Observation influence in convective-scale data assimilation: Reanalysis and PAI diagnostics for the Swabian MOSES 2023 campaign in southwestern Germany

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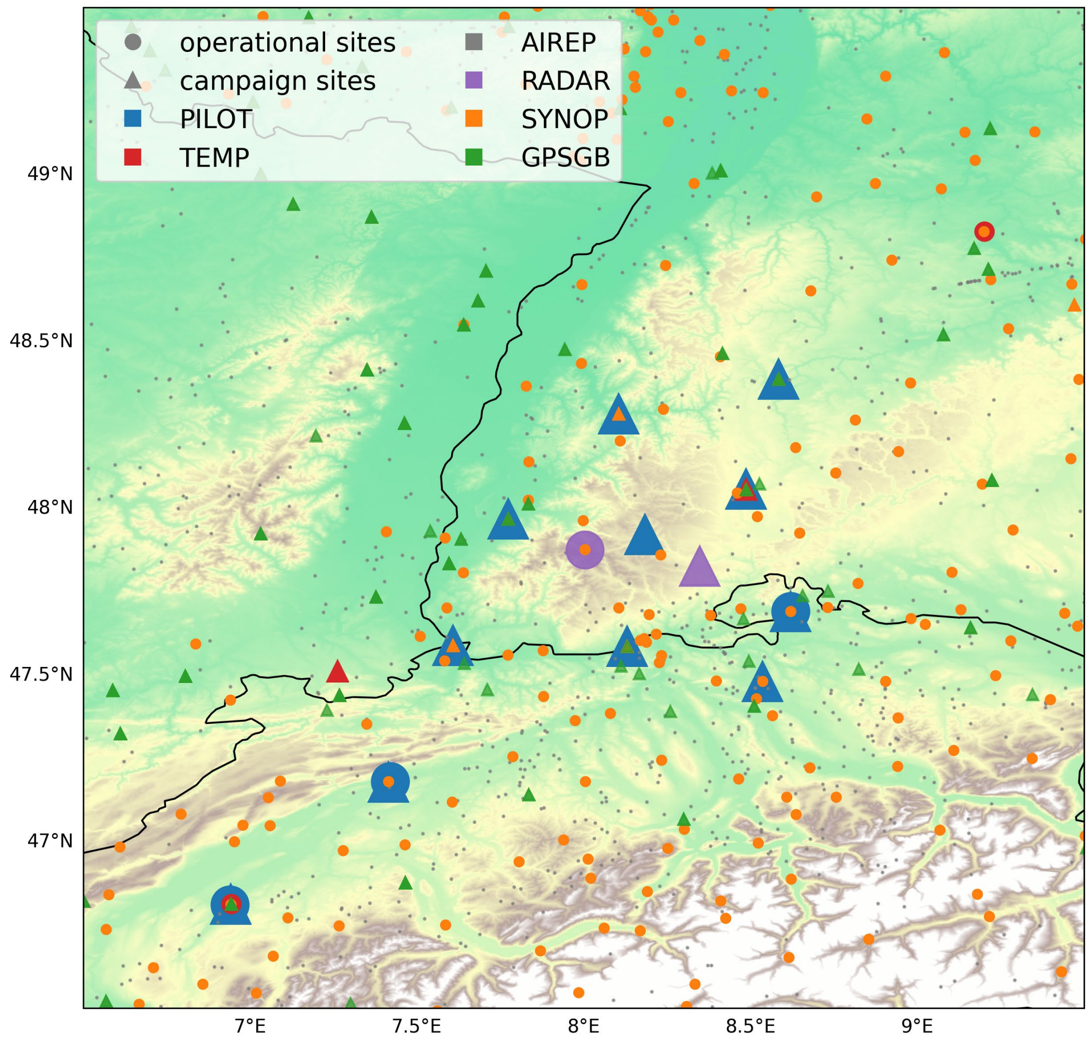
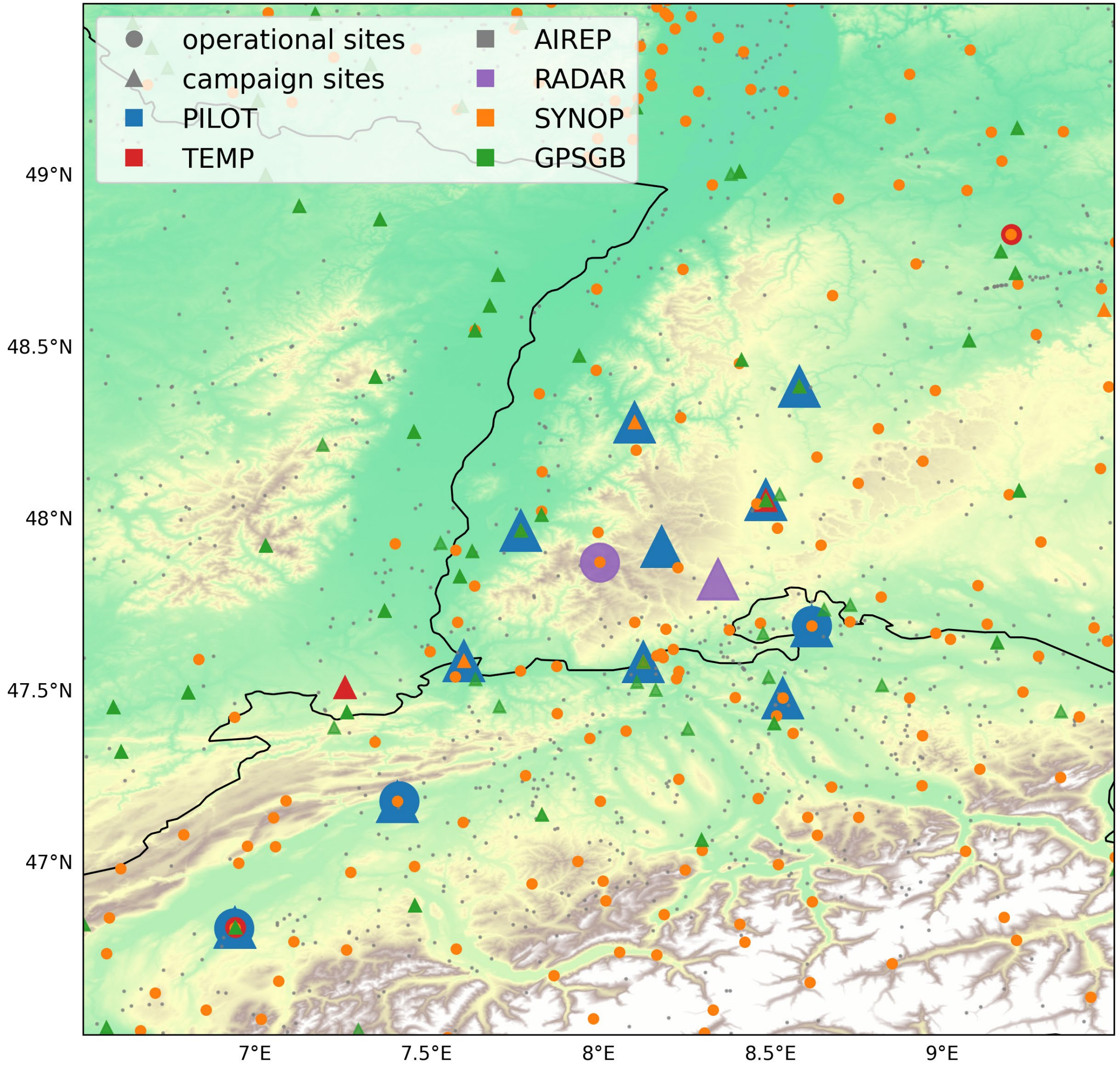
'Mesoscale Processes and Predictability', KIT

With contributions from DWD and MeteoSwiss



Swabian MOSES 2023 field campaign

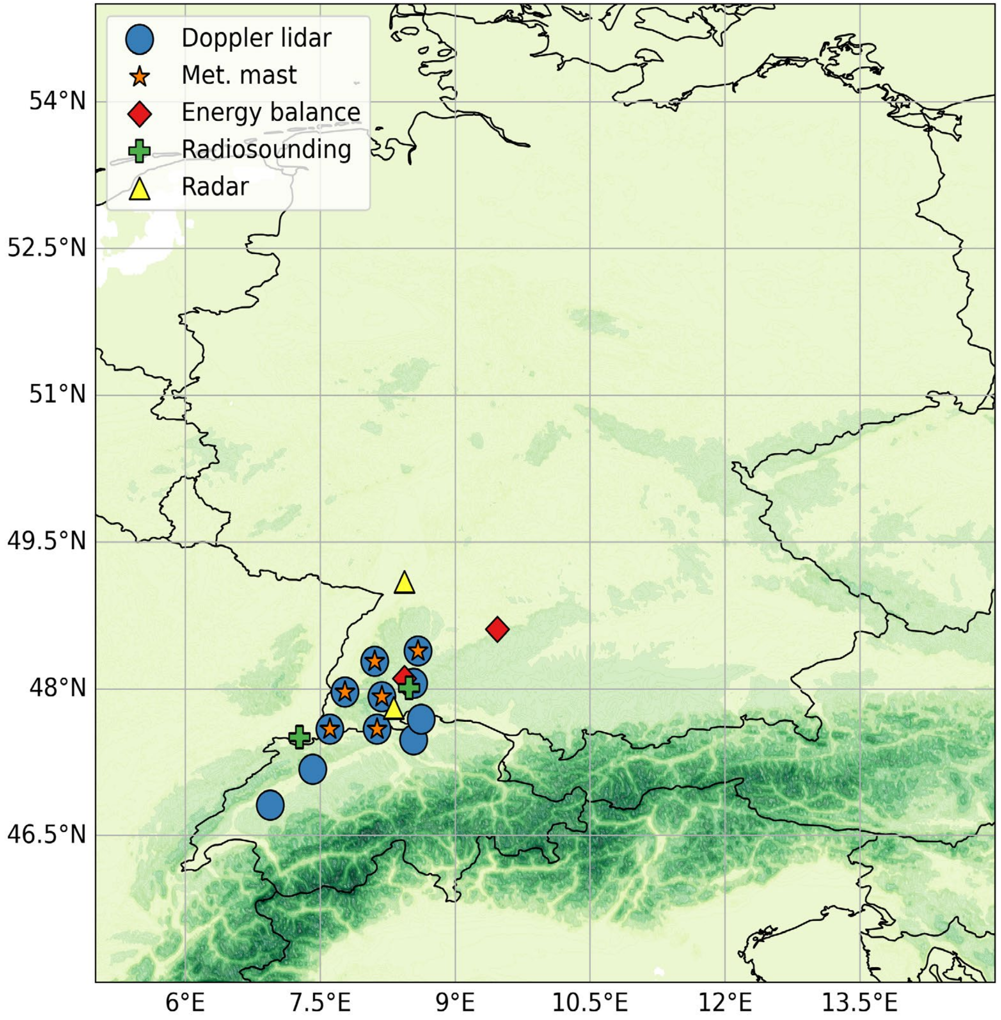
- Network of 12 Doppler wind lidars (DWLs) Handwerker et al., 2025
- June to August 2023
- Black Forest, southwestern Germany, moderately complex terrain
- Deployed network
  - 12 DWLs
  - 2 radiosounding sites
  - 1 X-band radar
  - 6 met. Masts
  - GNSS



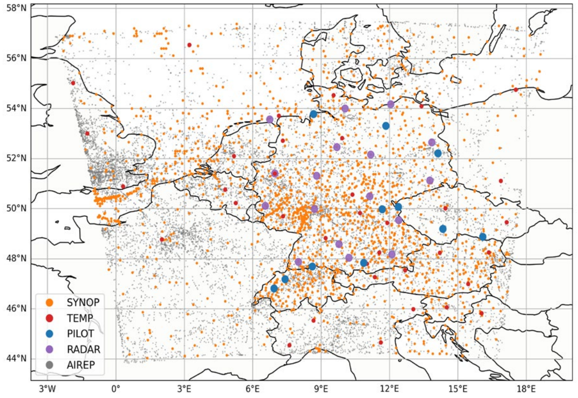
Data assimilation experiments

- ICON coupled to KENDA Zängl *et al.* 2015, Schraff *et al.* 2016, Hunt *et al.* 2007
  - Data Assimilation method: LETKF
  - Convective-scale resolution
  - 40 ensemble members
  - Continuous cycling June-August 2023

- ‘Campaign reanalysis’
  - Assimilation of
  - **operational observations**
  - **campaign observations**

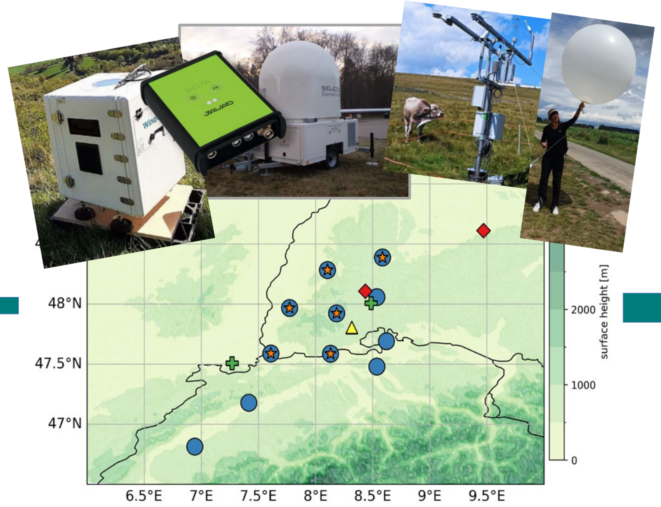


Campaign and Control reanalysis



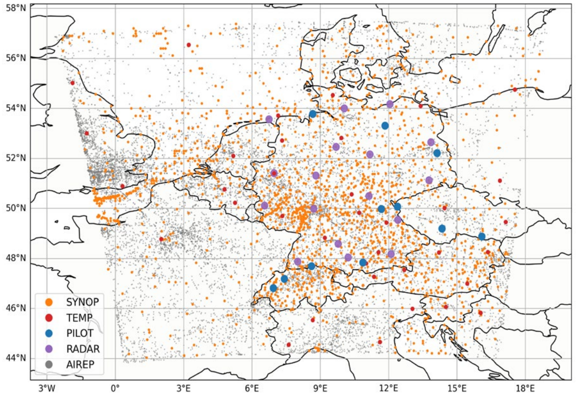
operational observations

+



campaign observations

→ 3-month KENDA cycling → **SWM** campaign reanalysis

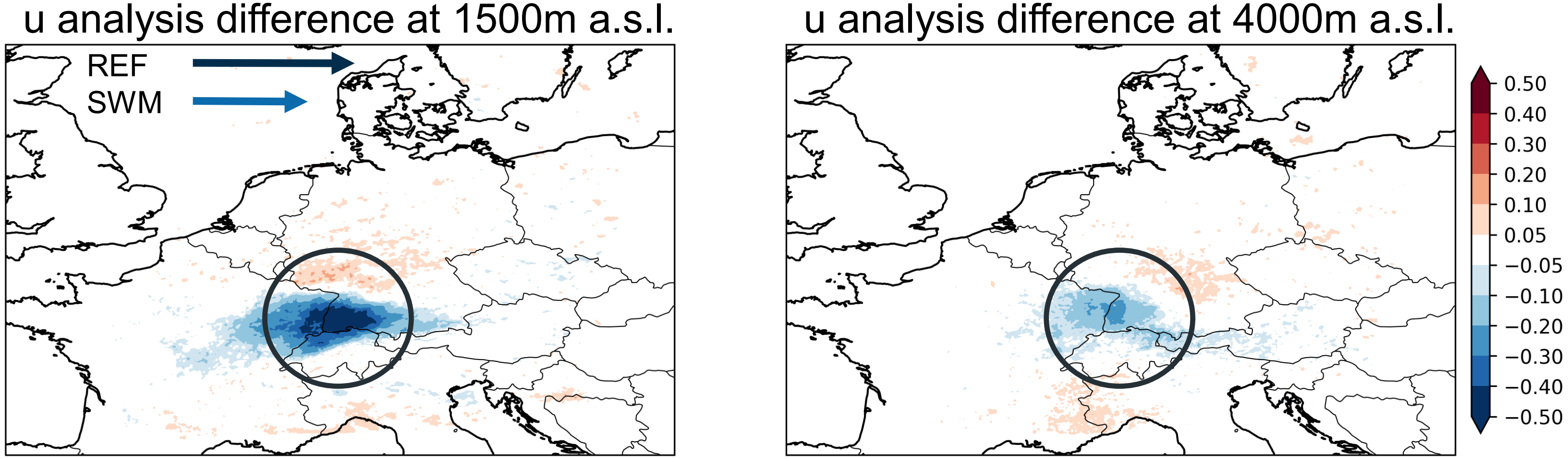


operational observations

→ 3-month KENDA cycling → **REF** control reanalysis

Systematic differences SWM - CTRL analyses

- In westerly flow conditions (85% of timesteps)



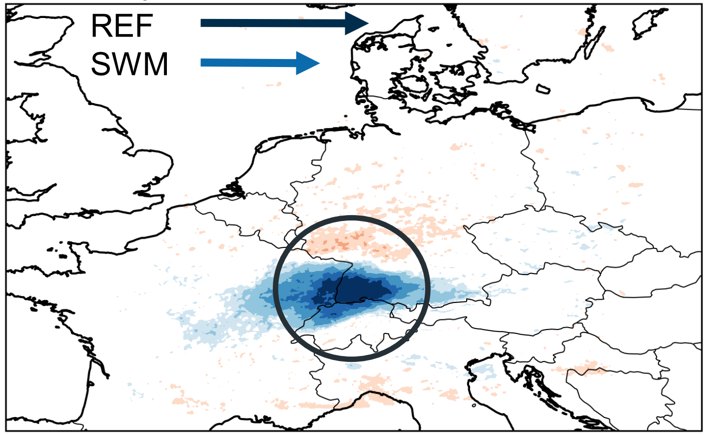
- The **DWL** network slows the zonal wind, most strongly in the lower troposphere.
- The signal spreads east and west, well beyond the campaign area.

Courtesy J. Thomas

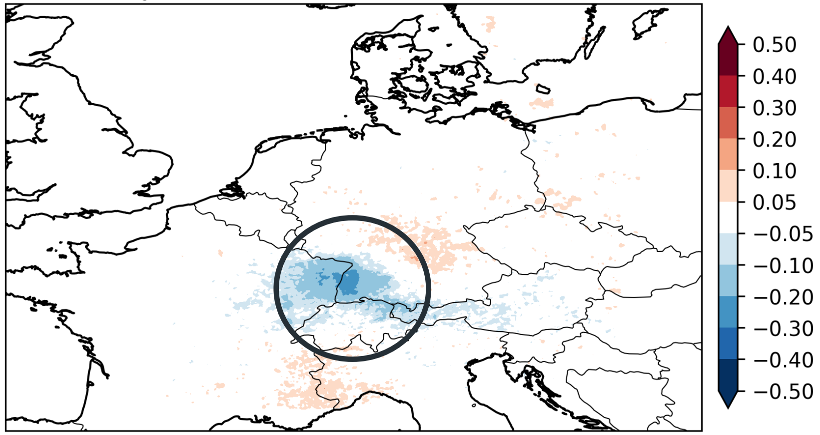
Systematic differences SWM - CTRL analyses

- In westerly flow conditions (85% of timesteps)

u analysis difference at 1500m a.s.l.



u analysis difference at 4000m a.s.l.



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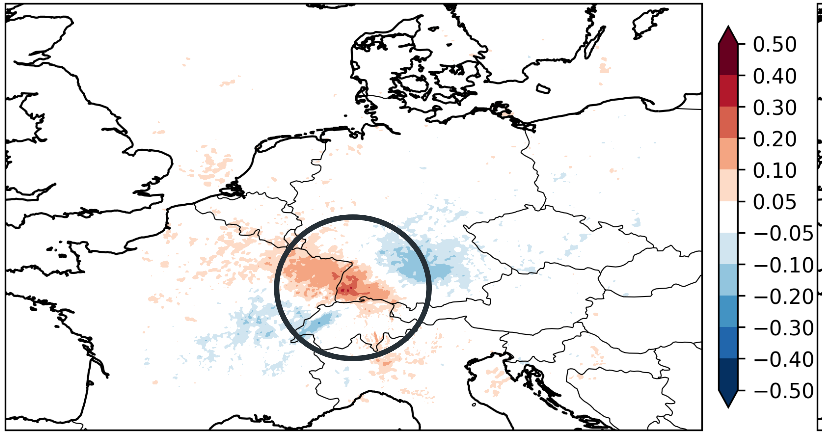
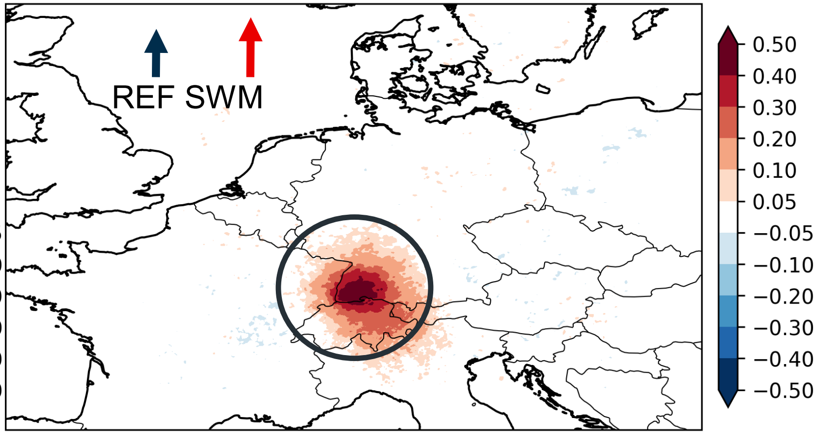
v analysis difference at 1500m a.s.l.



v analysis difference at 4000m a.s.l.



- It strengthens the meridional wind, peaking in the mid-troposphere.
- This signal spreads to the southeast.

Courtesy J. Thomas

Systematic differences SWM - CTRL analyses

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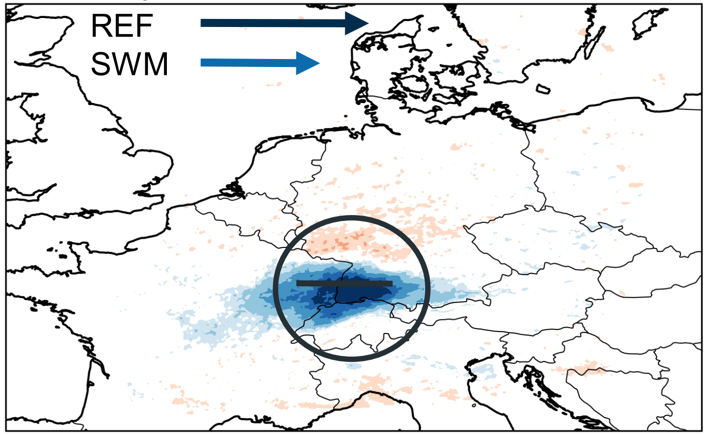
u analysis difference at 1500m a.s.l.



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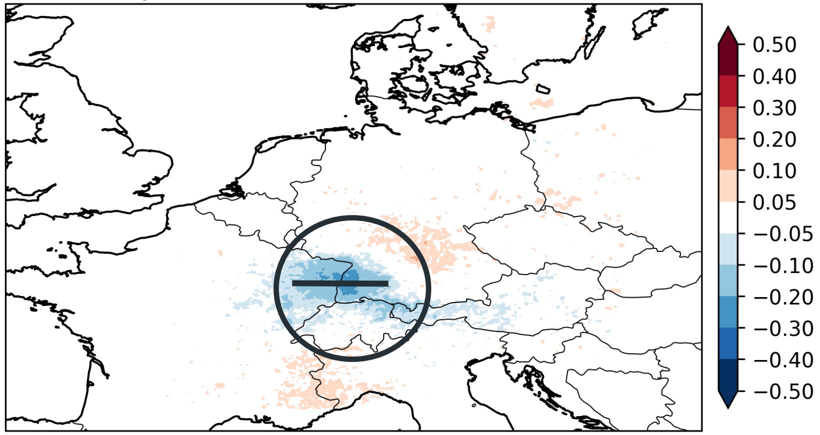
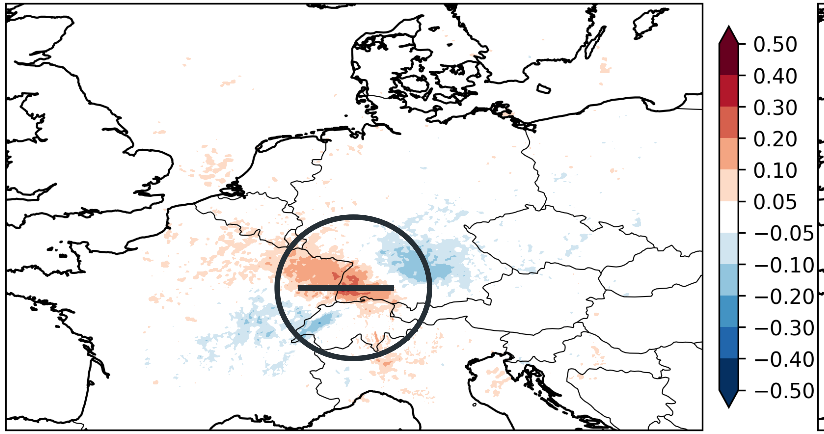


v analysis difference at 1500m a.s.l.



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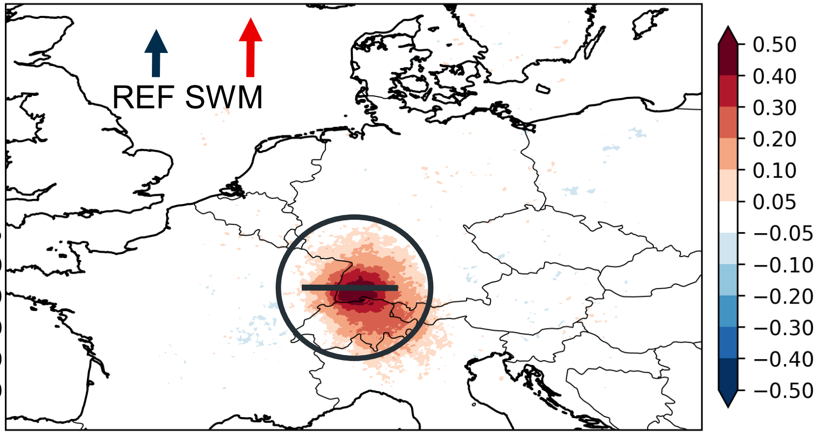

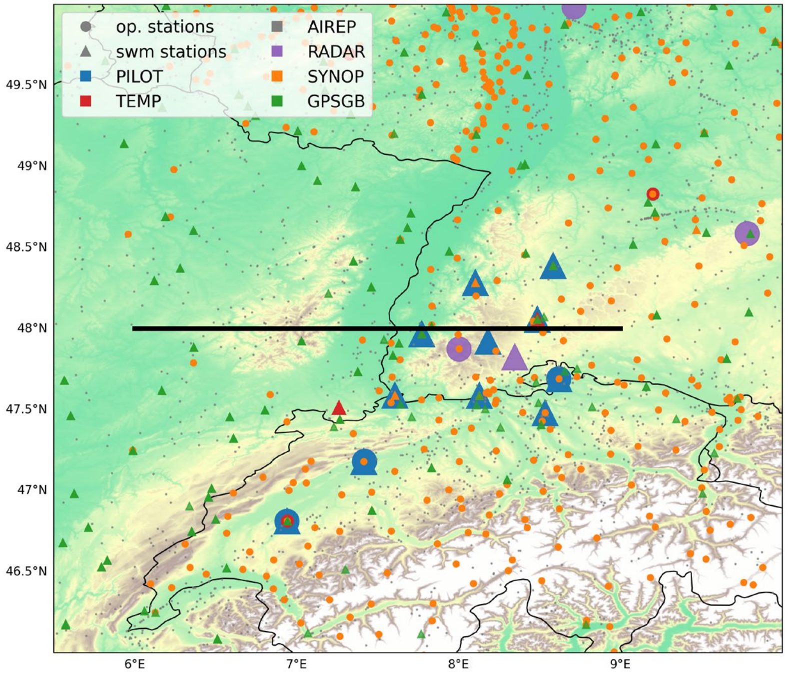

Courtesy J. Thomas

Systematic differences SWM - CTRL analyses

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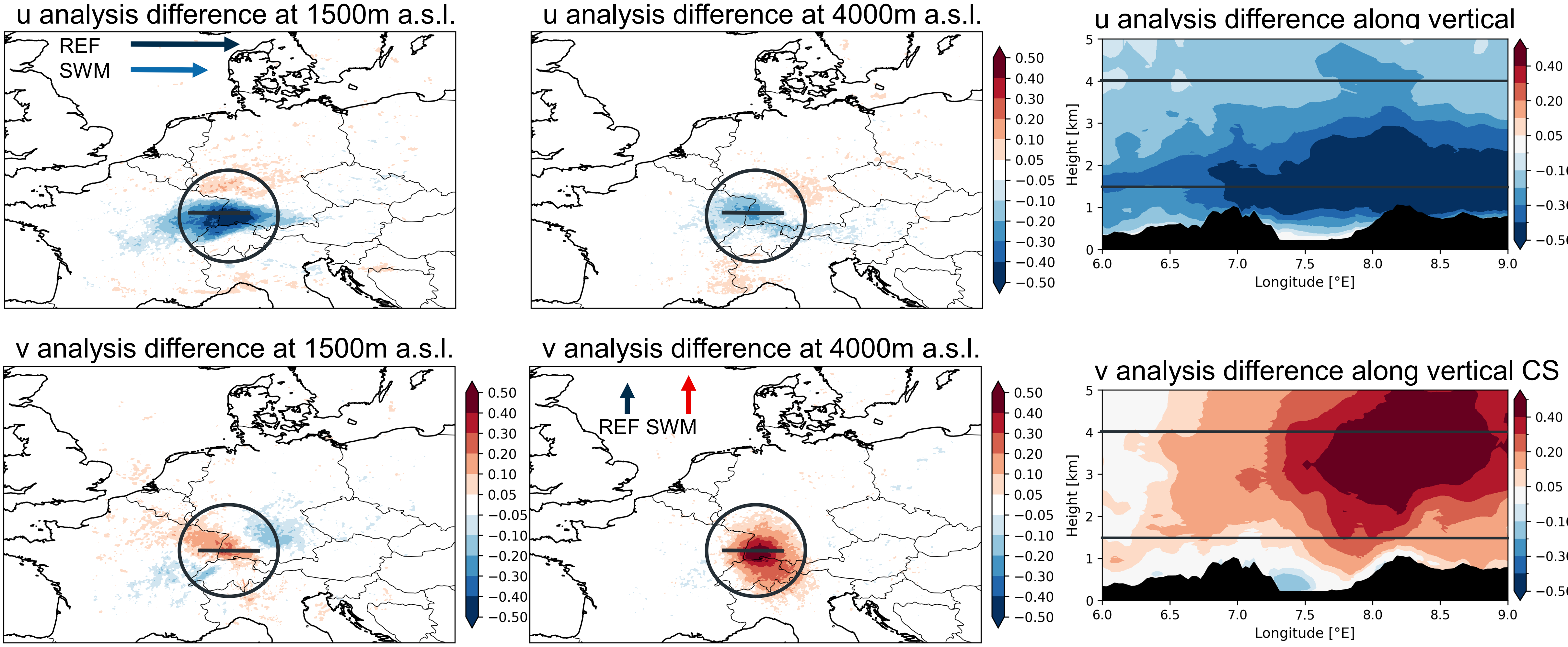
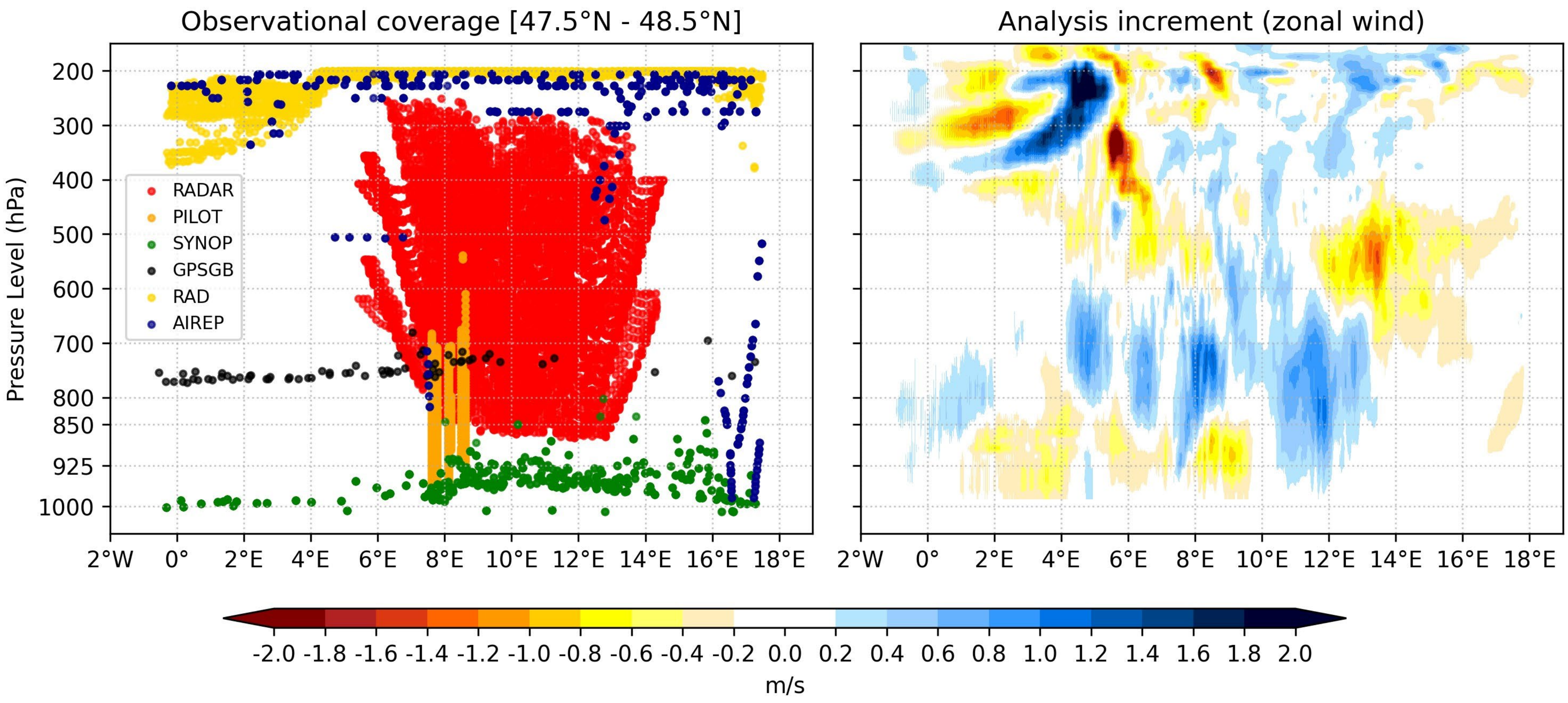


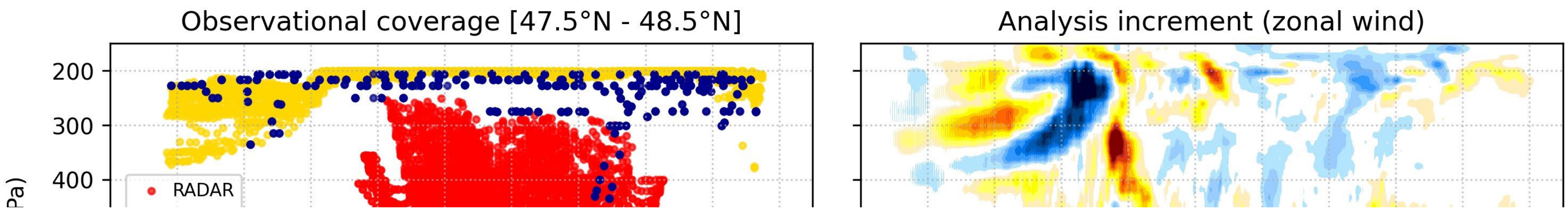
Courtesy J. Thomas

Observational coverage and increment

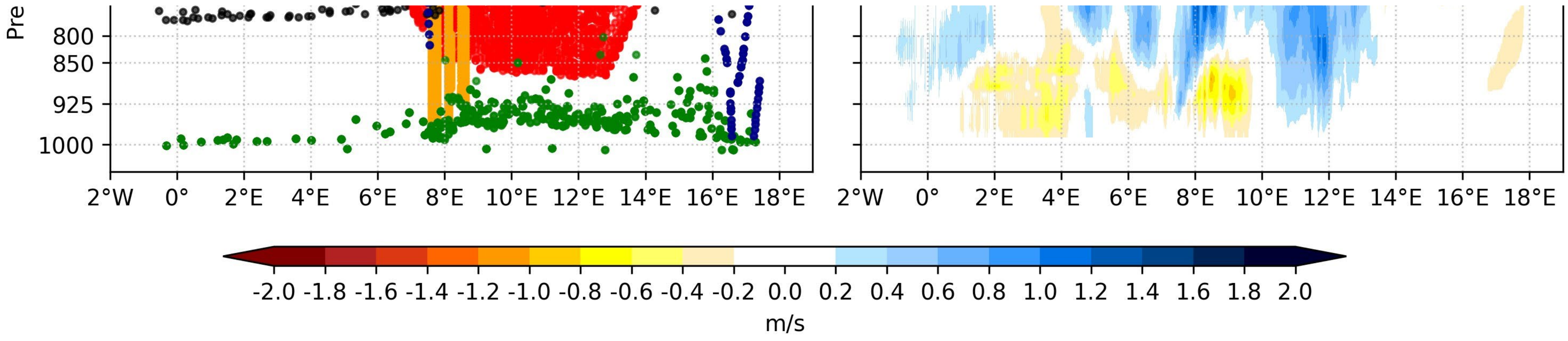


2023-08-01 01 UTC

Observational coverage and increment



What is the contribution of each observation to the total analysis increment?



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Partial analysis increments (PAI): formulation (1/2)

- **Partial analysis increments as diagnostic for LETKF data assimilation systems**, Diefenbach, 2023. *QJRMS.*
- **Investigate the 3D structure of the analysis contribution of one observation in model space**
- Analysis state $x_a = x_b + \boldsymbol{K}(y_o - H(x_b))$
- Analysis Increment $\delta x = x_a - x_b = \boldsymbol{K}(y_o - y_b)$
- Partial Analysis Increment $\delta x_j = K_j \ (y_o - y_b)_j$
- Total Analysis Increment $\sum_{j=1}^{p} \delta x_j = \delta x = \delta x_{\mathrm{PILOT}} + \delta x_{\mathrm{TEMP}} + \delta x_{\mathrm{SYNOP}} + \delta x_{\mathrm{GPSGB}} + \delta x_{\mathrm{RADAR}} + \delta x_{\mathrm{RAD}}$

Partial analysis increments (PAI): formulation (2/2)

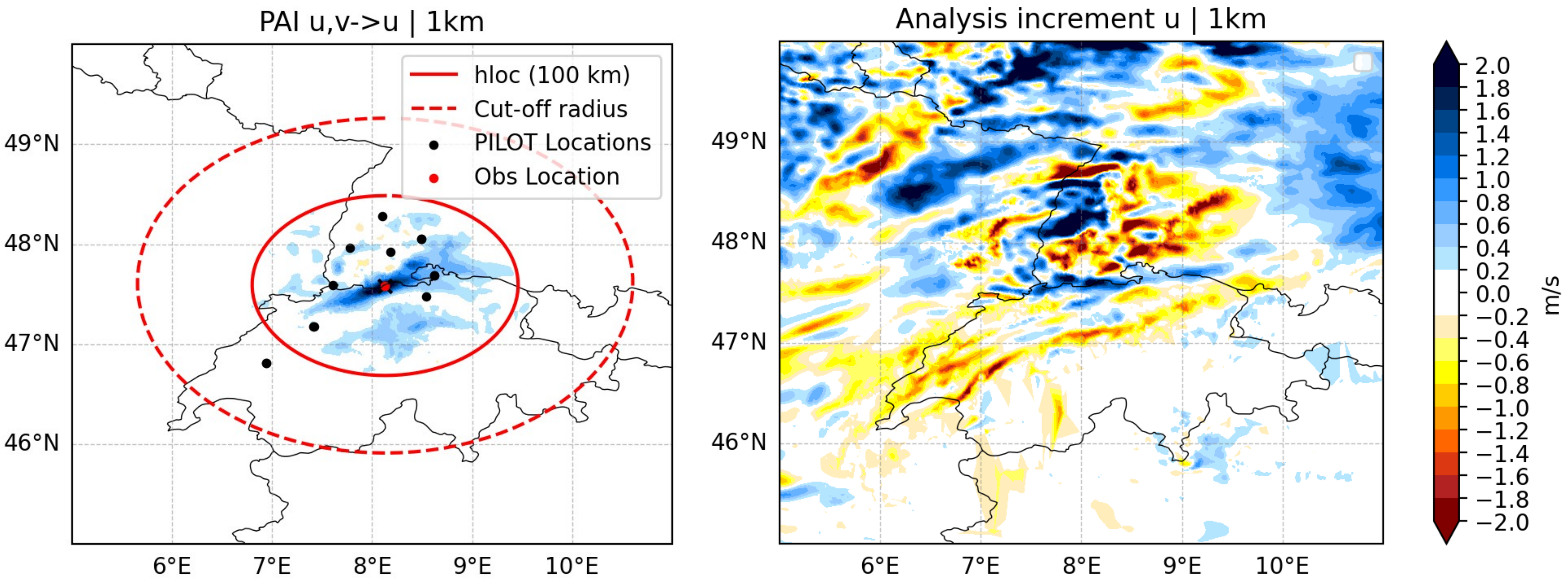
- It is possible to express K in terms of standard LETKF output data products as:

$$\mathbf{K}_{\mathrm{loc}} = \frac{1}{k-1}\,\mathbf{X}_a\,\mathbf{Y}_a^{\mathbf{T}}\,\mathbf{R}^{-1} \circ \boldsymbol{\rho}$$

- Ensemble analysis Perturbation Matrix in *model space* $\mathbf{X}_a$
- Ensemble analysis Perturbation Matrix in *observation space* $\mathbf{Y}_a$
- Observation Error Covariance $\mathbf{R}$ (diagonal)
- Localization matrix $\boldsymbol{\rho} = \boldsymbol{\rho}_{\mathrm{hor}} \circ \boldsymbol{\rho}_{\mathrm{ver}}$

PAI of single PILOT profile - single day (1/4)

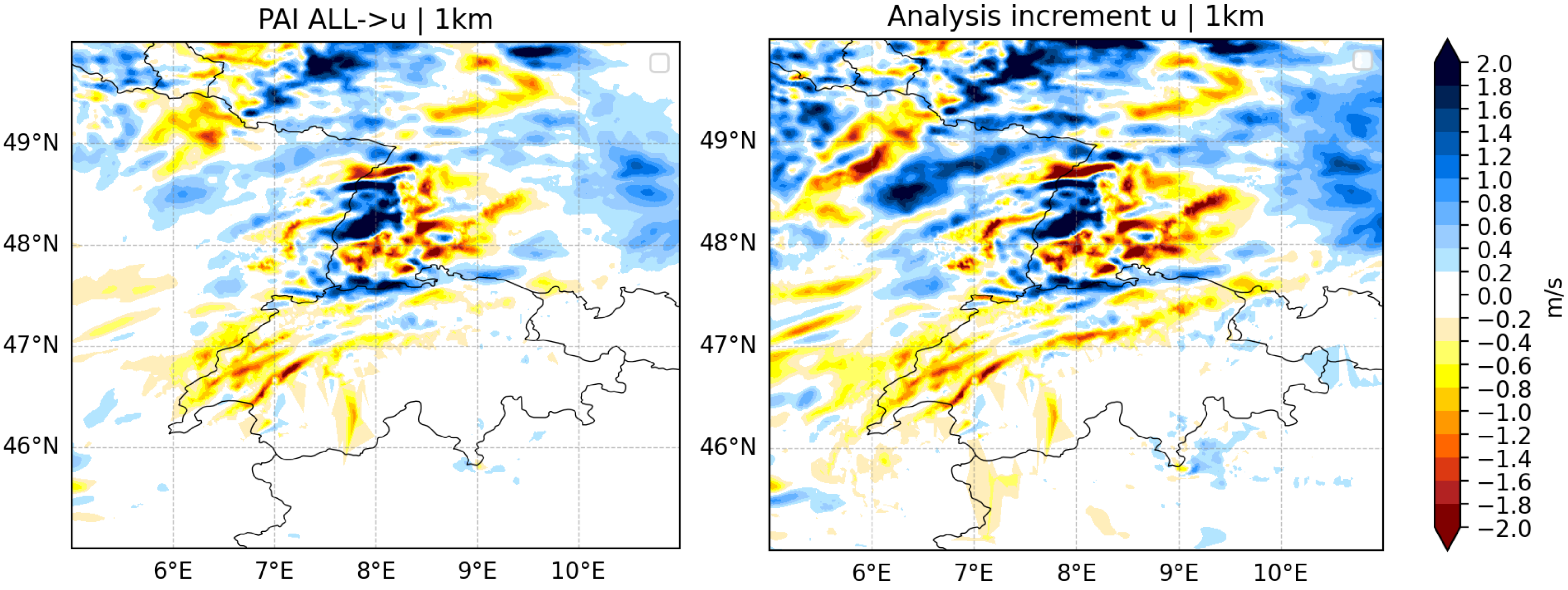
- PILOT at 47.59°N;8.12°E with 64 assimilated observations of u and v winds.



2023-08-01 01 UTC

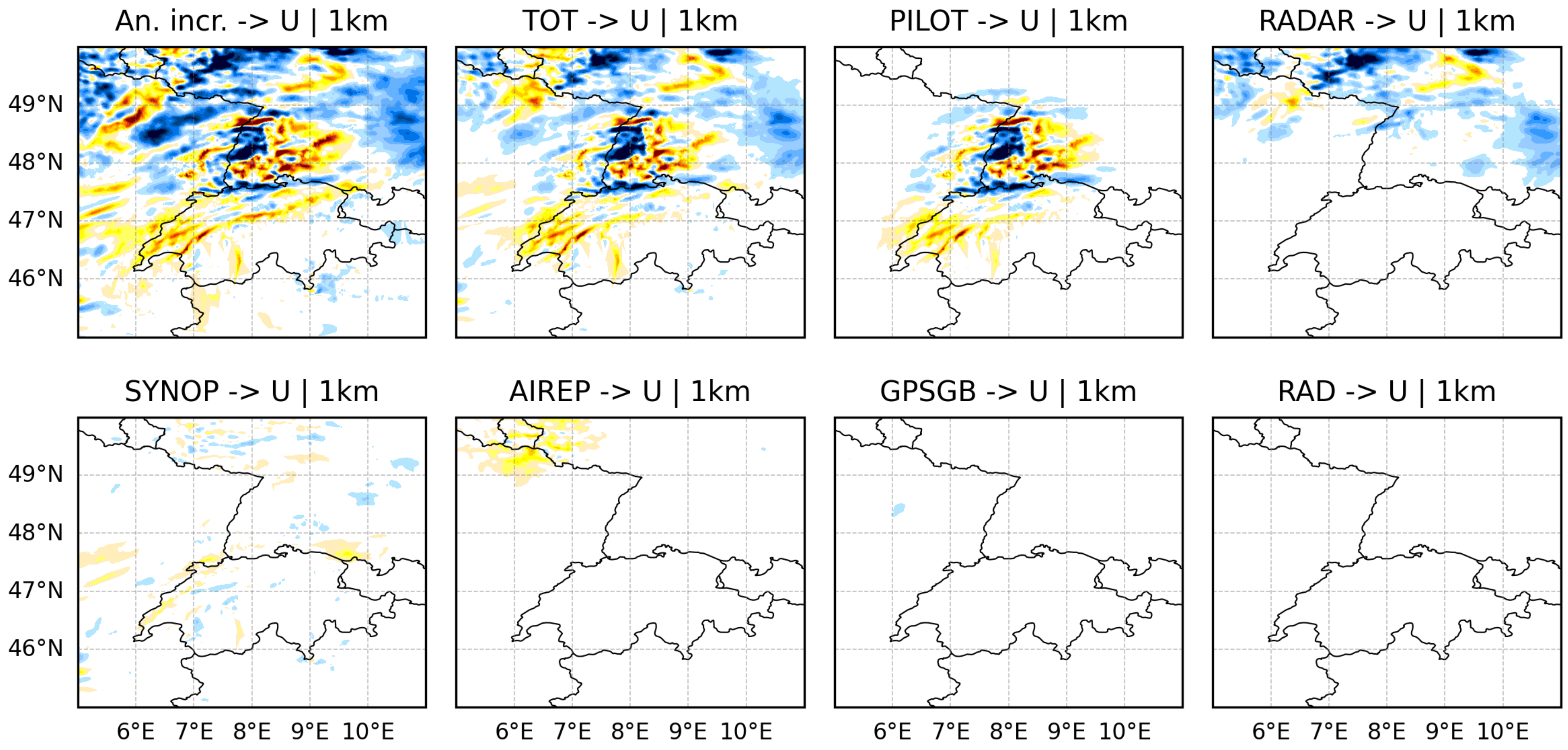
PAI of all observations - single day (2/4)

- ALL: PILOT, SYNOP, RADAR, RAD, AIREP, GPSGB



2023-08-01 01 UTC

PAI of all observations - single day (3/4)



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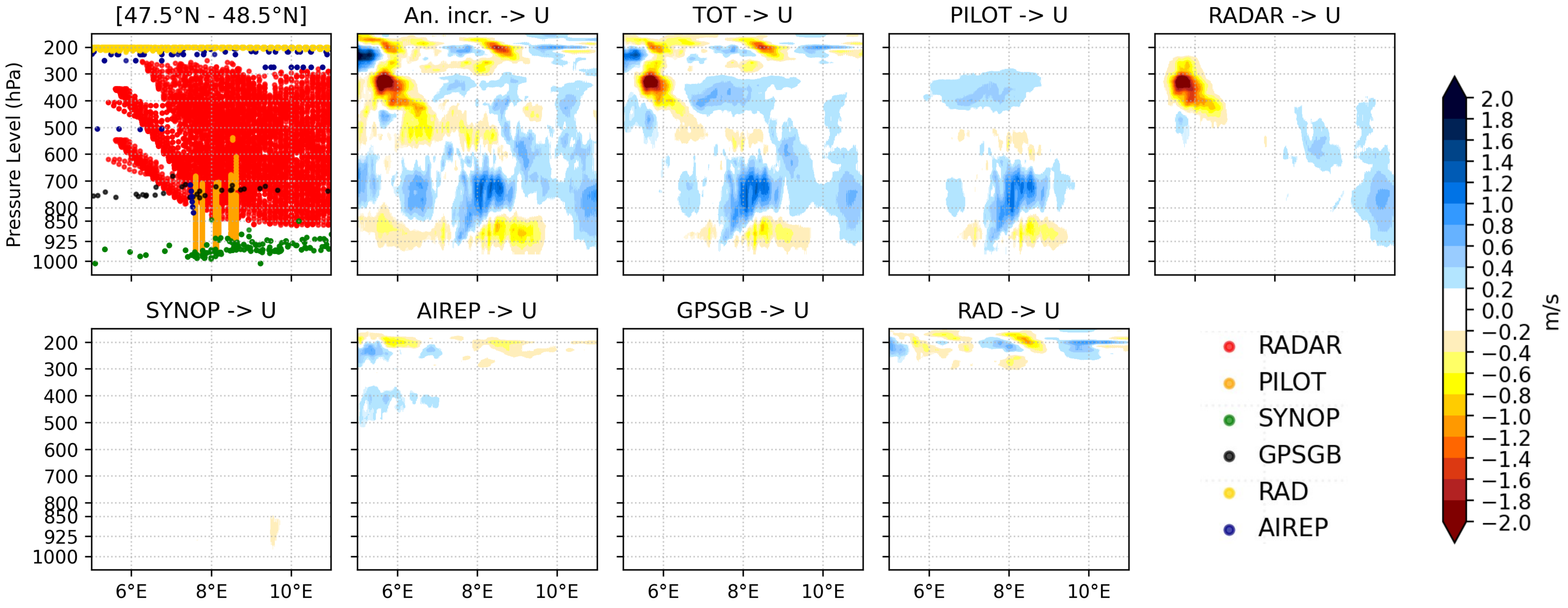
PAI of all observations - single day (4/4)



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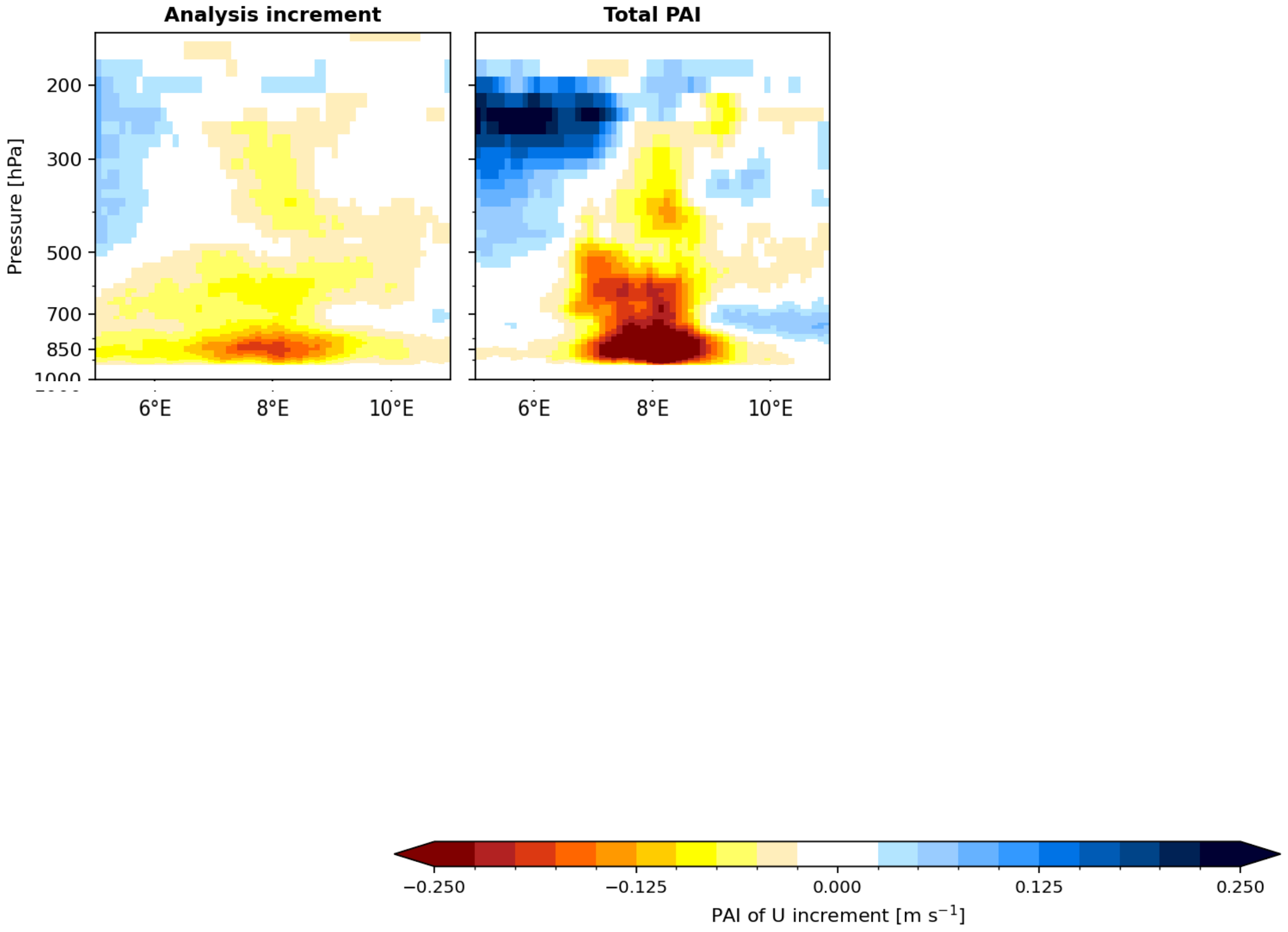
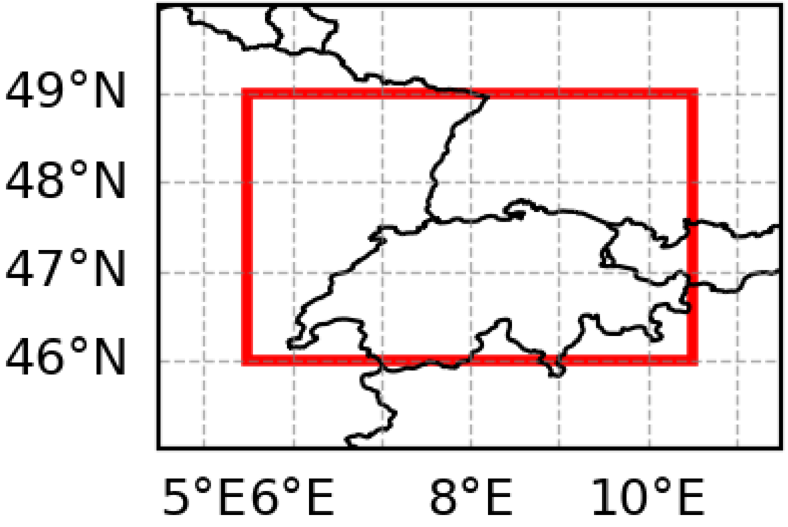
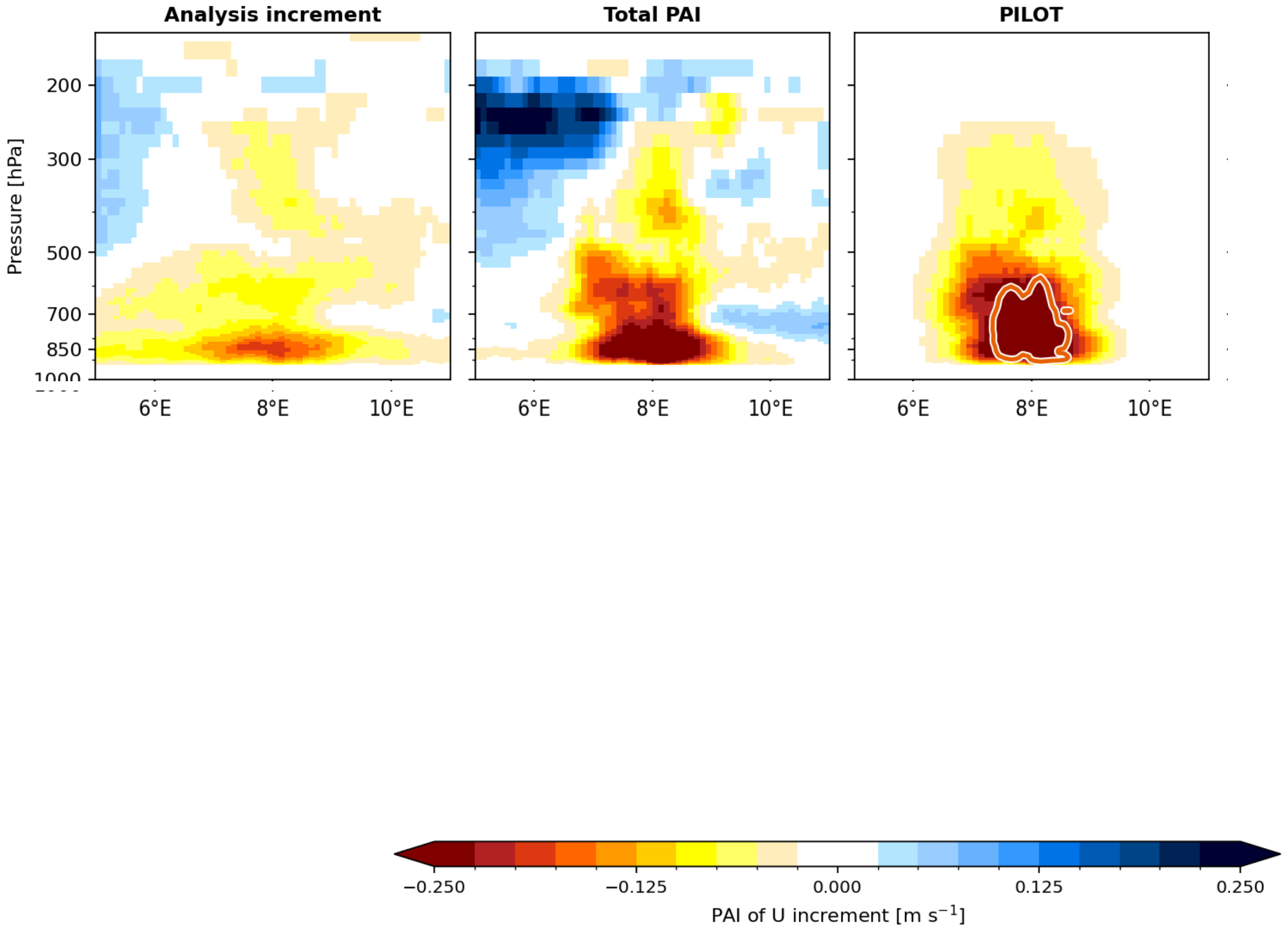
Mean PAI – June to August 2023 – Zonal Wind



- An. Incr. and PAI both fit the sign correctly; the difference is mainly due to **inflation effects** that PAI does not account for.



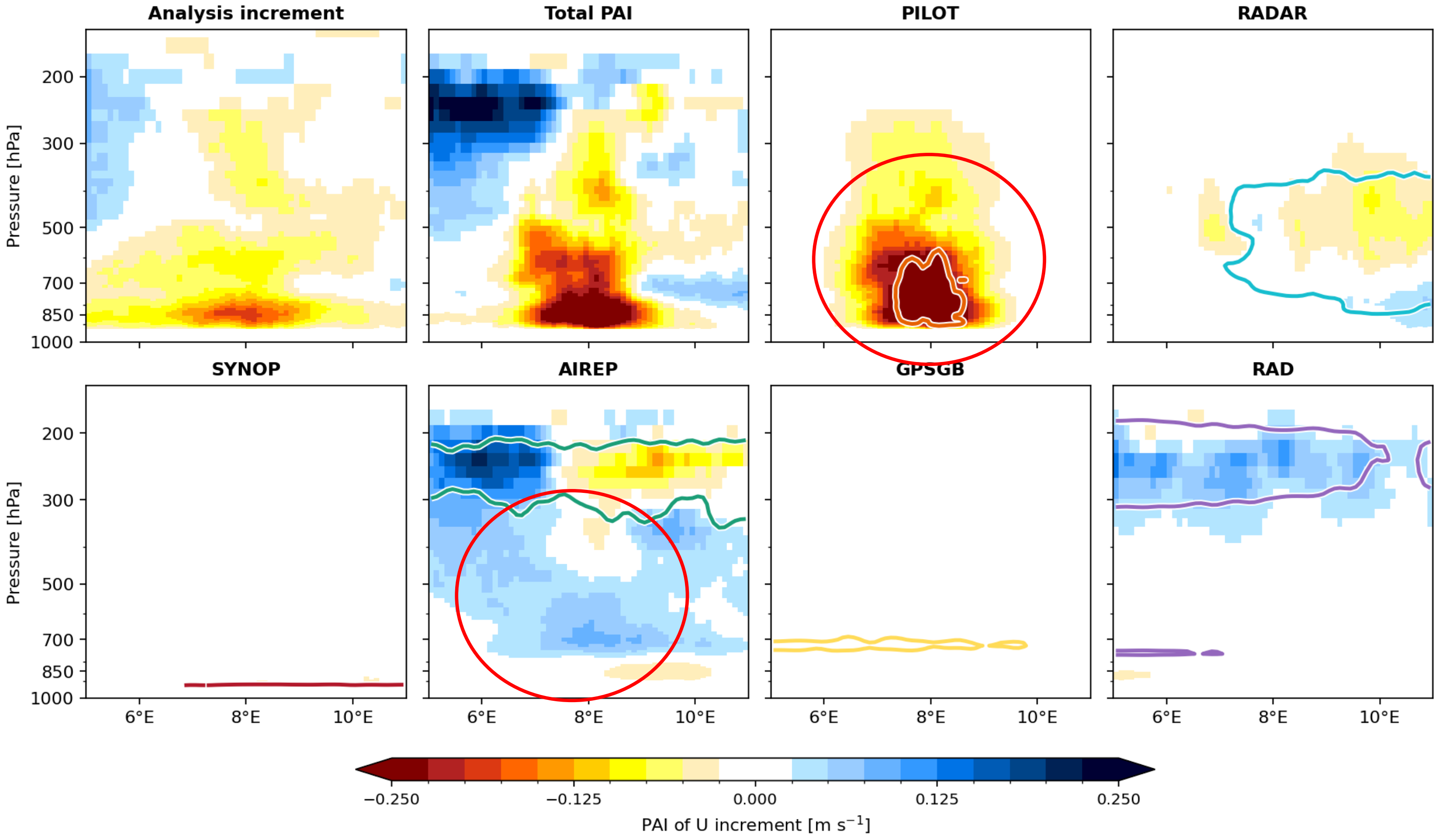
Mean PAI – June to August 2023 – Zonal Wind



U — Zonal wind

- PILOT drives the increment in the troposphere

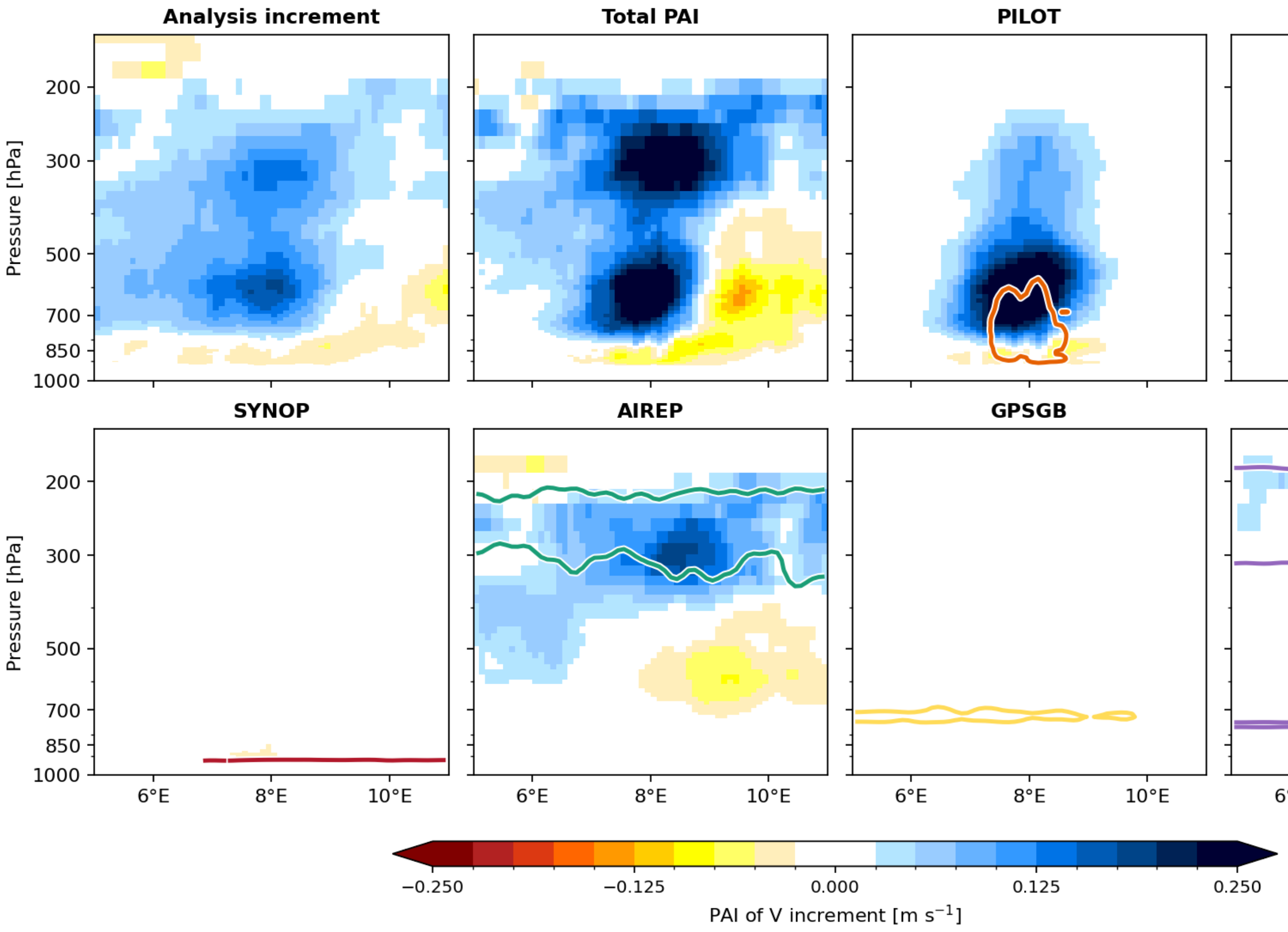
Mean PAI – June to August 2023 – Zonal Wind



U — Zonal wind

- PILOT drives the increment in the troposphere
- AIREP opposes it at 500–700 hPa: vertical localization effect

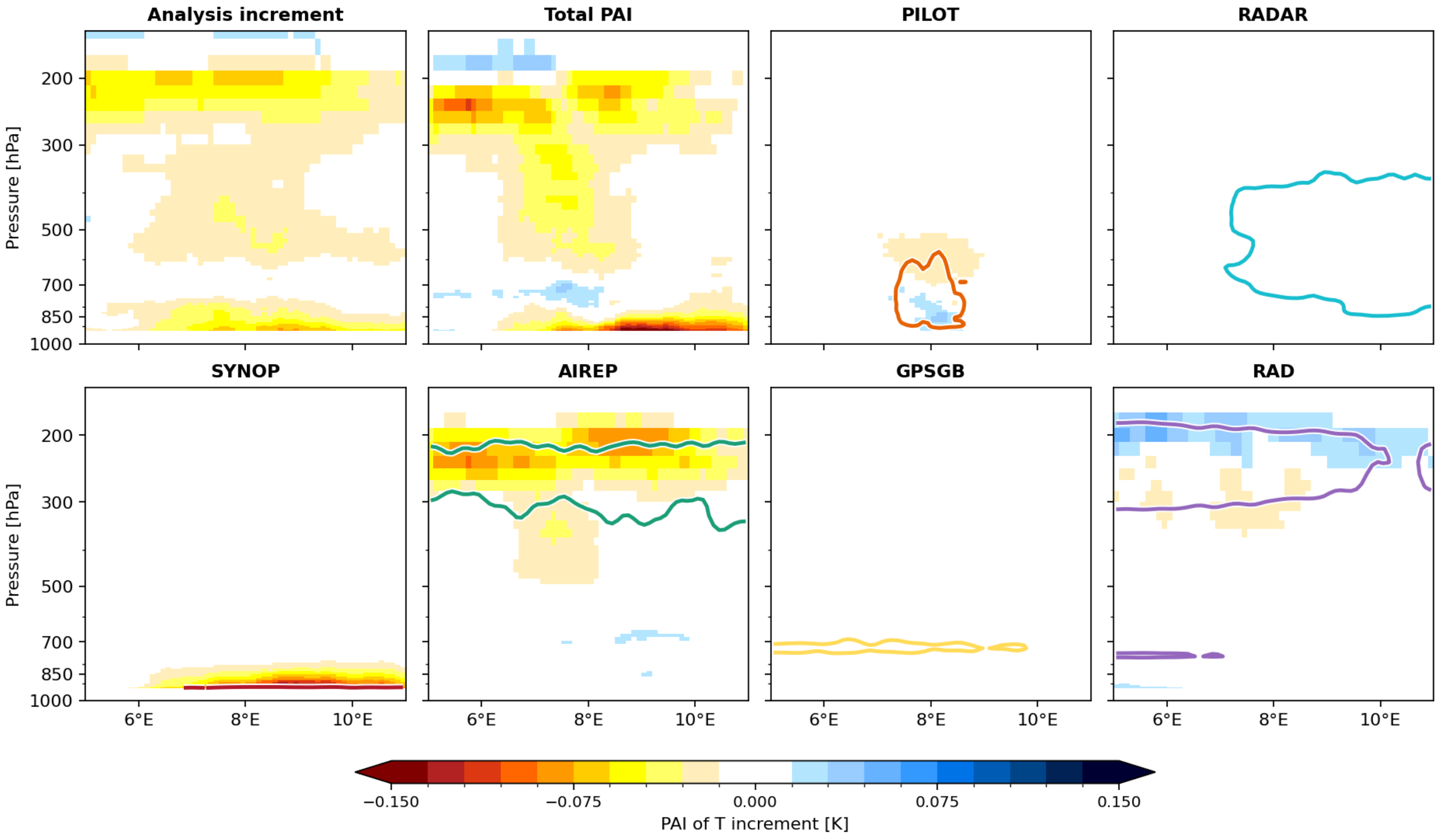
PAI – June to August 2023 – Meridional Wind



V — Meridional wind

- PILOT and AIREP both drive the increment
- Contributions are consistent (same sign)

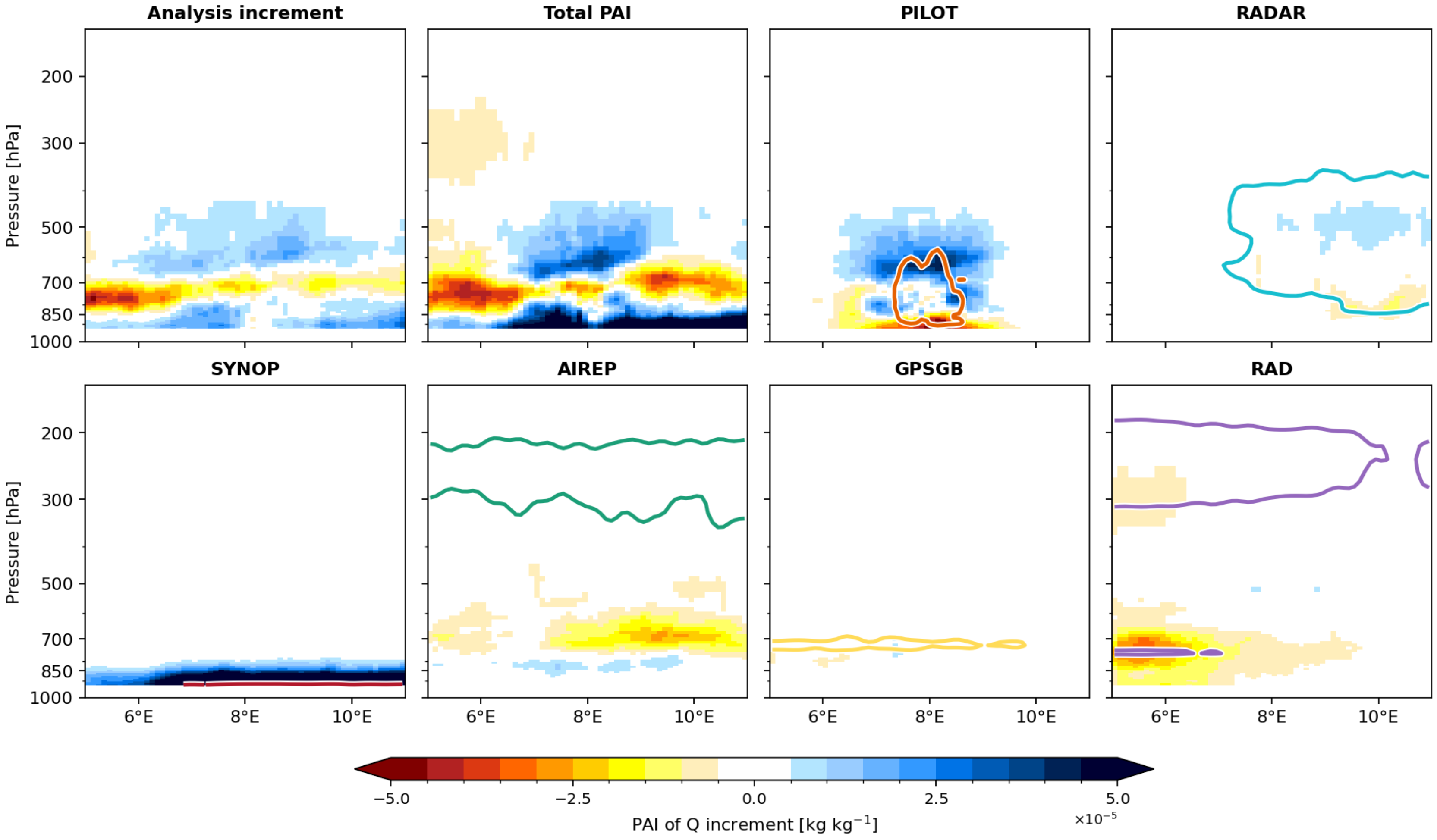
PAI – June to August 2023 – Temperature



T — Temperature

- SYNOP drives the surface; RAD and AIREP the UTLS
- RAD and AIREP oppose each other in the UTLS

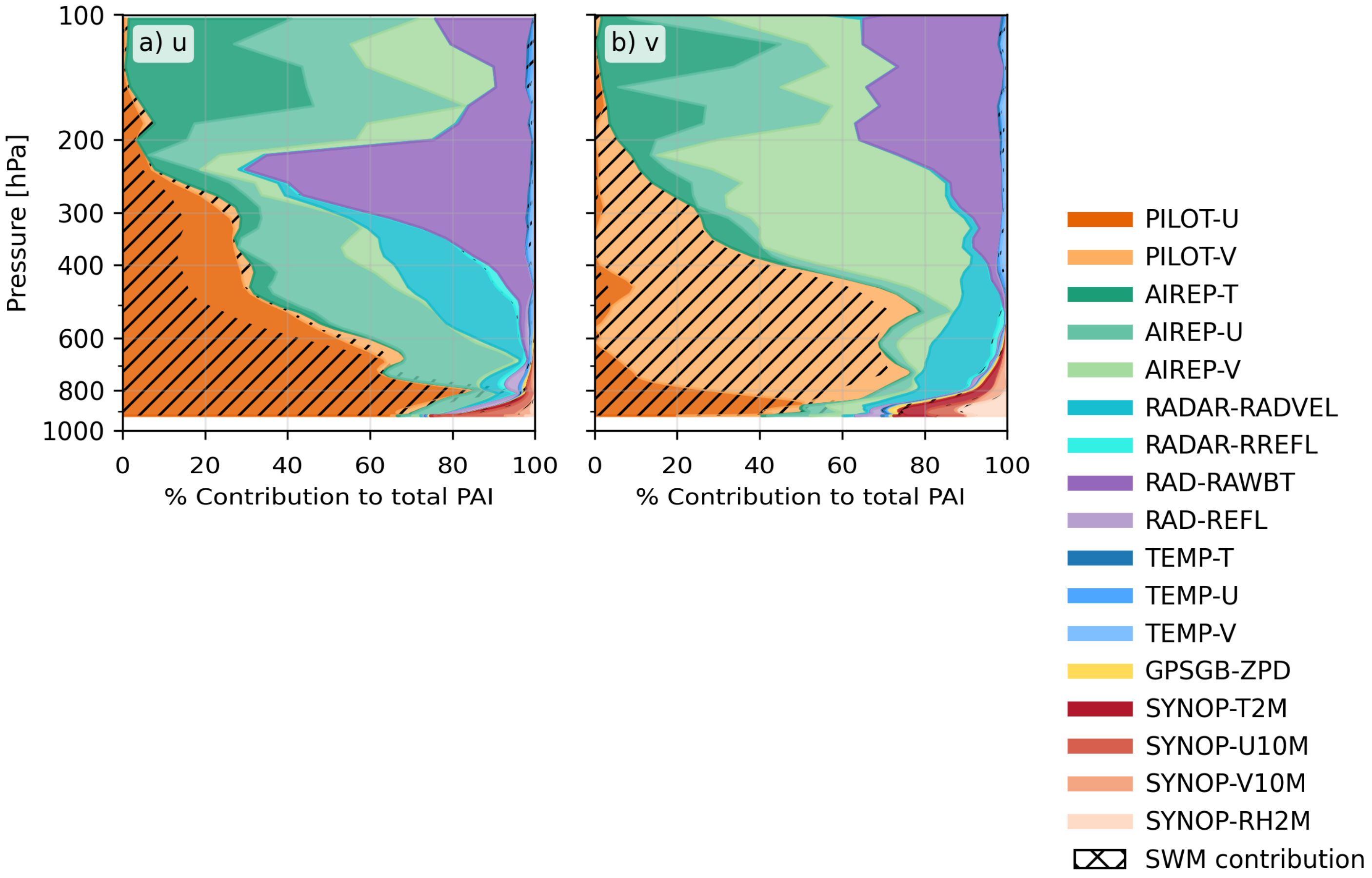
PAI – June to August 2023 – Humidity



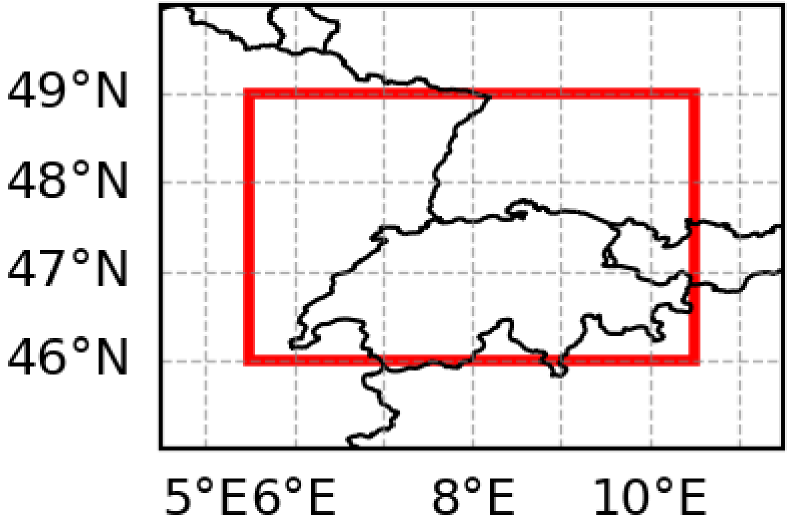
Q — Humidity

- SYNOP drives the surface increment
- RAD and AIREP contribute in the mid-troposphere (same sign)
- PILOT has a strong contribution in the mid-troposphere

Relative Contributions of each observation type



- **PILOT contributes most to U and V in the lower and middle troposphere**, while the upper troposphere is dominated by **AIREP** and **RAD**.



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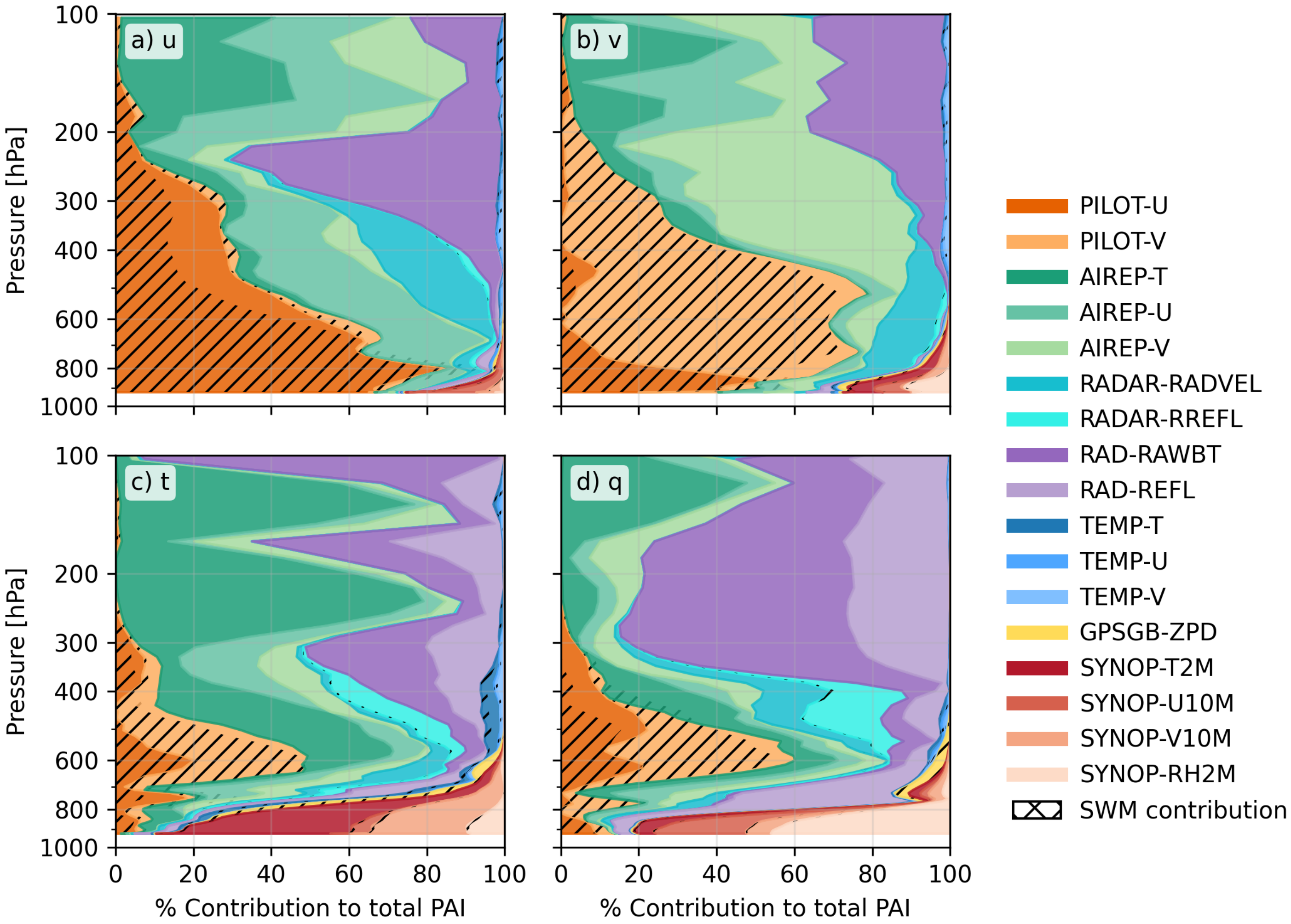
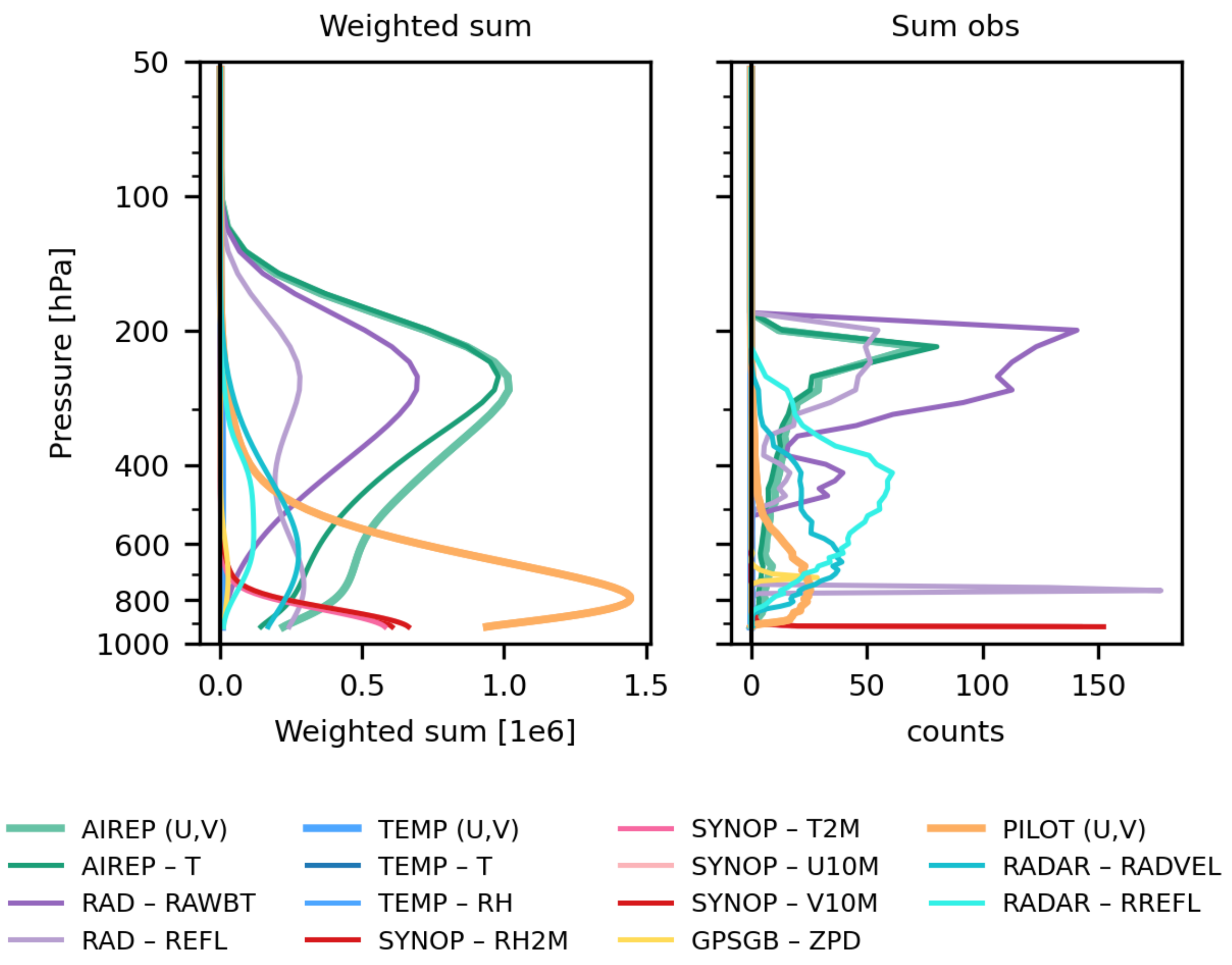
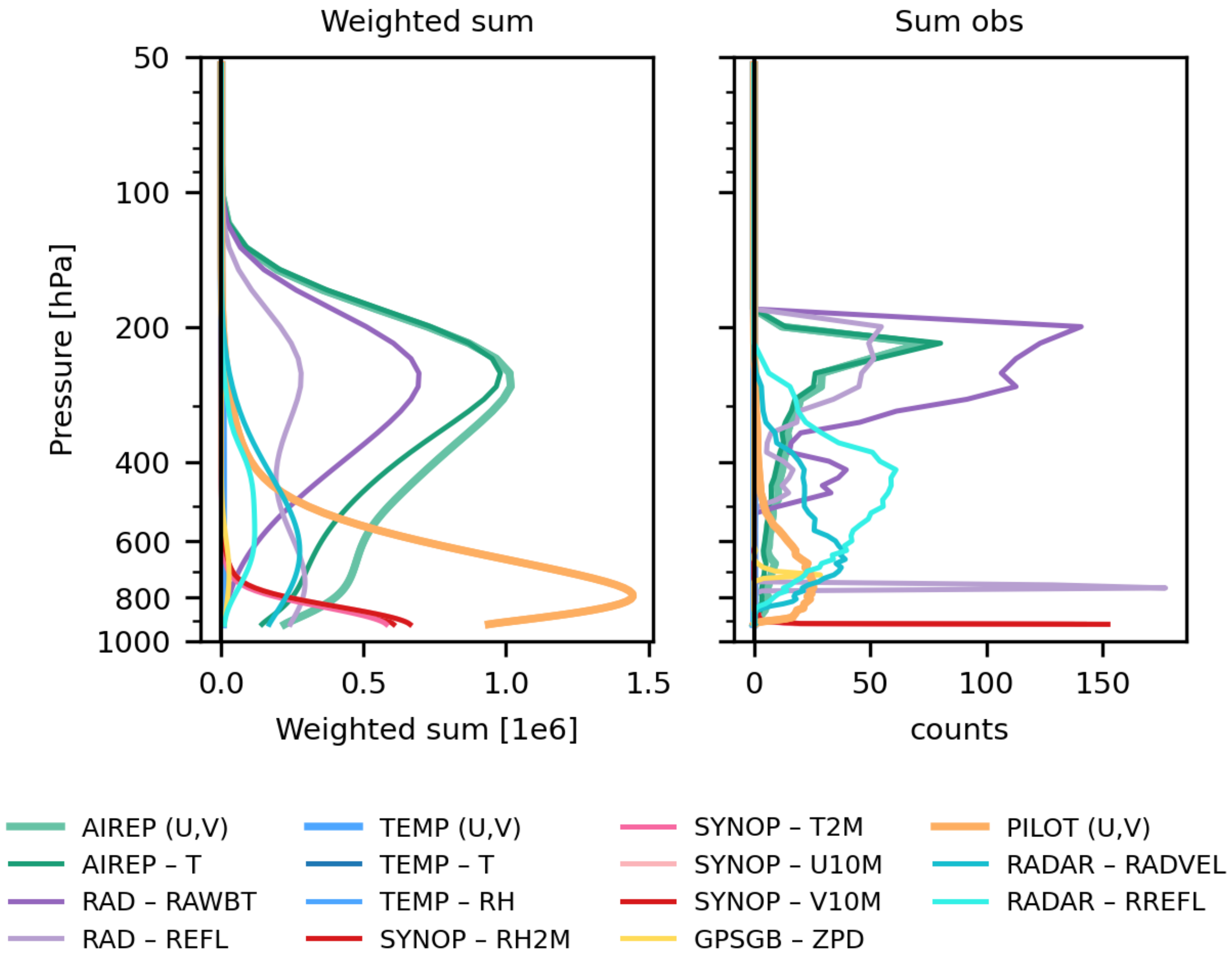


- **PILOT contributes most to U and V in the lower and middle troposphere**, while the upper troposphere is dominated by **AIREP** and **RAD**.
- **PILOT also has a strong contribution to q and T, particularly in the middle troposphere around 600 hPa**.
- **Lower troposphere q and T** is mostly influenced by **SYNOP**, while **RAD** and **AIREP** play a larger role in the **upper troposphere.**

Observation distribution (1/2)



Observation distribution (2/2)

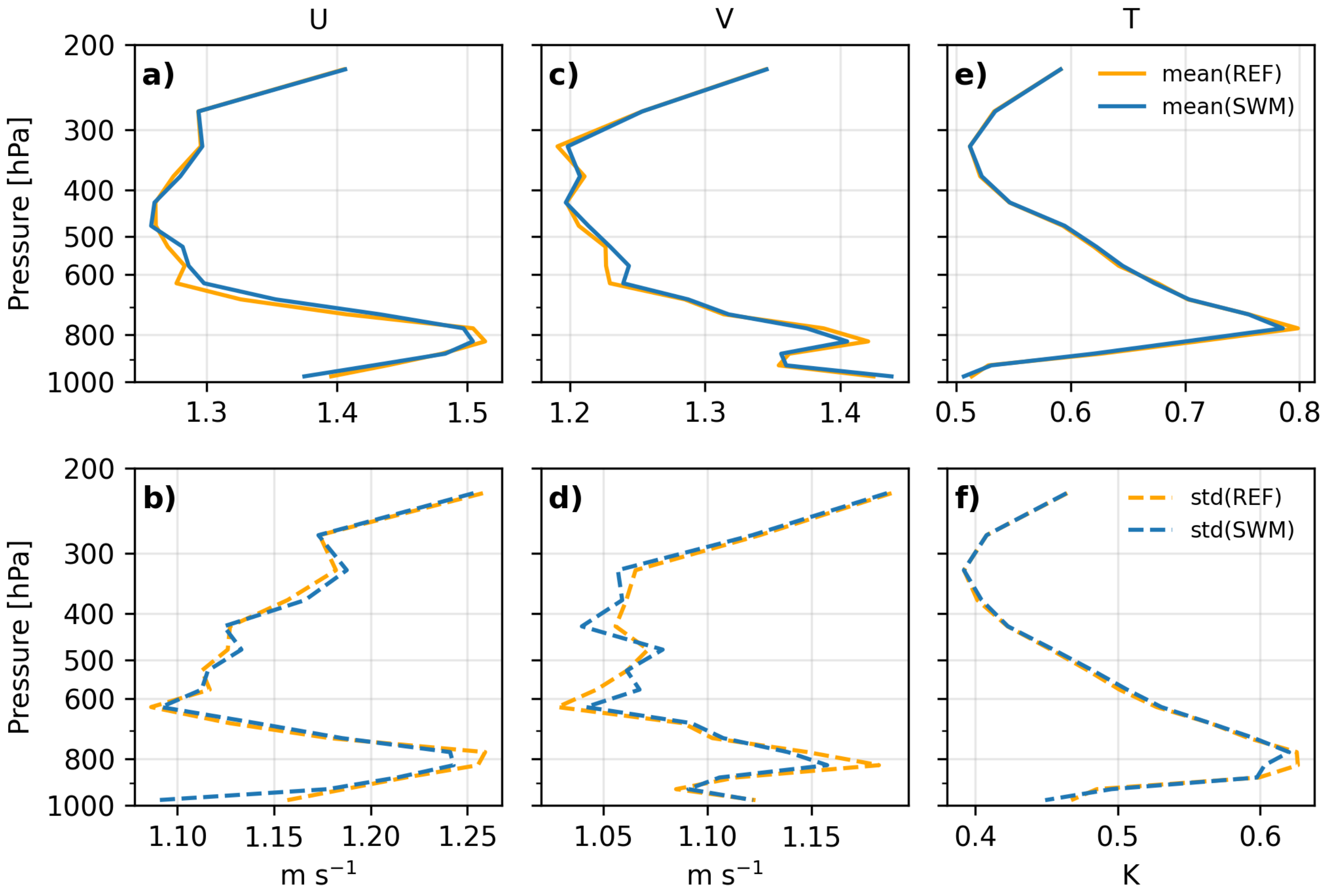


Localization length by observation type

Observation	Horizontal (km)	Vertical (log-p)
PILOT, TEMP, AIREP, SYNOP	50–100*	0.075–0.5
RAD	25	0.3
GPSGB	20	0.17
RADAR	16	0.07–0.3†

** adaptive horizontal localisation*
† RADAR vertical: 0.07 (reflectivity) – 0.3 (radial velocity)
Vertical localisation: Gaspari–Cohn function on log-pressure distance

Departure statistics (O-B) of AIREP observations

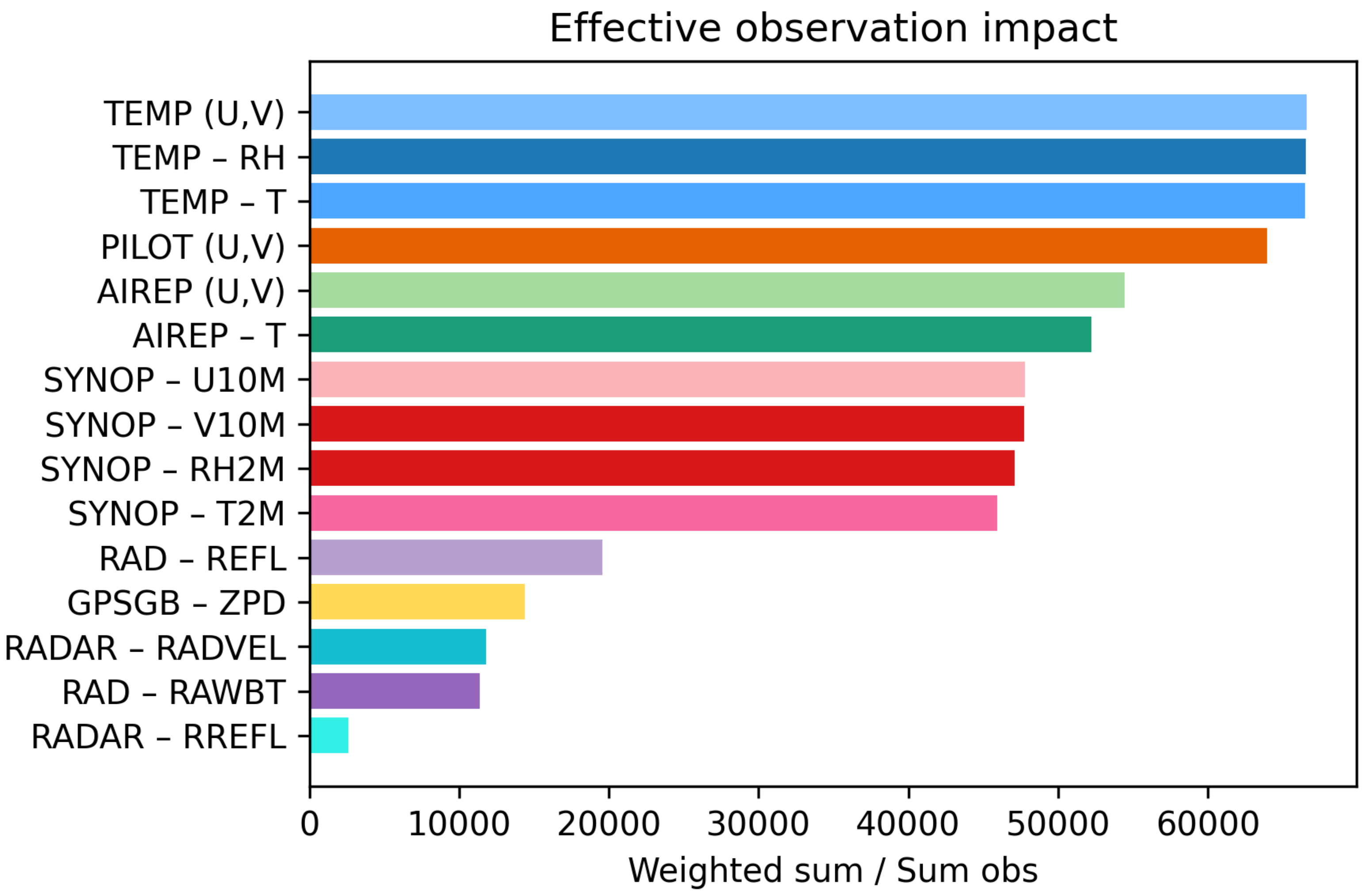


- Departures peak in the lower troposphere (~800 hPa), smallest at mid-levels.
- Departure shows improvement near 800 hPa, a first sign of positive impact

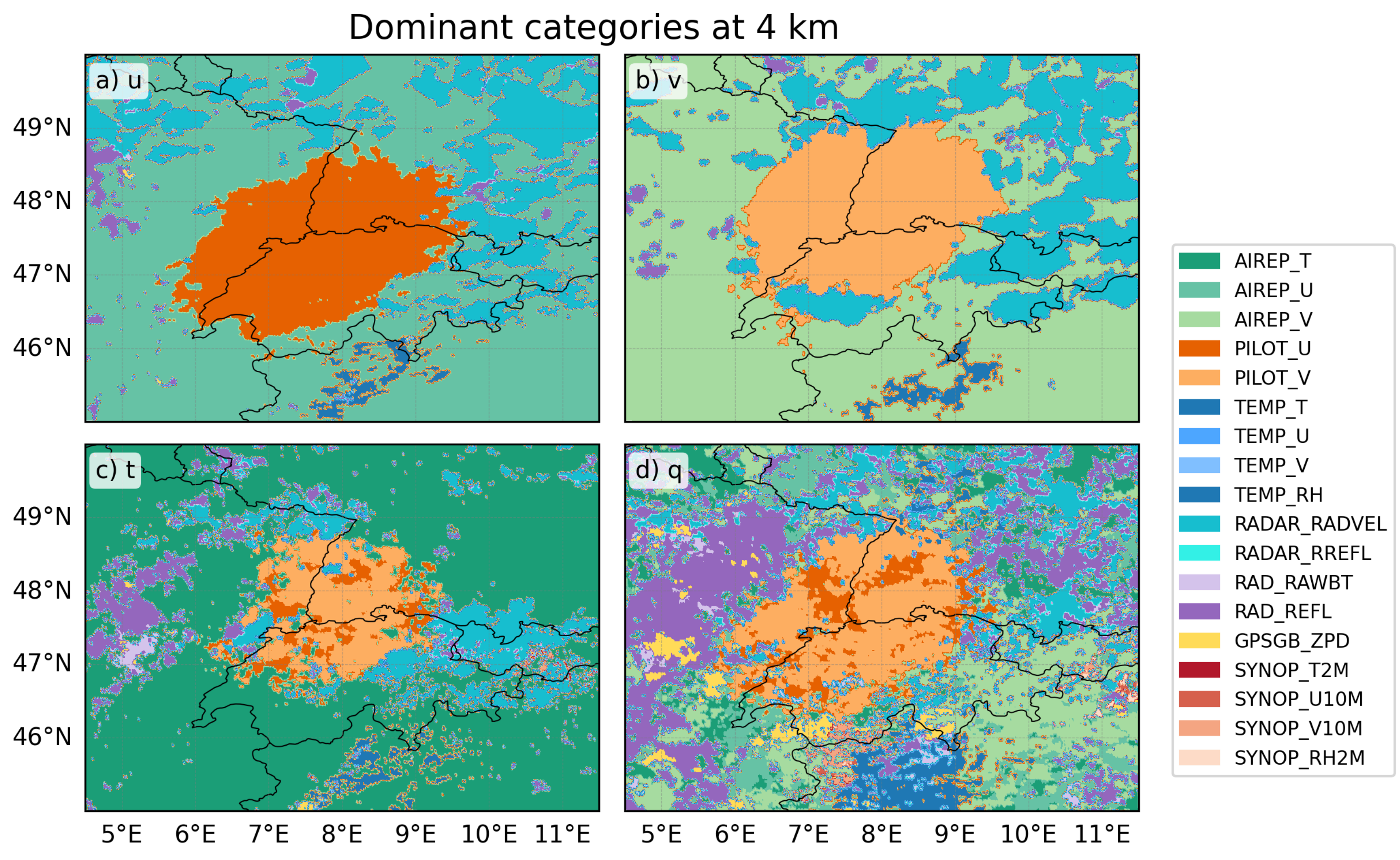
Conclusions

- The SWM wind-lidar network leaves a coherent, systematic fingerprint on the mesoscale analysis: In westerly flow conditions, it slows the zonal wind, strengthens the meridional wind, and spreads well beyond the campaign area
- PILOT/DWL dominates the wind increments in the lower and middle troposphere, thanks to both the dense network and its large localization length; it also reaches T and q near 600 hPa.
- Some observation types contribute with opposite signs in the same layer (AIREP vs PILOT wind in the mid-troposphere). This is suboptimal and points to a vertical-localization issue: observations still influence the analysis a few km above or below where they measure.
- The departure statistics of AIREP shows improvement in the lower troposphere (~800 hPa): a first indication of positive impact.
- Residuals mainly arise from inflation effect and observations outside the localization radius.

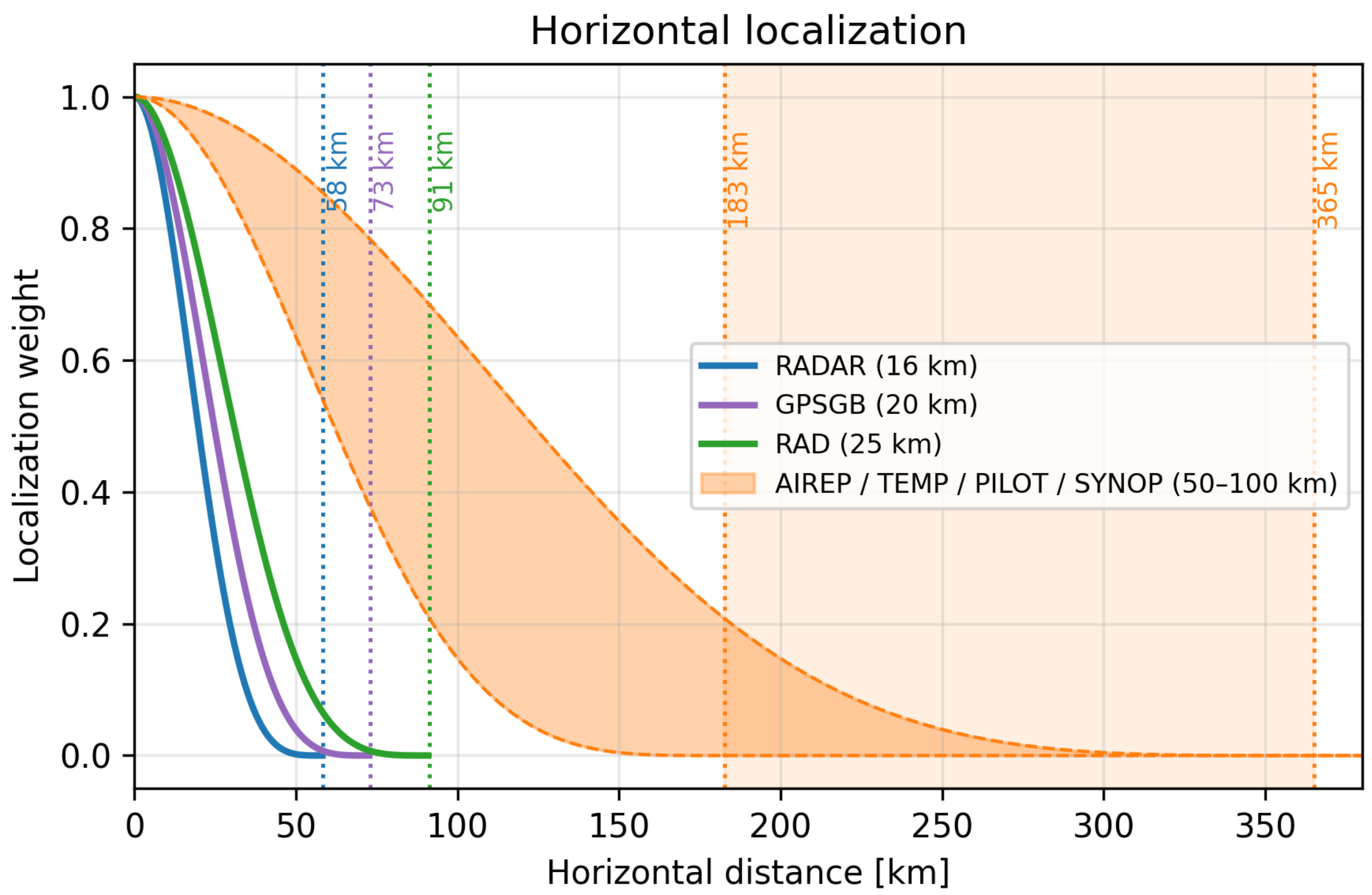
Effective observation impact

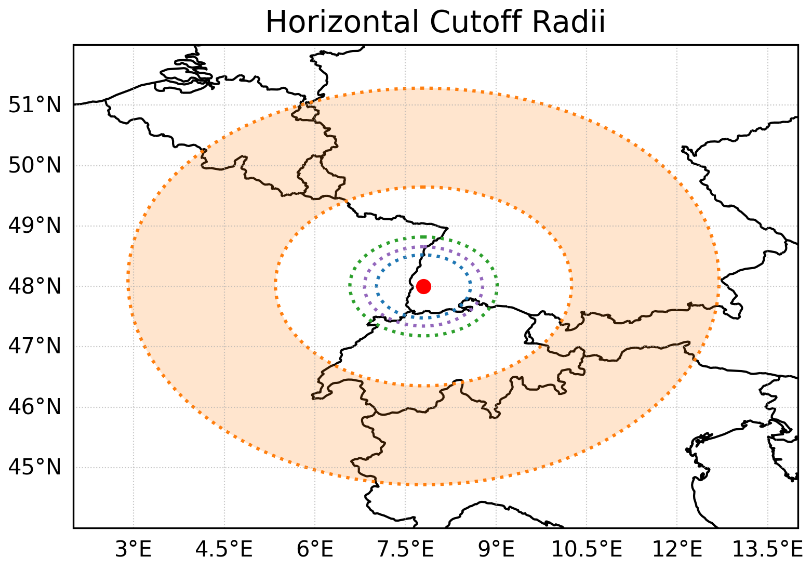


Relative Contributions of each observation type



How are the observation localized?





Gaspari–Cohn function: Gaussian-shaped curve that decays to zero after the cutoff radius

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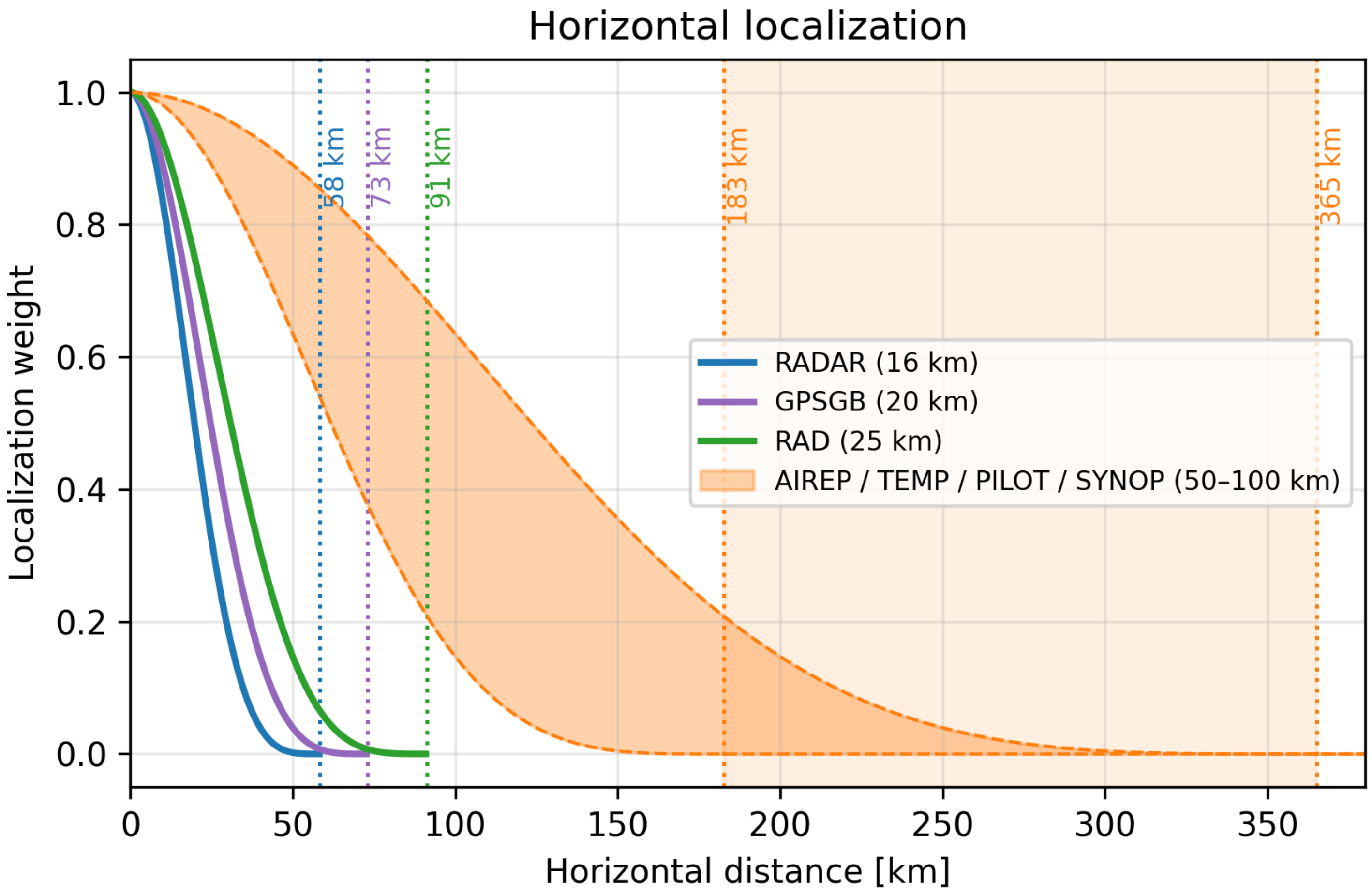
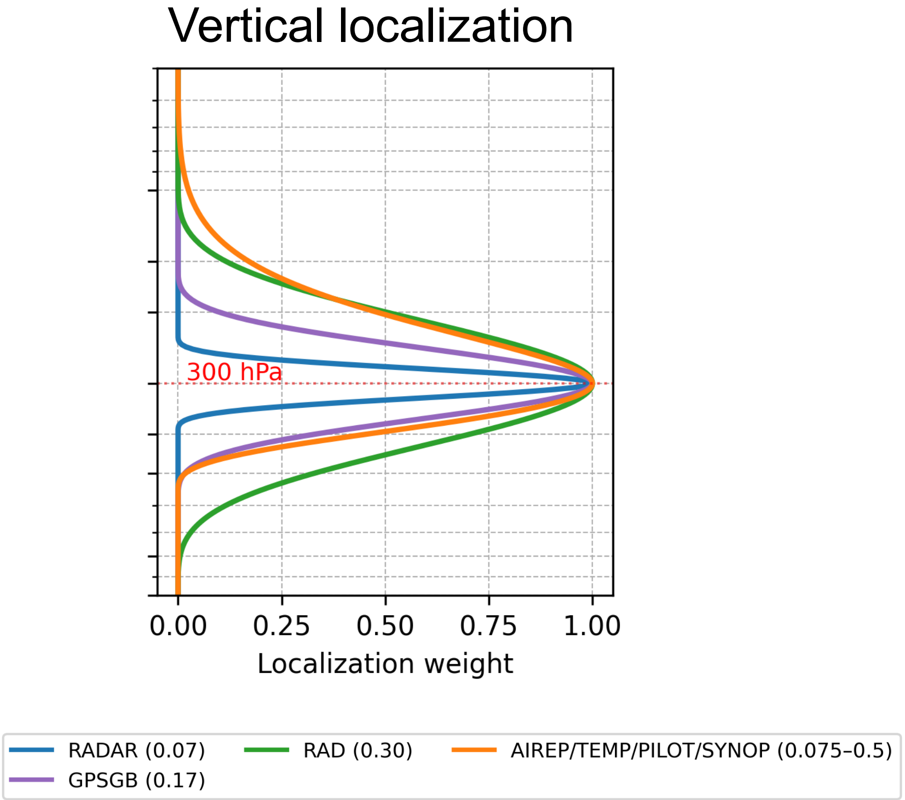
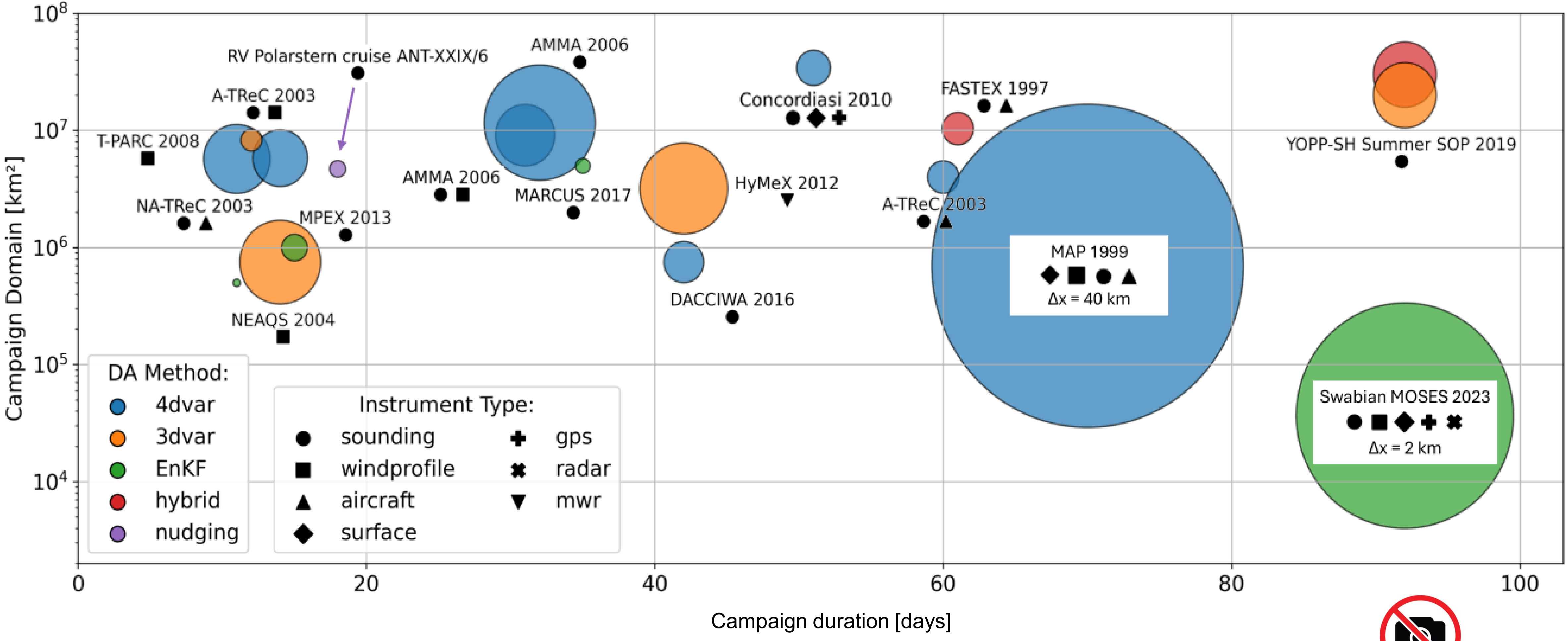




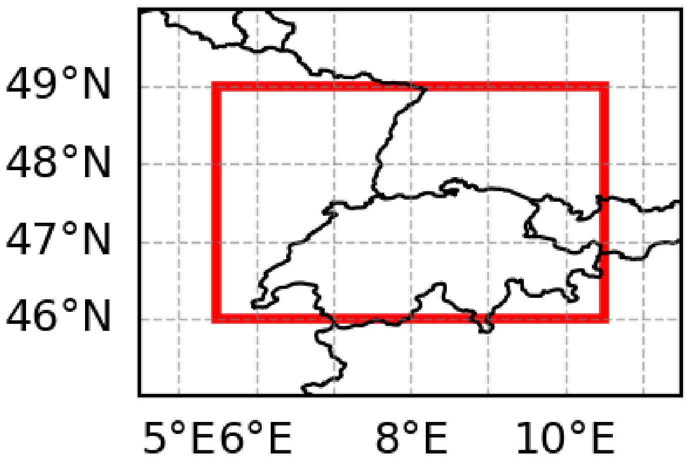
Gaspari–Cohn function: Gaussian-shaped curve that decays to zero after the cutoff radius

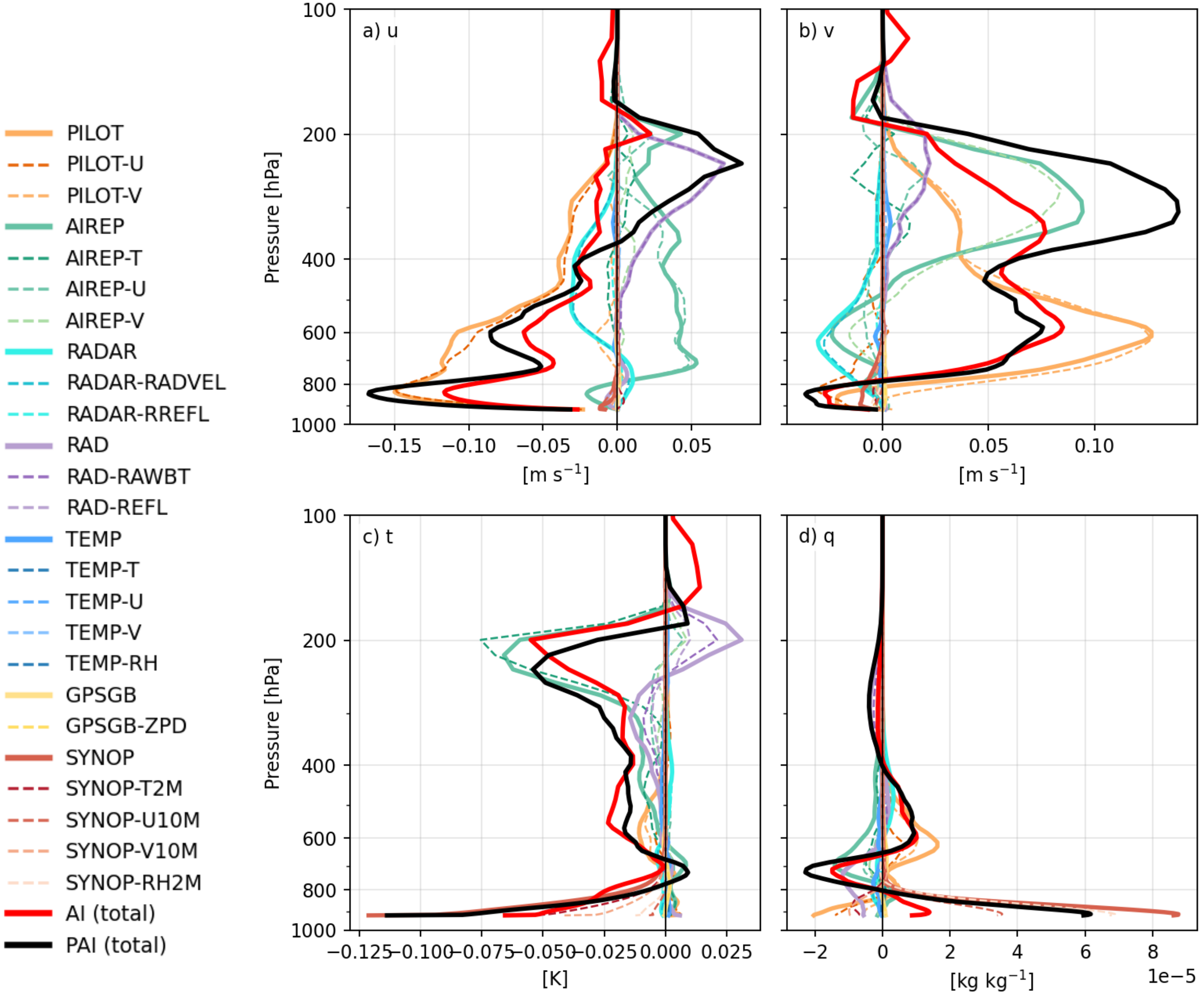
Overview of ground-based campaigns



Courtesy J. Thomas

TOTAL PAI


49°N
48°N
47°N
46°N
5°E6°E
8°E
10°E

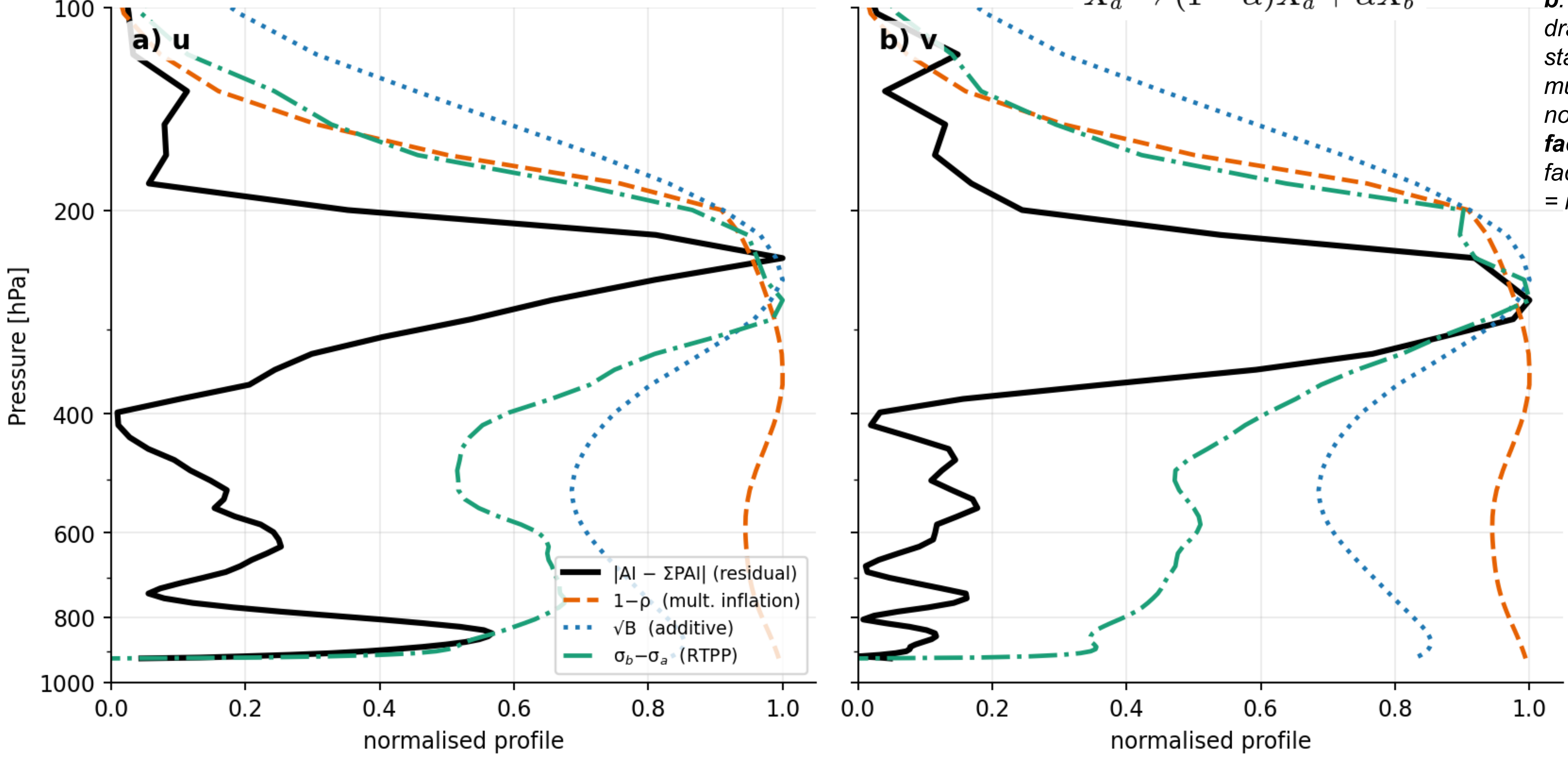

PILOT
PILOT-U
PILOT-V
AIREP
AIREP-T
AIREP-U
AIREP-V
RADAR
RADAR-RADVEL
RADAR-RREFL
RAD
RAD-RAWBT
RAD-REFL
TEMP
TEMP-T
TEMP-U
TEMP-V
TEMP-RH
GPSGB
GPSGB-ZPD
SYNOP
SYNOP-T2M
SYNOP-U10M
SYNOP-V10M
SYNOP-RH2M
AI (total)
PAI (total)
a) u
b) v
c) t
d) q
Pressure [hPa]
100
200
400
600
800
1000
−0.15 −0.10 −0.05 0.00 0.05
[m s^{-1}]
0.00 0.05 0.10
[m s^{-1}]
−0.125 −0.100 −0.075 −0.050 −0.025 0.000 0.025
[K]
−2 0 2 4 6 8
[kg kg^{-1}]
1e−5

Inflation

$$X_a \rightarrow \sqrt{\rho} X_a$$

$$X_a \rightarrow X_a + f_{\mathrm{add}} B^{1/2} b$$

$$X_a \rightarrow (1 - \alpha) X_a + \alpha X_b$$



B: *Background covariance matrix*
b: *Random vector drawn from the standard multivariate normal distribution*
fadd: *Scaling factor (0-1) with 0 = no inflation*