

The ECMWF coupled assimilation system for climate reanalysis

Patrick Laloyaux

Earth System Assimilation Section

patrick.laloyaux@ecmwf.int

Acknowledgement: Eric de Boisseson, Per Dahlgren, Dinand Schepers, Yuki Kosaka, Jacky Goddard, Paul Poli, Hans Hersbach, Shoji Hirahara, Massimo Bonavita, Elias Holm, Hao Zuo, Magdalena Balmaseda, Kristian Mogensen, Patricia de Rosnay, Adrian Simmons, Jean-Noël Thépaut, Dick Dee, Roberto Buizza



Outline of talk

- Earth-system modelling and assimilation
- Coupled atmosphere-ocean assimilation system (CERA)
- Preliminary results from the coupled climate reanalysis (CERA-20C)
- Challenges for coupled assimilation with atmospheric composition

Earth system modelling at ECMWF



Atmosphere



Land



Composition



Ocean

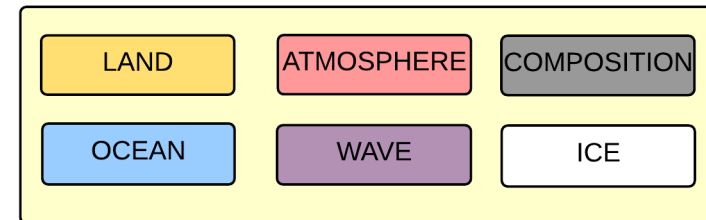


Wave



Sea ice

Coupled earth model



Complexity of the Earth model has increased with time:

- to improve the medium-range forecasts (better modelling of relevant processes)
- to extend the prediction horizon (monthly and seasonal)
- to make better use of the observations
- to provide new applications

Earth system modelling at ECMWF

Diversity in coupling methodologies between the components of the model

TYPE 1: fully integrated

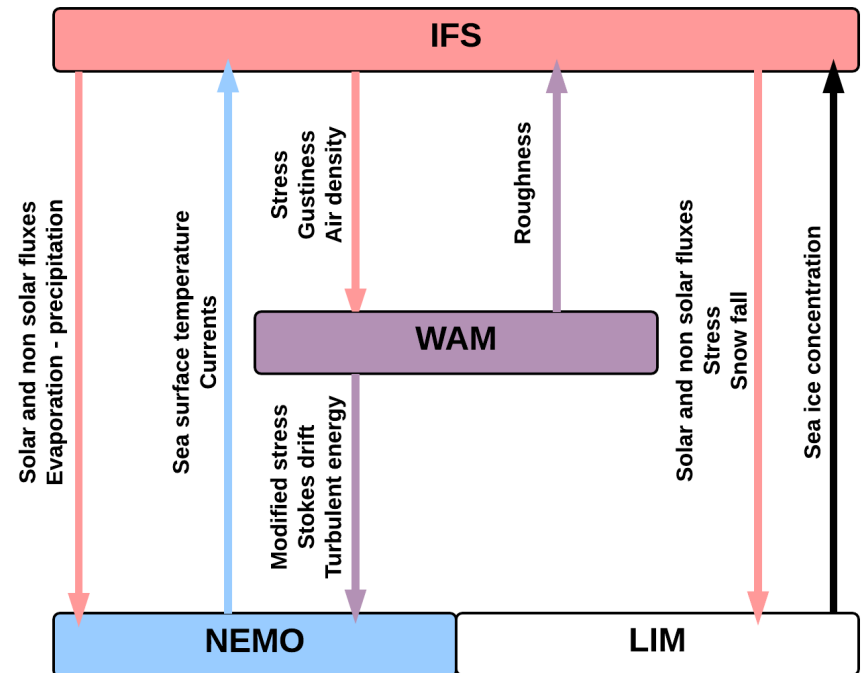
- atmosphere/composition
- composition rewritten for integration
- same grid and resolution
- composition can not be run offline

TYPE 2: single executable

- atmosphere/ocean/waves/sea ice
- sequential coupling
- different grids (interpolation)
- individual models can be run offline

TYPE 3: coupler

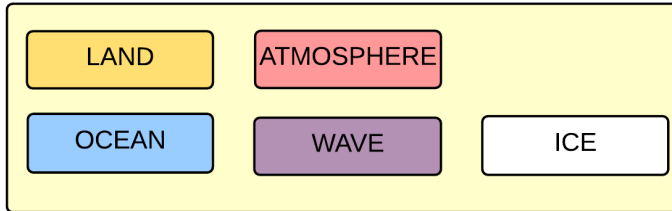
- information transferred by files
- not used anymore



Earth system forecasting at ECMWF

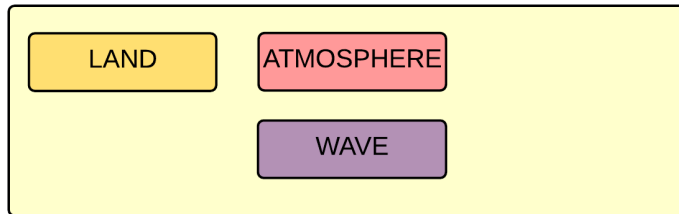
Different forecasting models for different applications

Medium, extended and long range



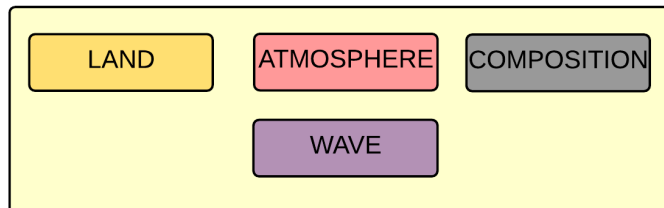
Sea ice model and $1/4^\circ$ ocean resolution to be implemented in Nov 2016

High-resolution



10-day forecast with a 9km grid resolution. Prescribed SST and sea ice.

Atmospheric composition

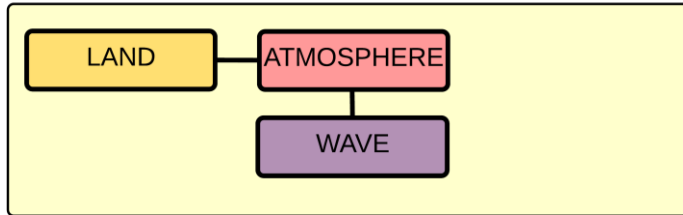


Forecasts for the Copernicus Atmosphere Monitoring Service (CAMS)

Initialisation of Earth system forecasts

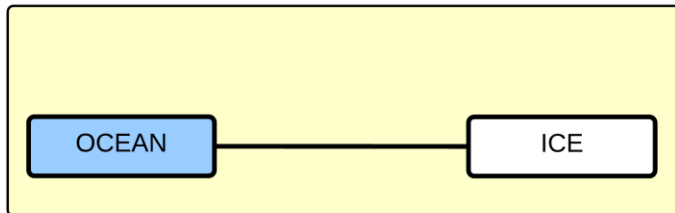
Different coupled assimilation systems to provide initial conditions for forecasts

Atmospheric assimilation system



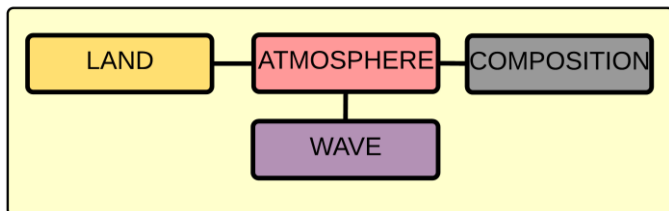
- weakly coupled assimilation
- prescribed SST and sea ice
- separate analyses: 4D-Var/OI/SEKF

Ocean assimilation system



- weakly coupled assimilation (Nov 2016)
- forcings from atmospheric analysis
- separate analyses: 3D-Var

Atmospheric composition assimilation system



- weakly coupled assimilation
- separate analyses: 4D-Var/OI/SEKF

→ Solid lines represent coupling during assimilation

→ Atmosphere/ocean are coupled in the forecasts, but atmospheric and ocean analyses are computed separately

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

Developments

Loosely	Impact of an observation in multiple components
Roughly	Consistent analysis
Relatively	Coupled background error
Quasi	Coupled TL/ADJ
Firmly	Balanced analysis
Strongly	Cross-fluid localization
Entirely	Cross-domain covariance
Perfectly	Multiple components as a single coherent system
Fully	

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

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- **Coupled atmosphere-ocean assimilation system (CERA)**
- Preliminary results from the coupled climate reanalysis (CERA-20C)
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Importance of the ocean coupling for weather prediction

The ocean is the lower boundary for atmosphere for a large part of the earth
→ modelling accurately this lower boundary should give feedback to the atmosphere

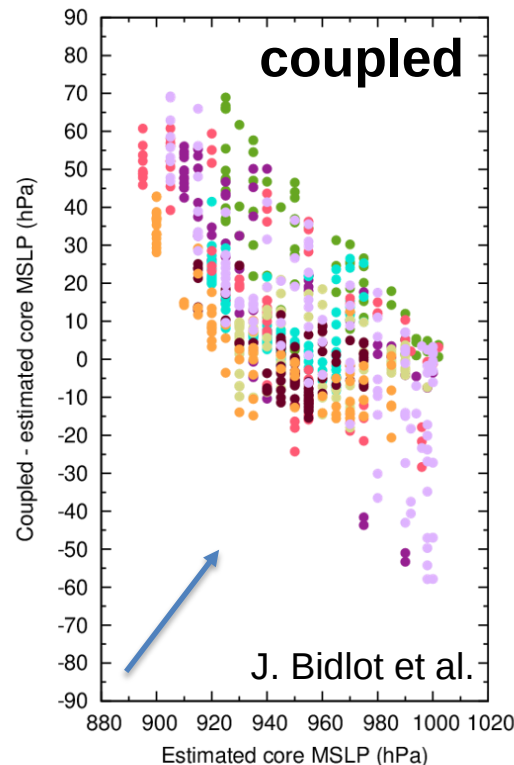
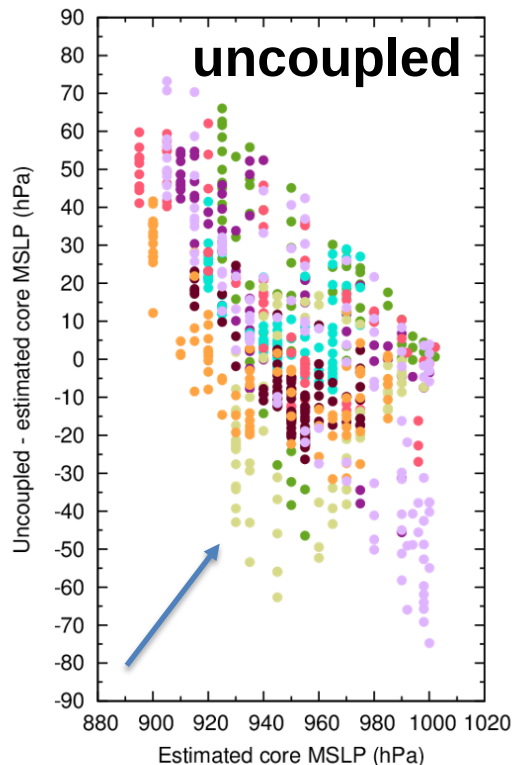
For seasonal forecasting

Ocean coupling provides better SST forecasts for ENSO predictions

For medium range forecasting

Ocean coupling improves the representation of Tropical cyclones

● Soulik ● Usagi ● Francisco ● Haiyan ● Neoguri ● Halong ● Vongfong ● Hagupit



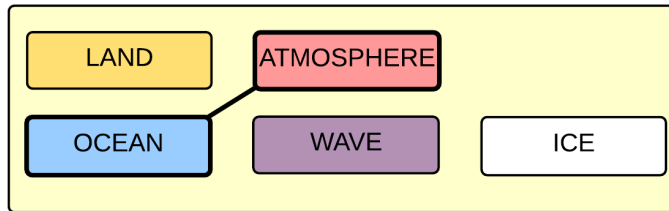
MSLP forecast error versus the estimated core MSLP

→ In the uncoupled case, too deep TCs (no cold wake feedback effect, infinite source of energy)

Atmosphere-ocean coupled assimilation

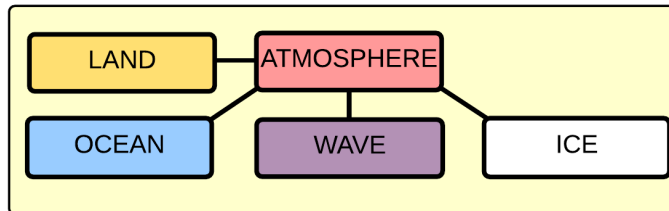
Atmosphere-ocean interactions need to be taken into account, not only during the forecast but also for the definition of the initial conditions of the forecasts

Coupled reanalysis (CERA-20C)



- 20th century reanalysis
- assimilation only in the atmosphere and ocean
- outer-loop coupling
- other components constrained by the fluxes

Coupled reanalysis (CERA-SAT)

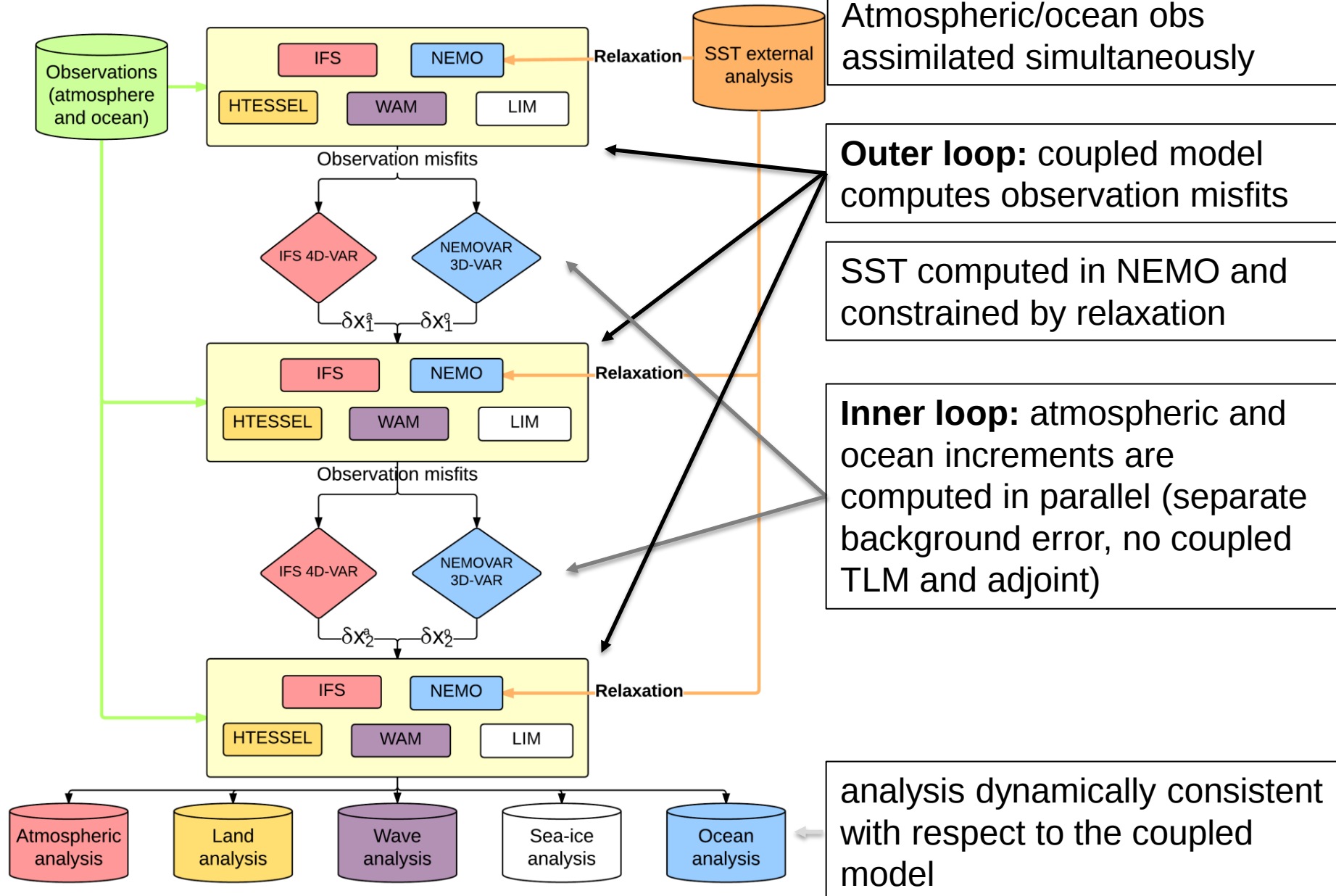


- full observing system (satellite, upper air, land, wave, sea ice)
- outer-loop/weakly coupling
- higher-resolution
- a couple of years of reanalysis

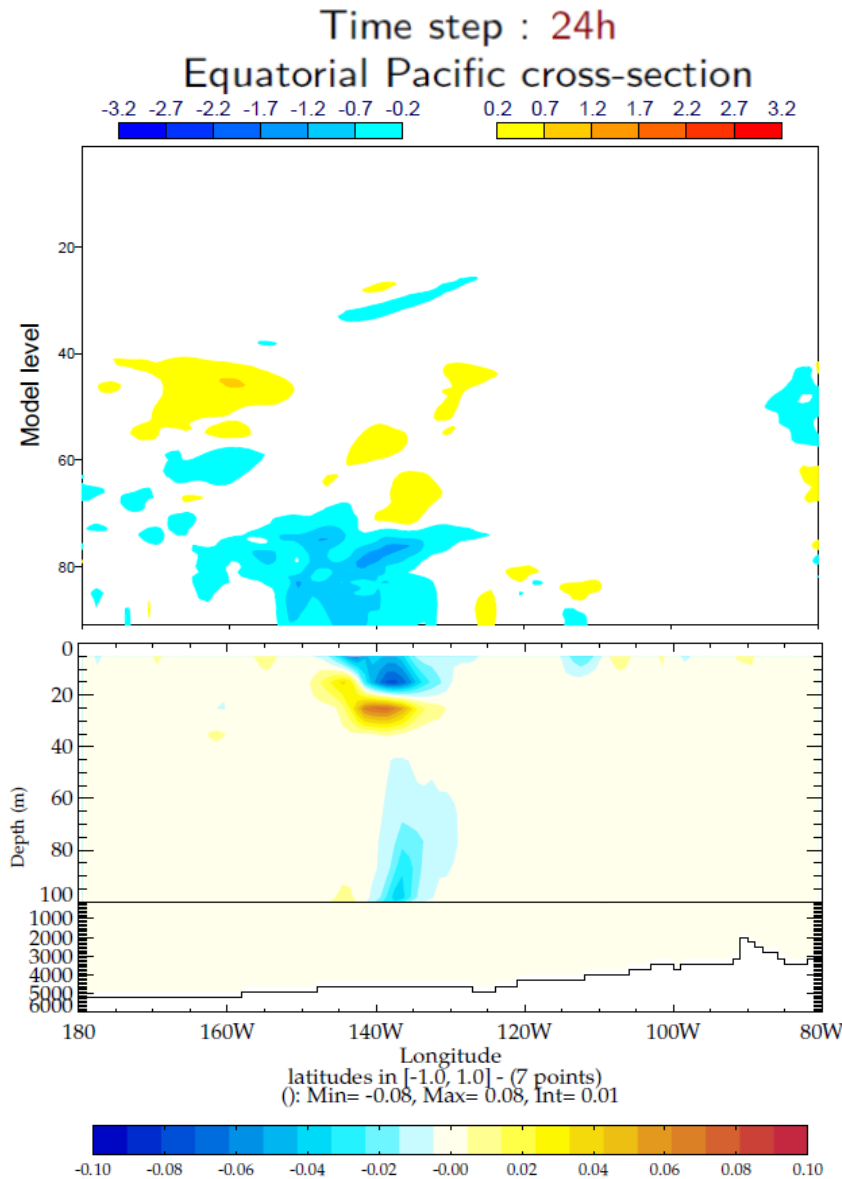
Developed in a reanalysis context, but pave the way for more advanced data assimilation for operational forecasting

Coupled atmosphere-ocean assimilation system (CERA)

Schematic for one assimilation cycle



Information exchange in the CERA system



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. QJRM, 142: 65–78, 2016.

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Extended climate reanalysis at ECMWF

Activity started in 2011 (ERA-CLIM) and funded until 2017 (ERA-CLIM2)

- reconstruct the past weather and climate spanning a period of 100+ years
- focus on consistency and low-frequency climate variability

ERA-20C: the ECMWF atmospheric reanalysis of the 20th century



Atmosphere



Land



Wave

Model: IFS (CY38R1, Jun 2012)
Forcing: SST/SIC prescribed (HADISST2)
Observation: surface conventional
Assimilation: 4D-Var
Resolution: 125km (T159L91)
Period: 1900-2010

ORA-20C: the ECMWF ocean reanalysis of the 20th century



Ocean



Sea ice

Model: NEMO/LIM2 (CY41R2, Mar 2016)
Forcing: SST nudged (HADISST2) and ERA-20C
Observation: salinity and temperature profiles
Assimilation: 3D-Var (10-member ensemble)
Resolution: ORCA1 Z42
Period: 1900-2010

Extended climate reanalysis at ECMWF

CERA-20C: the first ECMWF coupled reanalysis of the 20th century



Atmosphere



Land



Wave



Ocean



Sea ice

Model: IFS/NEMO/LIM2 (CY41R2, Mar 2016)

Forcing: SST nudged (HADISST2)

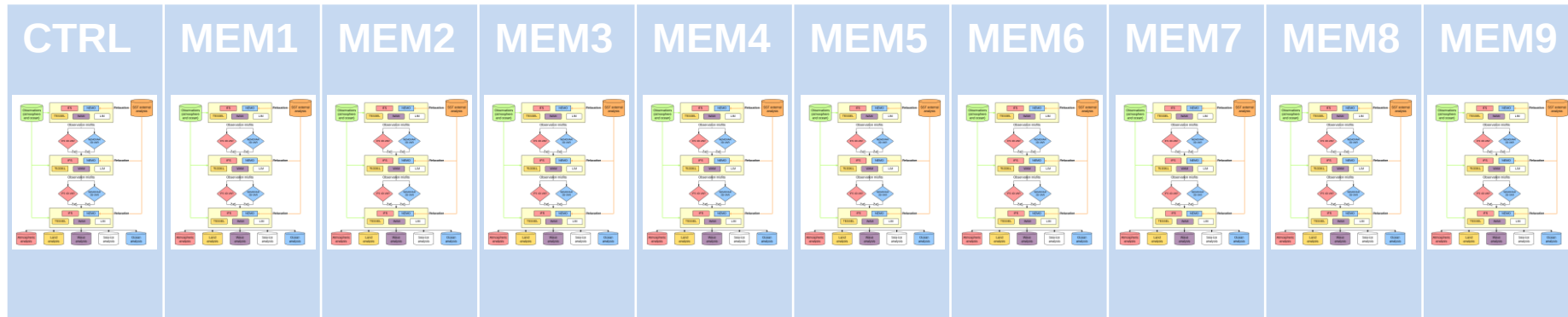
Observation: surface conventional, salinity and temperature profiles

Assimilation: new CERA system (10-member ensemble coupled hybrid DA)

Resolution: T159L91/ORCA1 Z42

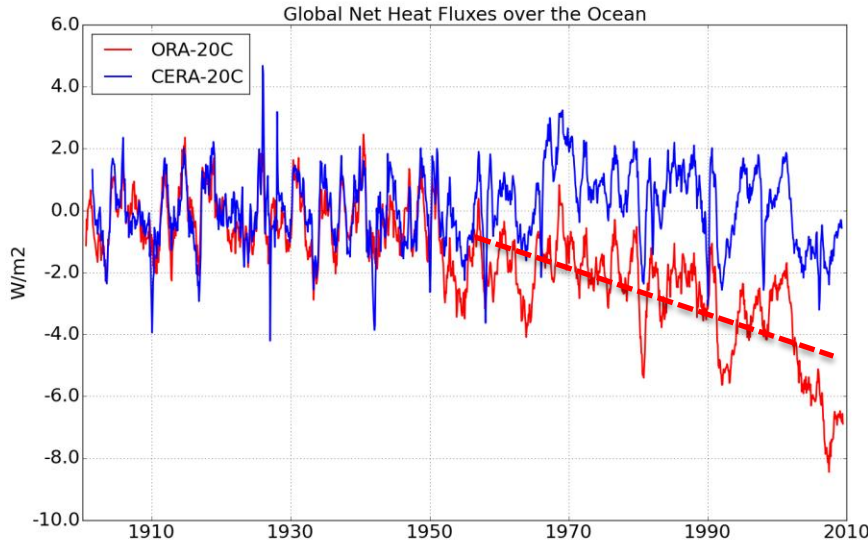
Period: 1901-2010

CERA implements a 10-member EDA system



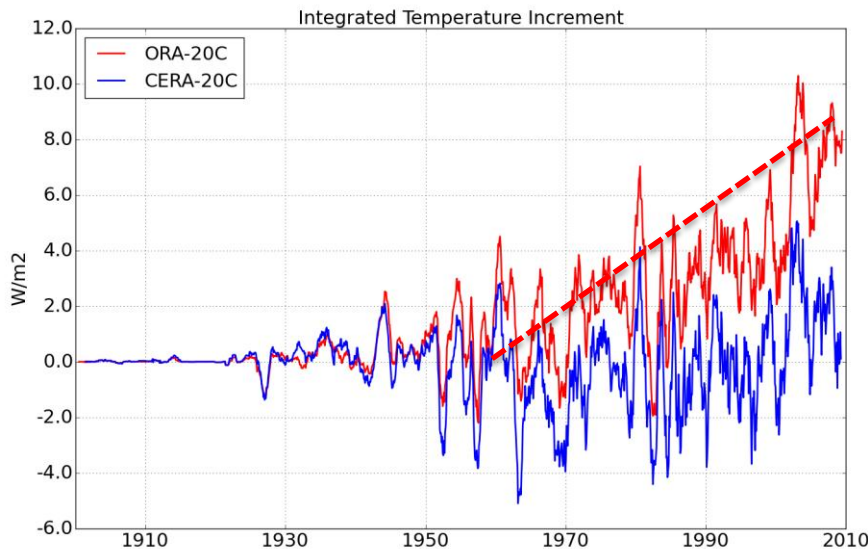
→ hybrid method for the background error in the atmosphere, not yet in the ocean

Preliminary results of CERA-20C



Global net **air-sea fluxes** toward the ocean in **CERA-20C** and **ORA-20C**.

→ spurious trend in ORA-20C probably due to shift in wind forcing in ERA-20C (heat lost)



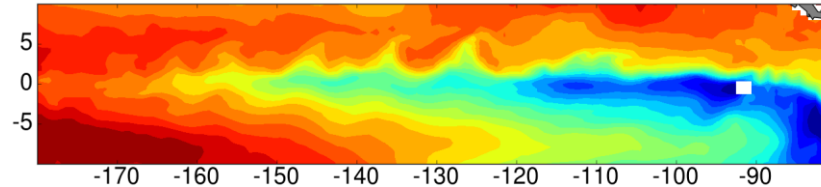
Ocean temperature increment in **CERA-20C** and **ORA-20C**.

→ increment in ORA-20C is trying to compensate the heat lost

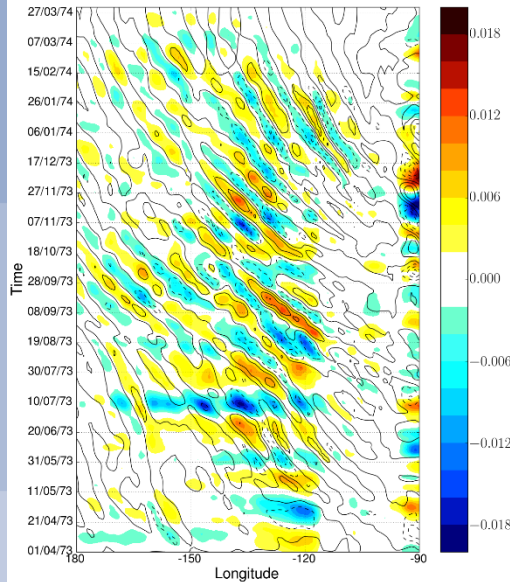
→ CERA-20C fluctuates around zero suggesting a more balanced air-sea interface

Preliminary results of CERA-20C

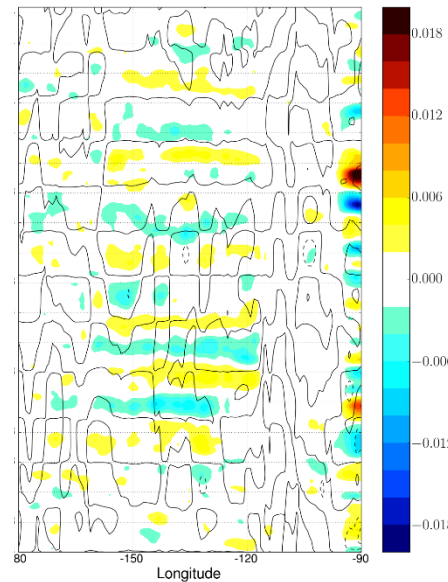
Tropical Instability Waves (TIW) are westward-propagating waves near the equator (intraseasonal coupled process)



CERA-20C



ERA-20C



CERA-20C

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

ERA20C

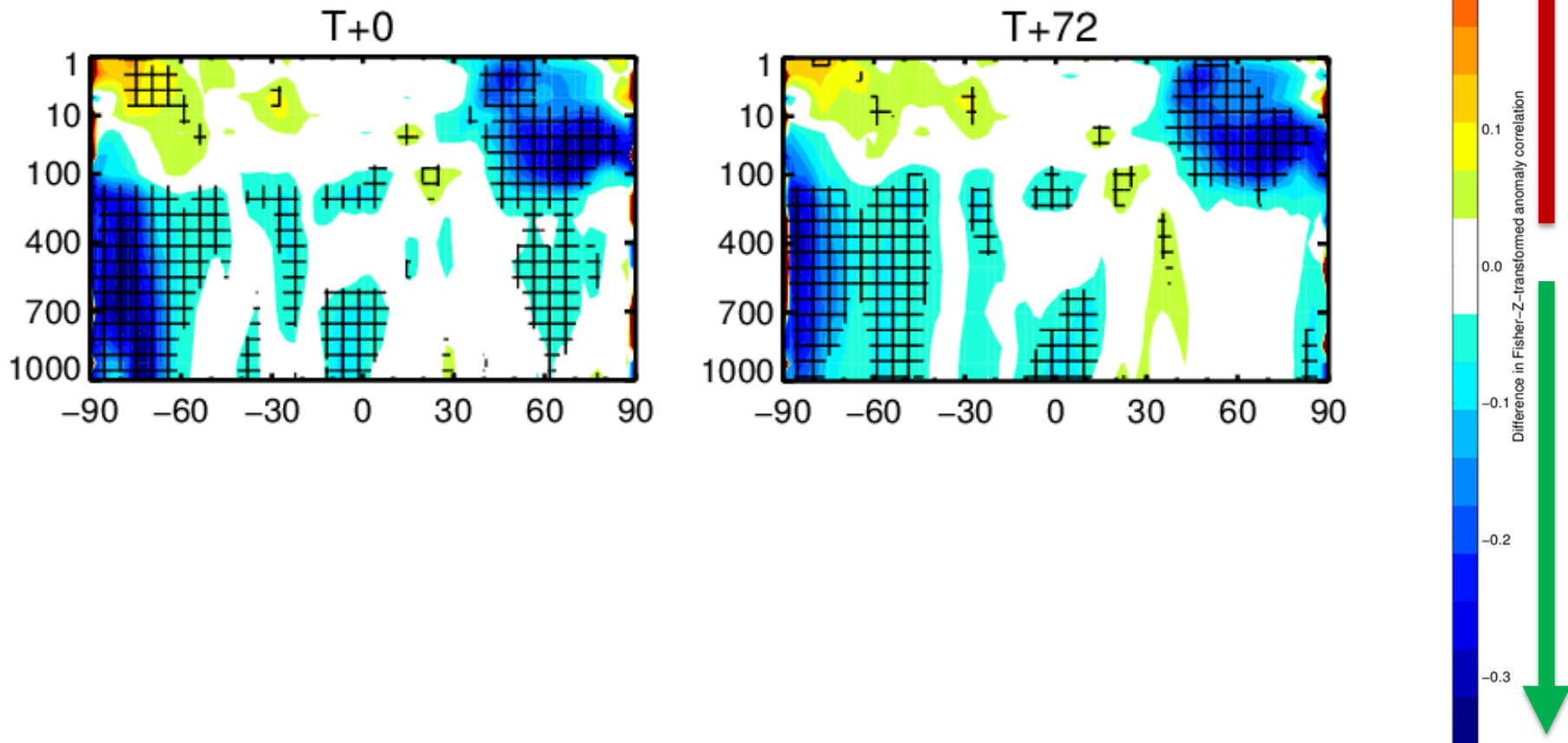
→ no TIWs and wind stress signals (forced by monthly SST)

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

Impact of ocean coupling during assimilation

CERA-20C compared to an atmospheric-only assimilation system in MAM 2010

Improvement in geopotential height when ocean is coupled during assimilation (analysis and 3-d forecast)



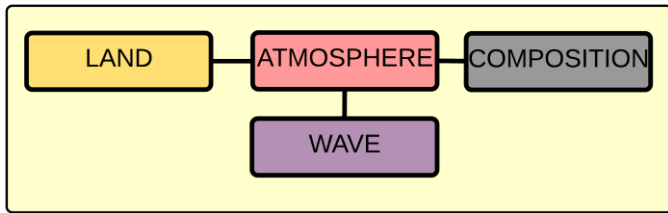
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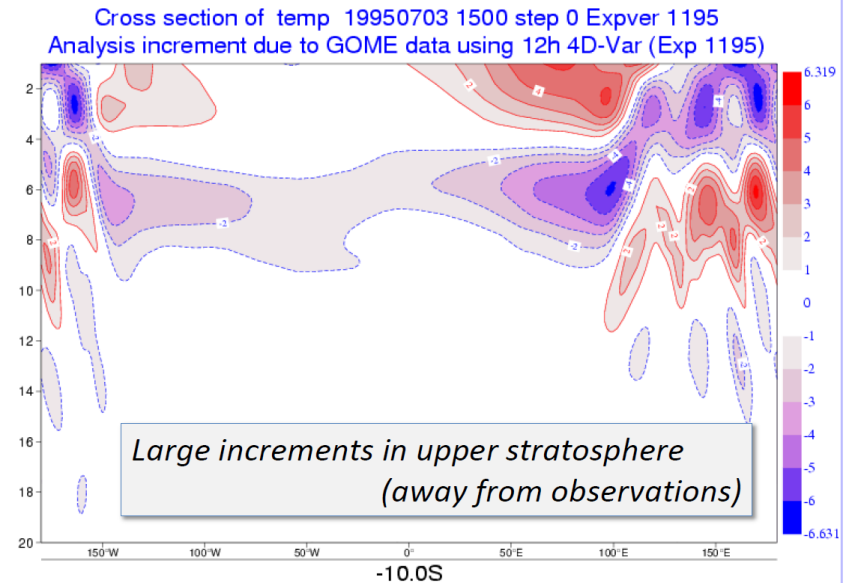
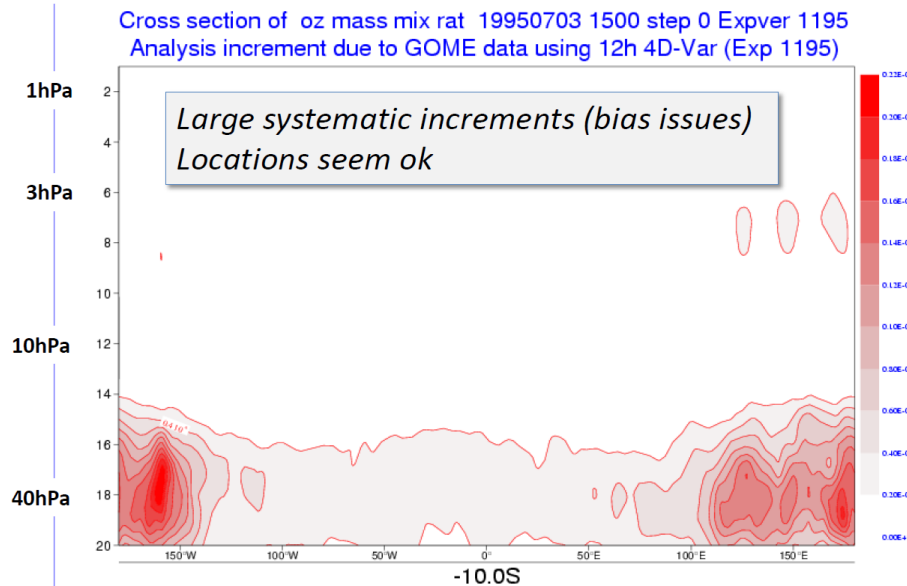
Using ozone data to extract wind information

Upper tropospheric humidity observations can be used to extract wind information
→ an early motivation for assimilating lower stratospheric ozone data.

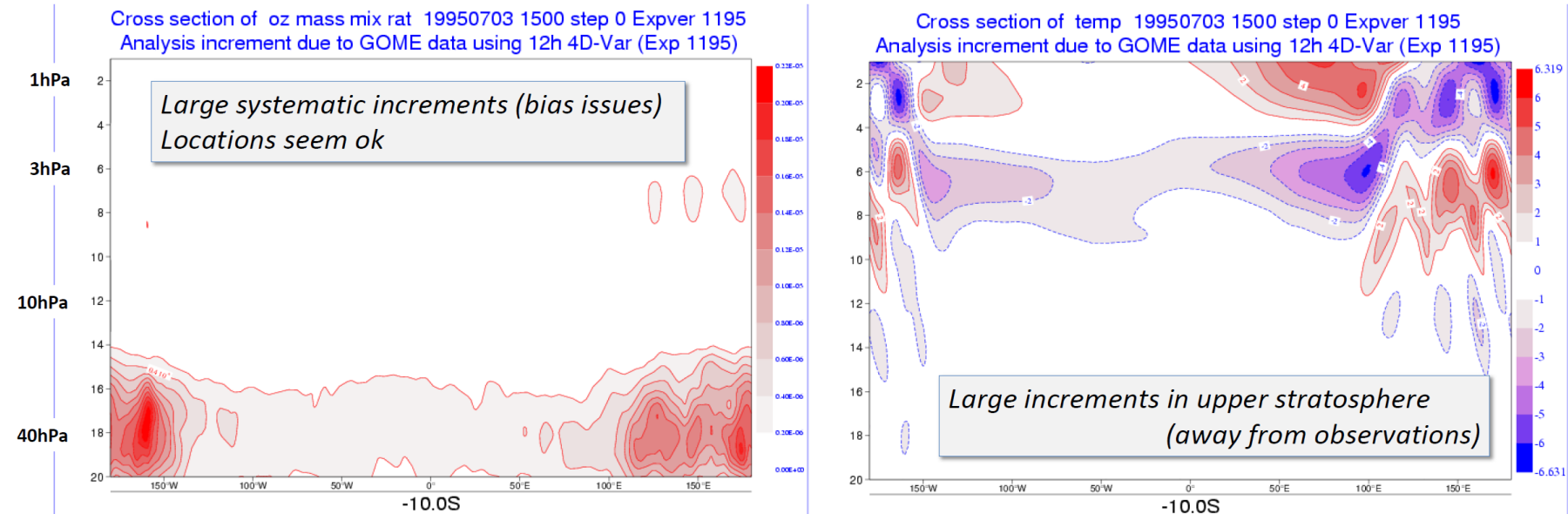
Atmospheric composition assimilation system



- coupled atmosphere/composition analysis
- coupled TL/ADJ model (coupling between tracer and wind fields)



Using ozone data to extract wind information



The stratosphere is not well constrained by observations

- biases in the model (ozone profile data generate large ozone increments)
- 4D-Var adjusts the flow where it is least constrained, to improve the fit to observations (large temperature increments)

To prevent this, the 4D-Var ozone analysis in the IFS has been decoupled

- background errors uncorrelated with other variables
- no coupled TL/ADJ model

Both models and observations must improve to allow full coupling

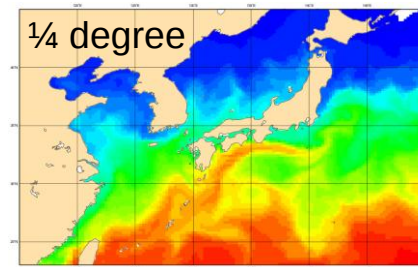
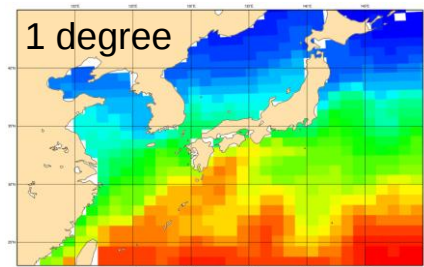
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Conclusions and comments

In operation, atmosphere and ocean analyses still computed separately

- dynamic sea-ice to be included in ocean analysis
- ocean resolution upgrade $\frac{1}{4}$ degree (75 levels)



Climate reanalysis CERA-20C (1901-2010) has been produced

- a coupled atmosphere-ocean analysis
- improvement with respect to uncoupled atmosphere/ocean reanalyses

CERA-SAT will deliver a proof-of-concept over a recent period

- full observing system (satellite, upper air, land, wave, sea ice) at higher resolution
- Outer-loop coupling for atmos/ocean/sea-ice and weakly coupling for land/wave
- could produce a near-real time coupled analysis

Working towards a common Earth system assimilation framework

- coupled assimilation at the outer loop level for all the components

Conclusions and comments

The CERA system is a test-bed for the development of coupled observation operator

- observations that depend on more than one component (radiances for the lower troposphere, scatterometer, SST measurements)

The CERA system is a test-bed for the development tighter/better coupling

- different assimilation windows for the different characteristic time scales
- estimate explicitly coupled cross-correlations

Coupled data assimilation is a relatively new field of research

- many questions are still open, future directions might evolve as experience is gained
- biases between the different Earth system components are another important aspect (Ozone example)

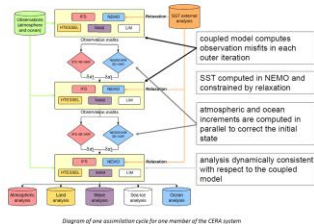
ECMWF Roadmap to 2025

“As ECMWF’s forecasts progress towards coupled modelling, interactions between the different components need to be fully taken into account, not only during the forecast but also for the definition of the initial conditions of the forecasts.”

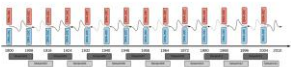
Evolution of the ocean state in the CERA-20C coupled climate reanalysis

An introduction to CERA-20C

CERA-20C is the first ensemble of climate reanalysis of the 20th century conducted at ECMWF. It relies on the ECMWF coupled data assimilation system that simultaneously ingests ocean and atmospheric observations



CERA-20C production was generated with a 10-member EDA. The production was conducted in 14 streams of 10 years running in parallel with a 2-year overlap for consistency in the final product.



CERA-20C provides a record of consistent coupled ocean-atmosphere states over the period 1901-2010

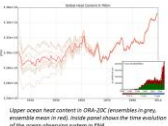
Ocean configuration in CERA-20C

The ocean component in CERA-20C is based on the NEMO framework

- Model configuration: ORCA1242 (1deg, 10m first layer), LIM2 sea-ice
- Assimilation: 3DVAR FGAT 1-day window
- Observations: temperature and salinity profiles from EN4 dataset
- Air-sea interface: relaxation to monthly SST analysis HadISST2.1.1
- Coupling with the atmosphere every hour in outer loops
- Perturbations: SST, ocean observations and surface fluxes

CERA-20C ocean streams are initialised from an ensemble of 20th century ocean reanalyses forced by ERA-20C and called ORA-20C.

ORA-20C ensembles provide a range of plausible initial conditions for CERA-20C streams. The large uncertainty in the ocean state in the early 20th century reflect the poor observing system. Uncertainties are greatly reduced in the second half of the period.

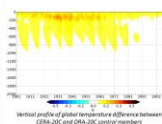
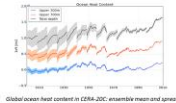


Eric de Boisseson, Patrick Laloyaux, Per Dahlgren, Dinand Schepers, Yuki Kosaka, Sami Saarinen, Magdalena A. Balmaseda, Shoji Hirahara and Roberto Buizza

Information on ECMWF Reanalysis at <http://www.ecmwf.int/en/research/climate-reanalysis>
Information on ERA-CLIM at www.era-clip.eu
Reanalysis data available at <http://apps.ecmwf.int/datasets/>

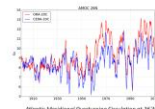
Response of the ocean in CERA-20C

Large uncertainties and discontinuities between streams are visible in the first half of the century and in particular in the ocean interior. The growing observing system allows to reduce uncertainties and discontinuities in the second half of the century. The last decades show a fast increase in heat content in agreement with increased heat uptake described in the literature.

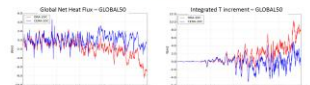


CERA-20C ocean is drifting from its initial condition. The drift is characterized by a surface warming that rapidly extends at depth. While the upper ocean adjusts relatively quickly, the length of a stream is too short to get consistency in the ocean interior. The increasing number of observation in the latest decades helps reducing the drift.

The AMOC is very low in the early 20th century as the ocean model is very cold and stratified in the North Atlantic and very warm in the Tropics. The ODA reactivates the AMOC bringing warmer waters to the subtropical regions and cooling down the Tropics.



On the bright side, the ocean-atmosphere coupling provides a more consistent set of forcing fields for ocean simulations. The flux forcing over the ocean from ERA-20C is not consistent over the 20th century. The net heat flux showed a negative trend from the 1940s onwards that is compensated by a growing ocean temperature increment. In CERA-20C, the net flux and the increments fluctuate around zero suggesting a more balanced air-sea interface.



(Left panel) Net heat flux toward the ocean (in 10^{15} J/s) in CERA-20C (black) and in an ocean reanalysis forced by ERA-20C (blue) over Antarctica for the 20th period. (Right panel) Vertically integrated temperature increment in the ocean (in 10^{15} J/s)

Conclusions

- The CERA-20C reanalysis provides a 20th record of ocean-atmosphere states with improved consistency at the air-sea interface
- The poor observing system in the early 20th century leads to large uncertainties in the initial state and to a poor constraint of the model drift
- The reasons behind the ocean/coupled model drift need to be addressed for future reanalyses



ECMWF land-atmosphere weakly coupled assimilation: status and perspectives



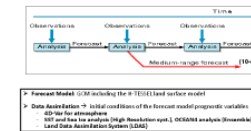
Patricia de Rosnay, Elias Hölm, Massimo Bonavita, Patrick Laloyaux, Dinand Schepers, Per Dahlgren, Hans Hersbach, and Steve English

European Centre for medium-Range Weather Forecasts (ECMWF), Reading, UK
Coupled Assimilation Workshop, Météo-France, Toulouse, 18-21 October 2016

Introduction: ECMWF Earth System

The ECMWF forecasting system relies on an Earth System approach, including atmosphere, ocean, waves, land, and sea ice. For NWP applications different data assimilation methods are used for the each component of the Earth System. A hybrid 4D-Var is used for the atmosphere, a simplified sea-surface temperature (SST) and sea ice analysis is used for medium-range forecasts and for the ERA-Interim and ERA5 reanalyses. A 3D-Var FGAT ocean analysis is also used to initialise ECMWF's extended- and seasonal-range forecasts.

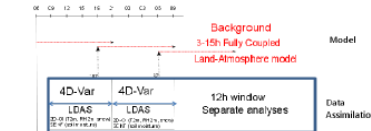
ECMWF Integrated Forecasting System (IFS)



Data assimilation coupling approaches

The operational ocean-atmosphere data assimilation system is currently uncoupled for NWP. A pioneering coupled ocean-atmosphere data assimilation approach was developed and used for the coupled reanalysis project CERA-20C, demonstrating the potential of a coupled ocean-atmosphere assimilation (see presentation by Laloyaux et al. and poster by de Boisseson et al.). The land-atmosphere data assimilation is weakly coupled, using a coupled land-atmosphere background forecast and separate analyses for the atmosphere and for the surface (soil moisture and snow).

Weakly coupled Land Data Assimilation



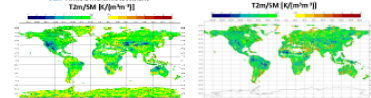
Weakly coupled approach $\Rightarrow$ Feedback ensured by coupled background forecasts

Land Data Assimilation methods

- Snow depth:**
- Method: 2D-Optimal Interpolation for NWP, ERA5, CERA-SAT (Cressman for ERA-Interim)
 - Observations: SYNOP snow depth and NOAA/NESDIS IMS snow cover
- Soil Moisture:**
- Method: Simplified Extended Kalman Filter (SEKF)
 - Conventional Observations: SYNOP or analysed (2D OI) 2m air relative humidity and temperature
 - Satellite Observations: ASCAT soil moisture (NWP, ERA5, CERA-SAT), SMOS (research), SMAP (research)

Toward stronger land-atmosphere coupling

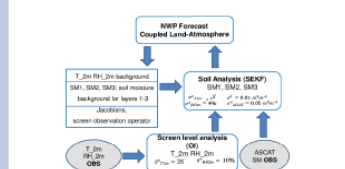
- Purpose:**
- Use the EDA (Ensemble Data Assimilation) spread to compute the EKF soil moisture analysis Jacobians
- Objective:**
- Reduce the surface analysis computing cost
 - Strengthen coupling between surface and atmospheric analyses (flow dependent and possibility of outer/loop coupling)



Weakly coupled Land Data Assimilation

- Justification:**
- Vertical correlations dominate land surface processes. Therefore each grid point is analysed independently. Land data assimilation is a 2D problem, whereas the atmosphere DA is a 4D problem.
 - Weak coupling gives flexibility to run land analysis without the expensive 4D-Var component (ERA-Land type, PILDAS)
- Weaknesses:**
- Increments related to fast coupled processes (e.g. precip/soil moisture) are potentially inconsistent at the interface.

Illustration of weakly coupled Soil analysis



Schematic representation of the weakly coupled soil moisture (SM) analysis used across ECMWF systems for NWP and for the reanalyses ERA5 and CERA-SAT

Summary and perspectives

- Weakly coupled land data assimilation approach used at ECMWF for NWP, ERA5 and CERA-SAT
- Important to developments tighter coupling
- Current developments: hybrid EKF-EDA land data assimilation system to strengthen land-atmosphere data assimilation coupling by:
 - Reducing the SEKF computing cost
 - Using EDA spread to compute the SEKF Jacobians
 - Makes it possible to account for flow dependence and tighter coupling, e.g. EKF at the outer loop level.

Patricia.Rosnay@ecmwf.int