The ECMWF coupled assimilation system for climate reanalysis

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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

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
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 modelling at ECMWF
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

- weakly coupled assimilation
- prescribed SST and sea ice
- 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**

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Loosely</td>
<td>Impact of an observation in multiple components</td>
</tr>
<tr>
<td>Roughly</td>
<td>Consistent analysis</td>
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<tr>
<td>Relatively</td>
<td>Coupled background error</td>
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<tr>
<td>Quasi</td>
<td>Coupled TL/ADJ</td>
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<tr>
<td>Firmly</td>
<td>Balanced analysis</td>
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<tr>
<td>Strongly</td>
<td>Cross-fluid localization</td>
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<tr>
<td>Entirely</td>
<td>Cross-domain covariance</td>
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<tr>
<td>Perfectly</td>
<td>Multiple components as a single coherent system</td>
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<tr>
<td>Fully</td>
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</table>

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

![Graphs showing MSLP forecast error versus the estimated core MSLP](image)

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

J. Bidlot et al.
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.

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

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

**Outer loop:** coupled model computes observation misfits

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

- SST computed in NEMO and constrained by relaxation
- Analysis dynamically consistent with respect to the coupled model

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

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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

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

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

CTRL   MEM1   MEM2   MEM3   MEM4   MEM5   MEM6   MEM7   MEM8   MEM9

→ 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.

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

Cross section of oz mass mix rat 19950703 1500 step 0 Expver 1195
Analysis increment due to GOME data using 12h 4D-Var (Exp 1195)

Large systematic increments (bias issues)
Locations seem ok

Cross section of temp 19950703 1500 step 0 Expver 1195
Analysis increment due to GOME data using 12h 4D-Var (Exp 1195)

Large increments in upper stratosphere (away from observations)
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)

![1 degree](image1)

![¼ degree](image2)

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 in ECMWF. It relies on the ECMWF Coupled 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 sessions of 10 hours 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: ORCA2124 (1deg. 16th first layer), LIM2 - assimilation: Tidal EM4 PI 3 day windows
- Observations: temperature and salinity profiles from EN4 dataset
- Assimilation: bi-monthly SST analysis HadISST 3.1
- Coupling with the atmosphere every hour in outer basins
- Parameterizations: SST, oceanic observations and surface fluxes

CERA-20C ocean reanalysis is initiated from an ensemble of 20th century ocean reanalyses forced by ERA-20C and called CERA-20C.

Conclusions

- The CERA-20C reanalysis provides a 20th century record of ocean-atmosphere states with improved consistency at the sea-air interface.
- The use of ensemble models leads to larger uncertainties at the initial state and a poor constraint of the model drift.
- The reason behind the ocean coupled model drift needs to be addressed for future reanalyses.

ECMWF land-atmosphere weakly coupled assimilation: status and perspectives

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 intermediate and ERA reanalyses. A 3D-Var approach for ocean analysis is also used to initialise ECMWF's extended- and seasonal-range forecasts.

Weekly coupled Land Data Assimilation

Weakly coupled approach to feedback ensured by coupled background forecasts

Land Data Assimilation methods

- Data assimilation: SDC (2D-Optimal Interpolation for NWP), ERA, GFS, GEPS, SAT (Grenson for ERA-Interim)
- Observations: SYNOP snow depth and NOAAMSOS IMS snow cover

Weaknesses

- Insufficient feedback of land data assimilation
- Underestimation of the impact of land data assimilation

Toward stronger land-atmosphere coupling

- Use the EDA (Ensemble Data Assimilation) scheme to compute the EKF soil moisture analysis Jacobian.
- Reduce the surface analysis computing cost
- Strengthen coupling between surface and atmospheric analyses (flow dependent and possible coupling of ocean models).

ECMWF Integrated Forecasting System (IFS)

The operational ocean-atmosphere data assimilation system is currently unconnected for NWP. A “plowing” coupled ocean-atmosphere data assimilation approach was developed and for the coupled reanalysis project CERA-20C, demonstrating the potential of a coupled ocean-atmosphere assimilation (see presentation by Lampare et al. at HPC-ERA-2014). The land-atmosphere data assimilation is weakly coupled, using a coupled land-atmosphere homogeneous treatment and separate analyses for the atmosphere and for the surface (soil moisture and snow).

ECMWF land-atmosphere weakly coupled assimilation: status and perspectives

Participants

- Patricia de Rosnay (Land weakly coupling)
- Eric de Boisseson (Ocean in CERA-20C)