Towards Earth system reanalysis

Patricia de Rosnay, Phil Browne, Eric de Boisséson, David Fairbairn, Sébastien Garrigues, Christoph Herbert, Kenta Ochi, Ewan Pinnington, Kirsti Salonen,
Dinand Schepers, Pete Weston, Hao Zuo,

Hans Hersbach, Gabriele Arduini, Magdalena Alonso Balmaseda, Gianpaolo Balsamo, Bill Bell, Niels Bormann, Souhail Boussetta, Carlo Buontempo, Anca Brookshaw, Jonny Day, Stephen English, Sean Healy, Tony McNally, Tracy Scanlon , Adrian Simmons, Tim Stockdale, Frédéric Vitart

and many others

ECMWF

What is Reanalysis

Reconstruction of the past weather and climate, using

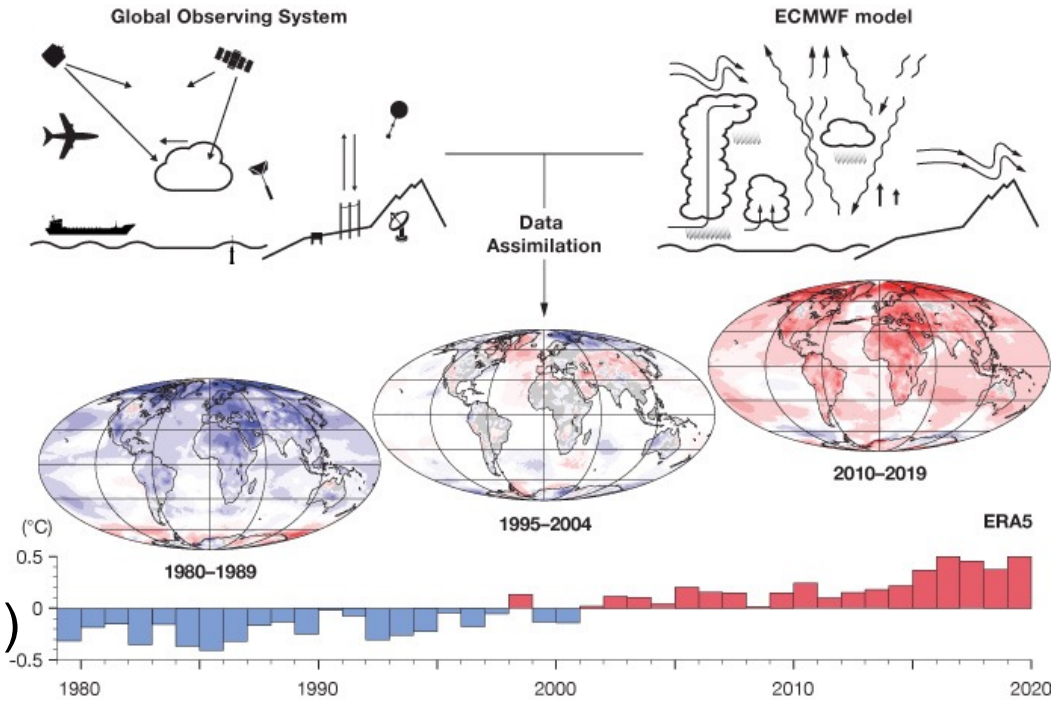
- Observations (satellite, in situ) and gridded boundary forcing,
- Modern weather forecasting model and data assimilation systems,

to *Re - analyse* the weather for past periods.

Reanalysis data provide the most reliable and consistent estimate of past weather and climate
→ Used for climate monitoring

Reanalysis are used by the climate community, Numerical Weather Prediction (NWP) seasonal prediction.
Huge impact for the general public, private sector, ….
More recently ERA5 has become a key input to train machine learning weather prediction models.
→ Matthew Chantry's talk on Thursday

Reanalyses are produced by several centres (e.g. ERA5, MERRA-2, JRA-3Q,CRA-40, CFSR, CARRA, and many more)



https://www.ecmwf.int/en/about/media-centre/focus/2023/fact-sheet-reanalysis

ECMWF experience with reanalysis

Reanalysis activities started in 1979 at ECMWF with the First Global Experiment of the Global Atmospheric Research Programme (FGGE reanalysis)

Annual Seminar on Data Assimilation Systems and Observing System Experiments with Particular Emphasis on FGGE

The Annual Seminar on Data Assimilation Systems and Observing System Experiments with Particular Emphasis on FGGE was held from 3 to 7 September 1984.

MONITORING OF OBSERVATION AND ANALYSIS QUALITY
BY A DATA ASSIMILATION SYSTEM

A. Hollingsworth, D.B. Shaw, P. Lönnberg,
L. Illari, K. Arpe, A.J. Simmons
European Centre for Medium Range Weather Forecasts
Reading, U.K.

→ Talk on Thursday

ABSTRACT

The purpose of this paper is to demonstrate the ability of a modern data assimilation system to provide long-term diagnostic facilities to monitor the performance of the observational network. Operational data assimilation

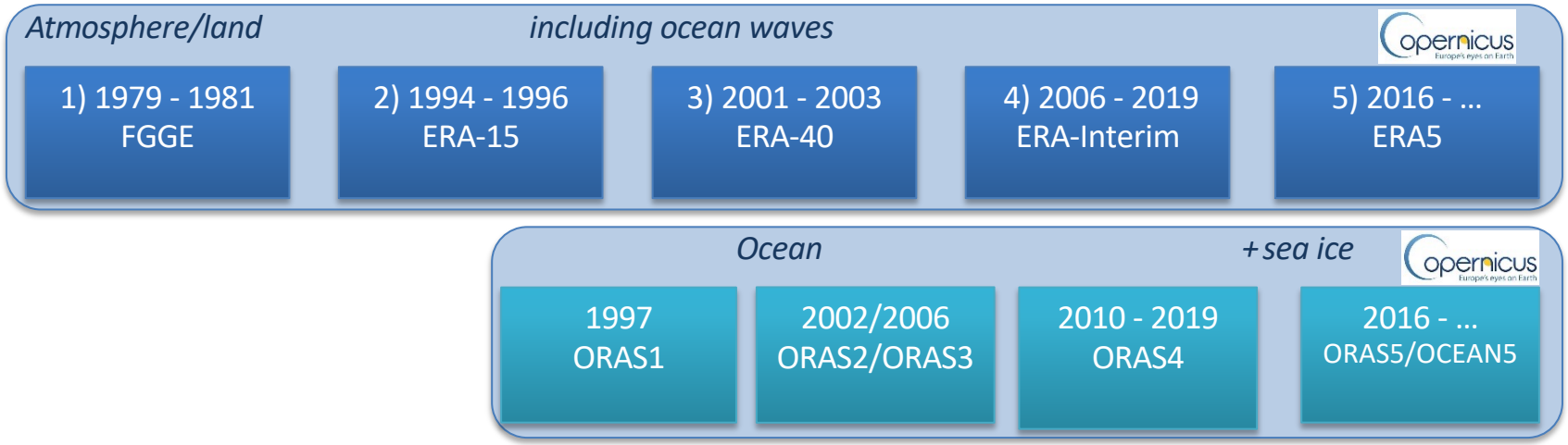
ECMWF experience with reanalysis

Dee et al., ECMWF Tech Memo 687, 2012
10.21957/3v3hcppnp

- FGGE and ERA-15: focused on atmosphere with very little interest in other components. Surface conditions were just needed as lower boundary condition of the atmospheric reanalysis.
- The current ERA5 reanalysis is funded by the Copernicus Climate Change Service (C3S).
- It accounts for atmosphere, land, ocean waves with sea surface temperature and sea ice prescribed

Hersbach et al., 2020 https://doi.org/10.1002/qj.3803

ECMWF experience with reanalysis



→ Hao Zuo tomorrow

ECMWF also started seasonal prediction developments in the 90's (SEAS1 in 1997)

→ Need for an ocean model and assimilation and ocean reanalysis

Temp increments (0-300m)

Global seasonal rainfall forecasts using a coupled ocean–atmosphere model

T. N. Stockdale ✉, D. L. T. Anderson, J. O. S. Alves & M. A. Balmaseda

Nature **392**, 370–373 (1998) | Cite this article

→ ORAS1 in 1997 (Ocean Reanalysis System1)

ECMWF experience with reanalysis

Atmosphere/land *including ocean waves*

1) 1979 - 1981 FGGE	2) 1994 - 1996 ERA-15	3) 2001 - 2003 ERA-40	4) 2006 - 2019 ERA-Interim	5) 2016 - … ERA5

Ocean *+sea ice*

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→ ORAS1 in 1997

The ECMWF Ocean Analysis System: ORA-S3

MAGDALENA A. BALMASEDA

European Centre for Medium-Range Weather Forecasts, Reading, United Kingdo

ARTHUR VIDARD

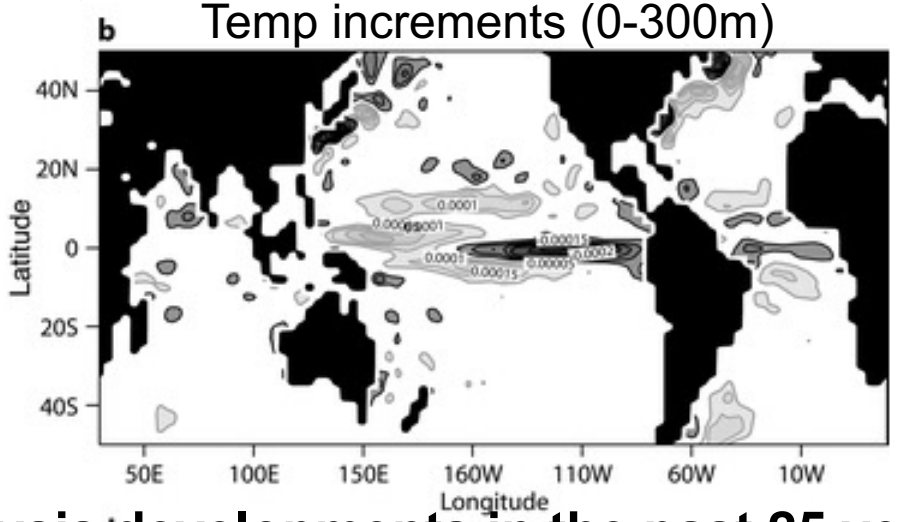
L'Institut National de Recherche en Informatique et en Automatique (INRIA), Grenobl

DAVID L. T. ANDERSON

European Centre for Medium-Range Weather Forecasts, Reading, United Kingdo

Monthly Weather Review 136, 8; 10.1175/2008MWR2433.1

Temp increments (0-300m)



Seasonal Prediction has been a key driver in ocean reanalysis developments in the past 25 years

ECMWF experience with reanalysis

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Centennial *Outer loop Coupling*

2013 - 2015 ERA-20CM/20C	2016 CERA-20C	2017 CERA-SAT

Enhanced land (from ERA atmosphere)

2012 ERA-Int/Land	2014 ERA-20C/Land	2018 - … ERA5L

Atmospheric composition

2008 - 2009 GEMS	2010 - 2011 MACC	2017 - … CAMS EAC4

Next generation

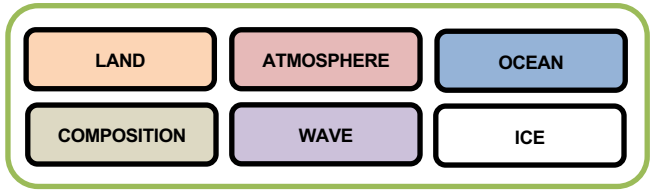
6) 2024 - … ERA6

2024 - … ORAS6/OCEAN6

2026 - … ERA6L

2024 - … CAMS EAC5

→ Hans Hersbach's talk tomorrow



ECMWF EUROPEAN CENTRE FOR MEDIUM-

ECMWF experience with reanalysis

Atmosphere/land *including ocean waves*

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5) 2016 - … ERA5

Next generation

6) 2024 - … ERA6

Ocean *+sea ice*

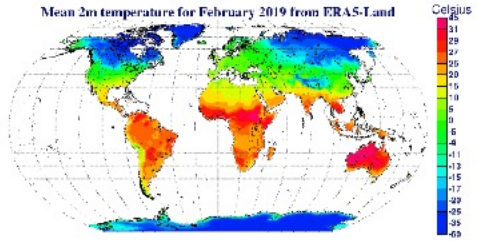
1… OR…

ERA5-Land hourly data from 1950 to present

Consistent input for NWP and climate studies & relevant for water resources, hydrological and agricultural modelling.

ERA5-Land is a reanalysis dataset providing a consistent view of the evolution of land variables over several decades at an enhanced resolution compared to ERA5. ERA5-Land has been produced by replaying the land component of the ECMWF ERA5 climate reanalysis. Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. Reanalysis produces data that goes several decades back in time, providing an accurate description of the climate of the past.

ERA5-Land uses as input to control the simulated land fields ERA5 atmospheric variables, such as air temperature and air humidity. This is called the atmospheric forcing. Without the constraint of the atmospheric



Muñoz-Sabater et al.,2021 https://doi.org/10.5194/essd-13-4349-2021

→ Hans Hersbach's talk tomorrow

Enhanced land (from ERA atmosphere)

2012 ERA-Int/Land

2014 ERA-20C/Land

2018 - … ERA5L

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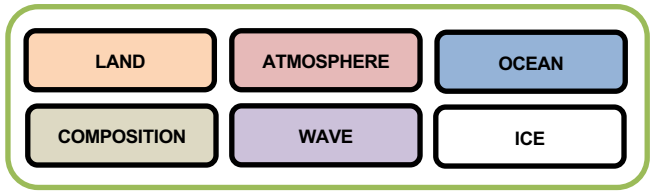
2008 - 2009 GEMS

2010 - 2011 MACC

2017 - … CAMS EAC4

2024 - … CAMS EAC5



ECMWF experience with reanalysis

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Next generation

6) 2024 - … ERA6

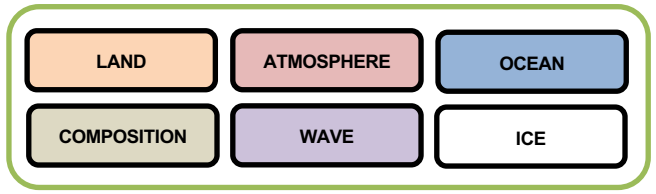
2024 - … ORAS6/OCEAN6

2026 - … ERA6L

2024 - … CAMS EAC5

Large diversity of reanalysis products covering atmosphere, ocean, ocean waves, sea-ice, land surface and atmospheric composition

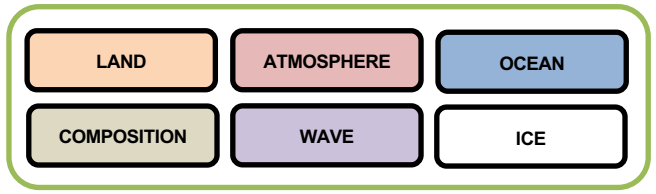
→ Hans Hersbach's talk tomorrow



ECMWF experience with reanalysis

→ Hans Hersbach's talk tomorrow

Pioneer work on ocean-atmosphere coupled data assimilation in the context of the ERA-CLIM2 project (Buizza et al., BAMS, 2018)



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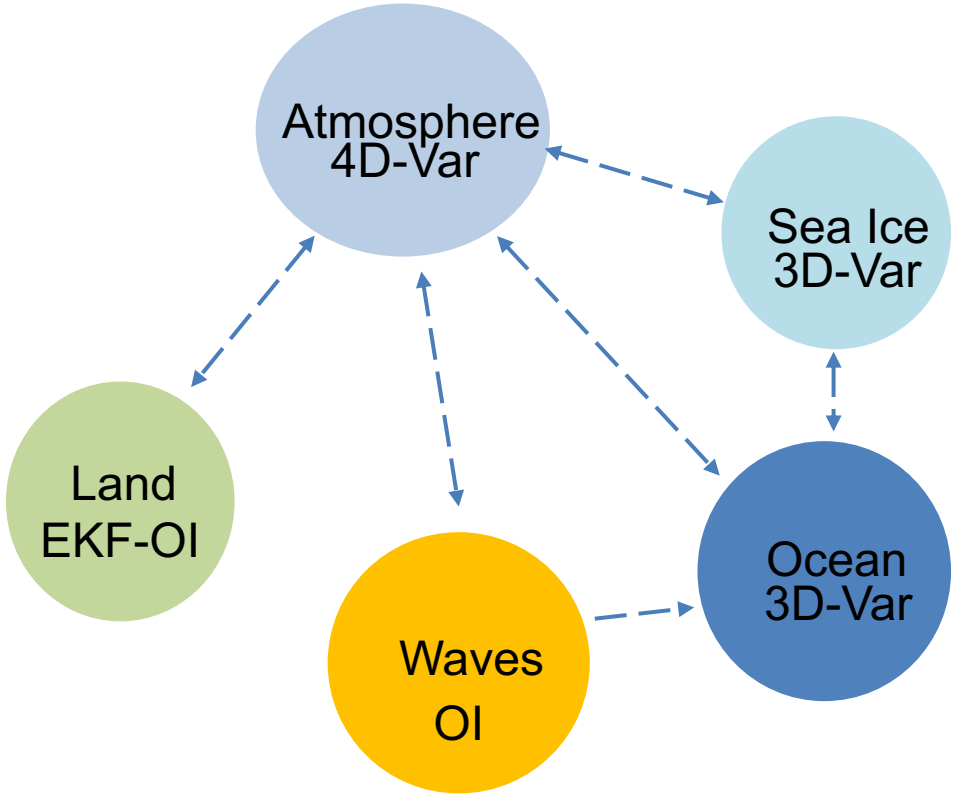
Earth system approach



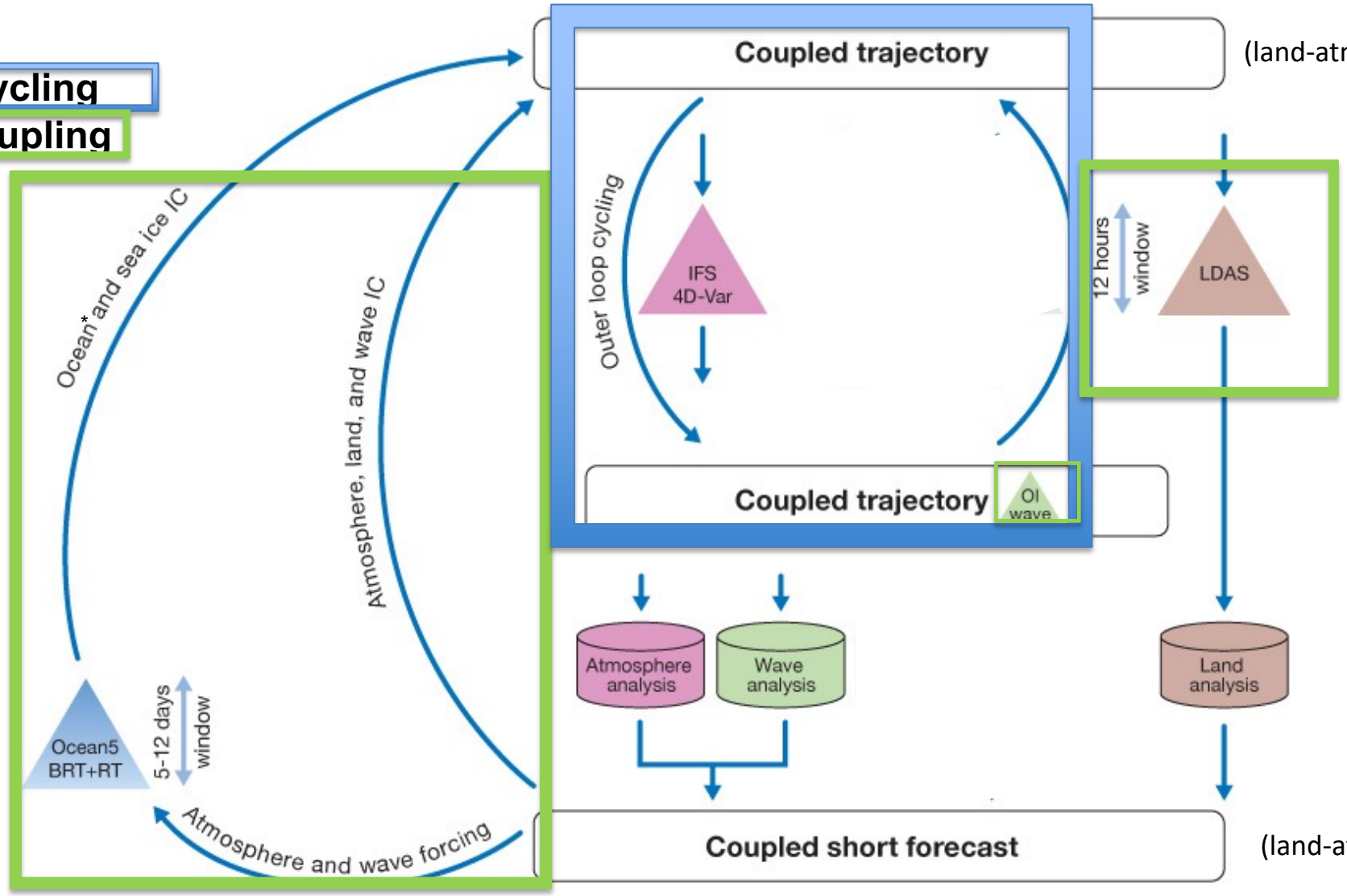
- Coupled assimilation developments for NWP and reanalyses
- Importance of interface observations (e.g. SST, sea ice, snow, soil moisture)

Coupled data assimilation

- What: Exchange of information between data assimilation systems so that observations from one component can influence the analysis of other components (Penny et al., WMO white paper, 2017)
- Why: to provide balanced initial conditions across the coupled forecast model components (e.g. Laloyaux et al.,QJRMS 2016)
- How: Diversity of methodologies ranging from weak to strong coupling (e.g. Fujii et al., QJRMS 2021, Browne et al., 2019; Fairbairn et al. JHM 2019; Schepers et al., ECMWF NewsLett 2018, Storto et al., MWR 2018; Karspeck et al., QJRMS 2018, Frolov et al., MWR 2016, Smith et al., TellusA, 2015);

Coupled data assimilation (DA): current status for NWP at ECMWF

Combined
outer loop cycling
and weak coupling



LDAS: Land data assimilation system

*patrial SST coupling (OSTIA in the Extratropics)

ECMWF

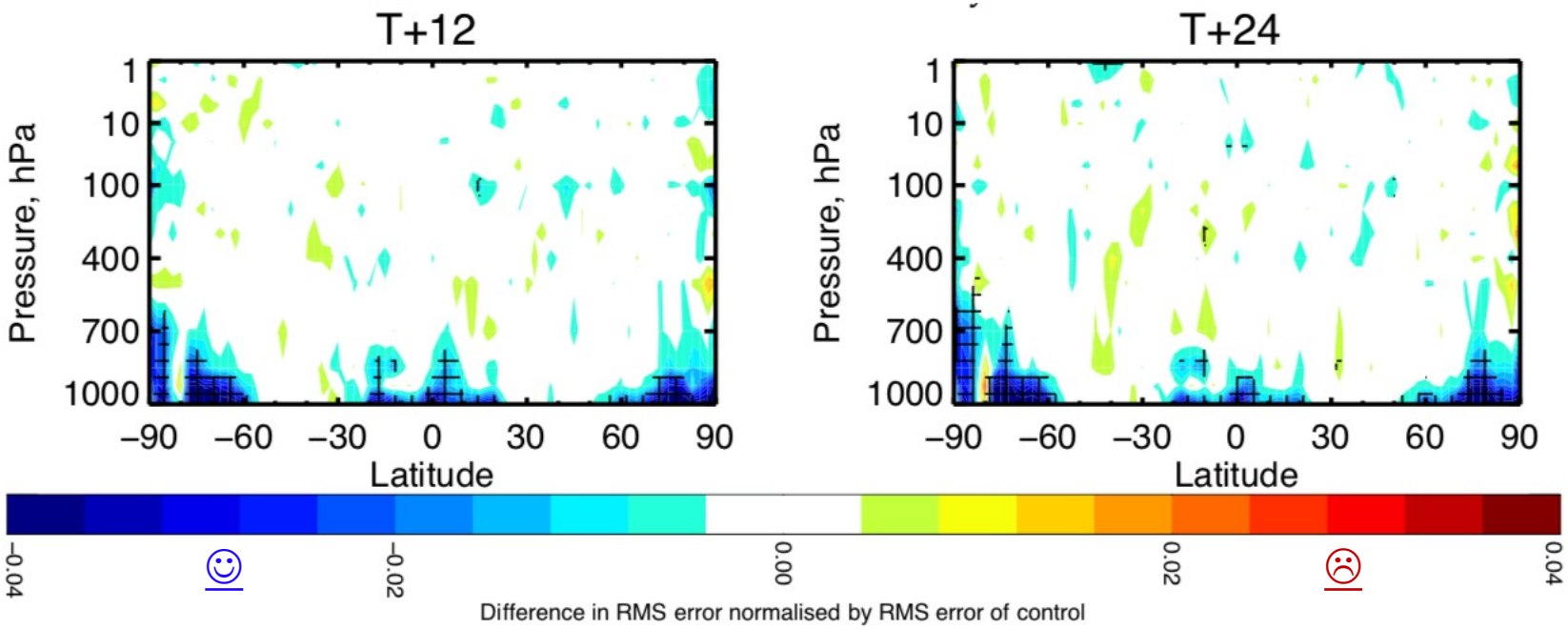
de Rosnay et al., QJRMS 2022
https://doi.org/10.1002/qj.4330

Ocean-atmosphere coupled DA: current status for NWP

Weakly coupled assimilation

June 2017-May 2018

Impact on Temperature Forecasts



(b) dRMSE of temperature (K)

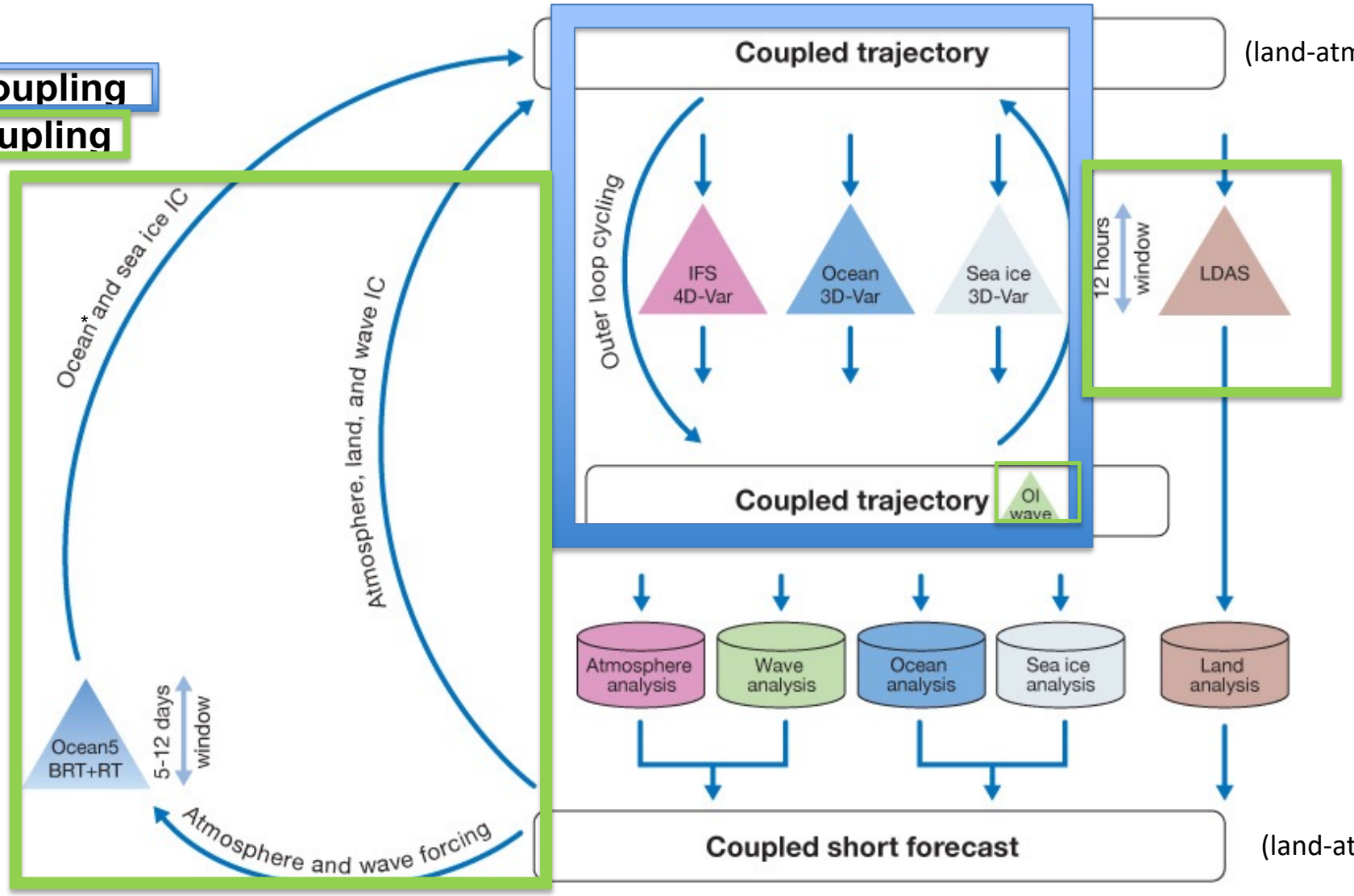
(June 2017 to May 2018)

Normalized RMSE difference
(weakly coupled DA – uncoupled DA)

Browne et al., Remote Sensing, 2019

Coupled data assimilation: current status in research

Combined
outer loop coupling
and weak coupling



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de Rosnay et al., QJRMS 2022
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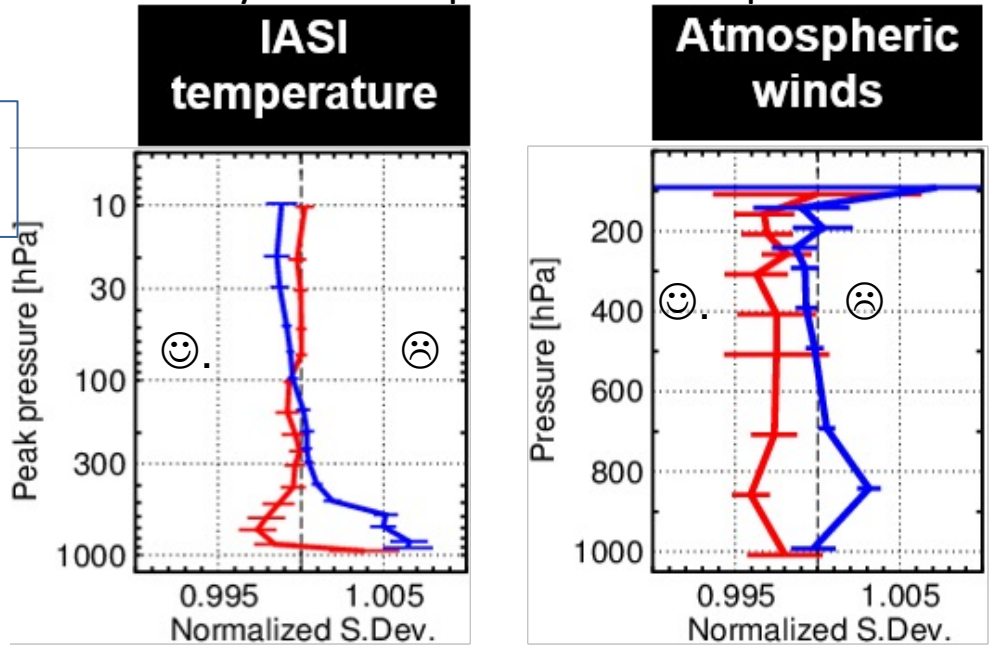
Outer loop coupling history and the ERA-CLIM2 project

- The ERA-CLIM2 (2014-2017) objective was to develop global centennial reanalysis based on coupled ocean-atmosphere data assimilation (Laloyaux et al., MWR 2016, JAMES 2018). It followed the ESA Coupled ECMWF ReAnalysis (CERA) project (2012-2014).

- CERA system → proposed the outer loop coupling methodology and demonstrated the relevance of the concept with CERA-20C (Laloyaux et al., JAMES 2018) & CERA-SAT (Schepers et al., ECMWF NewsLett. 2018).

The CERA system also showed challenges that needed to be addressed before operational applications.

First guess fit to observations in the CERA-SAT system compared to uncoupled CTRL



- Tropics
- Extra-tropics

Coupled ocean-atmosphere reanalysis challenges and progresses

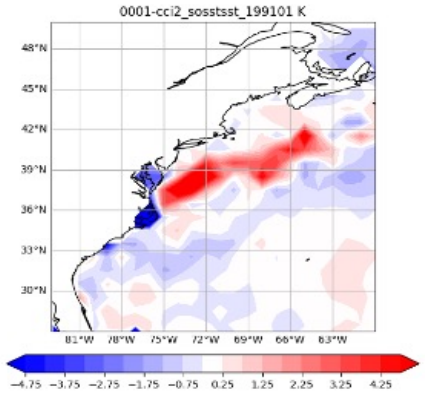
Western boundary current representation issues in the ocean model
→ affecting the Gulf Stream and the Kuroshio positions,
→ leading to wrong sea-surface temperature patterns
→ propagating into the atmosphere with degradation of the NWP performance.

ERA report series

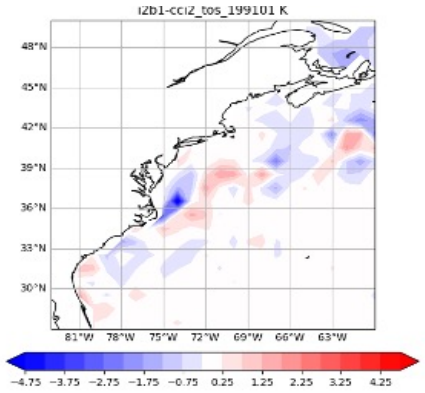
27 Operational global reanalysis: progress, future directions and synergies with NWP

Hersbach et al., ERA Report Series, 2018
10.21957/tkic6g3wm

ORAS5



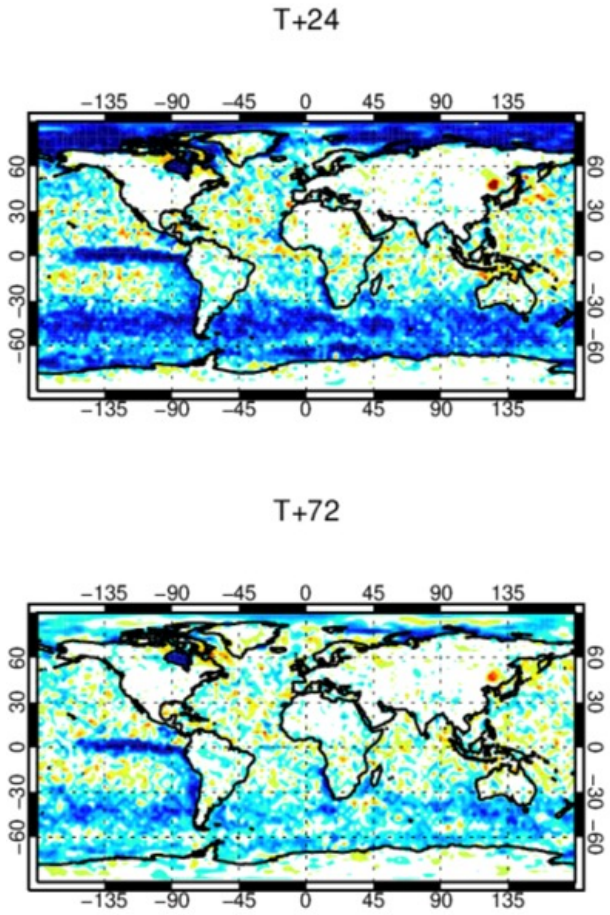
ORAS6 preparation



2018-2023 research progresses
→ Western boundary current issues addressed in the next ocean model and data assimilation system (Hao Zuo, Phil Browne, Marcin Chrust, Eric de Boisséson, Sarah Keeley, Kristian Mogensen and others).

→ **Improvements in the ocean system and coupled DA enhances the readiness level of the outer loop coupling methodology**
→ **We now revisit outer loop coupling performances and extend the approach**

Further research on ocean-atmosphere coupled assimilation



T2m forecast RMSE difference between outer loop coupling with RADSST and CRTL (operational configuration)

Outer loop ocean-atmosphere coupling with radiance-based SST analysis (RADSST) instead of using external SST from OSTIA.

Results with Infrared observations from IASI, CrIS and AIRS. DJF 2021/22

Research is ongoing to extend to microwave and sea-ice domain and exploration of the potential for altimeter assimilation simultaneously constraining sea level height and humidity with Extended Control Variable approach

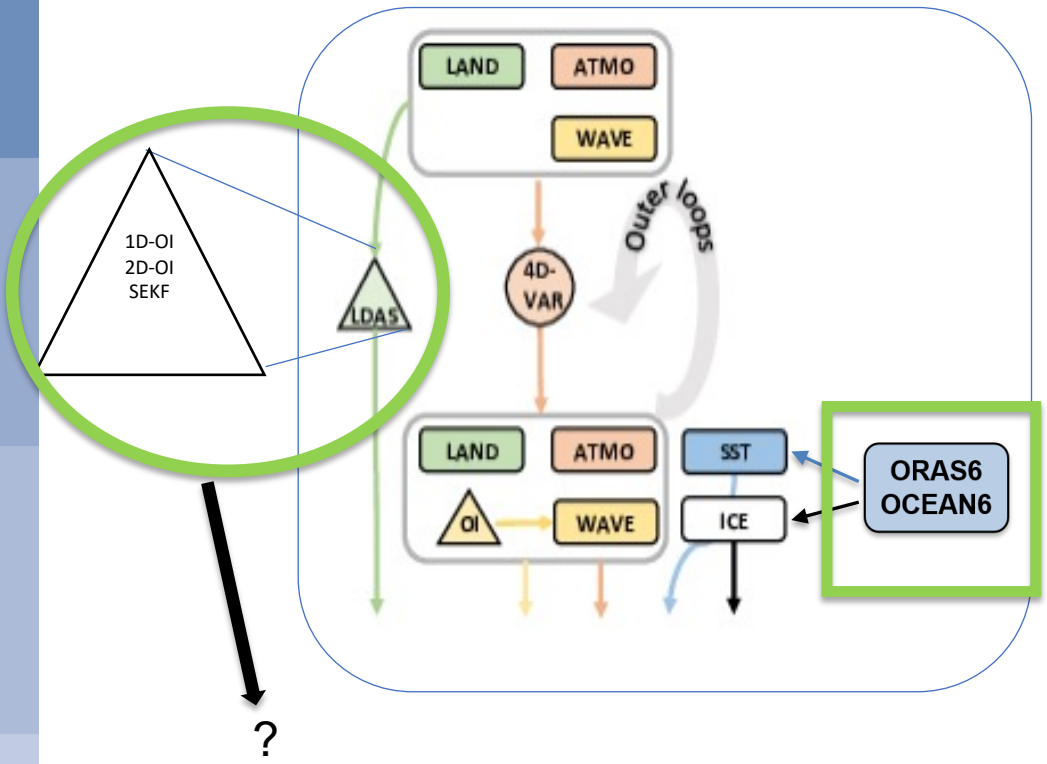
→ Phil Browne on Friday

What are we doing for operational reanalysis and where are we going?

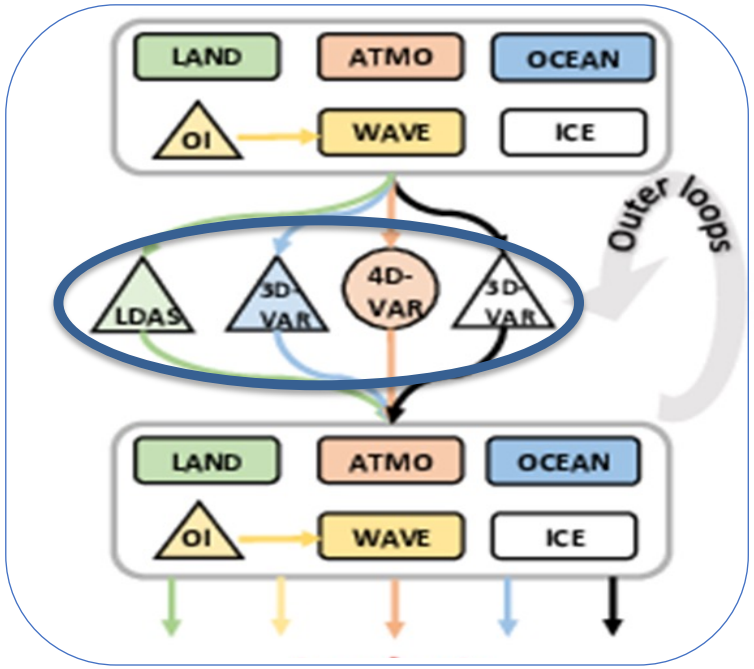
Weakly coupled data assimilation for
- Land-atmosphere-waves (ERA5)
- Land-atmosphere-waves-ocean-sea ice (ERA6)

Enhanced outer coupled data assimilation for
- Land-atmosphere-waves-ocean-sea ice (ERA7)

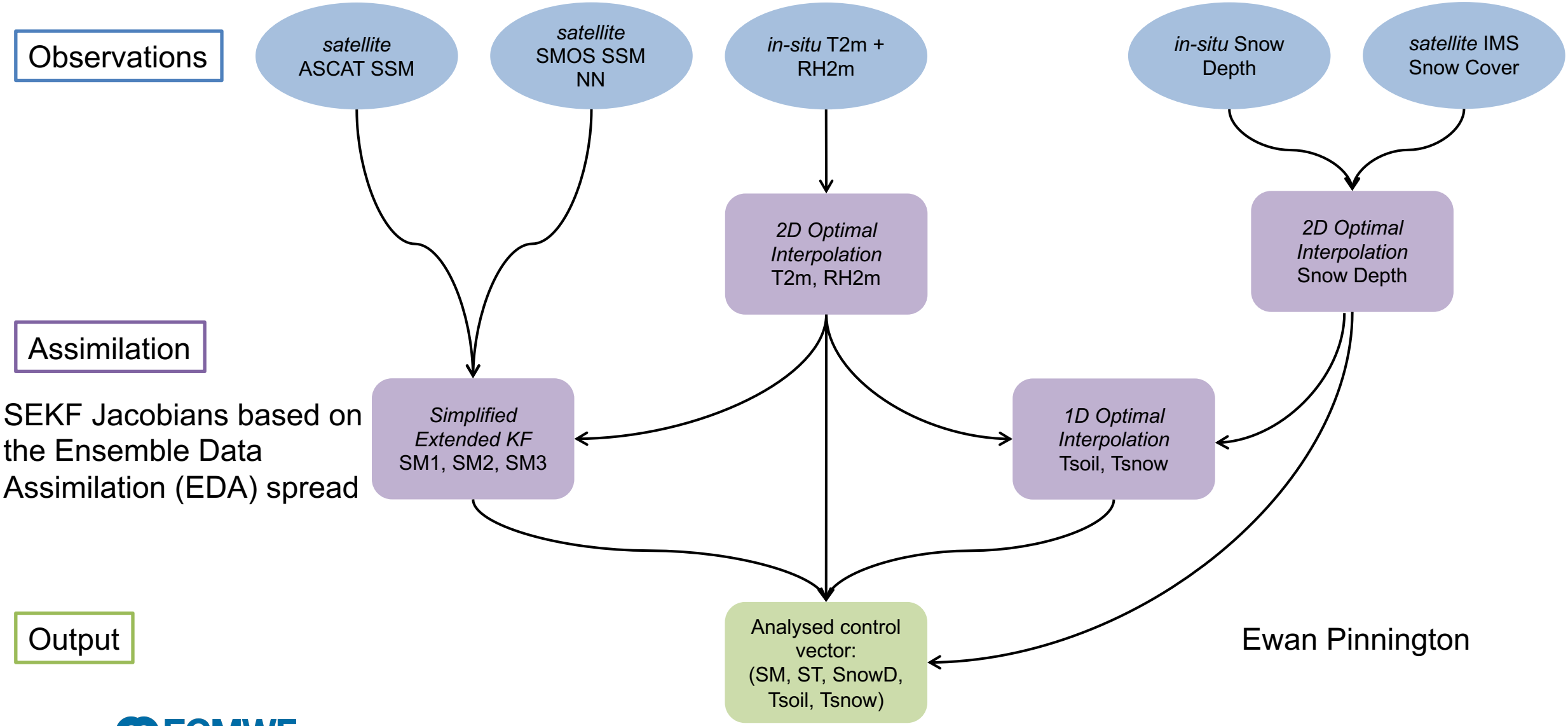
ERA5 and ERA6



ERA7



ECMWF Land Data Assimilation System (LDAS)



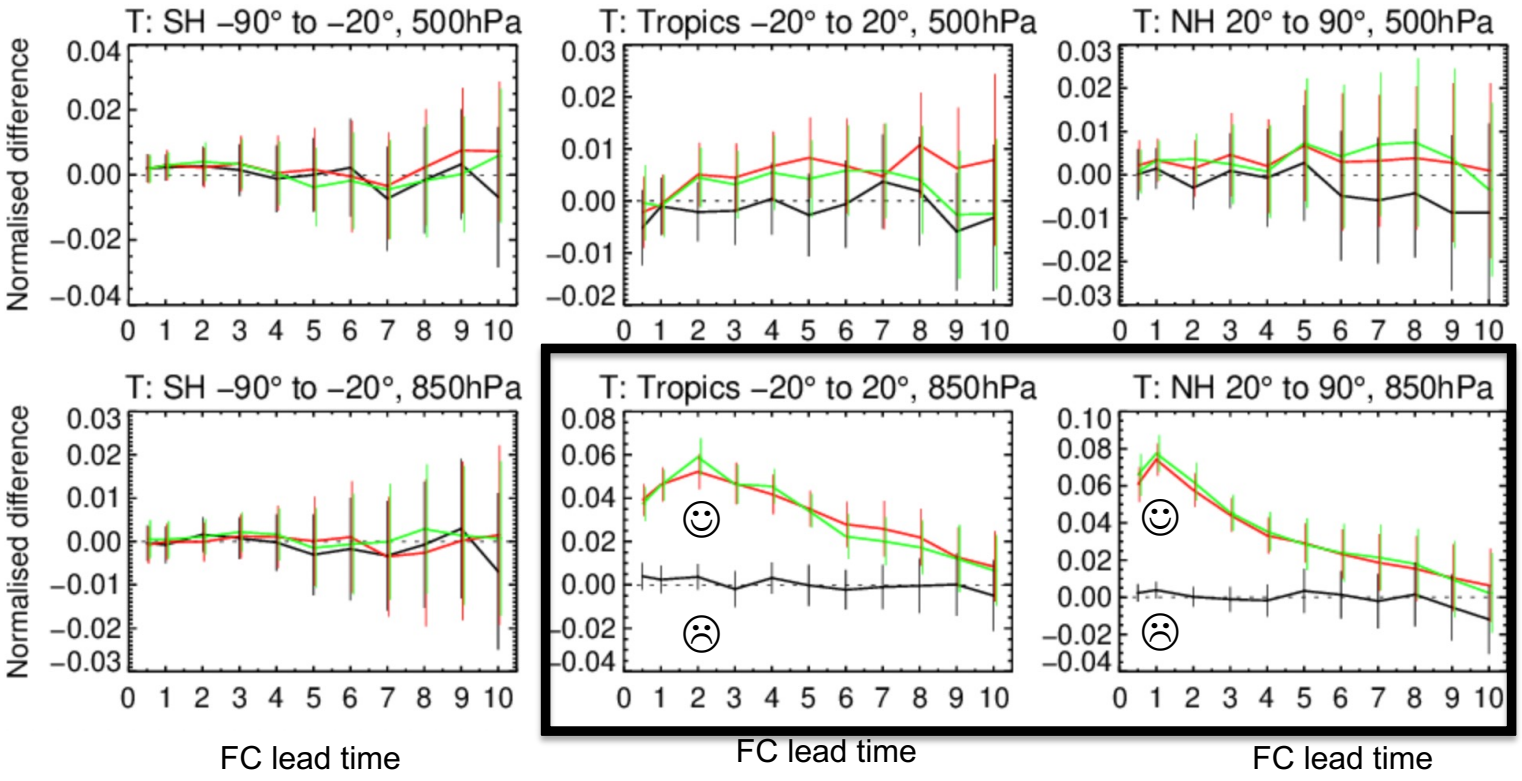
Ewan Pinnington

ECMWF

Soil analysis for NWP: impact on the atmospheric forecast

Temperature RMSE

JJA 2020
IFS cycle 48r1



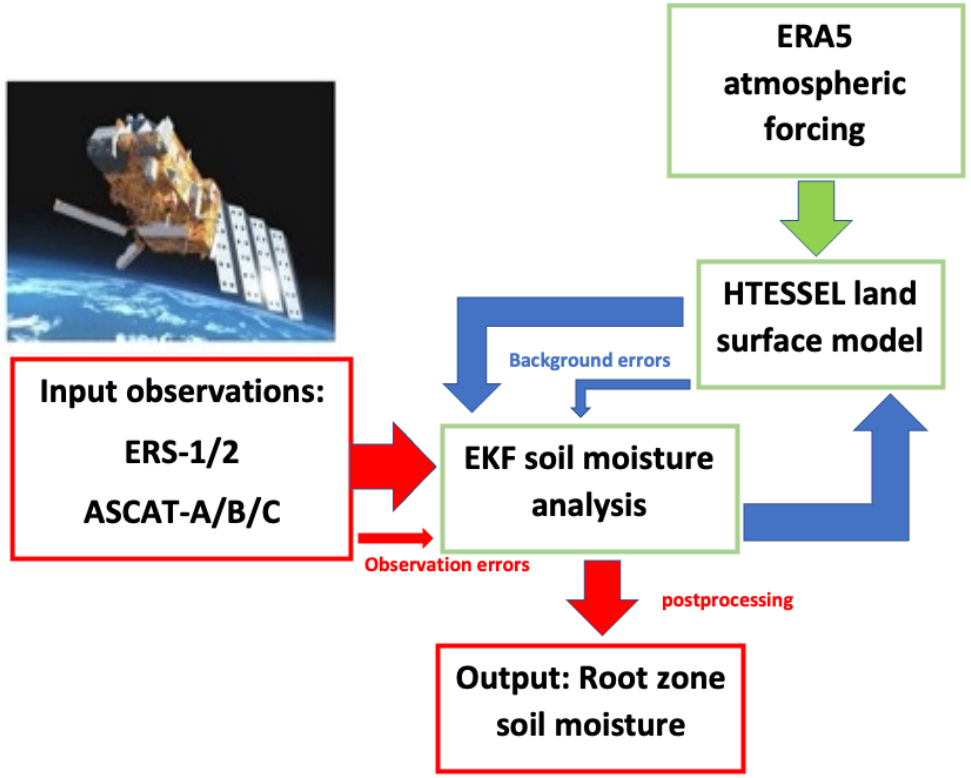
Without soil moisture DA
Without soil moisture DA
With soil moisture DA

Significant positive impact of land DA on low level atmospheric temperature forecasts

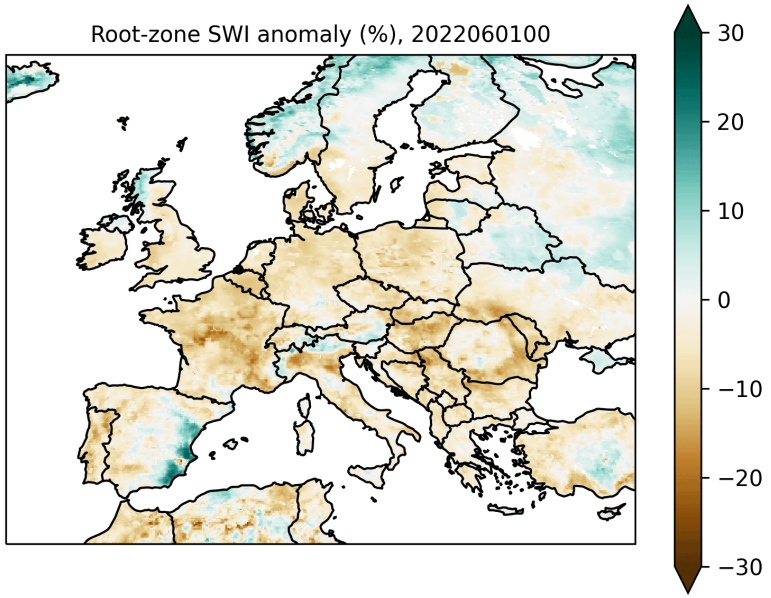
Sébastien Garrigues

H SAF root zone soil moisture data record

EUMETSAT H SAF
SUPPORT TO OPERATIONAL HYDROLOGY AND WATER MANAGEMENT



- Preparation of new SM data record (1992-2023, planned release 2024)
- Offline land DA with adaptive ASCAT SM bias-correction following Draper et al., JHM 2015



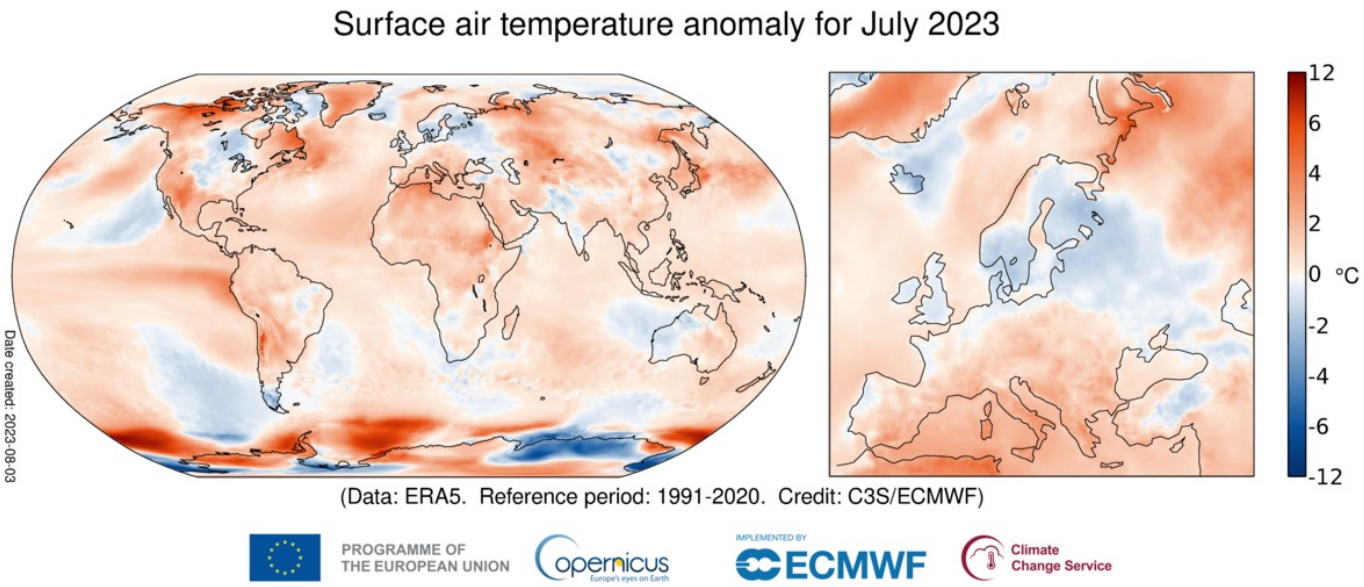
H SAF product RZSM-SCAT-ASCAT-CDOP-4-CDR-10km (H145)
+ offline extension (H146)

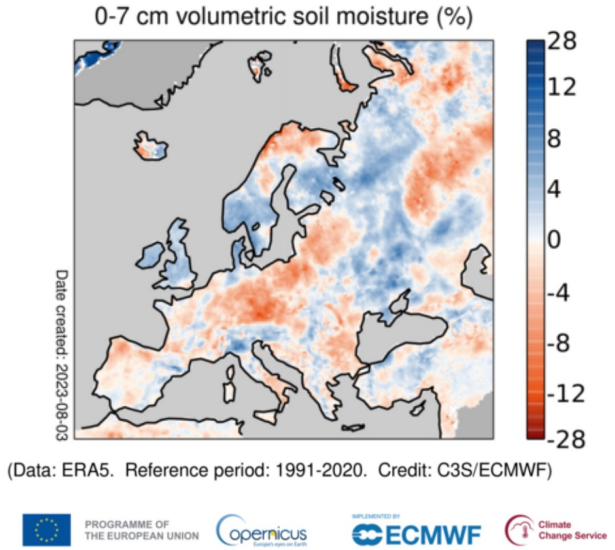
David Fairbairn

Land-atmosphere coupling progresses

Rolf Reichle tomorrow,
Clara Draper on Friday

- Developments of Land DA systems in the past 20 years (soil moisture, satellite DA, snow DA etc), but still univariate approach.
- And relatively little effort has been dedicated to land-atmosphere coupled data assimilation, despite the fact that near-surface conditions over land are of critical interest to users.



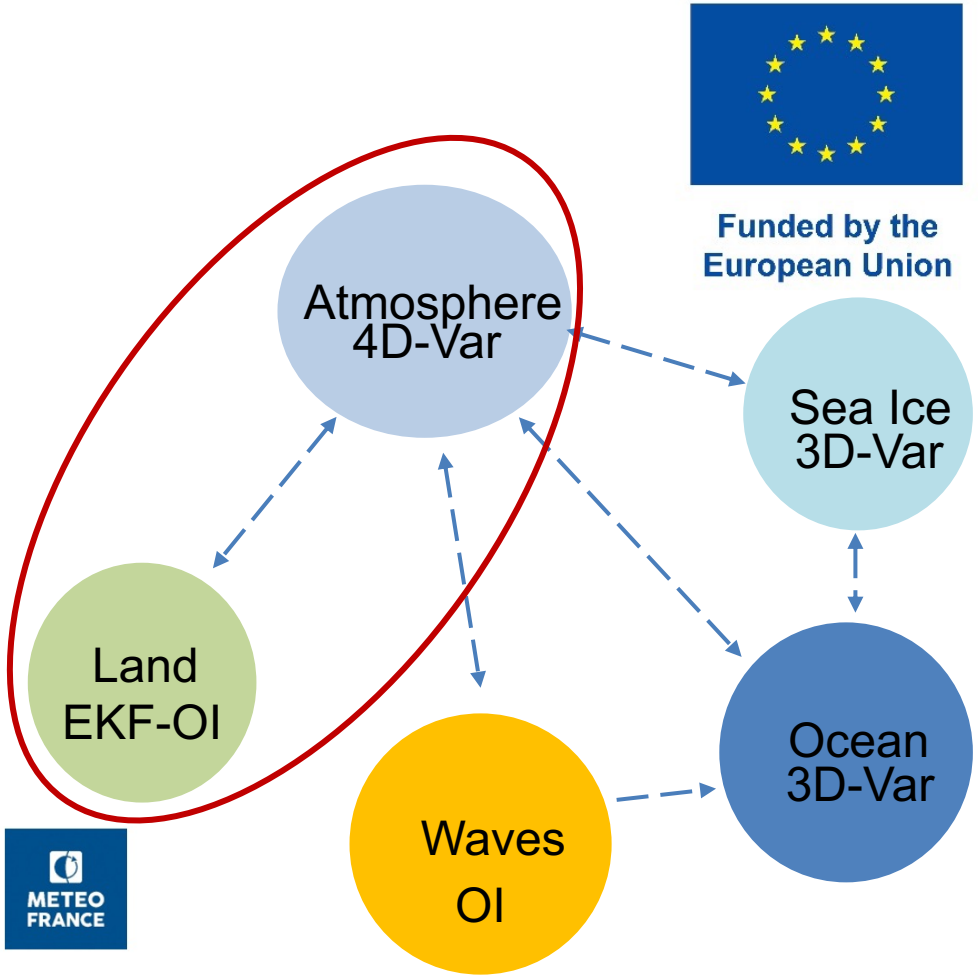


https://climate.copernicus.eu/climate-bulletins

CERISE Horizon Europe project

CERISE: CopERnIcus climate change Service Evolution (2023-2026)

→ **Support the long-term evolution of C3S for**
- regional and global climate reanalysis and
- multi-system seasonal prediction,
towards an Earth system approach with a focus on land-atmosphere coupling.



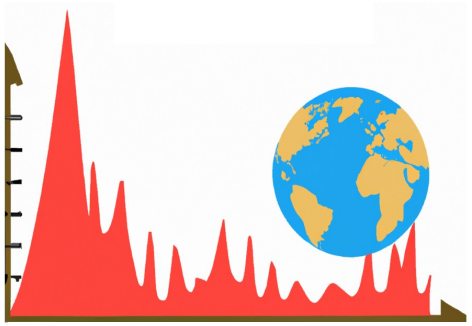
https://www.cerise-project.eu/

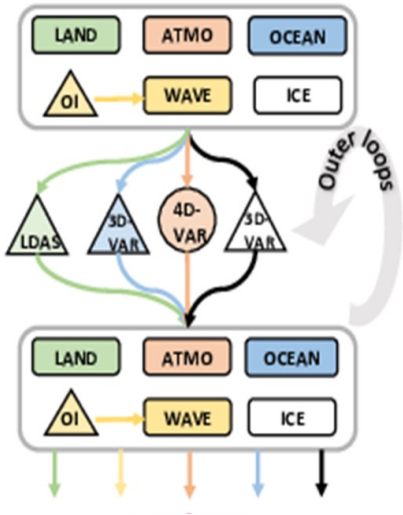
The CERISE project (grant agreement No101082139) is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Commission. Neither the European Union nor the granting authority can be held responsible for them.

CERISE developments

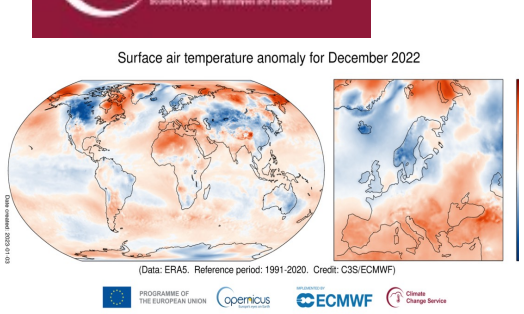
- Land and coupled land-atmosphere data assimilation
- Explore ML-based observation operators to improve the exploitation of satellite observations

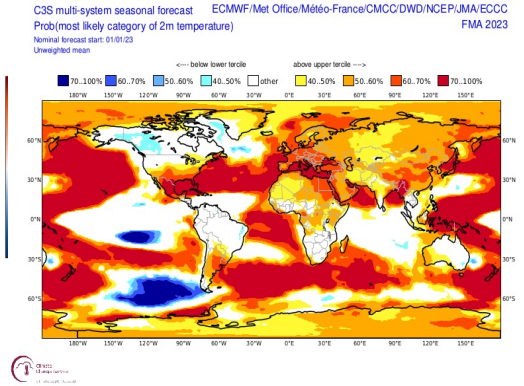
- Multidecadal representation of evolving vegetation and lakes, building up on CONFESS H2020 → Magdalena Balmaseda on Wednesday
- Prototypes of seamless reanalysis and multi-system seasonal prediction → High readiness level: ERA6-Land, ERA7, SEAS7
- Novel diagnostic tools to assess physical consistency of Earth system reanalysis and prediction





Funded by the European Union





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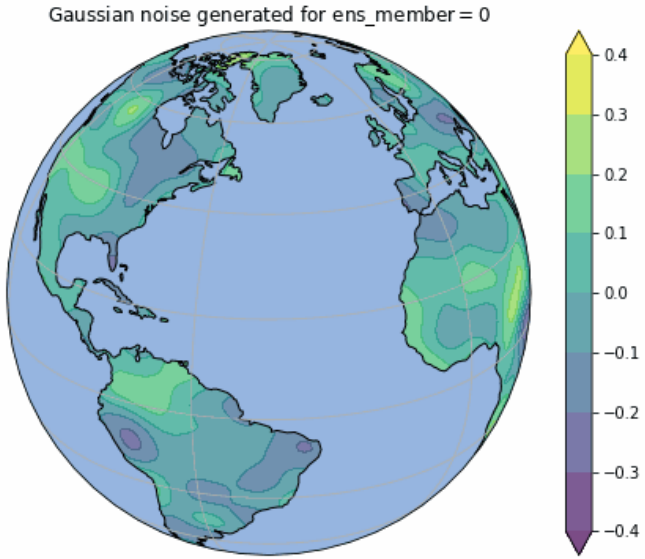
Land surface parameter perturbations

- The ECMWF Ensemble of Data Assimilations (EDA) is under-spread at the surface
- As part of CERISE project, we explore methods to increase ensemble spread at the land surface for future Land Surface Data Assimilation Systems (LDAS)
- Stochastic Parameter Perturbation approach for Leaf Area Index (LAI) and vegetation fraction in the offline land DA system



Perturbations generated with spatial and temporal correlation length scale

- Draper et al., JHM 2021 also investigated surface parameter perturbations https://doi.org/10.1175/JHM-D-21-0016.1 → Clara Draper's talk on Friday

Ewan Pinnington

Funded by the European Union

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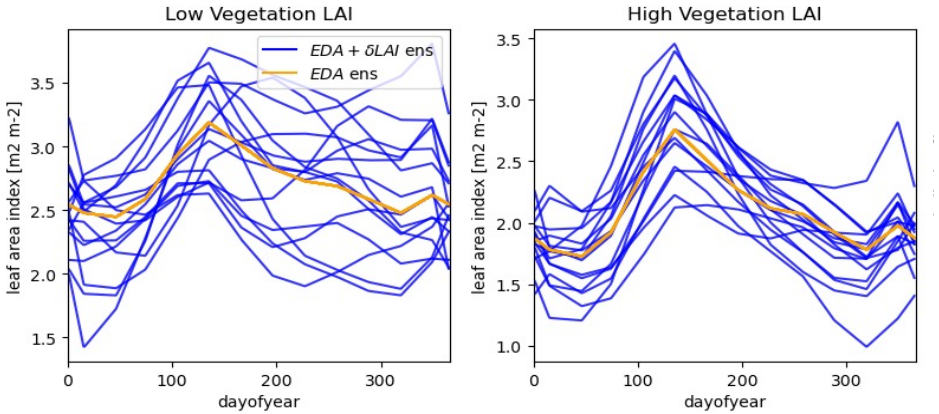
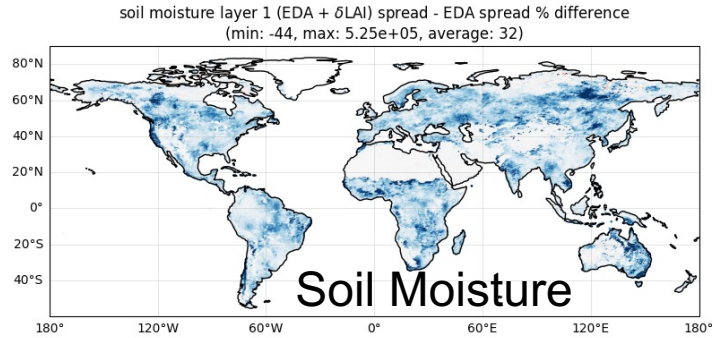
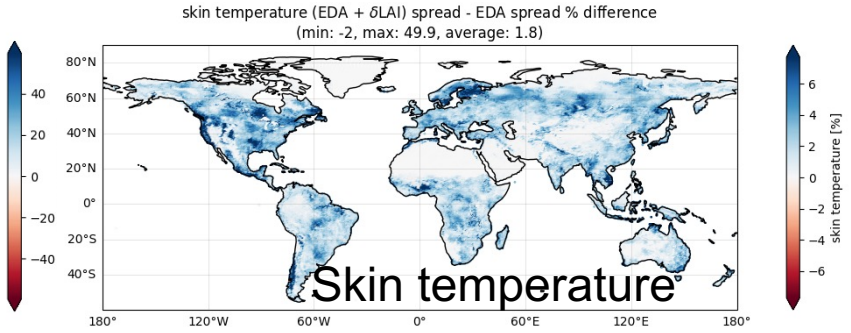
Land surface parameter perturbations

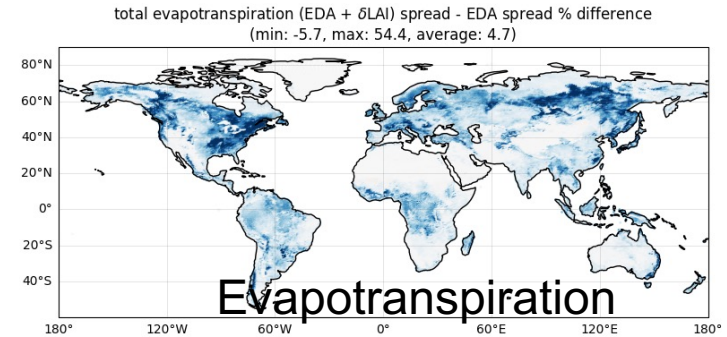
SPP-like Perturbations

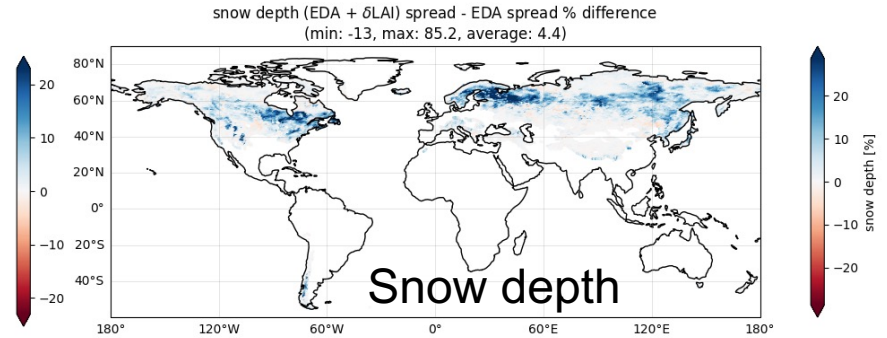


- Maps: differences in spread between the EDA offline surface ensemble with and without perturbations.
- Blue corresponds to an increase in spread
- Further increase expected in the coupled EDA









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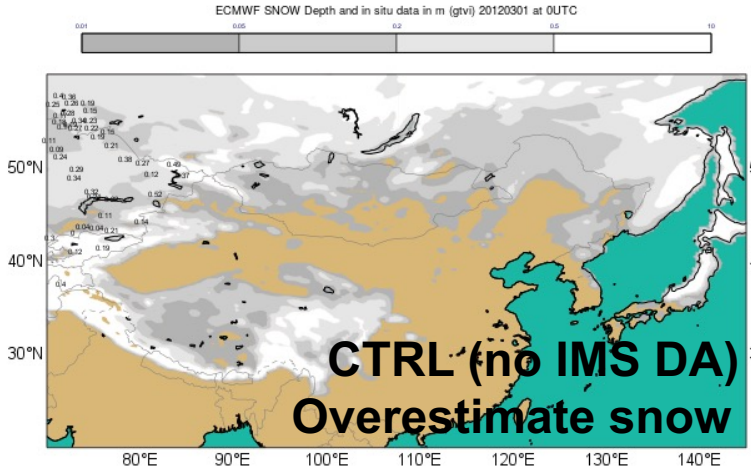
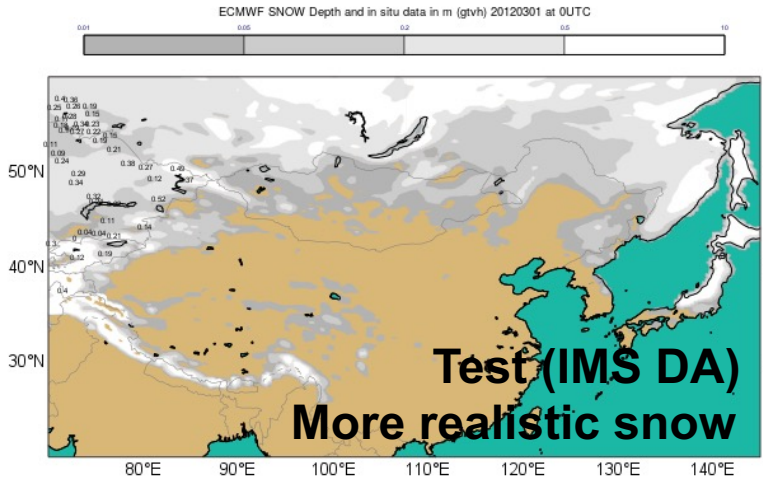
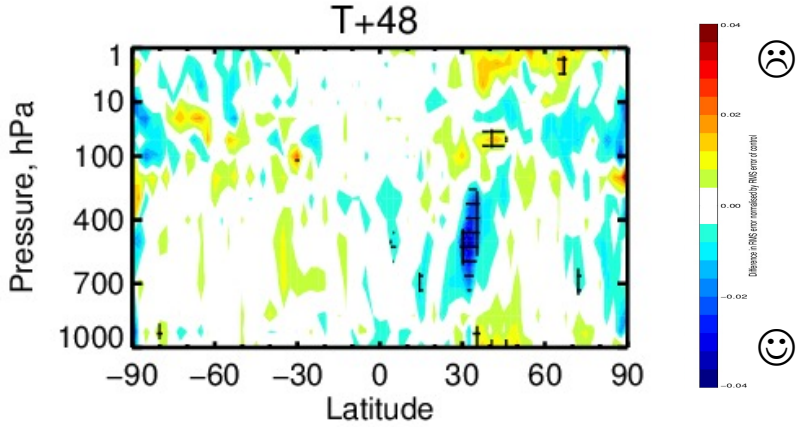
Coupled snow-atmosphere data assimilation





Impact on albedo and momentum
→ Modifies the jet circulation

Change in humidity FC error
Oct 2011 – June 2012

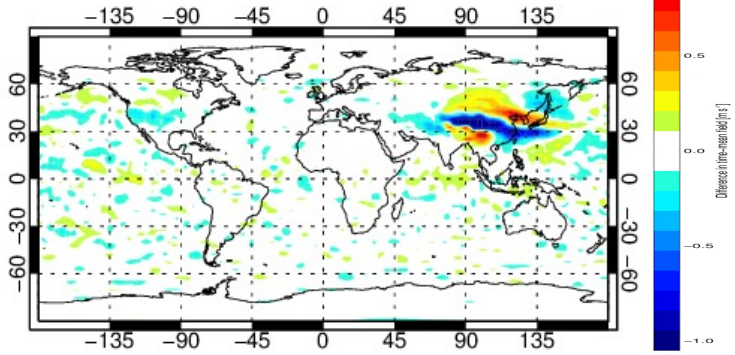


In previous studies, we showed the potential of snow cover data assimilation over the Tibetan Plateau (Orsolini et al, TC 2019, de Rosnay et al.).

Challenges related to model biases and snow-boundary layer coupling needed to be addressed to mitigate mixed atmospheric impact.

Multi-layer snow model reduced the snow model biases and enhanced consistency between snow and boundary layer processes. (Arduini et al, JAMES, 2020, https://doi.org/10.1029/2019MS001725)

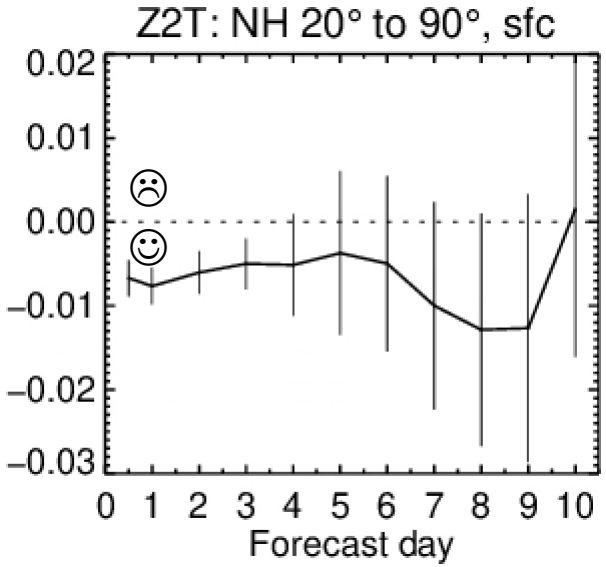
Change in zonal wind
Oct 2011 – June 2012



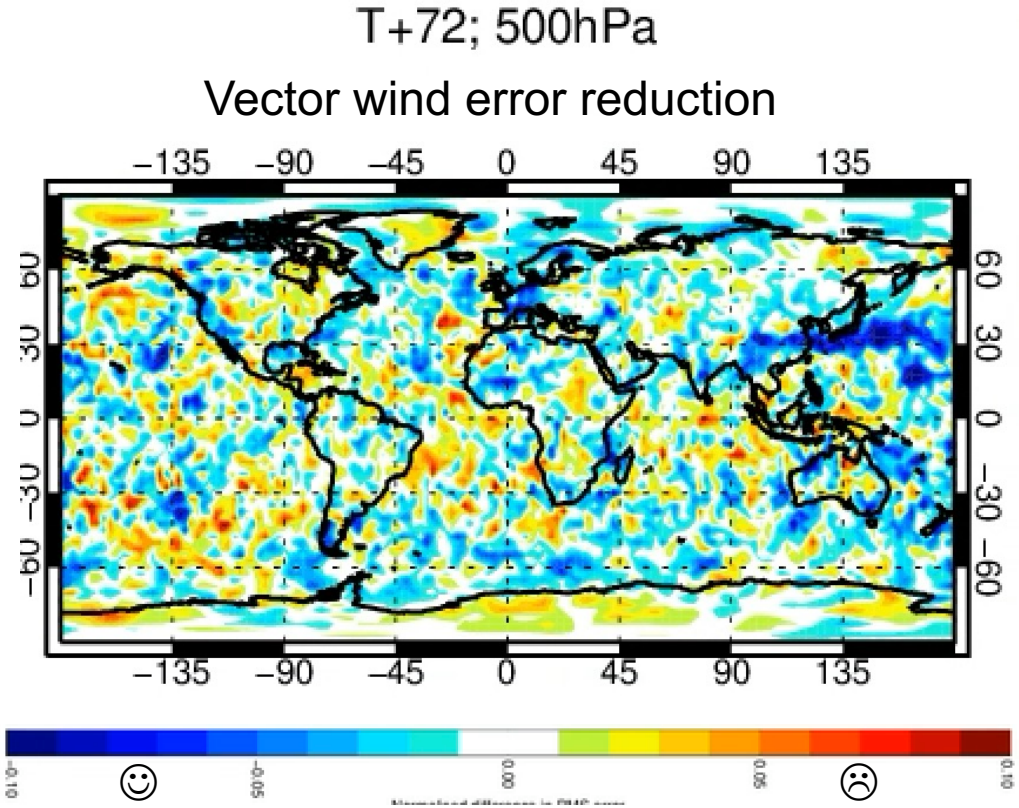
Further snow data assimilation improvements planned for ERA6

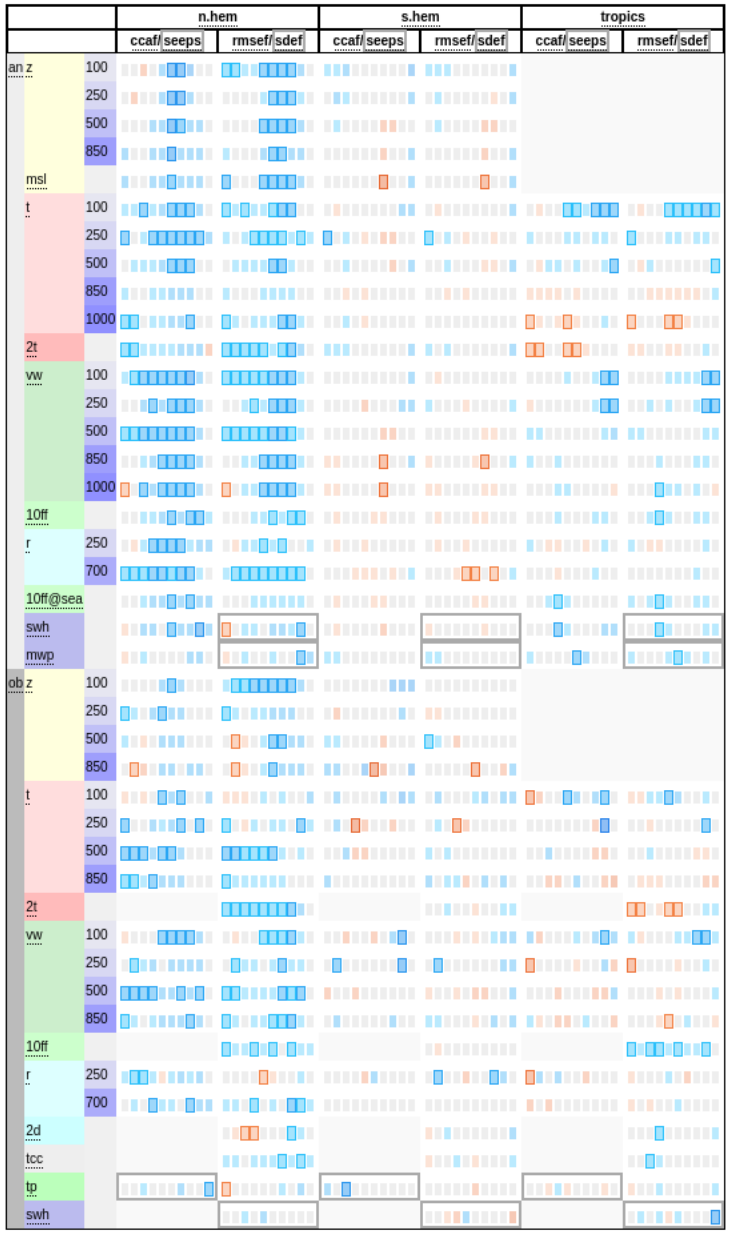
Refined snow cover modelling and assimilation methodology.

→ positive impact of IMS snow cover assimilation in mountainous areas
→ IFS cycle 49r1 & 49r2 (ERA6 and ERA6-Land)



Surface air temperature improvement



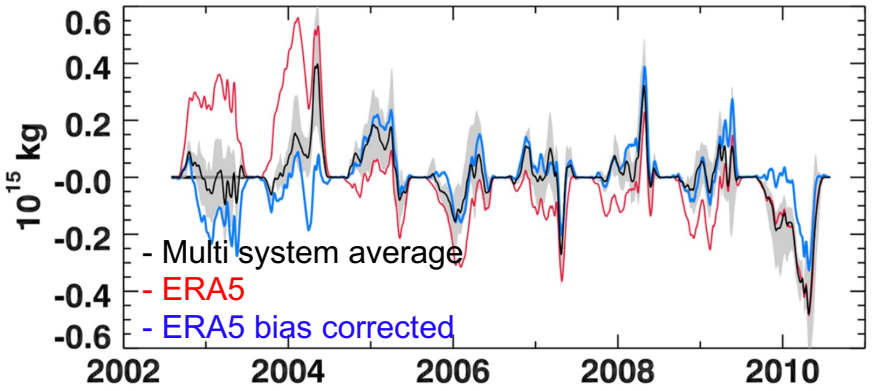


Scorecard →
(blue= improved
red=degraded)

Kenta Ochi

Snow reanalysis from ERA5 to ERA6

- Step change in the ERA5 snow mass from 2004 (IMS snow cover started to be assimilated)
- Snow DA reduced the positive snow cover bias, but it amplified the snow mass negative trend



Mortimer et al., The Cryosphere 2020
https://doi.org/10.5194/tc-14-1579-2020

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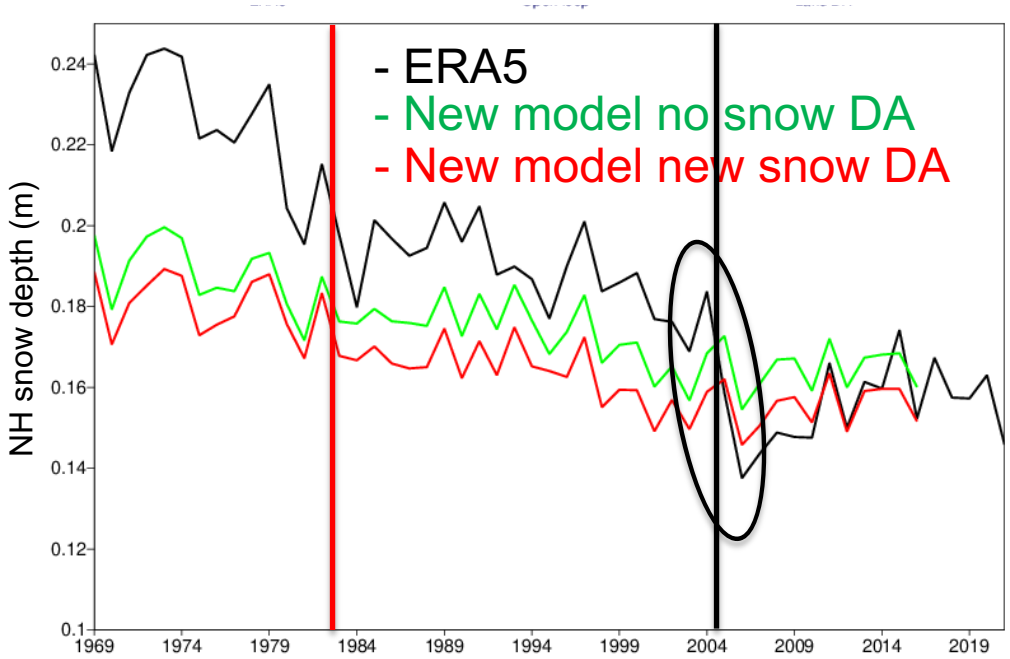
- In ERA6:
  - Snow model and a set of snow data assimilation improvements
  - ESA CCI AVHRR (1982-2017) + NOAA/NESDIS IMS (2017-NRT)

- → ERA6-Land 1st prototype in CERISE (1939-2022)



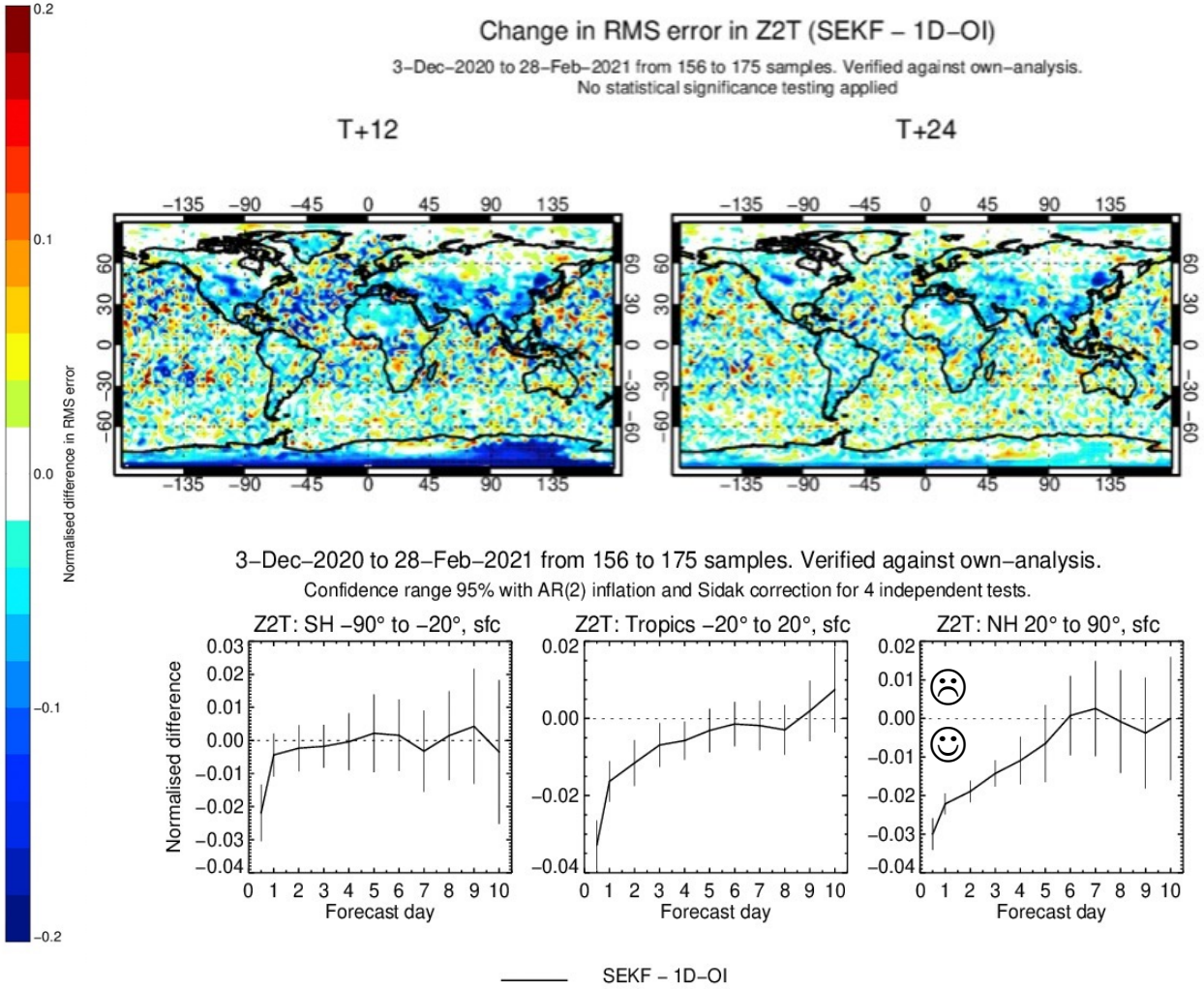
Kenta Ochi et al.

Soil and snow temperature analysis

Integration of the soil and snow temperature analysis in the SEKF, instead of using a 1D-OI approach

control variables $x_i =$

- swvl1
- swvl2
- swvl3
- stl1
- stl2
- stl3
- tsn



- Significant improvement in T2m analysis and forecasts

- Steps towards unified LDAS

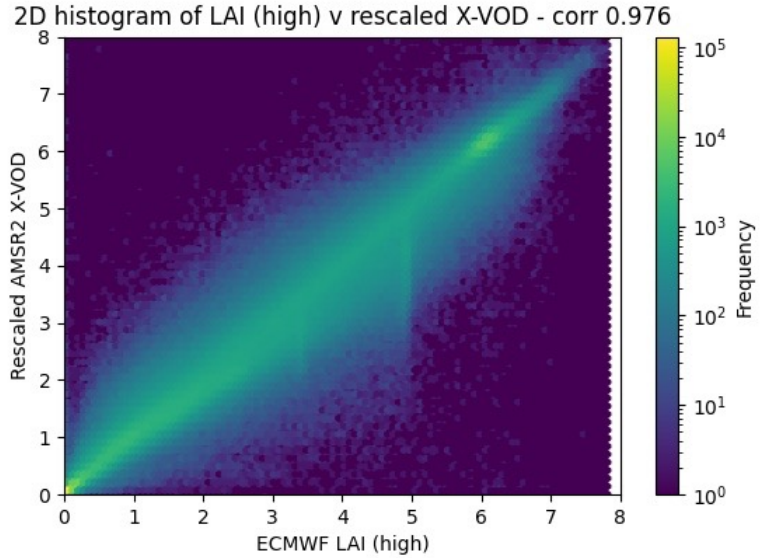
CoCO2 Horizon 2020 project

CoCO2
Prototype system for a Copernicus CO_2 service

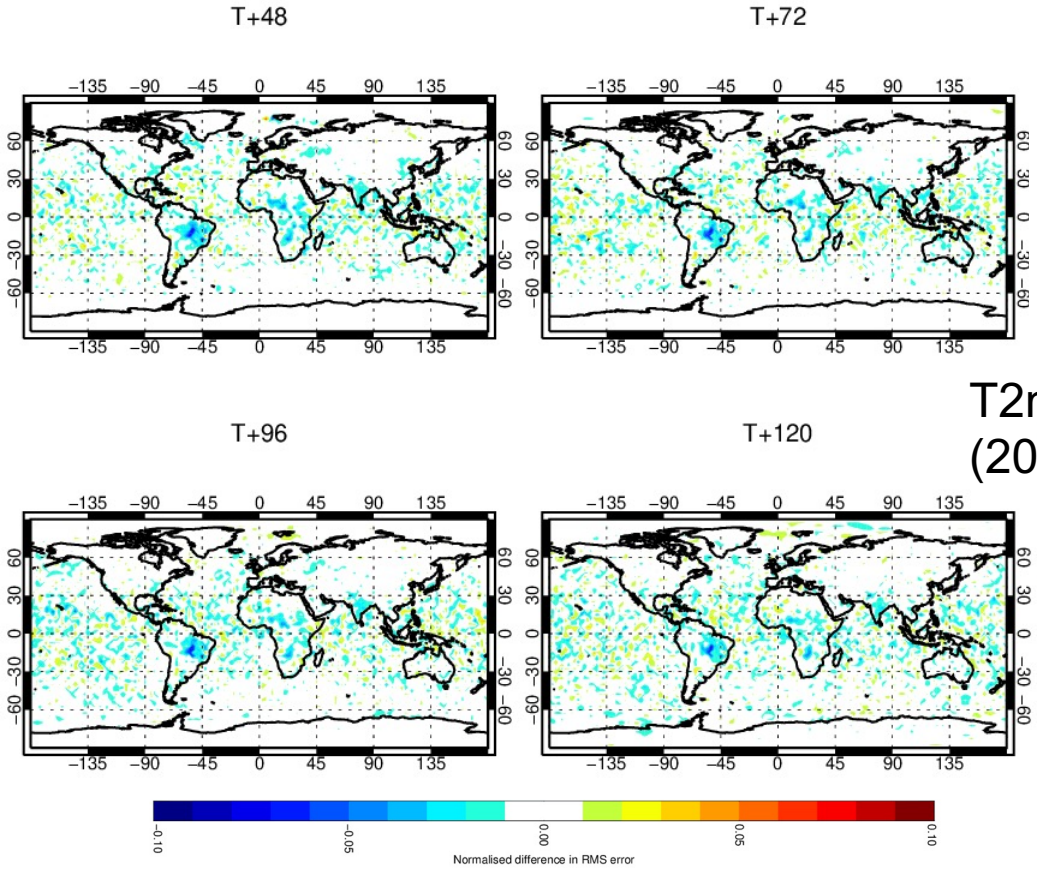
→ Anna Agusti Panareda

Assimilation of Vegetation Optical Depth (VOD) from passive microwave sensors to constrain vegetation water and carbon cycle variables.

- L-band VOD (1.41GHz) from SMOS
- C-band VOD (6.9GHz) and X-band VOD (10.65GHz) from AMSR2



Correlations between VOD observations and CONFESS (harmonization of the CGLS/C3S data and the AVHRR based data, Boussetta et al), LAI for high vegetation types for July 2018.



T2m RMSE reduction (2018-2021)

Pete Weston

Funded by the European Union

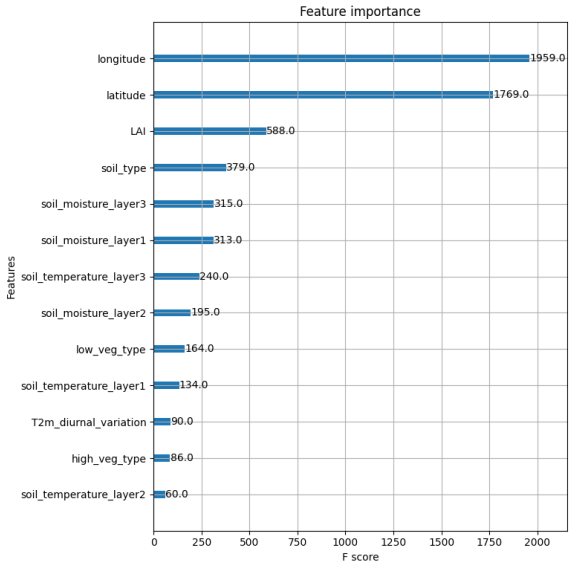
CORSO Horizon Europe project

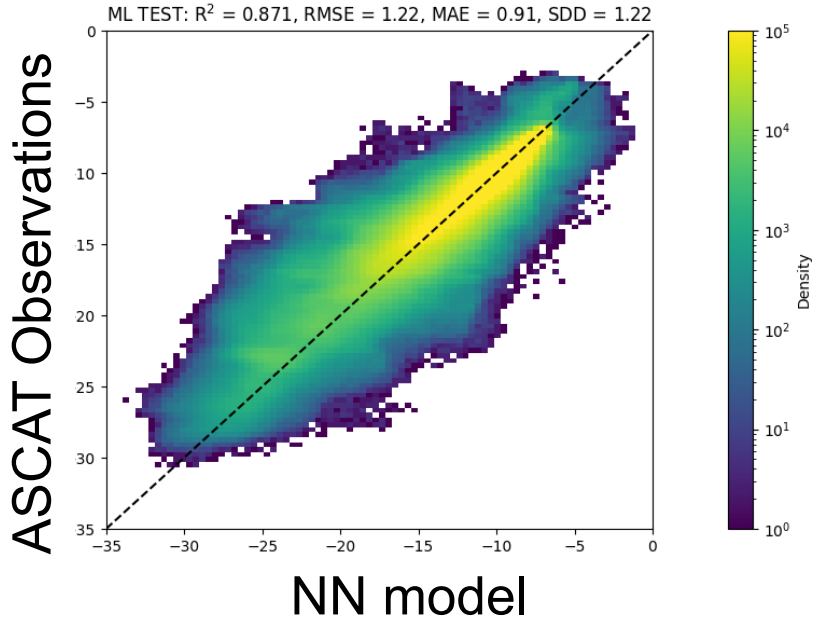
CORSO
CO2MVS Research on Supplementary Observations

Enhance the exploitation of satellite observations in coupled land-atmosphere assimilation to constrain vegetation water and carbon cycle variables.

→ Development of ML-based observation operators for MW and SIF observations

Information content analysis





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Sébastien Garrigues

→ Pave the way for future observations assimilation such as Metop-SG/SCA, Copernicus Expansion CO2 and CIMR missions, which are all relevant to consistently constrain vegetation and carbon fluxes in CO2MVS

ECMWF
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Summary

- ECMWF has a long experience in reanalysis of the different Earth system components.

- Progressive implementation of coupled assimilation towards a consistent Earth system approach for operational NWP and future generations of reanalyses.

- Consistency between NWP and reanalysis, and synergy in research developments:
  - Initial research on coupled ocean-atmosphere data assimilation was primarily for reanalysis applications
  - Coupled DA is a key aspect of the ECMWF Earth system strategy 2021-2030
  - Ongoing research projects support time varying vegetation (CONFESS) and coupled land-atmosphere data assimilation (CERISE) for the preparation of the C3S next generation of reanalyses and consistent benefit across ECMWF systems.

- Earth system reanalysis developments rely on consistent joint model, data assimilation, and coupling progresses.
- Earth system reanalysis approach has some practical implications in terms of production and quality assurance (→ Dinand Schepers on Thursday)
- Other components, e.g. river and flood forecast system (→ Christel Prudhomme on Tuesday)

ECMWF

Next steps and strategic directions

- Convergence of the DA systems in each component to support exchange of information across components
  - Developments in each components.

- Coupling methodology
  - Step-by-step approach with progressive implementation towards the optimal degrees of coupling for seamless NWP and reanalysis.

- Enhance the exploitation and monitoring of observations across the components
  - Existing & new observations type, and future missions including Metop-SG, MTG, Copernicus Expansion CIMR and CRISTAL,
  - Transition to lower level, observation operator coupling integrating AI/ML, towards an “all-surface” approach.

Special Collection Quarterly Journal of The Royal Meteorological Society

“Coupled Earth system data assimilation”

Submission deadline: 31 December 2023

https://rmets.onlinelibrary.wiley.com/