The ECMWF coupled assimilation system for climate reanalysis

Patrick Laloyaux

Earth System Assimilation Section

patrick.laloyaux@ecmwf.int

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ECMWF
EUROPEAN CENTRE FOR MEDIUM RANGE WEATHER FORECASTS

ERA CLIM2

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

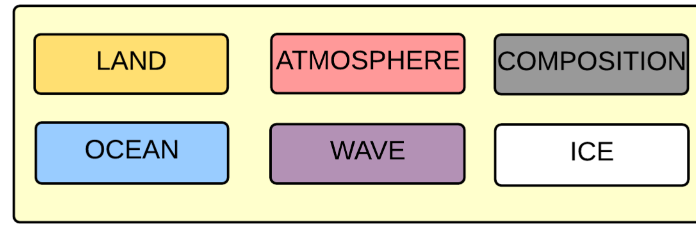
Composition

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

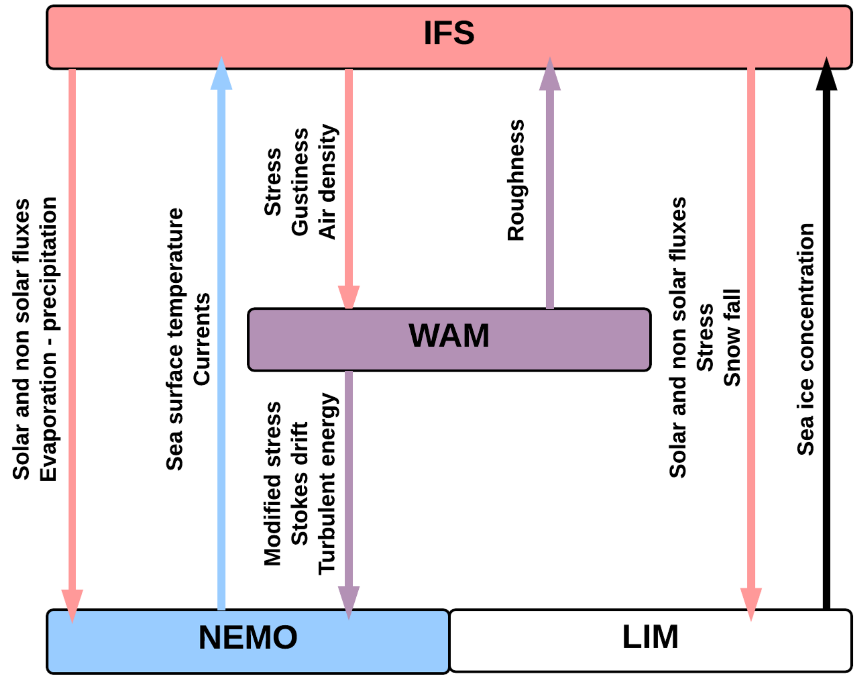
Diversity in coupling methodologies between the components of the model

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



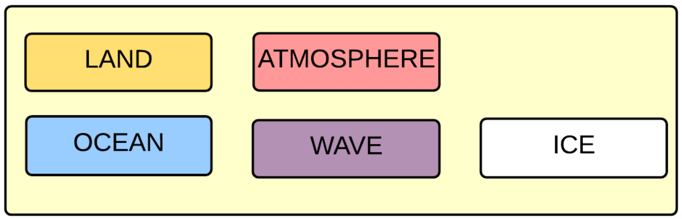
TYPE 3: coupler

- information transferred by files
- not used anymore

Earth system forecasting at ECMWF

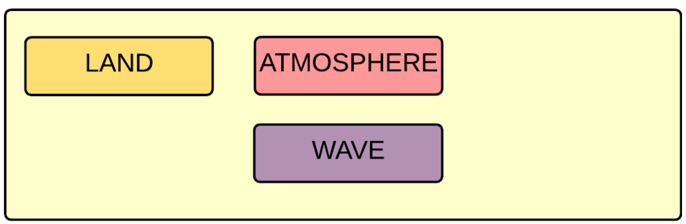
Different forecasting models for different applications

Medium, extended and long range



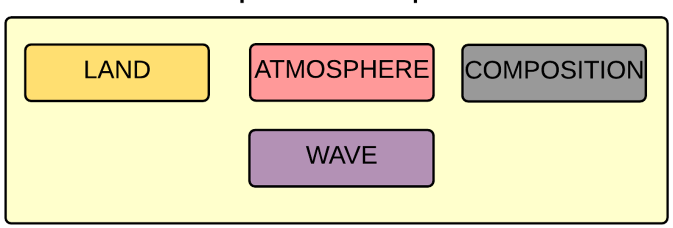
Sea ice model and 1/4° ocean resolution to be implemented in Nov 2016

High-resolution



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

Atmospheric composition

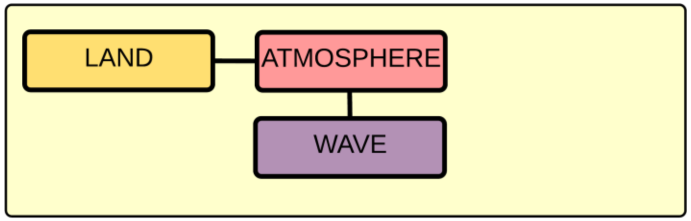


Forecasts for the Copernicus Atmosphere Monitoring Service (CAMS)

Initialisation of Earth system forecasts

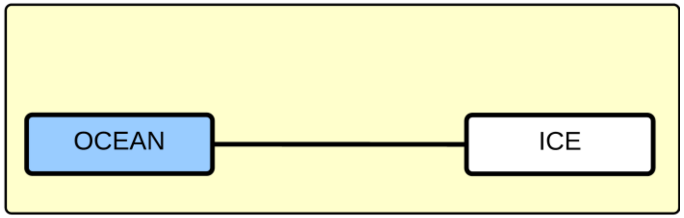
Different coupled assimilation systems to provide initial conditions for forecasts

Atmospheric assimilation system



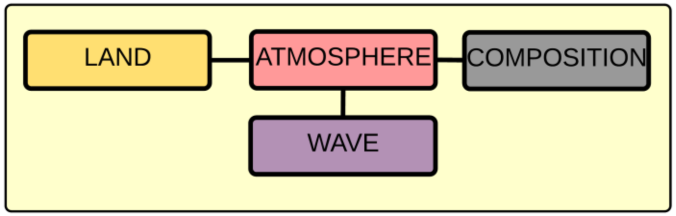
- weakly coupled assimilation
- prescribed SST and sea ice
- separate analyses: 4D-Var/OI/SEKF

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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Importance of the ocean coupling for weather prediction

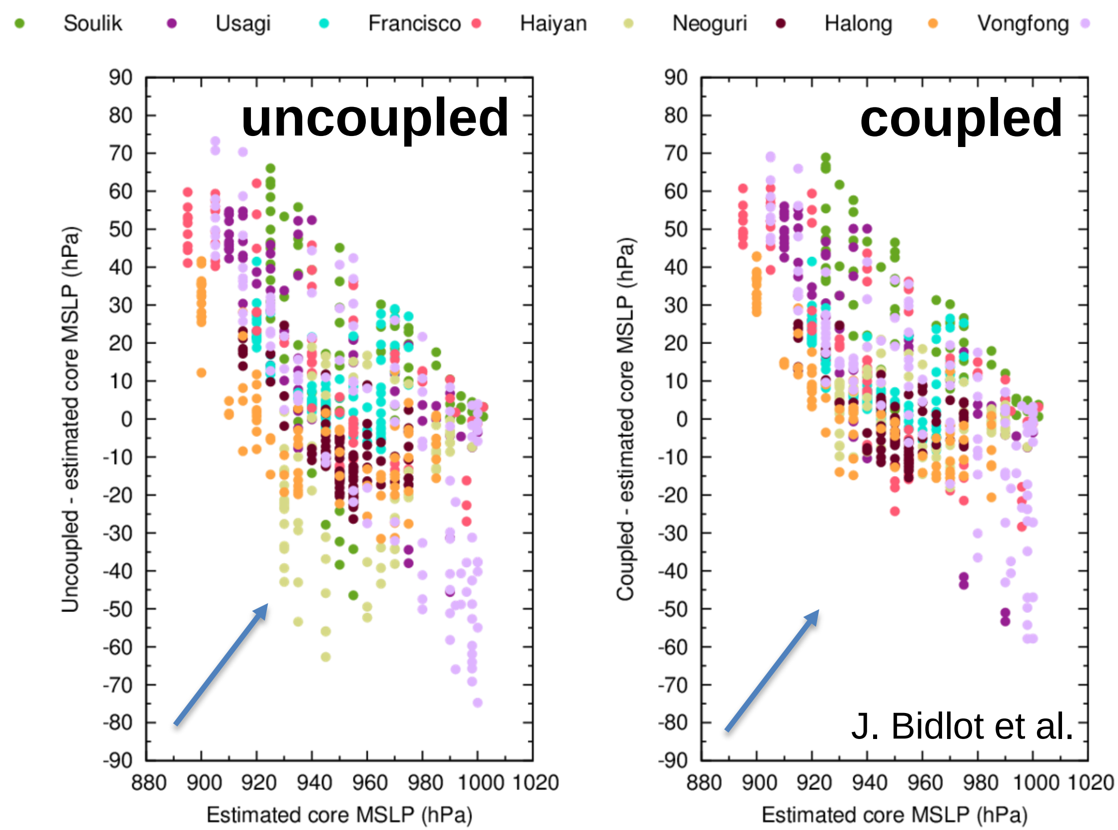
The ocean is the lower boundary for atmosphere for a large part of the earth
→ modelling accurately this lower boundary should give feedback to the atmosphere

For seasonal forecasting

Ocean coupling provides better SST forecasts for ENSO predictions

For medium range forecasting

Ocean coupling improves the representation of Tropical cyclones



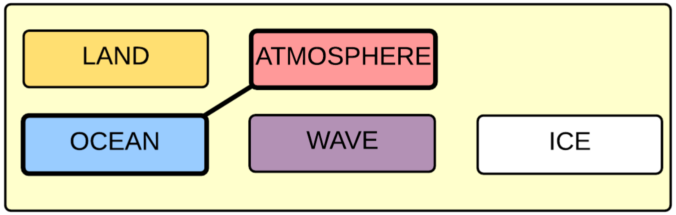
MSLP forecast error versus the estimated core MSLP

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

Atmosphere-ocean coupled assimilation

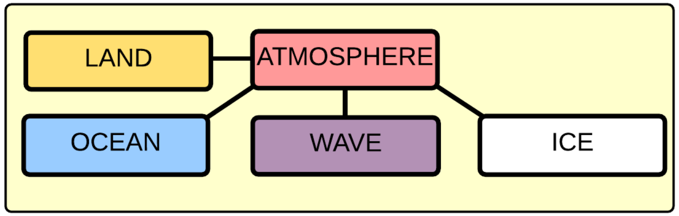
Atmosphere-ocean interactions need to be taken into account, not only during the forecast but also for the definition of the initial conditions of the forecasts

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)

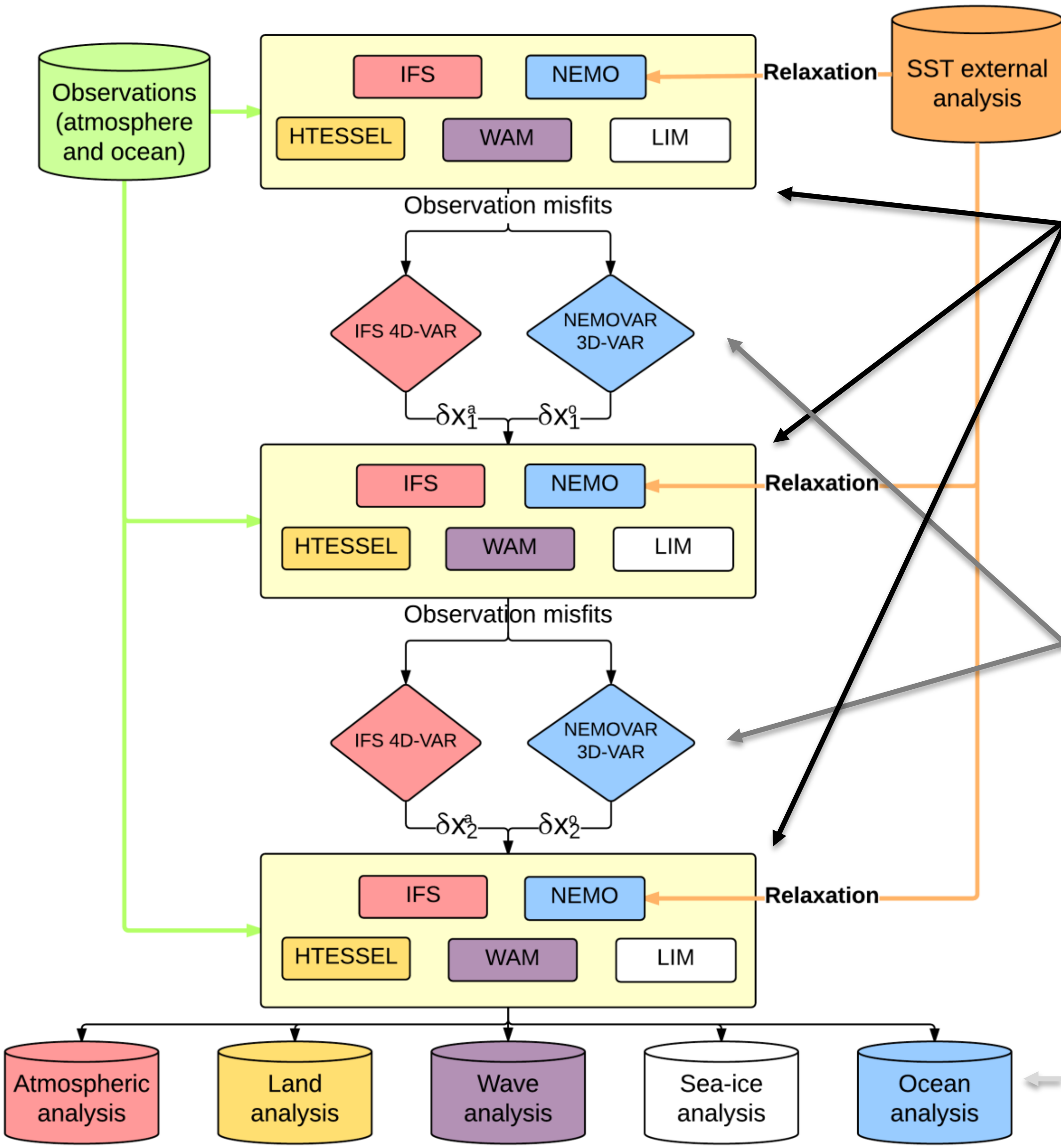


- full observing system (satellite, upper air, land, wave, sea ice)
- outer-loop/weakly coupling
- higher-resolution
- a couple of years of reanalysis

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



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

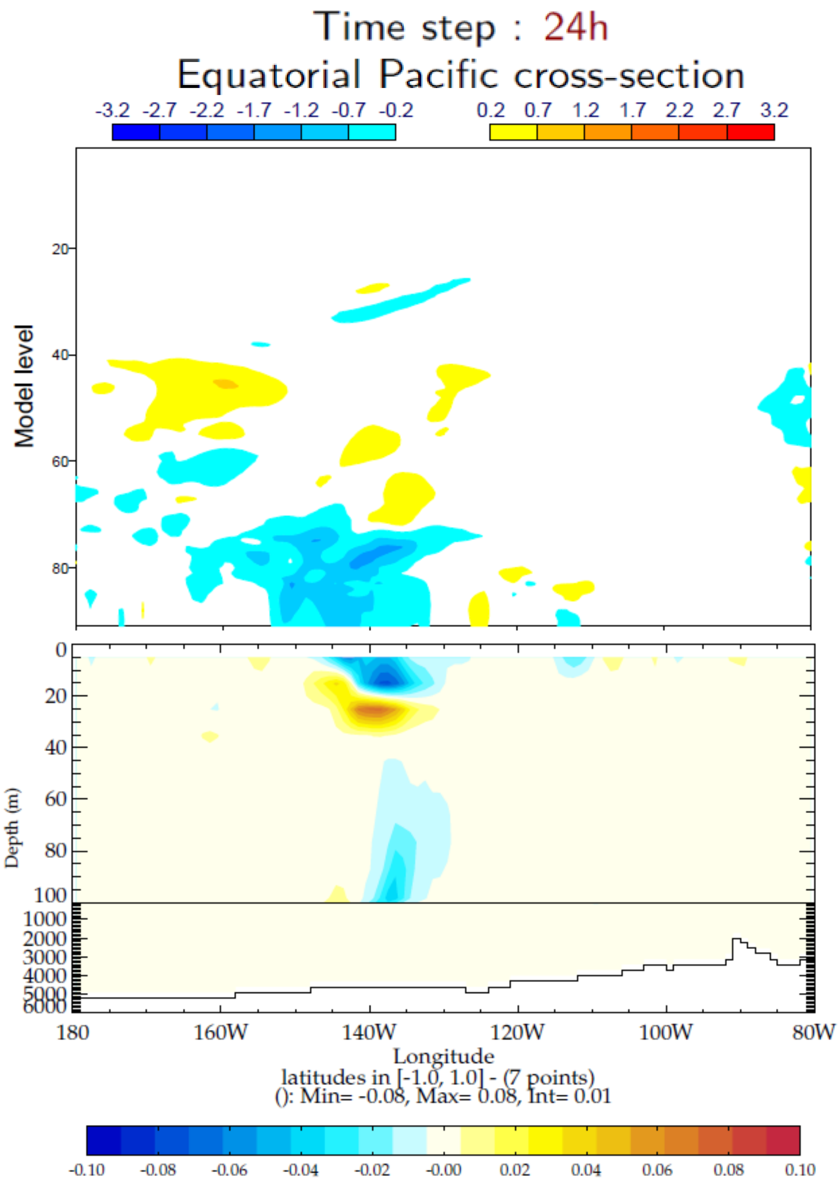
Outer loop: coupled model computes observation misfits

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

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. QJRMS, 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

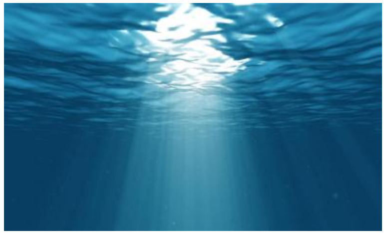
Atmosphere

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

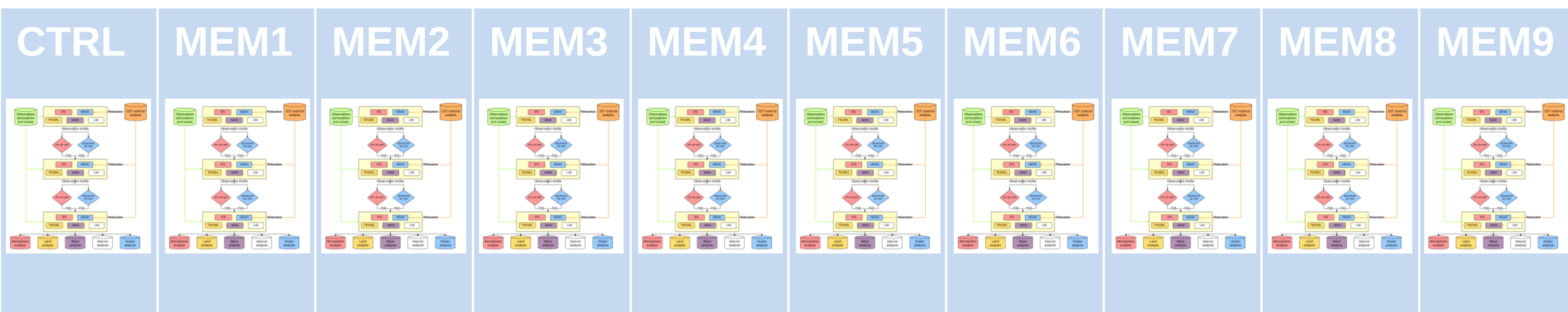
Wave

Ocean

Sea ice

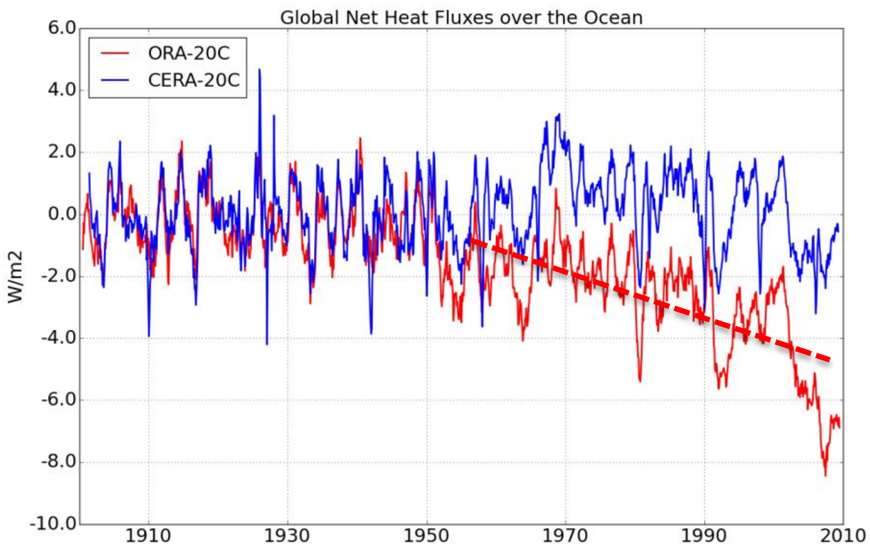
Model: IFS/NEMO/LIM2 (CY41R2, Mar 2016)
Forcing: SST nudged (HADISST2)
Observation: surface conventional, salinity and temperature profiles
Assimilation: new CERA system (10-member ensemble coupled hybrid DA)
Resolution: T159L91/ORCA1 Z42
Period: 1901-2010

CERA implements a 10-member EDA system



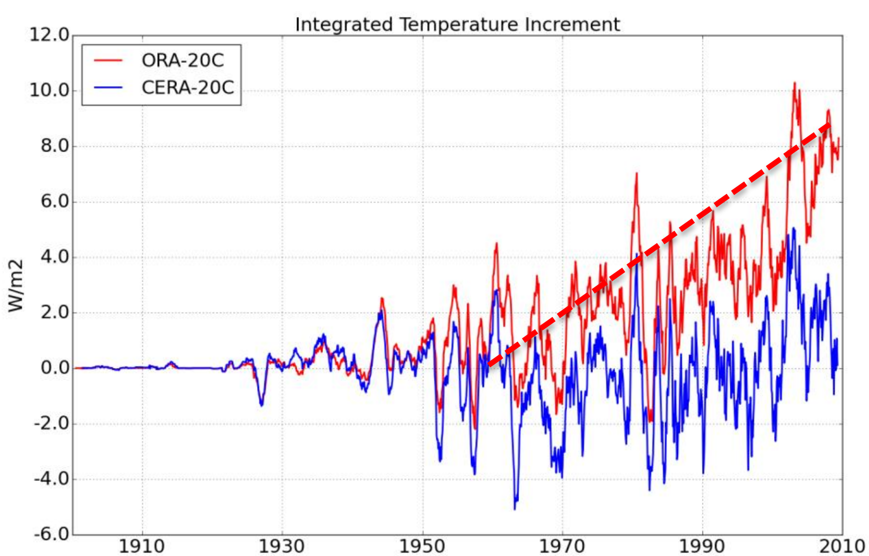
→ hybrid method for the background error in the atmosphere, not yet in the ocean

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)



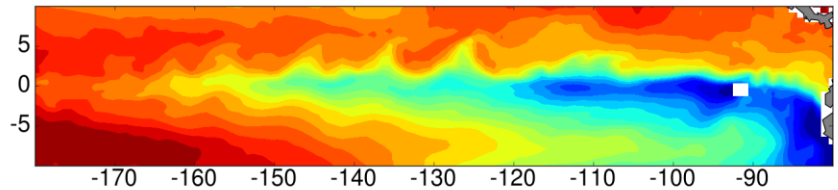
Ocean temperature increment in CERA-20C and ORA-20C.

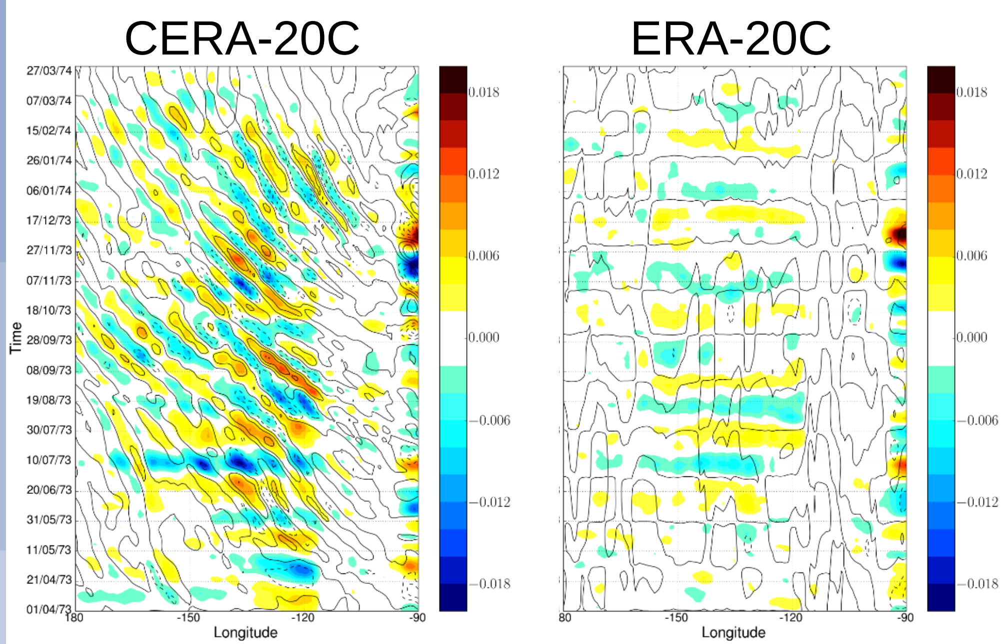
→ increment in ORA-20C is trying to compensate the heat lost
→ CERA-20C fluctuates around zero suggesting a more balanced air-sea interface

Courtesy of E. de Boisseson

Preliminary results of CERA-20C

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





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)

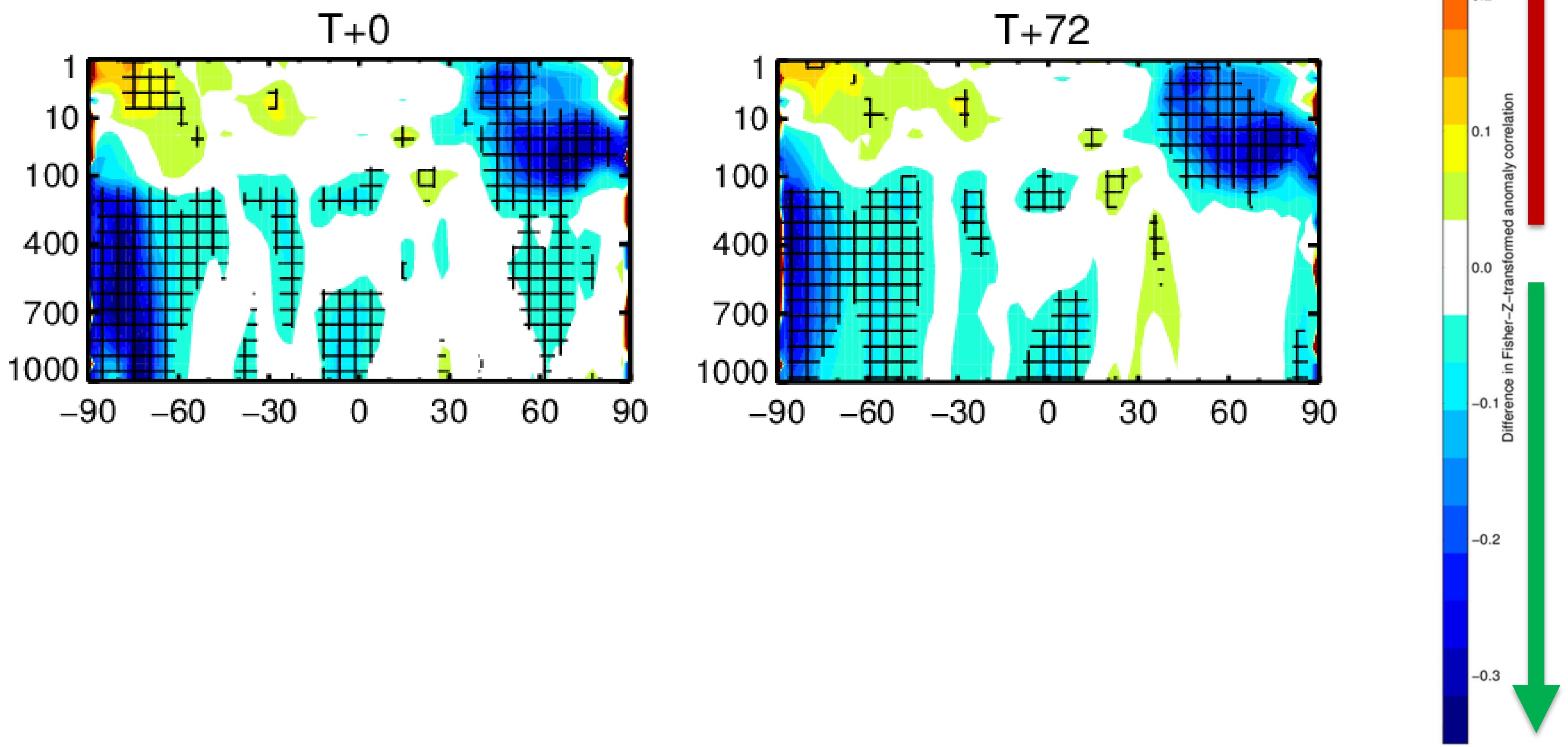
high-pass filtered SST (colour) and wind stress (contour)

Courtesy of E. de Boisseson

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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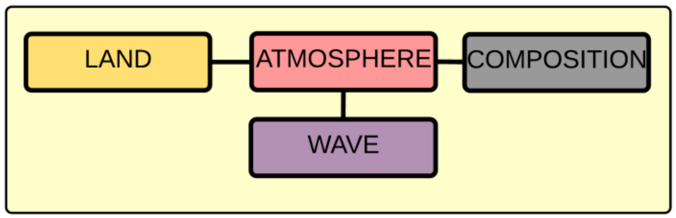
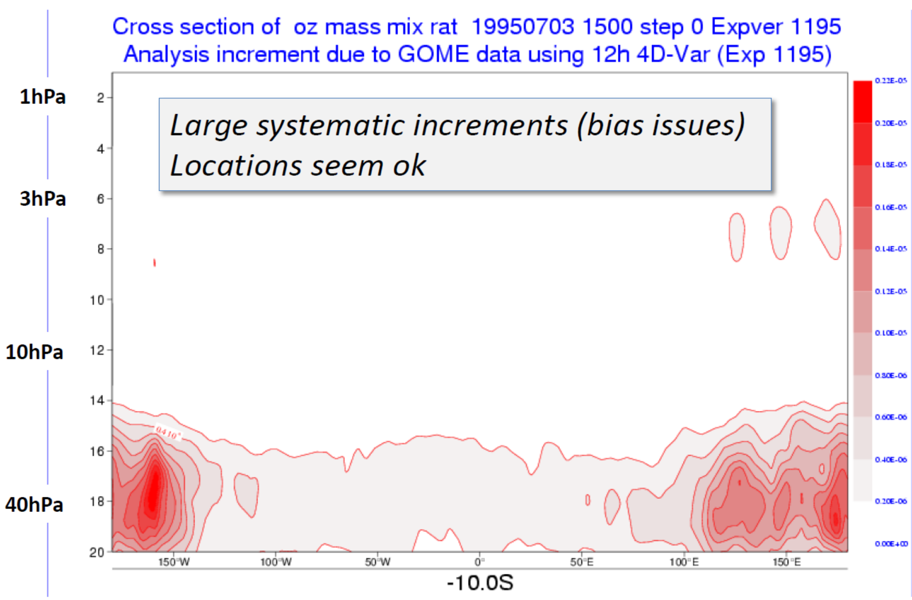
Using ozone data to extract wind information

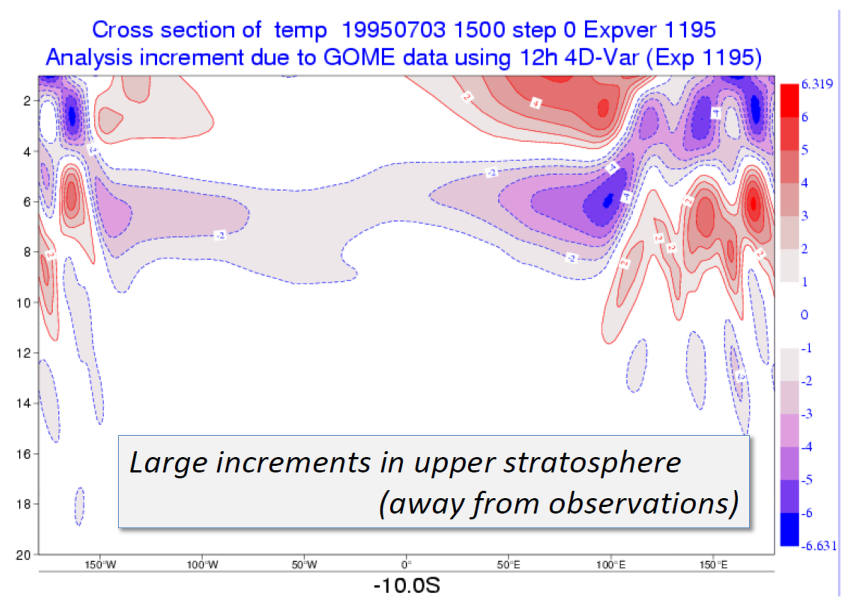
Upper tropospheric humidity observations can be used to extract wind information
→ an early motivation for assimilating lower stratospheric ozone data.

Atmospheric composition assimilation system



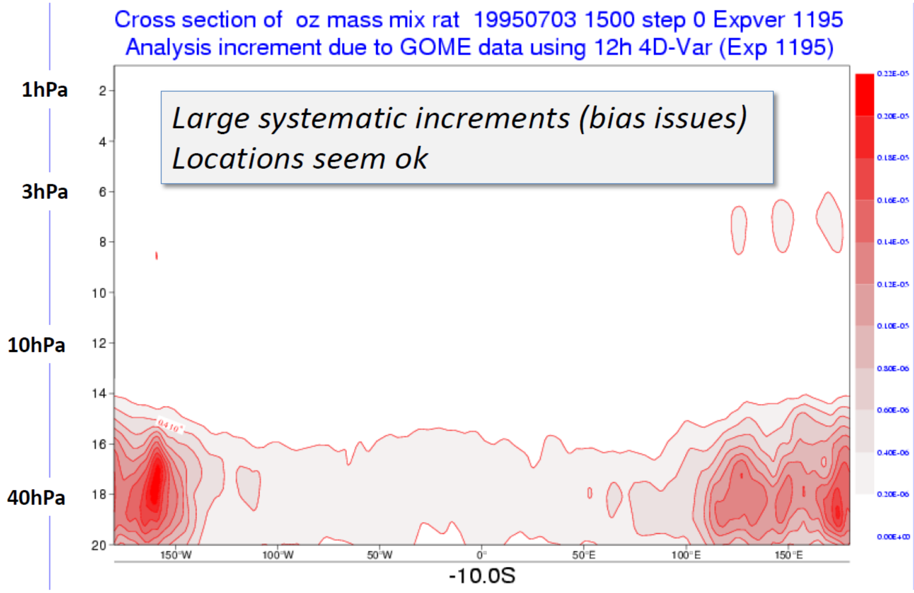
- coupled atmosphere/composition analysis
- coupled TL/ADJ model (coupling between tracer and wind fields)

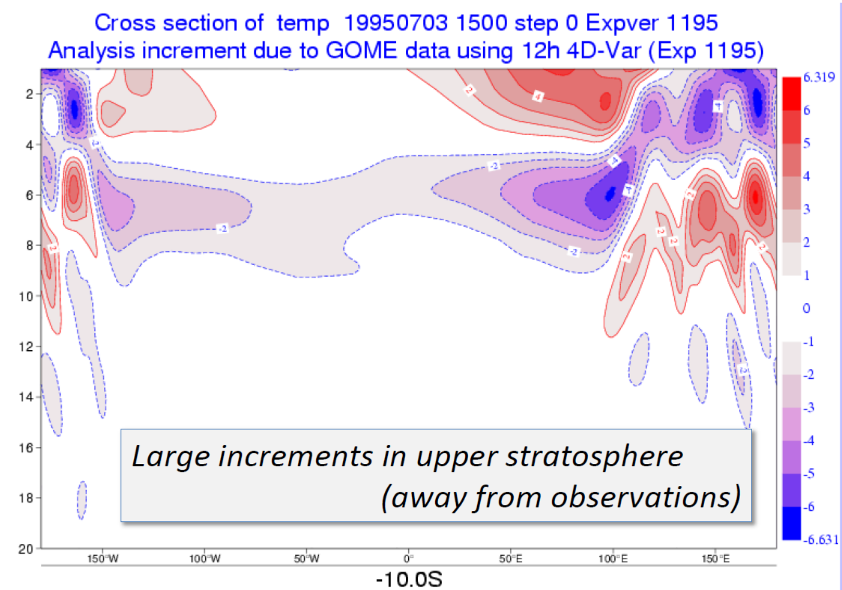




Courtesy of D. Dee

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

Courtesy of D. Dee

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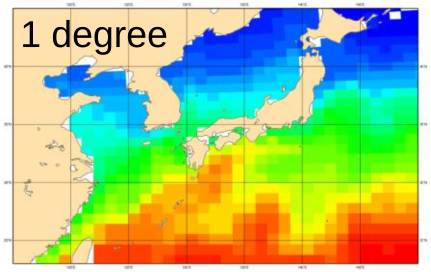
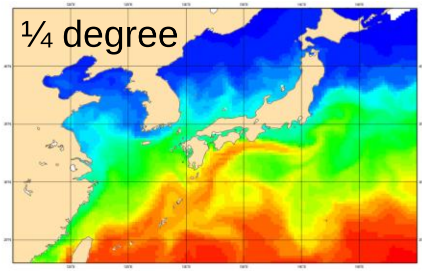
Conclusions and comments

In operation, atmosphere and ocean analyses still computed separately

- dynamic sea-ice to be included in ocean analysis
- ocean resolution upgrade ¼ 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

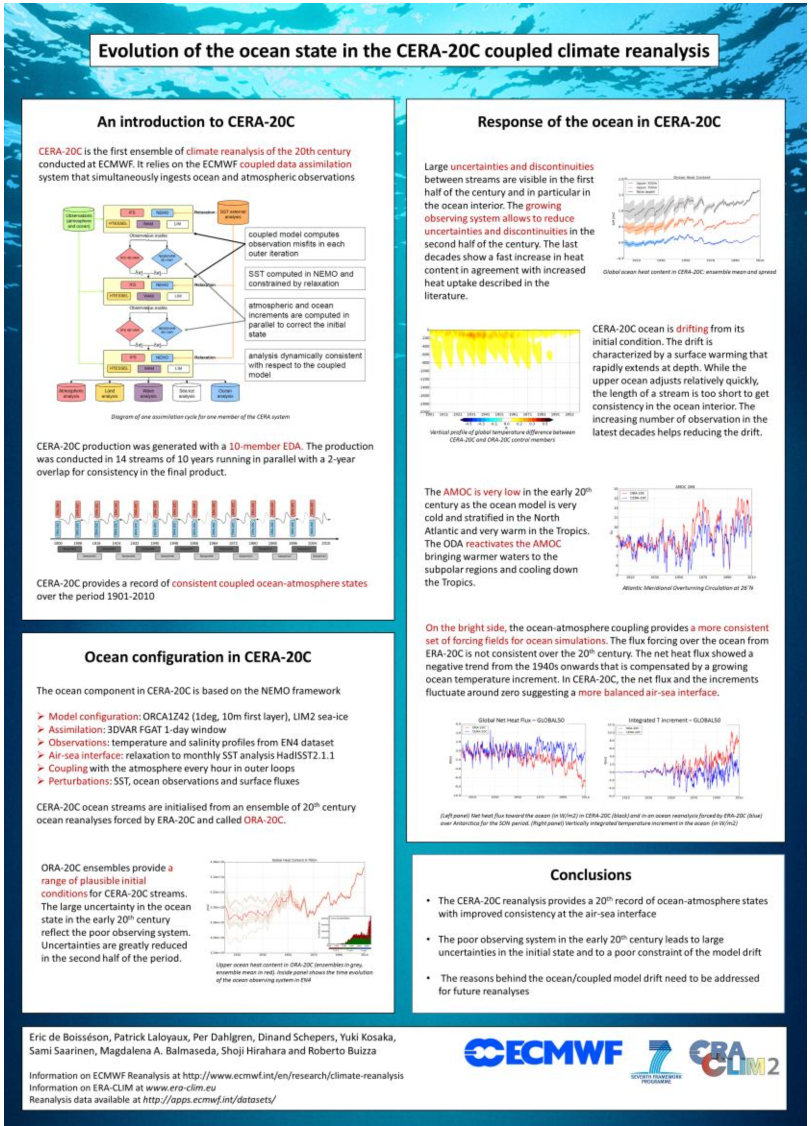
Coupled data assimilation is a relatively new field of research

- 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)

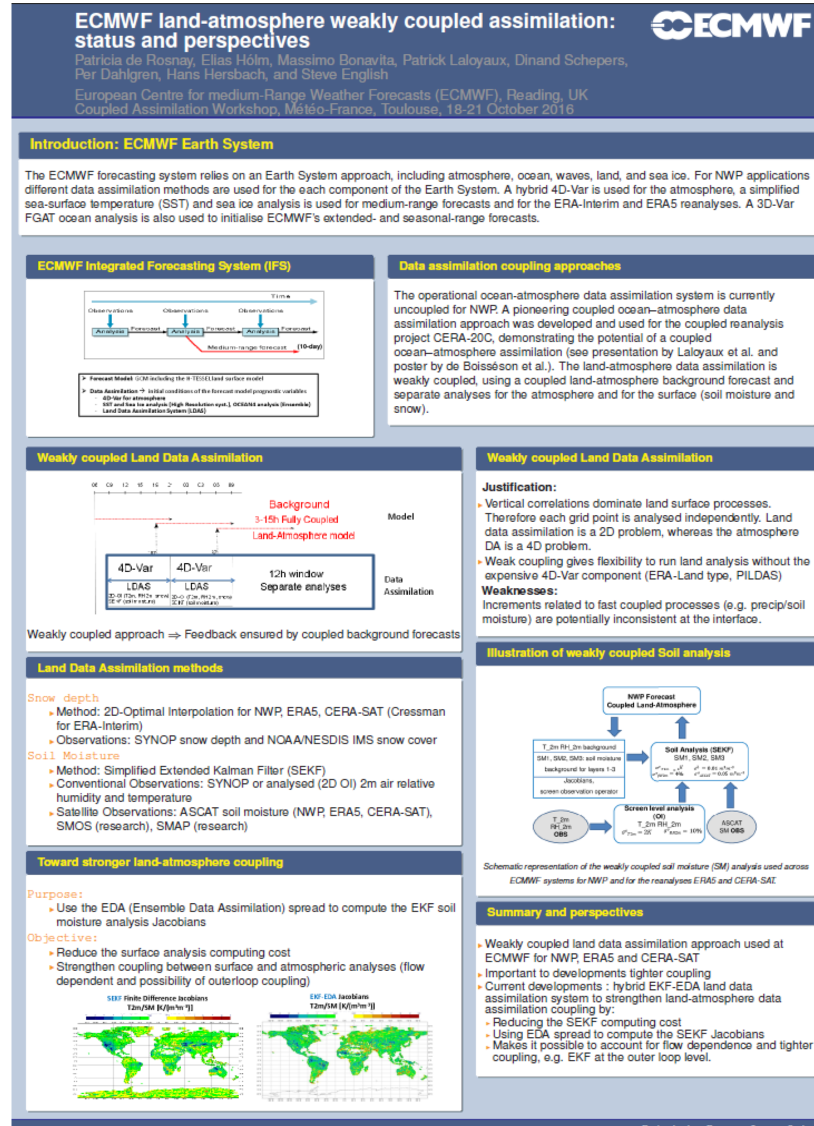
ECMWF Roadmap to 2025

“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.”

Posters



Eric de Boisseson (Ocean in CERA-20C)



Patricia de Rosnay (Land weakly couling)