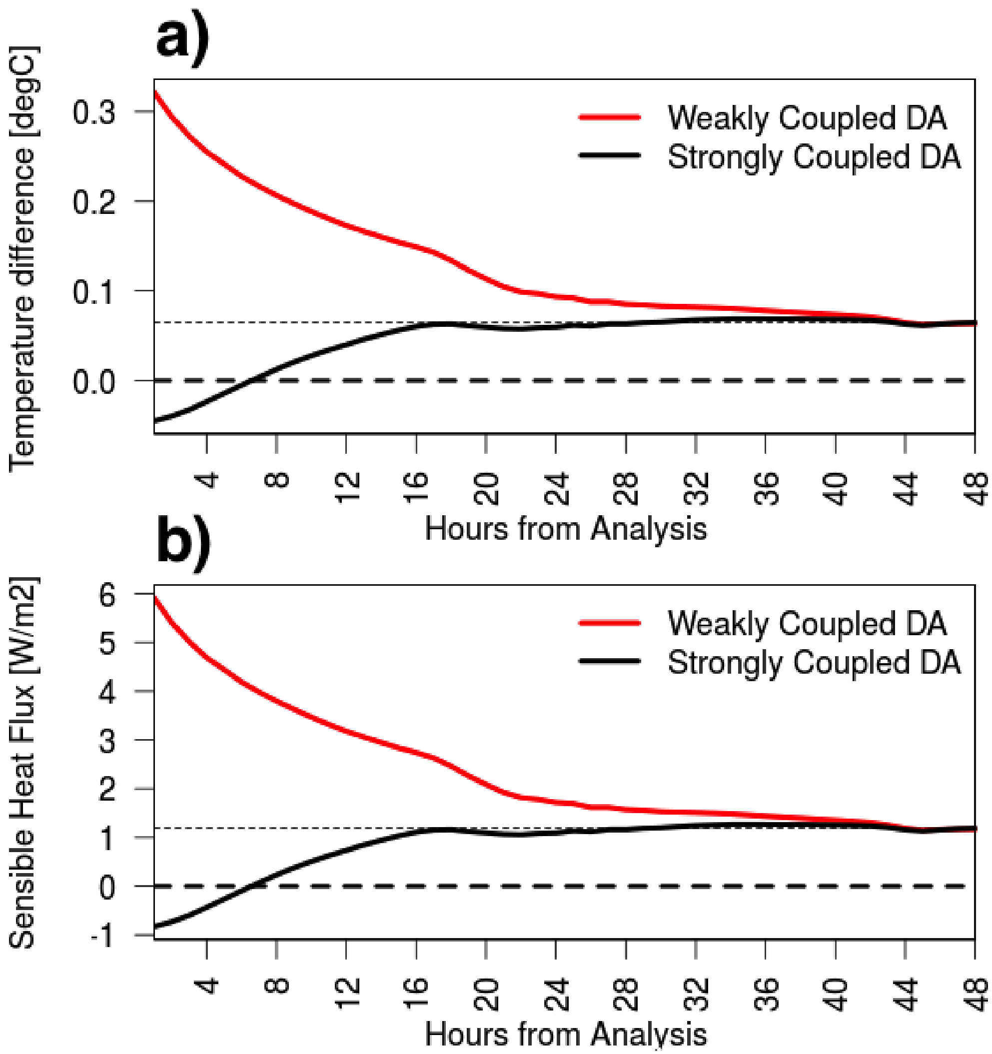


SST





Initialization shocks



Evolution with time of air-sea temperature differences and implied sensible heat flux

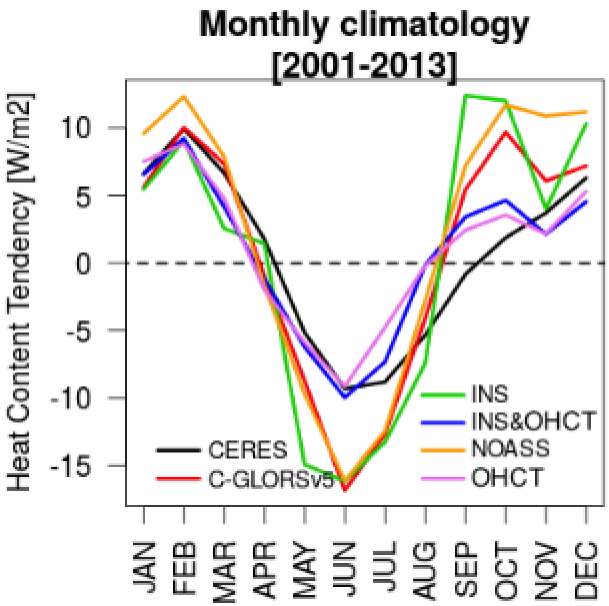
Weakly Coupled DA Analysis Increments

Strongly Coupled DA Analysis Increments

Budget Analysis

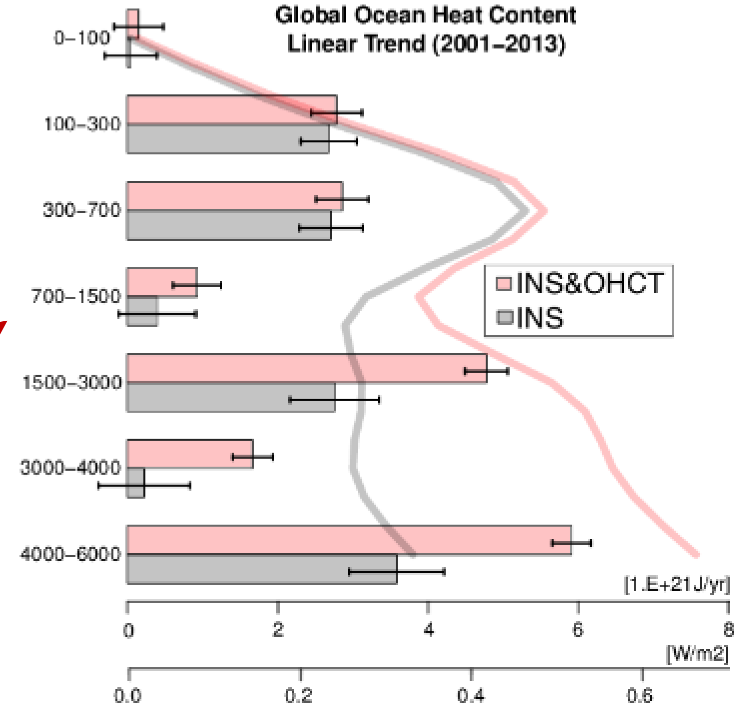
Introducing Constraint on Monthly Global Ocean Heat Content Tendencies (OHCT) for use in global ocean reanalyses, with Variational Cost function augmented with OHCT penalty term

Use of CERES (EBAF-TOA Ed4) Earth Energy Imbalance's data to constrain slowly-varying Ocean Heat Content through assimilation



Improved Seasonal Cycle and Monthly variability

Variational Cost function augmented with OHCT penalty term



Hidden energy (warming hiatus) Issue conciliated: Increase of heat Below 1500m

The use of global energy observations has enormous potential in coupled data assimilation system to constrain Earth's Energy budgets

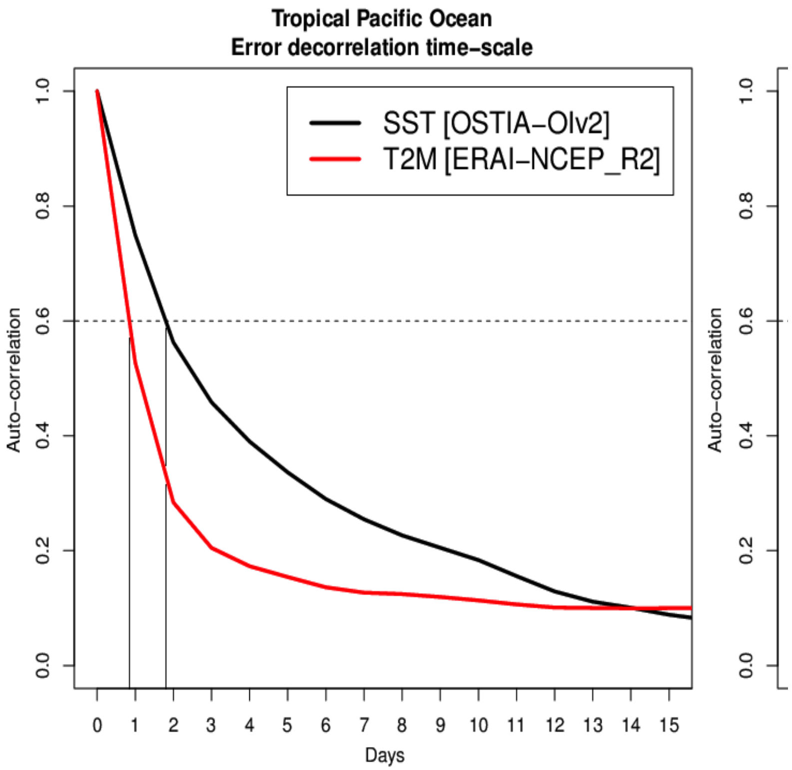
Storto & al, 2017, GRL, Constraining the global ocean heat content through assimilation of CERES-derived TOA energy imbalance

Strongly coupled data assimilation (SCDA)

SCDA is however very challenging: there are

Technical challenges

- **Requiring large ensemble size for ensemble data methods**
- **Requiring full TL/AD of coupled model and/or definition of cross-covariances (adjoint-free algorithms developed)**
- **Huge control vectors**
- **Interpolation issues or DA coupler**
- **Optimal resolution and time-window, and trade-off with costs**
- **Need to upgrade to the most advanced DA component (e.g. hybrid 4DVAR in all)**



Scientific challenges

- **Time-scales in ocean and atmosphere are different in general**
- **Certain observing networks may provide detrimental results (representativeness)**
- **Tropics and extra-Tropics behave differently**
- **Interface parameterizations (e.g. diurnal cycle) might be inadequate**
- **Large sensitivity of coupled GCM to parameters**
- **Biases and errors may easily propagate and amplify between media**

And probably many more than these...

Methods (and simplifications) for SCDA

Long-term strategy obviously is to have 1 coupled data assimilation system (possibly 1 software only, or alternatively a DA coupler), i.e. 1 coupled control vector, which embeds all cross-covariances and linearized physics

However, a number of simplifications have been proposed:

Ensemble Data assimilation (not used in most operational centers)

Although apparently straight-forward, coupling issues remain:

- **Different localization scales for ocean and atmosphere** (Frolov et al., 2016)
- **Lagged Cross-covariances** (to account for atmosphere-leading, Lu et al., 2015)
- **Optimal perturbation approaches to excite coupled modes of uncertainty** (Sluka et al., 2016)

Variational data assimilation

- **Different lengths of assimilation time-windows (asynchronous DA)**
- **Adjoint-free (ensemble-based) TL/AD model** (e.g. Local Ensemble Tangent-Linear Model, Bishop et al., 2017)
- **Interface coupler**
  - **ABL/ML** (Frolov et al., 2016)
  - **Bulk formulas adjustment coefficients** (JAMSTEC, Mochizuki et al., 2016)
- **Use of intermediate complexity coupled model (CMCC experiments)**
- **Cross-covariances implied by multiple outer loop coupling in 4DVAR** (CERA)

CMCC experiments

Full Ocean Model (NEMO) Coupled with ABL model, i.e. the coupling is only thermodynamic and not dynamical.

We introduce a balance operator that maps the increments of SST onto those of ($\mathbf{T}_{2m}$, $\mathbf{Q}_{2m}$) and uses tangent-linear version of CORE bulk formulas (Large & Yeager, 2007)

- $\delta \mathbf{T}_{2m} = \Delta t \; [\delta\, \mathbf{Q}_{LW}\, (\delta \mathbf{SST}) + \delta\, \mathbf{Q}_{SEN}\, (\delta \mathbf{SST})] \, / \, [\rho_A\, cp_A\, \mathbf{H}_{ABL}]$
  (no condensation in ABL)

TL model of air-sea thermodynamics

- $\delta \mathbf{q}_{2m} = \Delta t \; [\delta\, \mathbf{E}\, (\delta \mathbf{SST})] \, / \, [\rho_A\, \mathbf{H}_{ABL}]$

Physical space (T,S,η,T2m,Q2m)

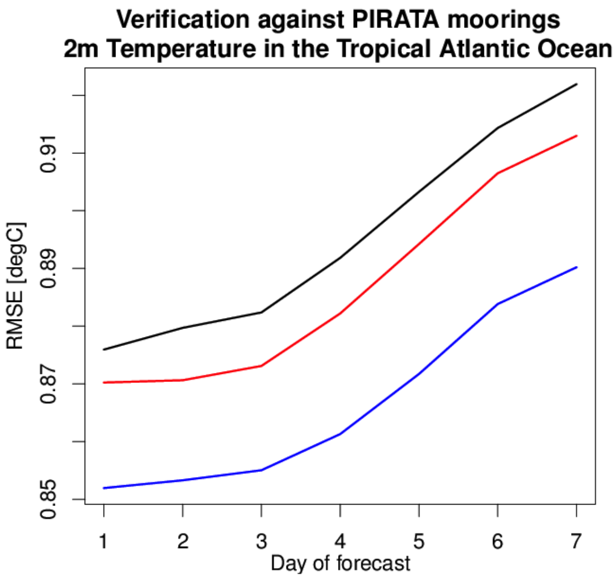
$$\boxed{\delta \mathbf{x} = [\, \mathbf{V}_A\, \mathbf{V}_\eta\, \mathbf{V}_H\, \mathbf{V}_V \,]\, \mathbf{v}}$$

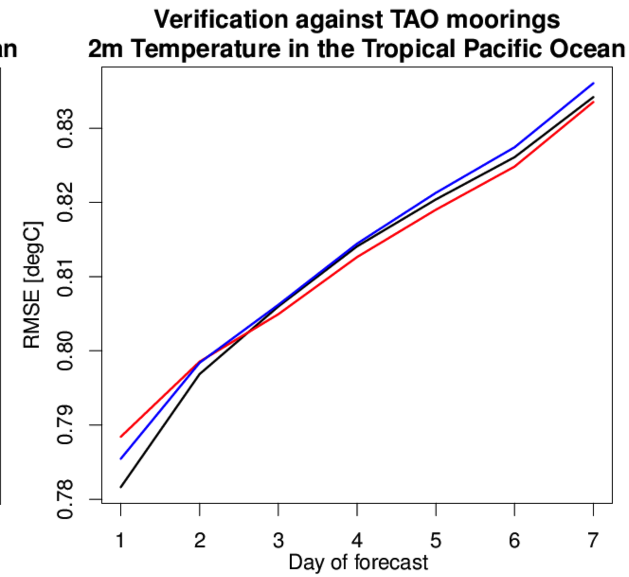
Control Variable

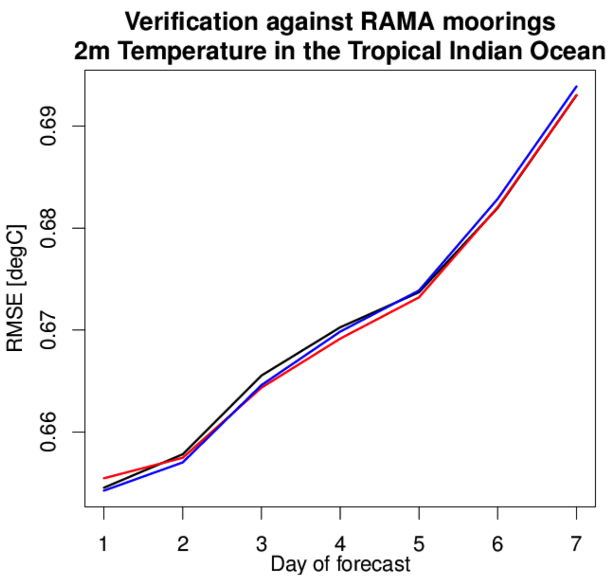
Air-Sea Balance Operator

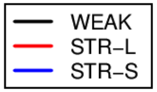
This “analytical balance” may be compared with purely “statistical balance” (cross-covariances deduced by previous experiments), in which case the air-sea balances are embedded in Vv and Va is not accounted for

Assimilation of Ocean obs, impact on air









Weakly Coupled

Strongly Coupled (air-sea balance)

Strongly coupled (statistics)

Negligible Impact in the Extra-Tropics (probably due to the thermodynamical coupling and not dynamical)

Persistent impact through the Forecast length in the Atlantic. In other basins emerges later

Positive everywhere, Although significant improvements only in the Atlantic Ocean

The CERA system

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

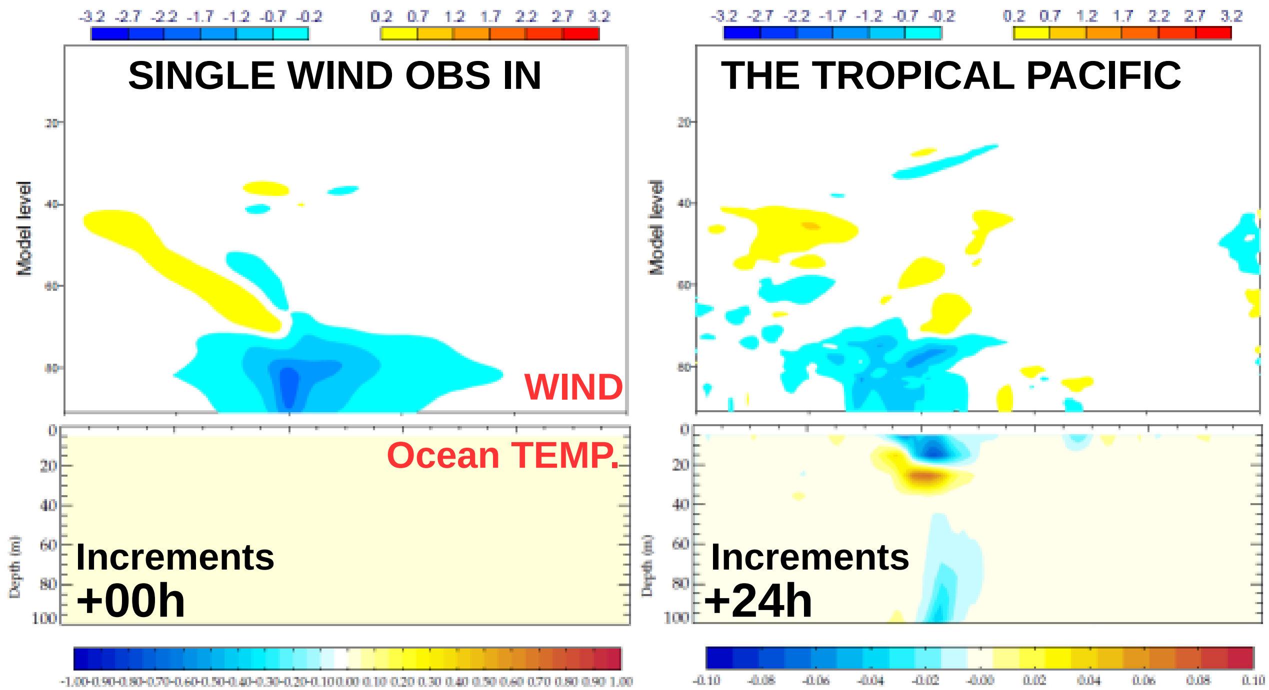
Outer loop: coupled model computes observation misfits

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

Scheme included in CERA-20C (ERA-CLIM2 main product) and CERA-SAT (in production)



Ocean-atmosphere correlations are implicitly generated within the CERA incremental variational approach through the coupling of the outer loop

A coupled data assimilation system for climate reanalysis. P. Laloyaux, et al. QJRMS, 142 65-78, 2016

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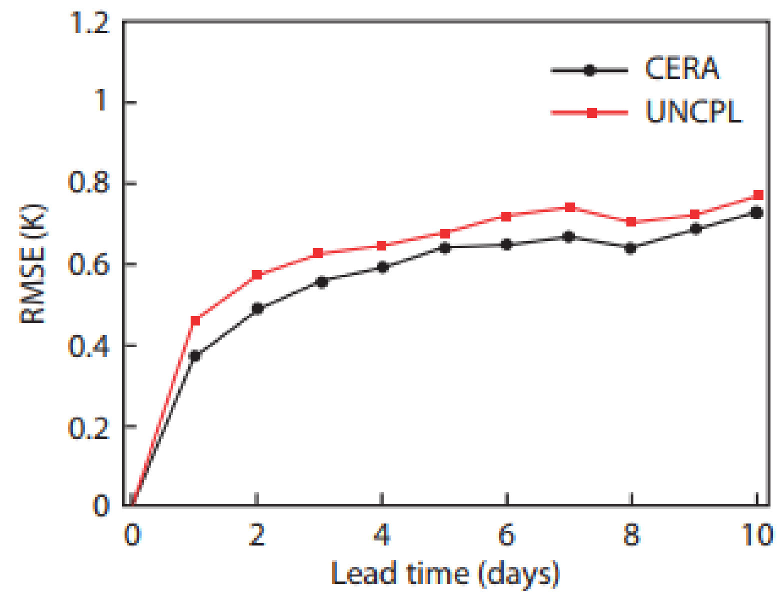
Verification against air temperature observations in NINO3 region

CERA System Outperforms UNCPL



This approach will likely be used for next generation reanalyses (ERA-6) and probably will be included in the ECMWF operational NWP system

A coupled data assimilation system for climate reanalysis. P. Laloyaux, et al. QJRMS, 142 65-78, 2016

Summary

- ***Coupled data assimilation is the natural way to conceive assimilation in the context of Earth's system modeling for any range of forecasts and reconstructions***

- ***Strongly coupled data assimilation in principle bears many advantages compared to weakly coupled data assimilation, but a number of technical and scientific challenges remains***

- ***Both ensemble and variational schemes are capable to extend to strongly coupled data assimilation, each with some difficulties and limitations***

- ***Simplification in strongly coupled data assimilation is the approach followed by many centers, including the CERA systems developed in ERA-CLIM2 for XX century Earth's system reanalyses***

Thank you