ECMWF Annual Seminar, 10-13 September 2018

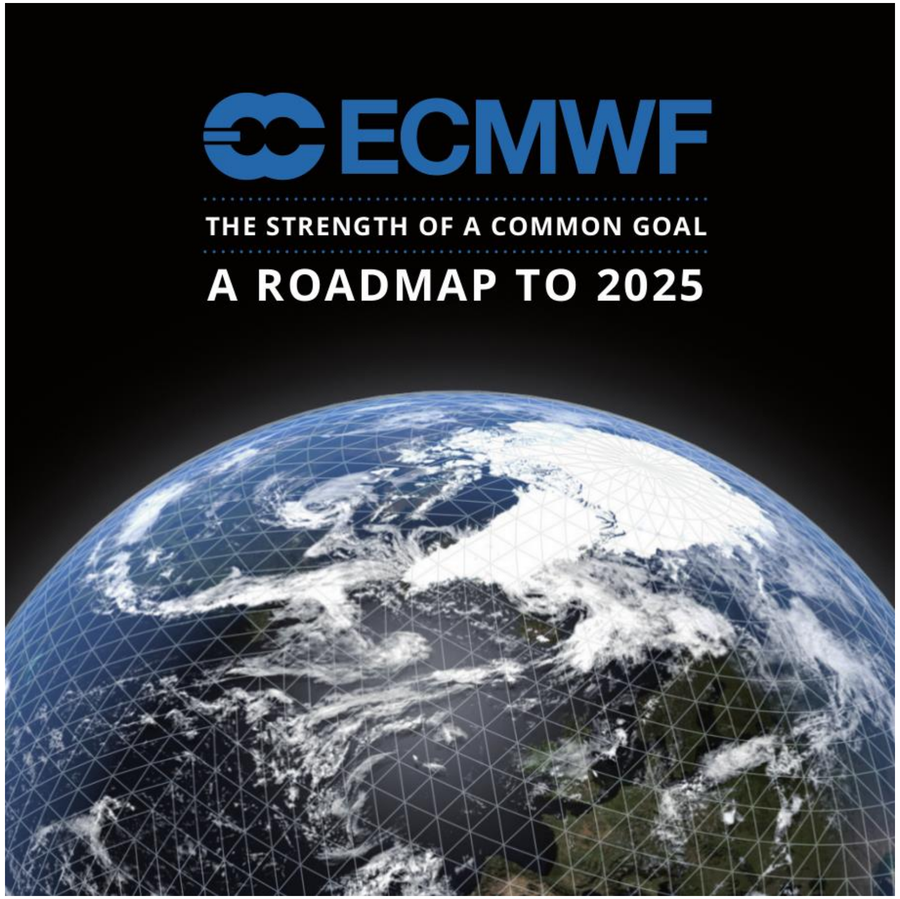
Towards coupled assimilation in operational systems

Patricia de Rosnay, Philip Browne, Eric de Boisséson, David Fairbairn,
Yoichi Hirahara, Dinand Schepers, Hao Zuo,
(Coupled Assimilation Team)

Hans Hersbach, Marcin Chrust, Elias Hólm,
Massimo Bonavita, Mohamed Dahoui, Steve English

Thanks to:
Magdalena Alonso-Balmaseda, Gianpaolo Balsamo, Andrew Bennett, Jean Bidlot, Axel Bonet, Per Dahlgren, Andrew Dawson, Giovanna De Chiara, Reima Eresmaa, Alan Geer, Lars Isaksen, Yuki Kosaka, Patrick Laloyaux, Cristina Lupu, Ioannis Mallas, Kristian Mogensen, Nemesio Rodríguez-Fernández, and many other colleagues

Earth system approach

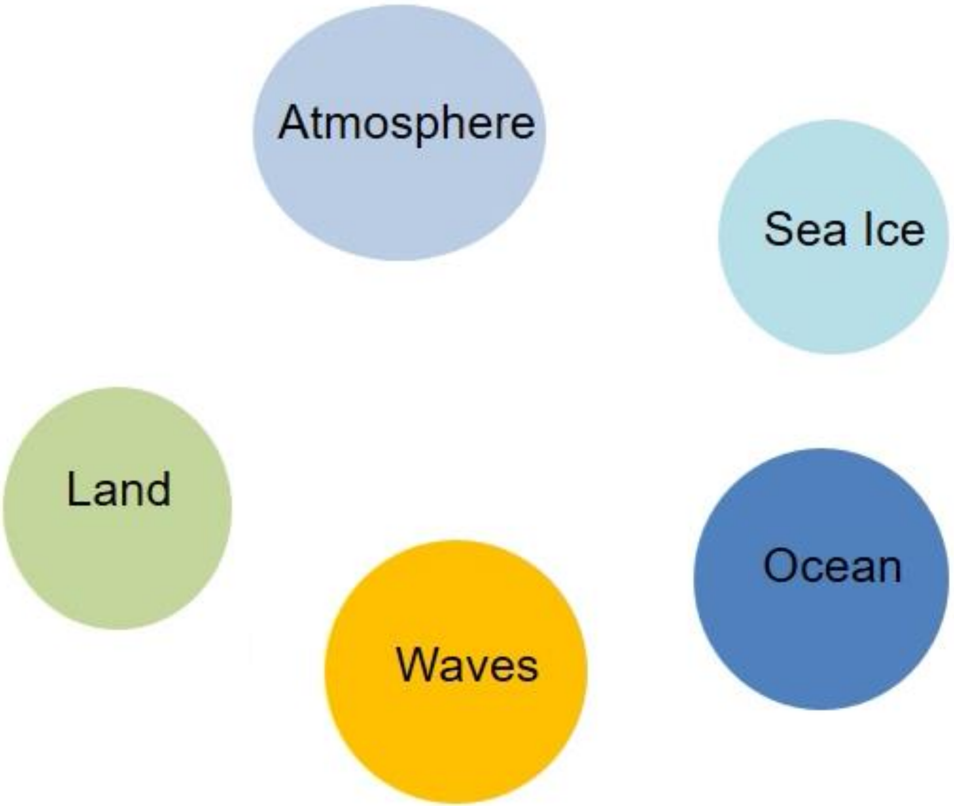


Strategy 2016-2025

- Coupled modelling of the Earth System Components
- Interactions between the different components in the model and assimilation
- Coupled assimilation → consistent initial conditions to the coupled model.

Earth System components

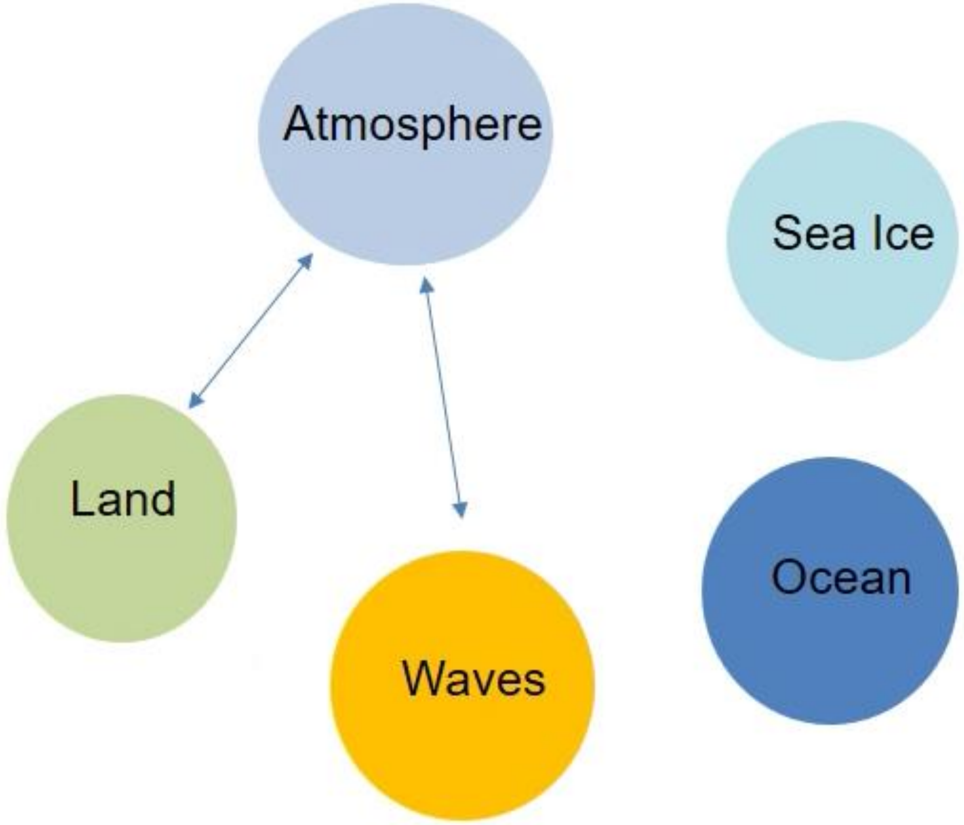
Integrated Forecasting System (IFS)



Earth System components

Coupled Models

Integrated Forecasting System (IFS)

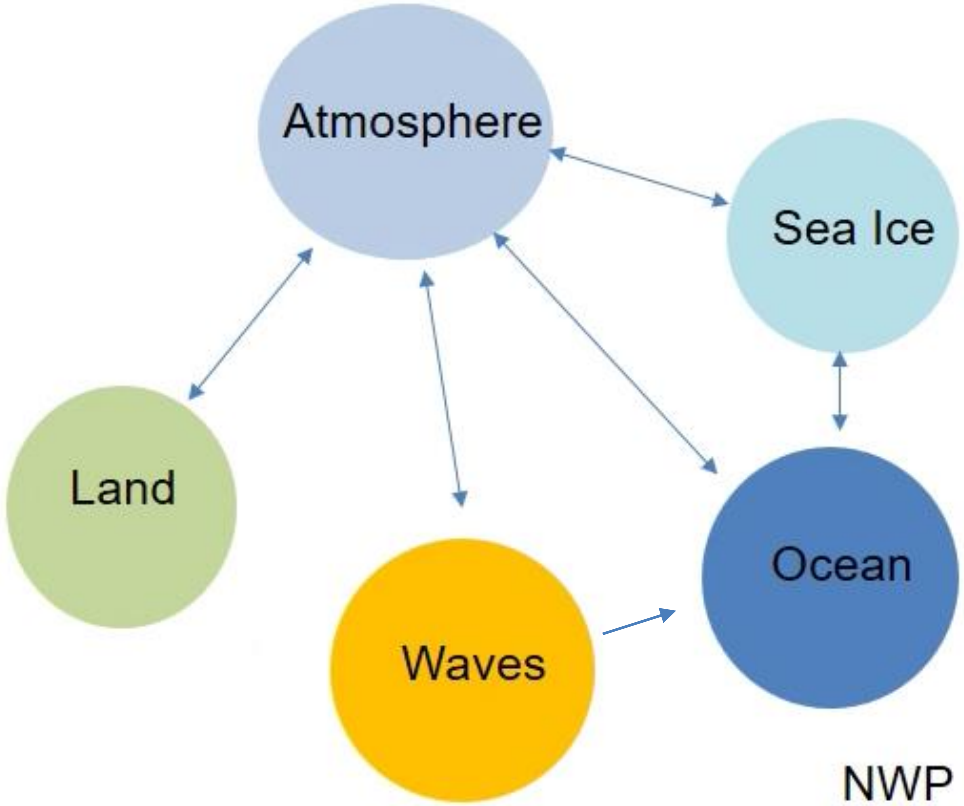


- Current operational analysis background FC,
- ERA-Interim, ERA5,
- NWP medium range HRES until June 2018

Earth System components

Coupled Models

Integrated Forecasting System (IFS)

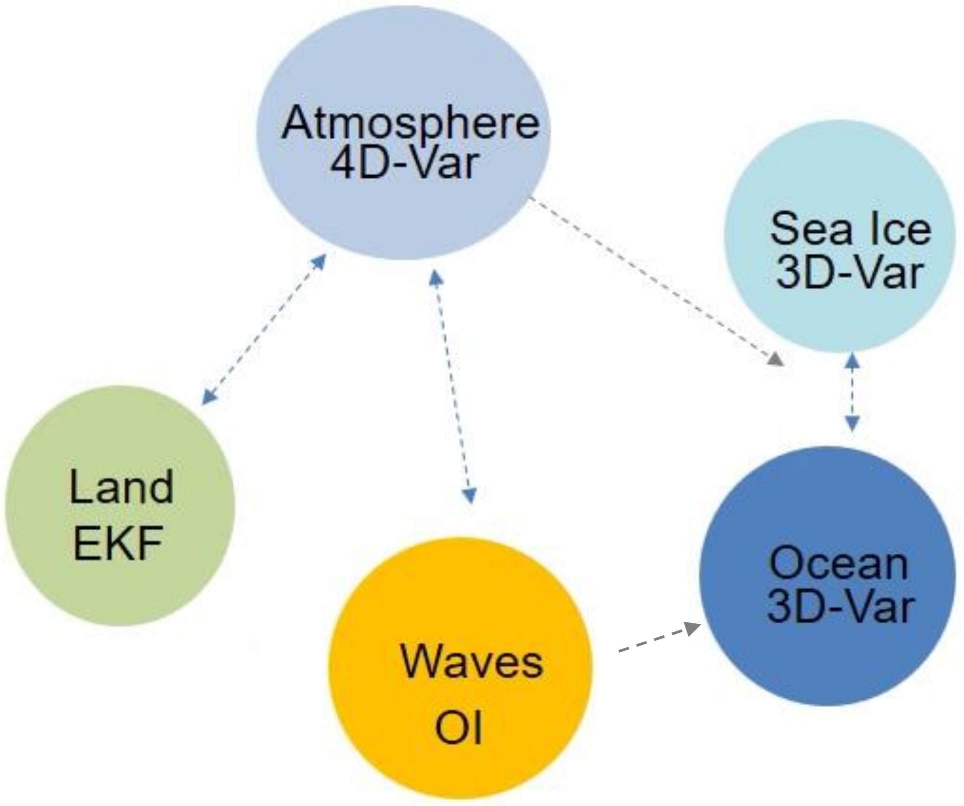


NWP HRES (since June 2018)
ENS, medium, extended, seasonal
CERA system

Earth System components

Coupled Assimilation

Integrated Forecasting System (IFS)

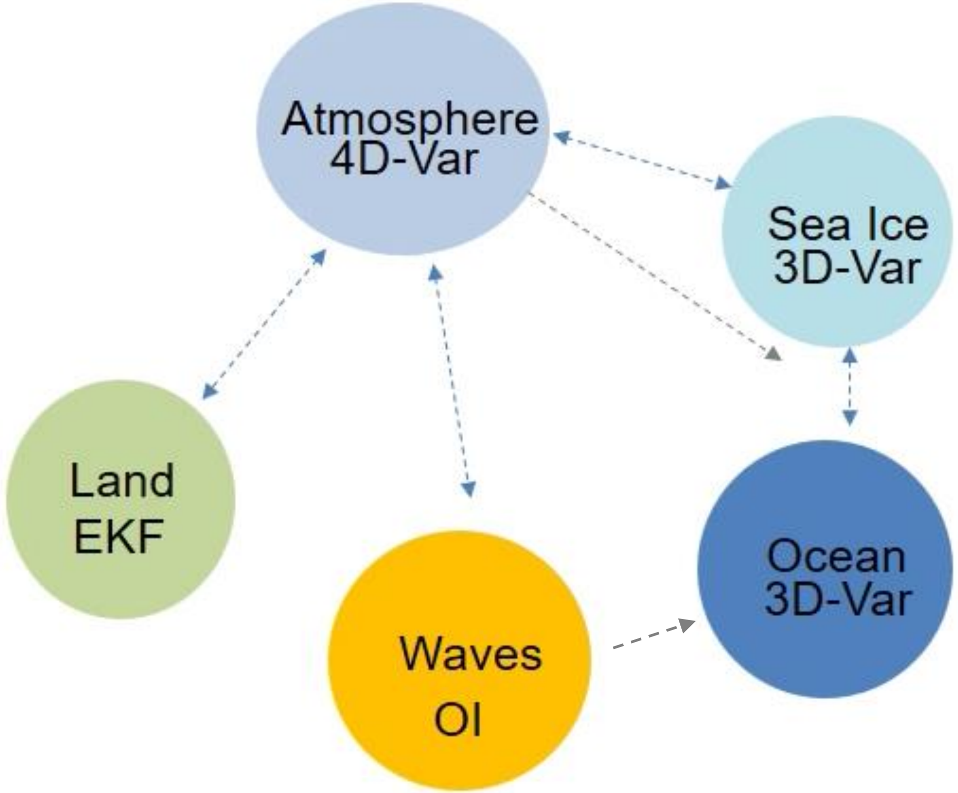


ERA-Interim, ERA5, Oper analysis until June 2018: land and waves weakly coupled approach
Uncoupled Ocean5/ORAS5 system for ocean and sea-ice (Zuo et al. ECMWF Tech Memo 823, 2018)

Earth System components

Coupled Assimilation

Integrated Forecasting System (IFS)

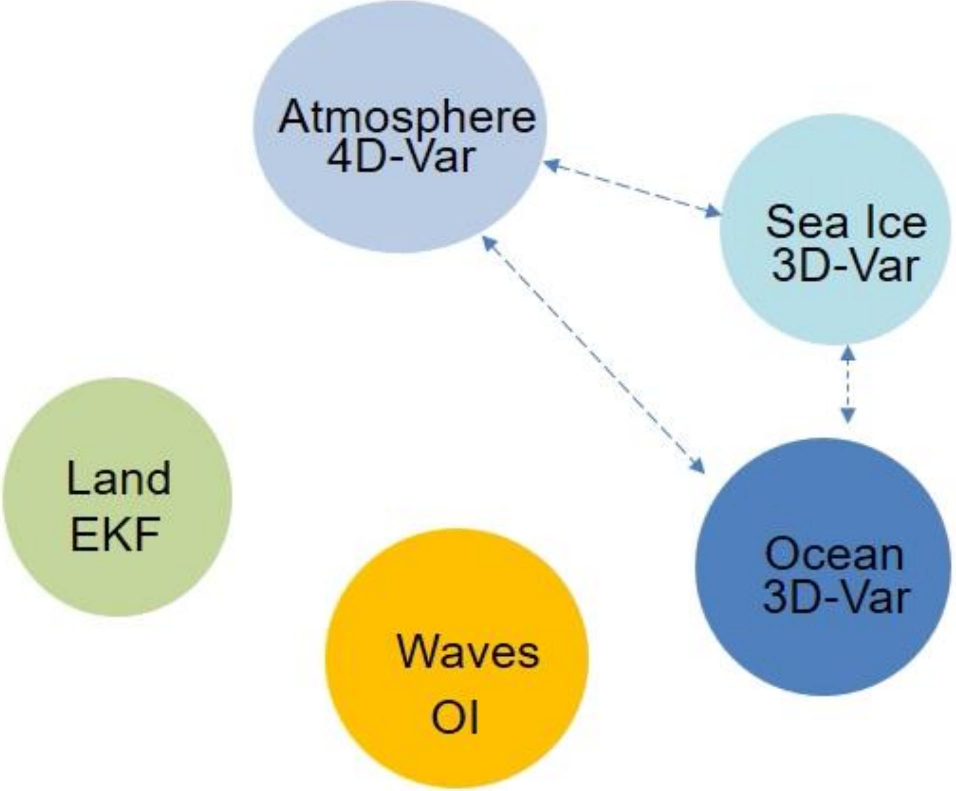


Oper analysis (HRES, EDA) since June 2018: coupling with the OCEAN5 system through sea-ice fields

Earth System components

Coupled Assimilation

Integrated Forecasting System (IFS)

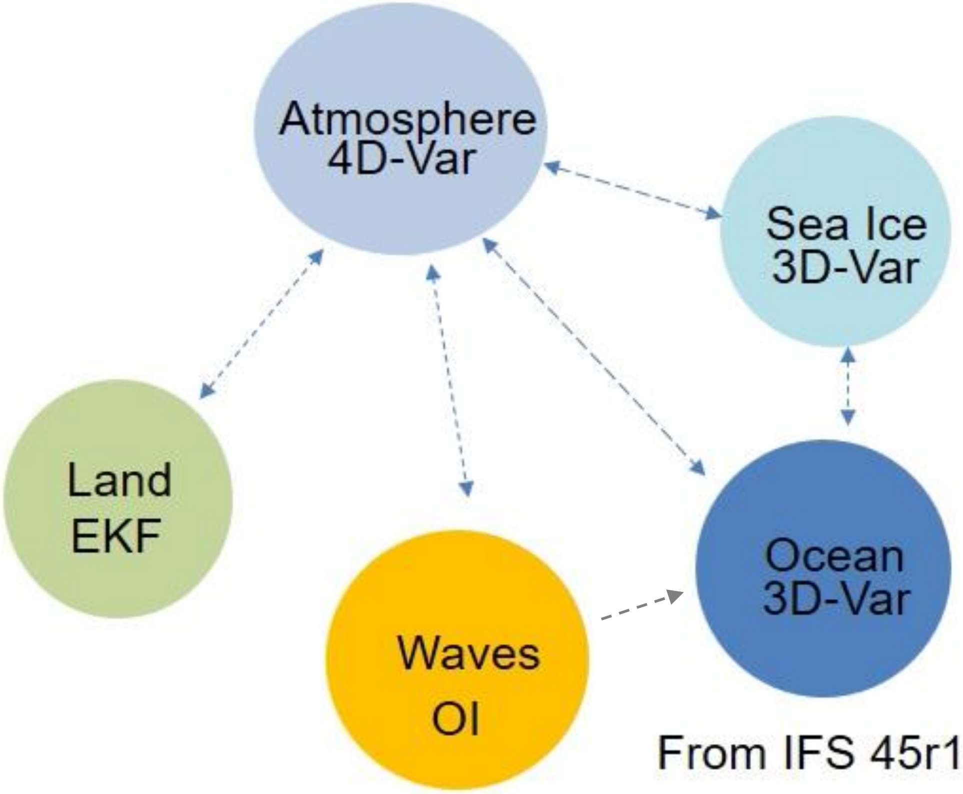


CERA-20C: “outer loop” coupling for atm-ocean, sea ice (Laloyaux et al., QJRMS 2016)

Earth System components

Coupled Assimilation

Integrated Forecasting System (IFS)



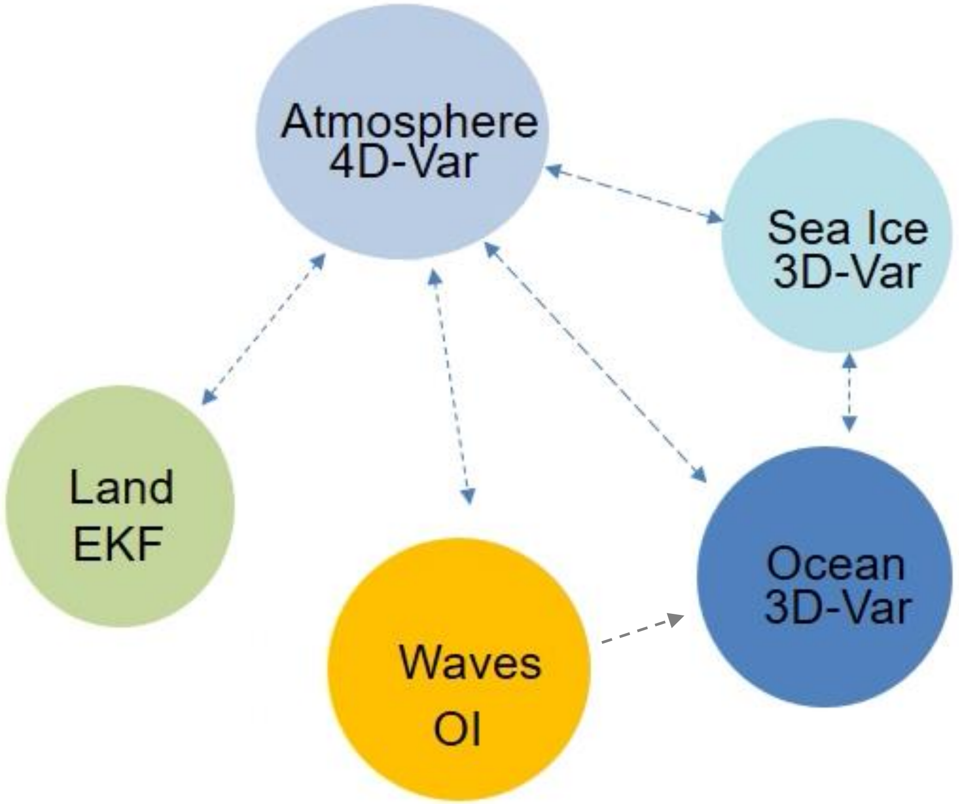
CERA-SAT: IFS 42r1, land,wave, sea-ice, full observing system

From IFS 45r1: modular option of suite definition

Earth System components

Coupled Assimilation

Integrated Forecasting System (IFS)

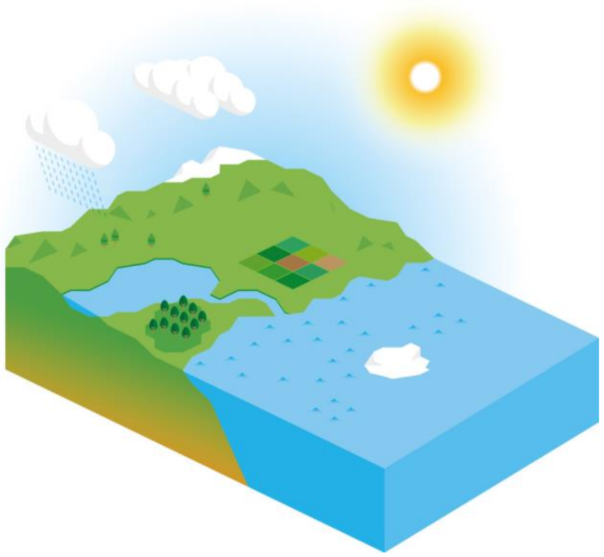


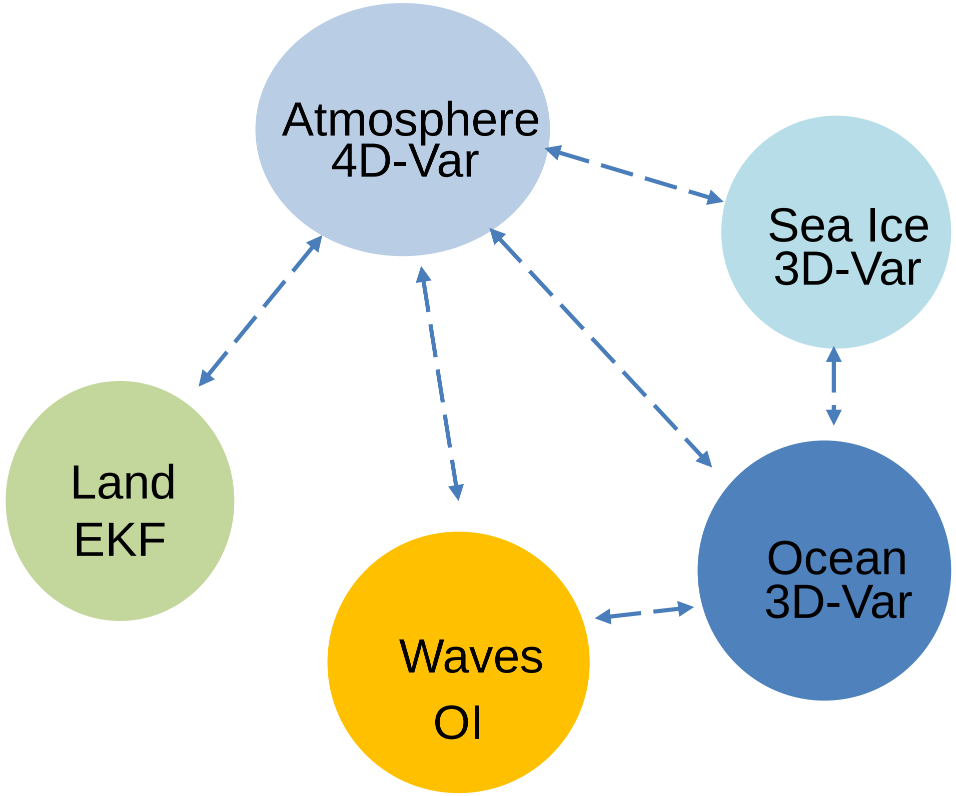
→ Diversity of model and assimilation coupling configurations depending on the systems (medium, extended, seasonal, reanalysis, etc)

Toward coupled assimilation in operational systems

Coupled assimilation

Integrated Forecasting System (IFS)





- Modular system to account for the different components in coupled assimilation
- Consistency of the coupling approaches across the different components of the Earth System

Toward coupled assimilation in operational systems

Methodology:

- Coupled assimilation is a relatively new field of research, with many open questions (error growth time scales, definition and use of cross-covariances, coupling strategy from weak to strong coupling, etc)

Further progress in coupled assimilation rely on modular approaches

→ Link to methodology and unified framework development (e.g. OOPS at ECMWF)

Infrastructure:

- Earth System approach is also valid for the suite definition which needs to be modular (no hard coded suites)

Observing system and monitoring:

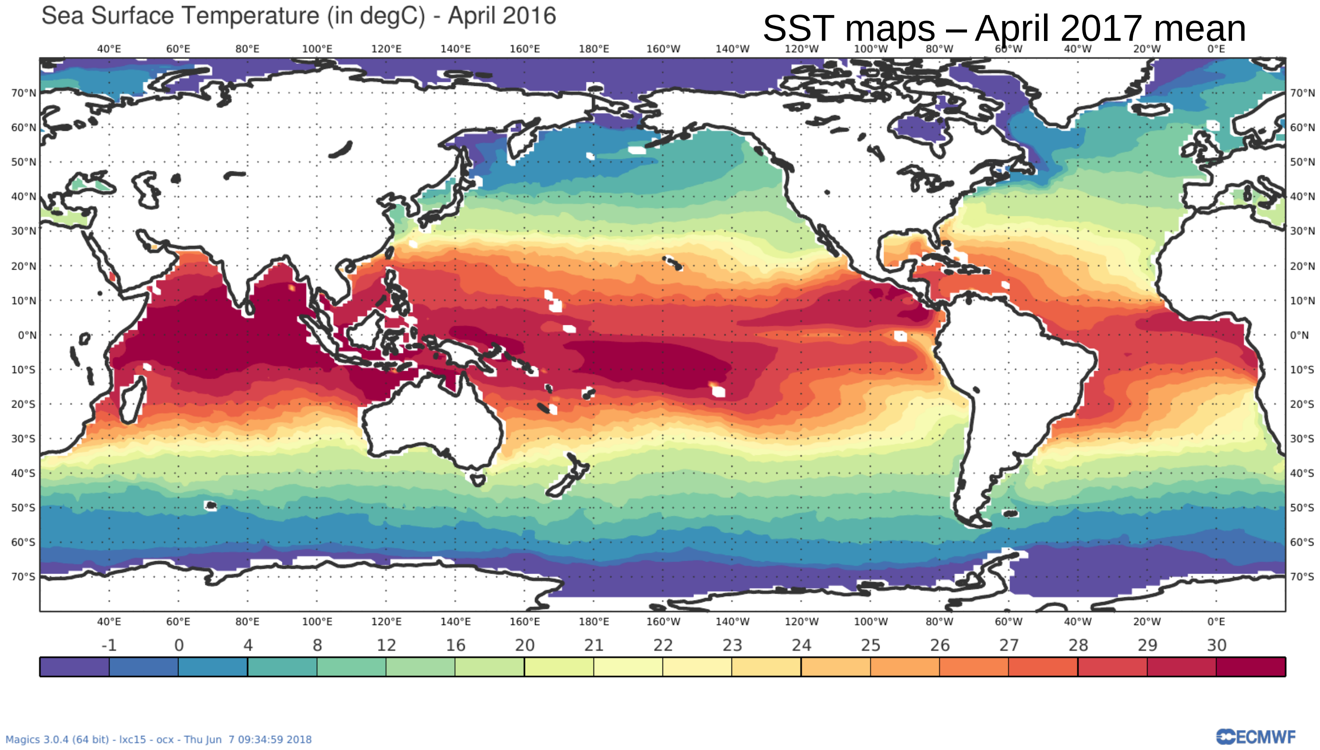
- Need to standardise acquisition, observation pre-processing, feedback files, and monitoring for ocean and sea ice in particular

Observation operators: developments for observations that depend on more than one sub-system (e.g. snow)

Toward coupled assimilation in operational systems

Infrastructure, observing system and monitoring

- Use of same file system for ocean than for land and atmosphere, develop research testing environment
- Capability for ocean fields archiving (NetCDF in MARS) ongoing for CERA-20C ocean component, ORAS5), also needed for coupled assimilation ocean fields – in development
- Operational monitoring in the model space (in progress for OCEAN5)

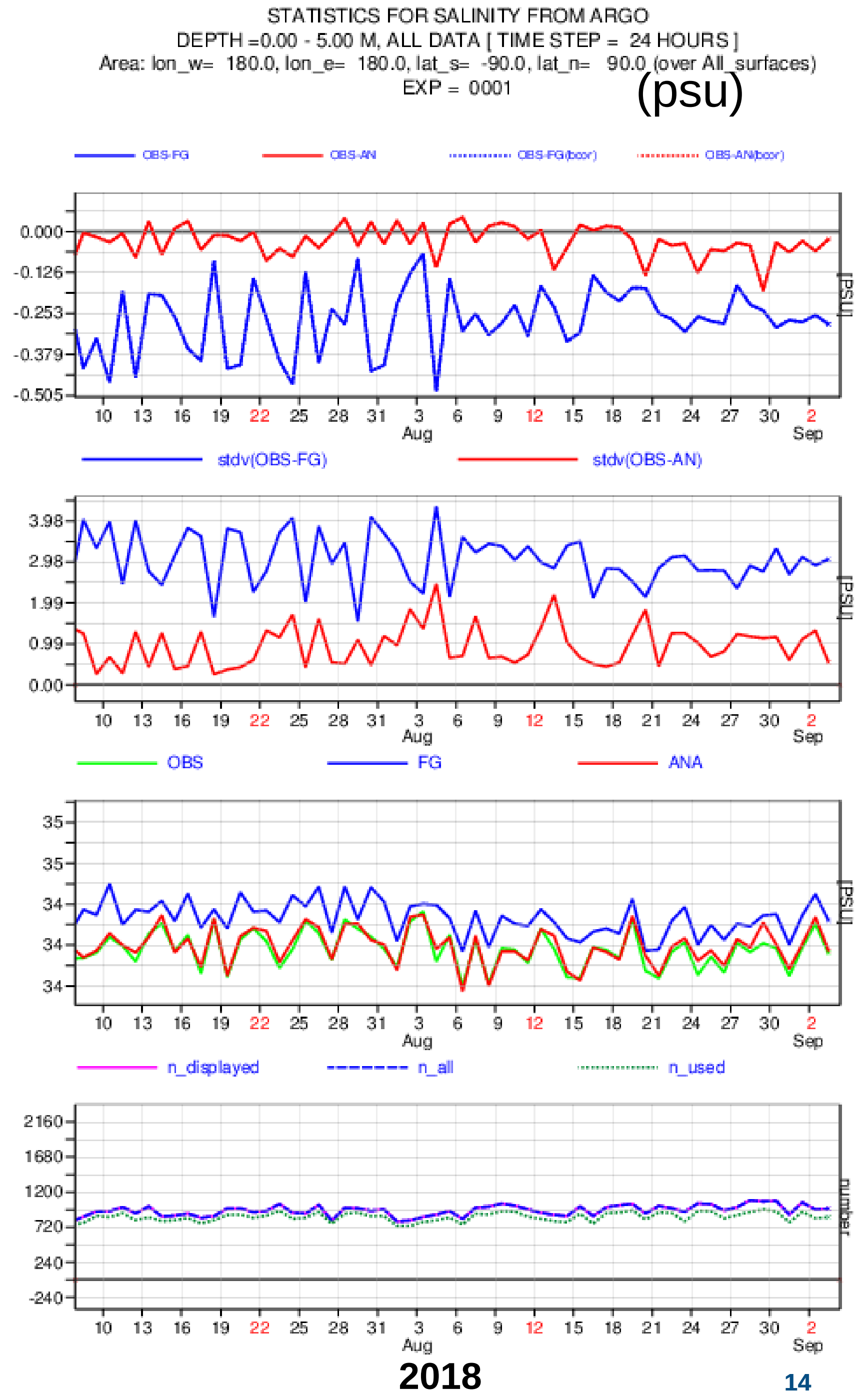


Infrastructure, observing system and monitoring

- OCEAN5 operational observation monitoring (since 2017)
https://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system#Ocean

- Observation acquisition
  - New Interface Control Document for Sea Level Observations acquisition (de Rosnay et al ECMWF Newsletter 2017)
  - Needed for SST acquisition

- Observation sustainability for the ocean / level of support from governing bodies to ensure in situ data provision



Coupled data assimilation (CDA): Terminology

Penny et al., Coupled Data Assimilation for Integrated Earth System Analysis and Prediction: Goals, Challenges and Recommendations. World Meteorol. Org. (WMO), WWRP 2017-3, 2017.

Observations increments in one component impact the other components

In the next data assimilation windows

- Independent DA for a sub-set of components — **Quasi WCDA**
- Independent DA for all components; Interaction through model coupling — **WCDA**

During the data assimilation window

- Multiple systems approach (e.g. outer loop coupling) — **Quasi SCDA**
- Single integrated system — **SCDA**

Weakly Coupled Data Assimilation - - - - - → **Strongly coupled Data Assimilation**

\- → +

(non-exhaustive) spectrum of coupling methods

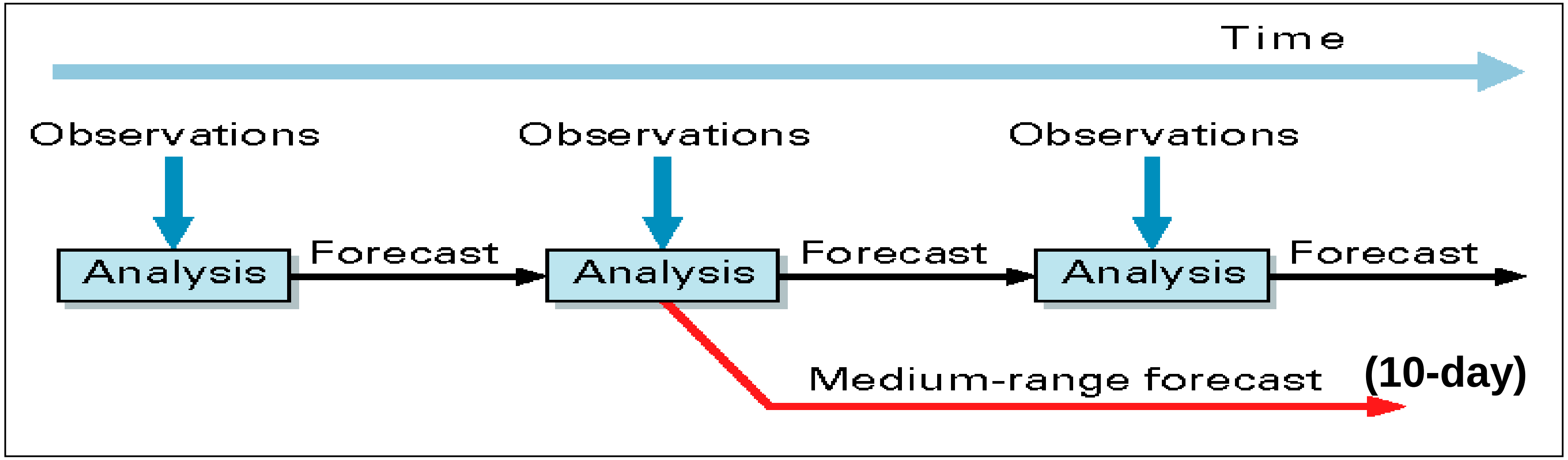
Current coupled assimilation approaches at ECMWF:

- **Weakly Coupled Data Assimilation (WCDA) for land-atmosphere:**
  Soil moisture and temperature,
  Snow depth, density and temperature

- **Weakly Coupled Data Assimilation (WCDA) for ocean-atmosphere:**
  Sea-ice
  Sea Surface Temperature

- **Quasi Strongly Coupled ocean-atmosphere Assimilation (QSCDA)**

Current operational system at ECMWF:

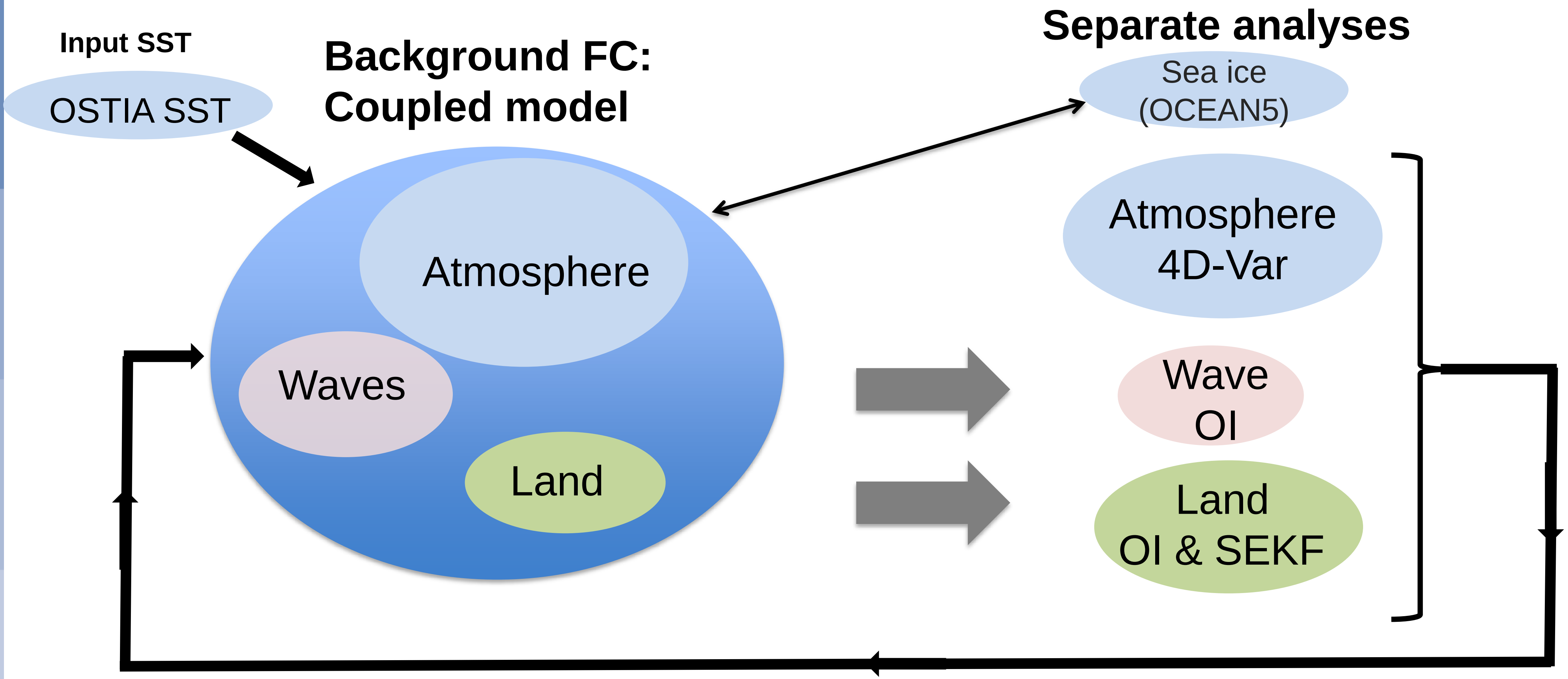


- **Coupled ocean-land-sea-ice-wave-atmosphere Forecast Model**
- **Coupled land-atmosphere-wave background**

- **Data assimilation systems:**
  - **Atmosphere (4D-Var), 12h assimilation window**
  - **Wave (OI), 12h assimilation window**
  - **Land (SEKF,OI), 12h assimilation window**
  - **Ocean & sea ice (3D-Var FGAT), 8-12 days DA window (OCEAN5 system)**

IFS 45r1, 2018

Current operational NWP DA system at ECMWF: weakly coupled land-atmosphere-wave and sea ice assimilation



(IFS cycle 45r1, since June 2018)

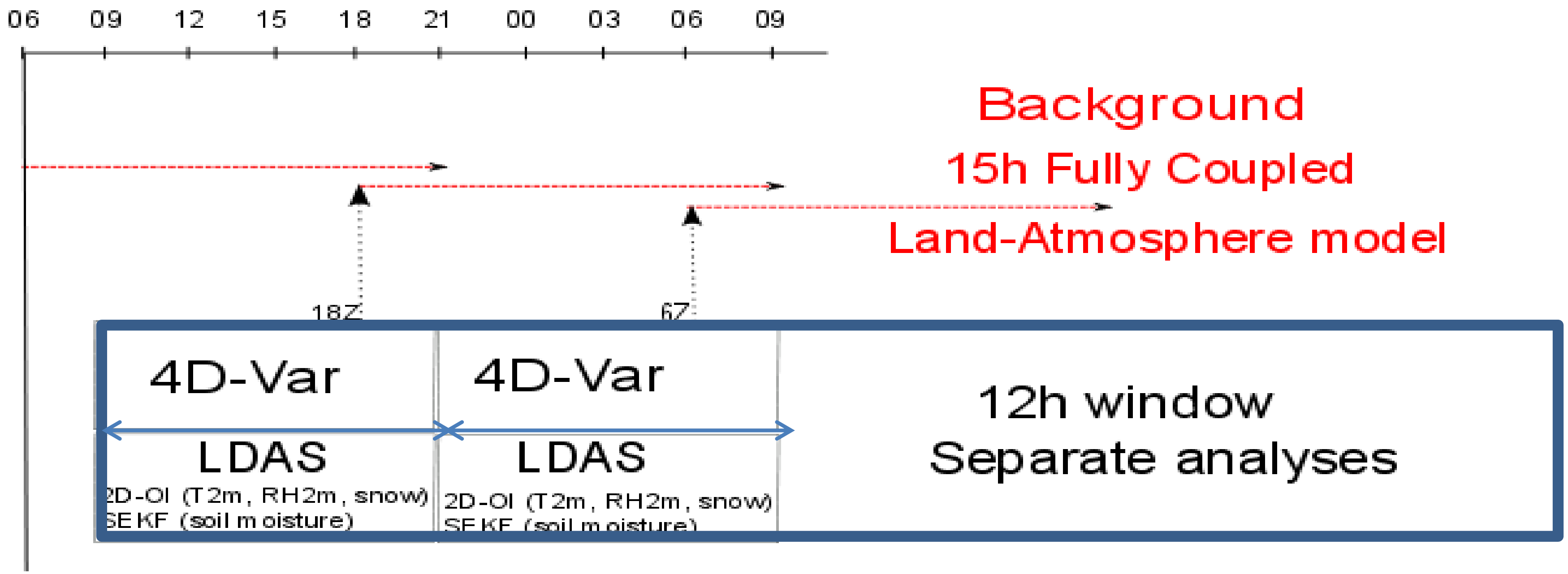
Current coupled assimilation approaches at ECMWF:

- **Weakly Coupled Data Assimilation (WCDA) for land-atmosphere:**
  Soil moisture and temperature,
  Snow depth, density and temperature

- Weakly Coupled Data Assimilation (WCDA) for ocean-atmosphere:
  Sea-ice
  Sea Surface Temperature

- Quasi Strongly Coupled ocean-atmosphere Assimilation (QSCDA)

ECMWF land-atmosphere WCDA approach



- Background produced by coupled land-atmosphere model
- Data Assimilation is separate for
  - Atmosphere (4D-Var)
  - Land surface (OI and SEKF)

→ Increments are computed separately for land and atmosphere

Coupled land-atmosphere data assimilation

Weakly coupled assimilation:

→ Feedback ensured by coupled background forecasts

Justified because:

- Vertical correlations dominate land surface processes. So, each grid point is analysed independently. Land data assimilation in this configuration is a 2D problem, whereas atmospheric DA is a 4D problem
- Weak coupling gives flexibility to run land analysis without the expensive 4D-Var component (modular stand-alone land assimilation available in the most recent IFS cycle 45r1)

Limitations:

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

Snow data assimilation

Snow Model: Component of H-TESSEL

(Dutra et al., JHM 2010, Balsamo et al JHM 2009)

Single layer snowpack

- Snow water equivalent SWE (m)
- Snow Density ρ_s

} **Prognostic variables**

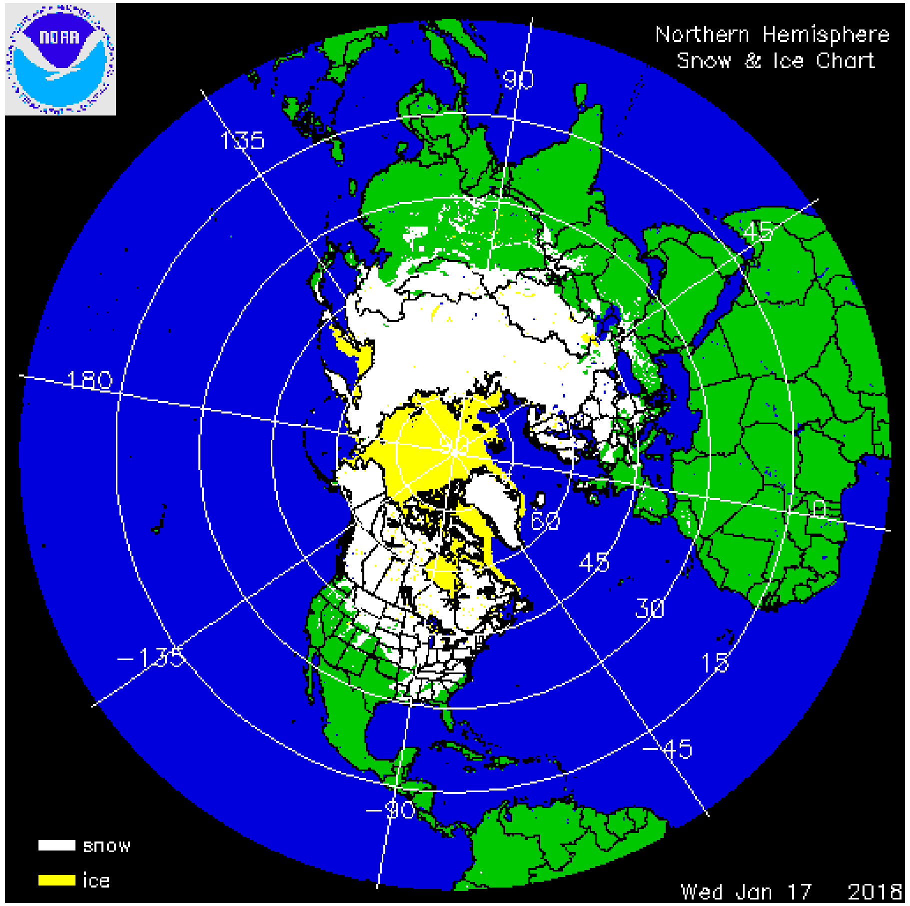
Observations:

(de Rosnay et al ECMWF Newsletter 2015)

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

Data Assimilation: **de Rosnay et al SG 2014**

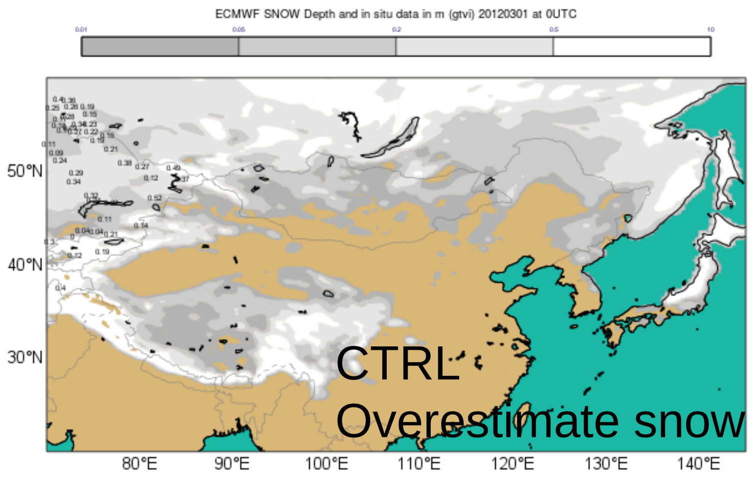
- 2D-Optimal Interpolation (OI) in NWP and ERA5

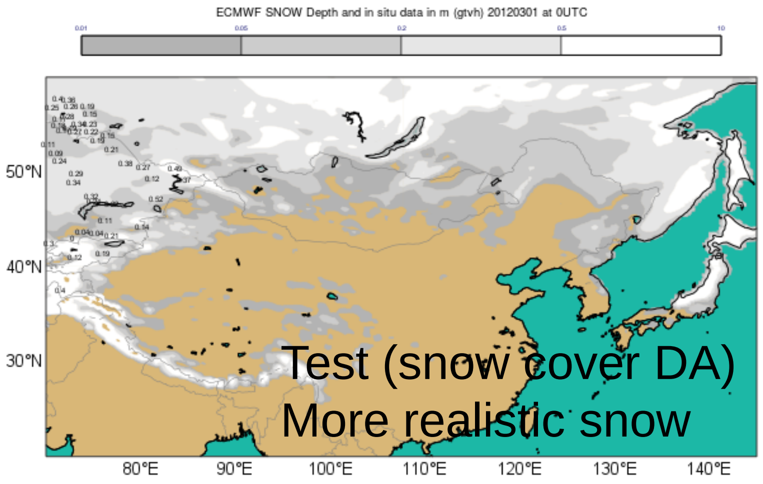


IMS snow cover

Snow data assimilation

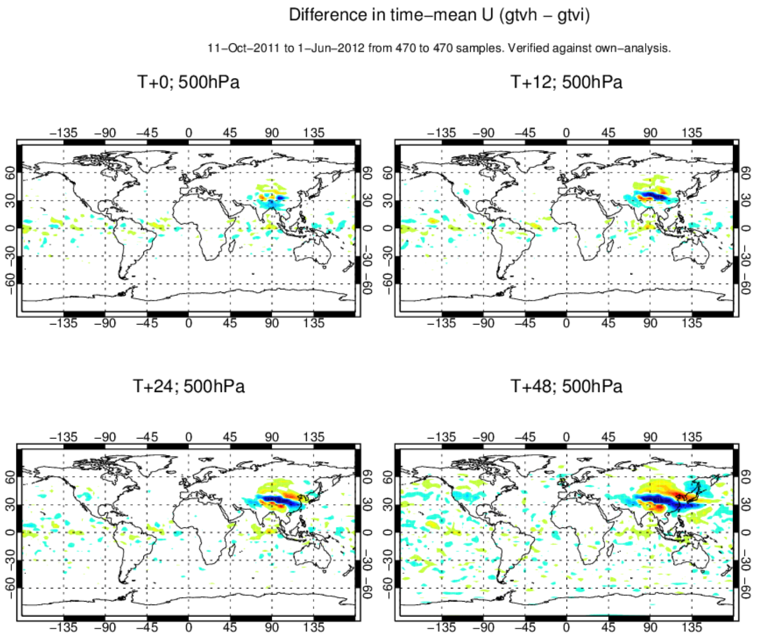
Impact of snow cover assimilation in Himalayas

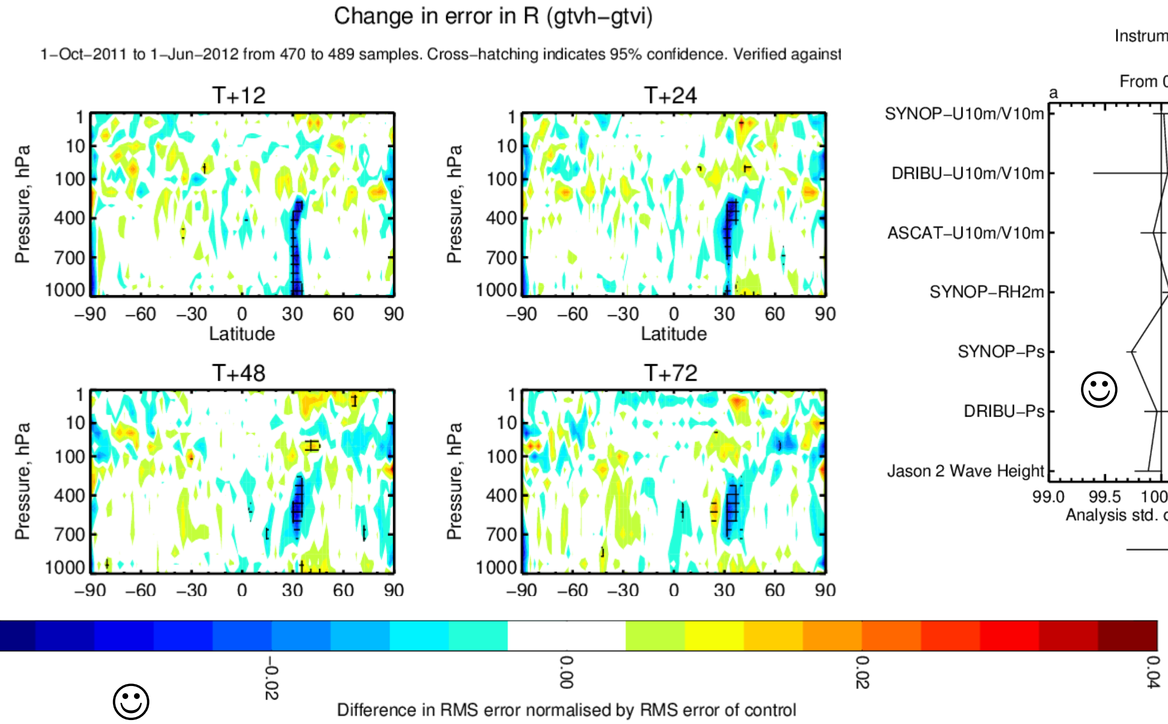


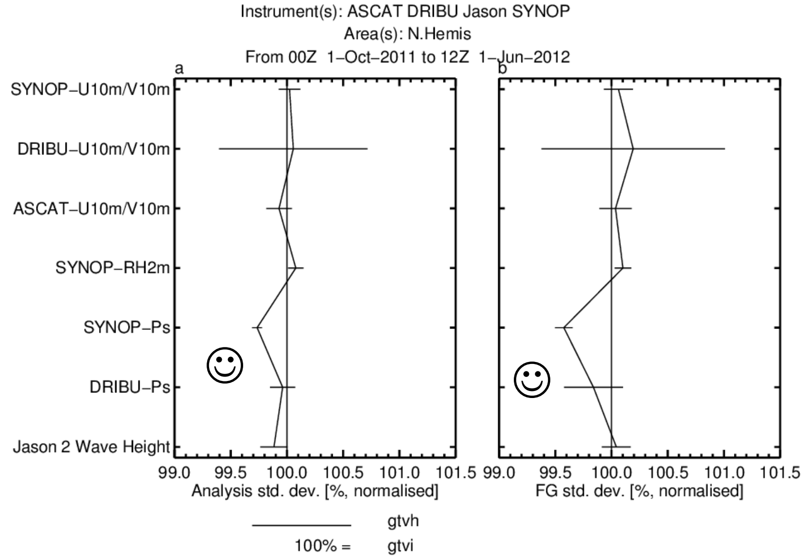


Impact on albedo and momentum

→ Modifies the jet circulation



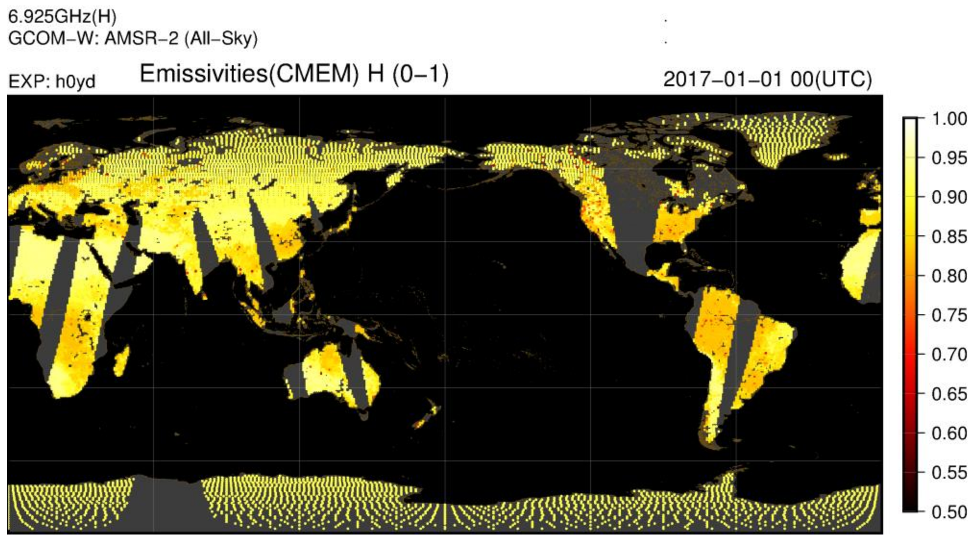




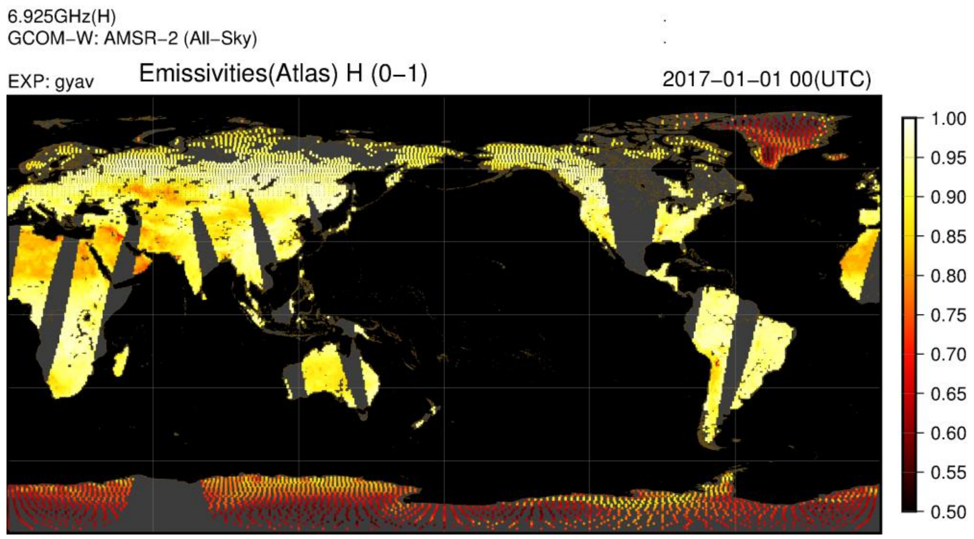
Land surface emissivity in the IFS

Coupling through the observation operator

- **Snow surfaces: strong influence on interface processes**
- Affect the monitoring and assimilation of microwave observations in 4D-Var
- Coupling between atmospheric and land surface radiative transfer models: CMEM (Community Microwave Emission Modelling Platform) and RTTOV
- Next: impact on the atmospheric analysis of using the CMEM snow emissivity in RTTOV



Emissivity (H) : CMEM/RTTOV



Emissivity (H) : Atlas

Soil moisture data assimilation

Point-wise Simplified Extended Kalman Filter (SEKF)

$$\mathbf{X_t^a = x_t^b + K\,(y_t - \mathcal{H}[x_t^b])}$$

Elements of the SEKF for each individual grid point in the case of assimilation of T2m, RH2m, ASCAT:

Control vector

$$xb_{(t)} = \begin{bmatrix} SM_{l1(t)} \\ SM_{l2(t)} \\ SM_{l3(t)} \end{bmatrix}$$

Observations vector

$$y_{(tobs)} = \begin{bmatrix} T_{2m} \\ RH_{2m} \\ ASCAT_{sm} \end{bmatrix} \begin{matrix} [K] \\ [\%] \\ [m^3/m^3] \end{matrix}$$

Observations operator

$$\mathcal{H}[x_b^t]) = \begin{bmatrix} T_{2m} \\ TH_{2m} \\ SM_{top} \end{bmatrix}$$

SM: volumetric soil moisture of the model layers in m3/m3

Background error

$$\mathbf{P} = \begin{bmatrix} 0.01^2 & 0 & 0 \\ 0 & 0.01^2 & 0 \\ 0 & 0 & 0.01^2 \end{bmatrix}$$

Observation error

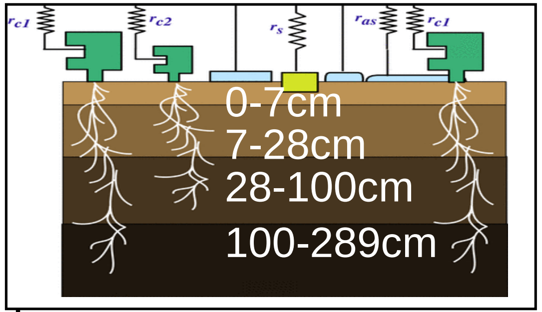
$$\mathbf{R} = \begin{bmatrix} 1^2 & 0 & 0 \\ 0 & 4^2 & 0 \\ 0 & 0 & 0.05^2 \end{bmatrix}$$

Configuration when ASCAT soil moisture is assimilated along with screen level temperature and humidity (T2m, RH2m)

Weakly coupled soil-atmosphere analysis (WCDA)

Current operational status
IFS cycle 45r1

NWP Forecast
Coupled Land-Atmosphere



Land initial conditions

Jacobians
T2m, RH2m
& soil moisture
Background

Soil Analysis (SEKF)
SM1, SM2, SM3
σ_{O_T2M}= 1K
σ_{O_RH2M}= 4%
$\sigma_{b\_}$= 0.01m3/m3
σ_{ASCAT}= 0.05m3/m3

In situ Observations

T_2m
RH_2m

Screen level analysis (2D-OI)
T_2m RH_2m
$\sigma^{o}{}_{T2m} = 2K$ $\sigma^{o}{}_{RH2m} = 10\%$

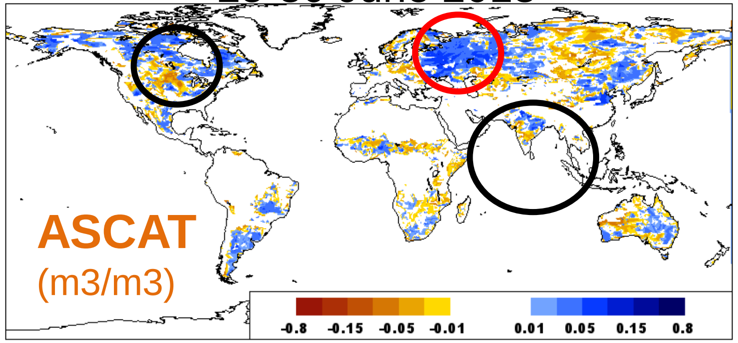
ASCAT SM

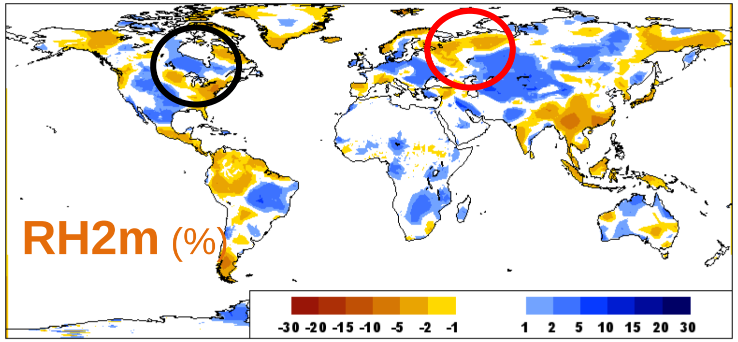
Satellite

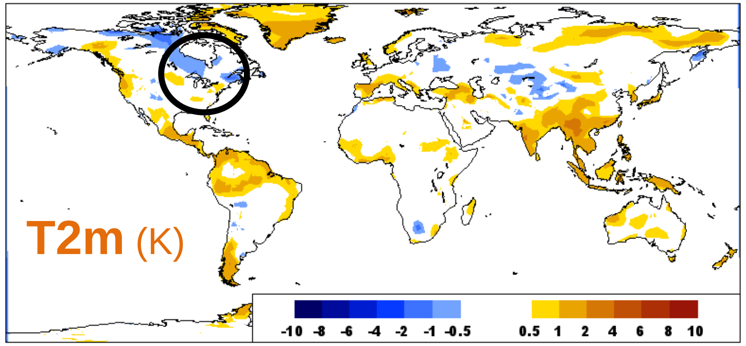
ASCAT Soil Moisture data assimilation for NWP

Innovation (Obs- model)

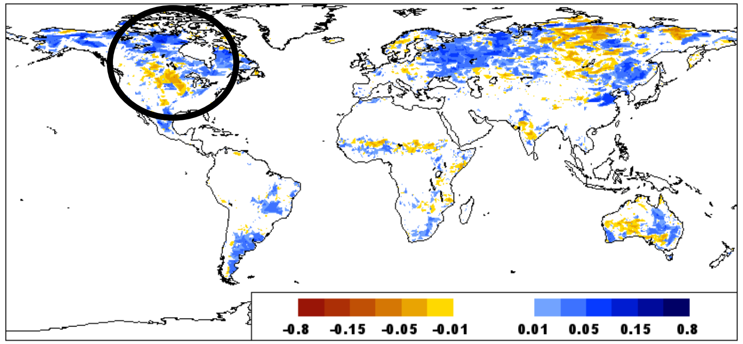
25-30 June 2013



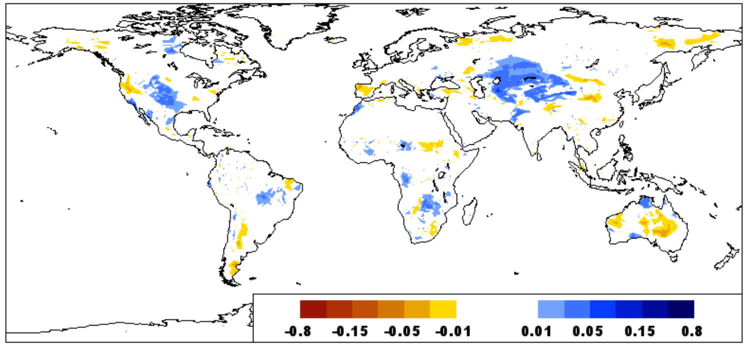




Accumulated Increments (m^3/m^3) in top soil layer (0-7cm)



Due to ASCAT



Due to SYNOP T2m and RH2m

Vertically integrated Soil Moisture increments (stDev in mm)

	SYNOP	ASCAT
Layer 1	0.68	**1.43**
Layer 2	**1.48**	0.68
Layer 3	**4.28**	0.46

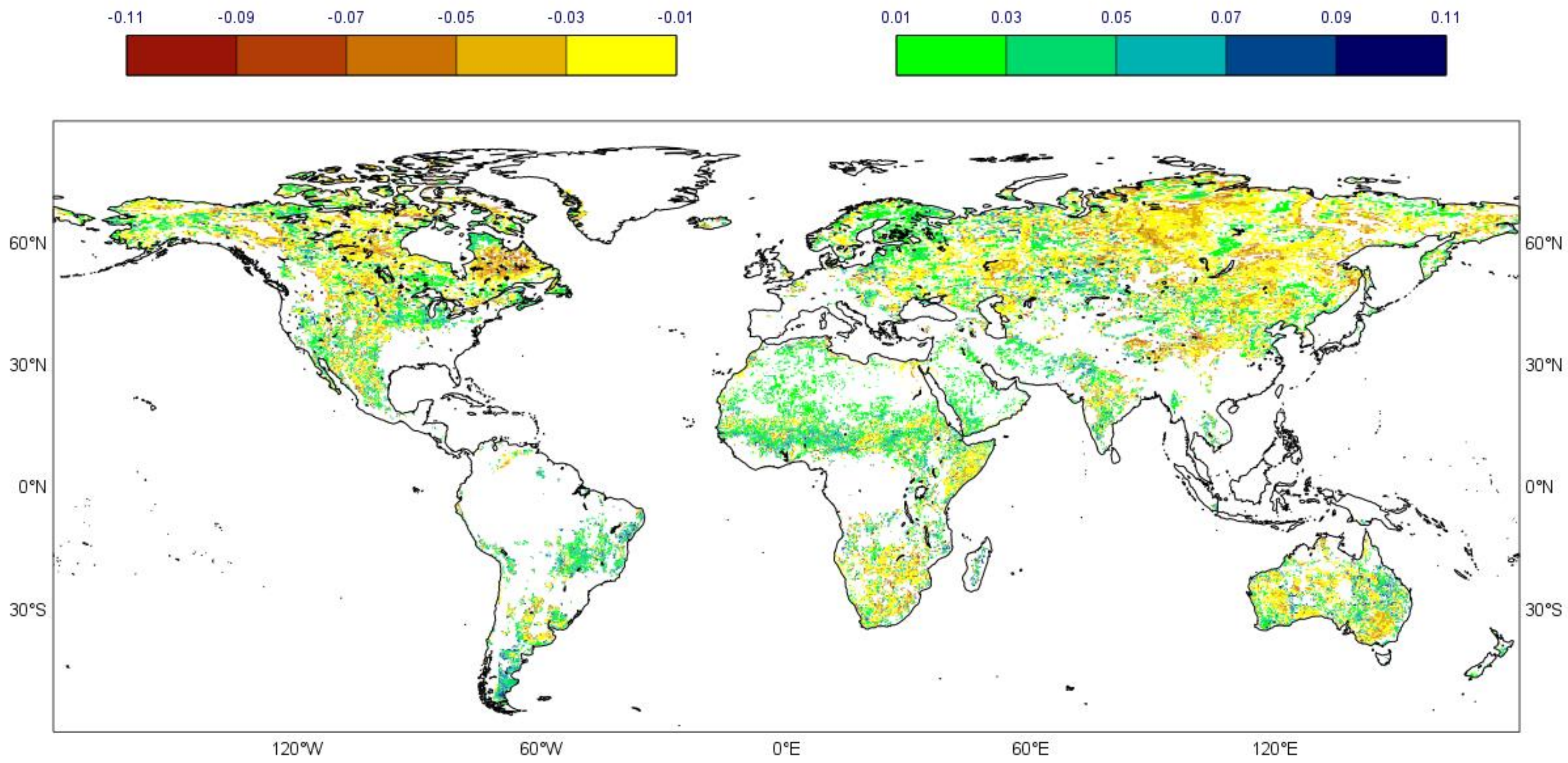
ASCAT more increments at surface
SYNOP more increments at depth

→ For 12h DA window, link obs to root zone stronger for T2m,RH2m than for surface soil moisture observations

ERA5: Weakly coupled land-atmosphere reanalysis

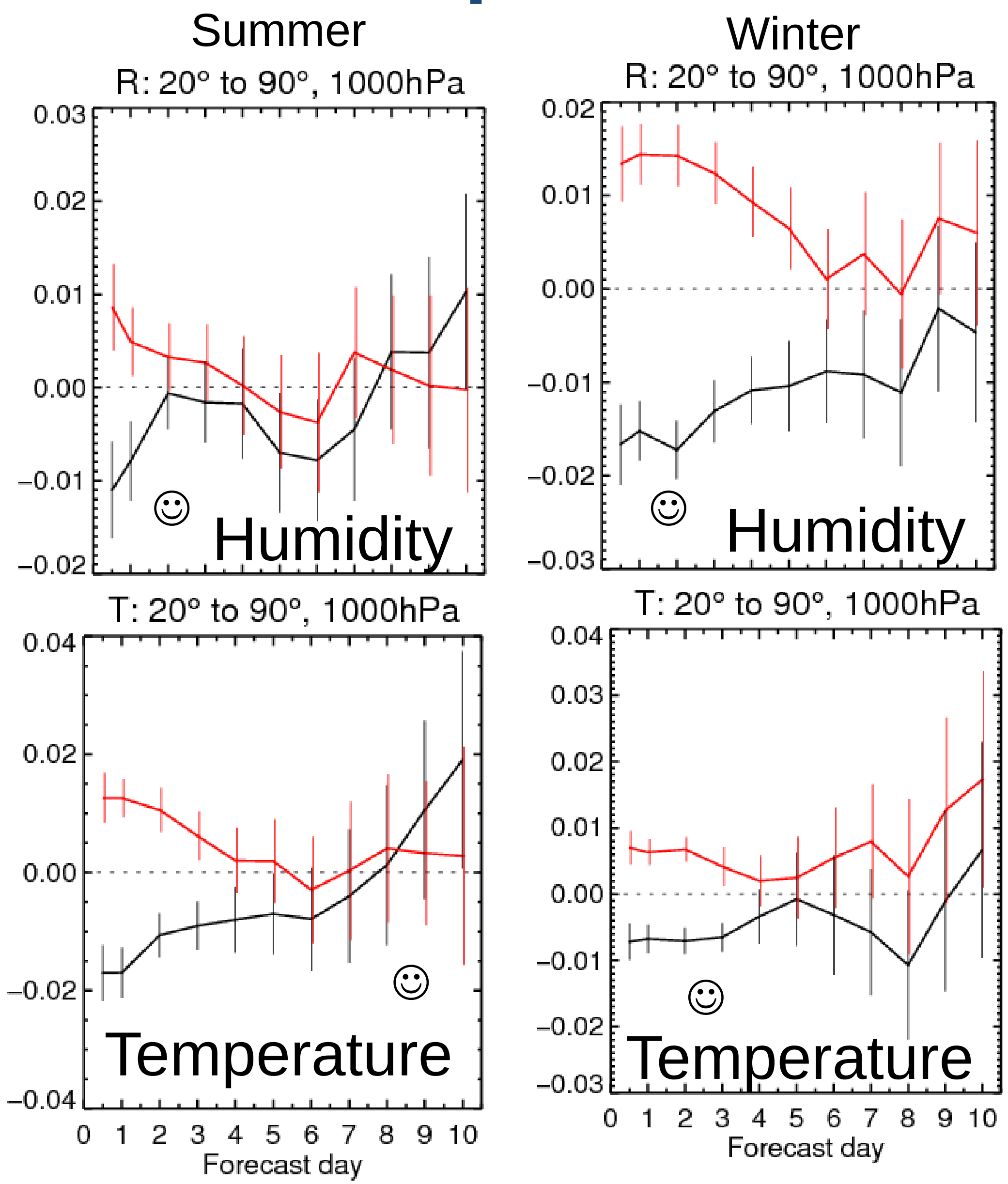
Scatterometer soil moisture Climate Data Record assimilation

ERS/SCAT innovation (O-B) in m3/m3 for assimilated soil moisture observations in ERA5 JAS 1997



Hersbach et al., ECMWF Tech Memo 2018 in prep

Land-Atmosphere WCDA: Impact on the forecast ?



No soil Analysis

zero line (ref): IFS with LDAS 40r1 (2013)

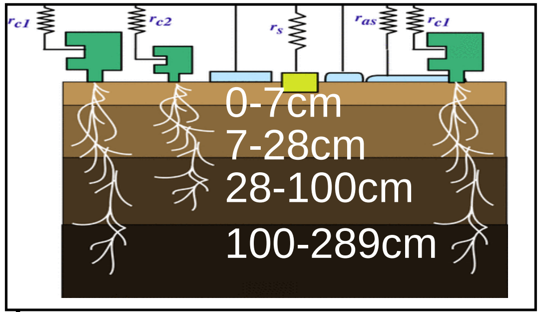
IFS with LDAS 41r1 (2015)
(revised soil analysis observation errors)

→ Significant impact of soil moisture initialisation on near-surface weather forecast

Weakly coupled soil-atmosphere analysis: EDA-SEKF

Ensemble Data Assimilation (EDA)

NWP Forecast
Coupled Land-Atmosphere



Land initial conditions

Jacobians

T2m, RH2m

& soil moisture

Background

Soil Analysis (SEKF)

SM1, SM2, SM3

σ_{O_T2M}= 1K $\sigma_{b\_}$ = 0.01m3/m3 **σ_{SMOS_NN}= 0.02+3ε**

σ_{O_RH2M}= 4% σ_{ASCAT}= 0.05m3/m3

In situ Observations

T_2m
RH_2m

Screen level analysis (2D-OI)

T_2m RH_2m

$\sigma^o{}_{T2m} = 2K$ $\sigma^o{}_{RH2m} = 10\%$

ASCAT SM
SMOS SM

Satellite

SMOS EC Neural network

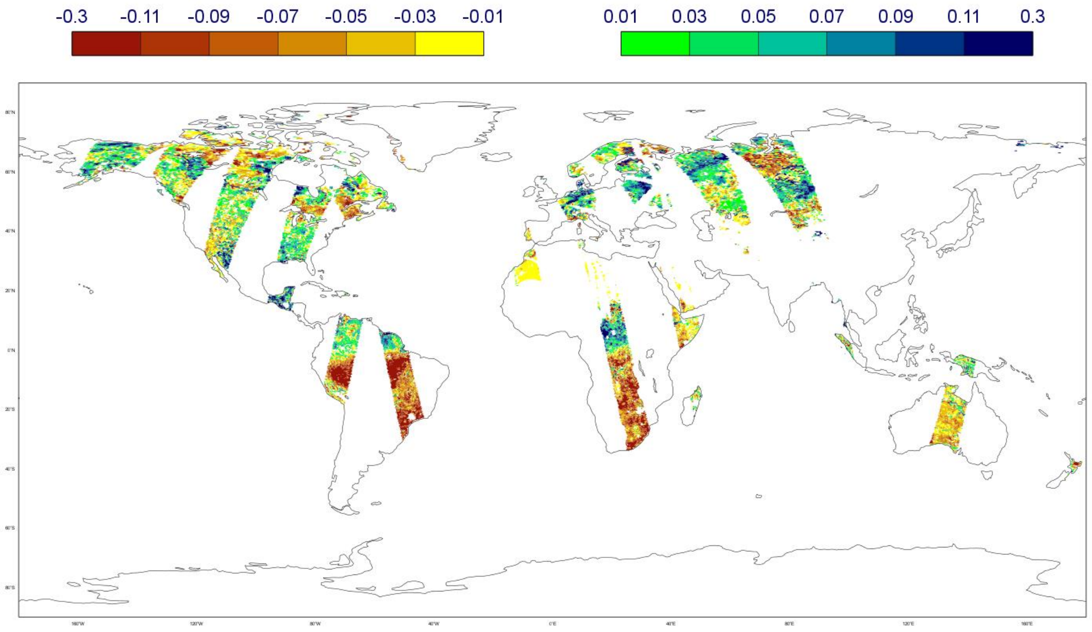
SMOS TB

New soil analysis (under evaluation): EDA SEKF and SMOS NN DA

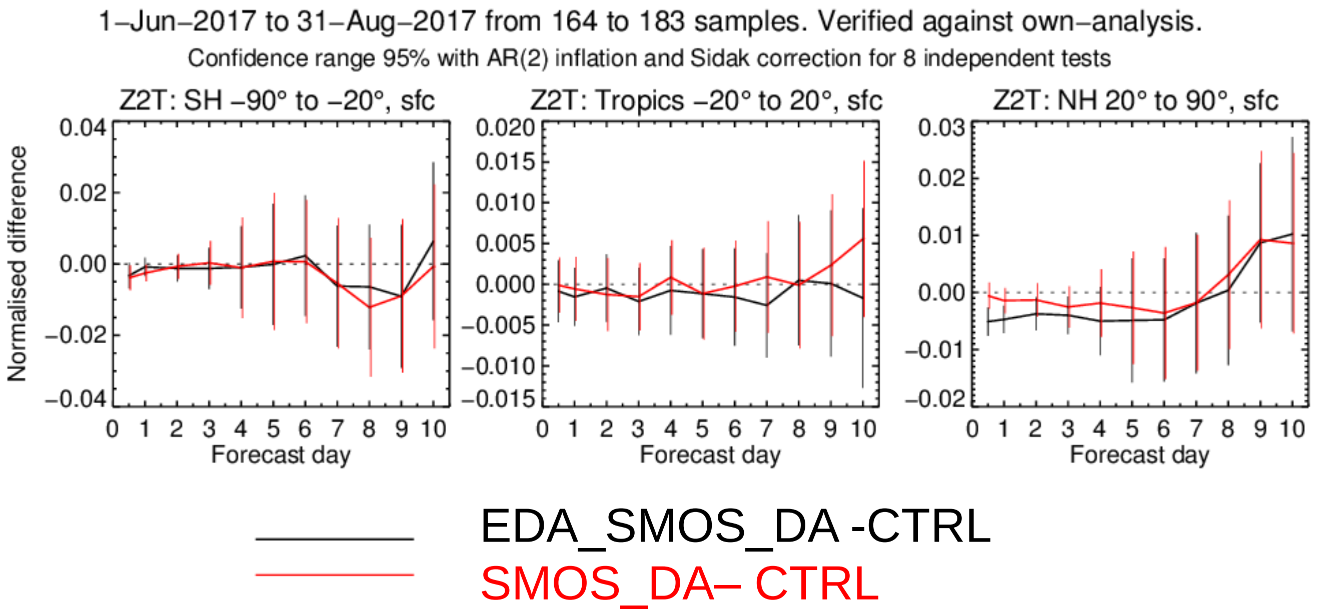
- ➢ Enhanced coupling:
- \- Use the EDA to compute the SEKF Jacobian
- ➢ SMOS neural network soil moisture assimilation
- ➢ CPU reduction from EDA SEKF, cost neutral for SMOS

Reduction of the SEKF CPU cost by a factor ~3.6

	NPES*THREADS	45r1	46r1
Tco 1279	300*9	1580	435
TCo399	54*6	815	235



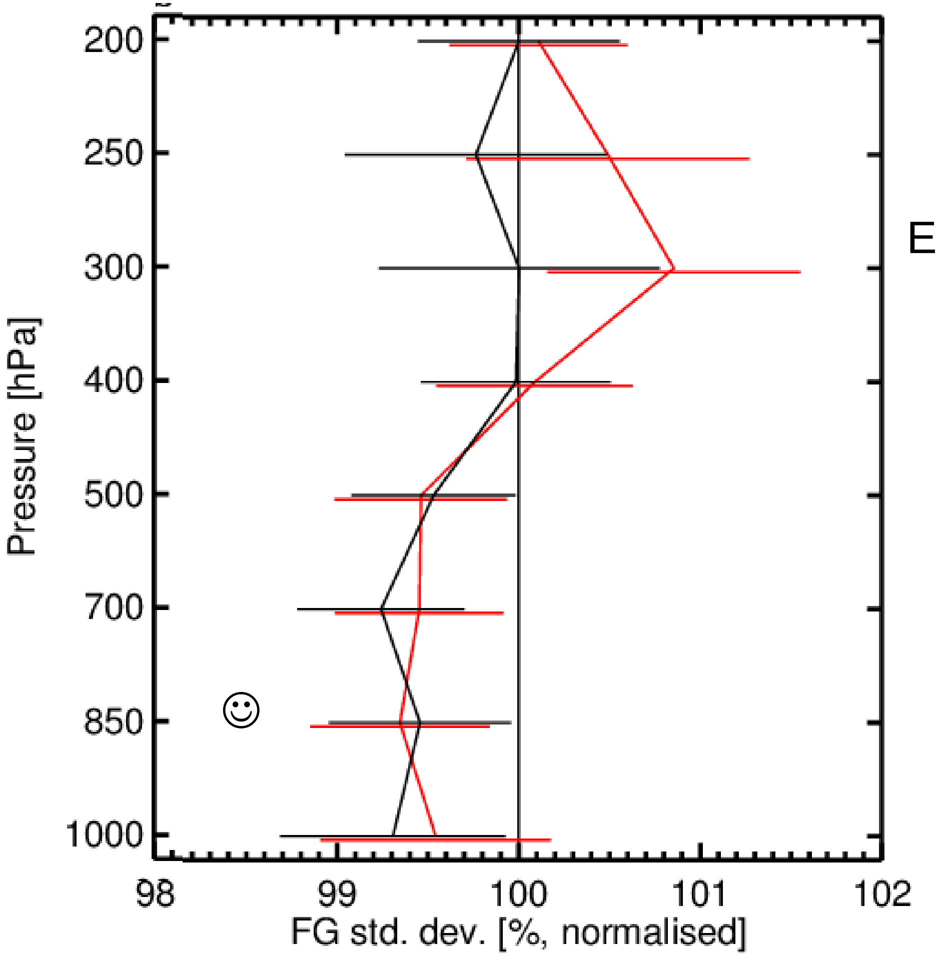
SMOS innovation (obs-model)
01 August 2017 (m3/m3)



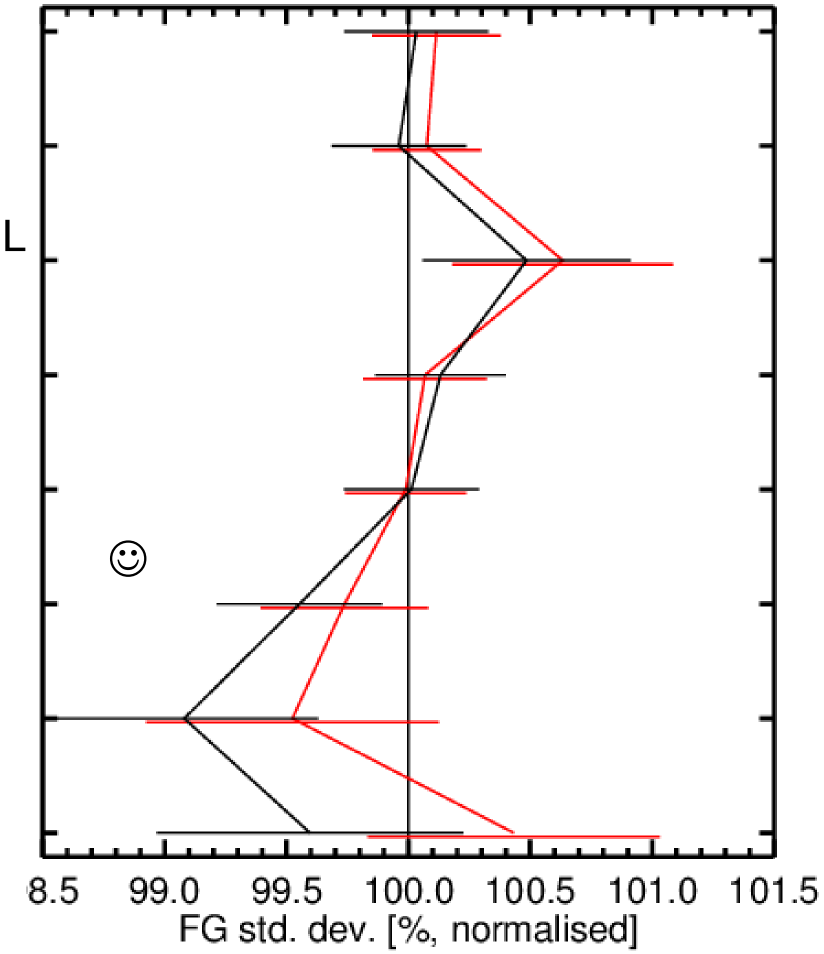
Atmospheric impact (T2m) compared to CTRL

EDA-SEKF and SMOS neural network impact
Fit between IFS first guess and independent observations (obs-model)

Aircraft humidity (JJA 2017)



Aircraft temperature (JJA 2017)



EDA SEKF+SMOS DA minus CTRL
SMOS DA minus CTRL

Improved fit
in lower troposphere

Evaluation of surface and root zone soil moisture against in situ data

More than 300 stations in US and Europe (SCAN, USCRN, SNOTEL and SMOSMANIA)

Experiment	R		Ranom		uRMSD		Bias	
	surface	root Zone	Surface	root zone	surface	root zone	surface	root zone
CTRL (oper)	0.617	0.65	0.518	0.428	0.052	0.031	0.06	0.058
SMOS DA (oper+SMOS DA)	0.609	0.667	0.507	0.443	0.052	0.030	0.058	0.052
SMOS+EDA (oper+SMOS+EDA)	0.623	0.64	0.521	0.421	0.051	0.029	0.055	0.052

→ Small impact, but on a slight improvement side in soil moisture

EDA-EKF and SMOS improve surface and root zone soil moisture (systematic on all four networks)

Current coupled assimilation approaches at ECMWF:

- Weakly Coupled Data Assimilation (WCDA) for land-atmosphere:
  Soil moisture and temperature,
  Snow depth, density and temperature

- **Weakly Coupled Data Assimilation (WCDA) for ocean-atmosphere:**
  Sea-ice
  Sea Surface Temperature

- Quasi Strongly Coupled ocean-atmosphere Assimilation (QSCDA)

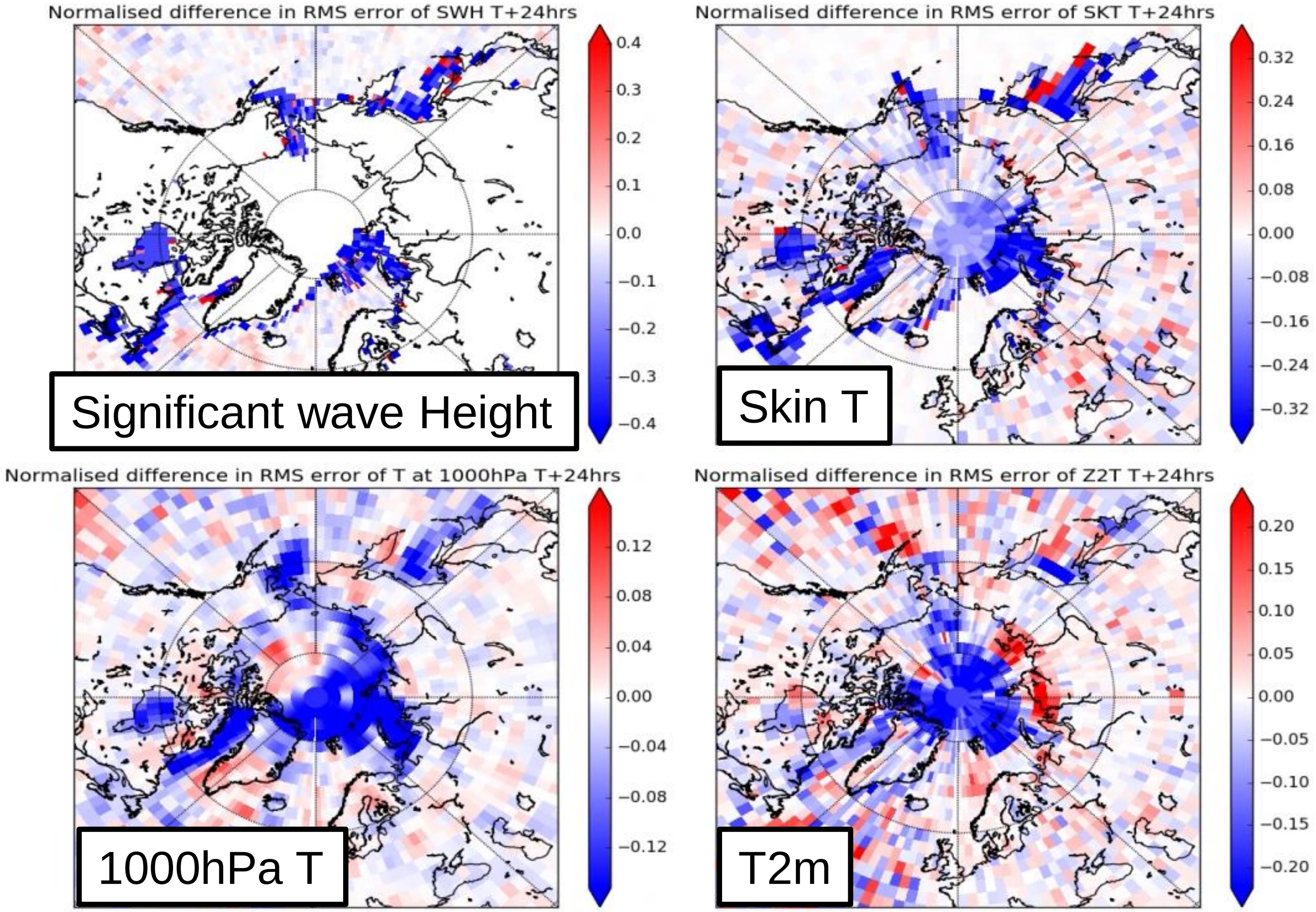
Weakly Coupled Assimilation for sea-ice-atmosphere

Weakly coupled sea-ice atmosphere assimilation in operations June 2018 (IFS cycle 45r1)

- OCEAN5 uses atmospheric analysis forcing
- Atmospheric analysis uses the OCEAN5 sea-ice

→ Observations in each Earth system component influences the other component

24-h forecasts RMS error difference between coupled and uncoupled assimilation



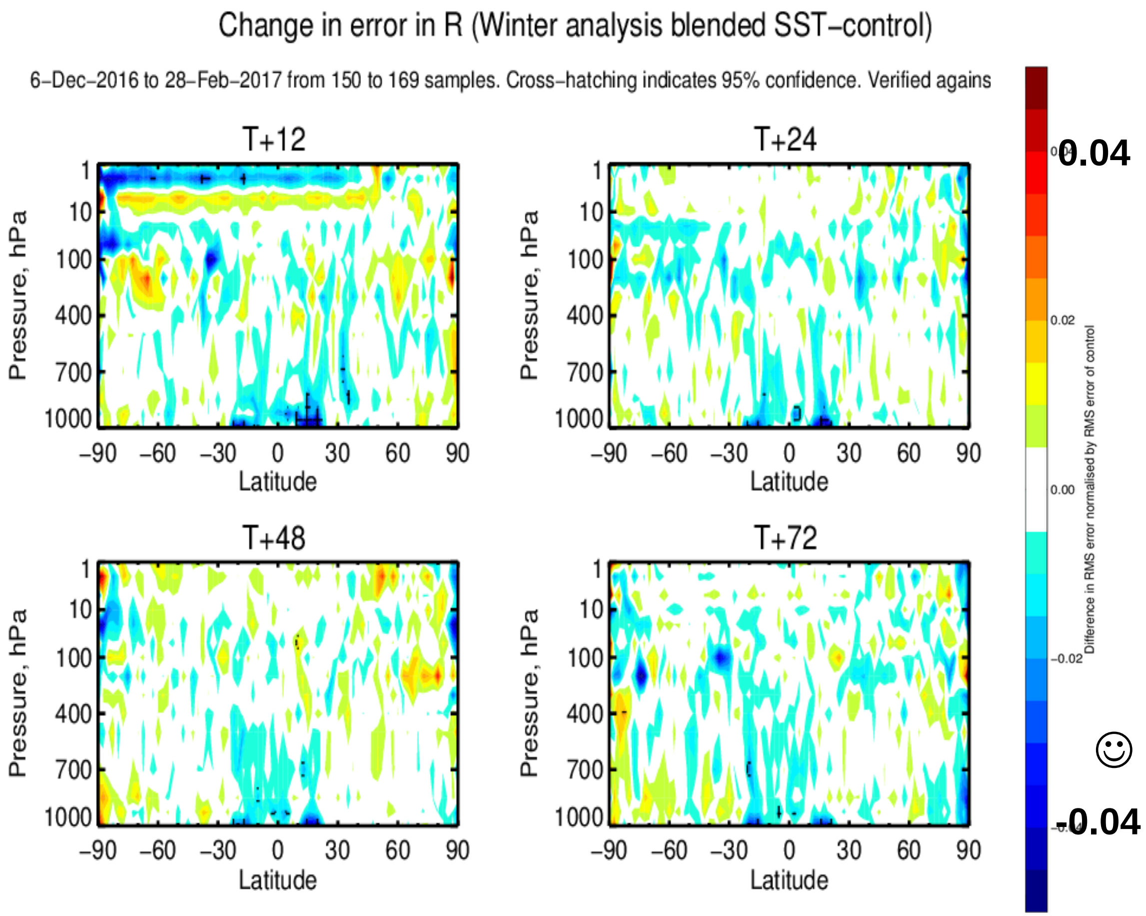
☺

Impact of WCDA SIC compared to CTRL using OSTIA

Weakly Coupled Assimilation for ocean-atmosphere

Progressively more coupling:

- 2018– weakly coupled assimilation through sea ice feedback
- 2019 – weakly coupled assimilation through SST in the tropics



Impact of WCDA SST compared to CTRL using OSTIA (both with coupled model)

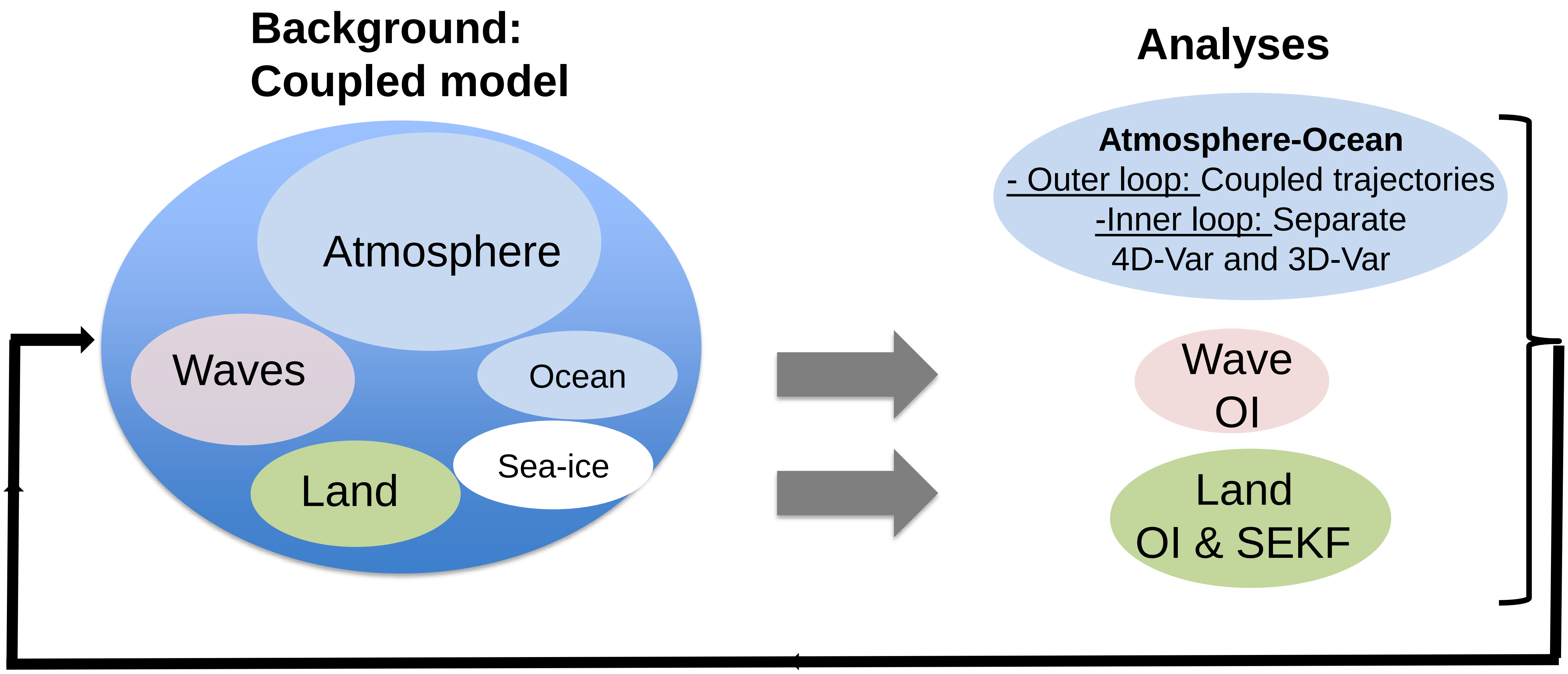
Current coupled assimilation approaches at ECMWF:

- Weakly Coupled Data Assimilation (WCDA) for land-atmosphere:
  Soil moisture and temperature,
  Snow depth, density and temperature

- Weakly Coupled Data Assimilation (WCDA) for ocean-atmosphere:
  Sea-ice
  Sea Surface Temperature

- **Quasi Strongly Coupled ocean-atmosphere Assimilation (QSCDA)**

WCDA for land-atmosphere-wave
QSCDA for ocean-atmosphere assimilation



Quasi Strongly coupled ocean-atmosphere Assimilation Coupled reanalyses CERA-20C

Pioneer work on ocean-atmosphere data assimilation coupling method initiated in the coupled reanalysis (CERA) framework

CERA-20C: A coupled reanalysis of the 20th century (Laloyaux et al. QJRMS 2016)

- ocean-atmosphere coupling at the outer loop level of 4D-Var
- based on conventional observations (atmospheric surface and ocean)
- IFS cycle 41r2, resolution TL159 (125km), 24-h assimilation window

→ Proof of concept: demonstrated capability of the outer loop coupling to simultaneously ingesting atmospheric and ocean observations in the coupled Earth system model.

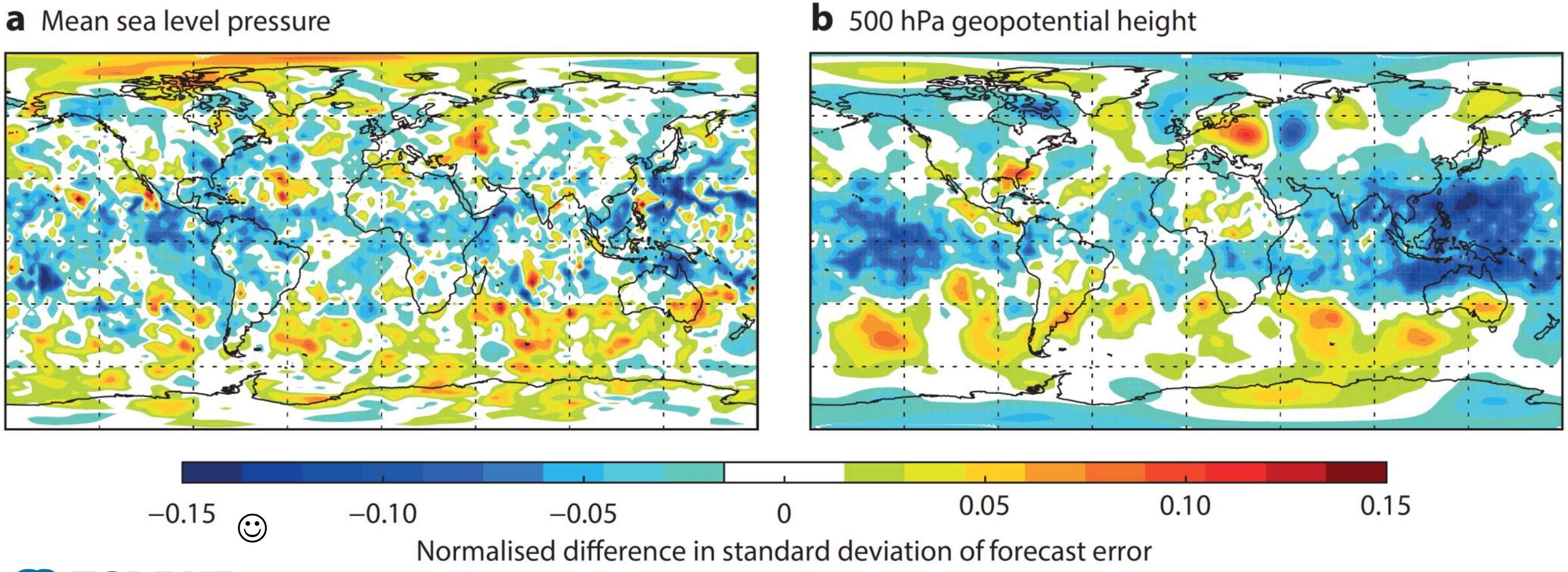
Quasi strongly coupled ocean-atmosphere assimilation
Coupled reanalyses CERA-SAT

(Schepers et al, ECMWF newsletter article 2018)

CERA system further developed to:

- Account for full observing system, period 2008-2016
- Include more earth system components in the data assimilation system (wave, land), and sea ice obs
- Run at high resolution (TL319, 60km), ocean ¼ degrees ORCA025

5-day FC verification against own analysis
(May 2015 – August 2016)



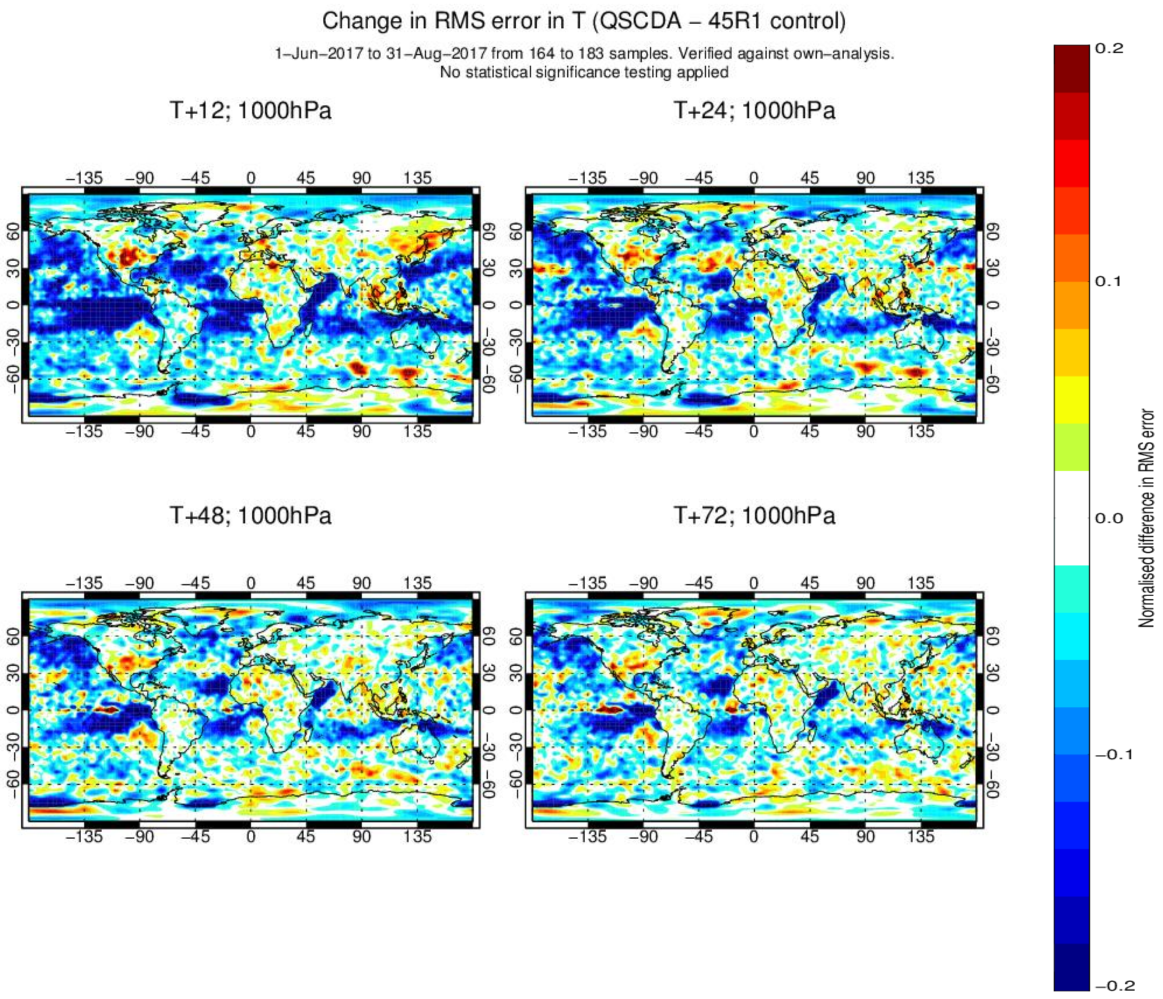
Blue -> reduction in StDev for CERA-SAT compared to uncoupled CTRL.

Combined impact of model and assimilation coupling

→ Talk by Dinand Schepers on Wednesday

Quasi strongly coupled ocean-atmosphere assimilation Modular option in the IFS

- QSCDA implemented in the most recent IFS cycles suite definition (modular),
- Flexible DA window length,
- Compatible with Early delivery/delayed cut-off streams
- Tested at a range of resolutions (Tco399 to Tco1279)
- Disentangle impacts of model and data assimilation coupling



→ Talk by Phil Browne on Thursday

☺

Conclusions and perspectives

- Progressive implementation of coupled assimilation in operations for NWP and future generation of reanalysis (ERA6, Copernicus Service C3S)

- **Weakly coupled assimilation for land-atmosphere** for NWP and operational reanalysis (ERA5)
  - Consistency between ERA5 and operational NWP, ERA5 assimilates scatterometer soil moisture data record
  - New enhanced land-atmosphere coupling with EDA-SEKF approach, improves efficiency, opens possibility for outer loop coupling for land-atmosphere and account for more land surface variables in the control
- **Weakly coupled ocean-atmosphere for NWP**
  - Sea-ice-atmosphere coupling for operational NWP,
  - SST weakly coupled approach between OCEAN5 and the IFS in the tropics

Conclusions and perspectives

- **Quasi Strongly Coupled assimilation (QSCDA)** ocean-atmosphere
  - CERA-SAT, coupled reanalysis for satellite data and full observing system
  - Also developed in the new suite definition system (Ecflow), modular, compatible with operational constraints (e.g. Early delivery), flexible data assimilation window length, etc…
  - Disentangle model coupling impact from data assimilation coupling impact

- Challenges:
  - Ocean-atmosphere: need to address extratropics issues in coupled system
  - Differences in observation latency, time scales -> combined WCDA and QSCDA
  - What degrees of coupling for development/testing/evaluation purpose

Conclusions and perspectives

- Extend the QSCDA outer loop coupling to land using the EDA-SEKF
- Coupling through the observation operator, e.g. snow surfaces (Alan Geer's talk on Wednesday)
- Transition to lower level ocean products assimilation (L4, to L3, L2 and eventually L1)
  - L3 sea-ice concentration assimilation facility implemented, slight improvement in polar areas
  - L2 SST assimilation preliminary work started (collaboration UKMO)
  - Also need to unify altimeter data assimilation in the wave and ocean systems
- Account to cross-domain error covariances and evaluate the impact
- Coupling with other components: atmospheric composition analysis, and river and flood forecast system

  → link Copernicus Services CMEMS, CEMS, CAMS