Coupling methodology approaches and the example of application to land / atmosphere interactions

Christoph Herbert and Sébastien Massart

Earth System Assimilation Section, Research Department, ECMWF

Annual Seminar, 14-18 September 2026, Reading

CopERnIcus climate change Service Evolution - CERISE

Funded by the European Union

Contents

Introduction

Land analysis in the atmospheric 4D-Var

Enhanced land-atmosphere coupling

Coupled data assimilation

Funded by the European Union

Advantages of coupled DA [Strategy at ECMWF: de Rosnay et al., 2022]

- **Enhanced consistency** between **DA systems** allows exchange of information [Laloyaux et al., 2016; Penny et al., 2017]
- **Balancing initial conditions** across different Earth-system components
- **Exploitation** of **interface observations** sensitive to more components

Types of coupling

- **WEAK**: analyses **separate** for Earth-system components; coupling through **cycling**
- '**QUASI-STRONG**': analysis **separate**; components **balanced** within same DA window
  - 1. Enhanced coupling through the **exchange of initial conditions**
  - 2. Enhanced coupling through the **use of interface observations**

Outer loop coupling

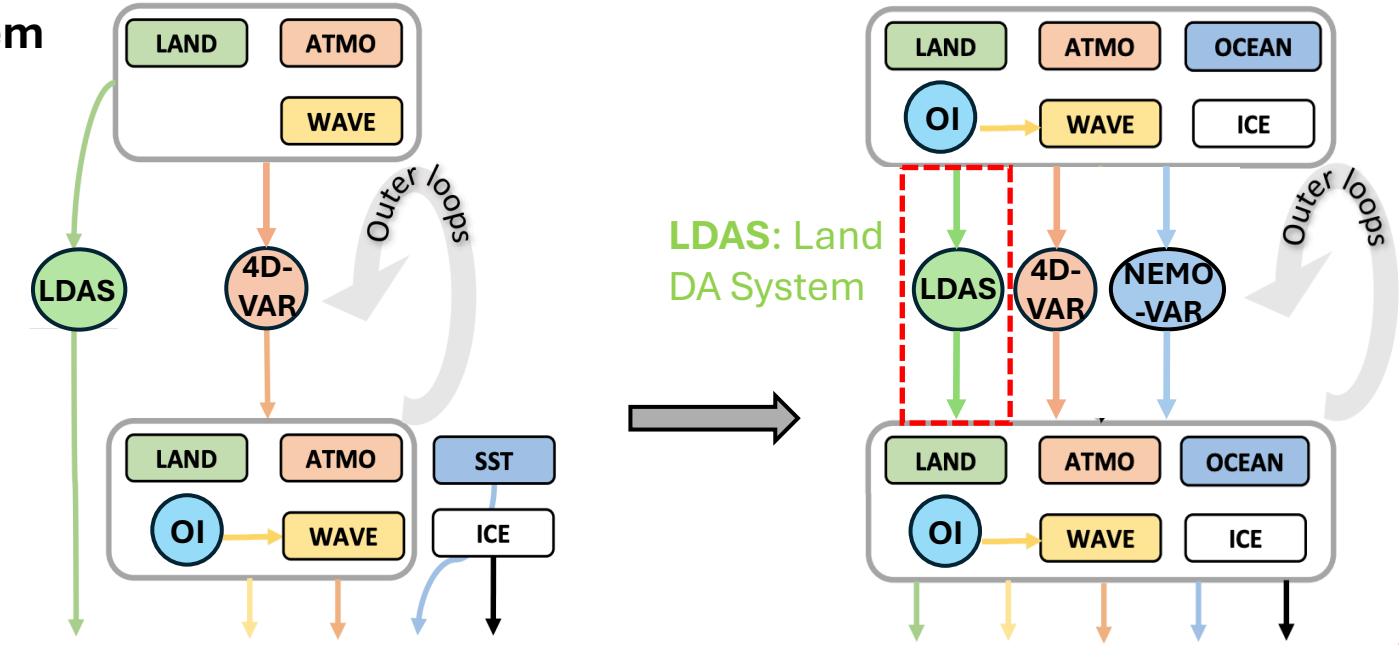
- **STRONG** (or **FULL**): **joint** analysis of all variables using the same control vector
  - Multivariate B matrix of entire state

CERISE project (2023-2026)

Funded by the European Union

Copernicus Climate Change Service Evolution (CERISE) project

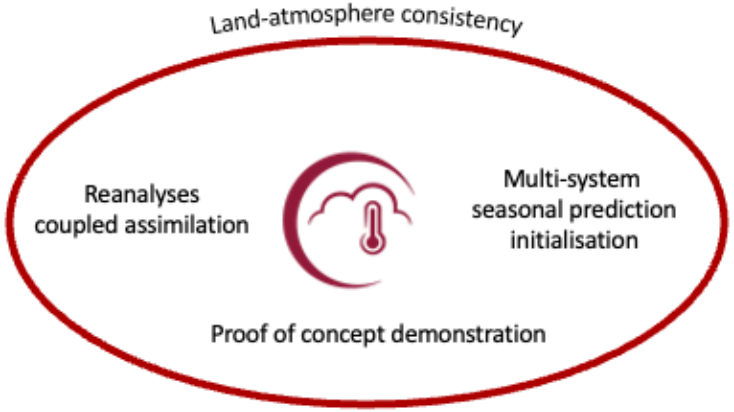
ERA5 system



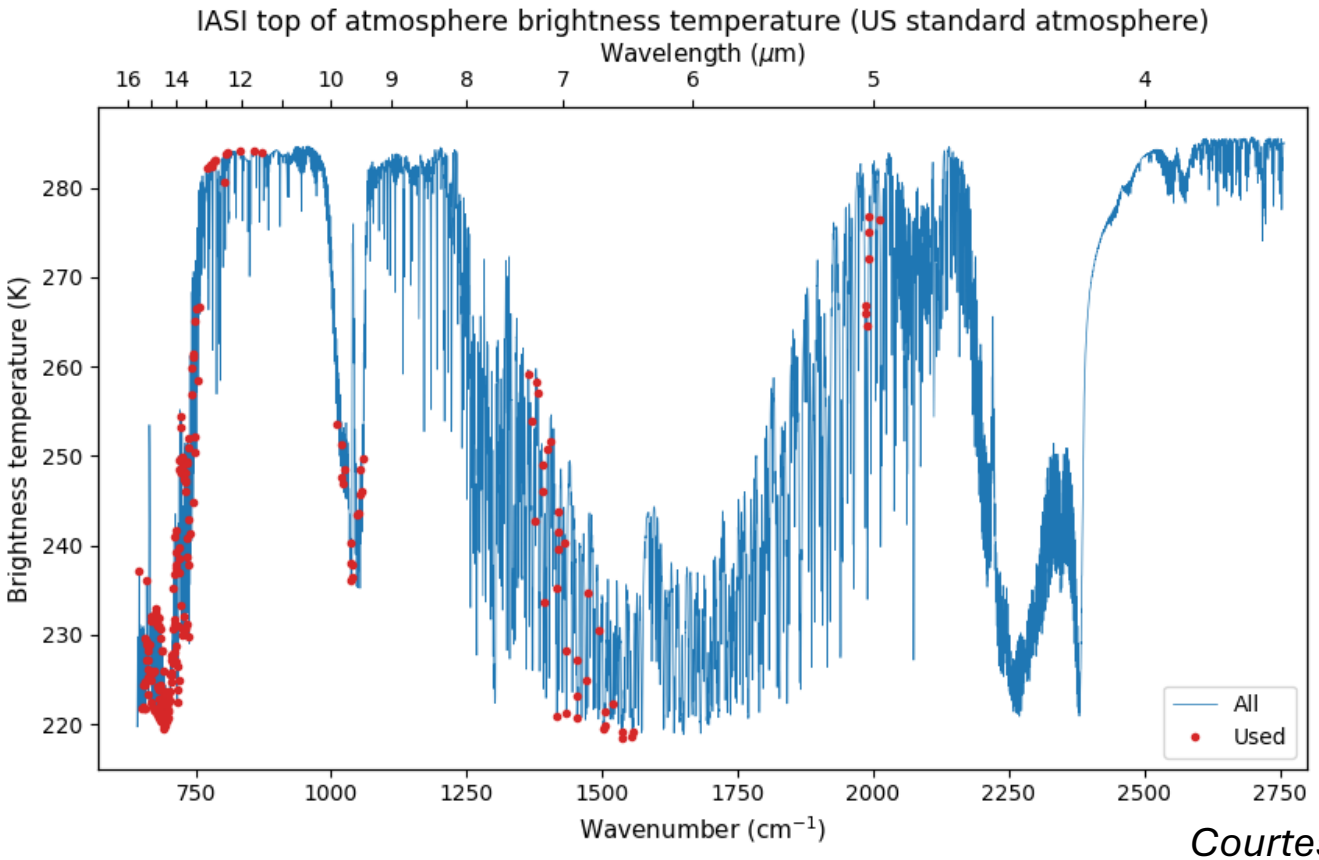
Next generation (beyond ERA6) system

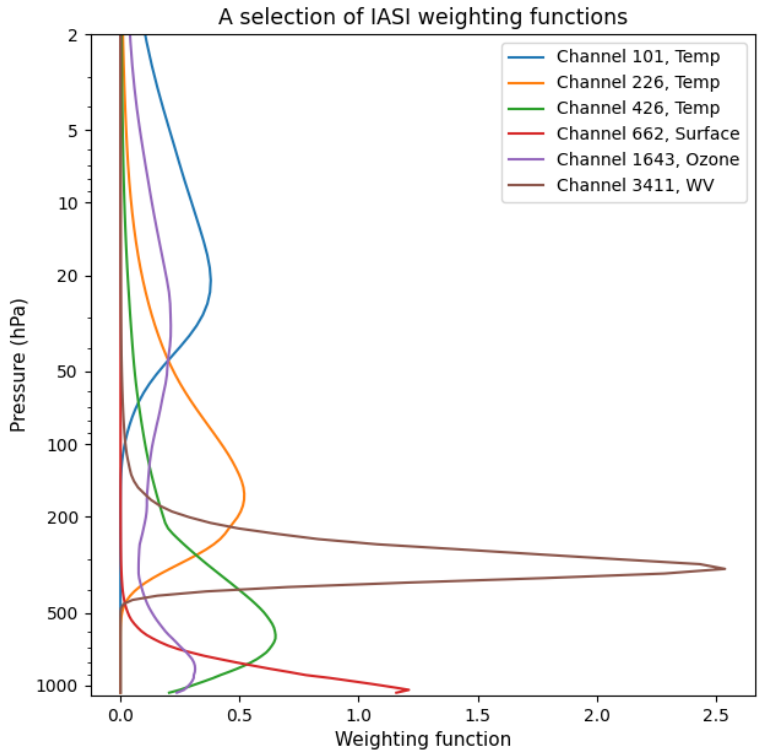
Outer loop ocean/sea ice /land-atmosphere coupled DA

- **Land-atmosphere coupled DA** for better climate consistency of the next generations of C3S Earth system reanalyses
  - ➢ Unified ensemble-based land DA system
  - ➢ Outer loop land-atmosphere coupled DA
- Proof-of-concept **global and regional reanalysis prototypes**



Surface observations are underexploited





Courtesy: Chris Burrows, ECMWF

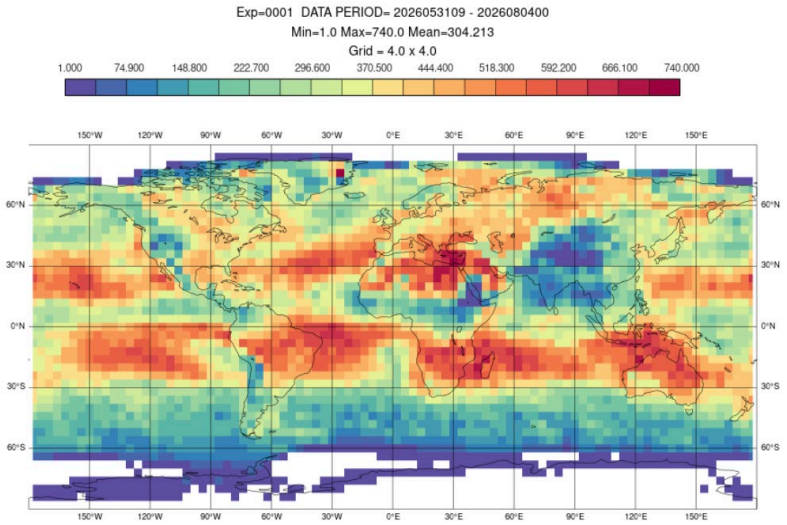
surface-to-TOA transmittance	τ_sfc > 0.9	→ pure surface / window channel
τ_sfc in a standard atmosphere	τ_sfc < 0.1	→ pure atmosphere (opaque channel)
	0.1 ≤ τ_sfc ≤ 0.9	**→ mixed ("both")**

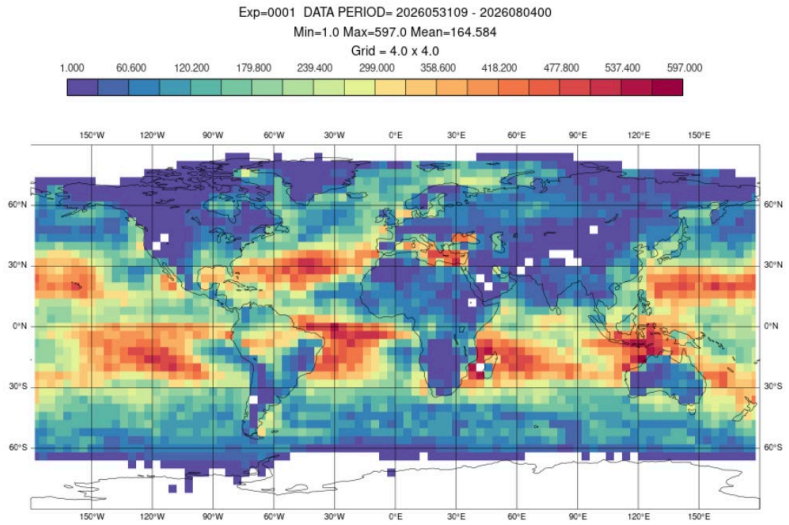
Radiances from METOP-B / IASI

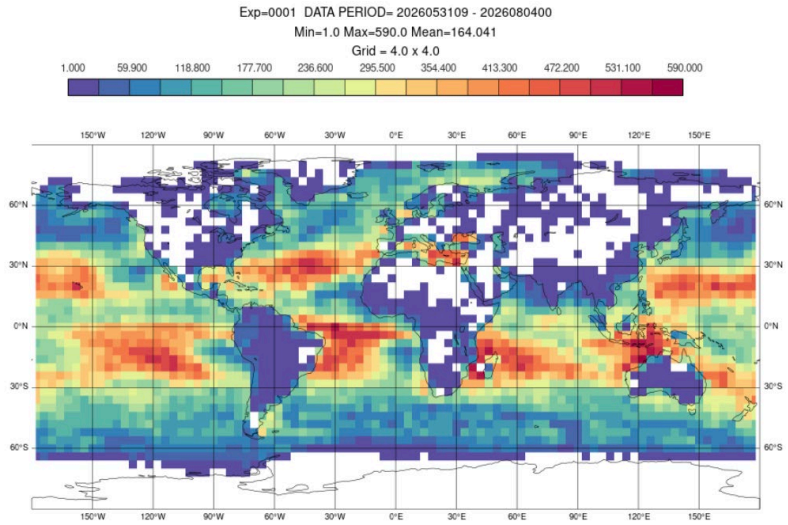
Surface-sensitive channels only assimilated <u>over ocean</u> and <u>clear-sky</u>

No window channels used over land!

CHANNEL (Wave function peak): **389** (515 hPa) **416** (777 hPa) **566** (1042 hPa)







<u>In operations:</u>

- **Mixed channels** already used but their surface component is discarded via bias correction / VarBC anchoring to model temperatures
- **Pure windows** treated as calibration reference, land information content unexploited

Retain and exploit surface-sensitive information

Funded by the European Union

From a clear-sky toward all-sky and all-surface approach

- Land surface heterogeneous
- Emissivity over land not well represented in observation operators

➢ **Distribute information content of observations across the land-atmosphere system**

Methodology to exploit underused channels

- Introduce additional sink variable (TOVSCV + XCV framework) in 4D-Var
- Assimilate the sink variable (analysis) as pseudo-observation into the land component

Application to outer loop land–atmosphere coupling

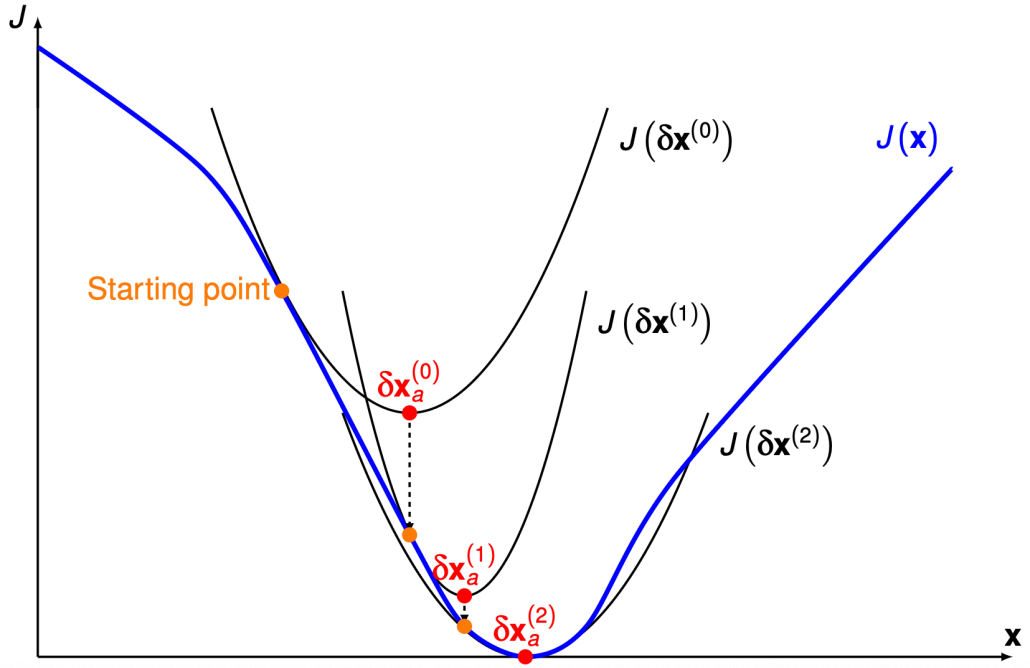
- Enhance the **exchange of state updates** between coupled model components
- Leverage the **XCV framework** to improve cross-component consistency

Land analysis in the atmospheric 4D-Var

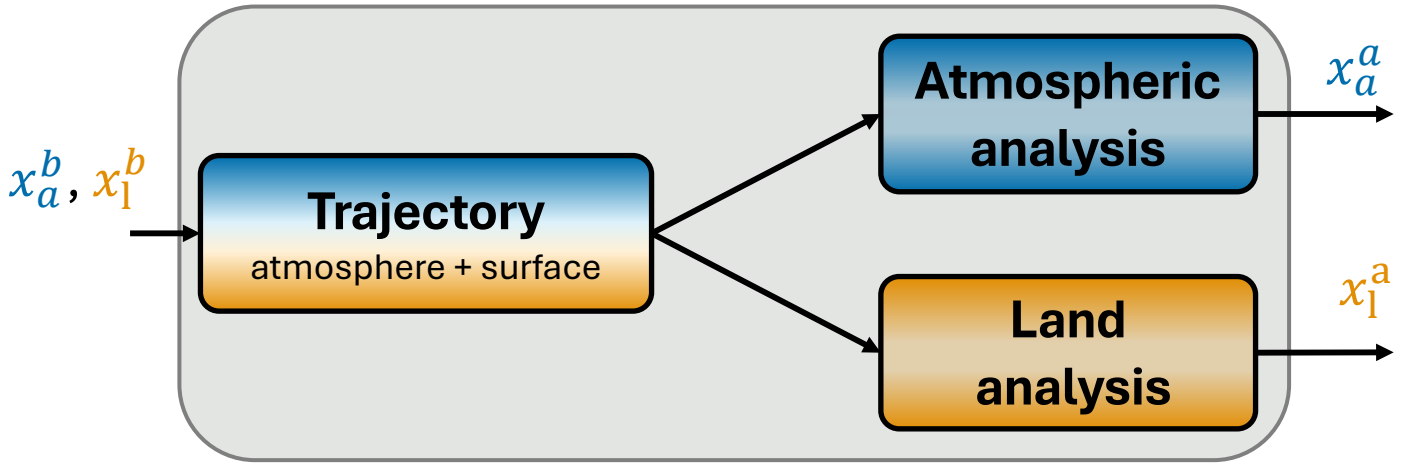
1. Current land-atmosphere coupling strategy
2. Integrating a land analysis in the atmospheric one and its variants
3. Proposed land-atmosphere coupling strategy

Current coupling strategy: outer loop coupling

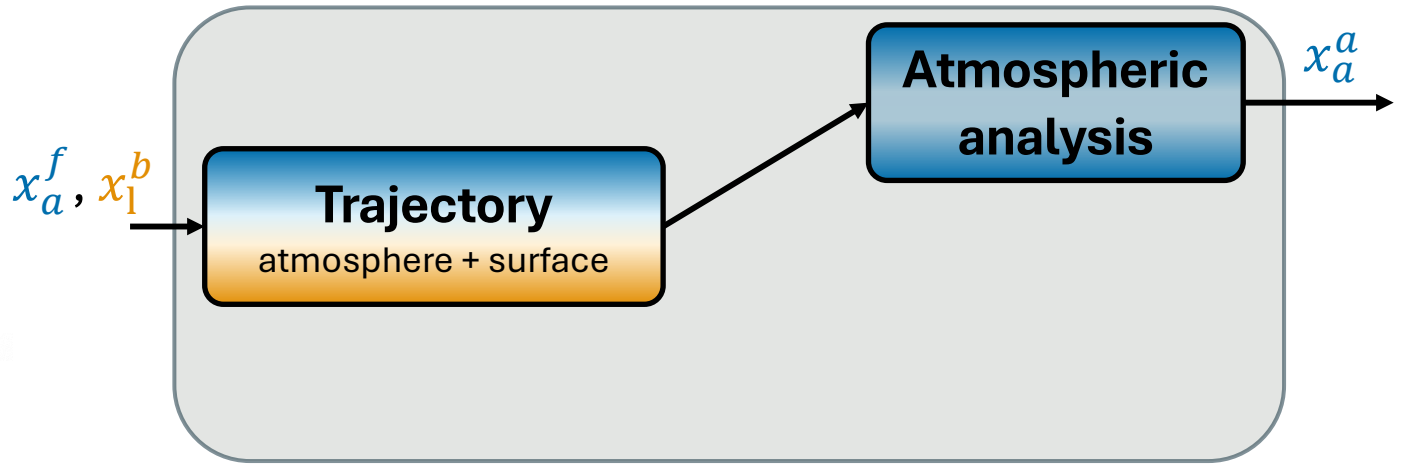
Incremental 4D-Var



Outer loop 1



Outer loop *n*



Integrating a land analysis in the atmospheric analysis

First step

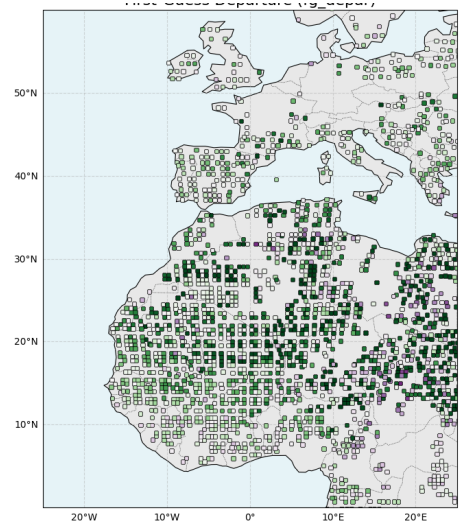
x_a^b, x_l^b → **Atmospheric analysis** → x_a^b, x_l^a

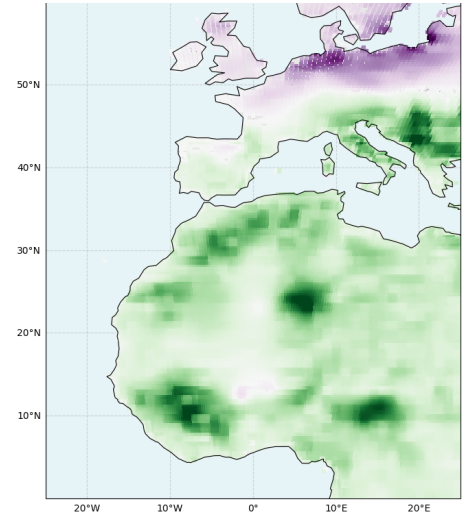
Observation space

- Addition in the control vector of sink variable in **observation space** (TOVSCV)

Model space

- Addition in the control vector of 2D field(s) in **model space** (XCV)
- At ECMWF, based on a simplified land surface model
  - Skin temperature (skt or tskin)
  - Soil temperature level 1 (stl1 or tsoil)



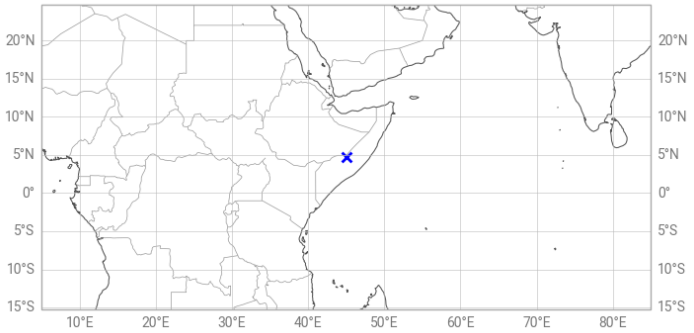


Single observation framework

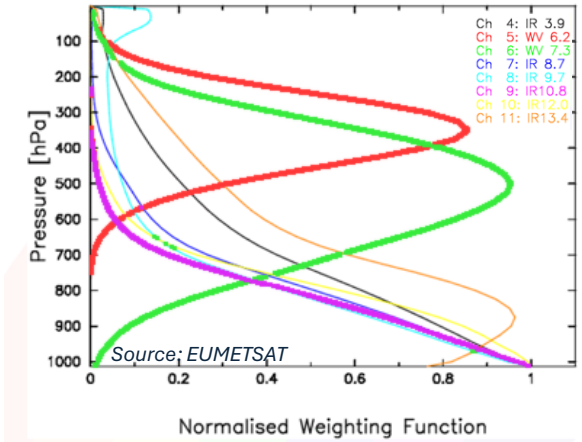
Framework

- Assimilation of SEVIRI data in one location over land
- December 2024, 00Z
- Addition of surface sensitive ch. 9 (over land)
- Hourly data
- Filtering using the cloud cover
- Coupled trajectory using
  - Skin temperature
  - Soil temperature

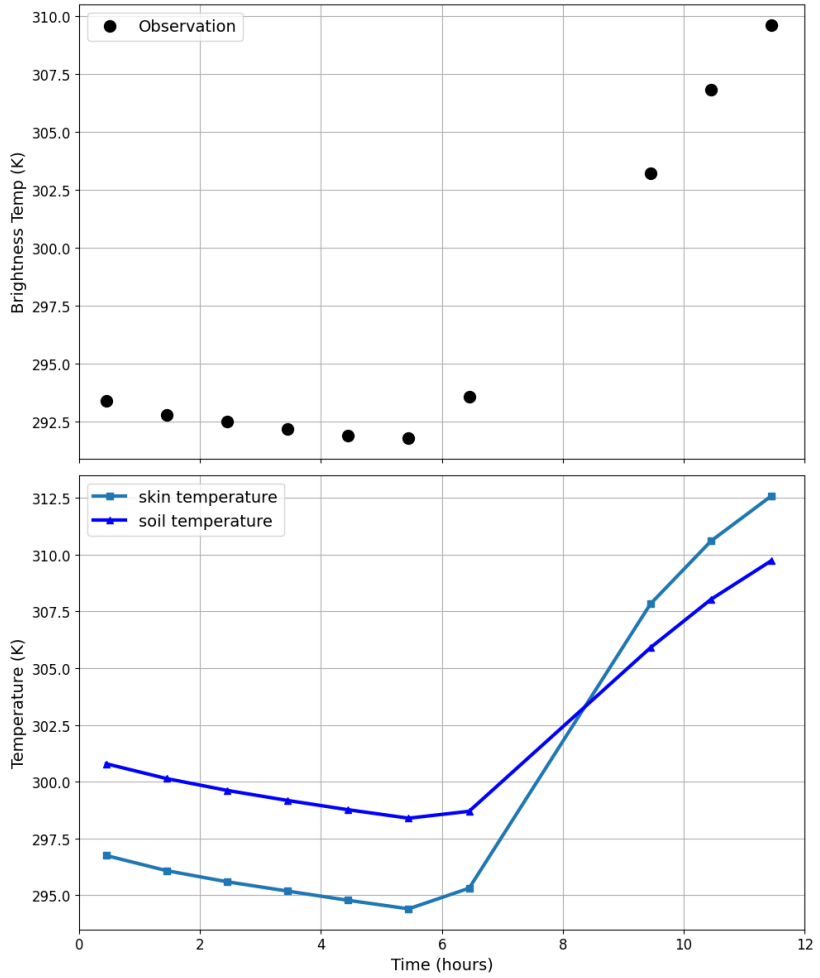
Observation location



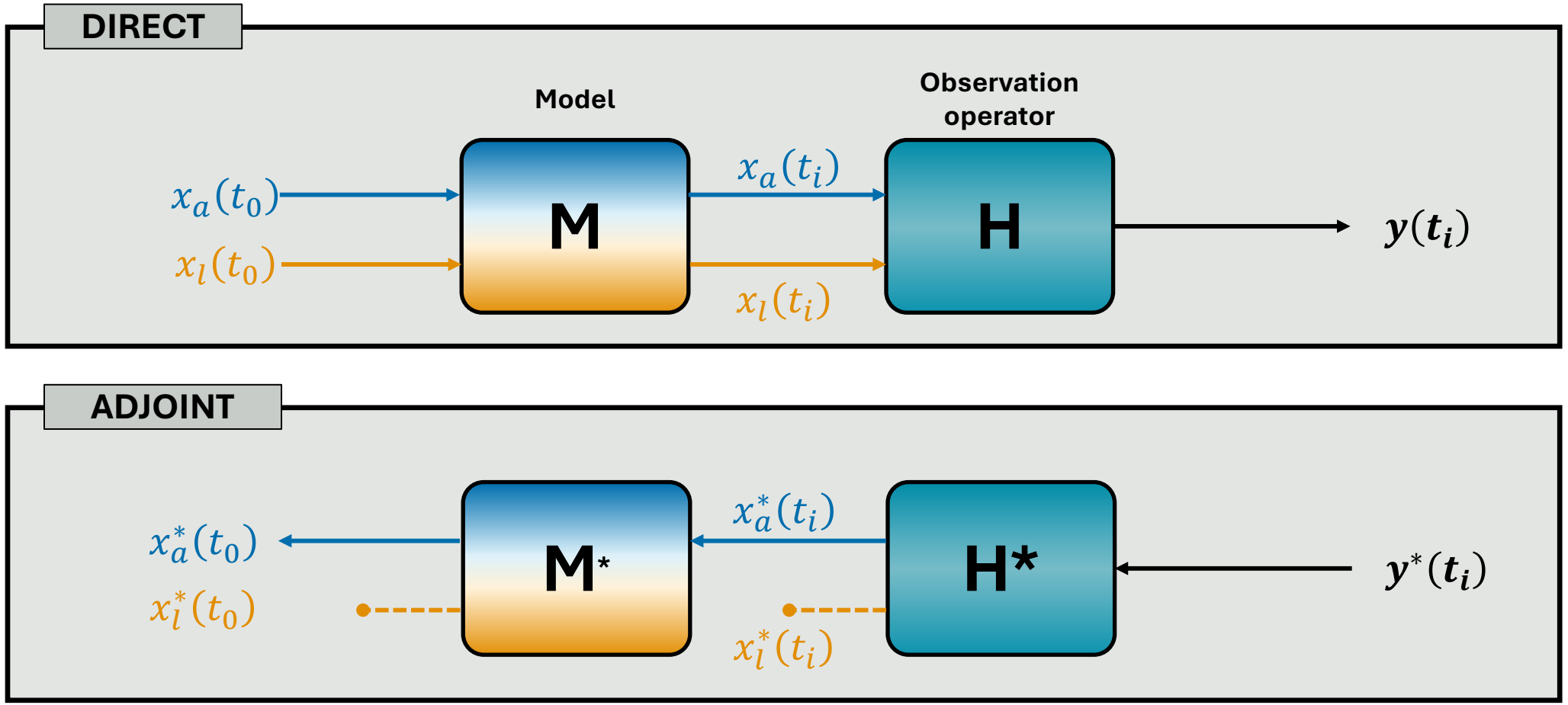
SEVIRI IR channels



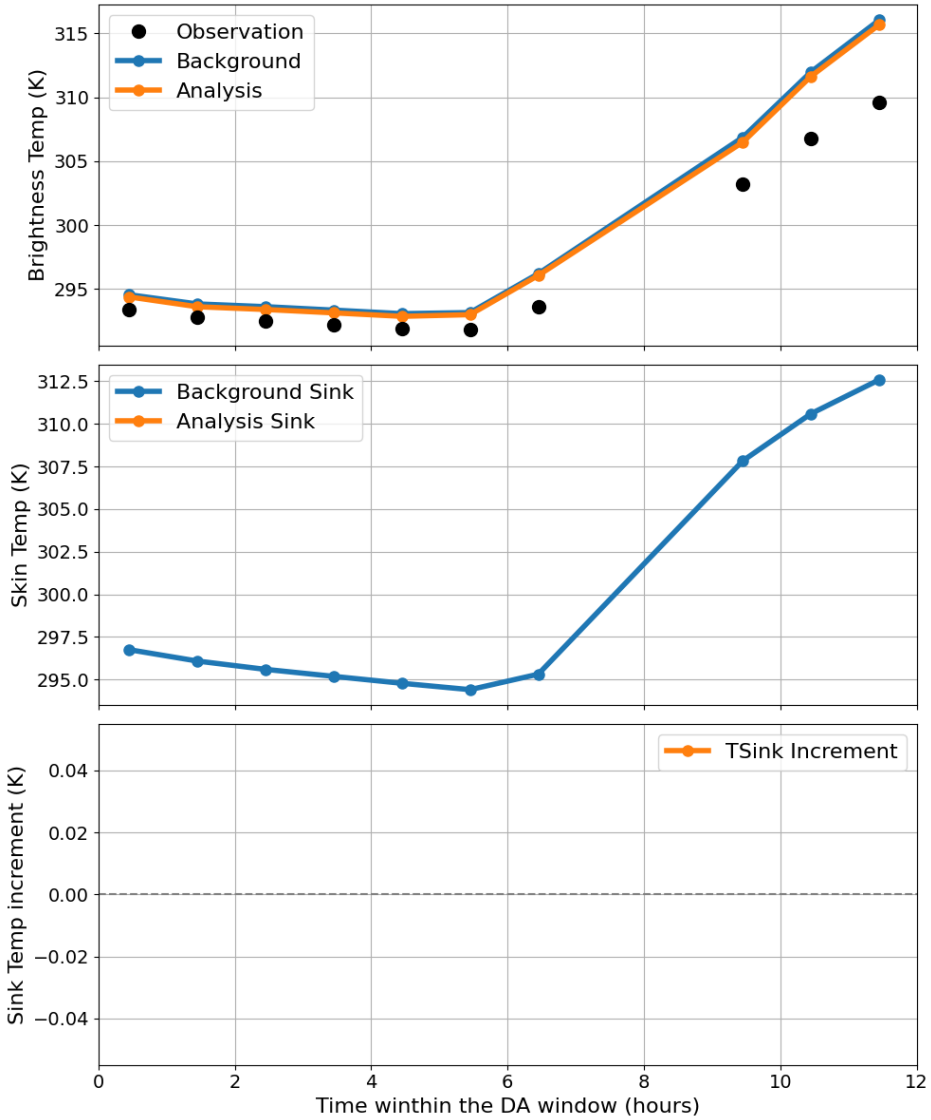
Time-serie at obs. location

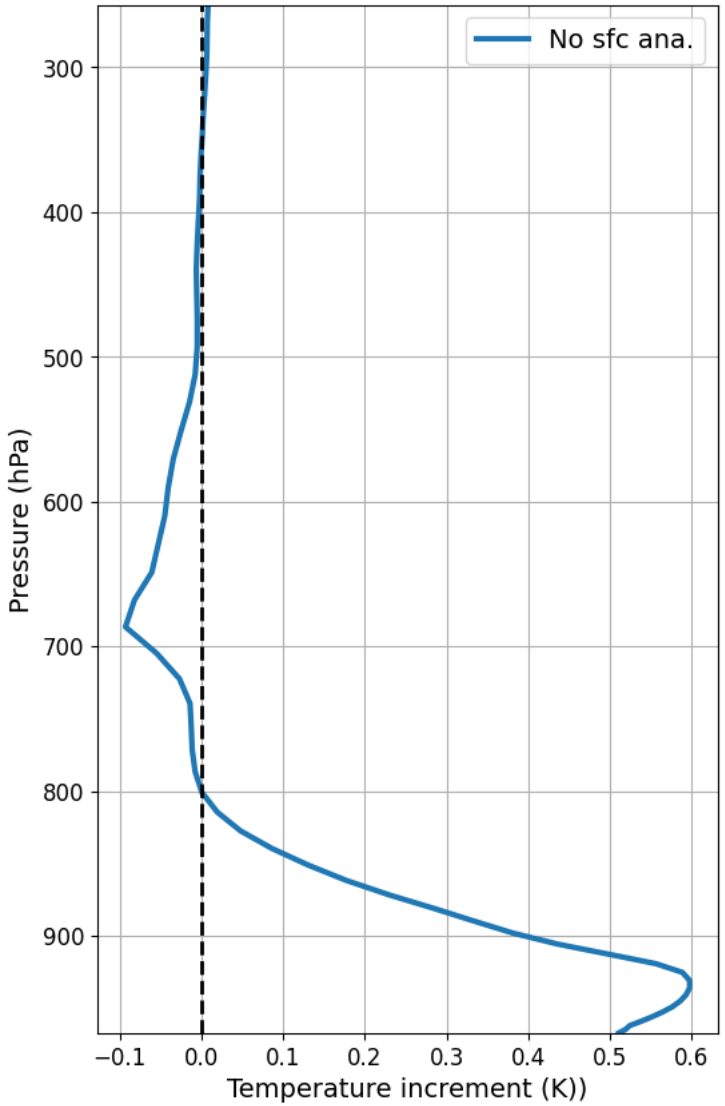


Atmospheric analysis w/o land



Atmospheric analysis w/o land

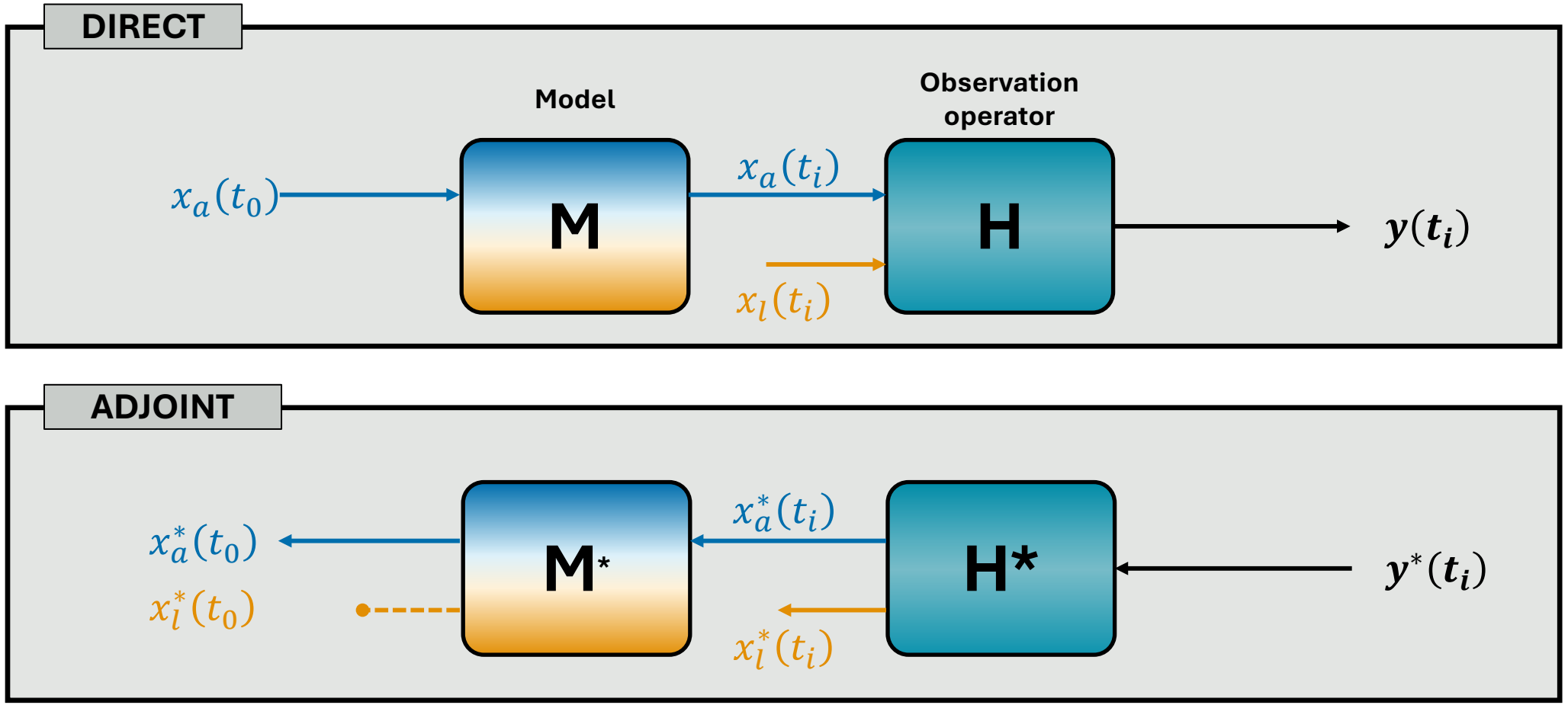




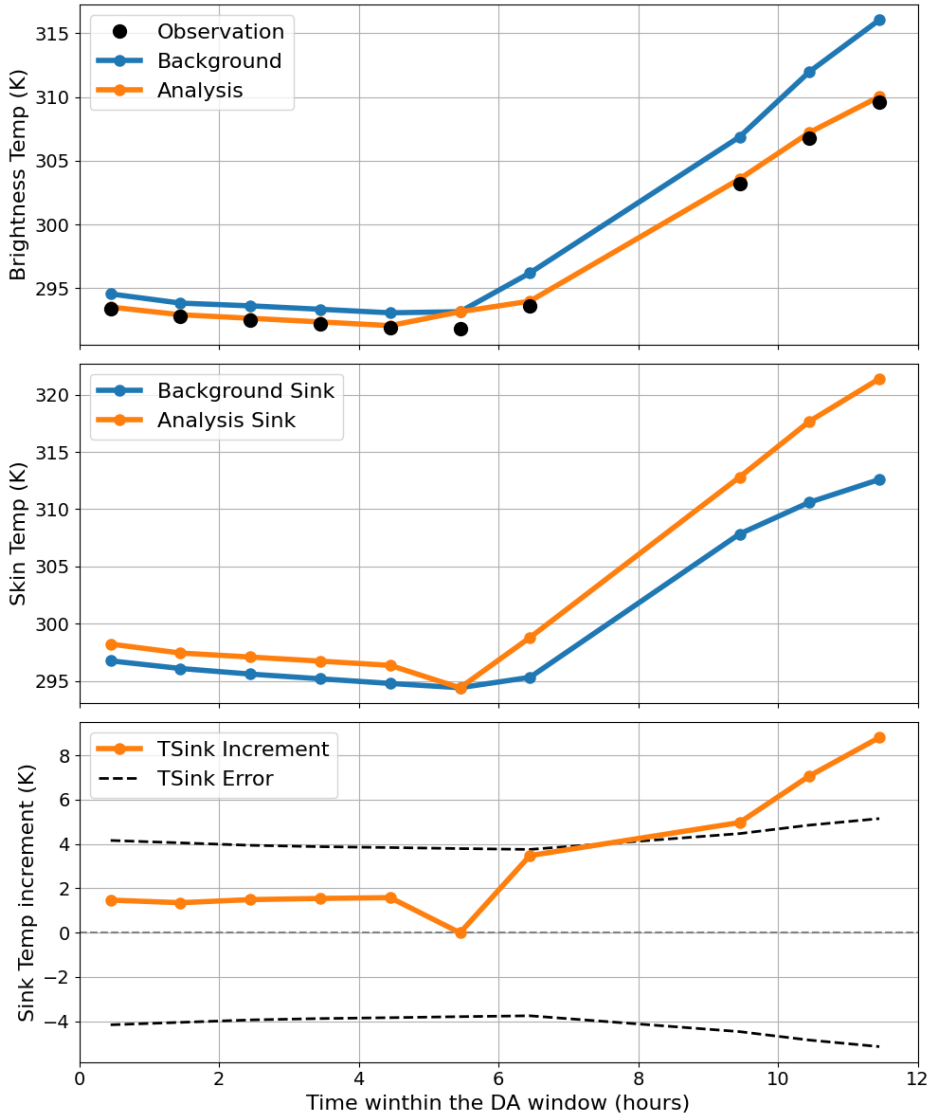
No land an.

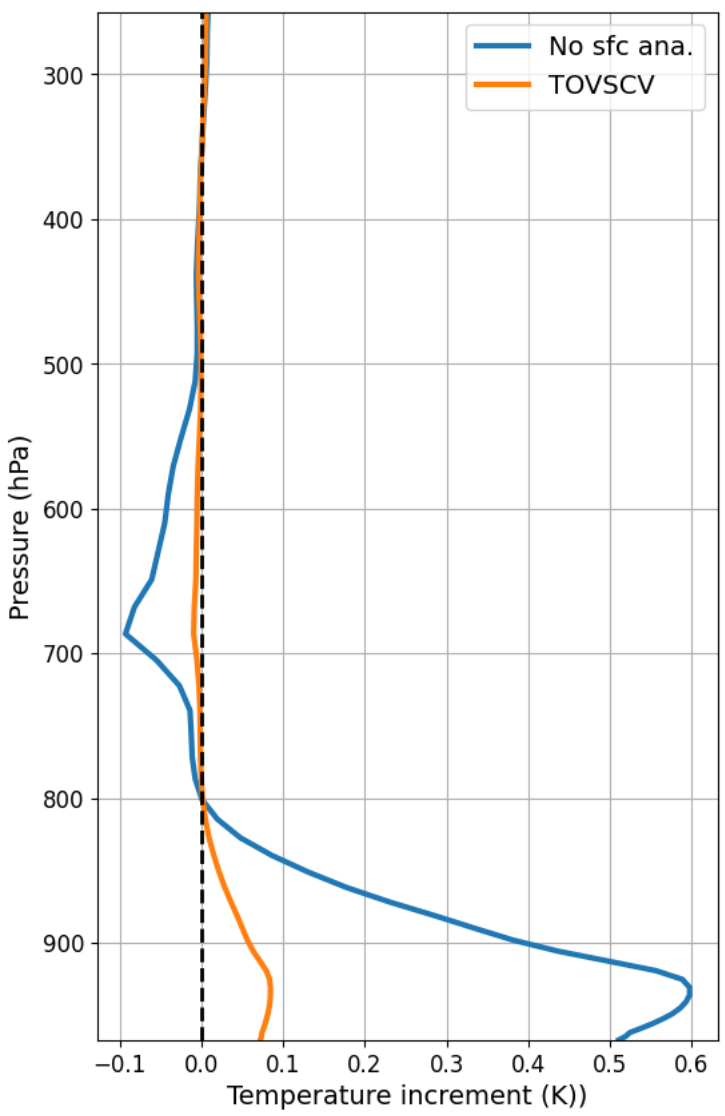
- Inc. on T only
- Fitting ch. 9 BT difficult

Atmospheric analysis w/ TOVSCV



TOVSCV analysis

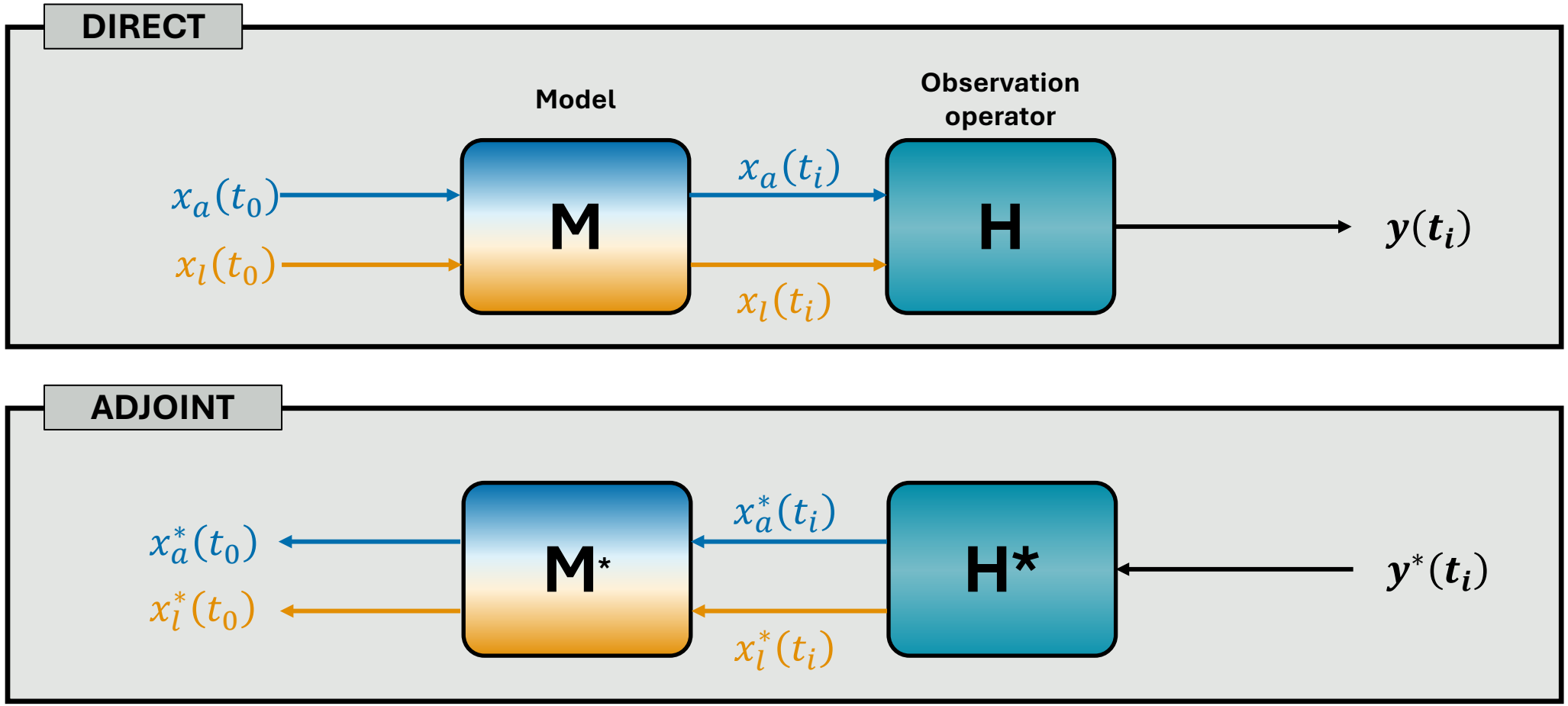




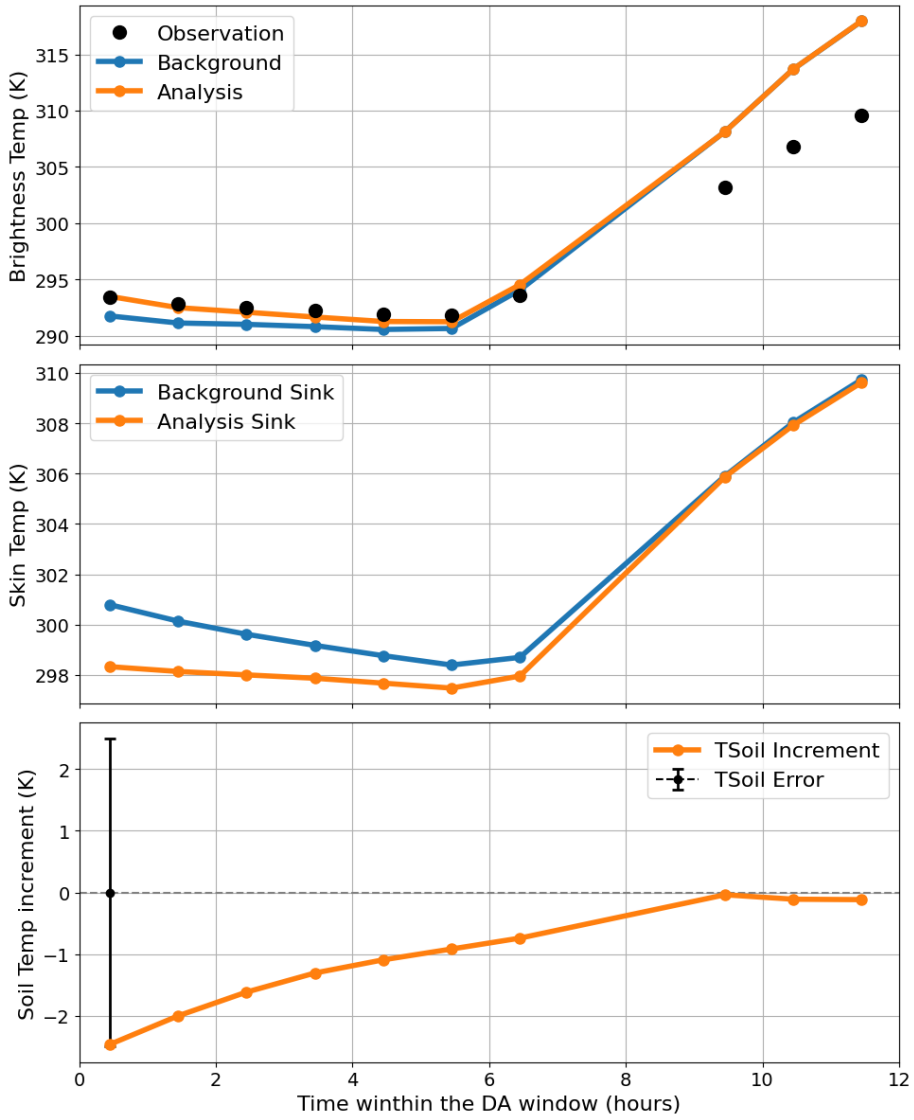
Results

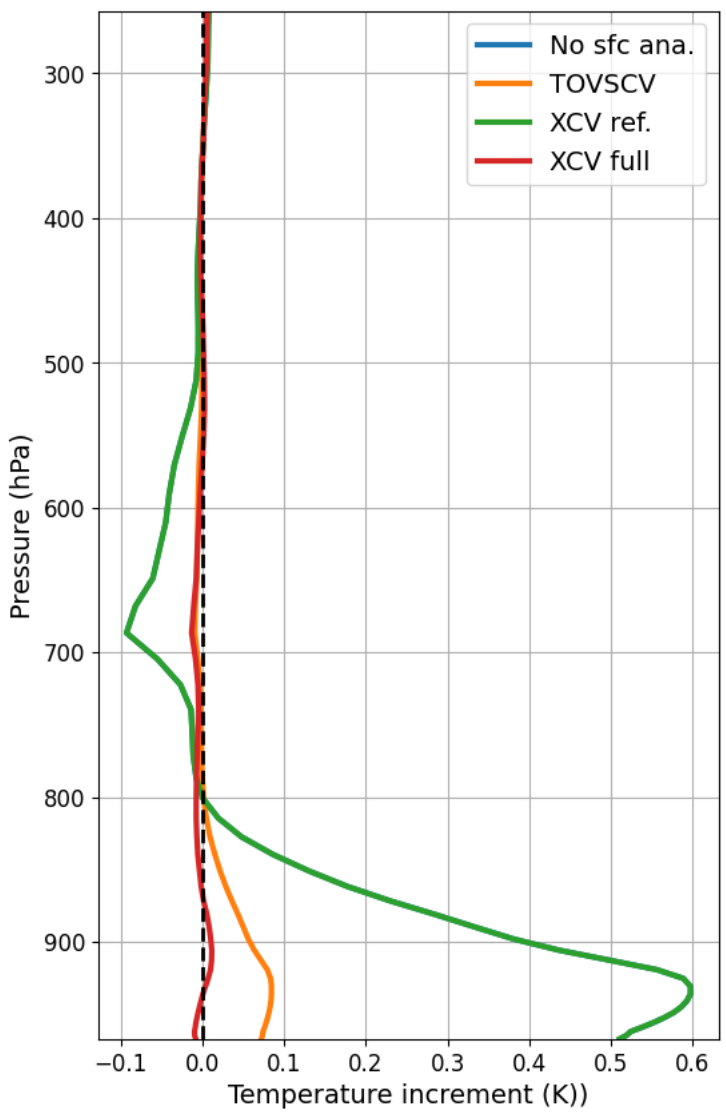
- Efficient to fit the obs
- Departure => sink variable
- No constraint on evolution

Atmospheric analysis w/ XCV (full)



XCV analysis (w/o observation operator)





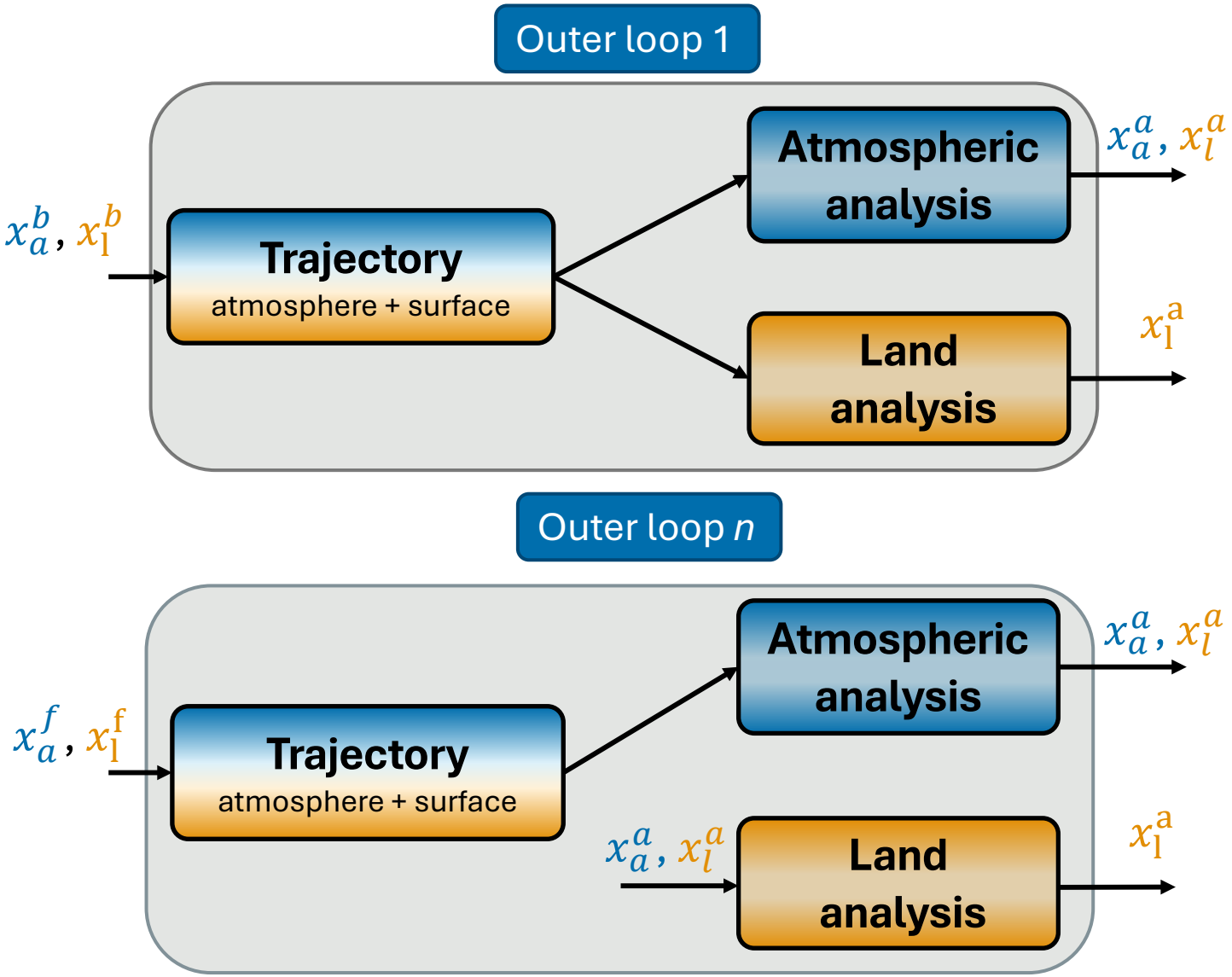
Results

- Obs. fit improved at the start of the window
- Departure => soil
- Strong constraint from model evolution

Solutions

- Include model error
- Include soil temperature level 2 in the control vector
- Outer loop coupling

Extended control variable options



Strategy

- Adding a land analysis at each outer loop
- Using an updated x_l^f in the trajectory
- Using x_a^a and x_l^a in the land analysis
- In practice
  - time constraint
  - x_a^a and x_l^a from the previous outer loop

Enhanced land–atmosphere coupling

1. Through the exchange of initial conditions
2. Through the use of interface observations

Enhanced coupling through the exchange of initial conditions

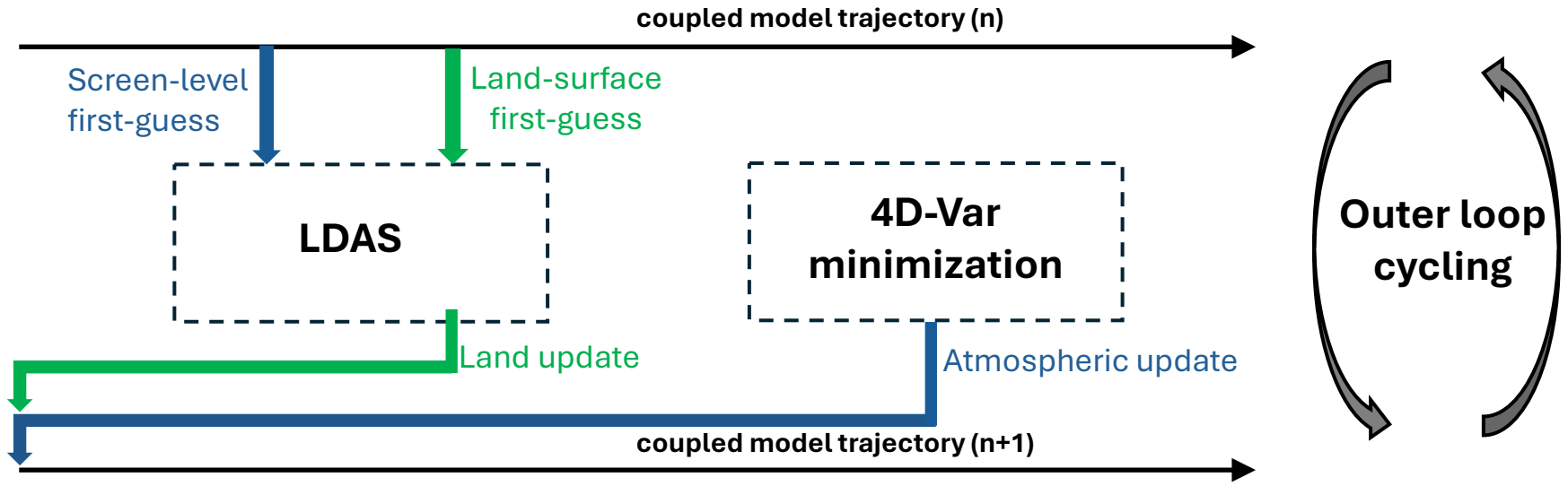
Outer loop land-atmosphere coupling

Outer loop land–atmosphere coupling

Funded by the European Union

Implementation in the Integrated Forcasting System (IFS)

1. Activate LDAS in outer loop running in parallel with atmospheric minimization
2. Write out fields required by the LDAS from the 4D-Var model trajectory
3. Feed back updated surface fields from surface analysis to subsequent outer loop(s)



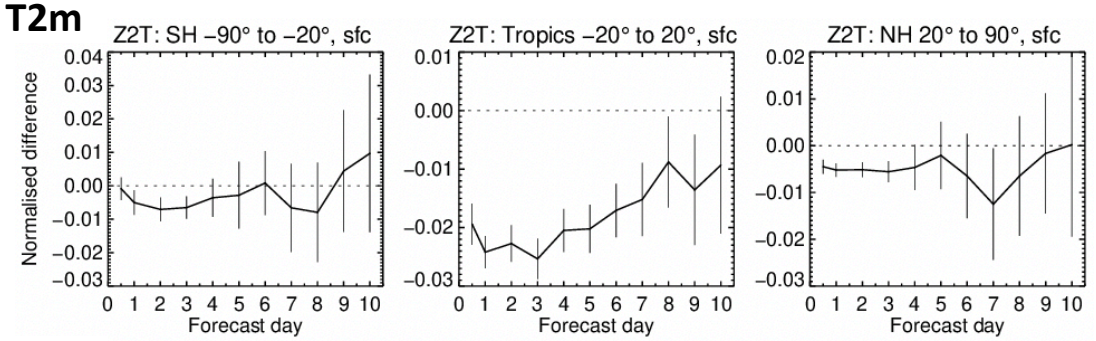
Atmospheric forecast impact

Control	Weak coupling
Experiment	Outer loop coupling – LDAS in **three** loops

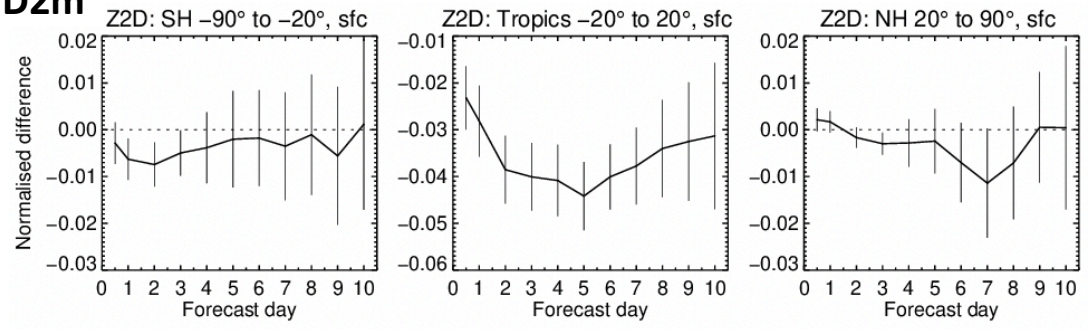
[ECMWF Newsletter Article: Herbert et al., 2026]

Forecast against operational analysis

T2m



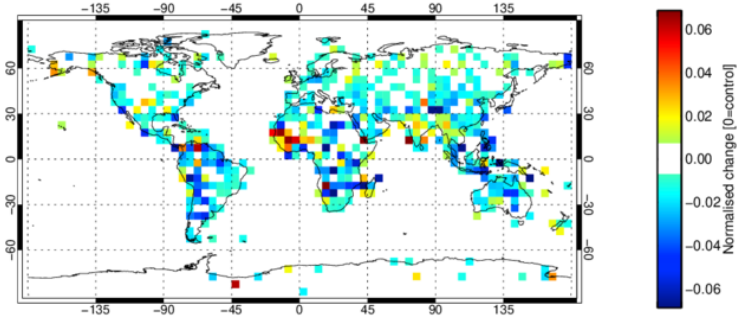
D2m



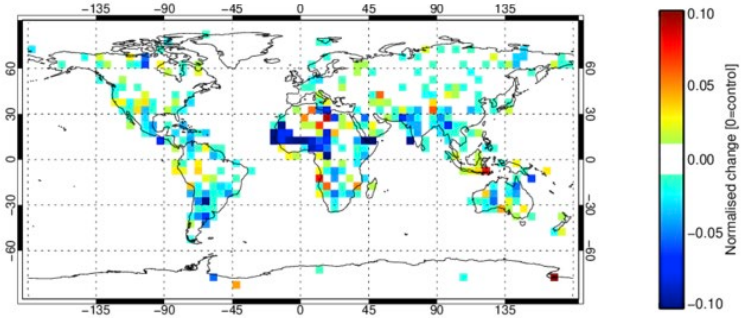
Outer loop coupling – Weak coupling

First-guess departures of short forecast

SYNOP T2m



SYNOP RH2m

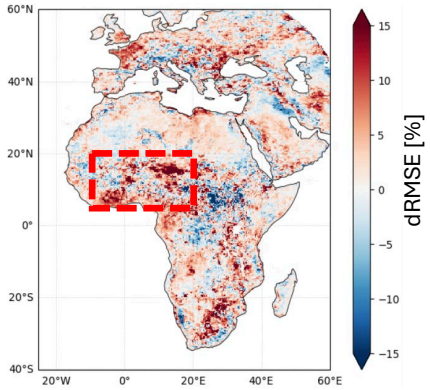


Validation at the land-atmosphere interface

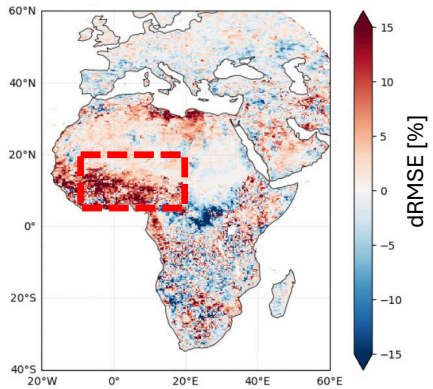
Funded by the European Union

Skin temperature compared to SEVIRI land surface temperature

JJA 2022

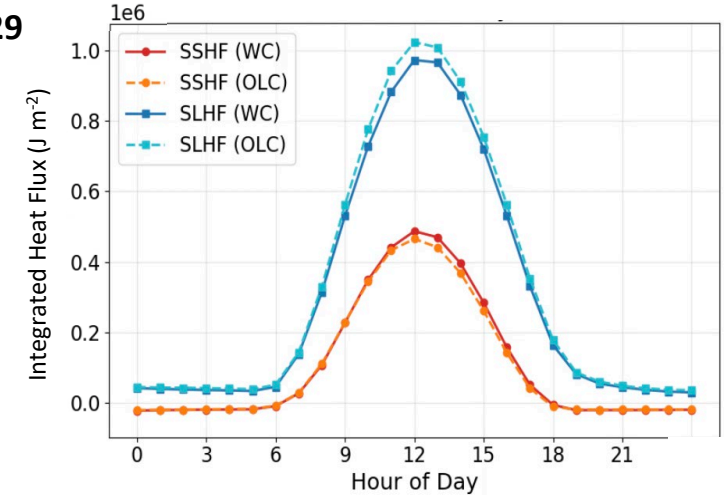


DJF 2022/23

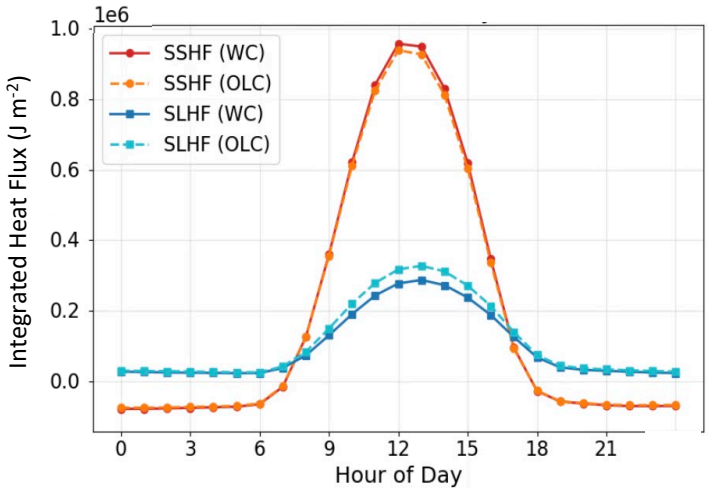


Surface sensible and latent heat flux

2022-08-29



2023-02-26



Enhanced coupling through the use of interface observations

Assimilation of the 4D-Var based XCV2D soil temperature analysis as pseudo-observations into the LDAS

Extended Control Vector (XCV) framework

Funded by the European Union

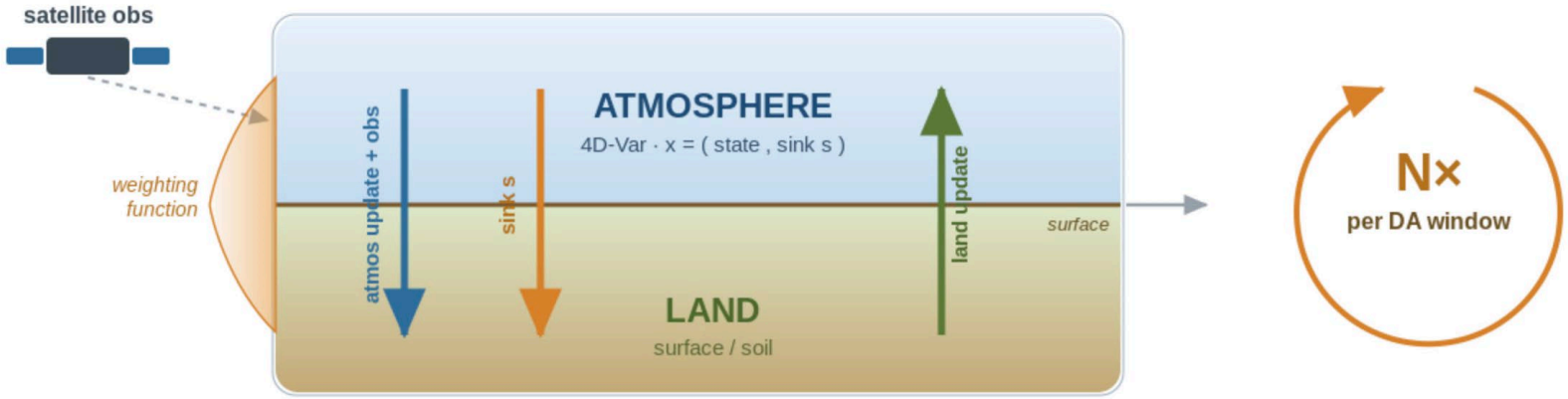
Exploitation of interface observations with the XCV2D framework

- For given observation $y_{i,c} = \mathcal{H}_{i,c}\begin{pmatrix} \mathbf{x}_1(t_i) \\ x_{cv}(t_i) \end{pmatrix} = \mathcal{H}_{i,c}\begin{pmatrix} \mathbf{x}_1(t_i) \\ \hat{I}_{cv} \circ \mathcal{M}_{i,cv}(\mathbf{x}_{cv}) \end{pmatrix}$

  $\mathcal{M}_{i,cv}$ is XCV forecast model

  $\hat{I}_{cv}$ is an interpolation operator

- Control vector extended with a **2D field $\mathbf{x}_{cv}$**
  - Used for a **selected number of variables** such as soil and skin temperature, …
  - Slight signal already without coupling if only activating XCV2D as "**sink variable**"

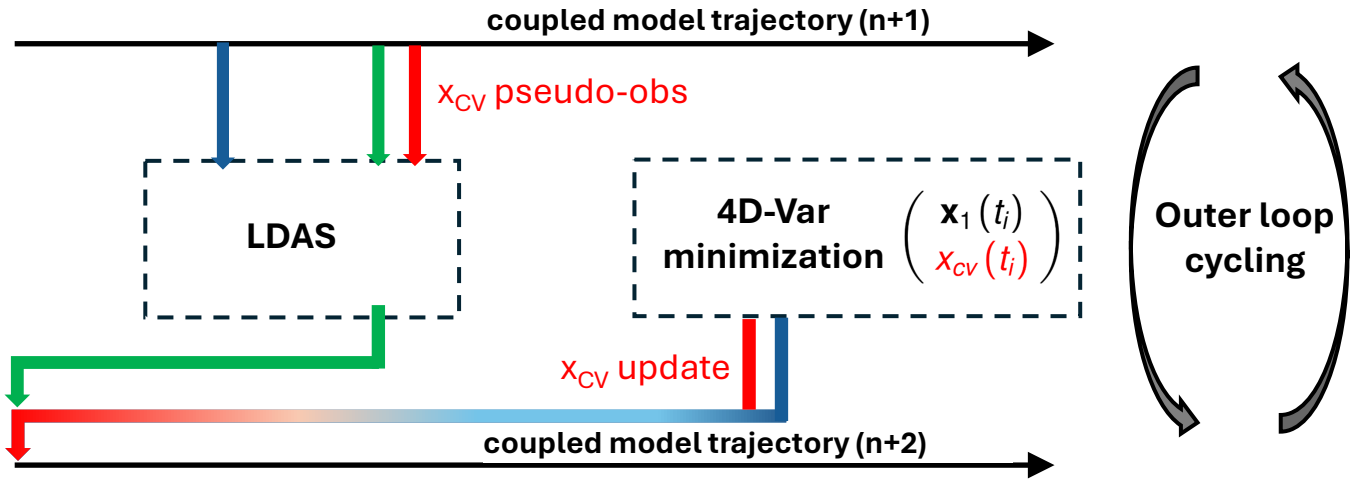


Using surface-sensitive observations

Funded by the European Union

Exploring the XCV2D framework in an outer loop coupling setup

1. Enable as $\mathbf{x}_{cv}$ **eXtended Control Variable** in **4D-Var**
2. Provide $\mathbf{x}_{cv}$ **2D soil temperature** analysis fields in each trajectory
3. Assimilate $\mathbf{x}_{cv}$ **2D soil temperature** as 'pseudo-observations' into the SEKF

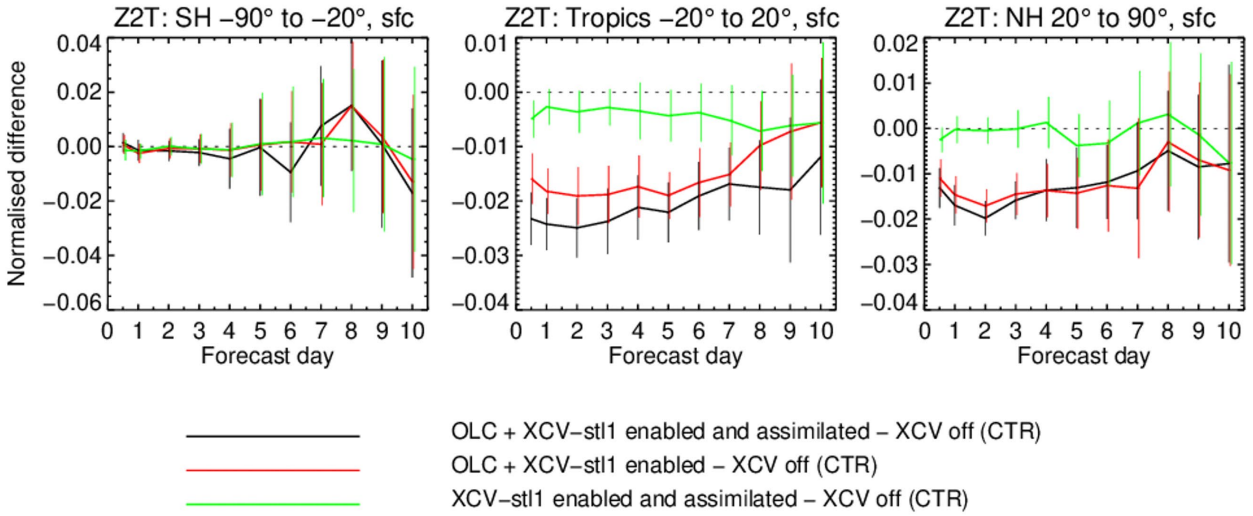


Assessment of assimilating XCV soil temperature

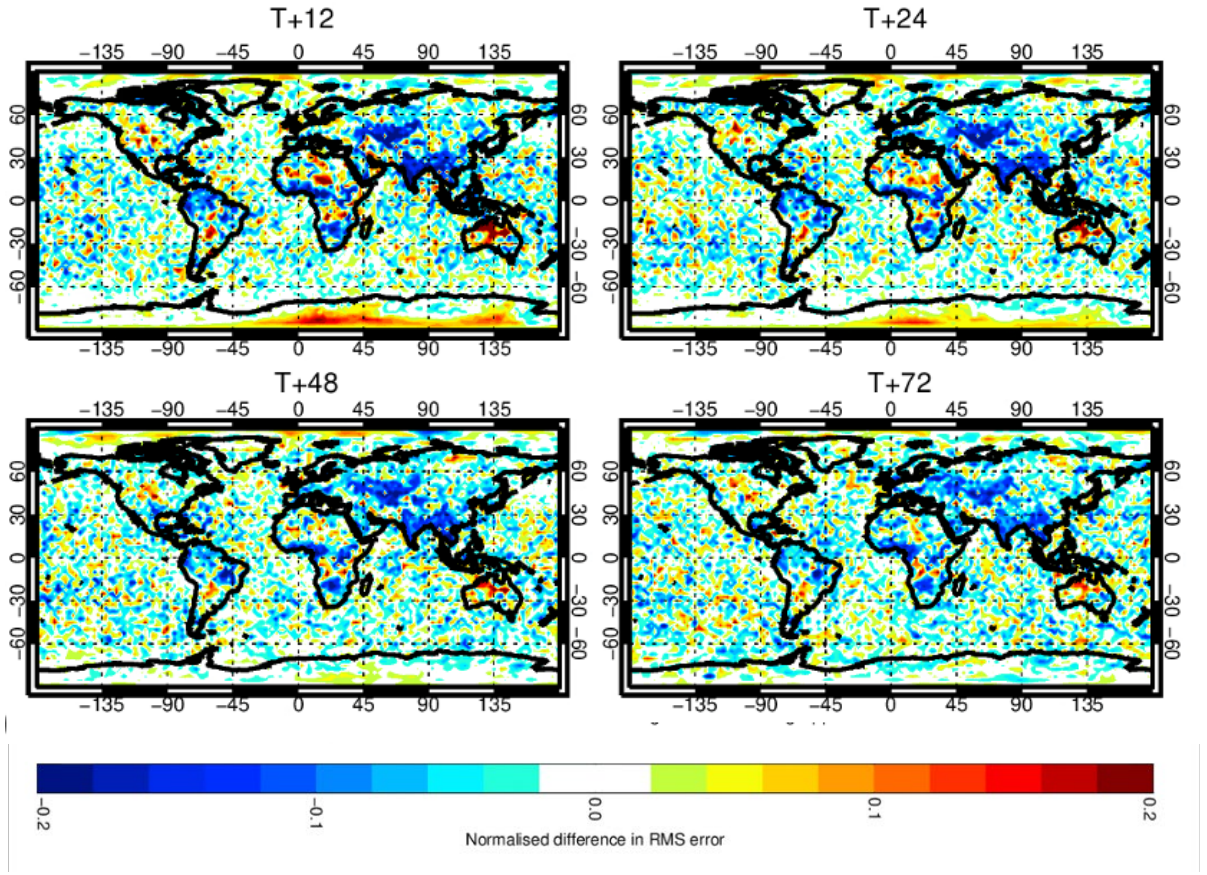
Funded by the European Union

Control	Weak coupling	no XCV
Exp 1	Weak coupling	enable and assimilate XCV
Exp 2	Outer loop coupling	enable XCV
Exp 3	Outer loop coupling	enable and assimilate XCV

Forecast against operational analysis



dRMSE: XCV enabled and assimilated into the LDAS (Exp3)

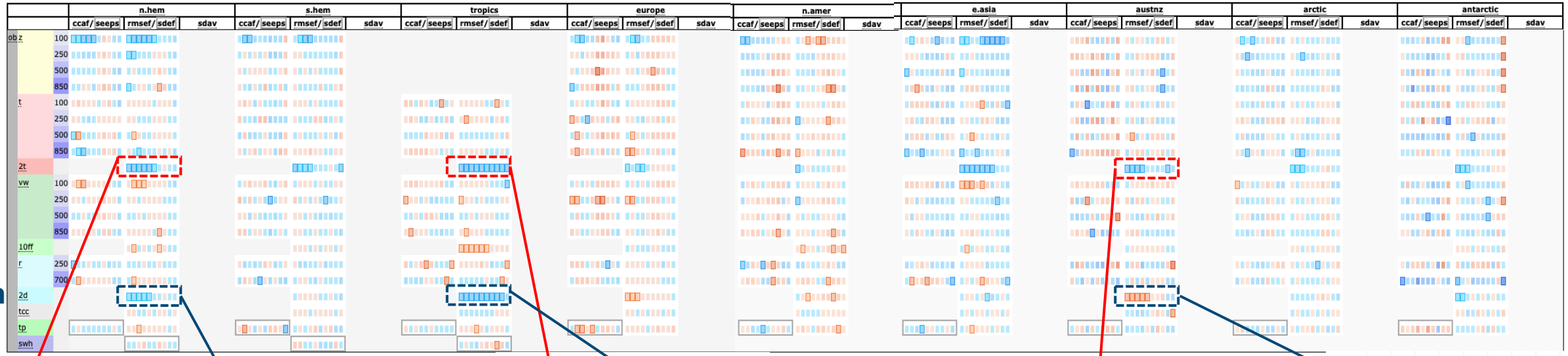


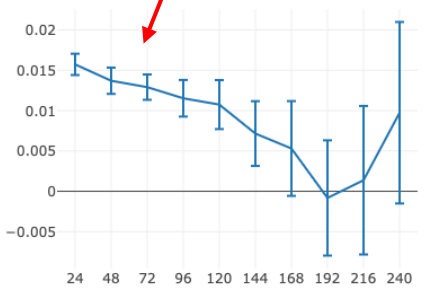
Scorecard of assimilated XCV into LDAS (uptraj_0-2)

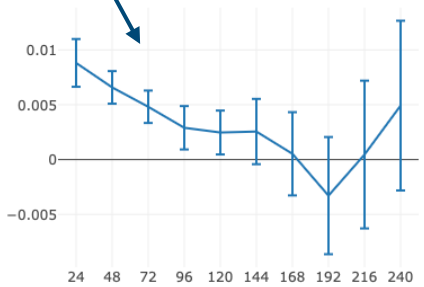
Funded by the European Union

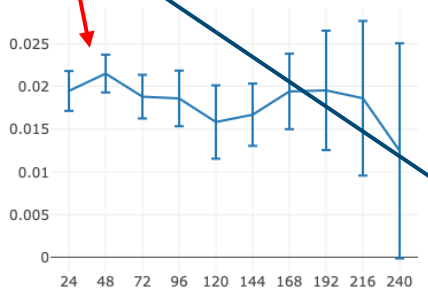
T2m

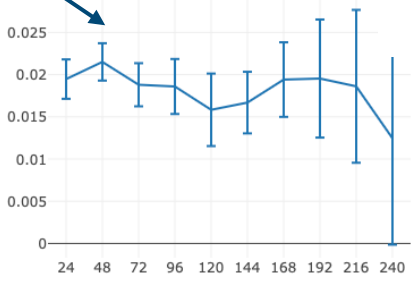
D2m

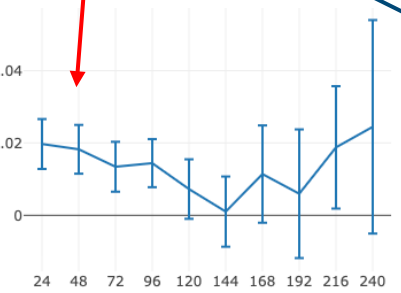


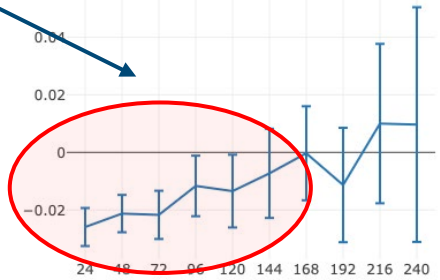












- Degradations in D2m are alleviated using inflated R for later outer loops

Key takeaways

XCV (model space)

- Need TL/AD of **M**
- Direct constrain by all sensitive observations
- Transferred to the land as “soil temperature” field
- Allow cross-correlation in **B** (for eg with atmospheric T in the lowermost levels)

Funded by the European Union

In the framework of CERISE, we explored enhanced land-atmosphere coupling through …

- Implementing outer loop land-atmosphere coupling
- Leveraging the XCV2D framework in 4D-Var for land surface-sensitive observations by assimilating XCV soil temperature into the land

The way forward

- Operationalising outer loop land-atmosphere coupling
- Exploiting **additional surface-sensitive** observations
- **CHERRI** project has started in September 2026
  - Advancing land DA with ML
  - ML-based observation operators to include more interface observations

Funded by the European Union

References

Laloyaux, P., Balmaseda, M., Dee, D., Mogensen, K., & Janssen, P. (2016). **A coupled data assimilation system for climate reanalysis**. *Quarterly Journal of the Royal Meteorological Society*, *142*(694), 65-78.

Penny, S. G., Akella, S., Buehner, M., Chevallier, M., Counillon, F., Draper, C., ... & Kumar, A. (2017). **Coupled data assimilation for integrated earth system analysis and prediction: goals, challenges, and recommendations** (No. GSFC-E-DAA-TN43810).

de Rosnay, P., Browne, P., de Boisséson, E., Fairbairn, D., Hirahara, Y., Ochi, K., ... & Rabier, F. (2022). **Coupled data assimilation at ECMWF: Current status, challenges and future developments**. Quarterly Journal of the Royal Meteorological Society, 148

Herbert, C., de Rosnay, P., Weston, P., & Fairbairn, D. (2024). **Towards unified land data assimilation at ECMWF: Soil and snow temperature analysis in the SEKF**. *Quarterly Journal of the Royal Meteorological Society*, *150*(764), 4133-4155.

Herbert, C., Weston, P., de Rosnay, P., Hersbach, H. (2026). **Enhanced land-atmosphere data assimilation**. ECMWF Newsletter, 187, 28-34.

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.

Other work applied to land

- Zdenko using the TOVSCV
- Pete lessons learned from what Allan had been doing with sea ice: emissivity
- CHERRI: ML based obs operator (AI-based RT) using land emulator (estimate feature importance, redundancy to disentangle land information content)


www.ecmwf.int