Met Office

Coupled DA

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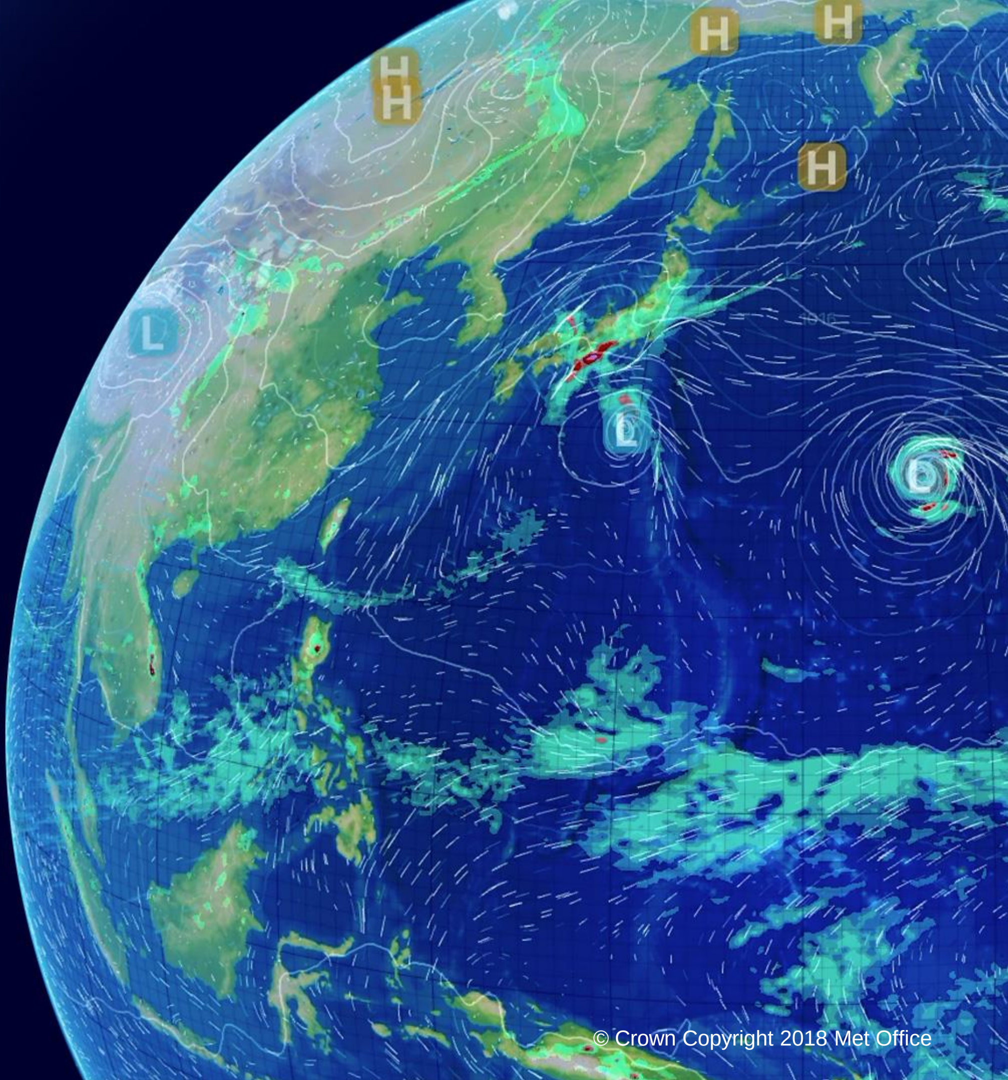
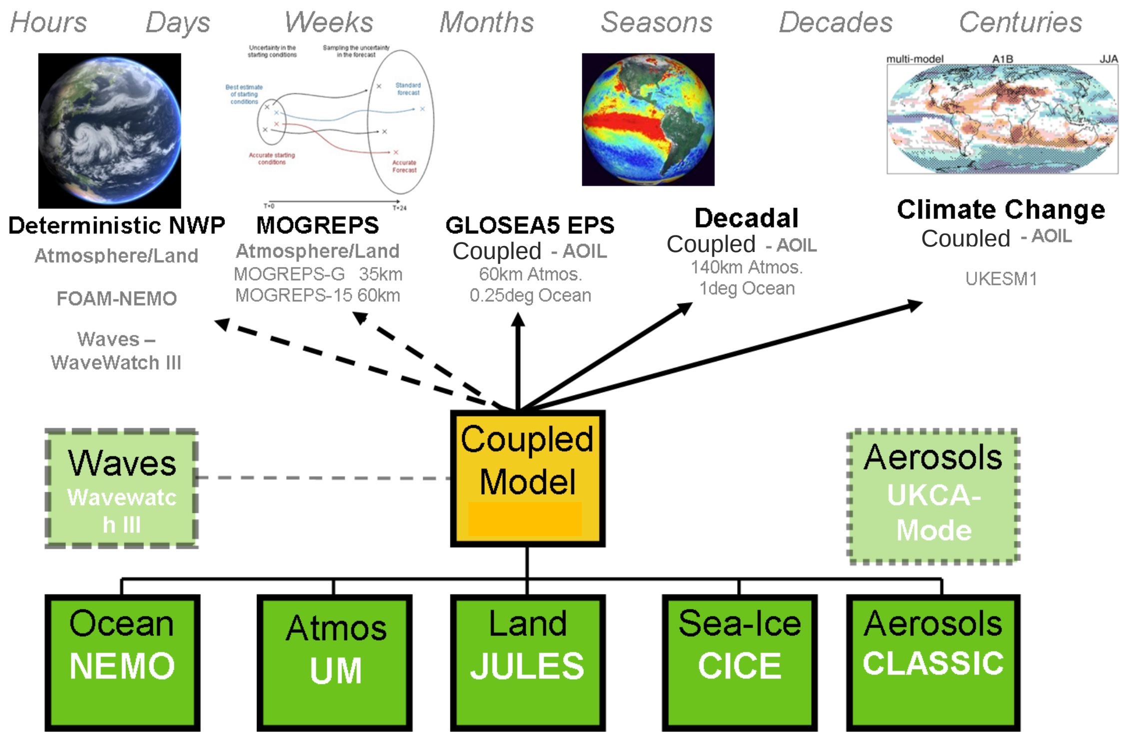


Why coupled DA

Motivated by the increasing awareness that coupled modelling of the ocean and atmosphere is important for short term forecasting

Move to higher resolution models further increases the impact of coupled modelling as many coupled processes operate on small spatial scales

Global modelling at the Met Office



Coupled assimilation vocabulary

- ***Coupled model***: A model that combines multiple components
- ***Coupled data assimilation:*** Data assimilation in a coupled model
- ***Weakly coupled data assimilation:*** Background produced with coupled model, analyses performed separately for each component

Levels of coupling
Loosely
Roughly
Relatively
Quasi
Firmly
Strongly
Entirely
Perfectly
Fully

Developments
Impact of an observation in multiple components
Consistent analysis
Coupled background error
Coupled TL/ADJ
Balanced analysis
Cross-fluid localization
Cross-domain covariance
Multiple components as a single coherent system

Each system should be described with enough detail to understand the level of coupling

Incomplete list of centres working on coupled DA

- ECMWF - weakly coupled (3DVar, 2 outer loops)
- NOAA NCEP - weakly coupled (3Dvar -> 4DEnVar)
- JMA/MRI - weakly coupled (3DVar -> 4DVar)
- BoM - weakly coupled (EnOI)
- Met Office - weakly coupled (3DVar, hybrid ensemble in dev)
- US Navy - weakly coupled (3DVar, hybrid ensemble in dev)
- GMAO NASA - weakly coupled (hybrid)
- NRL - strongly coupled (3DVar, hybrid ensemble, 4DVar)
- UCAR/NCAR - strongly coupled (ensemble DART)
- IAP, China Acad Sci - weakly coupled (EnOI)
- CMCC - weakly and (simplified) strongly coupled (3DVar)

Weakly coupled DA

- Straightforward development to running separate ocean and atmosphere systems
- The coupled model to provides the background for separate ocean and atmosphere assimilation systems
- Apply the increments back into the coupled model
- Disadvantage: observations in the ocean may have information to correct the atmosphere and vice versa which is not used.

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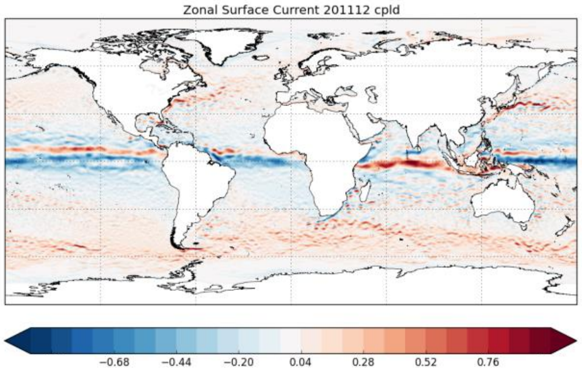
Met Office coupled model components

	Models	Observations	Data assim system	Initialisation
Atmos	UM (N216) ~60km/L85 *Increasing to N1280 ~ 10 km*	AIRS, IASI, ATOVS, GPSRO, SSMI, Aircraft, Sondes, Surf-Scat	4D-Var half model res ~120km	Direct
Land	JULES horiz res as atmos / 4 layers	3D-Var Screen, ASCAT, NESDIS	Nudging Analysis	T/2 Direct
Ocean	NEMO (Orca025) ~25km/L75 Plans to increase to ORCA12 ~8km	In situ SST, T/S profiles, AATSR, AVHRR, AMSRE/2, VIIRS, SLSTR, Jason 1/2/3, AltiKa, Cryosat-2, ENVISAT	3D-Var FGAT (NEMOVAR)	IAU
Sea Ice	CICE ~25km 5 categories	SSMI (SIC). (SIT under development)	3D-Var FGAT (NEMOVAR)	IAU

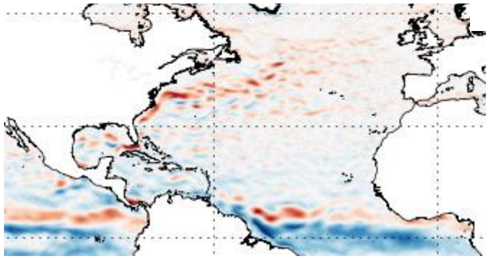
Model components coupling frequency 1 hour, DA systems separate (ie. weakly coupled DA)

Met Office: Ocean impact on atmosphere analysis (Dec 2011 average)

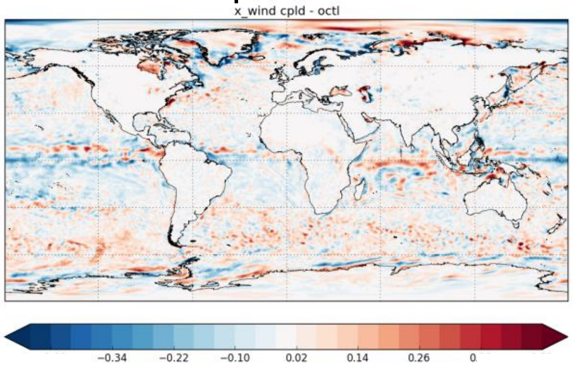
Ocean zonal current



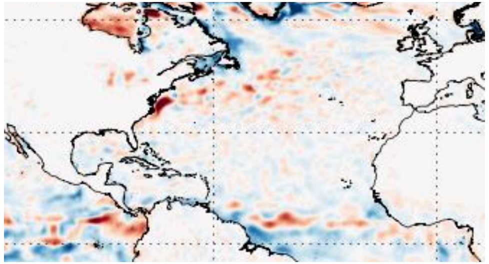
-1 1 m/s



Zonal wind: coupled control difference



-0.5 0.5 m/s



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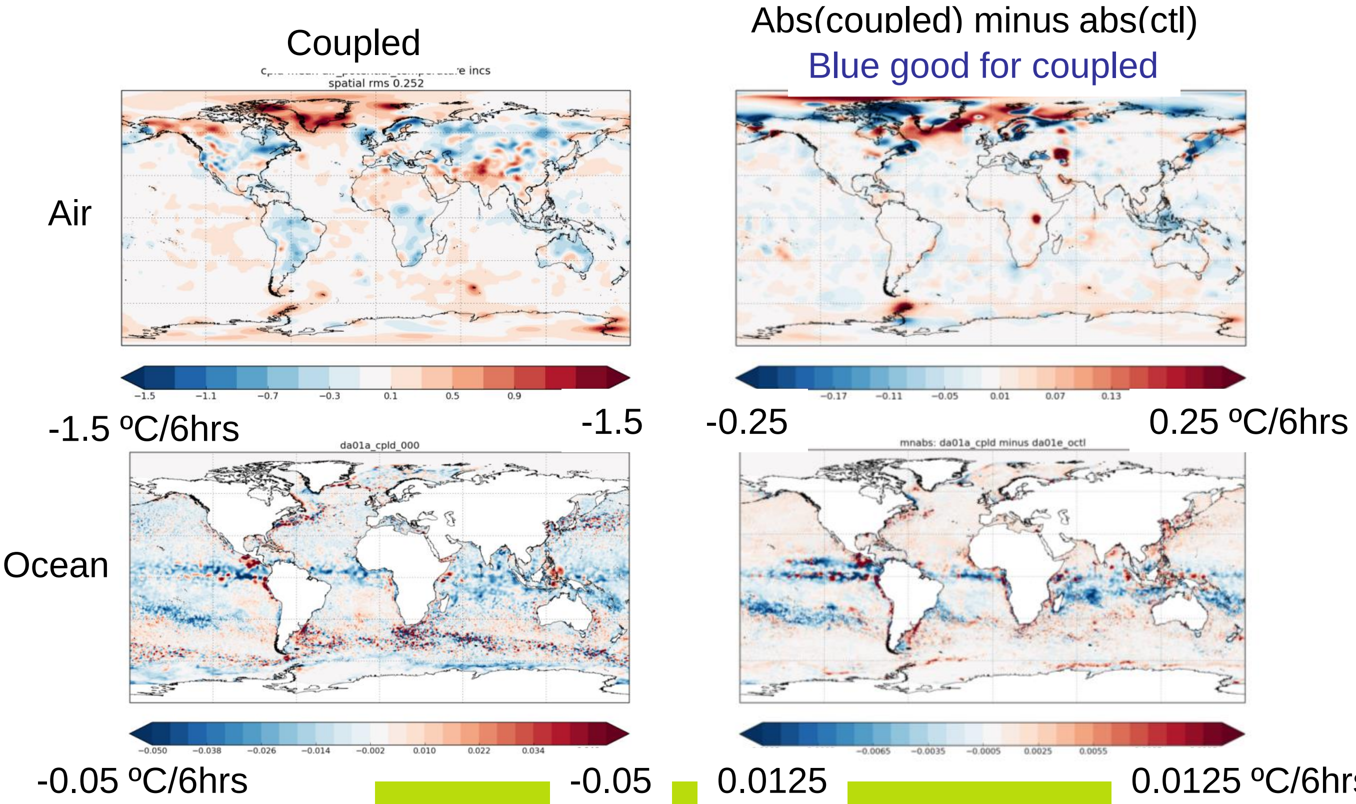
Monthly mean increments of surface air temperature (top) & ocean surface temperature (bottom) Dec 2011 – indication of model bias



Met Office: Ocean comparison to observations (obs-bkg RMS) coupled vs ocean control

	Coupled RMS	Ocean control RMS
SST in situ / deg C	0.4147	**0.3984**
SSH / m	0.0746	**0.0730**
Sea ice concentration	0.0296	**0.0295**
Profile T / deg C	0.6250	**0.6199**
Profile S / psu	**0.1243**	**0.1243**

- Not too bad given the coupled model had not been used in ocean data assimilation previously
- Atmosphere statistics (not shown) similar for coupled vs atmosphere control
- Would like to understand the reasons for the (slightly) degraded SST and SSH statistics in particular

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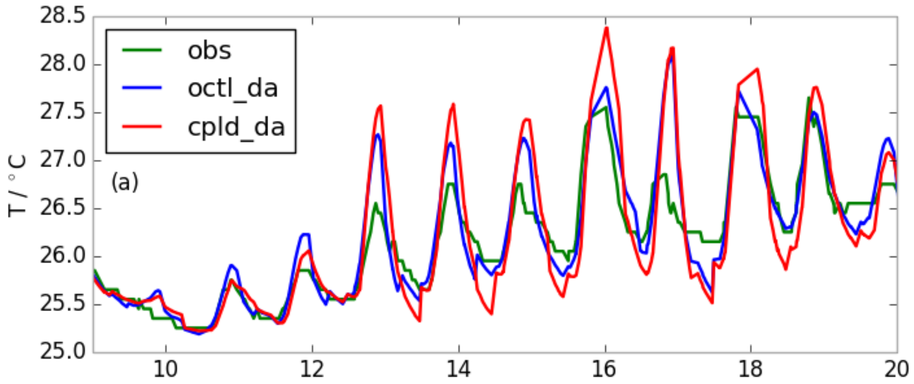
Met Office: Why SST statistics are a bit worse in the coupled model?

Only really the case where the diurnal cycle is strong.

E.g. SST from a drifter (30cm depth) in the South Pacific

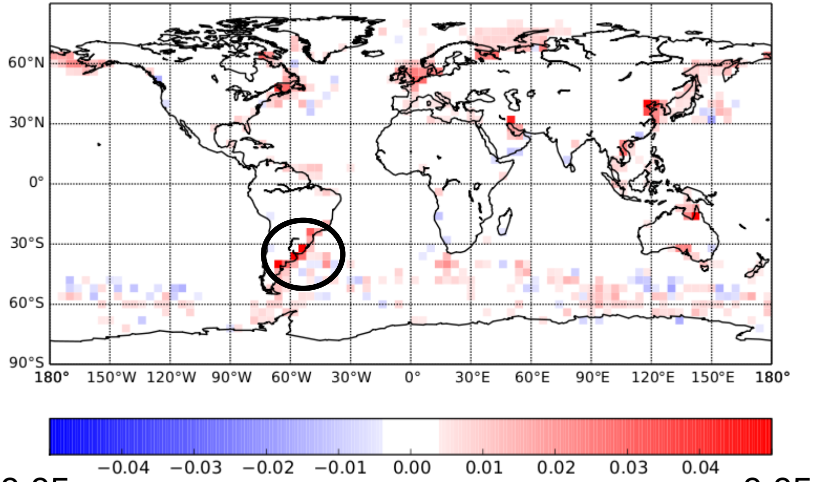
Observed SST
Control
Coupled DA



- Both coupled and uncoupled models lack an explicit diurnal model
- Ocean control errors lower but probably compensating errors

Met Office: Where does the SSH error increase in the coupled model and the cause

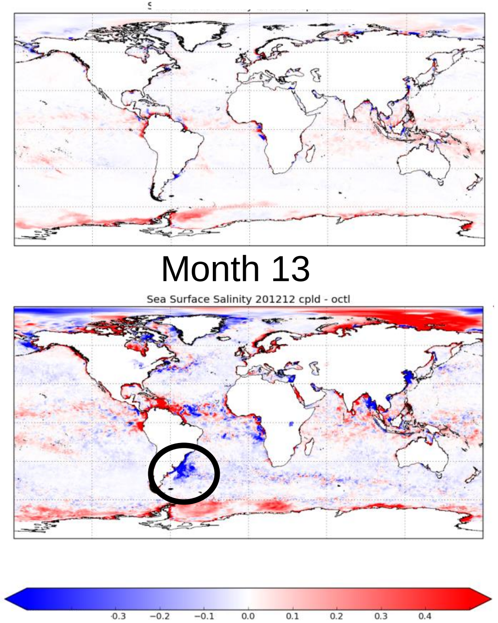
Binned SSH RMS obs model differences over the 13 months of the analysis. Coupled DA minus control



-0.05 0.05 m

Surface salinity difference coupled DA minus control

Month 1



-0.5 0.5 psu

Increasing differences in surface salinity between the coupled and control.

Comparison to salinity obs suggests the control may be closer to truth (but note limited sampling)

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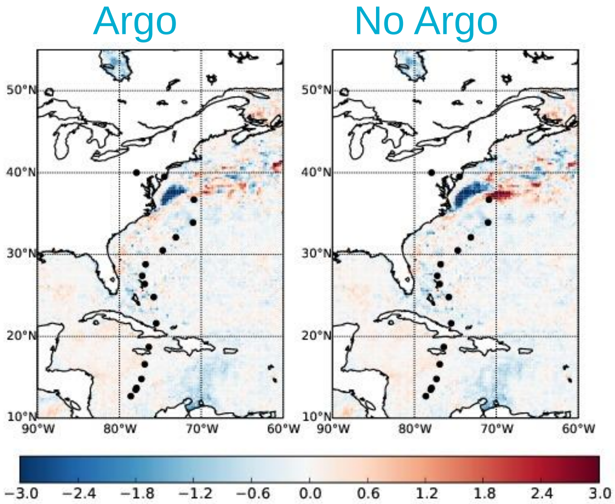
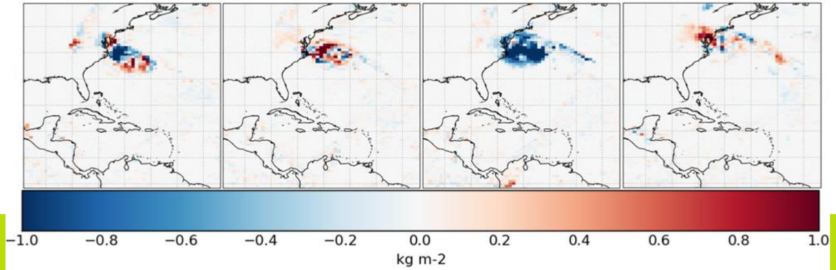
Met Office: OSE (Coupled) impact of Argo withholding on Hurricane Sandy in 2012

SST obs – bkg



With coupled DA Ocean observations can affect the atmosphere forecasts

Rainfall diff (Argo – No Argo)



Forecasts at different times

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Met Office: Demonstration operational coupled DA system

Dealing with the data delays using sub-cycles

(NB old numbers)

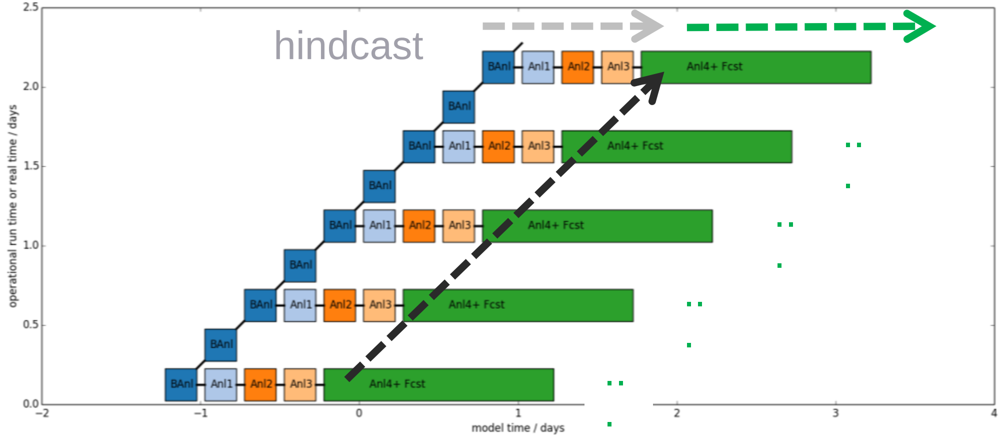
Profile: 20% data in 6 hours, 96% data within 24 hours

Altimeter: 0% data in 6 hours, 99% data within 24 hours

In-situ and satellite SST: 20%/40% data in 6 hours, 100% data within 24 hours

Seaice: 0% data in 6 hours, 100% in 24 hours

Operational run date/time



Forecast (7 days)

Model date/time

We hope to be able to reduce the number of sub-cycles as ocean observation latency is reduced

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Met Office: Coupled DA timeline

New HPC

LFRic

2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

Coupled DA system developed | **Coupled DA forecasts to CMEMS**

Weakly coupled analyses, N320 atmos (40 km),
¼ deg ocean (25 km)

Weakly coupled analyses, N1280 atmos (10 km),
¼ deg ocean (ensemble N640, 20 km, atmos)

Coupled NWP system developed | **Coupled NWP forecasts (to CMEMS?)**

Upgrade to ORCA12 (8km)
Introduce full ocean ensemble
Couple global wave configuration?

Atmos only

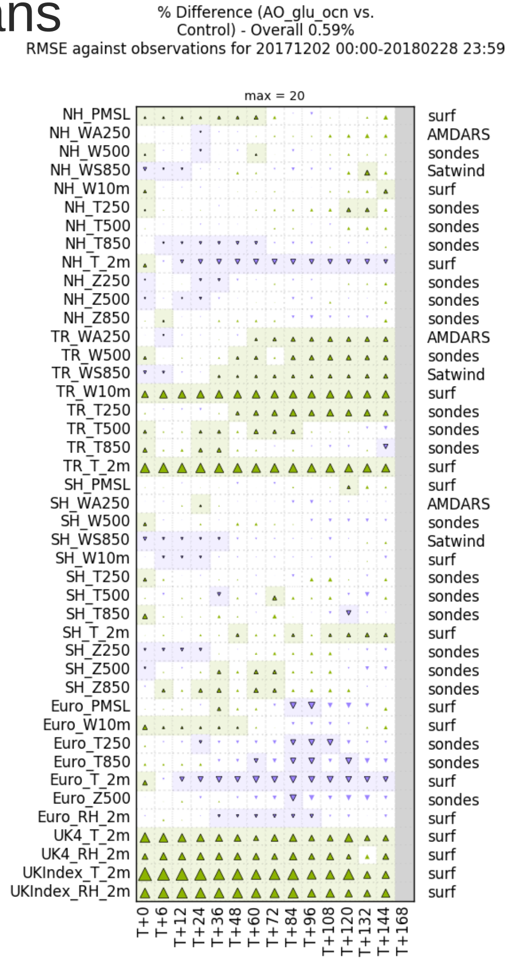
N768 Global Model | **N1280 Global Model**

Ocean only

¼ deg FOAM ocean | **1/12 deg FOAM ocean** | **FOAM retired?**

Met Office: Coupled NWP Status and Plans

- Working towards transitioning operational global NWP to an atmosphere-ocean coupled system on the current HPC in 2020/21
  - ‘Weakly coupled’ data assimilation using coupled model background fields but independent DA codes
- Building on previous work including the low resolution coupled DA system which provides ocean products to the Copernicus Marine Service
- Observation scorecard shown is for a 3-month winter 2017/18 trial period of an N320 atm-ocn coupled model (hybrid mode but with archived atm-only ensemble data) compared to a standard N320 atm-only PS41 set-up
- Shorter N640 trials (with N320 atm-ocn ensemble) show similar impact
- No trialling yet at operational (N1280) deterministic resolution but coupled forecasts (from un-coupled analyses) are being run routinely in near-real-time and have shown benefit for long lead time track prediction for strong tropical storms, and for Madden-Julian Oscillation forecasts
- Currently assessing best approach for ensuring late arriving ocean observations are not lost from system and how approaches to address this may interact with other proposed developments like multiple outer loops



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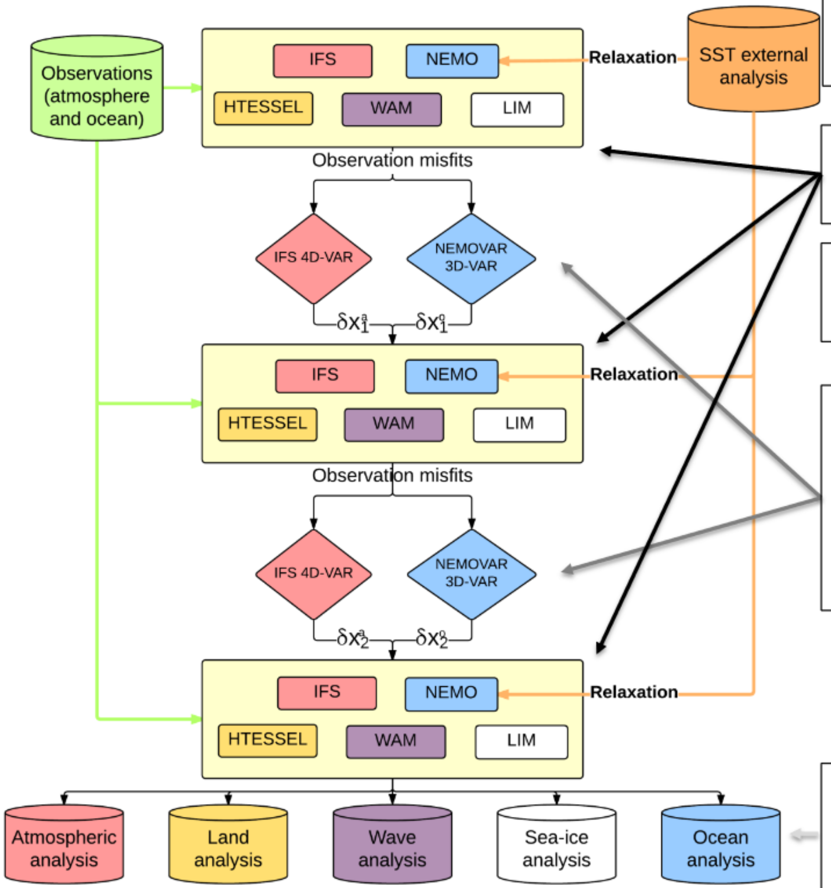
Coupled atmosphere-ocean assimilation system (CERA)

ECMWF

Schematic for one assimilation cycle



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

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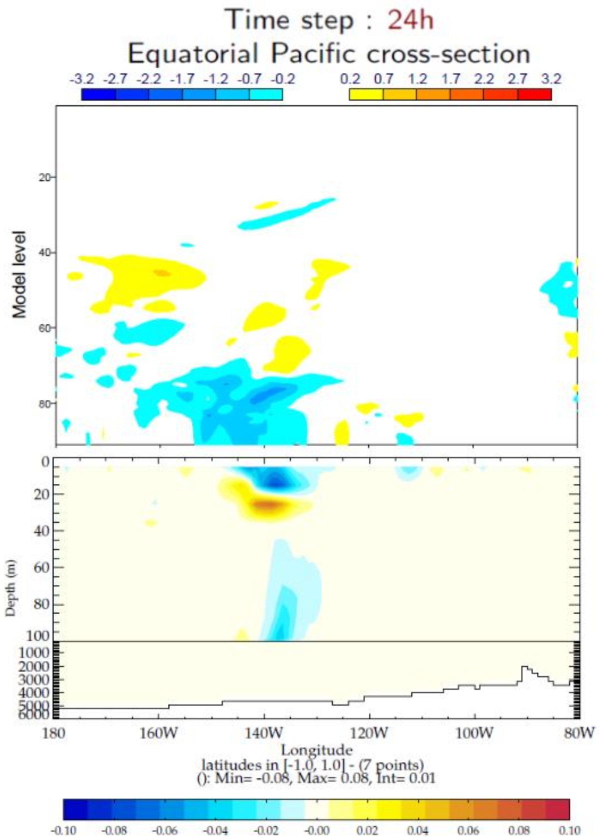
Information exchange in the CERA system

ECMWF



Atmosphere-ocean cross-section (wind and temperature)

Atmospheric wind increment (one station with hourly measurements of a 10m/s westward wind) spreads in the ocean as a temperature increment during the model integration (outer loop)

Ocean-atmosphere correlations are generated within the CERA incremental variational approach

A coupled data assimilation system for climate reanalysis. P. Laloyaux, M. Balmaseda, D. Dee, K. Mogensen and P. Janssen. QJRMS, 142: 65–78, 2016.

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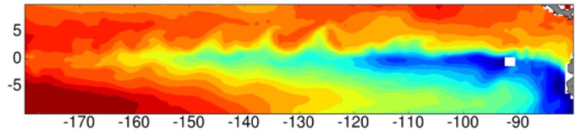
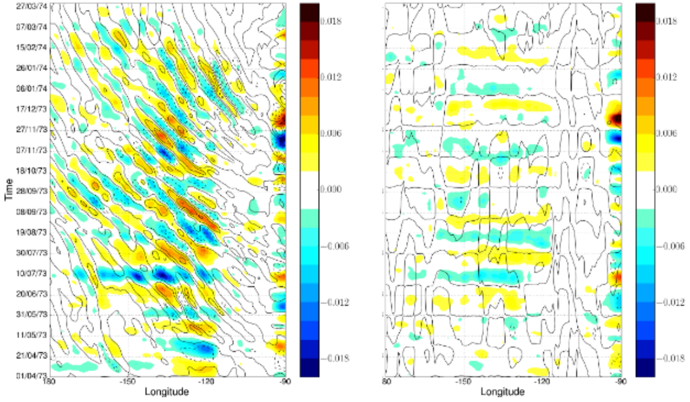
ECMWF

Preliminary results of CERA-20C

Tropical Instability Waves (TIW) are westward-propagating waves near the equator (intraseasonal coupled process)



CERA-20C ERA-20C



high-pass filtered SST (colour) and wind stress (contour)

CERA-20C
→ represents TIWs thanks to the ocean dynamics
→ atmosphere is responding accordingly (surface wind stress is sensitive to the ocean TIW)

ERA20C
→ no TIWs and wind stress signals (forced by monthly SST)

Courtesy of E. de Boisseson

Strongly coupled DA (combine the ocean and atmosphere DA)

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 advancedDA component (e.g. hybrid 4DVAR in all)

Scientific challenges

- Time-scales in ocean and atmosphere are different in general
- Certain observing networks may providedetrimental 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

Andrea Storto CMCC

Methods (and simplifications) for SCDA

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

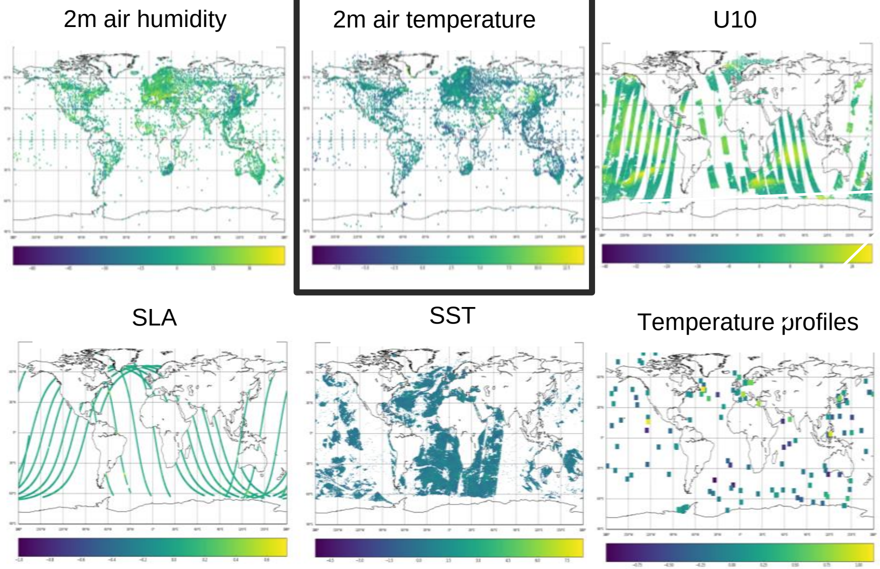
- Different lengths of assimilation time-windows (asynchronous DA)
- Adjoint-free (ensemble-based) TL/AD model (e.g. Local Ensemble Tangent-Linear Model, Bishop et al., 2017)
- Interface coupler
- ABL/ML (Frolov et al., 2016)
- Bulk formulas adjustment coefficients (JAMSTEC, Mochizuki et al., 2016)
-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

Met Office: Towards development of fully/strongly coupled data assimilation

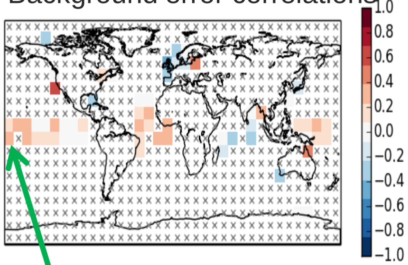
Results from innovation-based method using METO coupled DA system for Jan-March 2009. Atmos/ocean innovations match-ups within 0.1 degrees and 6 hours.

Want to see that where initial condition **errors** are correlated in ocean and atmosphere. This indicates where strongly coupled DA may offer a benefit over weakly coupled DA.

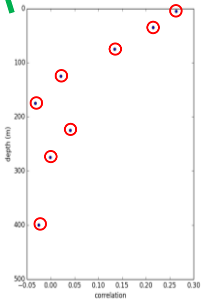
Ocean & atmosphere innovations from coupled DA run every 6-h



Background error correlations



2m air temperature and top 10m ocean temperature



2m air temperature and top sub-surface ocean temperature in selected 10 degree box

0.3 correlation

Requires match ups so may underestimate the potential for strongly coupled DA

Coupled Ocean-Atmos 4DVAR

NRL

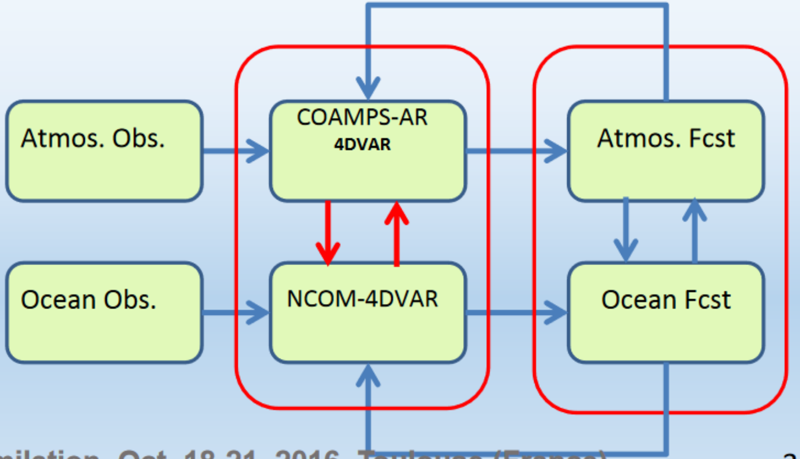
U.S. NAVAL RESEARCH LABORATORY

What is needed is a fully coupled and dynamically balanced analysis.

In the meantime, NRL has also developed individual 4dvar systems for the atmosphere and ocean models.

This study aims to coupled those 4dvar systems. The new coupled assimilation system will

1. ***Provide a fully balanced (dynamically consistent) analysis that accounts for all combined observations in both fluids.***
2. ***Reduce the errors in the state estimation and the forecast.***
3. ***Exploit the cross-covariance between the two fluids to provide corrections from observations in one fluid to the other***



Hans Ngodock

Coupled Ocean-Atmos 4DVAR

NRL

U.S. NAVAL RESEARCH LABORATORY

$$u = \begin{pmatrix} u^a \\ u^o \end{pmatrix}, \quad F = \begin{pmatrix} F^a\left(u^a, i^o\right) \\ F^o\left(u^o, i^a\right) \end{pmatrix}$$

Ocean input to atmosphere (bottom boundary condition) : SST
Impact: latent & sensible heat fluxes, temperature, moisture, winds (boundary layer)

Atmosphere input to ocean (surface boundary conditions) : pressure, heat flux, wind stress, precipitation
Impact: circulation, temperature (mixed layer depth), salinity, eddies, waves …

$$C = \begin{bmatrix} C^a & 0 \\ 0 & C^o \end{bmatrix}$$

$$y = \begin{pmatrix} y^a \\ y^o \end{pmatrix}, \quad H = \begin{pmatrix} H^a \\ H^o \end{pmatrix}, \quad R = \begin{bmatrix} R^a & 0 \\ 0 & R^o \end{bmatrix}$$

Analysis/update equation

$$\hat{u} = u^b + BH^T\left(HBH^T + R\right)^{-1}\left(y - Hu^b\right) = u^b + LCL^T H^T\left(HLCL^T H^T + R\right)^{-1}\left(y - Hu^b\right)$$

$$B = \begin{bmatrix} B^a & B^{oa} \\ B^{oa} & B^o \end{bmatrix}$$

The action of the fully coupled tangent linear and adjoint models provides the cross correlations that are needed to propagate information from the observation in one fluid to the other

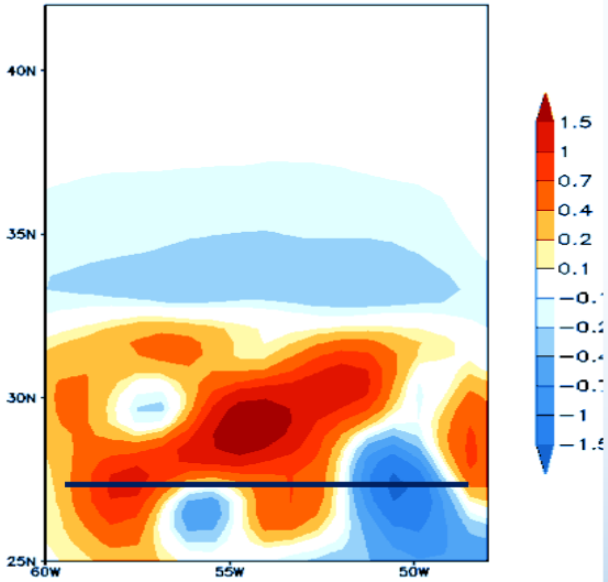
$$L = \left[\frac{\partial F}{\partial u}(u)\right]$$

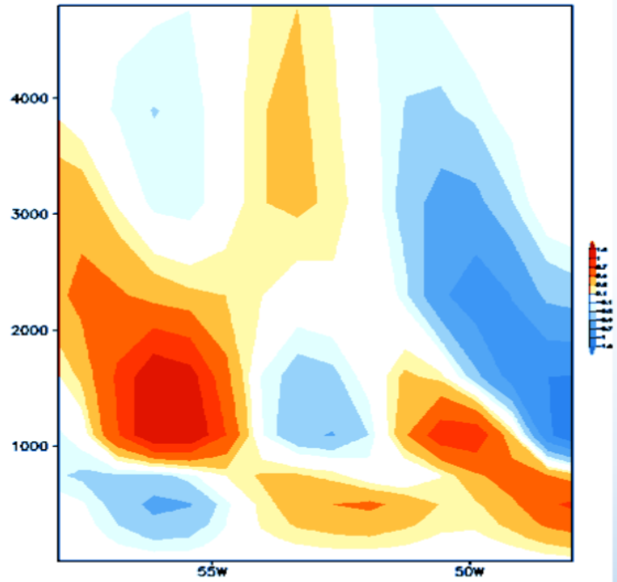
Linearization of atmospheric and ocean models, and all nonlinear air-sea fluxes exchange (coupling terms)

Hans Ngodock

Coupled adjoint

NRL





6 h sensitivity of atmospheric winds at 2000 m to the upper level ocean temperature (all initial atmospheric adjoint fields were 0)

Cross section of sensitivity indicated by line in above figure. Greatest sensitivity is above boundary layer.

Hans Ngodock

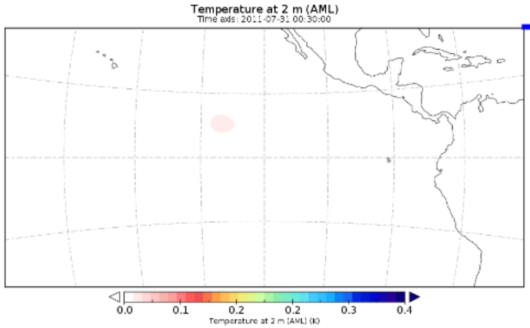
Met Office

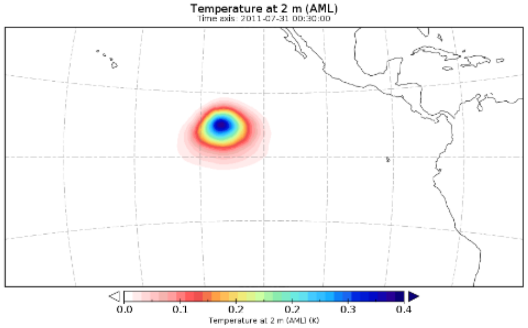
Initialization shocks

CMCC

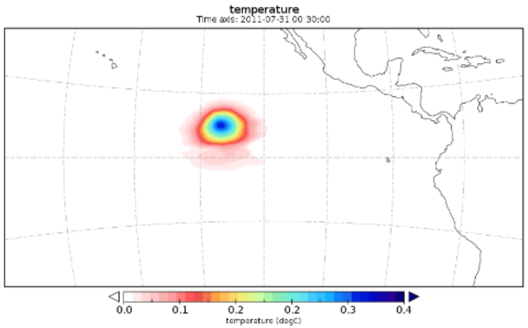
WEAKLY **STRONGLY** **+01h**

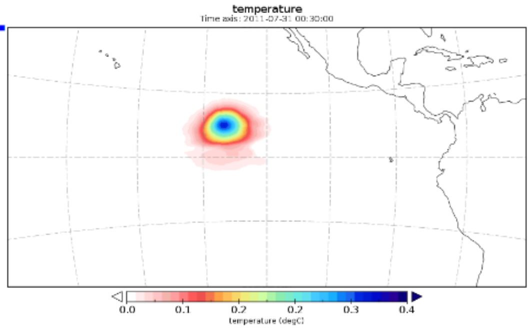
T2m





SST





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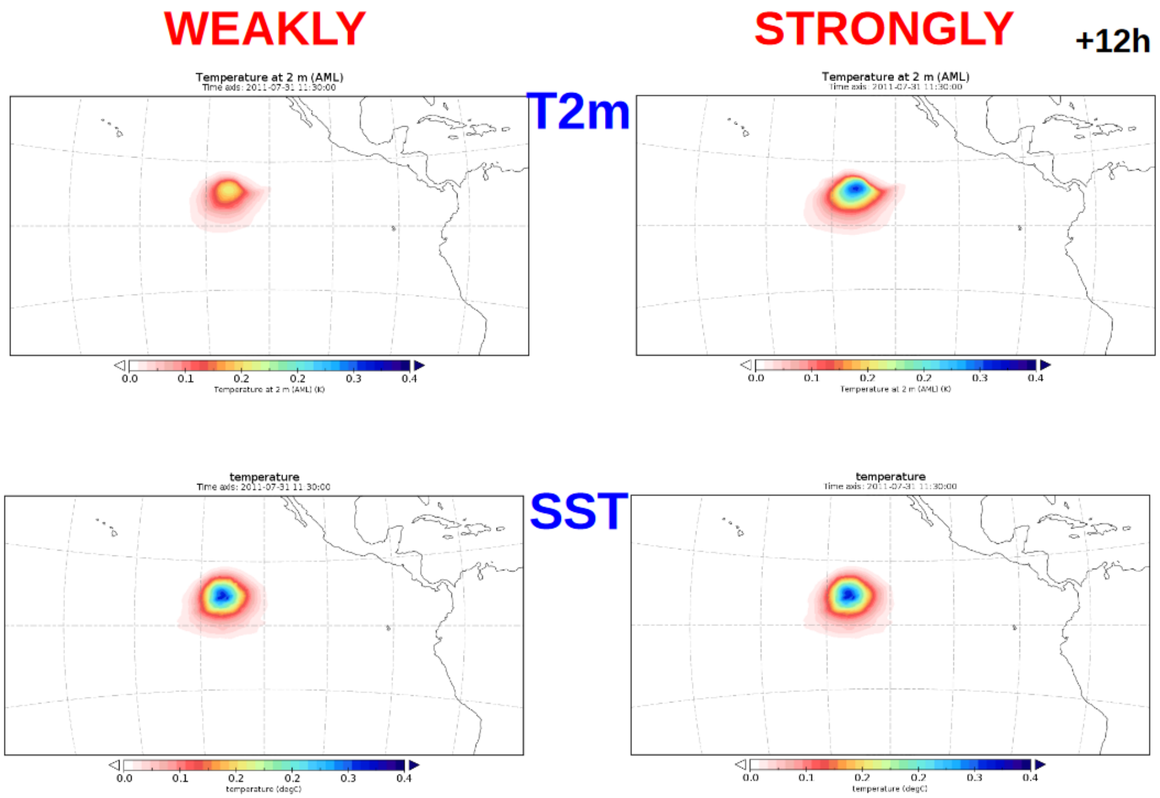
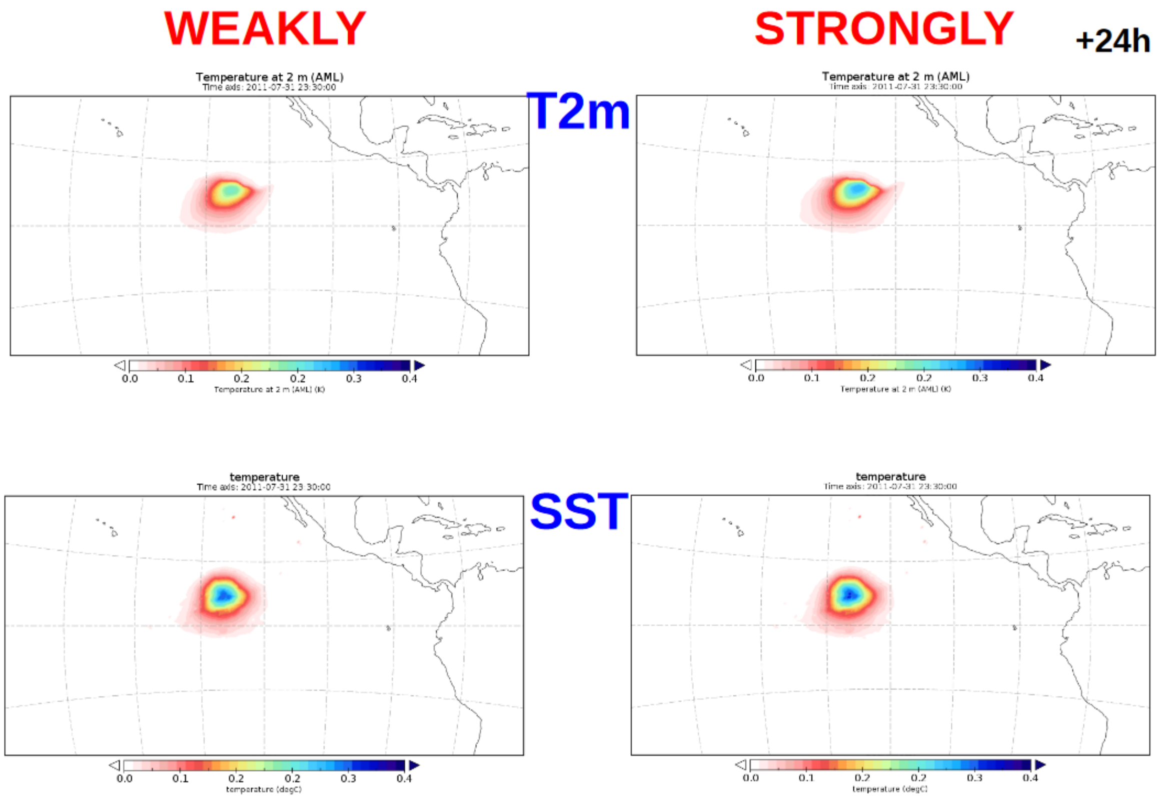
Initialization shocks

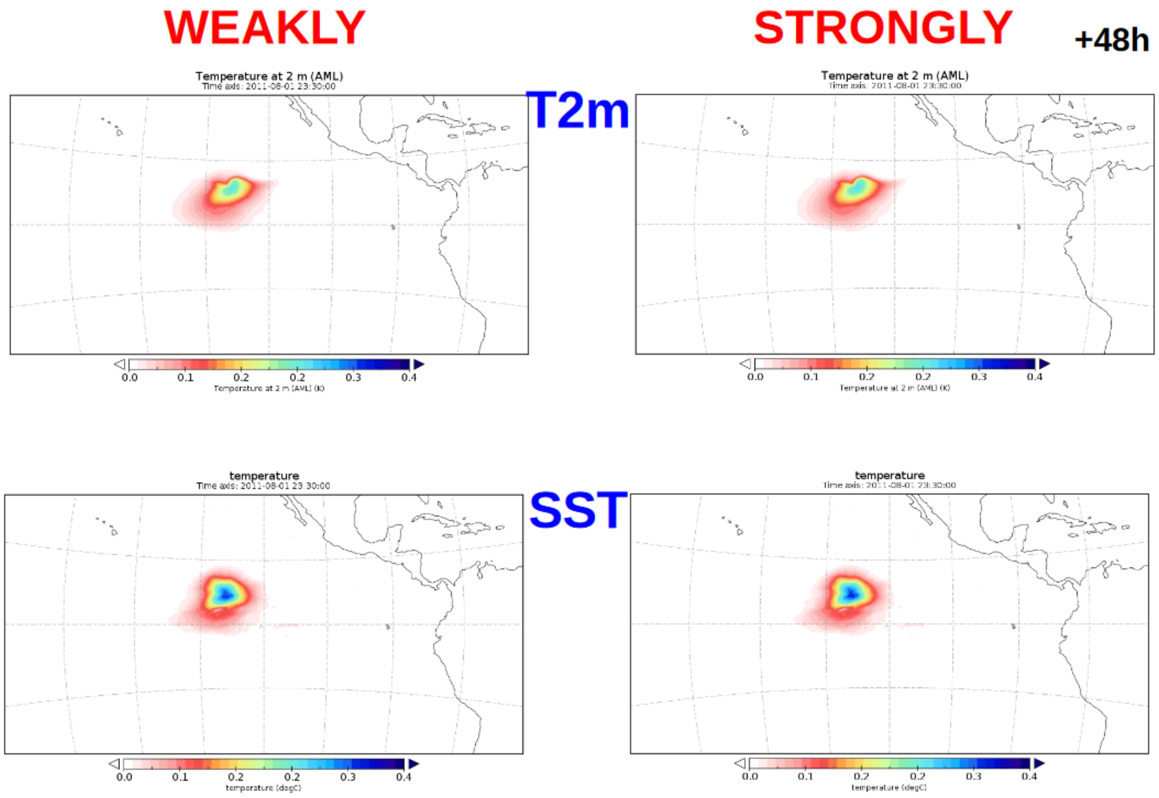
CMCC



Initialization shocks



Initialization shocks



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Summary

Coupled data assimilation is the natural way to do 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 remain
- Both ensemble and variational schemes are capable to extend to strongly coupled data assimilation, each with some difficulties and limitations
- Simplified strongly (firmly?) coupled data assimilation is the approach followed by many centres

(Borrowed from)
Andrea Storto CMCC

Met Office experimental setup

Already know to medium-range (to 15 day) that coupled model forecasts are superior to un-coupled ocean or atmosphere models on short forecasts (e.g. Johns et al., 2012).

Instead focus on the impact of the coupled initialisation strategy

- on the performance of the data assimilation
- on the performance of short-range coupled forecasts.

13 month coupled DA run Dec 2011 to Dec 2012

Compare to separate ocean and atmosphere DA runs (control) with configurations the same as the coupled model equivalents

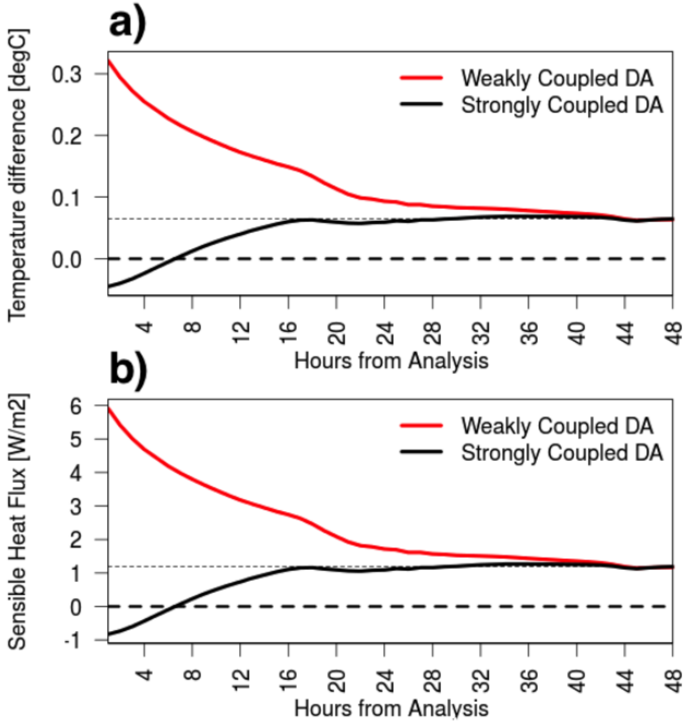
Changes for the demonstration system

Switched to climatological river runoff in the ocean to fix the salinity drift in the ocean

Now assimilating SST over the large lakes/inland seas which may fix some atmospheric biases seen on and near the large lakes.

Not yet implemented but a future version of the coupled model will include an explicit diurnal skin model and this should resolve some of the problems caused by not having this.

Initialization shocks



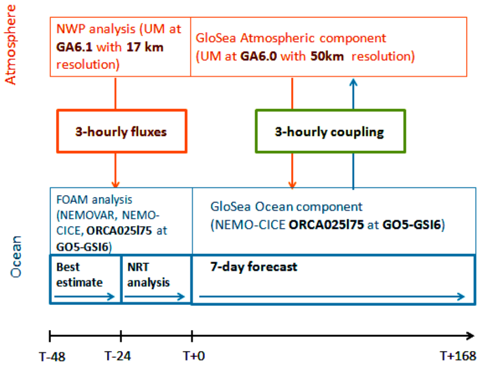
Evolution with time of air-sea temperature differences and implied sensible heat flux

Weakly Coupled DA Analysis Increments

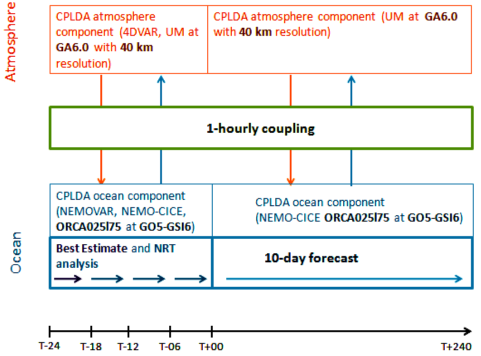
Strongly Coupled DA Analysis Increments

Met Office: GLO-CPL delivery to CMEMS

- Delivery to MyOcean2 and at start of CMEMS was a 'coupled model of opportunity' making use of the GloSea5 forecasts which are run every day (uncoupled DA)
  - Initialised from ocean-only (FOAM) analyses and reconfigured atmospheric (GM) analyses
  - Relatively low atmosphere resolution (N216)



- During CMEMS Phase 1 upgraded to a 'weakly coupled' analysis system (aka 'cplda')
  - Requires a complicated 'catch-up' cycling strategy to make use of late arriving ocean observations [see later]
  - Also increased atmosphere-ocean coupling frequency to 1 hour and atmosphere resolution to N320



- By the end of Phase 2 hope to be able to deliver GLO-CPL products from the Coupled NWP system now being developed

Met Office: Ocean obs requirements for coupled NWP

- ***Do we need to modify the existing GM cycling significant to deal with ocean obs for coupled NWP, particularly if NWP rather than ocean performance is the number one priority?***

- Although we don’t currently get it into metdb in time, the early version of the altimetry data is available with a latency of 2-3 hours
  - In FOAM we currently also use an orbit corrected version available much later but we’ve never clearly demonstrated the benefit of this over the initial version, even in the ocean

- ARGO profile data is probably more of an issue as typical latency from measurement to GTS is over 6 hours currently
  - Partly this is affected by old-style Argos comms which can take up to 10 hours but roughly 2/3 of floats now use Iridium (< 1 hour) so this transition will gradually improve timeliness
  - Some parts of the Argo processing chain (e.g. for UK floats) only run every 4-6 hours so seeking to influence these to help improve timeliness

- Hope to avoid need for special cycling for ocean obs but expect an ocean performance penalty initially
  - Not planning for the first coupled NWP implementation (with ¼ deg ocean) to replace FOAM (which will be 1/12 deg by then)