Coupled data assimilation development at ECMWF

Dick Dee

Coupled data assimilation – general issues

Specific context: Climate reanalysis

The ERA-CLIM and ERA-CLIM2 projects

CERA: a system for coupled reanalysis
Coupled data assimilation

Presentation by Michele Rienecker (WMO CAS 2010 Workshop): Good discussion of coupled DA, practical issues

Presentation by Keith Haines (ECMWF Seminar on DA for atmosphere and ocean, 2011): Review of coupled DA implementations and plans (Met Office, GFDL, JAMSTEC, BMRC, NCEP, Canada)

- Key challenge: Model errors can amplify in coupled systems
- Weak (loose) coupling: estimates produced by a coupled model, separate analyses for each component
- Strong (full) coupling: Coupled analysis updates
Weakly coupled data assimilation

- **Weak coupling:** background estimates produced by a coupled model, separate analysis updates for each component

- Weak coupling means that an observation in one model component cannot cause an analysis increment in the other components

- This prevents optimal use of observations related to fast processes (e.g. evaporation, convection, heat exchange)

- It also implies that the analysed model state may be inconsistent (unbalanced) at the interfaces
The IFS is a weakly coupled DA system

- The ECMWF forecast model has fully coupled components for atmosphere – land surface – waves
- Analyses are performed separately for each component
Strongly coupled data assimilation

**Strong coupling:** The analysis itself is coupled, so that any observation can affect analysis increments throughout the system.

Strong coupling requires coupled error covariance models

- *For a KF*, implementation is ‘trivial:’ the coupled model generates coupled background error covariances, used to update the state vector for the coupled model.
- *For 4D-Var*, augmenting the state vector is more complicated (the covariance model depends on the dynamical model).
- What about model errors??

Strong coupling requires a strong observational constraint
Is the MACC system strongly coupled?

- Based on the 4D-Var scheme of the IFS

- CO₂, CH₄ and aerosols are incorporated in the IFS
  Data assimilation has been developed for AIRS and IASI radiances, SCIAMACHY retrievals, MODIS aerosol optical depth, … GOSAT …

- IFS also carries O₃, CO, NO₂, SO₂ and HCHO
  Chemical production and loss come from the coupled CTM
  Data for assimilation come from GOME, GOME-2, IASI, MIPAS, MLS, MOPITT, OMI, SBUV/2, SCIAMACHY, …

- Chemistry modules are being built fully into IFS
Using trace gases to extract wind information

- Demonstrated from upper tropospheric humidity observations
  - by Thépaut (1992)

- An early motivation for assimilating lower stratospheric ozone data
  - proposed by Riishøjgaard (1996), investigated by Hólm (1999)
  - demonstrated by Semane et al. (2009) using MLS data
Impact of ozone data in 12h 4D-Var

GOME 15-layer profiles (~15,000 per day)
SBUV 6-layer profiles (~1,000 per day)
Ozone increments at 10S

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
Associated temperature increments at 10S

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)
A coupled ozone analysis is not (yet) practical

The stratosphere is not well constrained by observations:

- Ozone profile data generate large temperature increments
- 4D-Var adjusts the flow where it is least constrained, to improve the fit to observations

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

- Background errors uncorrelated with other variables
- Model adjoint modified to cut link with dynamic variables

In MACC, trace gas analyses have been similarly decoupled

Both models and observations must improve to allow full coupling
A brief history of reanalysis productions at ECMWF

Why reanalysis?

• Improving medium-range forecast skill
• Extending the forecast range: monthly and beyond
• Developing air-quality monitoring and forecasting
• Data sets for verification, diagnostics, and research
• *Services to society*: Science, climate monitoring

1979-1981 FGGE
1993-1996 ERA-15
1998-2003 ERA-40
2006 ERA-Interim
2006 ORAS3
2010 ORAS4
2012 El/Land
2008-9 GEMS
2010-11 MACC
Climate reanalysis: Two types of products

Reanalyses of the modern observing period (~30-50 years):

- Produce the best state estimate at any given time
- Use as many observations as possible, including from satellites
- Closely tied to forecast system development (NWP and seasonal)
- Near-real time product updates

Extended climate reanalyses (~100-200 years):

- Long perspective needed to assess current changes
- As far back as the instrumental record allows
- Focus on low-frequency variability and trends
- Use only a restricted set of observations
The ERA-CLIM project (2011-2013)

An EU-funded research collaboration with 9 global partners

**Goal:** Preparing input observations, model data, and data assimilation systems for a global atmospheric reanalysis of the 20th century

- Data rescue and digitisation
- Incremental development of new reanalysis products
- Use of reanalysis feedback to improve the data record
- Access to reanalysis data and input observations
### ERA-CLIM reanalysis products

**20th-century atmospheric reanalysis (1900-2010)**

10 complete datasets based on different SST/sea-ice evolutions

125km global resolution, 91 vertical levels

<table>
<thead>
<tr>
<th>ERA-20CM</th>
<th>Atmospheric model integration</th>
<th>IFS Cy38r2 + CMIP5 data HadISST v2.1</th>
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</thead>
<tbody>
<tr>
<td>ERA-20C</td>
<td>Assimilation of surface weather observations (ps, wind)</td>
<td>ICOADS v2.5.1 ISPD v3.2.6 (incl. ERA-CLIM)</td>
</tr>
<tr>
<td>ERA-20CL</td>
<td>High-resolution land surface (25km global)</td>
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</tbody>
</table>

*Final ERA-20C/M/L datasets (~1Pb) will be available by spring 2014*

[http://apps.ecmwf.int/datasets](http://apps.ecmwf.int/datasets)
ERA-20CM: Ensemble of model integrations

Annual-mean temperatures averaged over all CRUTEM4 grid boxes in extratropical northern hemisphere

- ERA-20CM (ensemble mean)
- CRUTEM4

Hersbach et al, 2013, ERA Report
ORAS4: Changes in ocean heat content

Balmaseda et al, GRL 2013
Need for a coupled atmosphere-ocean reanalysis

- Representation of large-scale coupled modes (e.g. MJO)
- Consistent surface fluxes, mass and energy budgets
- Improving the use of near-surface observations
- Enhancing SST variability as provided by observations

(N. Rayner, Met Office Hadley Centre)
Enhancing SST variability

SST global products contain information only on monthly time scales
The ERA-CLIM2 project (2014-2016)

Production of a consistent 20th-century reanalysis for all components of the earth system: atmosphere, land surface, ocean, sea-ice, and the carbon cycle

- Production of a coupled 20C atmosphere-ocean reanalysis
- Research and development in coupled data assimilation
- Earth system observations for extended climate reanalysis
- Quantifying and reducing uncertainties
Topics in coupled DA development

- Key challenge is to constrain model drift at the interface
- Initially use HadISST global products to constrain monthly mean SST
- Develop ability to analyse SST observations in the coupled system
- Research on sea-ice modelling and assimilation
- Development of a consistent 20C carbon reanalysis
Coupled DA development in the IFS

A first prototype for coupled reanalysis (CERA) has been implemented in the IFS:

- Patrick Laloyaux: Coupling the IFS with NEMO
- Eric de Boisseson: Introducing the SST constraint

- IFS coupled with NEMO ocean model in 4D-Var outer loop
- External SST/SIC product to constrain model bias
- NEMOVAR in inner loop
Coupled data assimilation system [CERA project]

Configuration:
Atmosphere: IFS 38R1 T159L91
Ocean: NEMO V3.4 ORCA1 and 42 levels
1-hour coupling in a single executable environment

Assimilation:
A common 24-hour window
SST nudging (currently) not activated
Computation of only one ocean increment

Experiments:
January and February 2005
August and September 2010
Year 2012
→ Average speed 25d/d
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Technical challenges during the implementation

Synchronize the ocean and atmospheric data flows

Initially:
- IFS uses a 24-hour window starting at 21:00
- NEMO uses a 10-day window starting at 00:00

Finally:
- A common 24-hour window starting at 21:00
  (NEMO code has been updated)
- Production of coupled short and long forecasts
- A proper archiving system for ocean forecasts
Coupled experiments: SST bias for September 2010

Free coupled model

Experiments run in August and September 2010
Bias computed with respect to NCEP RTG SST
SST nudging not activated

- Cold SST bias in northern Pacific and Atlantic
- Large cold tongue bias

Atmospheric coupled assimilation

- The atmospheric DA reduces consistently the SST biases

Atmospheric and ocean coupled assimilation

- Adding the ocean DA further reduces the SST biases
Impact of the ocean assimilation in the atmosphere

Atmospheric and ocean coupled assimilation vs Atmospheric coupled assimilation

Atmospheric departure vector (analysis and conventional temperature observations)

RMSE of temperature coupled forecast @925hPa (with respect to operational analysis)
Summary

• We are developing a coupled atmosphere-ocean DA framework for climate reanalysis (CERA) in the IFS

• A fully coupled model is used in the outer loops; the linearized analysis updates are separate; the final analysis is a coupled model trajectory

• An external SST product will be used to constrain model drift on monthly timescales (*presentation after the break*)

• Plans are to start a first coupled 20C reanalysis late next year with a baseline version of the CERA system

• DA research in the ERA-CLIM2 project is targeted to improve the CERA system for future reanalyses