Coupled Earth System Assimilation in NWP at ECMWF

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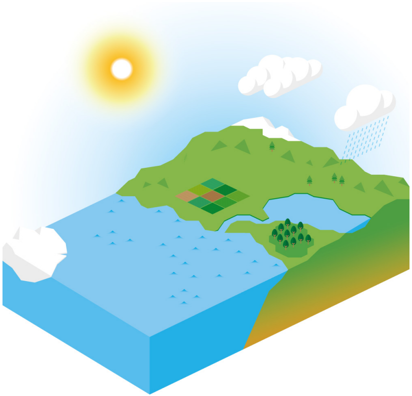
Components of ECMWF forecasts



Components of ECMWF's Earth system.
Along with the atmosphere, there are the ocean, wave, sea ice, land surface, snow, lake, and river models.

Ocean–Sea-Ice–Atmosphere Coupling

Currently

High resolution 10-day forecast has no ocean component

All other forecasts are coupled

- ensemble at 10 days
- extended range
- seasonal forecasts

From June 2018

All forecasts will be coupled to the ocean

Coupled DA nomenclature

We follow the terminology of Penny et al. 2017:

- Observations affect the analysis of different components
  - at a later analysis
    - Assimilation not in all components → Quasi-Weakly Coupled Data Assimilation
    - Through the coupled forecasts → Weakly Coupled Data Assimilation
  - at analysis time
    - Modified DA methods → Quasi-Strongly Coupled Data Assimilation
    - Treated as one single system → Strongly Coupled Data Assimilation

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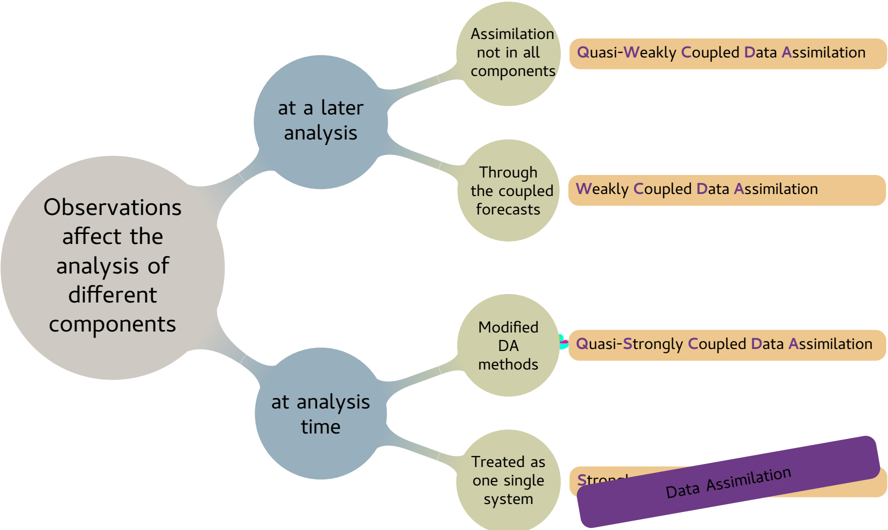

Outline

Current system

Weakly coupled land-surface–atmosphere assimilation

- Snow
- Soil moisture

Weakly coupled ocean–atmosphere assimilation at ECMWF

- WCDA through Sea Ice
- WCDA through Sea Surface Temperature

Quasi-strongly coupled ocean-atmosphere assimilation at ECMWF

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Current ECMWF assimilation systems

Atmosphere

Hybrid 4D-Var with 12 hour assimilation window
Uses OSTIA SST and Sea Ice Concentration (SIC) as lower boundary conditions

Land surface

Weakly coupled to the atmosphere using 2D-OI & SEKF.

Waves

Weakly coupled to the atmosphere using 2D-OI.

Ocean and sea ice

3D-Var FGAT with 8–12 day assimilation window forced by the atmospheric analysis.

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Weakly coupled Land Data Assimilation

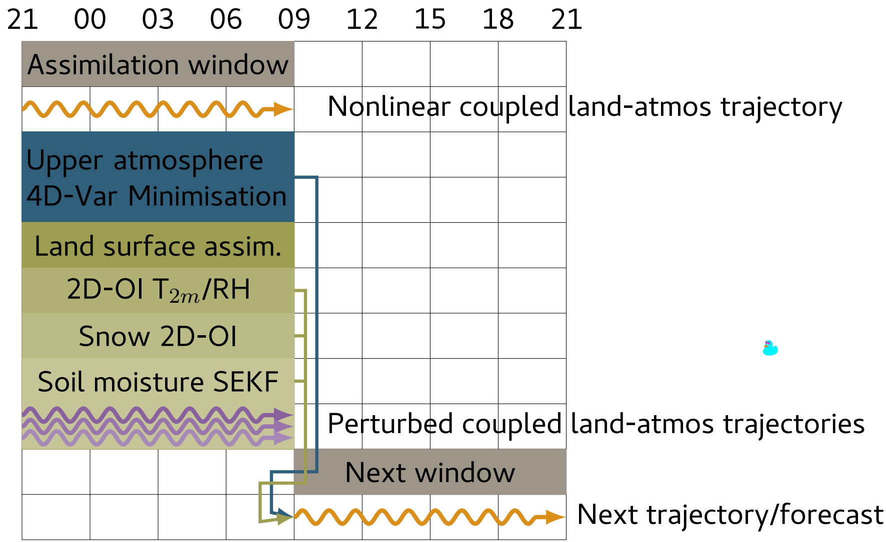
Justification

- Vertical correlations dominate land surface processes. Therefore each grid point is analysed independently. Land data assimilation is a 2D problem, whereas the atmosphere DA is a 4D problem.
- Weak coupling gives flexibility to run land analysis without the expensive 4D-Var component (ERA-Land type).

Weaknesses

- Increments related to fast coupled processes (e.g. precip/soil moisture) are potentially inconsistent at the interface.

Weakly coupled land-surface–atmosphere overview



Snow depth assimilation

Snow model — Dutra et al. 2010,Balsamo et al. 2009

Component of H-TESSEL — Single layer snowpack

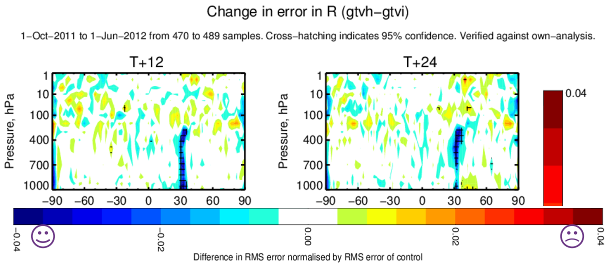
Snow water equivalent (m)
Snow density(ρ)
} prognostic variables

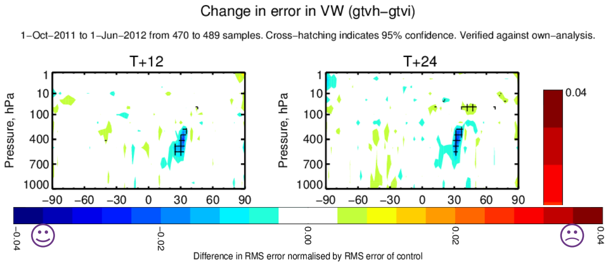
Observations

- Conventional snow depth data: SYNOP and National networks
- Snow cover extent: NOAA NESDIS/IMS daily product (4km)

We use a 2D OI for snow assimilation.
The 2D structure function is a function of both horizontal and vertical separation - snow at two (horizontally) nearby points are less related if one point is at sea level and the other on a mountaintop.

Impact of assimilating snow cover in Himalayas





Impacts of snow assimilation are felt throughout the troposphere

This is due to change in albedo and its influence on the whole atmospheric column

Simplified EKF soil moisture analysis

$$x^a = x^b + K(y - \mathcal{H}(x^b)) \qquad K = PH^T(HPH^T + R)^{-1}$$

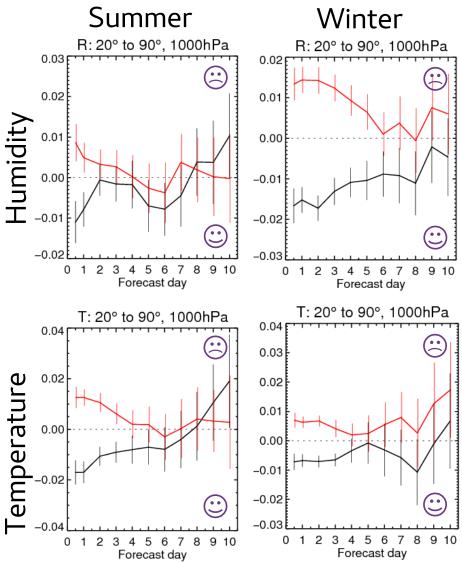
$$x = \begin{bmatrix} SM_{\ell_1} \\ SM_{\ell_2} \\ SM_{\ell_3} \end{bmatrix} \qquad y = \begin{bmatrix} T^*_{2m} \\ RH^*_{2m} \\ ASCAT_{sm} \end{bmatrix} \qquad \mathcal{H}(x^b) = \begin{bmatrix} T_{2m} \\ RH_{2m} \\ SM_{top} \end{bmatrix}$$

* pseudo-observations computed by 2D-OI.

The Jacobians H are computed via perturbed trajectories - i.e. a finite difference approximation.

Future plans are to approximate H directly from the EDA (Ensemble of Data Assimilations)

Impact of (weakly coupled) soil moisture analysis on NWP



No soil moisture analysis

zero line: IFS cycle 40r1 (2013)

IFS cycle 41r1 (2015) Revised σ_o

Very large impact of soil moisture initialisation on near-surface weather forecast

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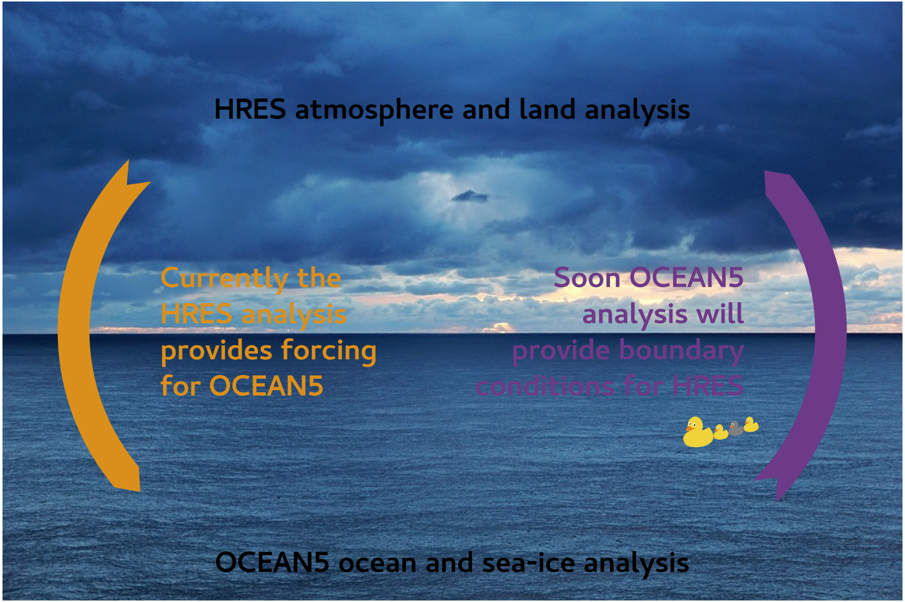
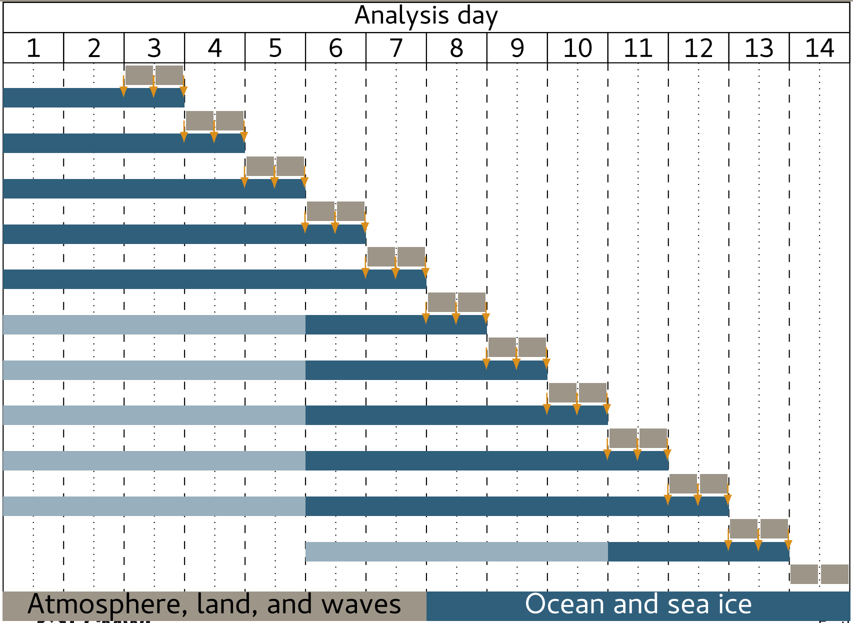
Quasi-strongly coupled ocean-atmosphere assimilation at ECMWF

Weakly coupled assimilation concept

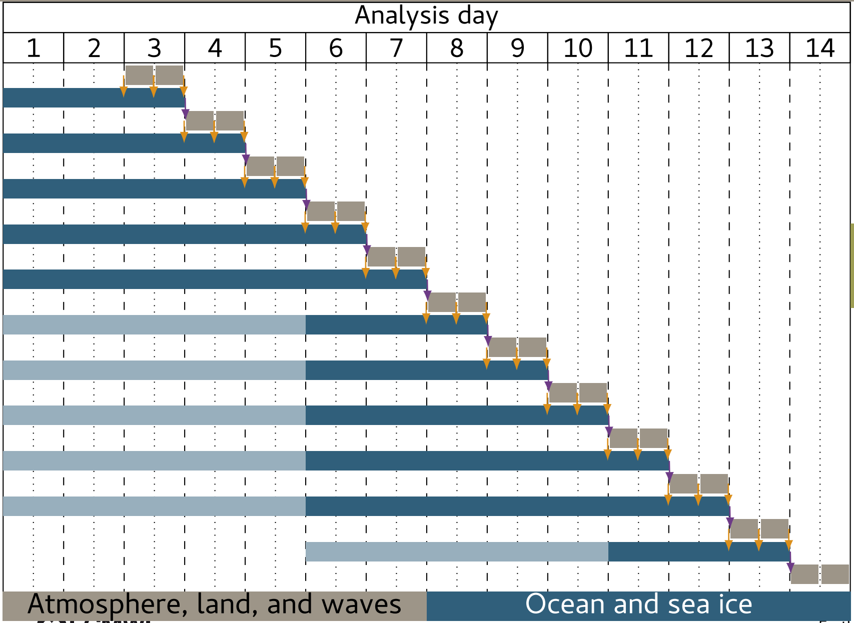


WCDA Information Flow



Atmospheric forcings fluxes, winds, precipitation, radiation

WCDA Information Flow



Atmospheric forcings fluxes, winds, precipitation, radiation

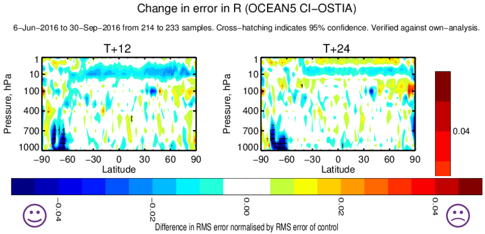
SIC/SST from Ocean Analysis

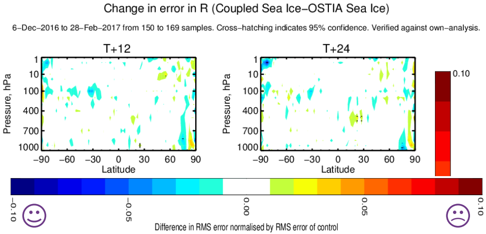
WCDA Sea Ice Concentration impact on Humidity and Temperature

Southern hemisphere winter

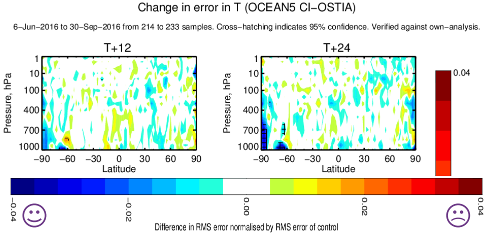
Northern hemisphere winter

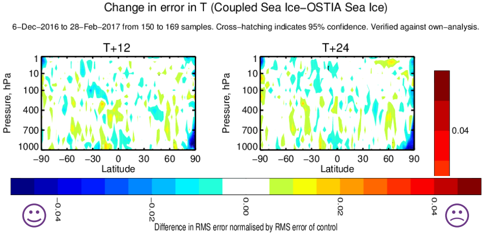
Humidity





Temperature



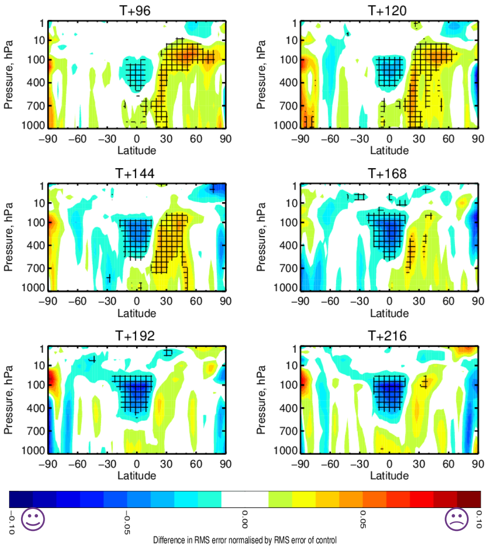


In these results we show $$\frac{||\boldsymbol{x}_f^e(t)-\boldsymbol{x}_a^e(t)||-||\boldsymbol{x}_f^c(t)-\boldsymbol{x}_a^c(t)||}{||\boldsymbol{x}_f^c(t)-\boldsymbol{x}_a^c(t)||}$$

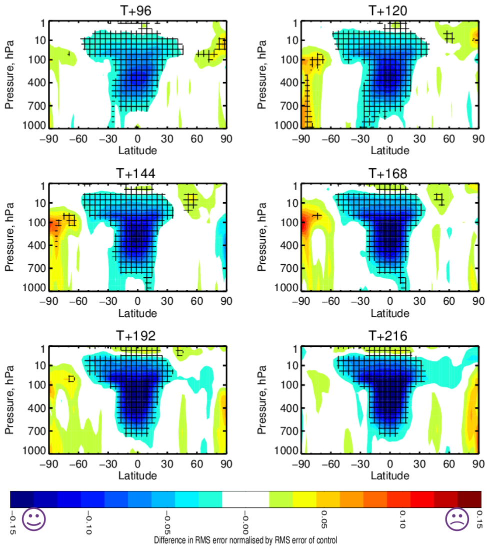
fc uncoupled

WCDA Sea Surface Temperature impact on Geopotential

SST globally



SST tropics only

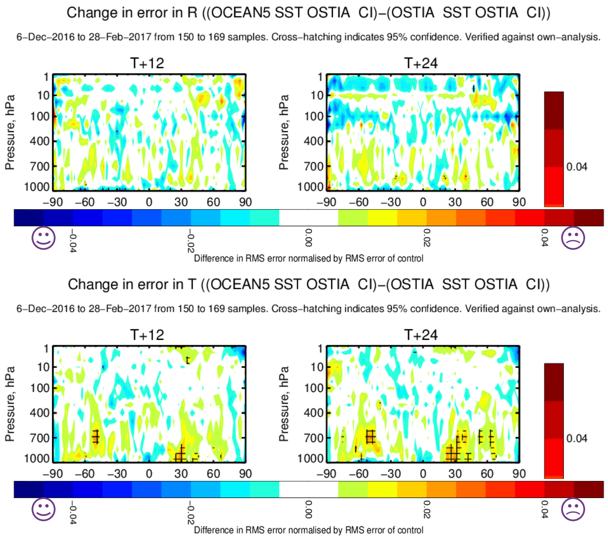


fc uncoupled

ECMWF EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

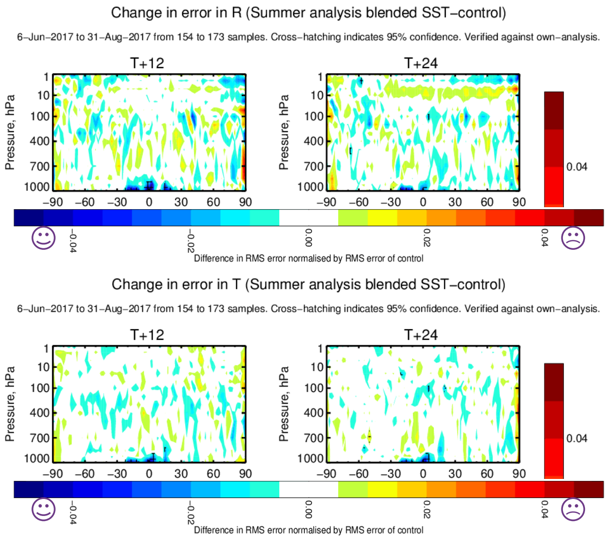
Earth System CDA. ISDA2018

WCDA SST impact on Humidity and Temperature



fc uncoupled

WCDA SST in tropics only impact on Humidity and Temperature



fc coupled

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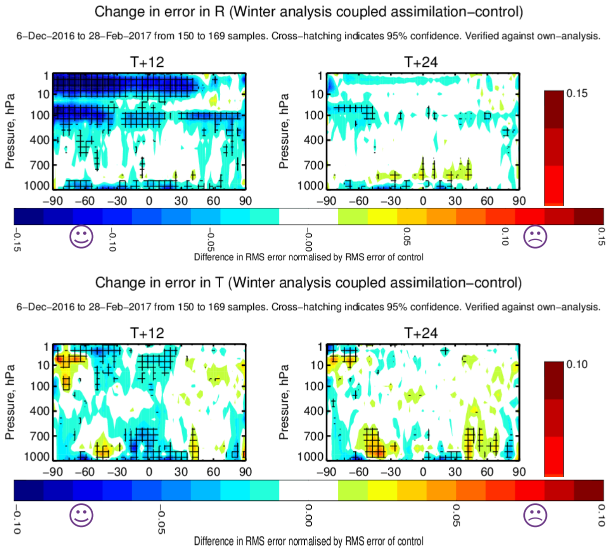
Quasi-strongly coupled ocean-atmosphere assimilation at ECMWF

Quasi-strongly coupled assimilation at ECMWF - outer loop coupling

We follow the approach taken in the CERA-20C (Laloyaux et al. 2016) and CERA-SAT reanalyses.

- Coupled forecasts
- Coupled non-linear trajectories
- Separate minimisations:
  - Upper air 4D-Var
  - Ocean and sea-ice 3D-Var FGAT
- Assimilation windows aligned with the atmosphere; 12 hour window

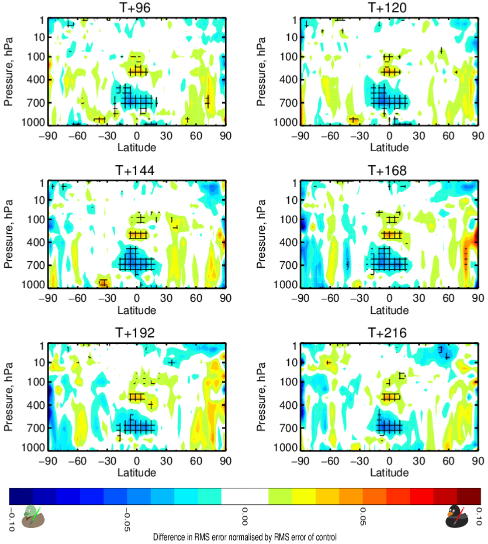
QSCDA (Outer loop coupling) impact on Humidity and Temperature



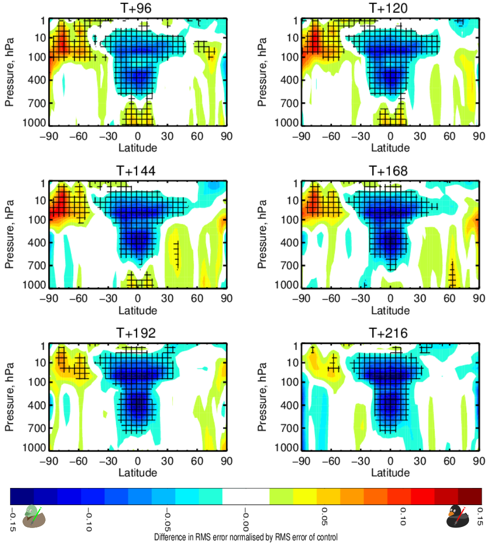
fc coupled

QSCDA Medium-range impact on Temperature and Geopotential

Temperature



Geopotential



fc coupled

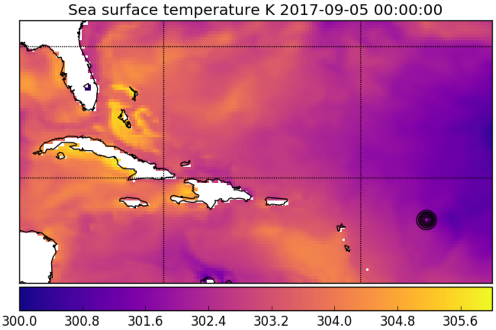
Earth System CDA. ISDA2018

Conclusions

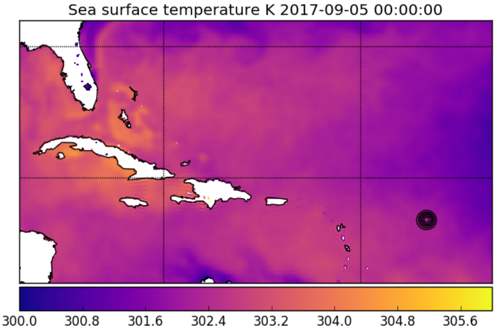
- At ECMWF we have to initialise coupled models
- Progressively more levels of assimilation coupling are being targetted for operational NWP
- Weakly coupled land-surface–atmosphere assimilation has been successful for improving NWP
- Ocean–atmosphere weak coupling through sea-ice field will be first, followed by SST coupling in the tropics
- Global ocean–atmosphere WCDA and QSCDA will require improvements to the ocean model to be used operationally
- QSCDA needs further research in terms of ocean observation usage/latency and drifts

QSCDA for Hurricanes Irma and Jose

Coupled assimilation



Uncoupled analysis (OSTIA)



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Dutra, Emanuel et al. (2010). “An Improved Snow Scheme for the ECMWF Land Surface Model: Description and Offline Validation”. In: *Journal of Hydrometeorology* 11.4, pp. 899–916. ISSN: 1525-755X. DOI: 10.1175/2010JHM1249.1. URL: http://journals.ametsoc.org/doi/abs/10.1175/2010JHM1249.1.

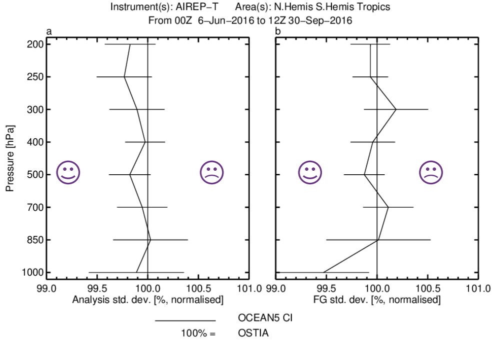
Laloyaux, Patrick et al. (2016). “A coupled data assimilation system for climate reanalysis”. In: *Quarterly Journal of the Royal Meteorological Society* 142.694, pp. 65–78. ISSN: 1477870X. DOI: 10.1002/qj.2629.

Penny, Stephen G et al. (2017). *Coupled Data Assimilation for Integrated Earth System Analysis and Prediction: Goals, Challenges and Recommendations*. Tech. rep. World Meteorological Organisation WWRP 2017 - 3.

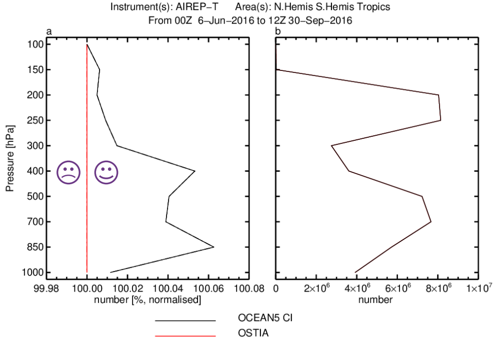
Extra slides

WCDA Sea Ice Concentration impact on AIREP-T observations

Fit to observations

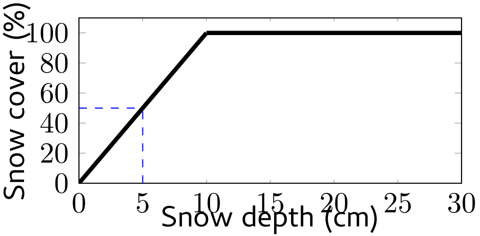


Observation counts



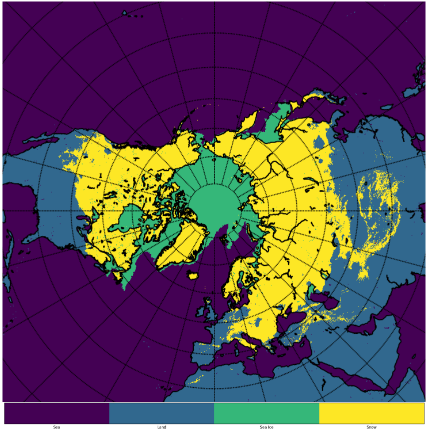
Assimilation of IMS snow cover

- IMS snow cover (SC) means SC$> 50\%$
- No quantitative information on snow depth



FG / IMS	Snow	No snow
Snow	NO DA	$y = 5$ cm
No Snow	$y = 0$ cm	$y = 0$ cm

IMS product 20180226



De Rosnay et al. 2015