Reanalysis activities at ECMWF

Patrick Laloyaux - Earth System Assimilation Section

Acknowledgement: Paul Poli, Hans Hersbach, Dick Dee, Adrian Simmons, Magdalena Balmaseda, Hao Zuo, Gianpaolo Balsamo, Massimo Bonavita, Jean-Noël Thépaut.

ECMWF

Outlines

Introduction to reanalysis activities

Atmosphere: from ERA-Interim to ERA5

Surface: ERA-Interim/Land

Ocean: from ORAS4 to ORAS5

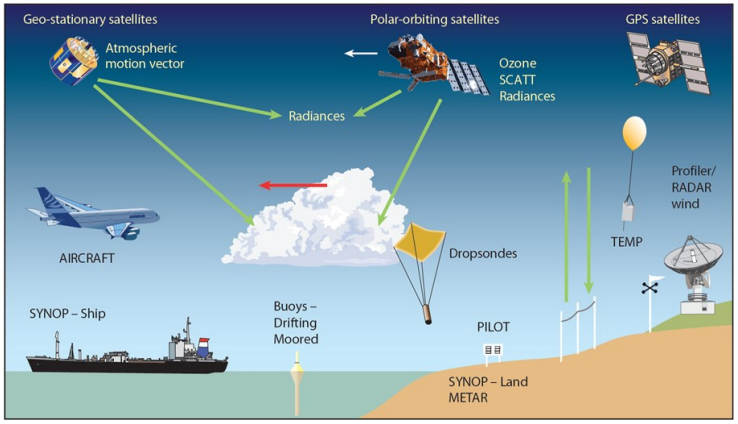
Coupled atmosphere-ocean reanalysis

Last operational upgrade

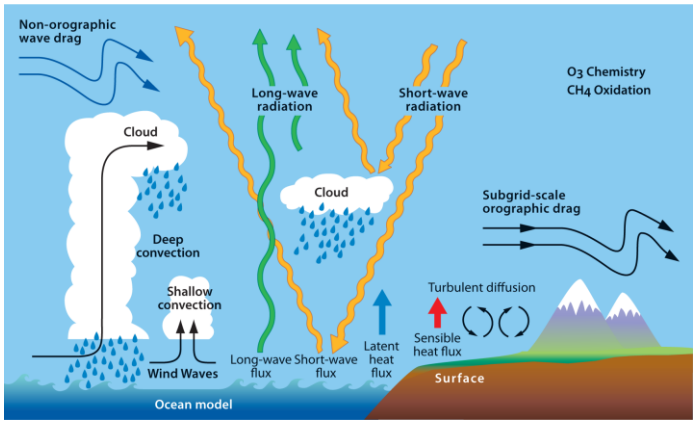
Numerical weather prediction at ECMWF

Provide global weather forecasts to member states since 1975

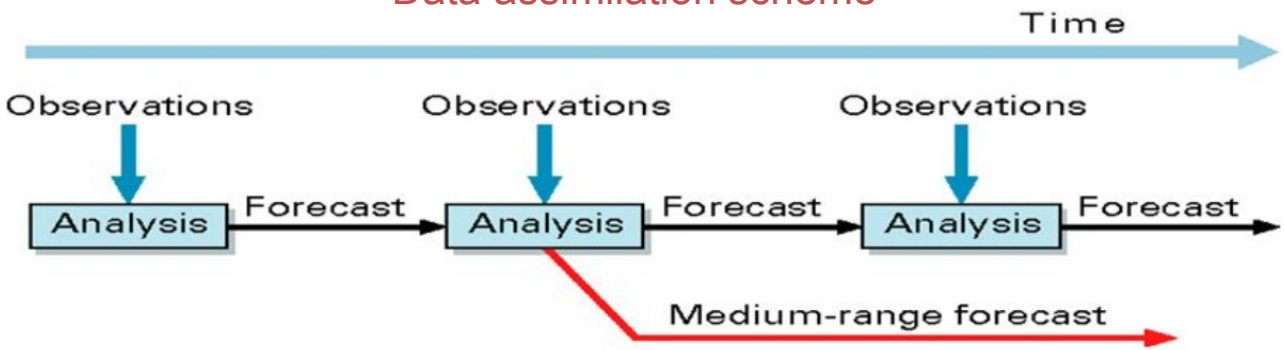
Model (atmosphere, ocean, wave, land)



Observations



Data assimilation scheme



Observations are ingested by the model to generate an initial condition (analysis) for the weather forecast

From weather analysis to climate reanalysis

ECMWF provides climate reanalyses for atmosphere, surface and ocean

- use an invariant version of its data assimilation system and forecast model
- assimilate selected/reprocessed observation datasets
- run over a long time period

Reanalyses produce reconstruction of the past climate/weather

- compute estimate for all the model outputs and prognostic variables at any given time
- ensure consistency in horizontal/vertical dimensions and across geophysical variables

Key aspects that require particular attention in reanalysis

- external forcing fields for the forecast model
- biases in the model and observations
- changes in the observing system
- specification of background and observation errors

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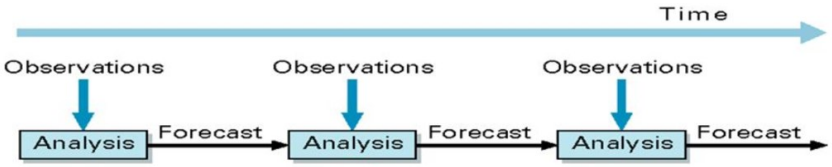
Atmospheric reanalysis: ERA-Interim



prior state constraints prior parameter constraints

$$J(\mathbf{x},\boldsymbol{\beta}) = (\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1}(\mathbf{x}_b - \mathbf{x}) + (\boldsymbol{\beta}_b - \boldsymbol{\beta})^T \mathbf{B}_\beta^{-1}(\boldsymbol{\beta}_b - \boldsymbol{\beta}) + [\mathbf{y} - \mathbf{b}_o(\mathbf{x},\boldsymbol{\beta}) - \mathbf{h}(\mathbf{x})]^T \mathbf{R}^{-1}[\mathbf{y} - \mathbf{b}_o(\mathbf{x},\boldsymbol{\beta}) - \mathbf{h}(\mathbf{x})]$$

observational constraints

ERA-INTERIM

MODEL: IFS (CY31R2, Dec 2006)
OBSERVATIONS: Conventional & Satellite
ASSIMILATION: Deterministic 4D-VAR
RESOLUTION: 80km (T255L60)
PERIOD: 1979-present

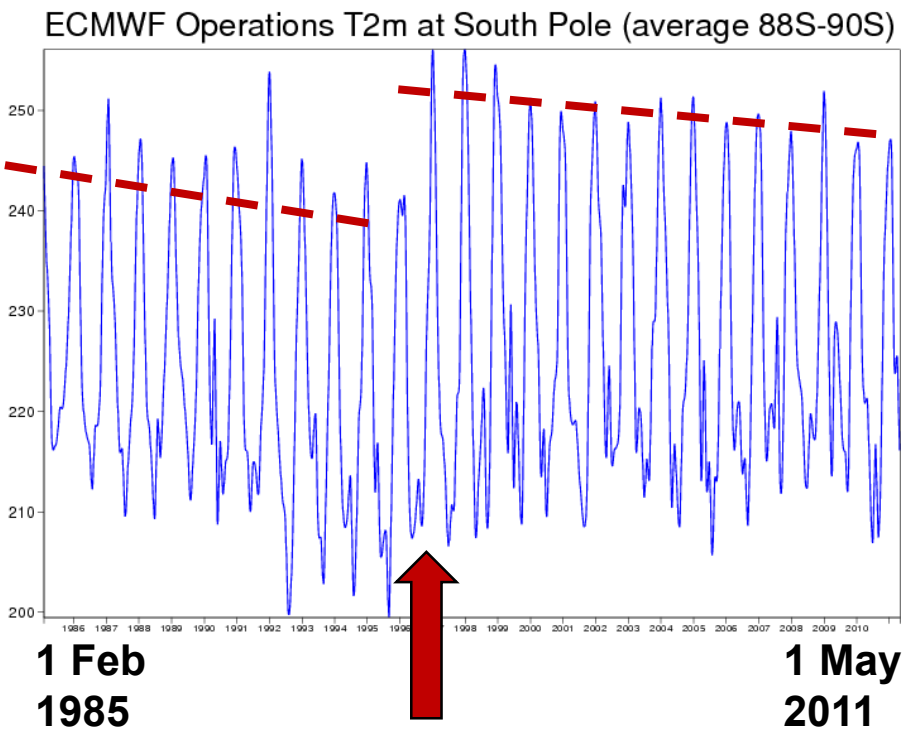
For each 12-hour assimilation window, conventional and satellite observations are assimilated with a 4D-Var method to compute an atmospheric analysis

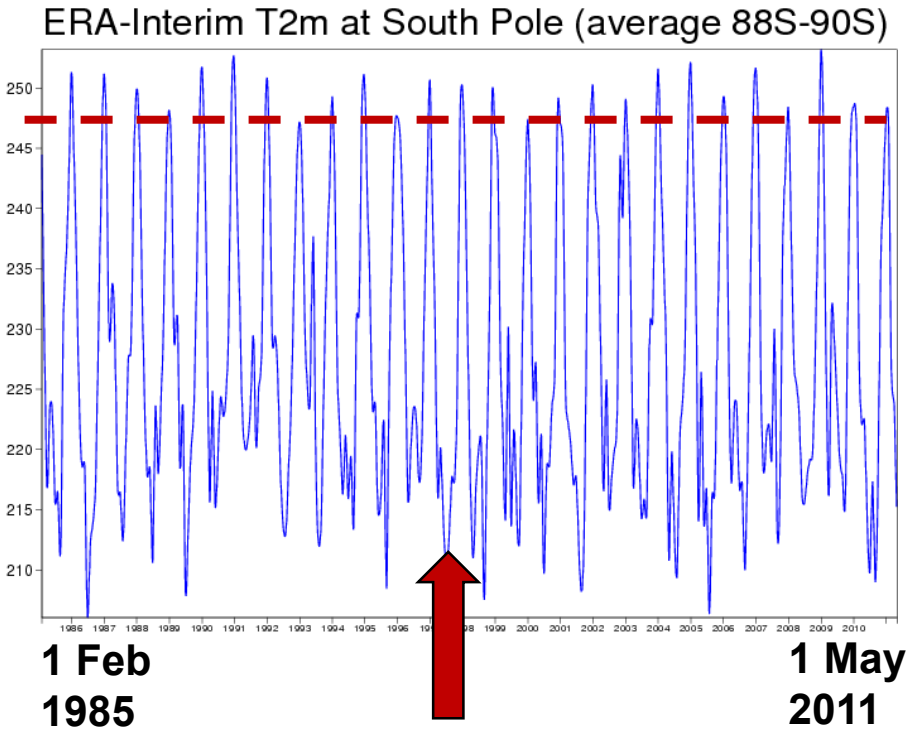
Bias corrections of satellite observations is computed in the 4D-Var method

ERA-Interim products are updated once per month, with a delay of two months to allow for quality assurance and for correcting technical problems with the production

Why not use simply operational NWP analysis?

The models and data assimilation methods have improved a lot over time, so analysis timeseries feature spurious changes.





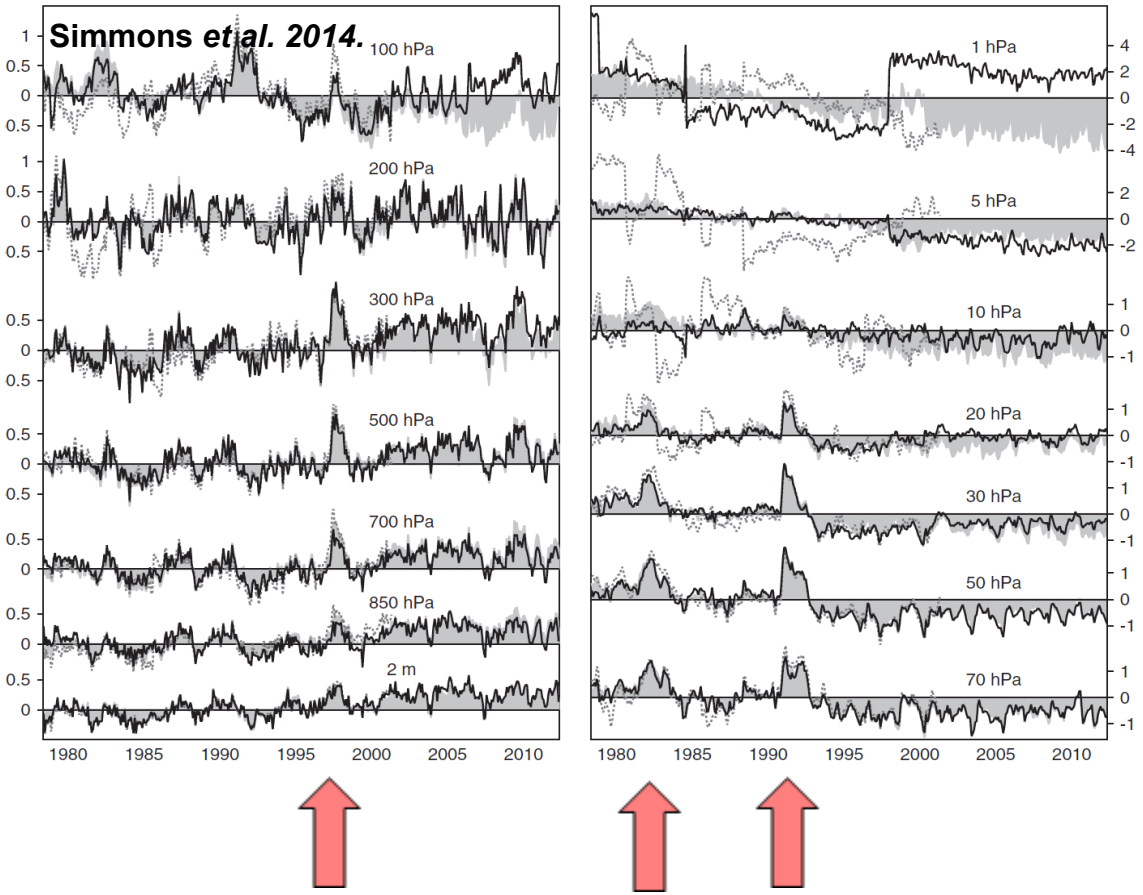
Was there a sudden change in South Pole summer variability in 1997?

No.

To remove these spurious sources of variability, model and data assimilation systems are frozen and rerun to produce a reanalysis dataset

Reanalysis supports climate studies

Solid line: ERA-Interim temperature anomalies relative to 1979–2001 (monthly and globally averaged)



Net warming at tropospheric levels up to 300 hPa (1997/1998 El-Niño event)

Short-term warning in the stratosphere (El Chichon and Pinatubo events)

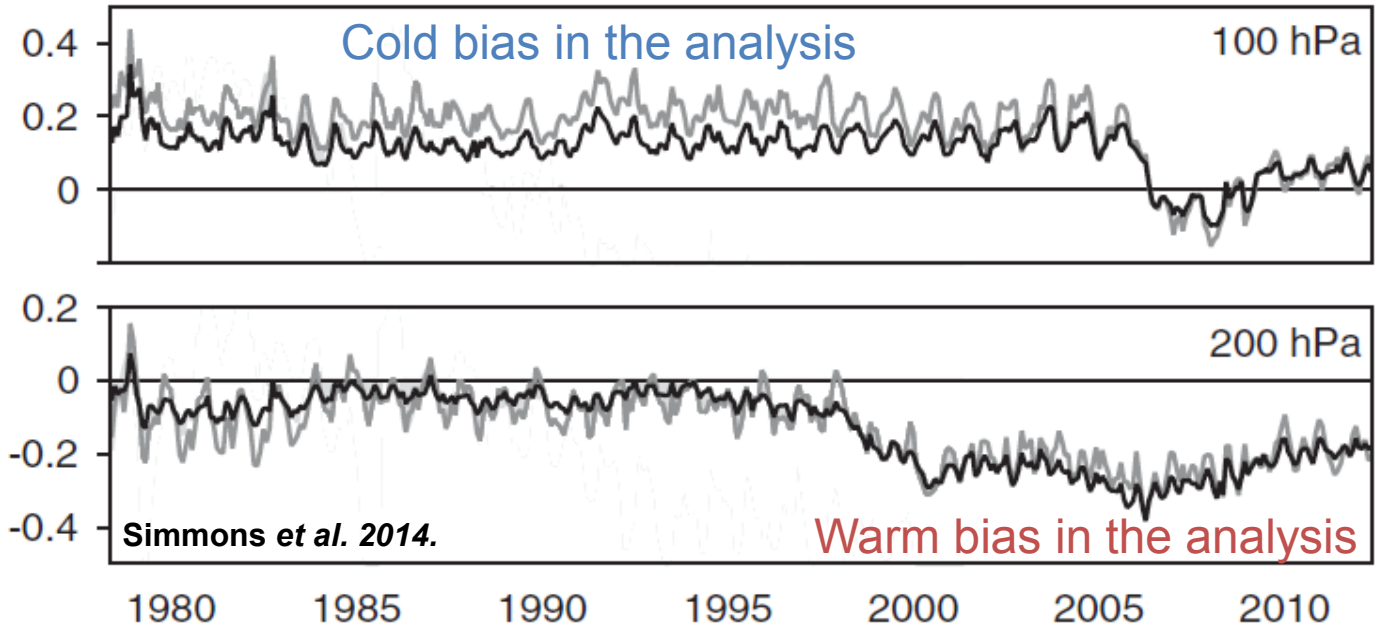
Issue at 1hPa due to observing system changes (SSU from NOAA-7, SSU from NOAA-9 and AMSUA from NOAA-15)

Observing system changes can cause spurious climate signals

A major challenge for reanalysis therefore is to smoothly handle data events and bias changes, to minimise their effect on the representation of trends and variability

Reanalysis to detect model and observation biases

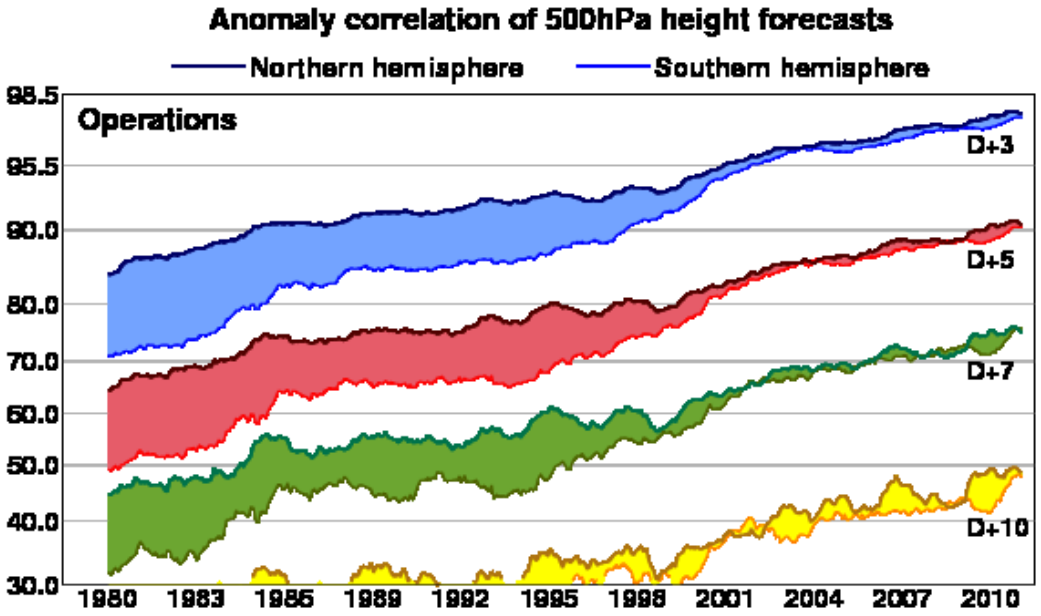
ERA-Interim **observation-minus-analysis** (black lines) and **observation-minus-background** (grey lines) differences for radiosonde temperatures (K)



100hPa: before 2006, cold bias in the analysis relative to the assimilated radiosondes. Assimilation of GPSRO data from late 2006 onwards brings the analysis into much closer agreement with radiosondes

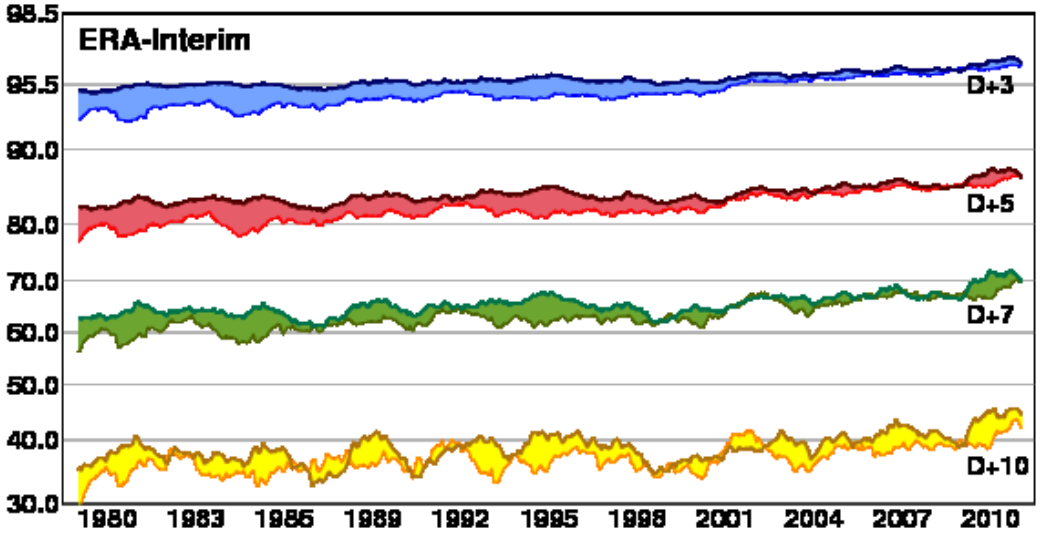
200hPa: in the late 1990s, warm bias in the analysis relative to the assimilated radiosondes. This is associated with the assimilation of an increasing amounts of temperature data from commercial aircrafts (warm-biased)

Reanalysis supports NWP development and evaluation



Rate of improvements in operations:

- model
- data assimilation
- observing system



Rate of improvement in reanalysis:

- observing system

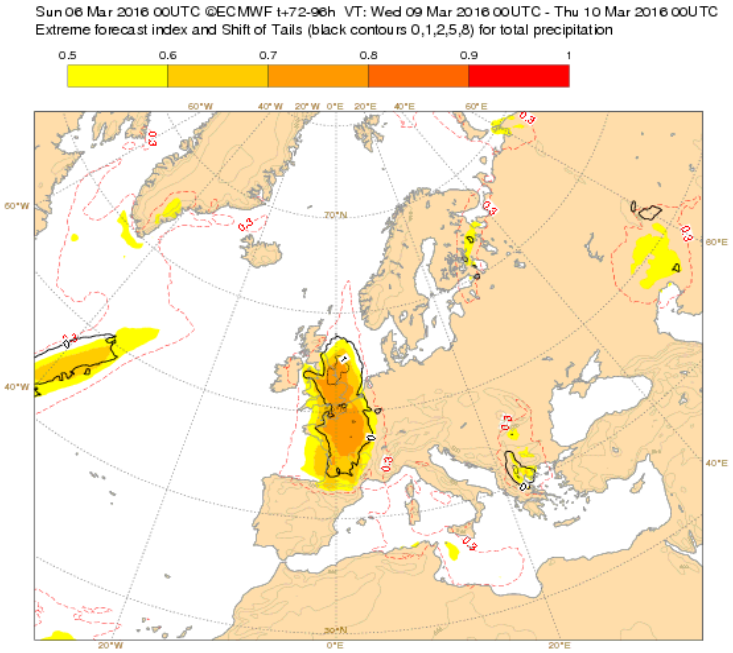
The comparison shows that most of the improvements in operational forecasts comes from a better model and data assimilation system

These improvements benefits from better observations

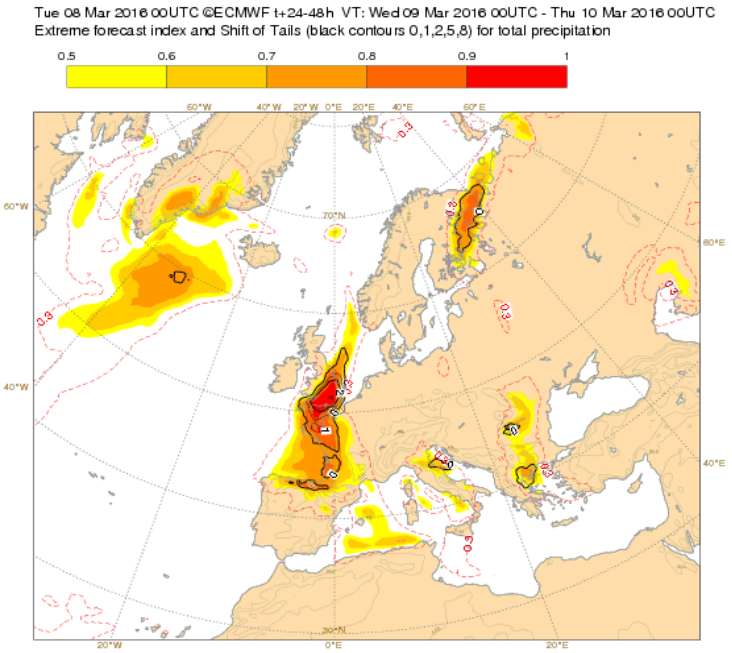
Reanalysis supports the computation of operational products

Extreme Forecast Index (EFI) detects extreme events in the ensemble forecast

Difference between the ensemble forecast distribution and a reference (M-climate)
- reference distribution is an ensemble of reforecast for the most recent 20 years
- initial conditions taken from ERA-Interim



EFI for precipitation for 09/03/16 (issued on 06/03/16, warning 3-days in advance)



EFI for precipitation for 09/03/16 (issued on 08/03/16, warning 1-days in advance)

Next generation of atmospheric reanalysis: ERA5

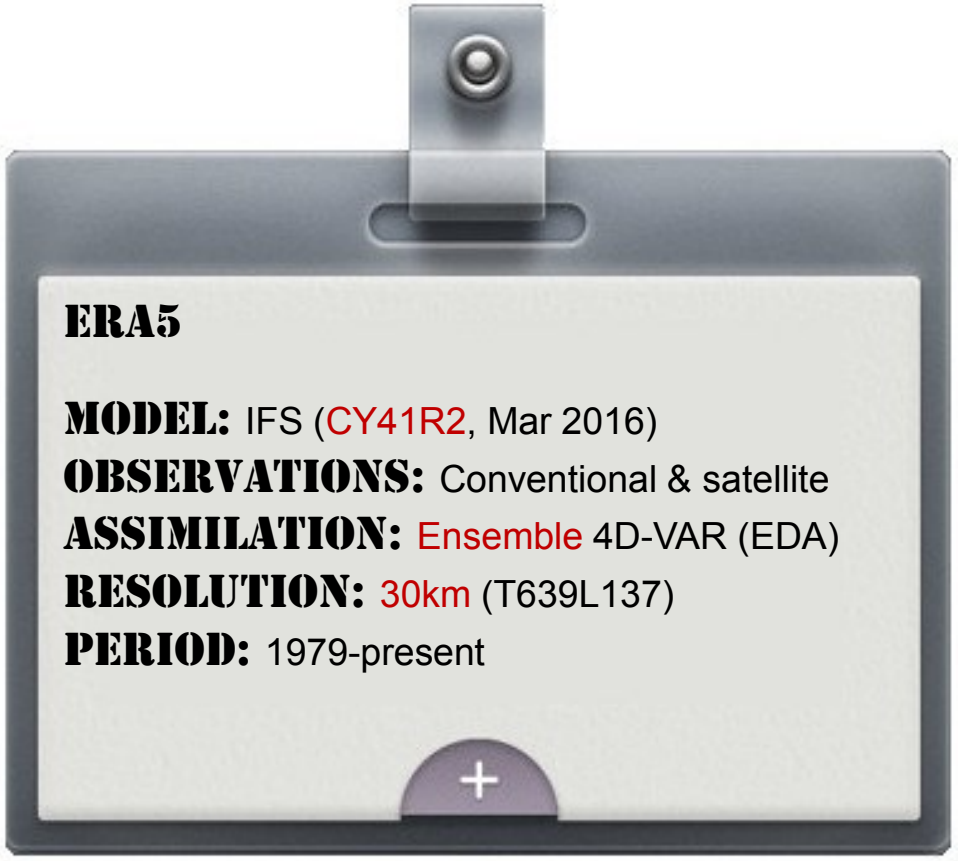
Reanalysis is worth repeating as all ingredients continue to evolve

- model, data assimilation, observation reprocessing
- with each new reanalysis, understanding of model/observations biases is improved

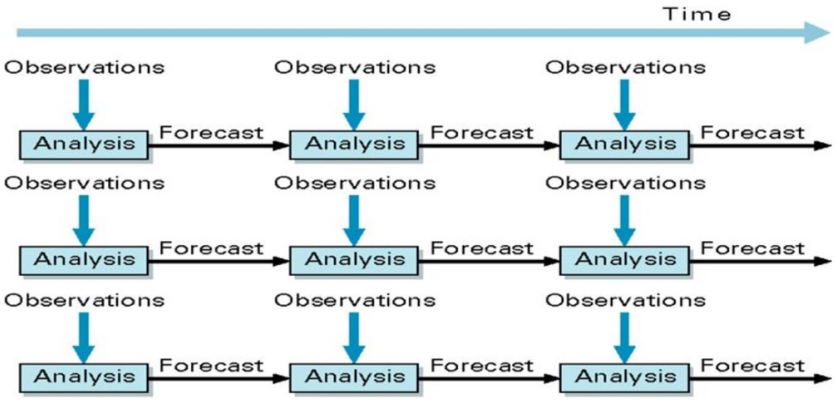
ERA-5 takes on board 10 years of research and development in NWP model and data assimilation methods:

- EDA technique
- surface analysis (SEKF)
- improved bias correction
- improved model physics
- higher resolution,…

Improved observations: **34** observation data records either reprocessed or updated



Ensemble Data Assimilation (EDA)

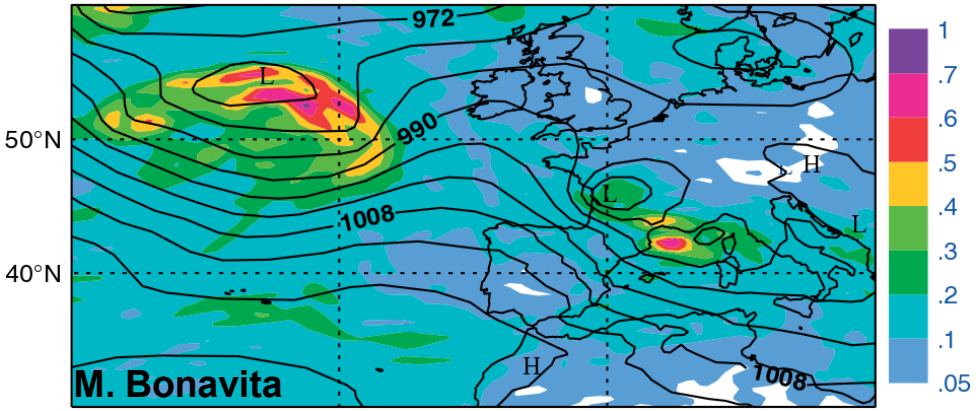


Data assimilation with perturbations in:

- observations
- sea-surface temperature
- model physics tendencies

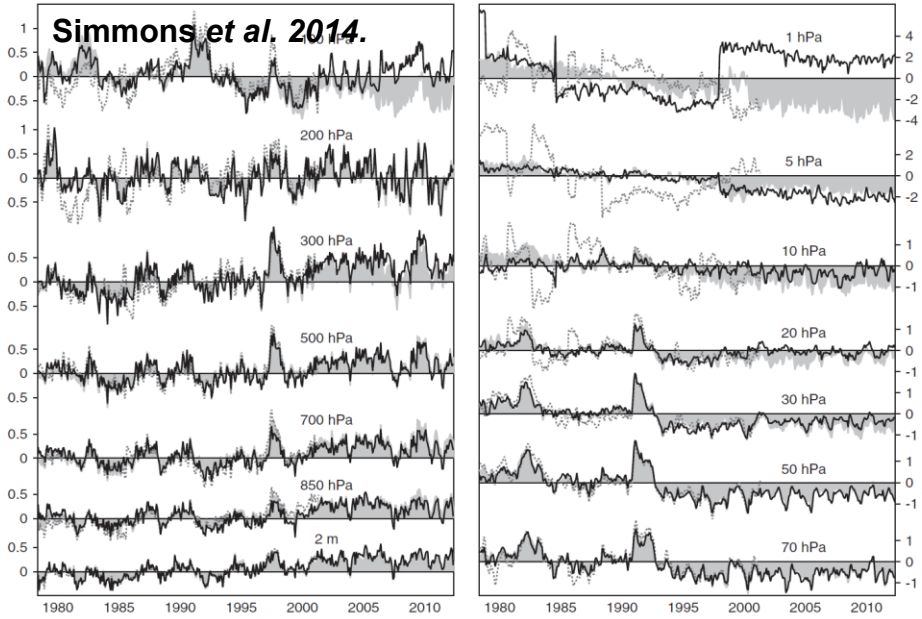
Differences between the forecasts provide background error estimations (flow dependent variances/correlations)

Variance of vorticity near the surface from EDA(24 Jan 2009 at 0900 UTC)

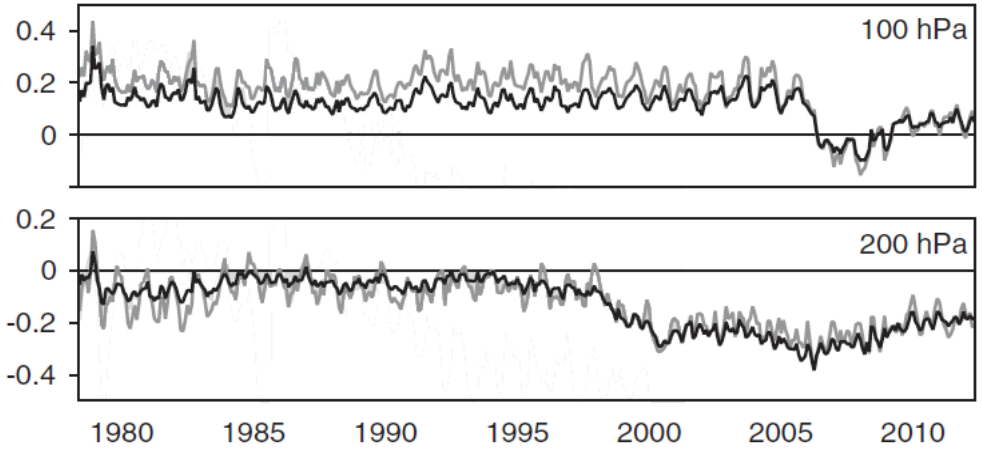


Larger variance of vorticity associated with the extratropical storm event is well captured by the EDA

Improved bias correction



At 1hPa, bias correction will be implemented to have a smooth transition between the instruments (SSU from NOAA-7, SSU from NOAA-9 and AMSUA from NOAA-15)

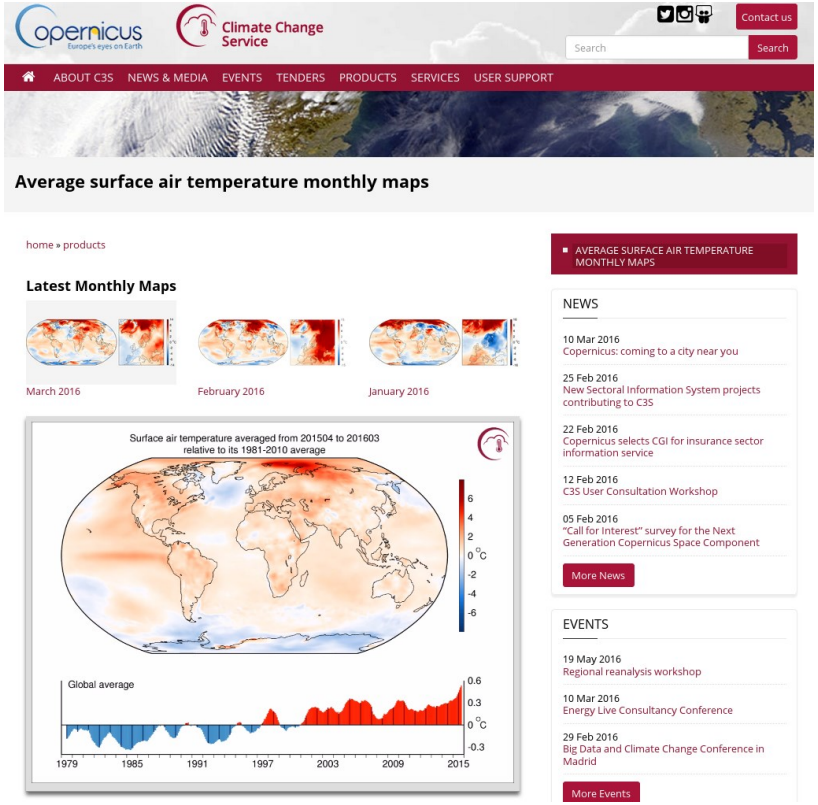


Aircraft data will be bias corrected to avoid the warm bias at 200hPa

ERA5 produced by Copernicus Climate Change Service (C3S)

Copernicus is the European Union's earth observation programme

http://climate.copernicus.eu/



The Copernicus Climate Change service is under implementation with ERA5 reanalysis.

The service will provide access to
- climate indicators (temperature increase, sea level rise,…)
- climate indices (based on records of temperature, precipitation, drought event,…)

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Atmosphere: from ERA-Interim to ERA5

Surface: ERA-Interim/Land

Ocean: from ORAS4 to ORAS5

Coupled atmosphere-ocean reanalysis

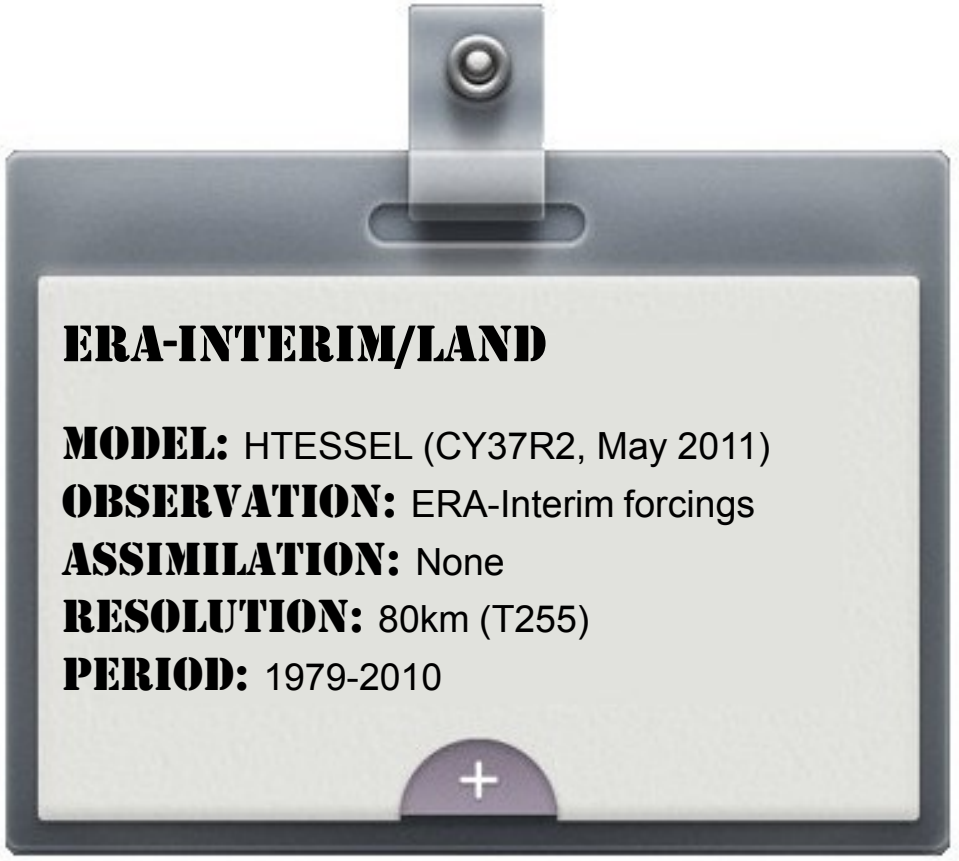
Last operational upgrade

Surface reanalysis: ERA-Interim/Land

In ERA-Interim: the IFS model uses the TESSEL scheme (Tiled ECMWF Scheme for Surface Exchanges over Land) and computes the analysis of surface parameters over land and ocean using the LDAS system (CY31R2, Dec 2006)

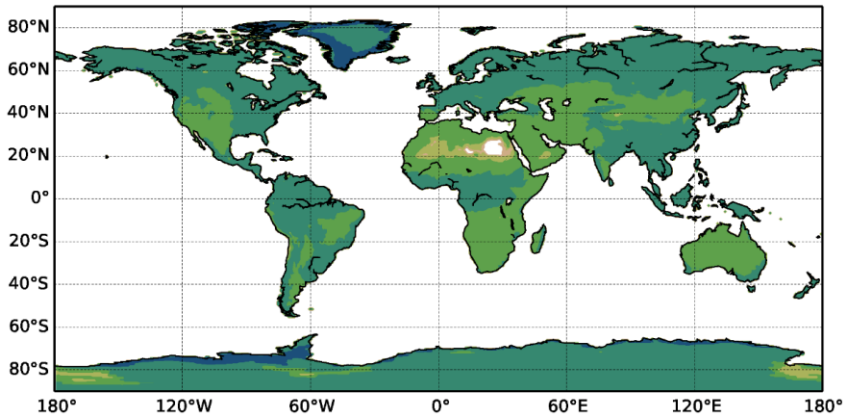
In ERA-Interim/Land: the HTESSEL land surface model (Hydrology) is forced by atmospheric fields from ERA-Interim

HTESSEL benefits from
- an improved soil hydrology
- a new snow scheme
- a revised bare soil evaporation

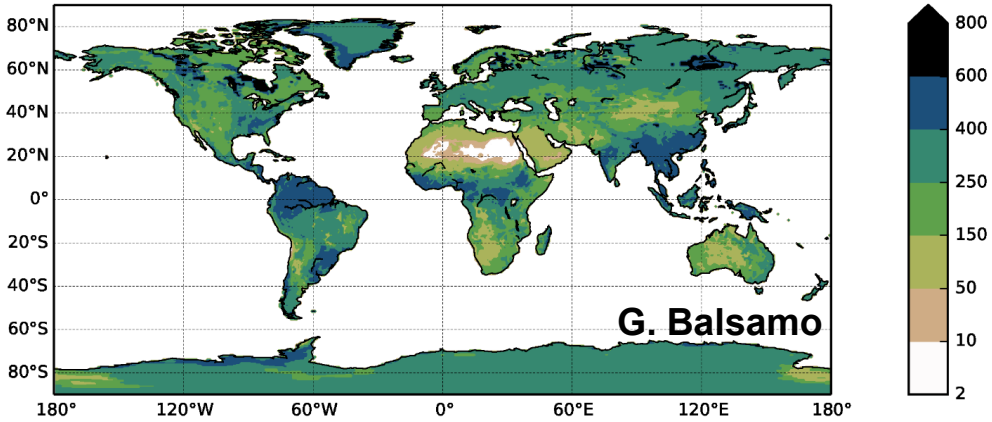


Surface reanalysis: ERA-Interim/Land

Top 1m soil moisture in ERA-Interim
July mean (1979-2010)



Top 1m soil moisture in ERA-Interim/Land
July mean (1979-2010)



ERA-Interim/Land shows more spatial variability than ERA-Interim thanks to

- spatial variability of soil properties (coarse, fine, organic, loamy,…)
- reformulation of the bare soil evaporation

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Ocean reanalysis: ORAS4

ECMWF produces daily an ocean real time analysis (ORTA4)

- provide initial conditions for the coupled atmosphere-ocean forecasts

ECMWF produces an ocean reanalysis (ORAS4) with a few days delay

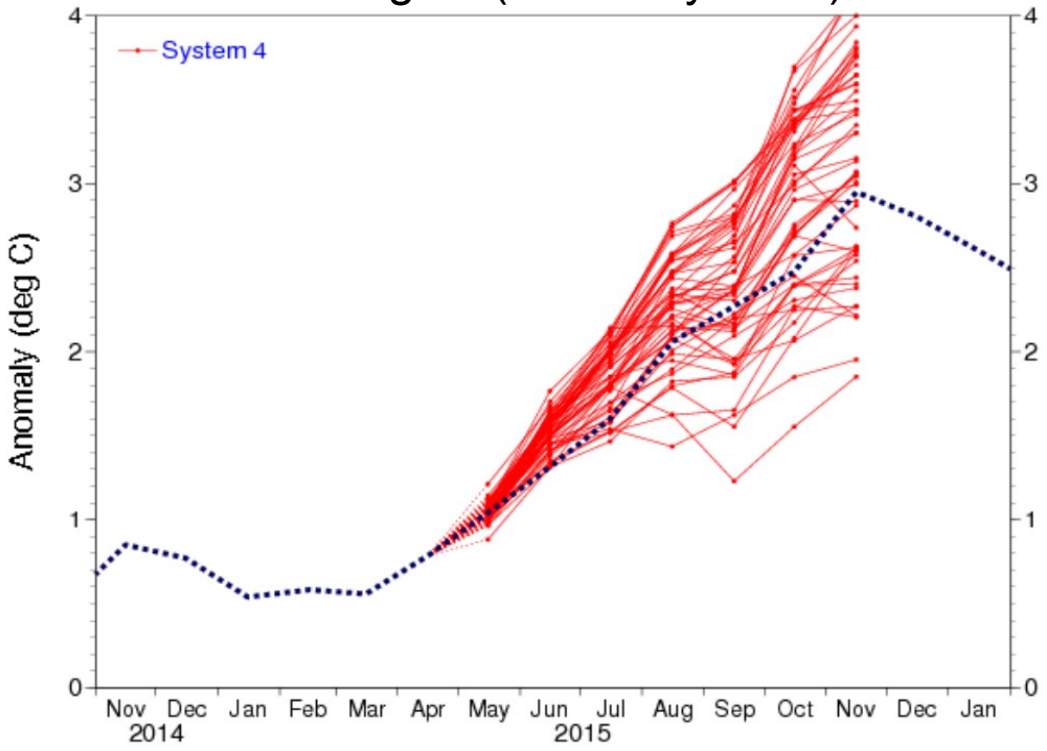
- valuable resources for climate monitoring, climate variability studies
- provide initial conditions for the calibration of the coupled forecasts

Calibration of the coupled forecasts (El Niño)

For the seasonal forecasts, model outputs are corrected to reduce systematic errors:

- produce a series of seasonal hindcasts (using ORAS4 and ERA-Interim, 1981-2010)
- compute the mean bias in the model (difference between hindcasts and observations)
- calibrate the forecasts removing the model bias

SST anomalies in the seasonal ensemble forecasts for the Nino3.4 region (from May 2015)

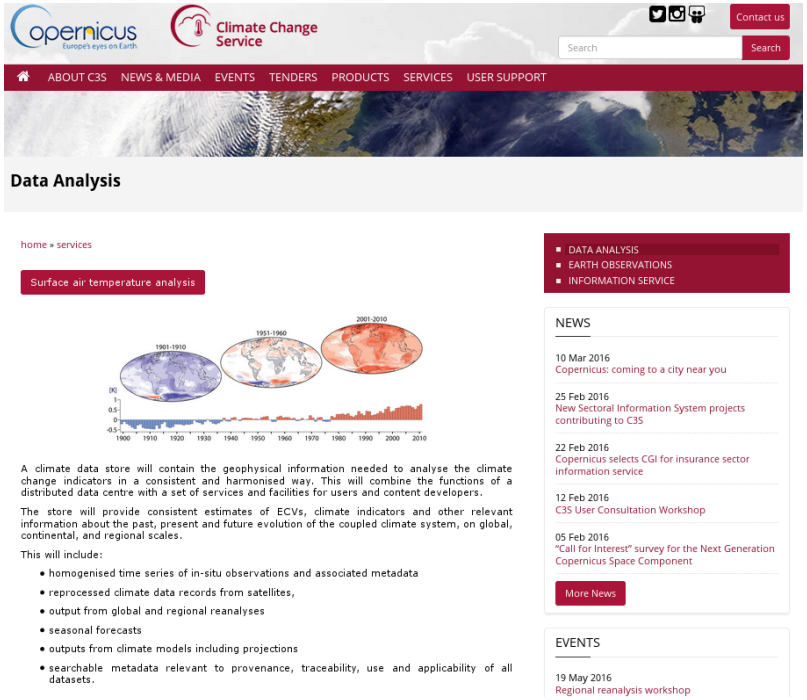


Next generation of ocean reanalysis: ORAS5

ORAS5

MODEL: NEMO (V3.4) + LIM2
OBSERVATION: Conventional & satellite
ASSIMILATION: 3D-Var NEMOVAR (V3.4)
ENSEMBLE: 5 members (new perturbations)
RESOLUTION: 25km (ORCA025Z75)
PERIOD: 1979-present

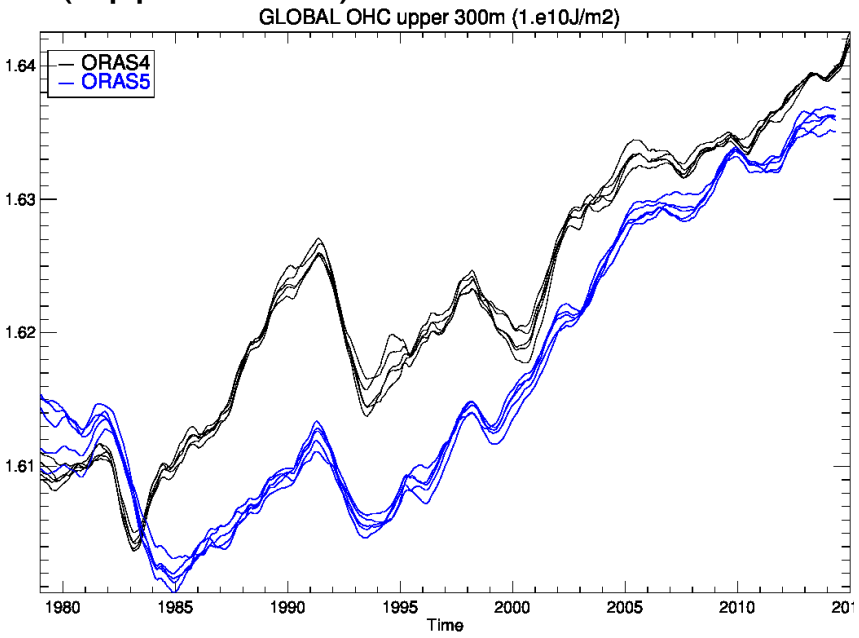
Contribution to the multi-model seasonal forecast products of C3S



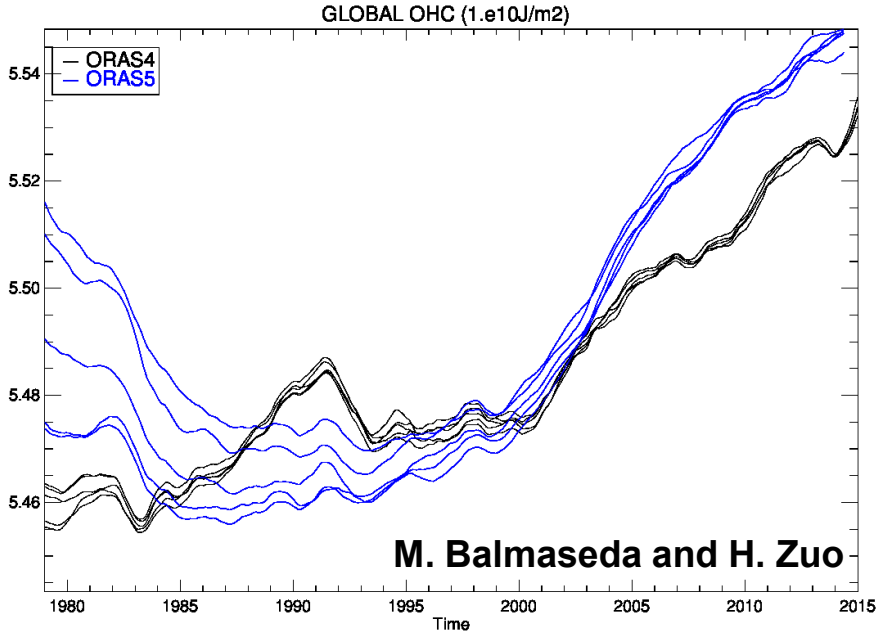
http://climate.copernicus.eu/

Evaluation of ORAS5

Heat content in **ORAS4** and **ORAS5** (Upper 300m)



Heat content in **ORAS4** and **ORAS5** (Total Column)



ORAS5 shows more heat uptake by deep ocean than ORAS4
Some differences in interannual/decadal variability (to be investigated)

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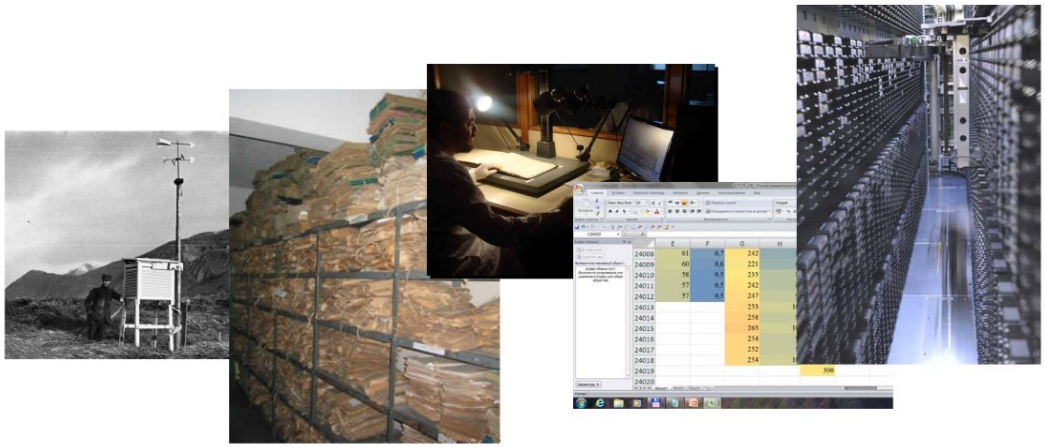
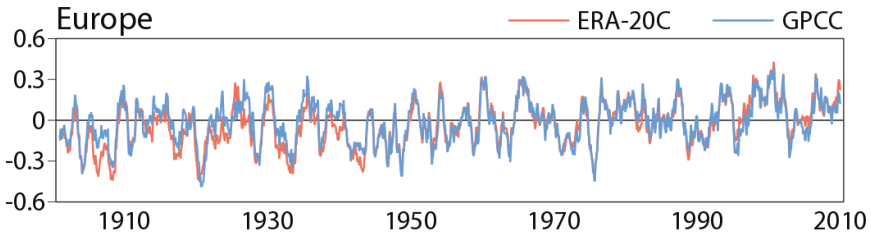
ERA-CLIM and extended climate reanalyses



Data rescue activities:

- inventory past measurements
- produce high resolution image
- digitalize
- reformat to ASCII files
- import to our MARS system

Precipitation anomaly averaged over Europe in mm/day relative to 1961-1990)

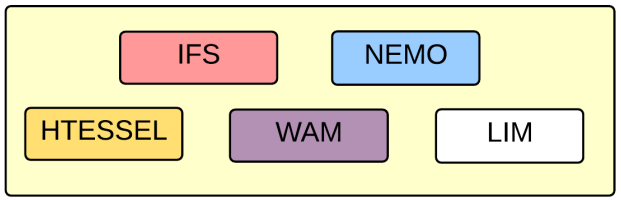


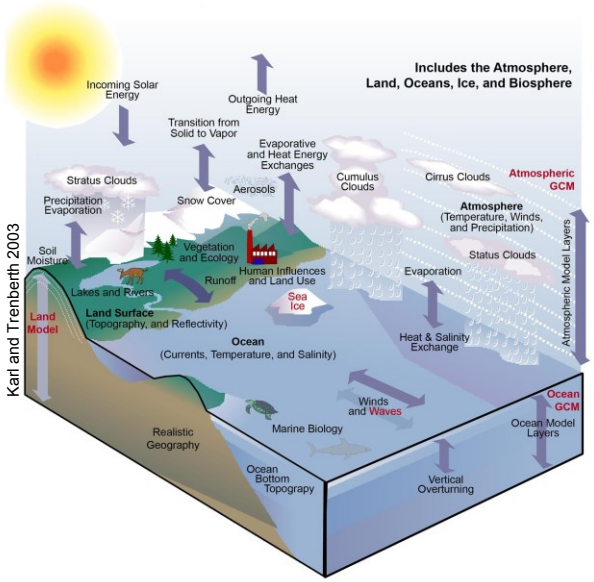
ERA-20C

MODEL: IFS (CY38R1, Jun 2012)
OBSERVATION: Surface conventional
ASSIMILATION: 4D-VAR (varying background error)
RESOLUTION: 125km (T159L91)
PERIOD: 1900-2010

Extended climate reanalyses for the coupled earth model

ECMWF coupled Earth model for medium-range weather forecasting





CERA-20C

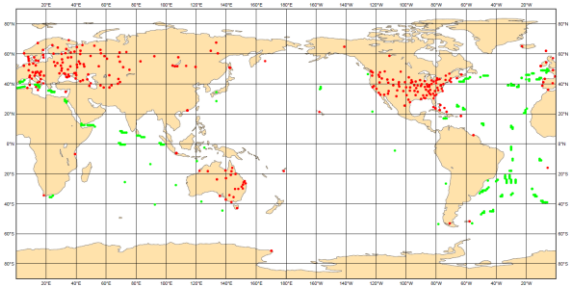
MODEL: IFS-NEMO (CY41R2, Mar 2016)
OBSERVATION: Surface and subsurface conventional
ASSIMILATION: Coupled EDA (CERA)
RESOLUTION: 125km (T159L137-ORCA1Z42)
PERIOD: 1901-2010

New coupled assimilation system (CERA) for the coupled Earth model:

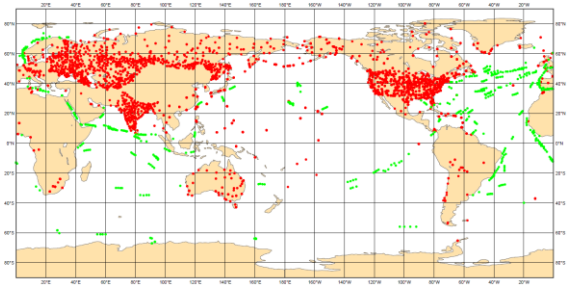
- atmospheric and ocean observations assimilated simultaneously
- ocean observations can impact atmospheric estimate and conversely
- CERA-20C reanalysis in production (1901-2010)

Observations assimilated in CERA-20C

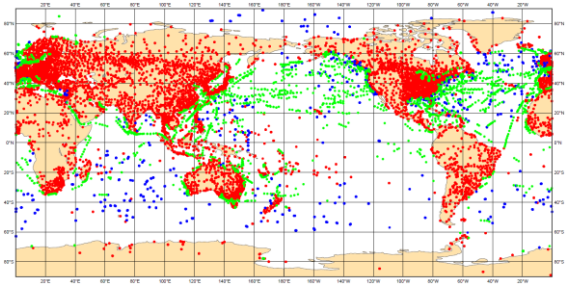
Surface pressure observations (observations per day) Stations Ships Buoys



1900

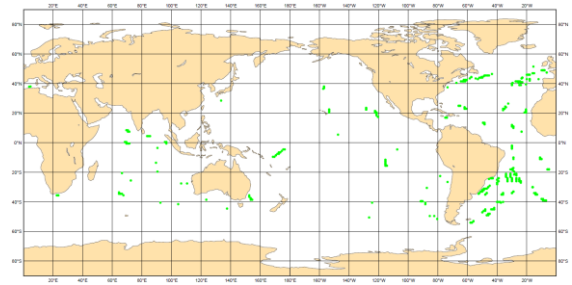


1950

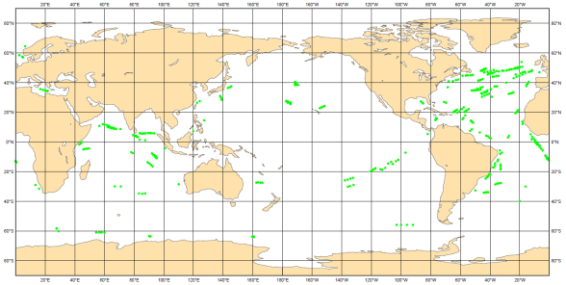


2010

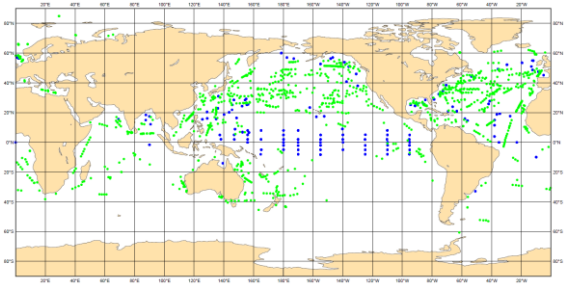
Surface marine wind observations (observations per day) Ships Buoys



1900

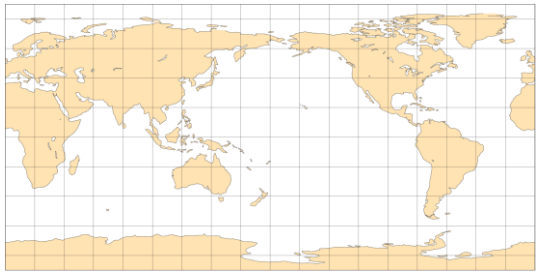


1950

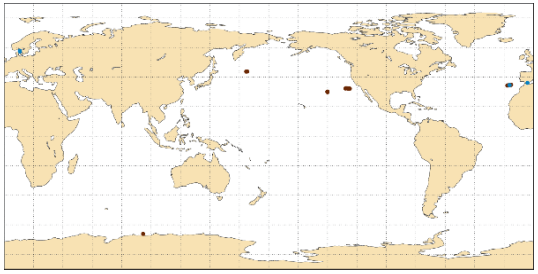


2010

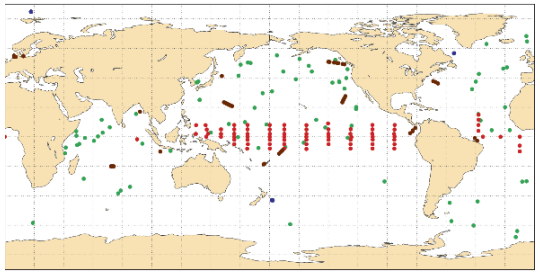
Temperature and salinity profiles (observations per day) Ships Moorings Buoys



1900



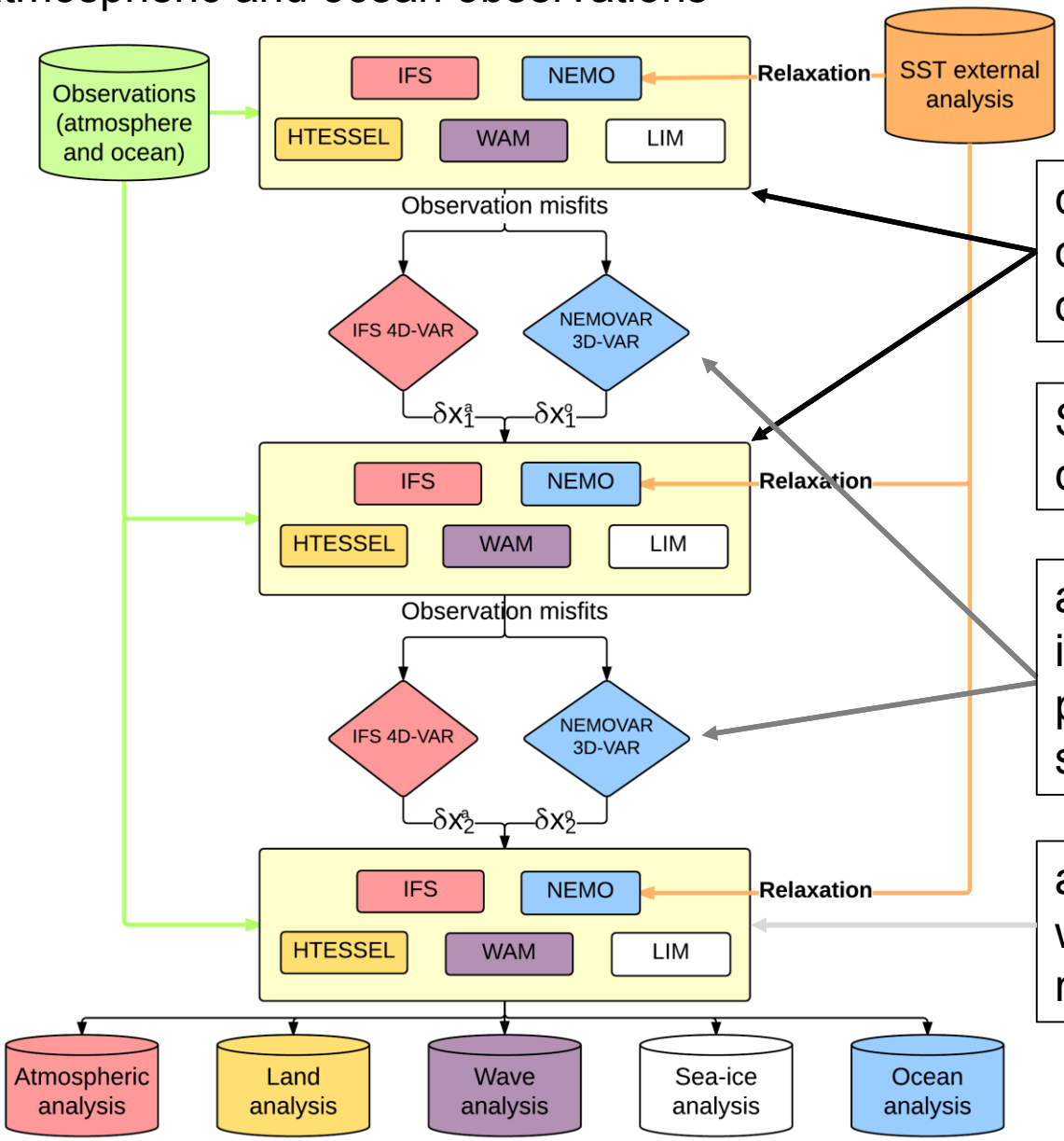
1950



2010

Coupled assimilation system (CERA)

EDA variational approach with a 24-hour window that assimilates simultaneously atmospheric and ocean observations



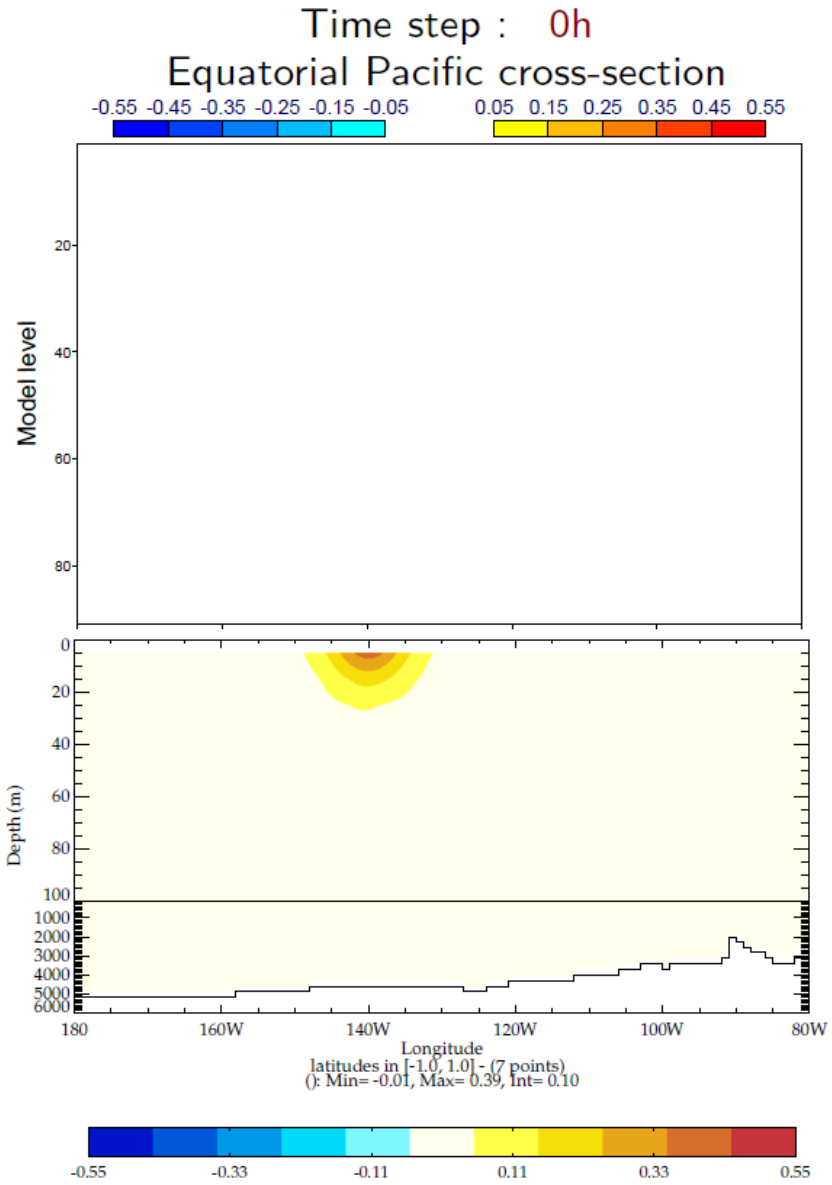
coupled model computes observation misfits in each outer iteration

SST computed in NEMO and constrained by relaxation

atmospheric and ocean increments are computed in parallel to correct the initial state

analysis dynamically consistent with respect to the coupled model

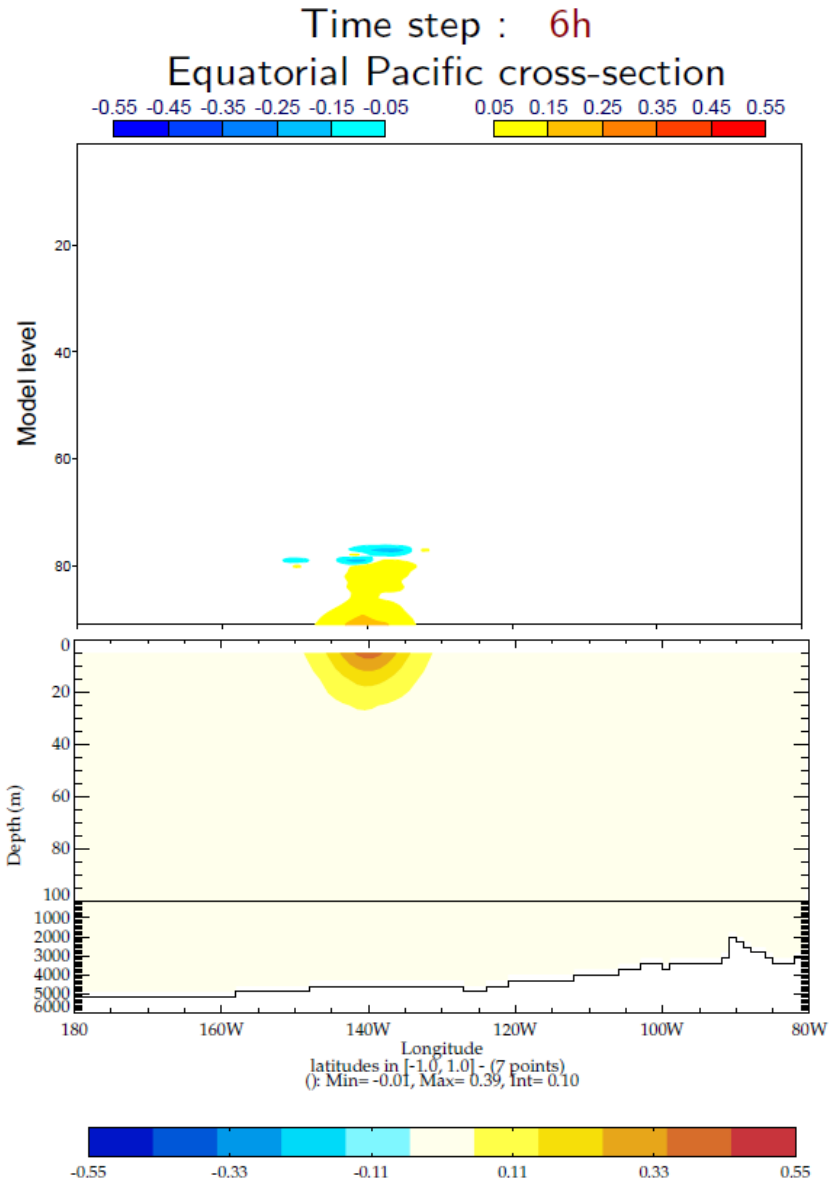
Information exchange in a coupled assimilation system



Atmosphere-ocean temperature cross-section

Ocean increment (assimilation of one temperature observation at 5-meter depth) spreads in the atmosphere during the assimilation process

Information exchange in a coupled assimilation system



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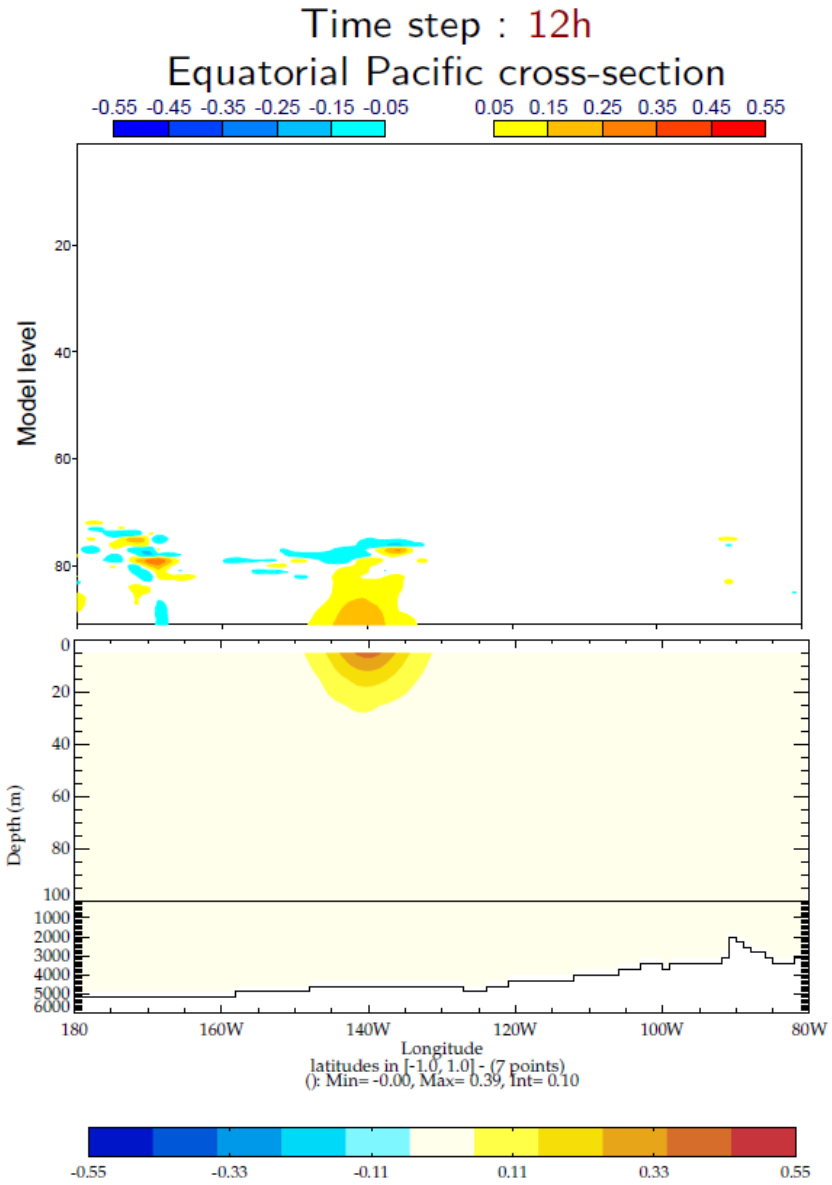

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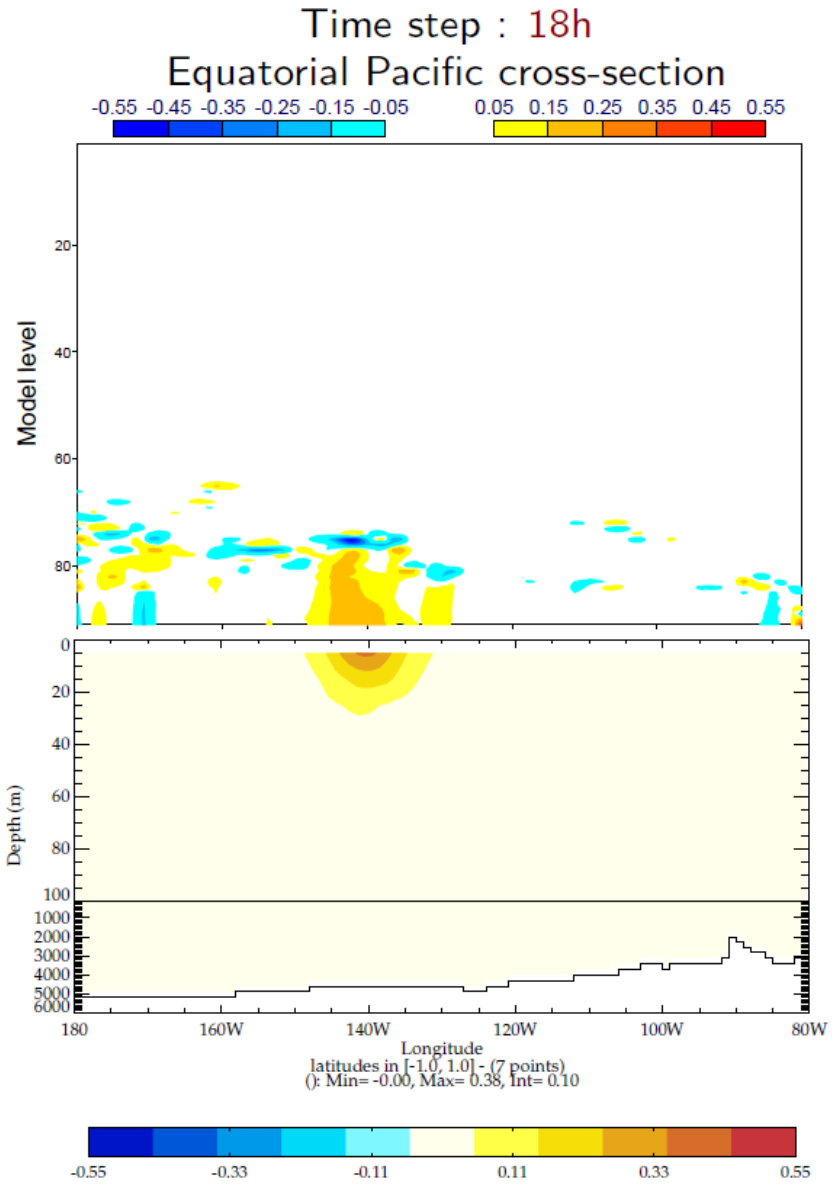

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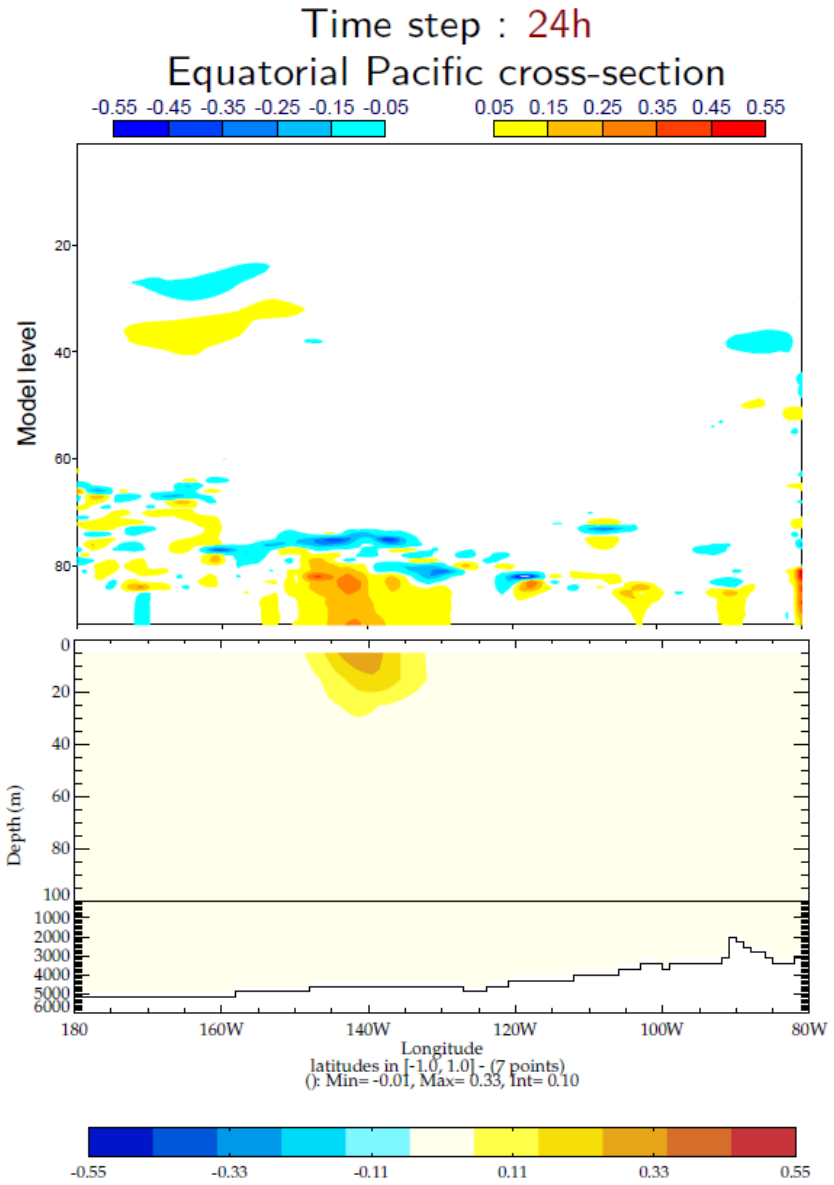


Atmosphere-ocean temperature cross-section

Ocean increment (assimilation of one temperature observation at 5-meter depth) spreads in the atmosphere during the assimilation process

Production of a coupled analysis which should be better balanced and consistent with respect to the coupled model

A coupled data assimilation system for climate reanalysis. P. Laloyaux, M. Balmaseda, D. Dee, K. Mogensen and P. Janssen. QJRMS

Outlines

Introduction to reanalysis activities

Atmosphere: from ERA-Interim to ERA5

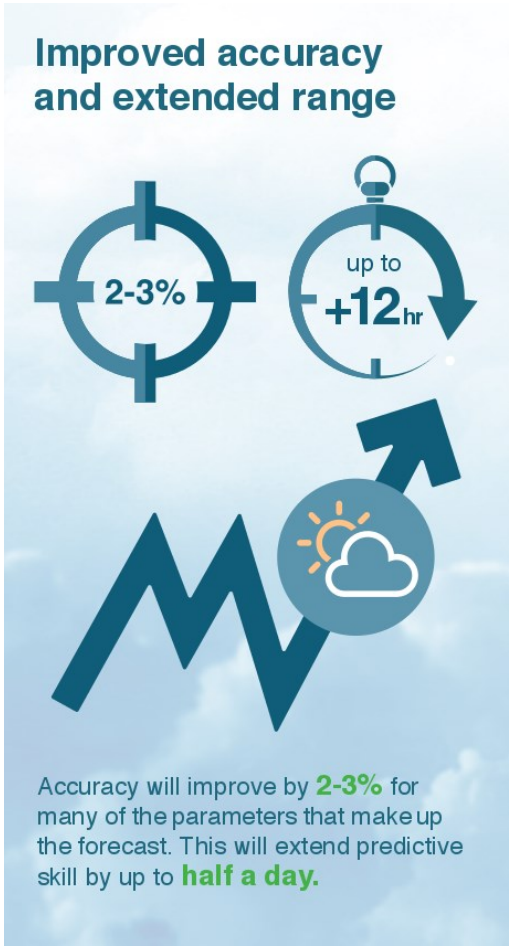
Surface: ERA-Interim/Land

Ocean: from ORAS4 to ORAS5

Coupled atmosphere-ocean reanalysis

Last operational upgrade

Operational upgrade (cycle 41r2 since 08-Mar-16)

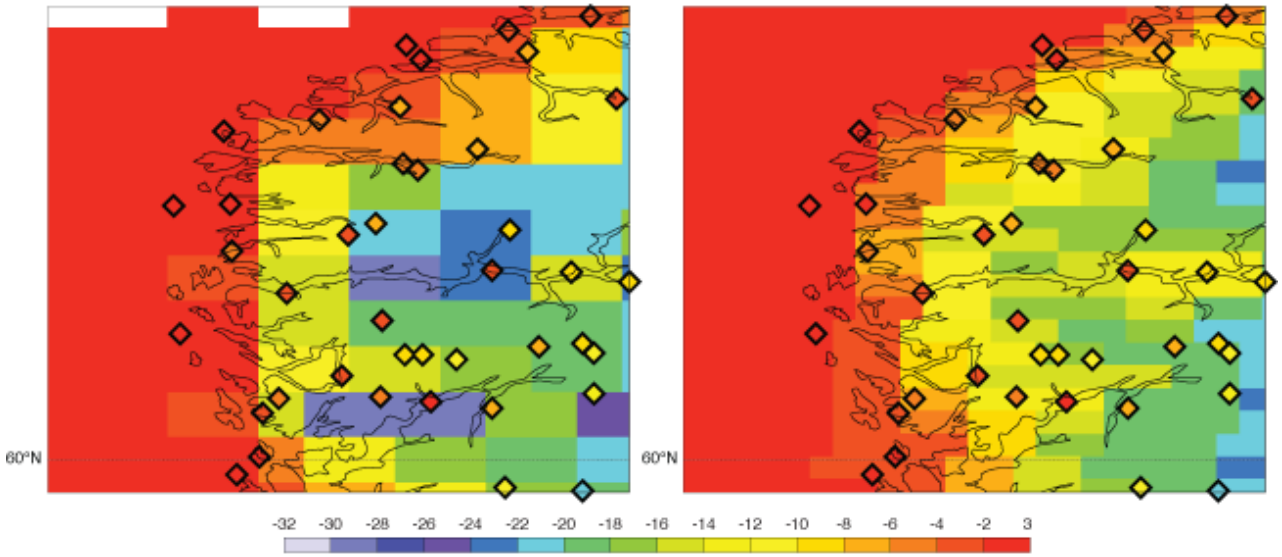


Resolution upgrade for operational analysis and forecasts

Reduction in the distance between points from 16 km to 9 km using a cubic truncation and an octahedral reduced Gaussian grid

Operational upgrade (cycle 41r2 since 08-Mar-16)

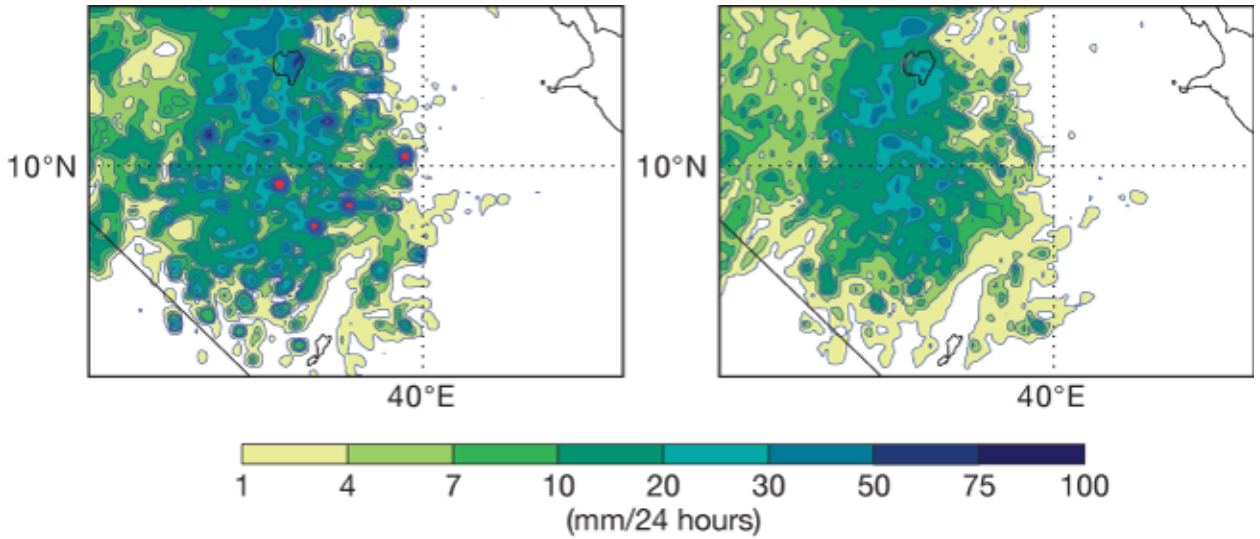
2m temperature forecasts (41r1- left, 41r2 - right)



spurious cold areas have disappeared in the 41r2 forecast

- higher resolution
- improved radiation physics

Accumulated 24-hour precipitation (41r1- left, 41r2 - right)



spurious ‘grid-point storms’ where the predicted accumulated precipitation is larger than 100 mm are not present in 41r2

Conclusions

The next generation of reanalysis to support climate and operational activities

ERA5

MODEL: IFS (CY41R2, Mar 2016)
OBSERVATIONS: Conventional & satellite
ASSIMILATION: Ensemble 4D-VAR (EDA)
RESOLUTION: 30km (T639L137)
PERIOD: 1979-present

ORAS5

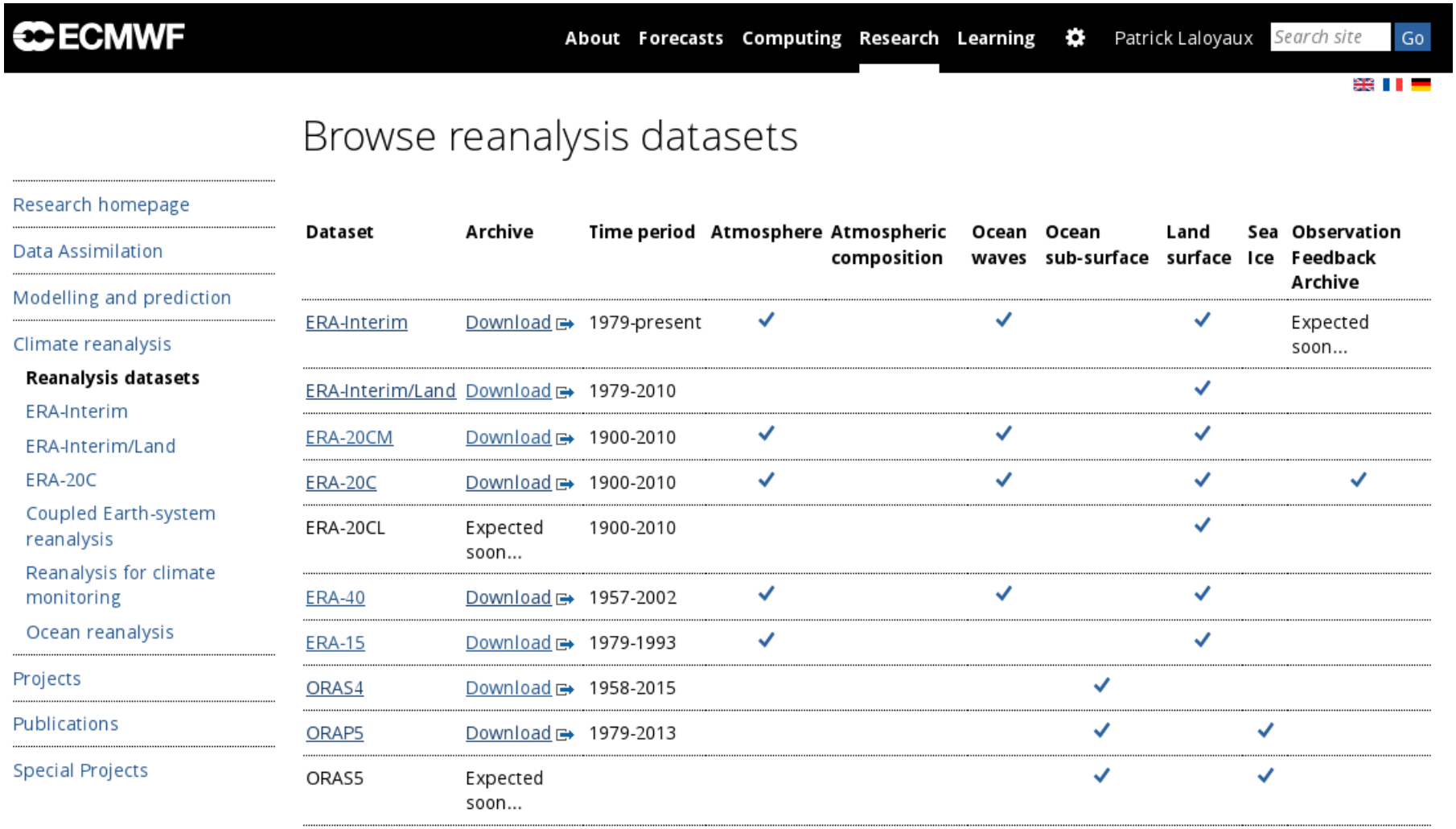
MODEL: NEMO (V3.4) + LIM2
OBSERVATION: Conventional & satellite
ASSIMILATION: 3D-Var NEMOVAR (V3.4)
ENSEMBLE: 5 members (new perturbations)
RESOLUTION: 25km (ORCA025Z75)
PERIOD: 1979-present

CERA-20C

MODEL: IFS-NEMO (CY41R2, Mar 2016)
OBSERVATION: Surface and subsurface conventional
ASSIMILATION: Coupled EDA (CERA)
RESOLUTION: 125km (T159L137-ORCA1Z42)
PERIOD: 1901-2010

ECMWF reanalysis datasets

http://www.ecmwf.int/en/research/climate-reanalysis



ECMWF About Forecasts Computing Research Learning Patrick Laloyaux Search site Go

Browse reanalysis datasets

- Research homepage
- Data Assimilation
- Modelling and prediction
- Climate reanalysis
  - **Reanalysis datasets**
  - ERA-Interim
  - ERA-Interim/Land
  - ERA-20C
  - Coupled Earth-system reanalysis
  - Reanalysis for climate monitoring
  - Ocean reanalysis
- Projects
- Publications
- Special Projects

Dataset	Archive	Time period	Atmosphere	Atmospheric composition	Ocean waves	Ocean sub-surface	Land surface	Sea Ice	Observation Feedback Archive
ERA-Interim	Download	1979-present	✓		✓		✓		Expected soon...
ERA-Interim/Land	Download	1979-2010					✓		
ERA-20CM	Download	1900-2010	✓		✓		✓		
ERA-20C	Download	1900-2010	✓		✓		✓		✓
ERA-20CL	Expected soon...	1900-2010					✓		
ERA-40	Download	1957-2002	✓		✓		✓		
ERA-15	Download	1979-1993	✓				✓		
ORAS4	Download	1958-2015				✓			
ORAP5	Download	1979-2013				✓		✓	
ORAS5	Expected soon...					✓		✓	