Earth-system modelling and assimilation at ECMWF

Patrick Laloyaux
Earth System Assimilation Section
patrick.laloyaux@ecmwf.int

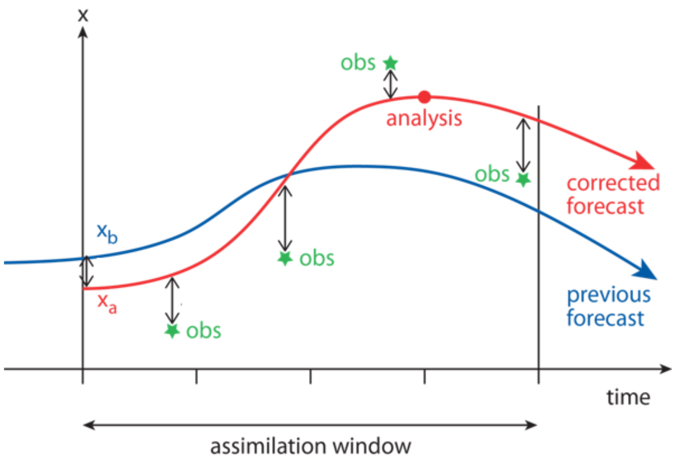
Acknowledgement: Eric de Boisseson, Magdalena Balmaseda, Kristian Mogensen, Gianpaolo Balsamo, Hao Zuo, Massimo Bonavita, Yannick Trémolet, Elias Holm, Sarah Keeley, Franco Molteni, Frederic Vitart, Simon Lang, Antje Weisheimer, Paul Poli, Hans Hersbach, Per Dahlgren, Dinand Schepers, Yuki Kosaka, Shoji Hirahara, Adrian Simmons, Dick Dee, Roberto Buizza

ECMWF
EUROPEAN CENTRE FOR MEDIUM RANGE WEATHER FORECASTS

Outline of talk

- Operational data assimilation system at ECMWF (atmosphere and ocean)
- The coupled atmosphere-ocean assimilation system (CERA)
- Preliminary results in the context of climate reanalysis
- Preliminary results in the context of NWP
- Directions for future strategy

Data assimilation at ECMWF



For each component of the Earth system:

- a short-range forecast from the previous cycle
- available observations in the assimilation window
- assimilation scheme to produce an analysis trajectory
- a corrected short-range forecast for the next cycle

Data assimilation systems have been developed separately for each component:

- **atmosphere: 4D-Var**
- **ocean: 3D-Var**
- sea-ice: 3D-Var
- wave: OI
- land: OI and SEKF
- atmospheric composition: 4D-Var

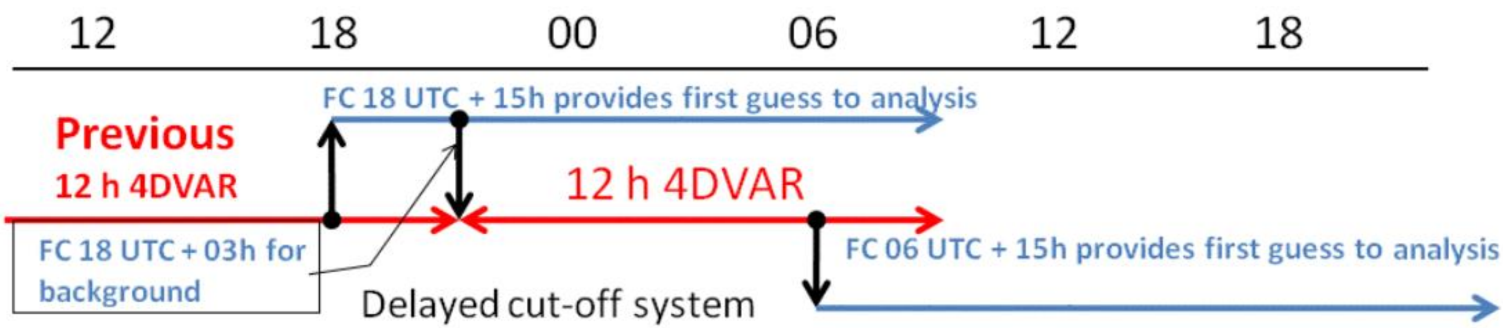
Assimilation for the atmosphere

4D-Var: the analysis trajectory is the solution of minimisation problem which is solved by an incremental method

$$J(\mathbf{x}) = \overbrace{(\mathbf{x}^{\mathrm{b}} - \mathbf{x})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x}^{\mathrm{b}} - \mathbf{x})}^{\text{prior state constraints}} + \underbrace{(\mathbf{y} - \mathbf{h}(\mathbf{x}))^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y} - \mathbf{h}(\mathbf{x}))}_{\text{observational constraints}}$$

Possibility to have additional terms for bias correction, digital filter, model bias, …

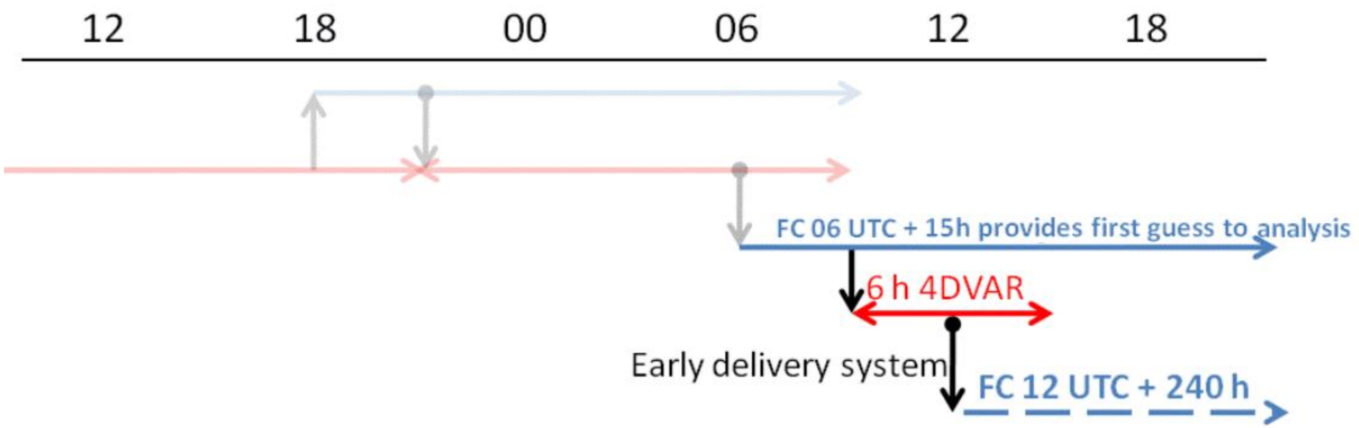
A delayed cut-off system in operation



- 4D-Var system cycling every 12 hours (09Z-21Z and 21Z-09Z)
- first-guess from the 15-hour forecast of the previous cycle
- observations with a delayed cut-off (5 hours, starting 14Z) to ensure the most comprehensive global data coverage

Assimilation for the atmosphere

A delayed cut-off system, with an early delivery system for 00Z and 12Z analyses



- timeliness of analyses at 00Z and 12Z to initialise the medium-range forecasts
- 6-hour 4D-Var with a short cut-off (1 hour, starting 16Z)
- first-guess from the 15-hour forecast of the previous cycle
- early delivery suite produces analyses at 00Z and 12Z significantly earlier (10 hours earlier)

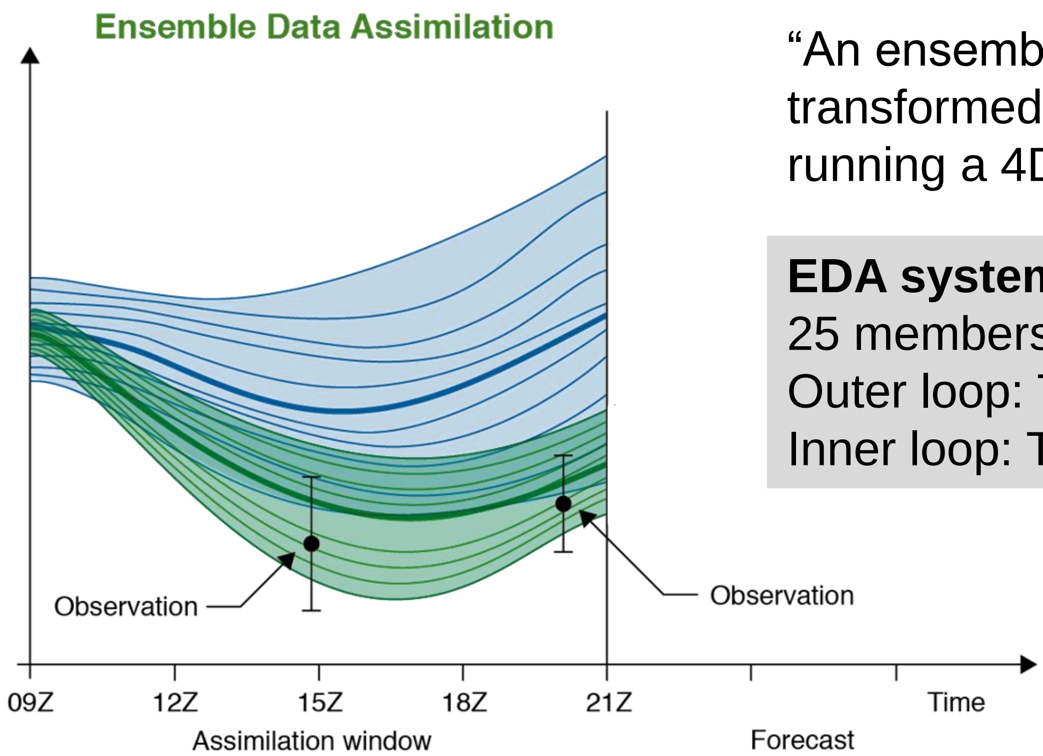
Delayed cut-off and early delivery systems
Outer loop: TCo1279 L137
Inner loop: TL255-319-399
HRES forecast (days 1-10): TCo1279 L137

Assimilation for the atmosphere

We need to account for error sources in observations, forcing and model
→ a Monte Carlo simulation of the reference 12-hour 4D-Var system is implemented

An Ensemble of Data Assimilation (EDA) is computed with perturbations on

- observations
- sea surface temperature
- model error parameterization (Stochastically Perturbed Parameterization Tendencies)



"An ensemble of perturbed first-guesses is transformed in an ensemble of analysis by running a 4D-Var on each member"

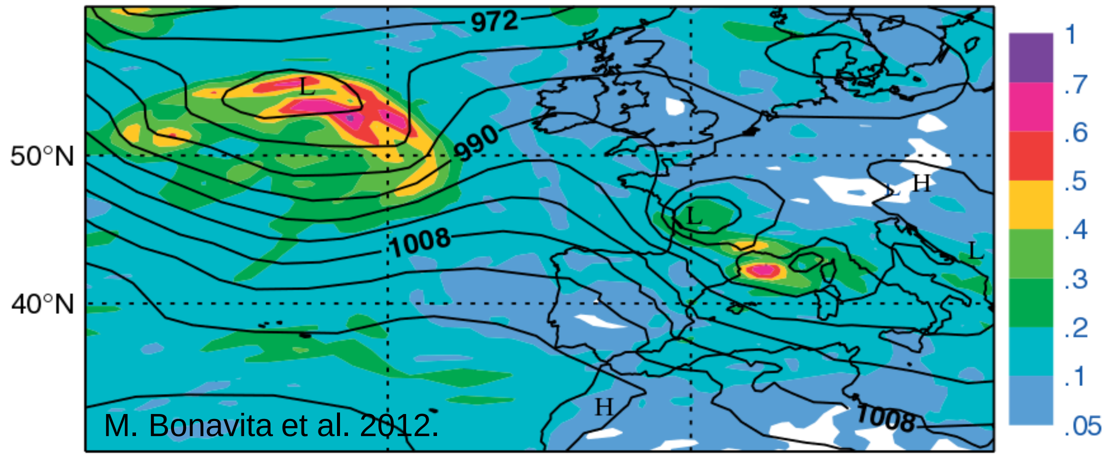
EDA system
25 members
Outer loop: TCo639 L137
Inner loop: TL191-191

Assimilation for the atmosphere

Ensemble information from the EDA is used to compute flow-dependent variances and correlations of the background error (B)

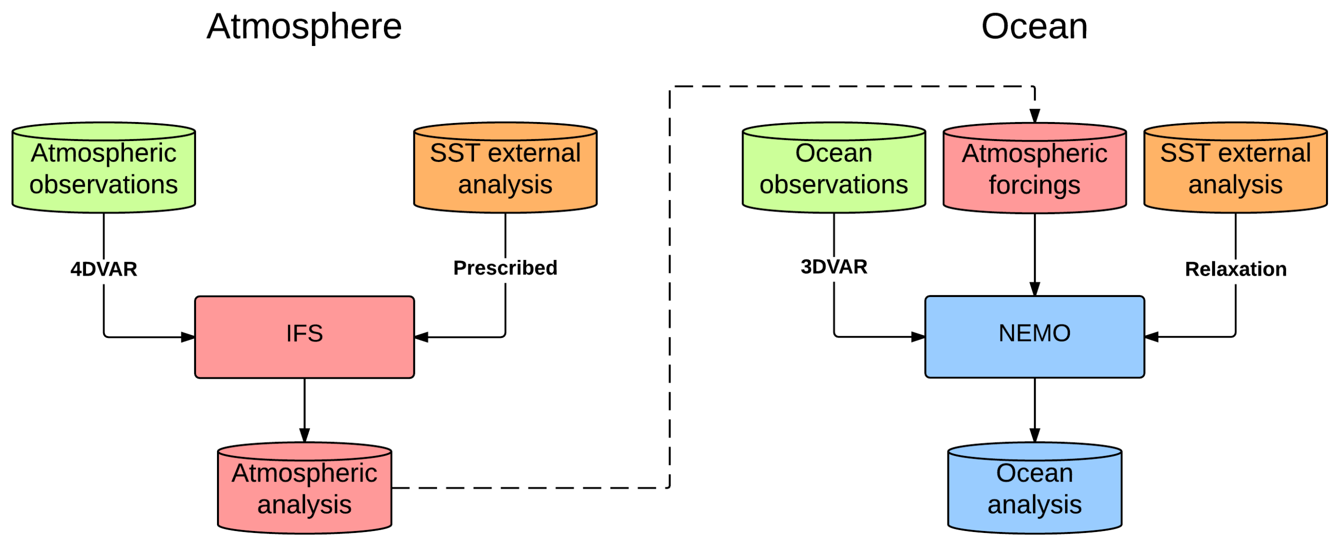
- variances of the day from the 25 EDA members
- covariance matrix based on a hybrid method (mix of 400 samples spread through the year and 200 samples from the current cycle)

The uncertainty of the background is larger in a developing low than in a subtropical high-pressure system



Background standard deviation of vorticity near the surface (24 January 2009 at 0900 UTC). Mean-sea-level surface pressure analysis (contour).

Link between atmospheric and ocean assimilation



Ocean analysis:

- NEMO model
- 3D-Var (10-day assimilation window)
- atmospheric forcings (computed from the atmospheric analysis with a bulk formula)

Ocean-S4
ORCA1 Z42 grid
5 members (perturbed observations and forcings)

Sea Surface Temperature is based on an external analysis:

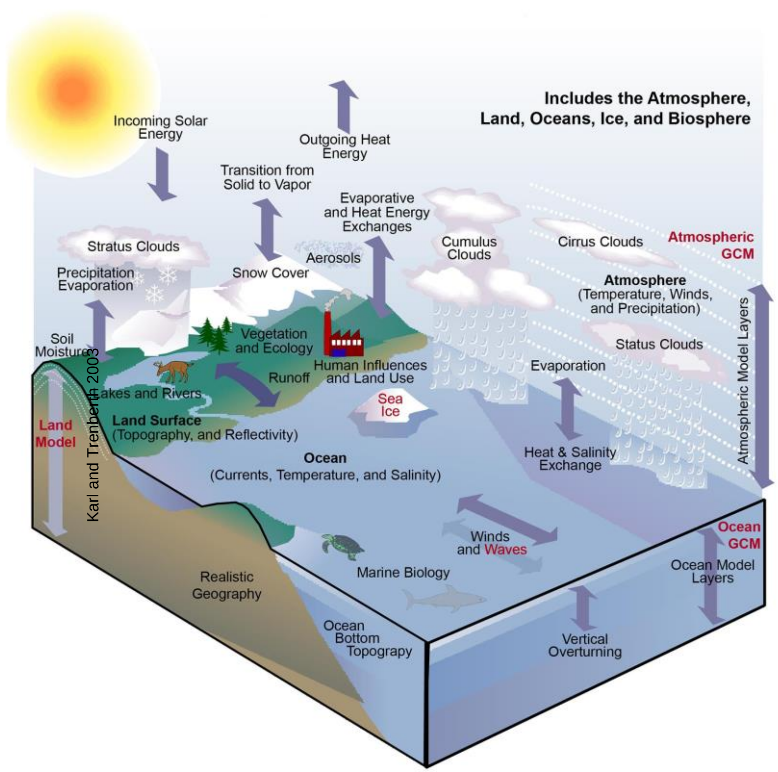
- prescribed in IFS
- relaxed in NEMO

Earth-system modelling for weather forecast

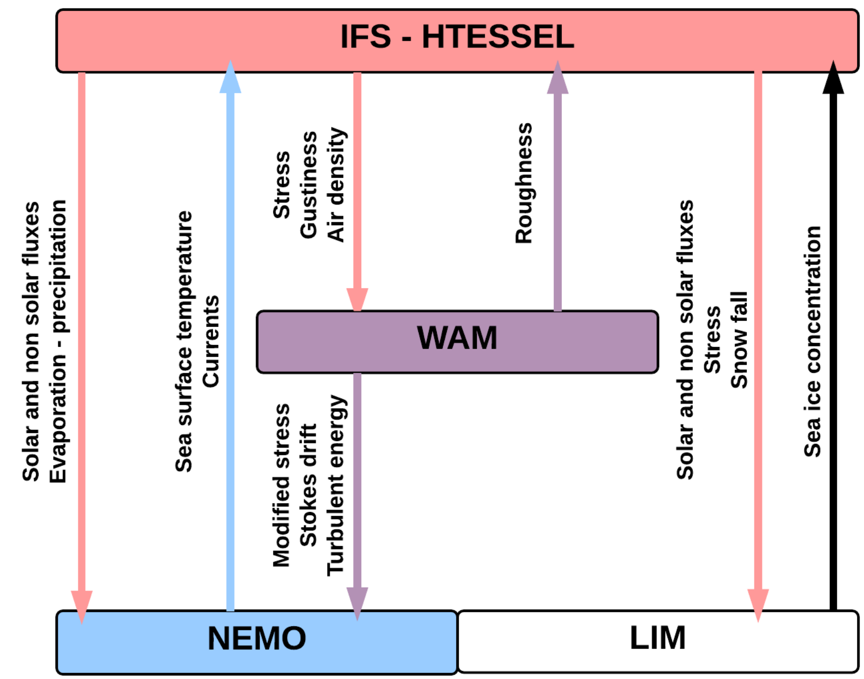
Atmospheric and ocean analyses (initial conditions) are computed separately, but atmosphere and ocean are coupled in the forecasts

An earth system approach with advanced modelling techniques

Earth system physical processes



Coupled earth model for weather forecasts

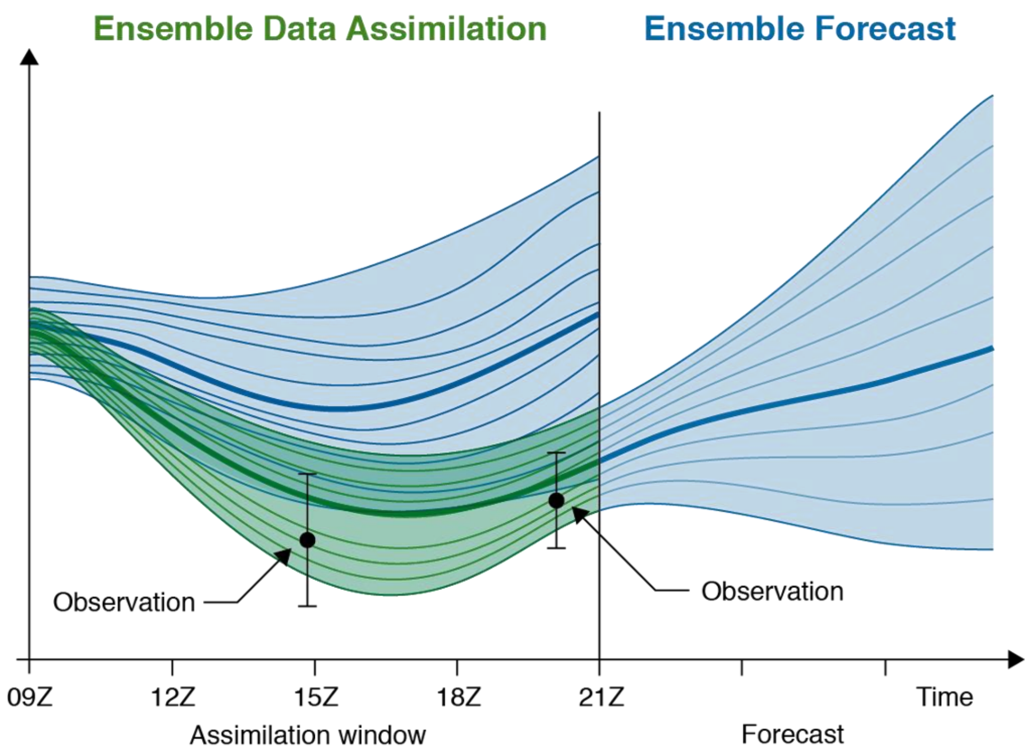


→ active research (G. Balsamo & J. Bidlot)

Coupled earth model for the ensemble prediction system (ENS)

The ENS system is the ECMWF ensemble prediction system for the medium-range and monthly timescales

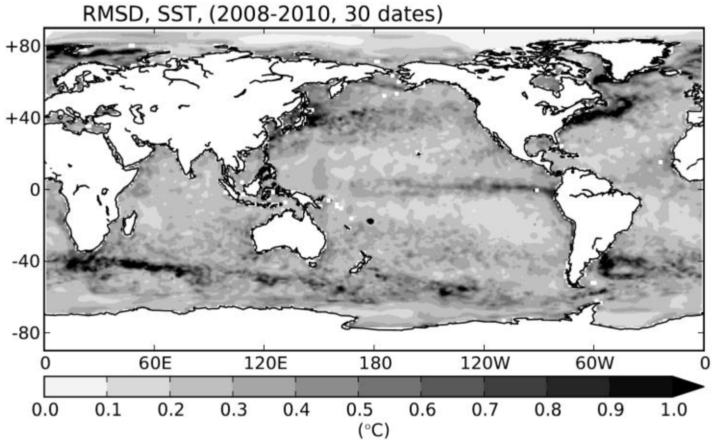
- Perturbations from EDA members (with singular vectors) are used to initialise the atmospheric component of ENS
- Ocean-S4 is used to initialise the ocean component of ENS



ENS system
50 members
Days 1-15: TCo639 L91
Days 16-46: TCo319 L91

Sea surface temperature coupling in ENS

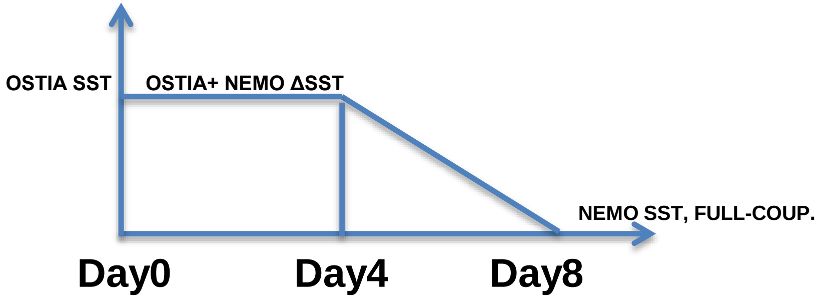
During assimilation, SST is prescribed in IFS and relaxed in NEMO (using an external analysis)



RMS difference between the SST in the ocean and atmospheric analyses (30 dates, 2008-2010)
→ large differences in regions with high variability and eddies

Coupled ocean-atmosphere forecasts are exposed to the problem of initial shock as the atmosphere is not yet in balance with the ocean.

Partial coupling is implemented for day 0-4
→ forecast starts from the SST seen by the atmosphere and evolves the tendency of the ocean model (day 0-4)
→ it works well only in the short range as ocean eddies are assumed stationary



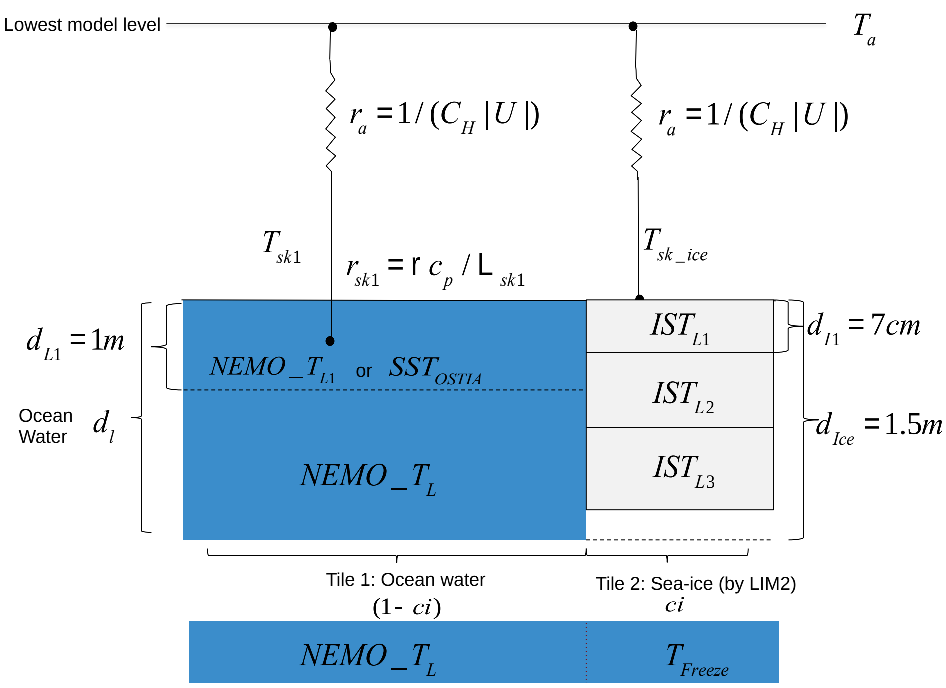
Full coupling from day 8
→ uses the dynamic ocean to advect eddies

Sea-ice coupling in ENS (in the next operational cycle)

The coupling of sea-ice/SST information to the atmosphere is implemented through the land model

→ represent these fields on the atmospheric grid

→ account for fractional ocean/ice contributions to the energy fluxes



The LIM2 ice model is currently coupled to the IFS only via the sea-ice cover

The thermodynamics is currently uncoupled

→ LIM2 and TESSEL performs different calculations of the Surface Energy Budget (SEB), with only TESSEL being interactive with the atmosphere

Therefore it is correct to name this as an Ice-to-ice coupling

Courtesy of G. Balsamo

Outline of talk

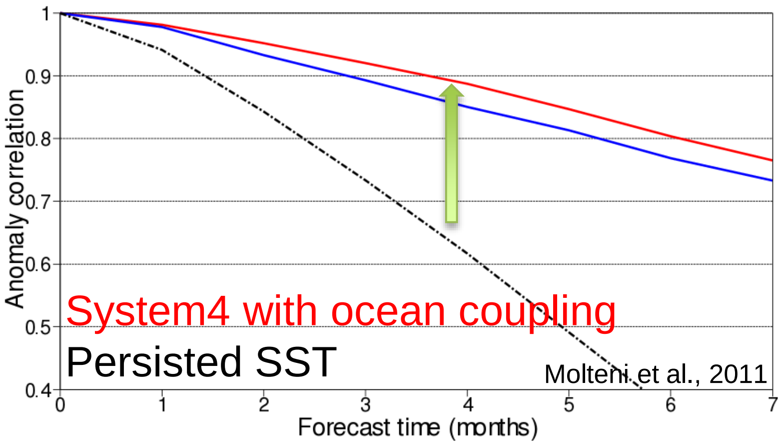
- Operational data assimilation system at ECMWF (atmosphere and ocean)
- The coupled atmosphere-ocean assimilation system (CERA)
- Preliminary results in the context of climate reanalysis
- Preliminary results in the context of NWP
- Directions for future strategy

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

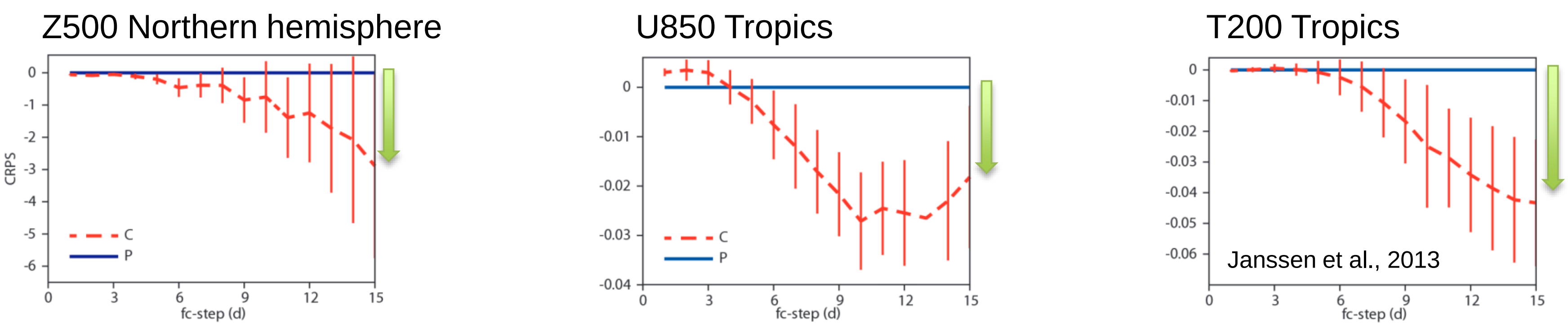
SST anomaly correlation for NINO3 (360 dates, 1981-2010)



→ Ocean coupling provides SST forecasts which are substantially better than persistence Important for El Niño–Southern Oscillation (ENSO) prediction

For medium range forecasting

Continuous Rank Probability Score (CRPS) forecast skill score (61 cases in Jan–Aug 2012)



Coupled atmosphere-ocean assimilation system (CERA)

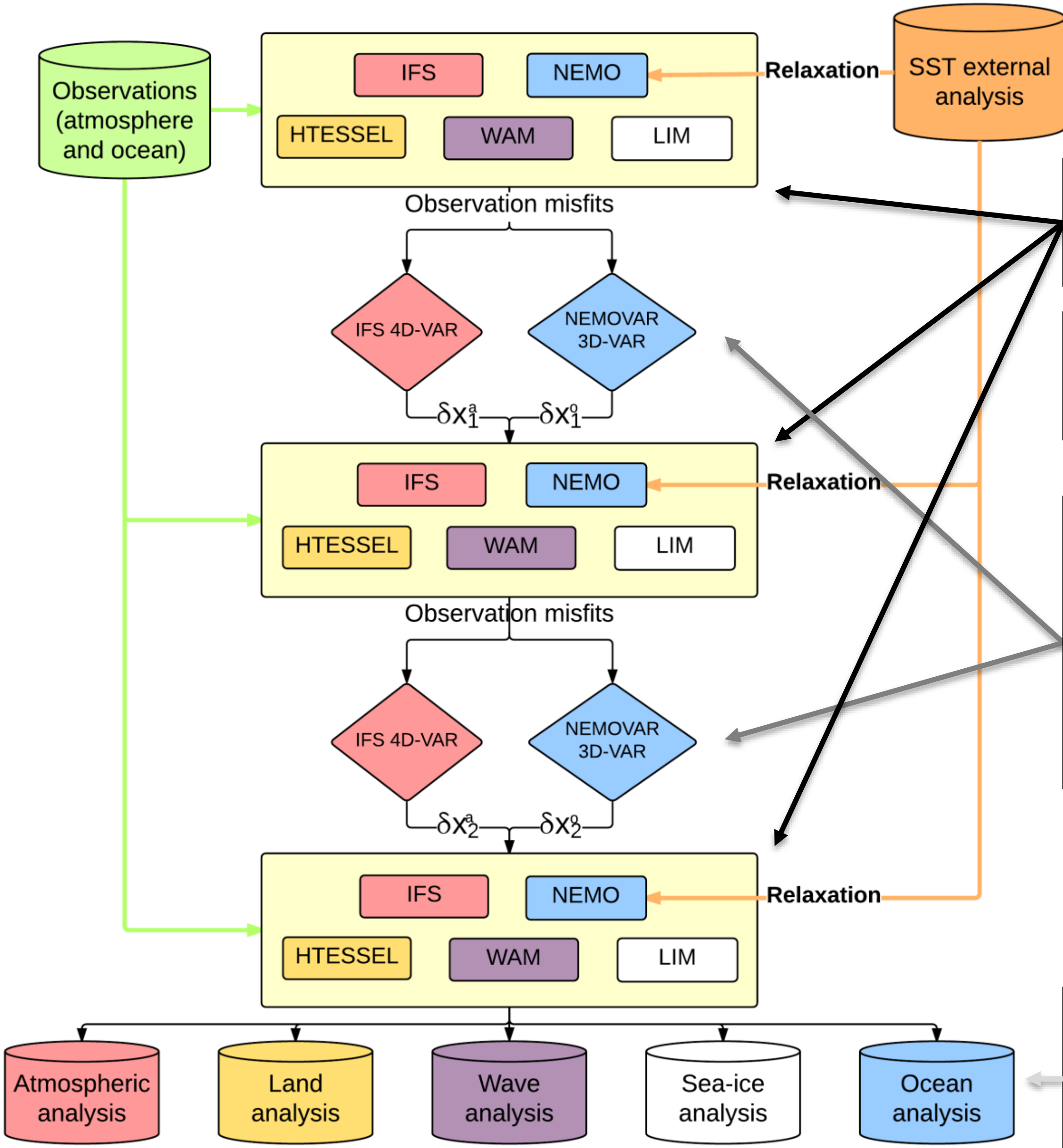
Atmosphere-ocean interactions need to be taken into account, not only during the forecast but also for the definition of the initial conditions of the forecasts

A new coupled assimilation system (CERA) for the coupled model:

- the coupled earth model is used for assimilation
- atmospheric and ocean observations assimilated simultaneously
- a common 24-hour assimilation window for atmosphere and ocean
- ocean observations can impact atmospheric estimate and conversely

Coupled atmosphere-ocean assimilation system (CERA)

Schematic for one assimilation cycle



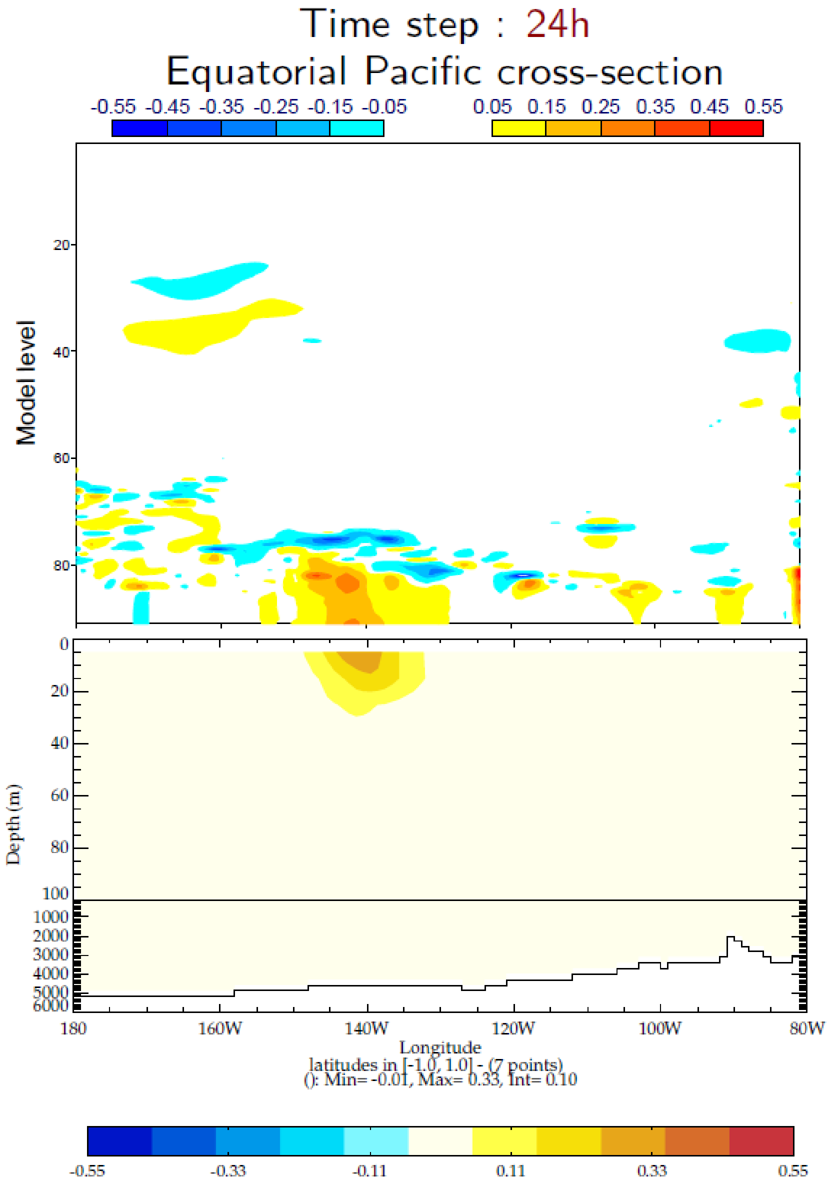
Outer loop: coupled model computes observation misfits

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

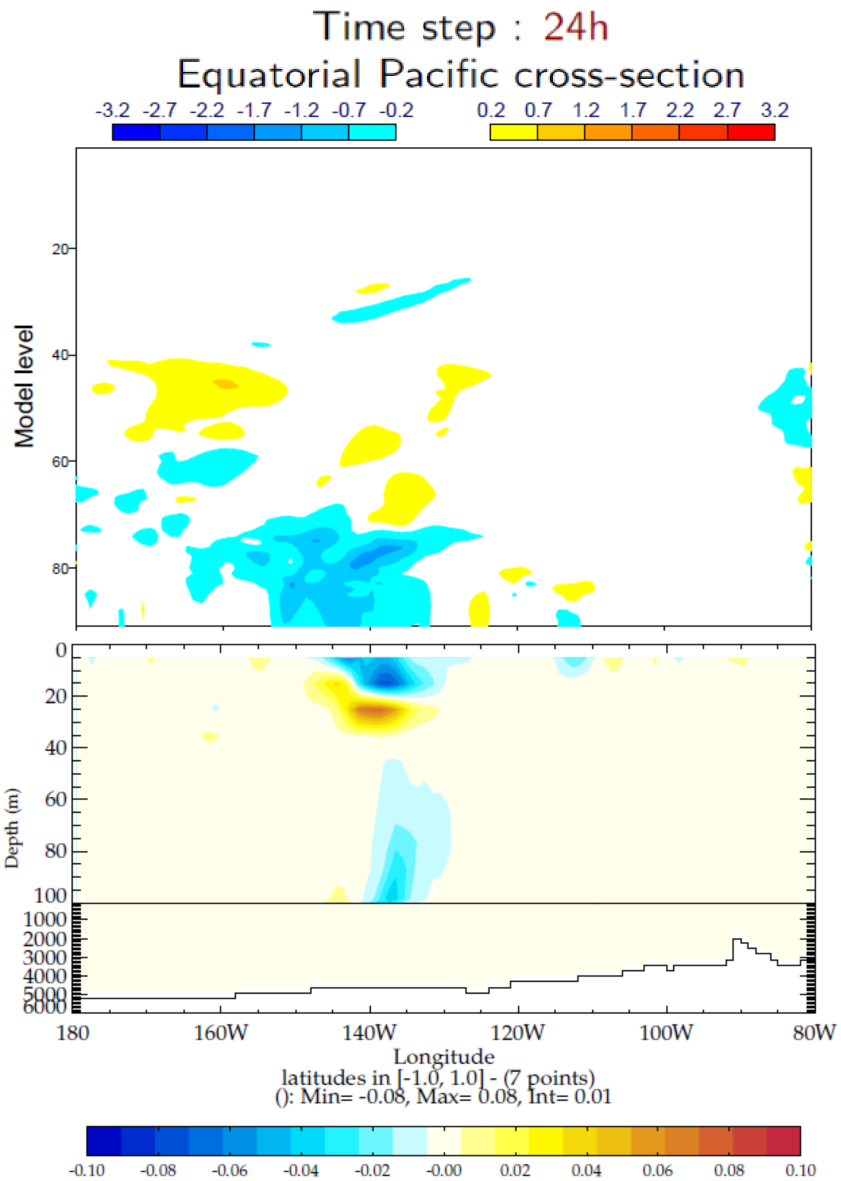


Atmosphere-ocean temperature cross-section

Ocean increment (assimilation of one temperature observation at 5-meter depth) spreads in the atmosphere during the model integration (outer loop)

Coupled analysis should be better balanced and 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)

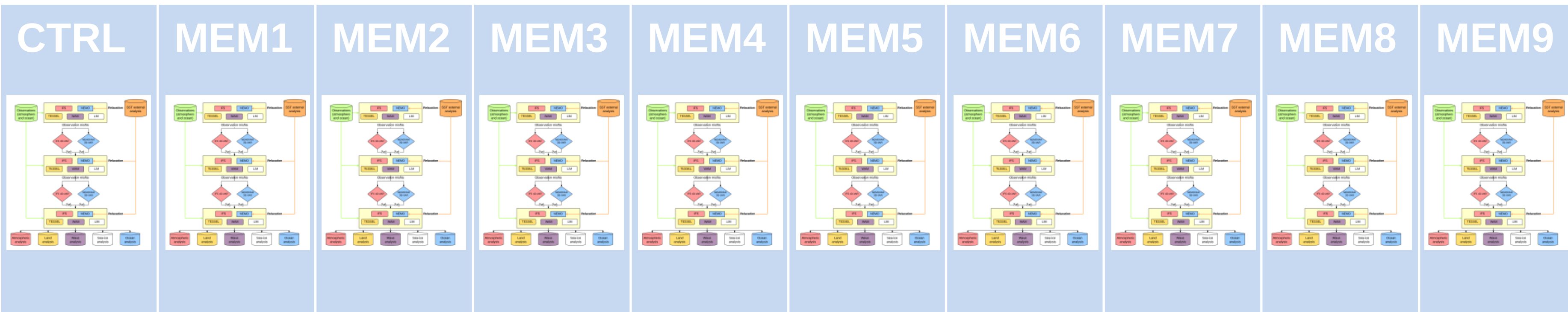
Ocean-atmosphere correlations are generated within the CERA incremental variational approach

A coupled data assimilation system for climate reanalysis. P. Laloyaux, M. Balmaseda, D. Dee, K. Mogensen and P. Janssen. QJRMS, 142: 65–78, 2016.

Ensemble technique in the CERA system

CERA implements a 10-member EDA system with perturbations:

- atmospheric and ocean observations
- perturbation in the sea surface temperature
- stochastic physics in IFS atmospheric model



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

CERA system
10 members
Atmosphere: TL159 L91
Ocean: ORCA1Z42

→ CERA system initially targets the production of climate reanalysis

Outline of talk

- Operational data assimilation system at ECMWF (atmosphere and ocean)
- The coupled atmosphere-ocean assimilation system (CERA)
- Preliminary results in the context of climate reanalysis
- Preliminary results in the context of NWP
- Directions for future strategy

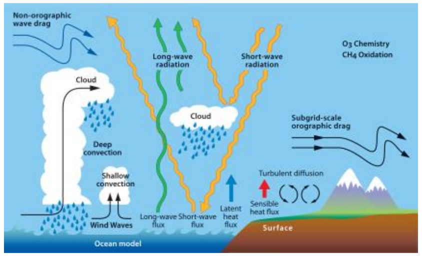
Extended climate reanalysis at ECMWF

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

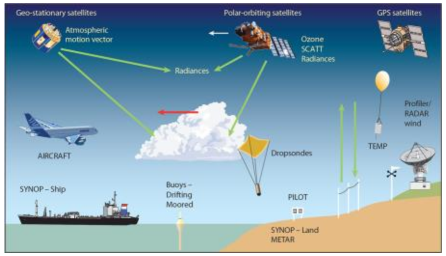
Use the key elements developed for Numerical Weather Prediction (NWP)

Model



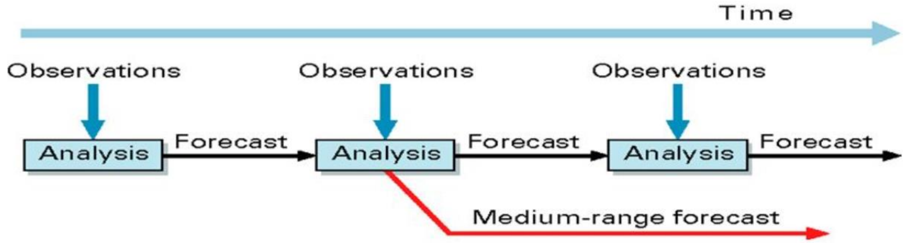
general circulation model representing different earth system components

Observations



International databanks from data rescue activities

Data assimilation scheme



observations are ingested in the model to estimate the model state

Particular attention is required for

- observation selection and quality control (whitelisting)
- specification of model and observation errors
- bias correction required to reduce systematic errors

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

Atmosphere

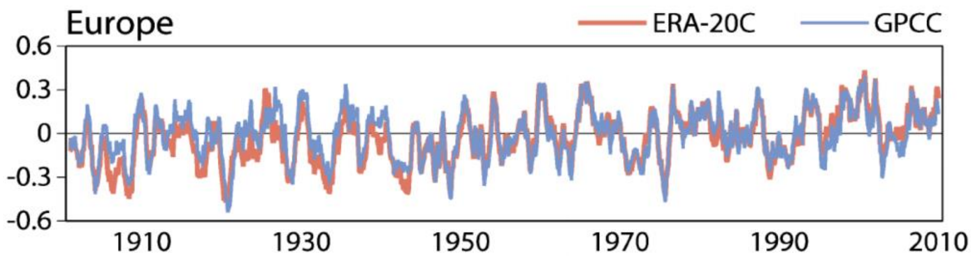
Land

Wave

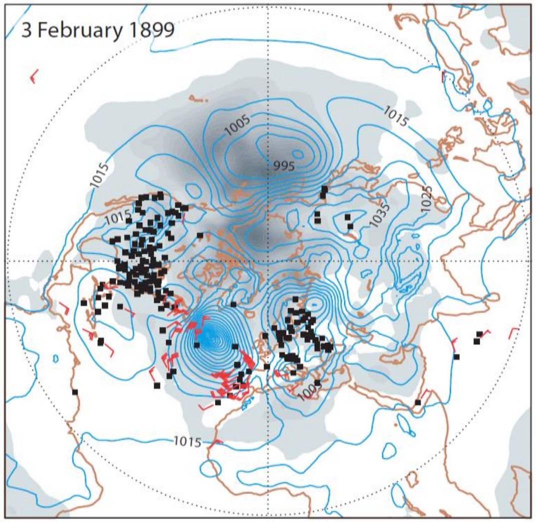
Model: IFS (CY38R1, Jun 2012)
Forcing: SST/SIC prescribed (HADISST2)
Observation: surface conventional
Assimilation: 4D-Var
Resolution: 125km (T159L91)
Period: 1900-2010

Production of long timeseries of ECVs and representation of synoptic situation

Precipitation anomaly averaged over Europe in mm/day



Surface pressure analysis (3 February 1899) showing the severity of the weather in the North Atlantic.



The New York Times
Published: February 16, 1899
Copyright © The New York Times

TERRIFIC STORMS AT SEA

Steamships from All Quarters Report Extremely Rough Voyages.

ALL MORE OR LESS BATTERED

Vessels Sighted in Distress and Abandoned — Blinding Snow and Waves Like Mountains.

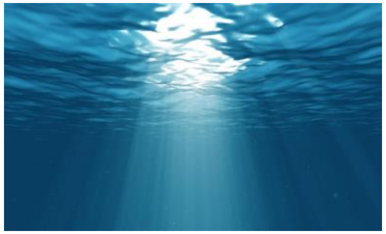
All the steamers that came in yesterday were coated with ice from the tops of the masts down to the water line, and all had passed through storms of blinding snow and mountainous waves. The British steamer Ethelgonda, from Bristol and Swansea, which left the latter port on Jan. 19, ran into a gale of hurricane force, and seas swept her decks repeatedly. So fierce was the wind that the boat drifted before the gales and was barely able to keep steerage way. She anchored outside the bar late Sunday afternoon. The cable parted and she lost her anchor, together with 100 fathoms of chain. Then the great snowstorm drove her 150 miles off the shore. She succeeded in getting back late on Tuesday night.

The French liner La Bretagne, from Havre, came in a little before noon yesterday, with 58 cabin and 225 steerage passengers. She left Havre on Feb. 4, and two days later she encountered a fierce gale, which soon raised tremendous seas. This lasted until Feb. 12, and during this time the vessel had to be slowed down. The following day heavy head seas were encountered, but the steamship proved herself a stanch craft in heavy weather. She had hard work in breaking the ice while getting into her slip.

P. Poli et al. ERA-20C: An atmospheric reanalysis of the 20th century. Journal of Climate, In Press, 2016.

Two new extended climate reanalyses at ECMWF

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



Ocean

Sea ice

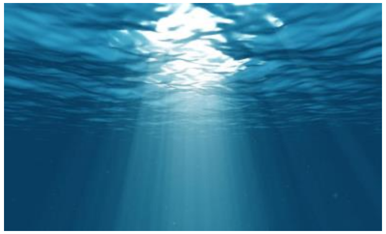
Model: NEMO/LIM2 (CY41R2, Mar 2016)
Forcing: SST nudged (HADISST2) and ERA-20C
Observation: salinity and temperature profiles
Assimilation: 3D-Var (10-member ensemble)
Resolution: ORCA1 Z42
Period: 1900-2010

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

Atmosphere

Land

Wave

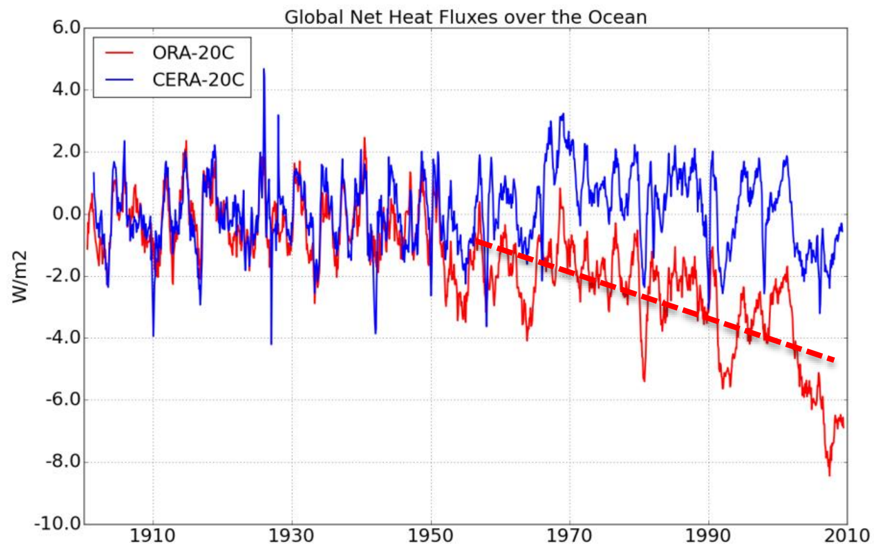


Ocean

Sea ice

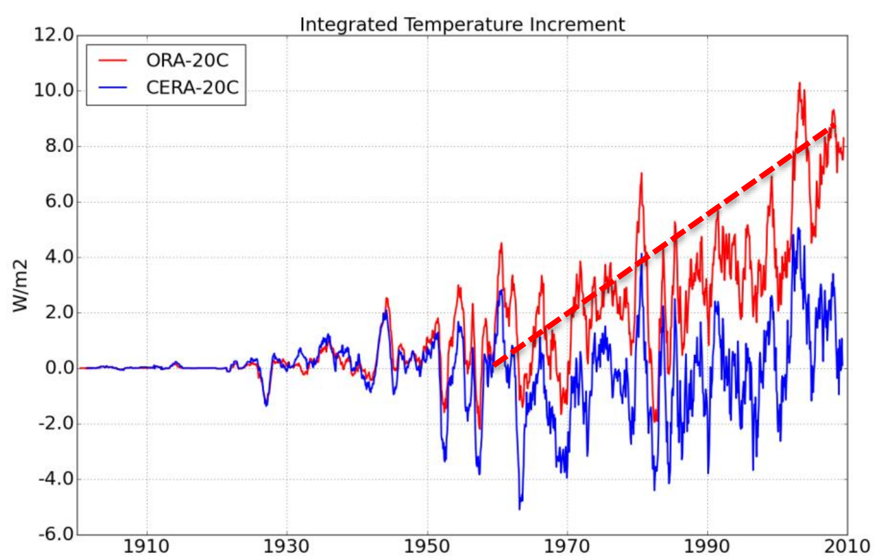
Model: IFS/NEMO/LIM2 (CY41R2, Mar 2016)
Forcing: SST nudged (HADISST2)
Observation: surface conventional, salinity and temperature profiles
Assimilation: new CERA system (10-member ensemble coupled hybrid DA)
Resolution: T159L91/ORCA1 Z42
Period: 1901-2010

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



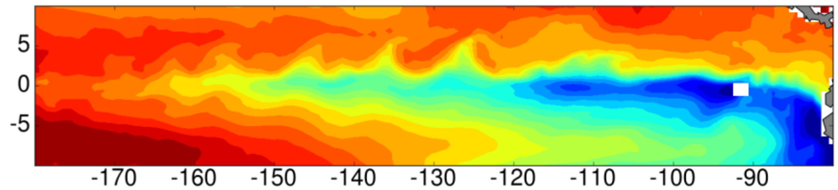
Ocean temperature increment in CERA-20C and ORA-20C.

→ increment in ORA-20C is trying to compensate for the trend in the net fluxes
→ CERA-20C is a much more balanced system

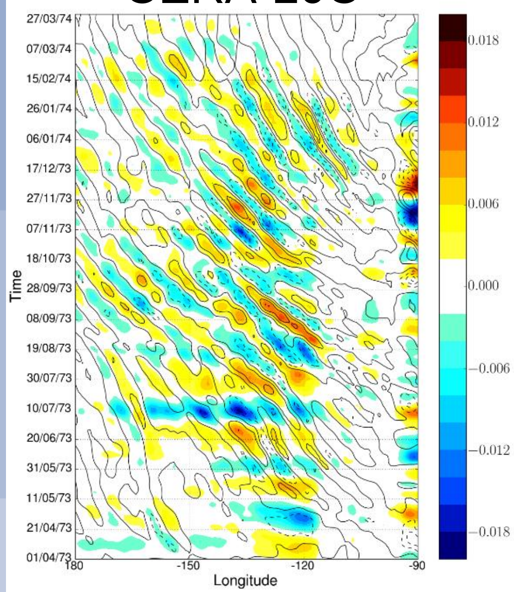
Courtesy of E. de Boisseson

Preliminary results of CERA-20C

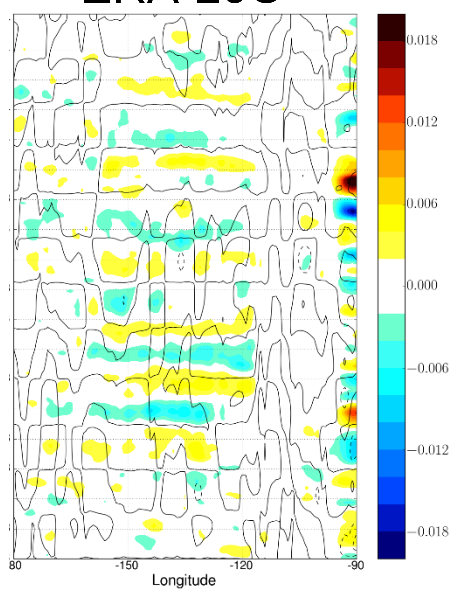
Tropical Instability Waves (TIW) are westward-propagating waves near the equator (intraseasonal coupled process)



CERA-20C



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
→ does not capture the TIW and wind stress signals (forced by monthly SST)

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

Courtesy of E. de Boisseson

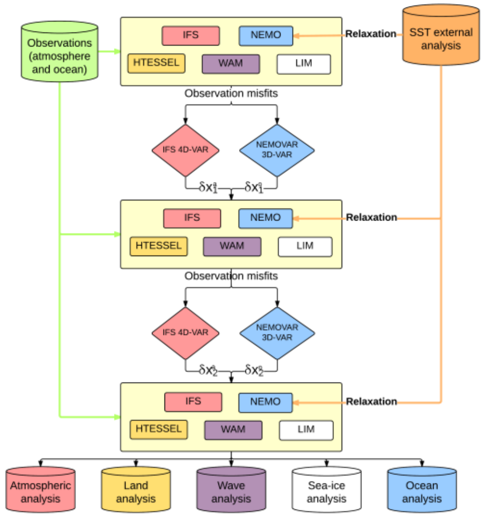
Outline of talk

- Operational data assimilation system at ECMWF (atmosphere and ocean)
- The coupled atmosphere-ocean assimilation system (CERA)
- Preliminary results in the context of climate reanalysis
- Preliminary results in the context of NWP
- Directions for future strategy

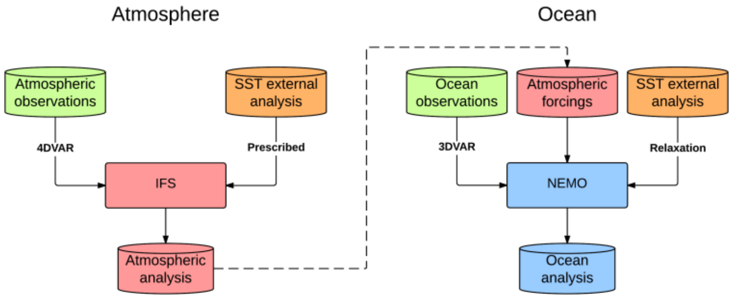
CERA system for Numerical Weather Prediction

CERA system has been compared to the uncoupled approach over recent periods

CERA



UNCPL



To get a fair comparison, an UNCPL system has been set up using:

- same model cycle
- same resolution
- 1-day assimilation window for ocean and atmosphere
- same number of outer and inner iterations
- run for Apr-May 2010, Aug-Sept 2010 and Dec-Jan 2010/2011

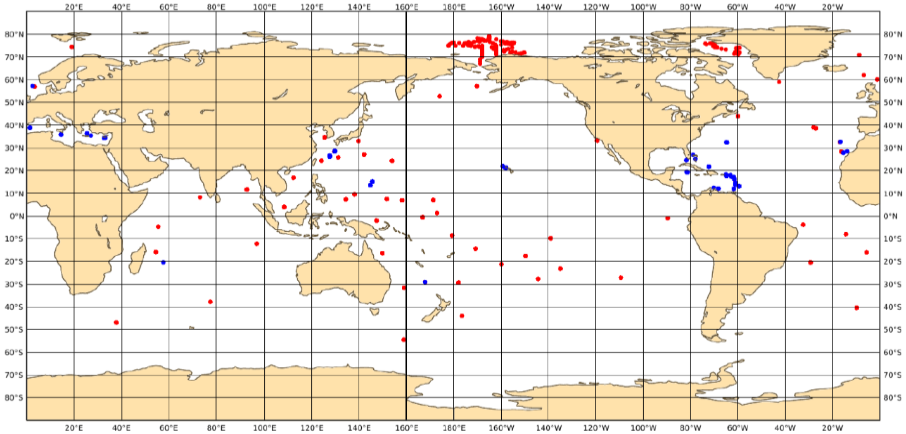
Possible improvements in the coupled analysis?

Possible improvements in the use of near-surface observations?

Possible improvements in the initialisation of coupled forecasts?

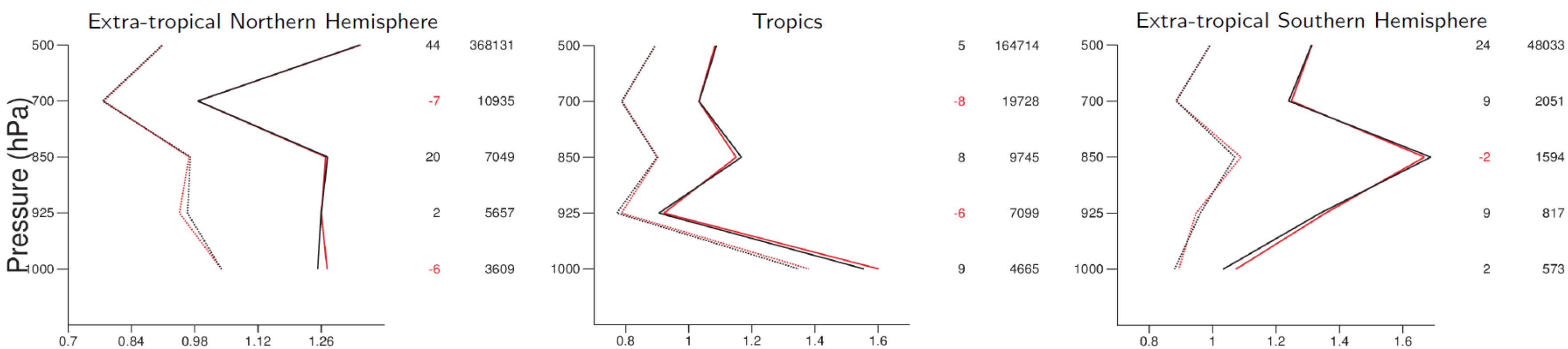
Quality of the coupled analysis - Atmospheric temperature

Conventional near-surface temperature observations over sea (lsm<0.1, p>700hPa, Sep 2010)



Radiosondes
aircrafts

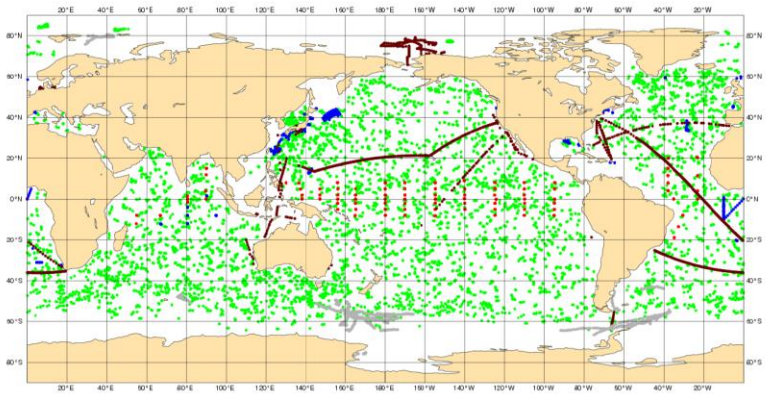
CERA compared to UNCPL – Vertical profiles for the analysis RMSE (dashed) and background RMSE (solid) for September 2010 with respect to the selected observations



The CERA background RMSE is slightly smaller near the surface, neutral elsewhere
Same conclusions for May 2010 and January 2011

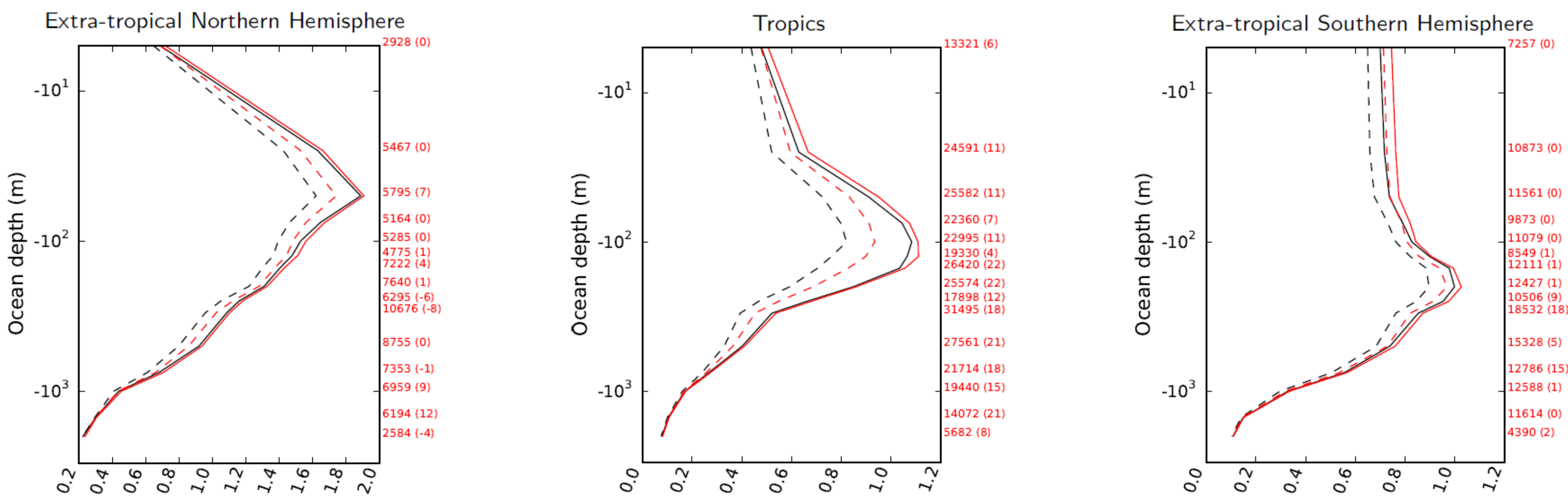
Quality of the coupled analysis - Ocean temperature

Conventional ocean temperature profiles (Sep 2010)



Argo
Moorings
CTD
XBT
Marine mammals

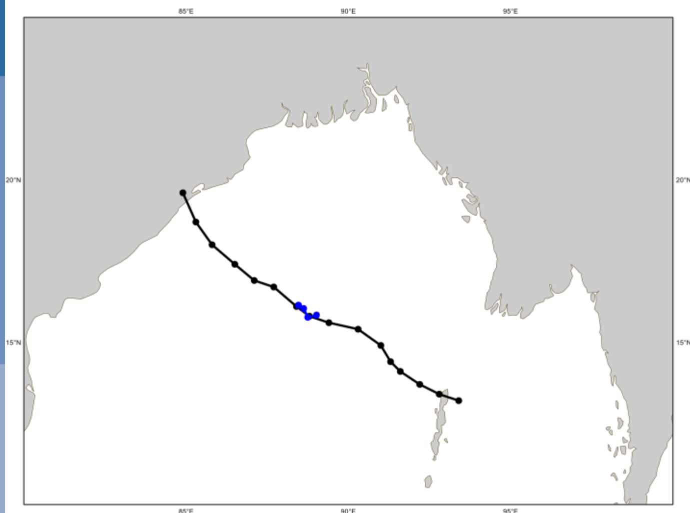
CERA compared to UNCPL – Vertical profiles for the analysis RMSE (dashed) and background RMSE (solid) for September 2010 with respect to the observations



The CERA background and analysis RMSE are smaller in the mixed layer
Same conclusion for May 2010 and January 2011

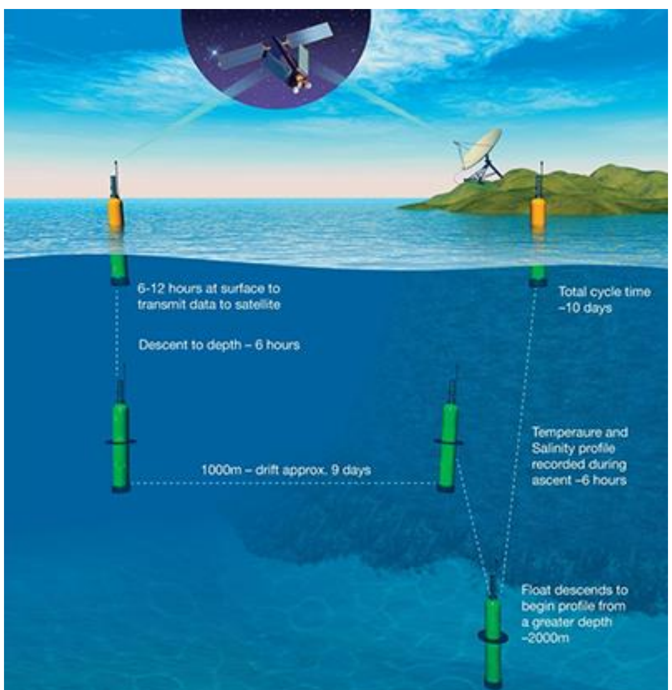
Use of near surface measurements

Impact of scatterometer data in the CERA and UNCPL systems

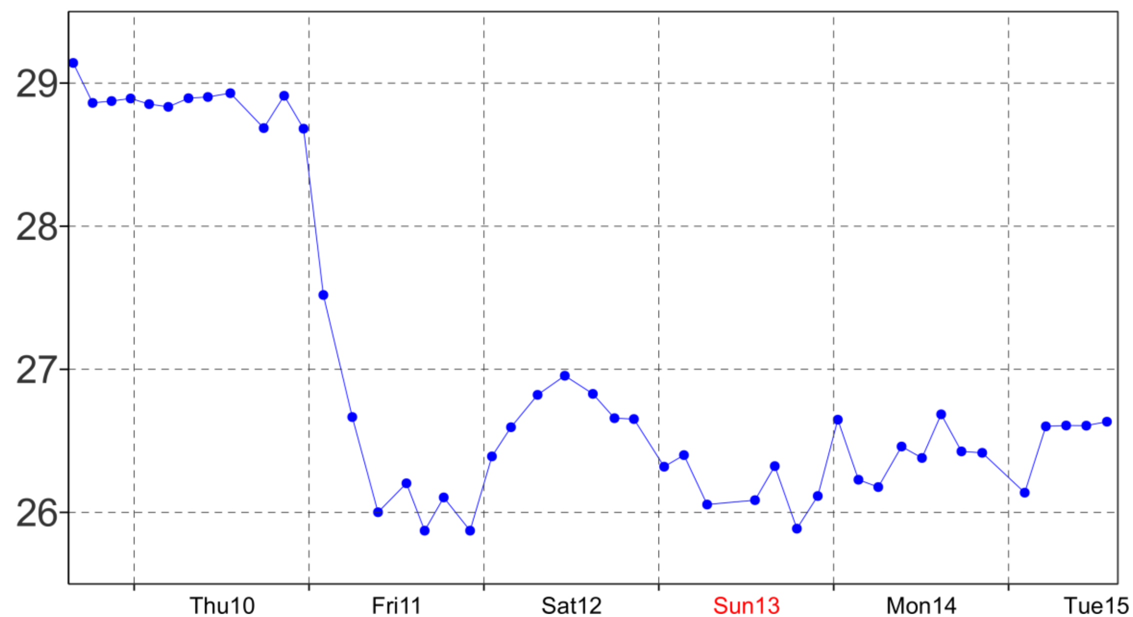


Focus on a specific weather event:

- Tropical cyclone Phailin
- Bay of Bengal
- formed on the 4th October 2013
- Argo probe with high-frequency measurements

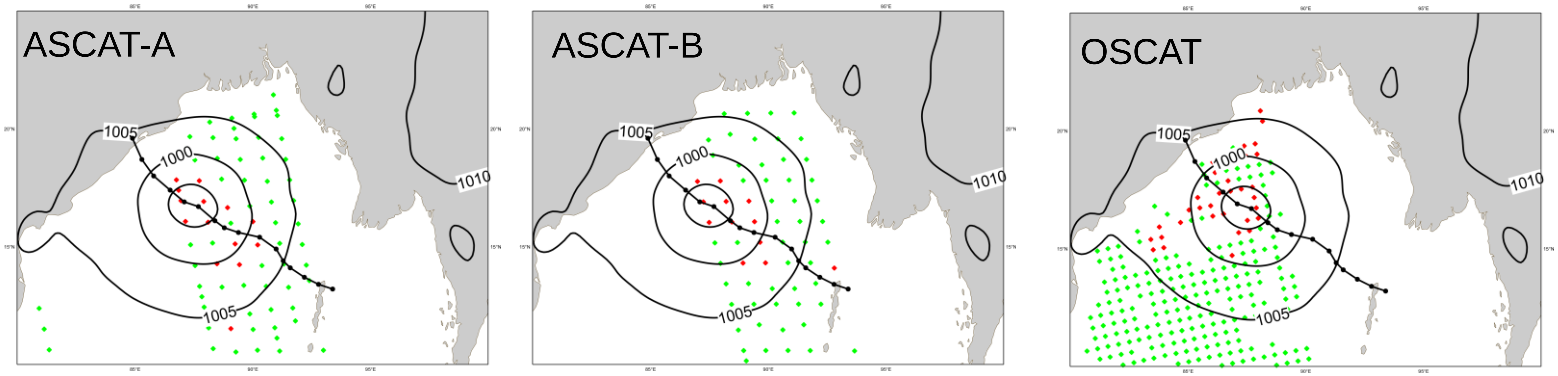


Temperature measurements at 40-meter depth



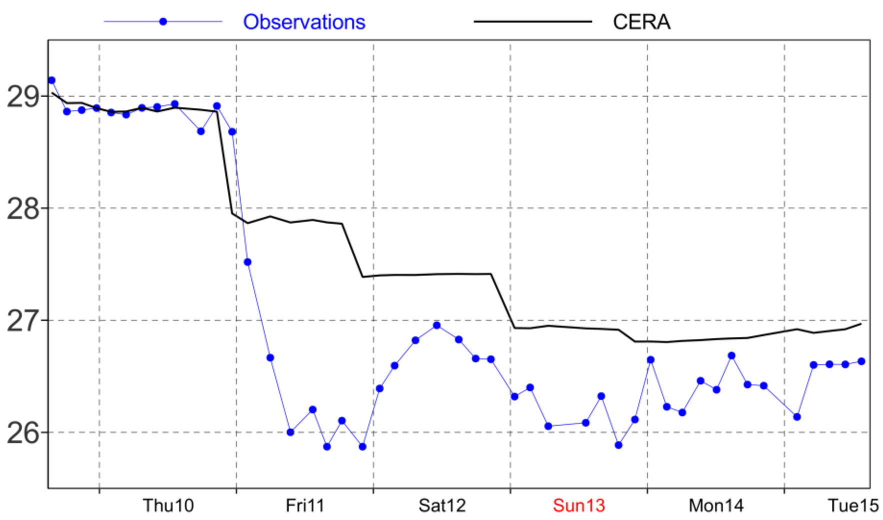
Use of near surface measurements - Tropical cyclone Phailin

Wind measurements from scatterometers (ascending pass, 11 October 2013)

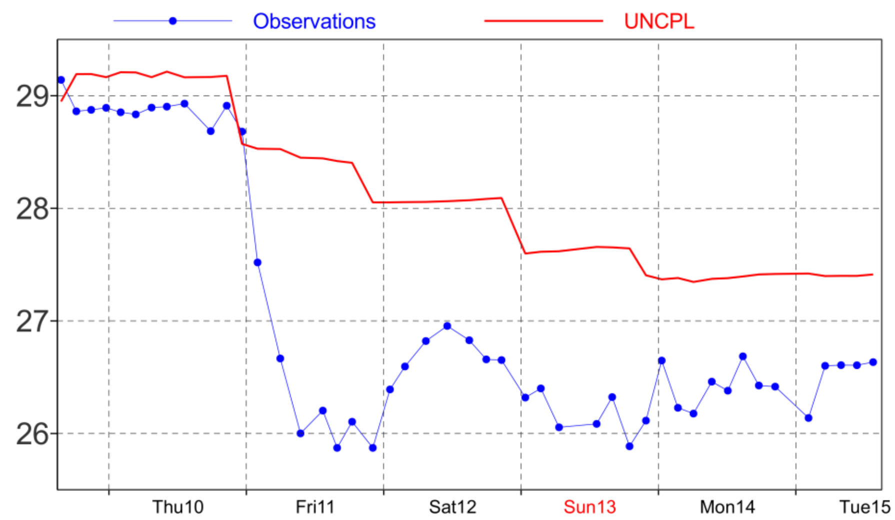


Ocean temperature analysis at 40-meter depth (scatterometer data are assimilated)

CERA



UNCPL

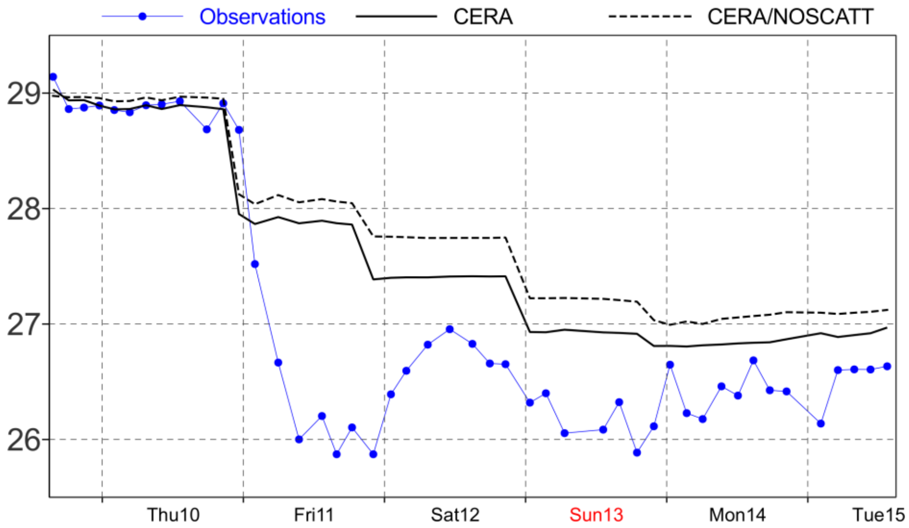


Coupled analysis is closer to the observations with a stronger cold wake

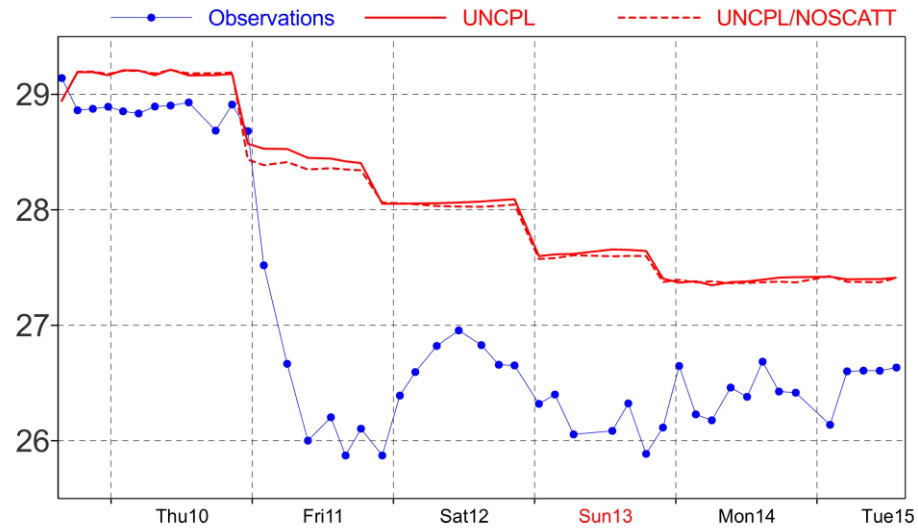
Use of near surface measurements - Tropical cyclone Phailin

Ocean temperature analysis at 40-meter depth (no scatterometer data in dashed)

CERA



UNCPL

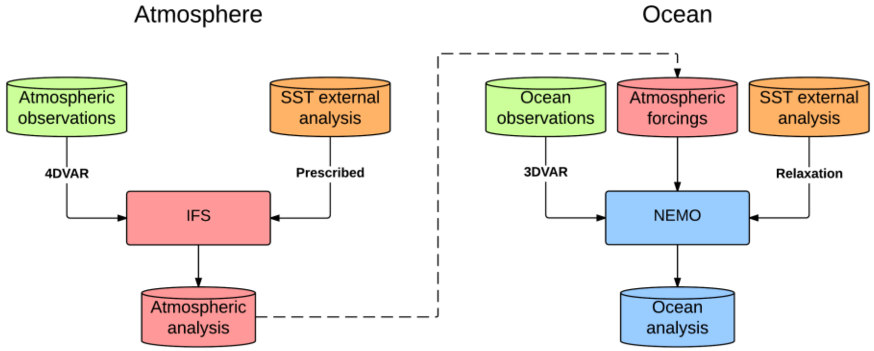


→ Crucial role of scatterometer data to estimate the ocean in coupled assimilation
→ Atmospheric observations have the potential to improve ocean analysis
→ Fit to observations is not perfect: vertical resolution, relaxation to a daily SST product

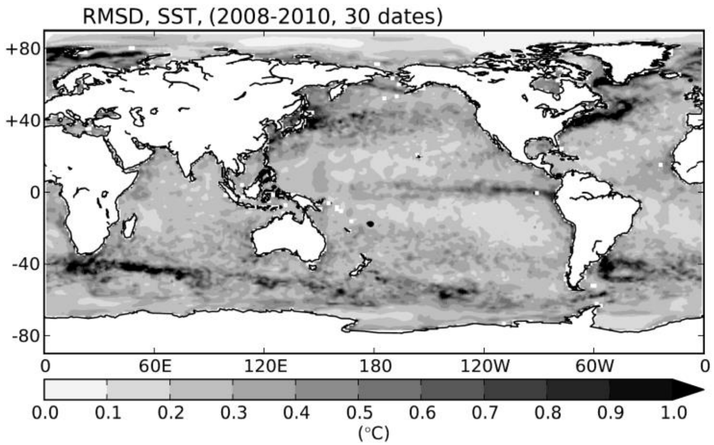
Impact of scatterometer surface wind data in the ECMWF coupled assimilation system
P. Laloyaux, J-N Thépaut and D. Dee. MWR, 2016

Initialisation of coupled forecasts

In the UNCPL system, the atmospheric and ocean analyses are not consistent by construction



During assimilation, SST analyses is prescribed in IFS and relaxed in NEMO



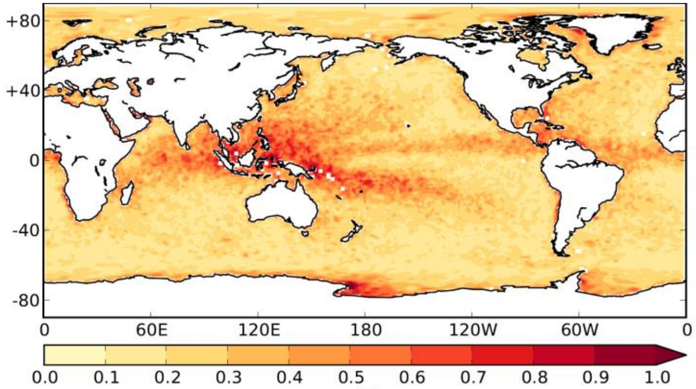
RMS difference between the SST in the ocean and atmospheric analyses (30 dates, 2008-2010)

In the CERA system, the SST is computed in the NEMO model and transferred every hour to the atmosphere

30 medium-range forecasts over 2008-2010 initialised by CERA and UNCPL analysis (full SST coupling)

Initialisation of coupled forecasts

Error in the coupled forecasts initialised by **CERA** analysis
1000hPa temperature RMSE after 12 hours
versus own analysis



model drift:

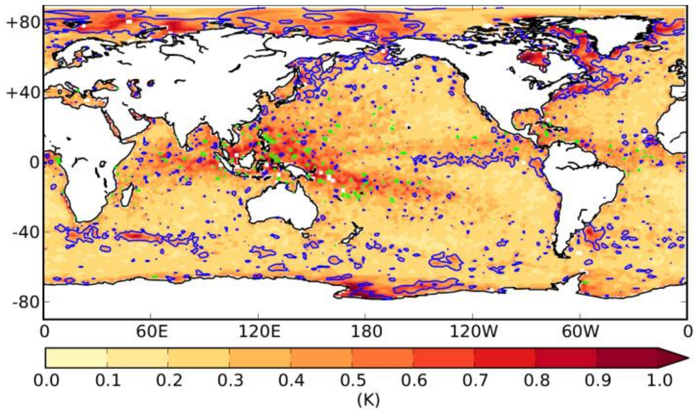
- biases in the model

model adjustment:

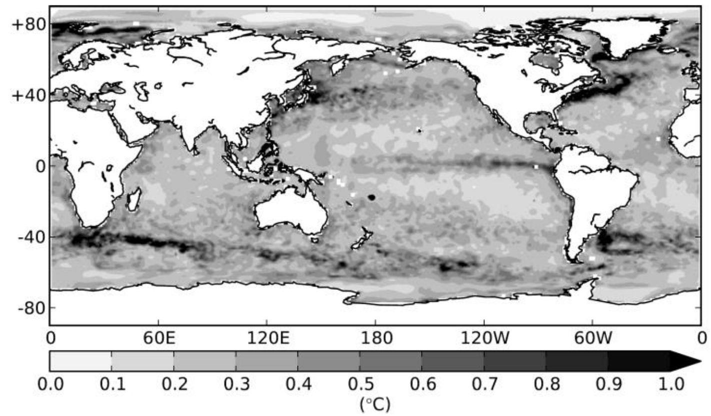
- assimilation switch-off
- imperfections in the CERA initialisation

Error in the coupled forecasts initialised by UNCPL analysis (with the full SST coupling)

1000hPa temperature RMSE after 12 hours
versus own analysis



RMS difference between the SST in the ocean and
atmospheric UNCPL analysis



Blue contours +0.15 in RMSE
Green contours -0.15 in RMSE

Initial shocks linked to unbalanced analysis
SST differences in the UNCPL analysis produce larger

D. Mulholland, P. Laloyaux, K. Haines and M. Balmaseda. Origin and impact of initialisation shocks in coupled atmosphere-ocean forecasts. Monthly Weather Review, In Press, 2016.

Outline of talk

- Operational data assimilation system at ECMWF (atmosphere and ocean)
- The coupled atmosphere-ocean assimilation system (CERA)
- Preliminary results in the context of climate reanalysis
- Preliminary results in the context of NWP
- Directions for future strategy

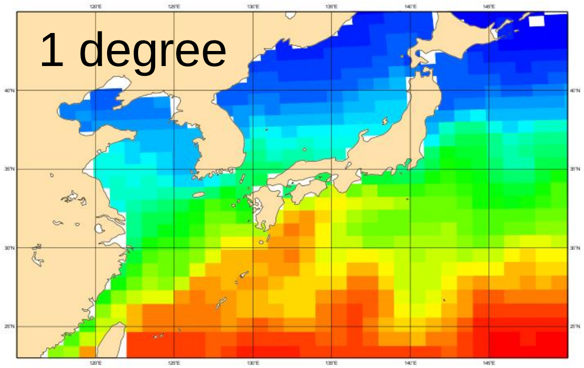
Improving the atmospheric and ocean analysis

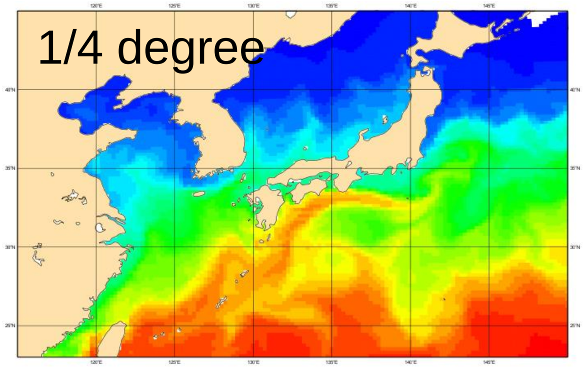
Research activities for new data assimilation strategies for the atmosphere

- overlapping windows (12-hour 4D-Var with a shorter cut-off)
- time-parallelization of the 4D-VAR (based on a weak-constraint formulation)
- improving the EDA, aiming a seamless transition to ENS

From Ocean-S4 to Ocean-S5

- resolution upgrade ¼ degree (75 levels)
- dynamic sea-ice
- new forcing and observation perturbations





Coupling in ENS

- ocean coupling at higher resolution ORCA025 Z75
- dynamic sea-ice coupling

Improving the coupled assimilation system

Working towards a common Earth-system assimilation framework

- coupled assimilation at the outer loop level for all the components
- implemented for sea-ice, ongoing for land surface

Coupled assimilation at higher resolution with upper-air and satellite assimilation

- atmosphere from 110km to 65km
- ocean from 1 degree (42 levels) to ¼ degree (75 levels)
- deliver a proof-of-concept over a recent period (2009 onwards)
- could produce a near-real time coupled analysis

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 coupled cross-correlation from the coupled short-forecast
- coupled tangent linear and adjoint models for the 4D-Var

Improving the coupled assimilation system

A coupled atmosphere-ocean assimilation system has been developing at ECMWF with promising results

- quality of coupled analysis
- use of near surface observations
- initialisation of coupled forecasts

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."

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 that might prove very important in practice (Ozone example, J. Flemming)
- research efforts towards models bias correction in the coupled data assimilation context will be necessary