Evaluating forecast impact of current and future observations

(focus on the atmosphere)

Niels Bormann

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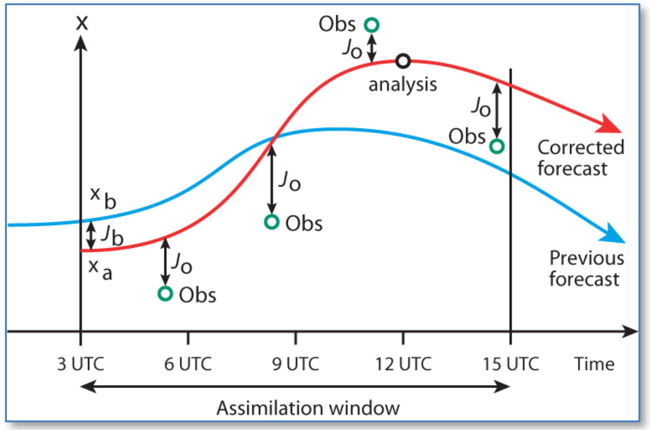
ECMWF

What impact can observations have in a data assimilation system?

- **Impact on the estimation of systematic errors** → e.g., Patrick Laloyaux's talk; reanalysis talks
- **Impact through diagnostics** (incl to aid the assimilation of other observations, e.g. to describe surface emissivity) → e.g., talks by Mohamed Dahoui, Alan Geer
- **Impact on model development** → e.g., Philippe Chambon's talk
- **Impact on forecast quality** (reduction of forecast errors)

Why do we evaluate the forecast impact of observations?

- Check "health" of the assimilation set-up
- Investigate assimilation mechanisms



- Assess strengths/weaknesses of the current global observing system

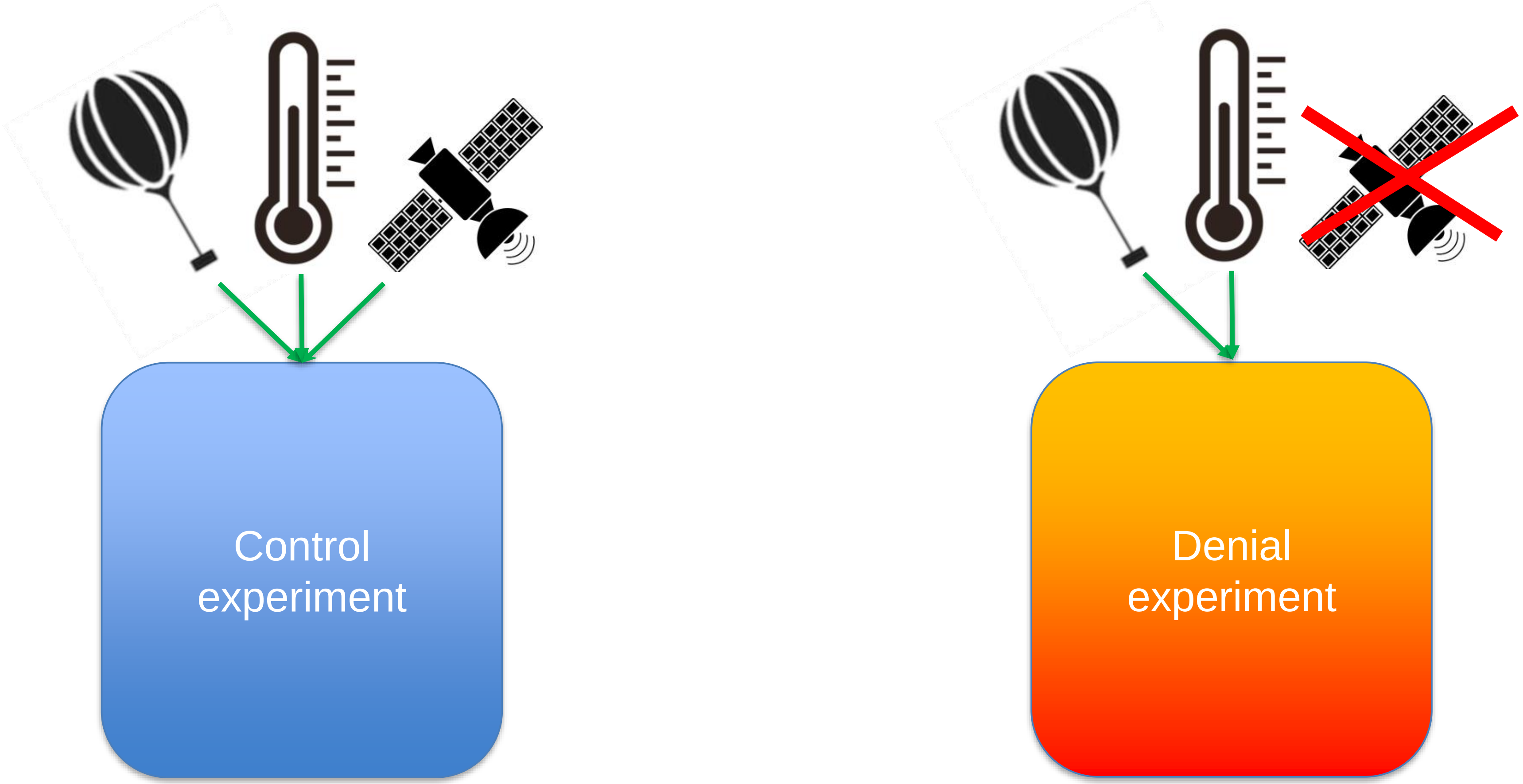
- Justify investment in the global observing system

- Inform evolution of the global observing system

Outline

1. **Introduction: OSEs and FSOI**
2. **Current impact of various observing systems at ECMWF**
   - OSEs, FSOI
3. **Using DA systems to guide the evolution of the global observing system**
   - OSEs, OSSEs, EDA simulations
4. **Other aspects of forecast impact - what else can OSEs tell us?**
   - Examples from recent polar OSEs

How do we evaluate the forecast impact of observations?
Observing system experiments (OSE)



Observing system experiments (OSEs) - features

Address the question: What happens if we didn't have a certain observing system?

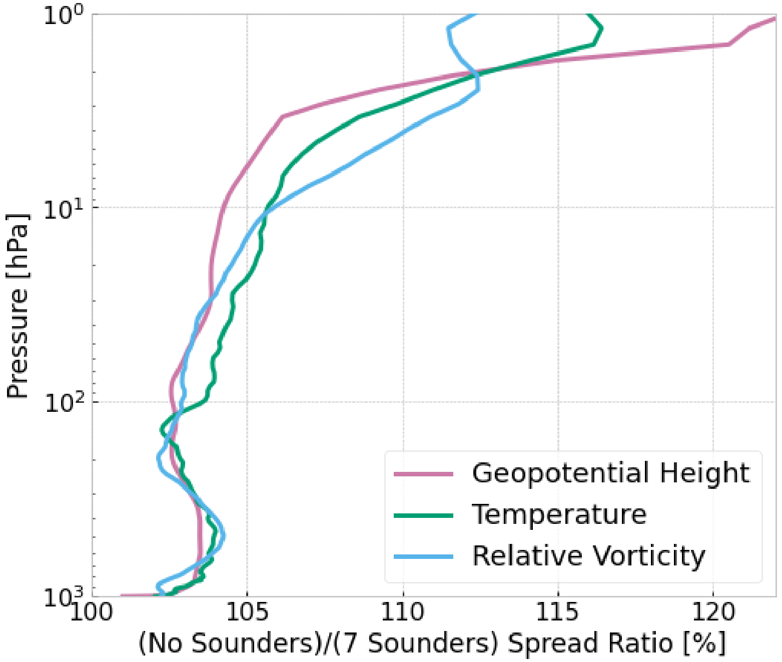
- Allow verification for all variables/ levels/regions/features, etc
- Free choice of verification reference.
- Allow measuring impact at all forecast ranges, thus capturing non-localised impact.

- Expensive – unaffordable to study impact of individual observations or satellite channels.
- Results depend on how good the control system is.
- Major data denials may require re-evaluation of background errors, which is even more expensive.

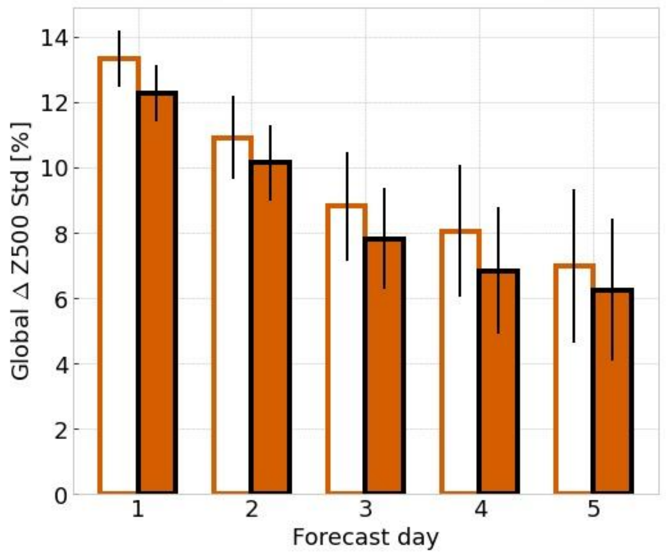
Influence of updating background errors in OSEs
Example of an OSE with 7 MW sounders

- A change in the observing system will change the size of the errors in the background, estimated through an Ensemble of Data Assimilations (EDA).
- Two tailored EDAs used for specification of B:
  - Full system with 7 MW sounders
  - No MW sounders
- Impact from denying the observations appears slightly larger when the inconsistent B is used.

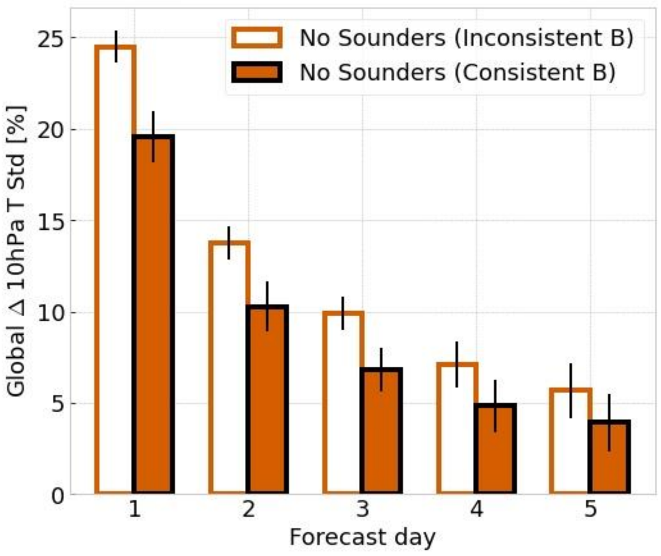
Larger Ensemble Spread (→ B) for No MW Sounders EDA



Global Z500



Global 10hPa T



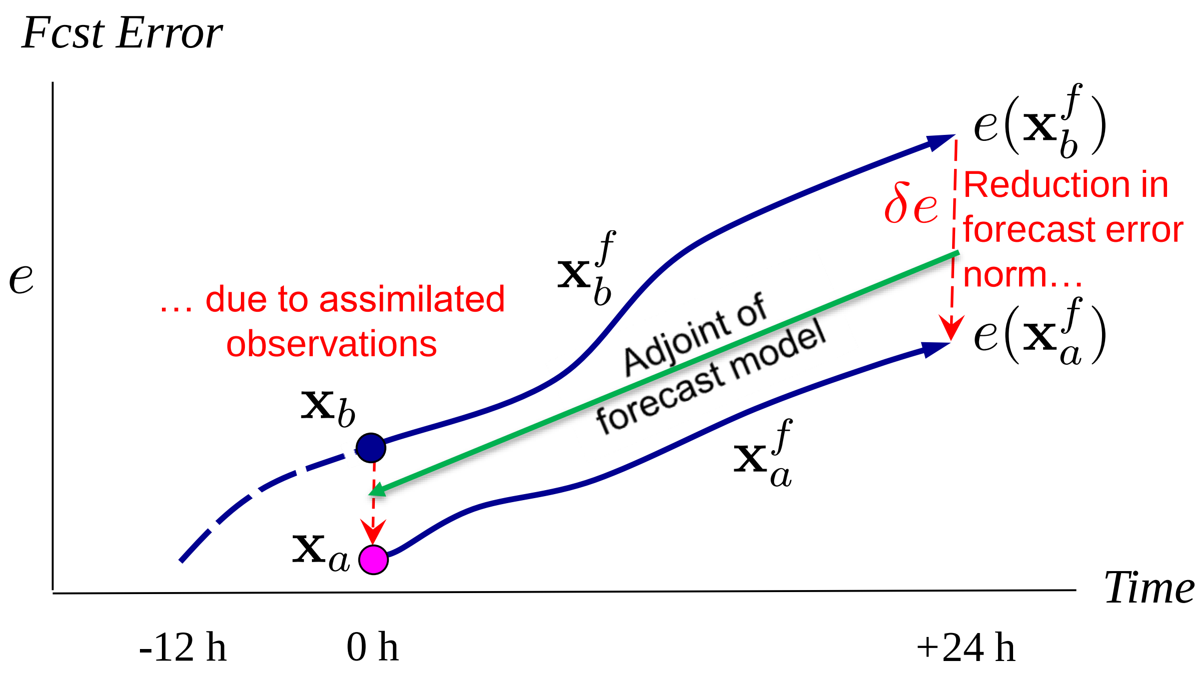
Effect of updating B for an OSE of this size is comparatively small.

(Duncan et al 2021)

How do we evaluate the forecast impact of observations?
Forecast Sensitivity Observation Impact (FSOI)

What did a particular sample of observations contribute in the given DA system?

- Estimates how *individual observations* contribute to reducing short-range forecast errors.
- Defined for a specific error norm e
  - Typically global dry or moist total energy norm
  - Forecast minus analysis
- Reduction in the error norm for 36h vs 24h forecast valid at the same time is:
  - propagated backwards in time using the adjoint of the forecast model,
  - mapped onto individual observations using the "inverse" of the assimilation system



(e.g., Langland and Baker 2004, Cardinali 2009)

Forecast Sensitivity Observation Impact (FSOI) - features

Address the question: What did a particular sample of observations contribute in the given DA system?

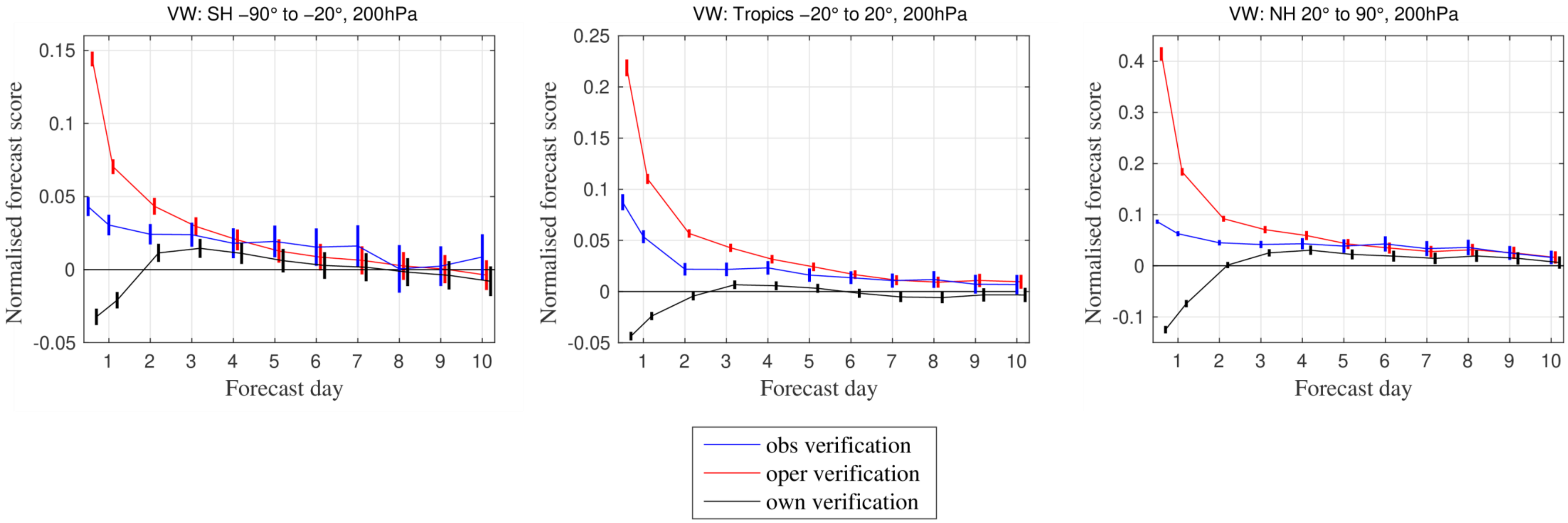
- Allows affordable detailed analysis for multiple observation types in one go.
- Allows routine monitoring.
- Can help identify cases/regions etc for further study.

- Evaluates impact in the current run – does ***not*** answer the question "what if we do not have this data type?"
- Can only be used for short-range forecasts (0 to 48 hours) – relies on linearised model.
- Requires prior choice of verification metric.
- Results depend on how well-tuned the system is. Poorly tuned systems can give misleading results (e.g., poor obs error settings).

(see also CGMS-46-WMO-WP-13: ECMWF position paper on OSE vs FSOI)

Role of the verifying reference

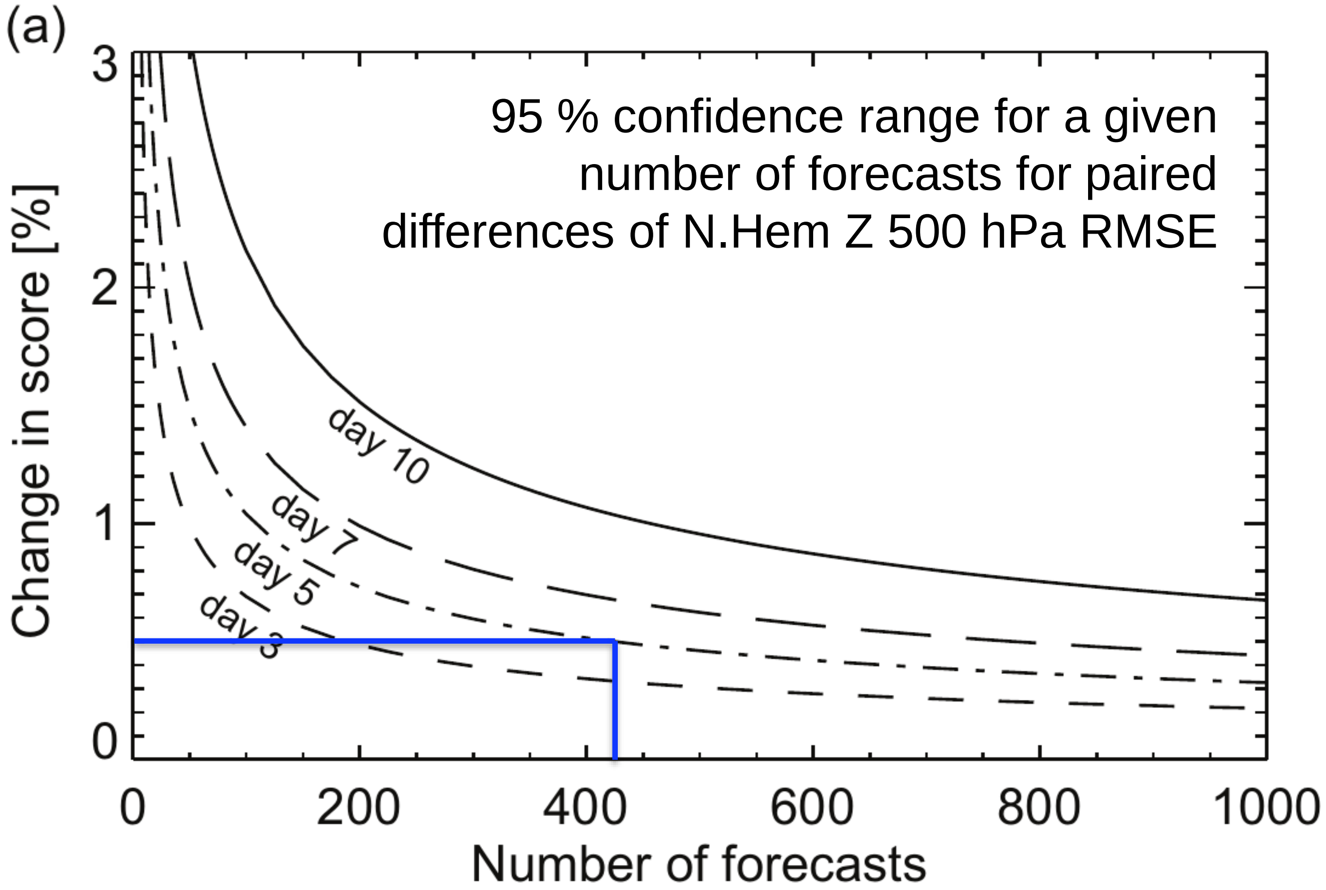
- Assessing forecast impact relies on a verifying reference.
- Ideally, the reference is available everywhere and highly accurate, with errors that are independent and small compared to forecast errors.
  - This is often not the case, especially for short-range forecast verification against analyses.
  - **Different references can give very different impressions of impact. E.g., denial of in-situ observations:**



(Bormann et al 2019)

Role of sampling – when are results statistically significant?

- Forecast scores are affected by chaotic variability.
- Need many forecasts to achieve statistically robust results – particularly for longer-range forecasts.
- Need to indicate statistical confidence in scores.



Geer (2016)

Current impact of various observing systems at ECMWF

- OSEs, FSOI

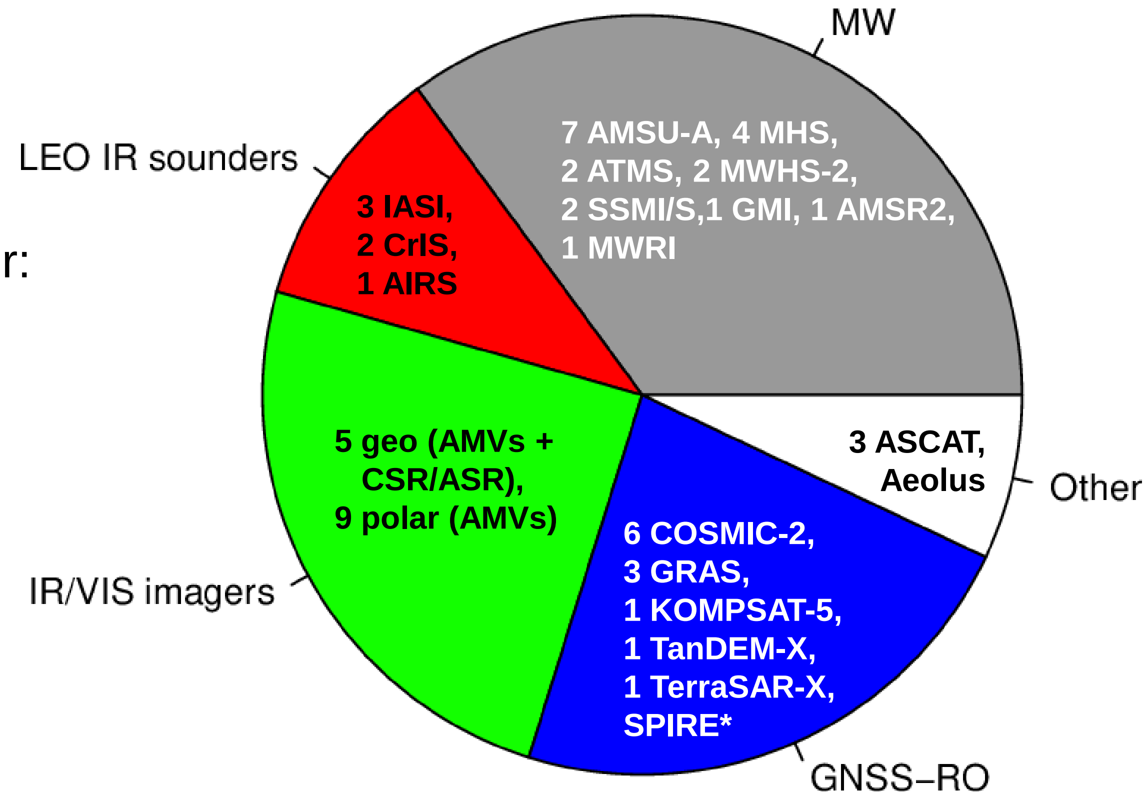
Observing system experiments

- Periods, 6 months in total:
  5 Sept – 2 Nov 2020
  1 Jan – 28 Feb 2021
  1 May – 30 June 2021
  (each + 4 days spin-up prior)

- Denial experiments compared to a full system for:
  - Conventional in-situ observations
  - MW radiances
  - IR sounders from LEO
  - IR/VIS imagers (AMVs + IR radiances)
  - GNSS-RO

- Resolution: T_{CO} 399 (~25 km)
- Background error from operational system

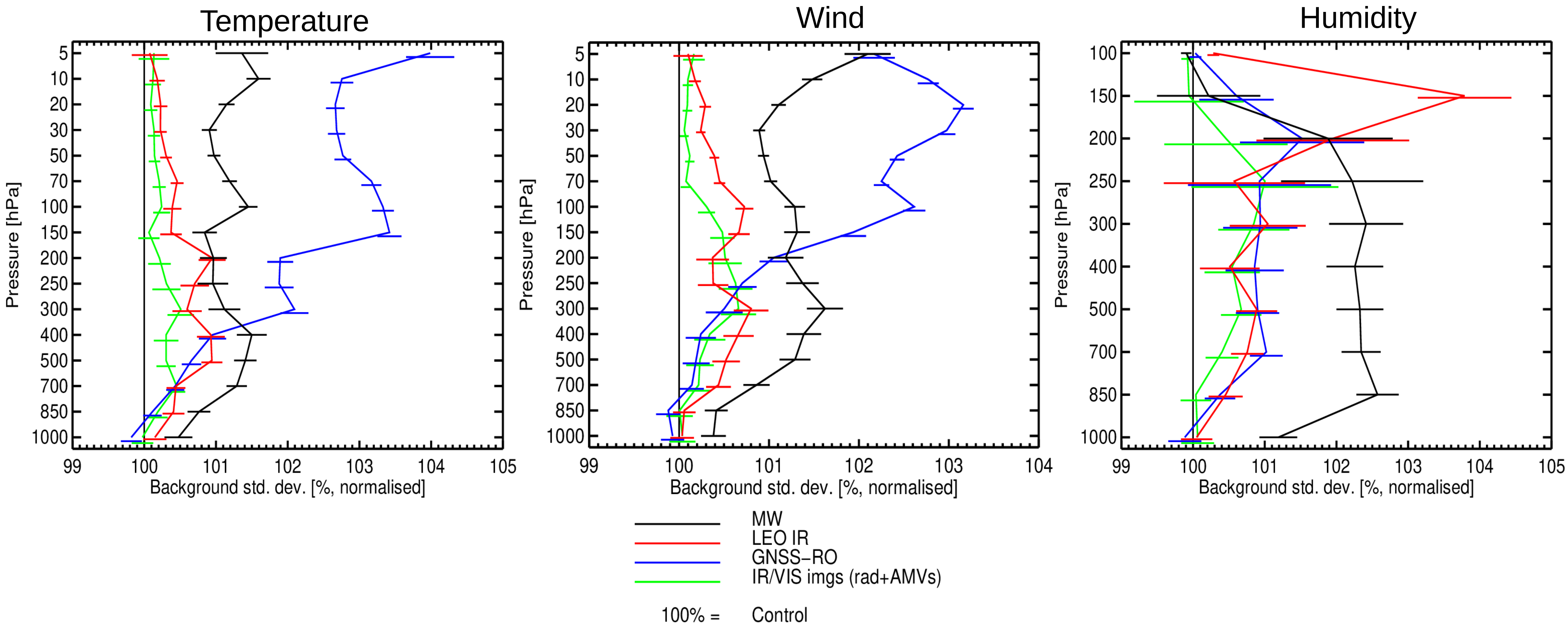
Number of assimilated satellite instruments



* SPIRE: Sept 2020 only

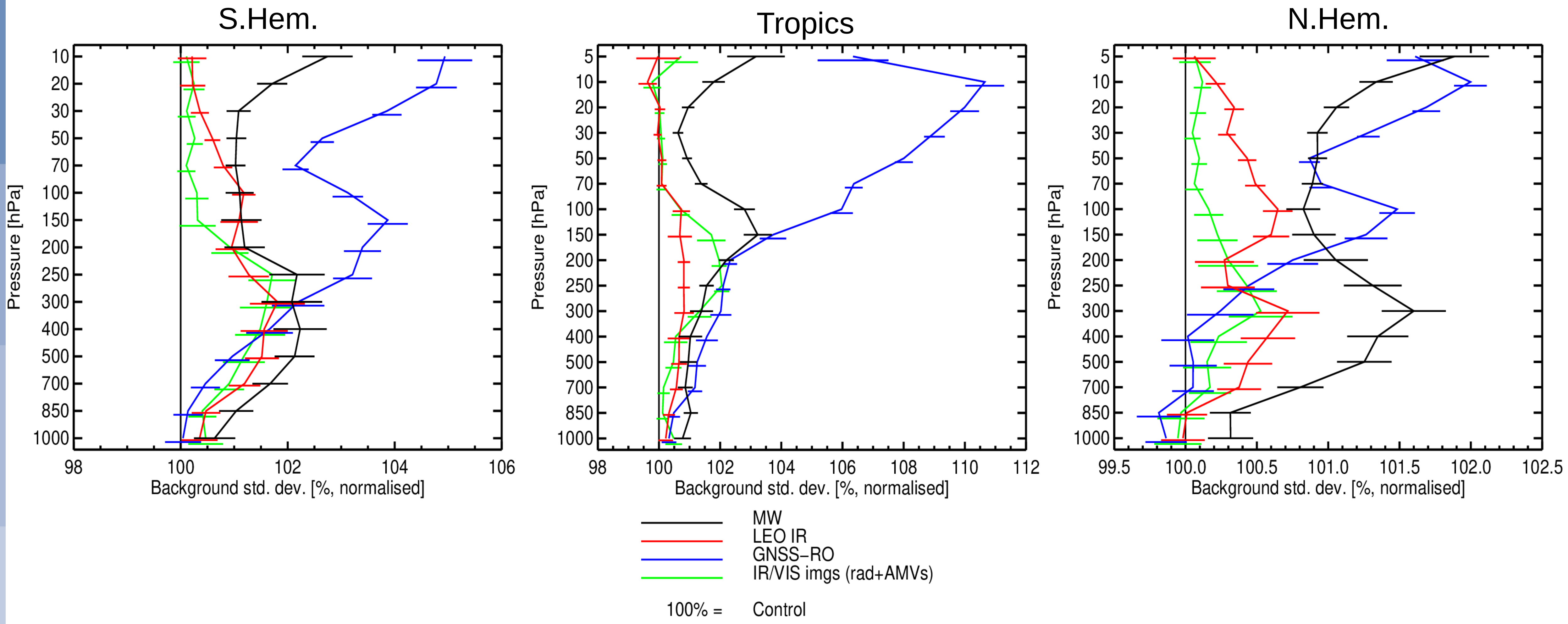
Short-range impact evaluated against in-situ observations: Stdev(o-b)

Global, 3 periods combined



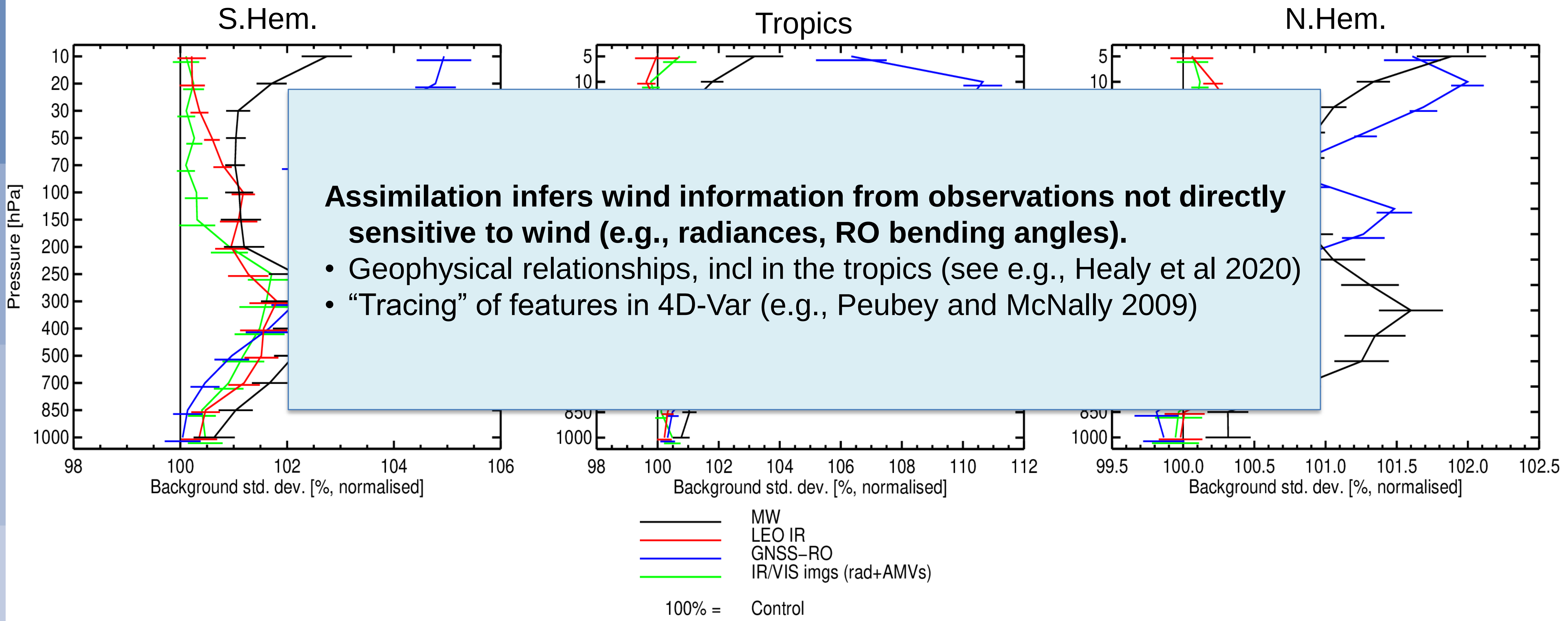
Short-range impact evaluated against in-situ observations: wind

3 periods combined



Short-range impact evaluated against in-situ observations: wind

3 periods combined

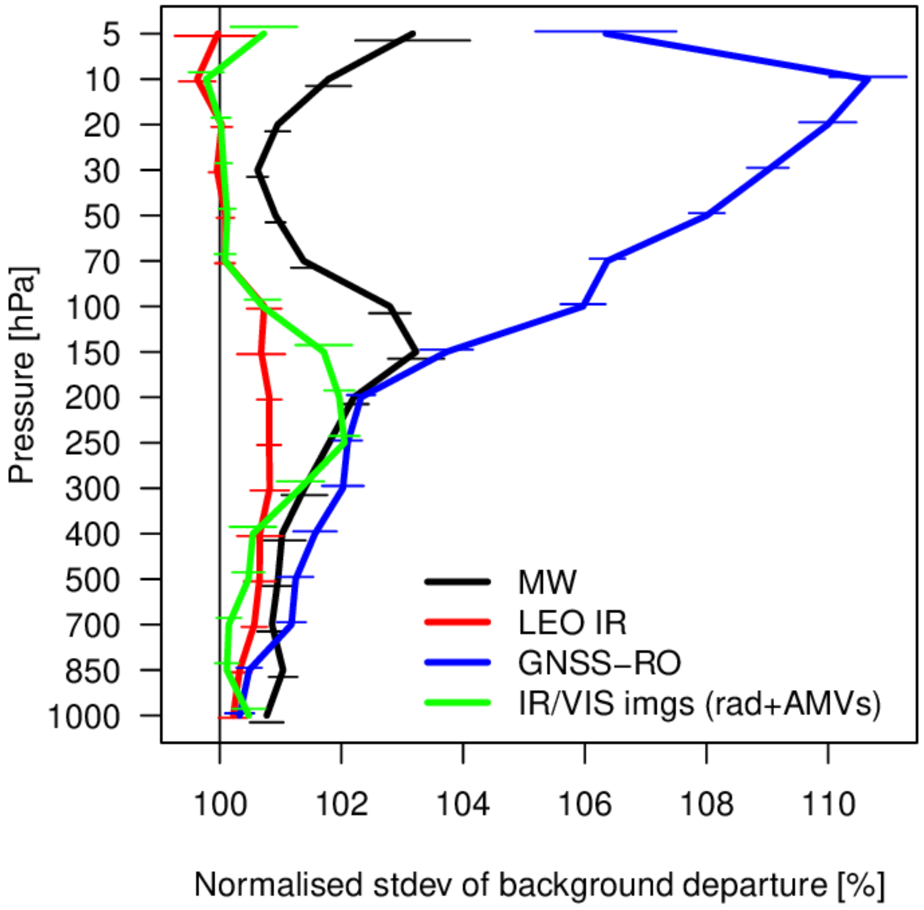


Assimilation infers wind information from observations not directly sensitive to wind (e.g., radiances, RO bending angles).

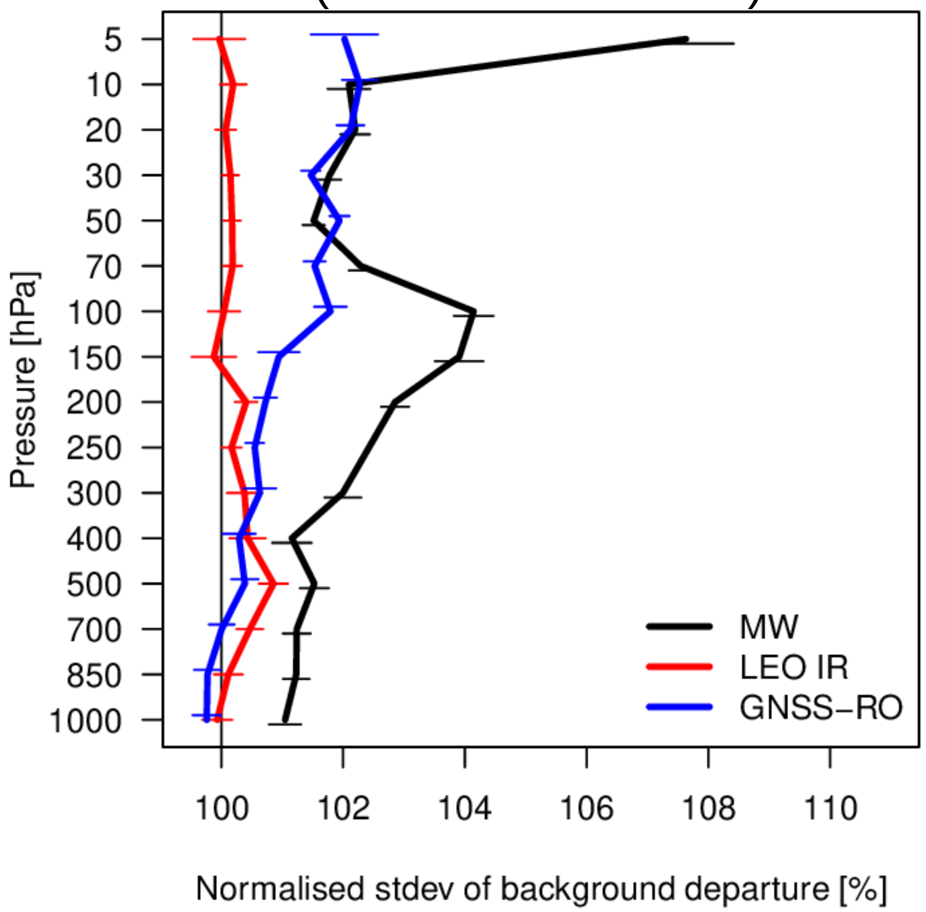
- Geophysical relationships, incl in the tropics (see e.g., Healy et al 2020)
- “Tracing” of features in 4D-Var (e.g., Peubey and McNally 2009)

Short-range wind impact in the tropics vs in-situ observations

2020/21 OSEs



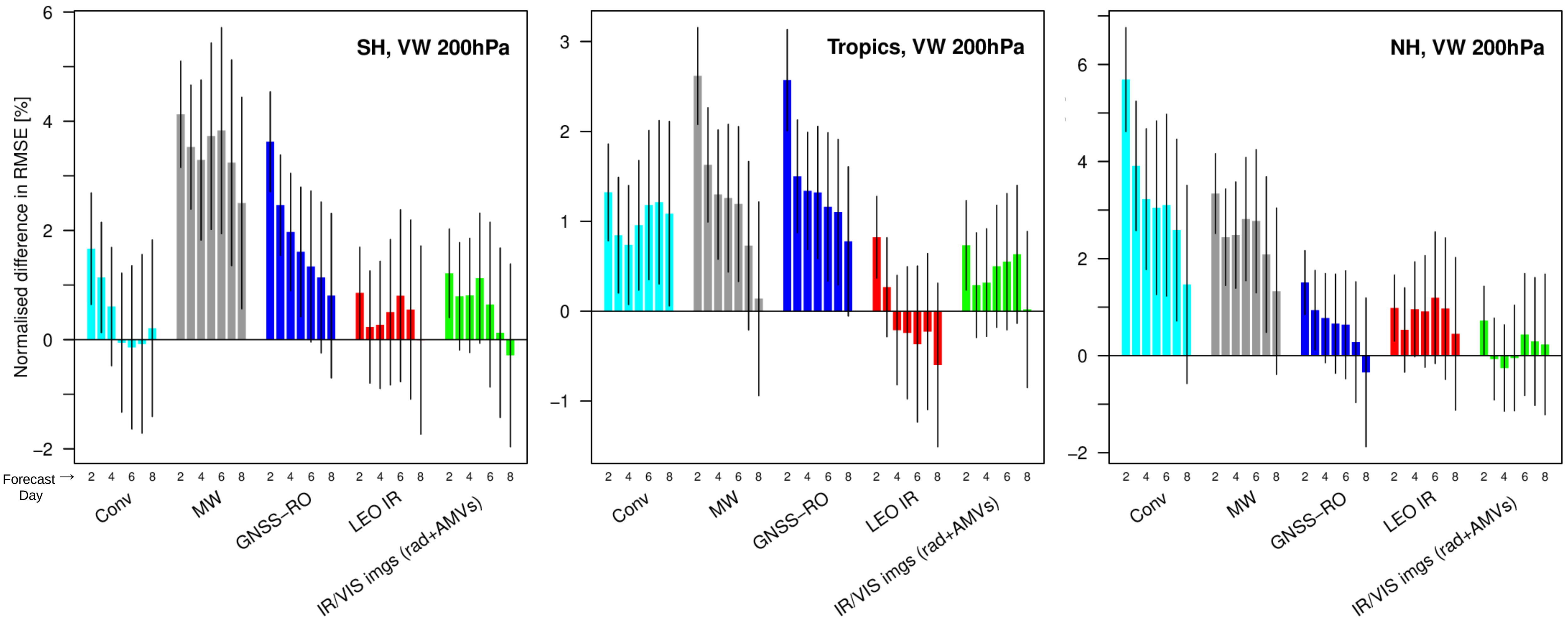
Summer 2016/winter 2017/18 OSEs
(Bormann et al 2019)



Large change in impact of GNSS-RO since the previous OSEs!

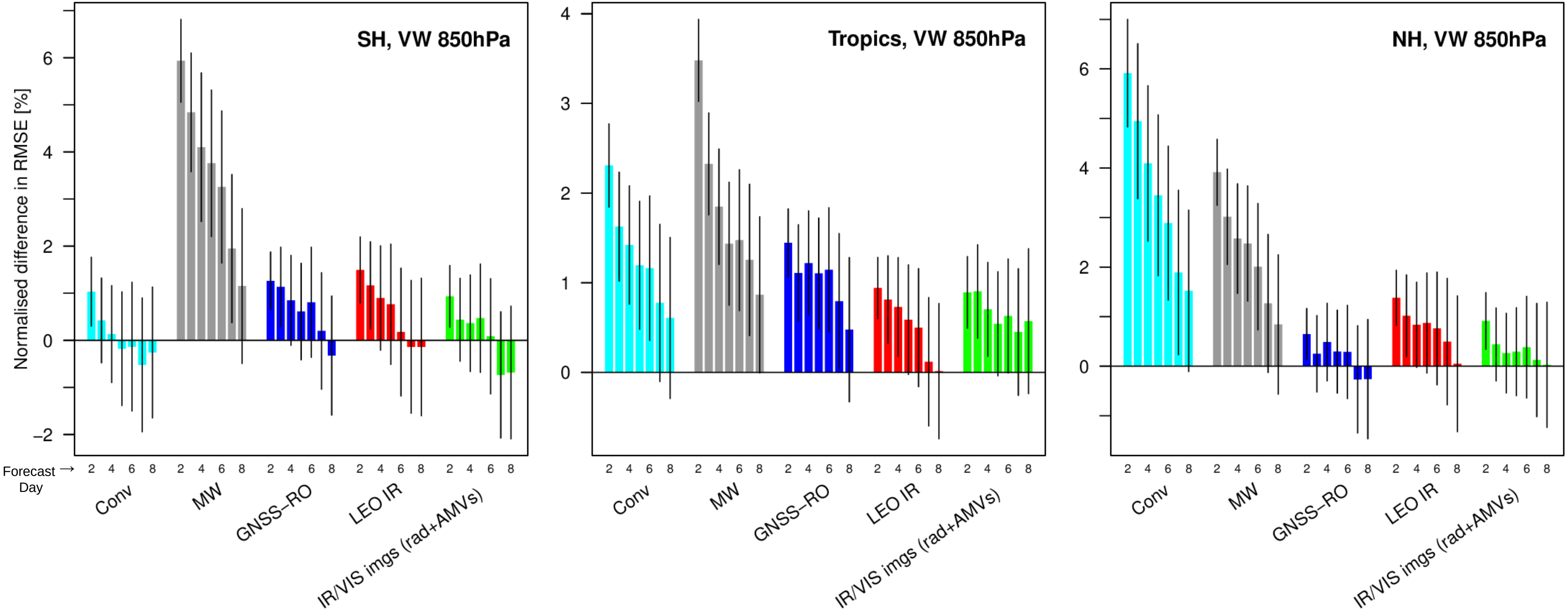
Forecast impact, day 2-8: Wind at 200 hPa

Verified against operational analyses, 3 periods combined



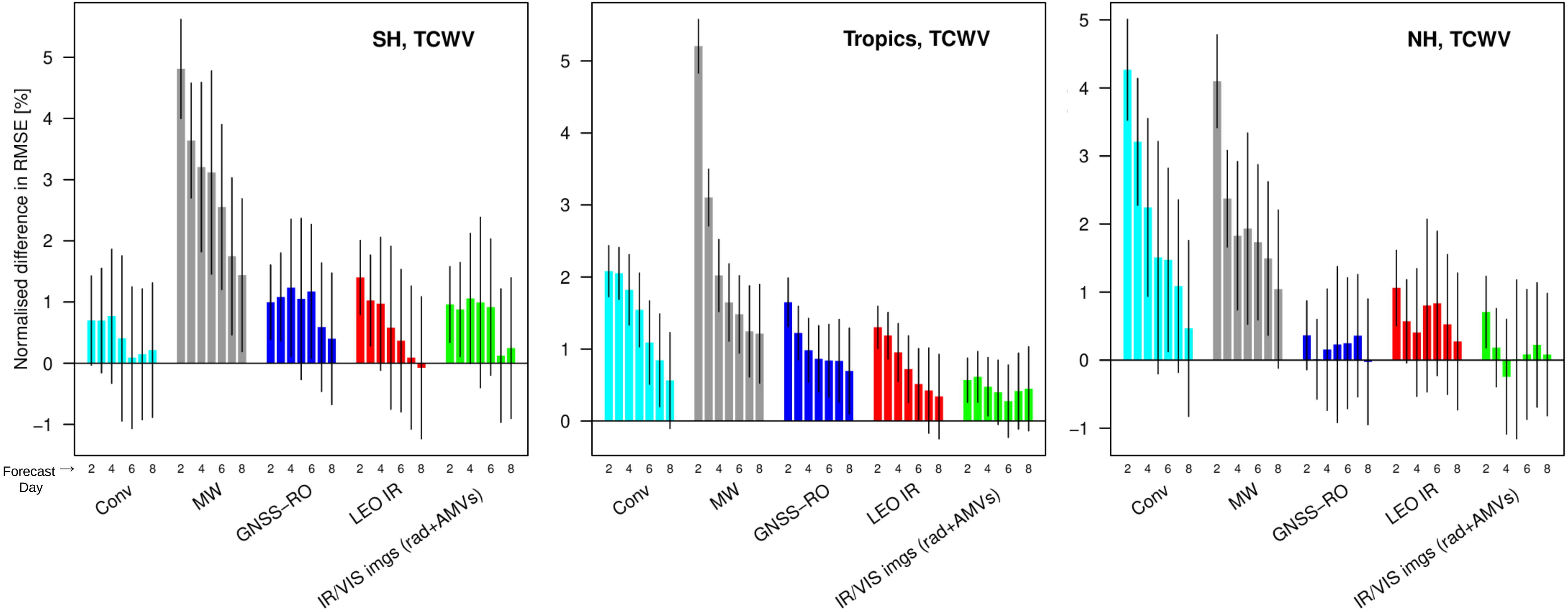
Forecast impact, day 2-8: Wind at 850 hPa

Verified against operational analyses, 3 periods combined



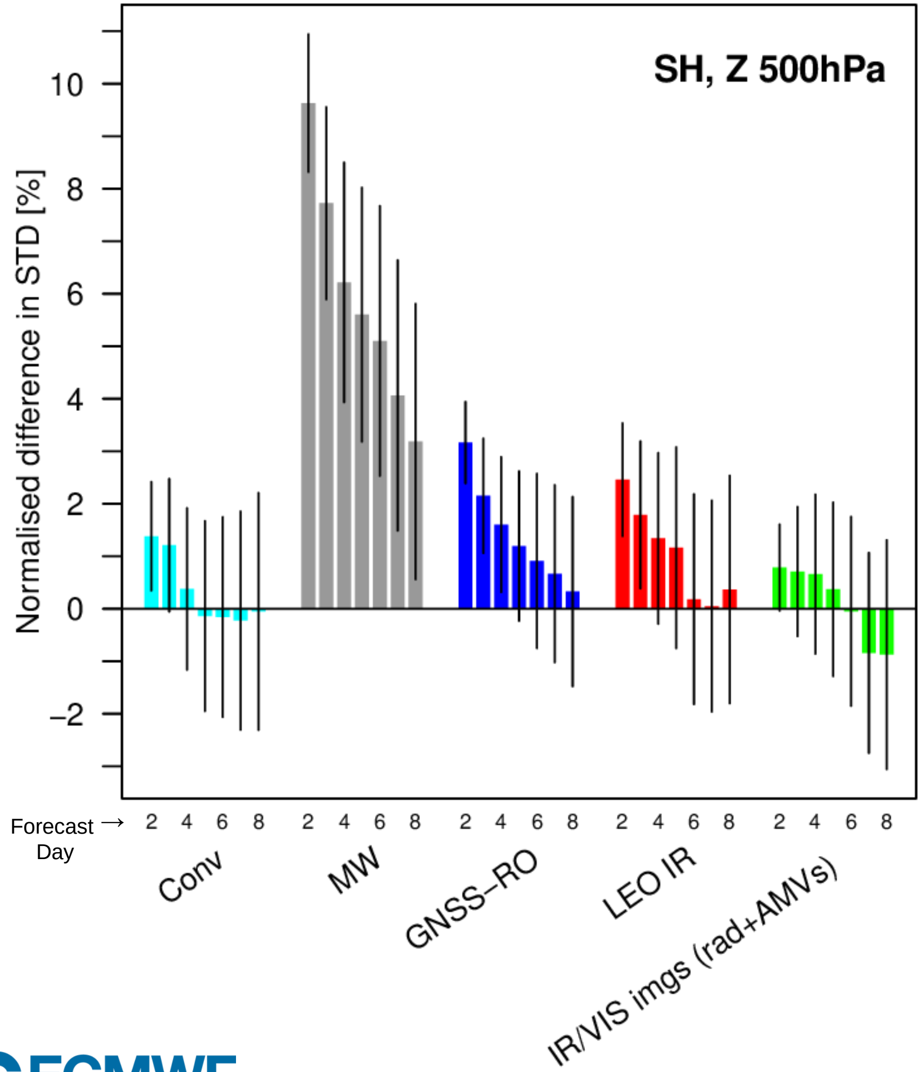
Forecast impact, day 2-8: Total column water vapour

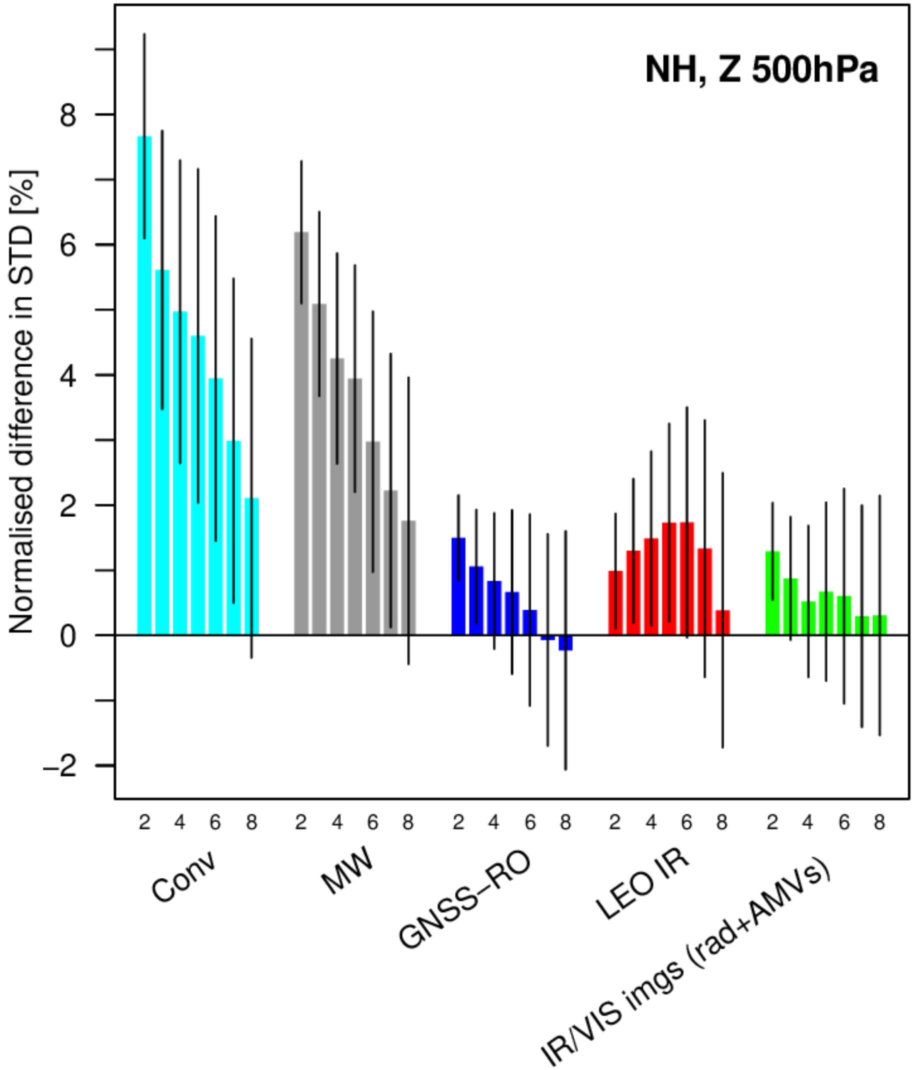
Verified against operational analyses, 3 periods combined



Forecast impact, day 2-8: 500 hPa geopotential

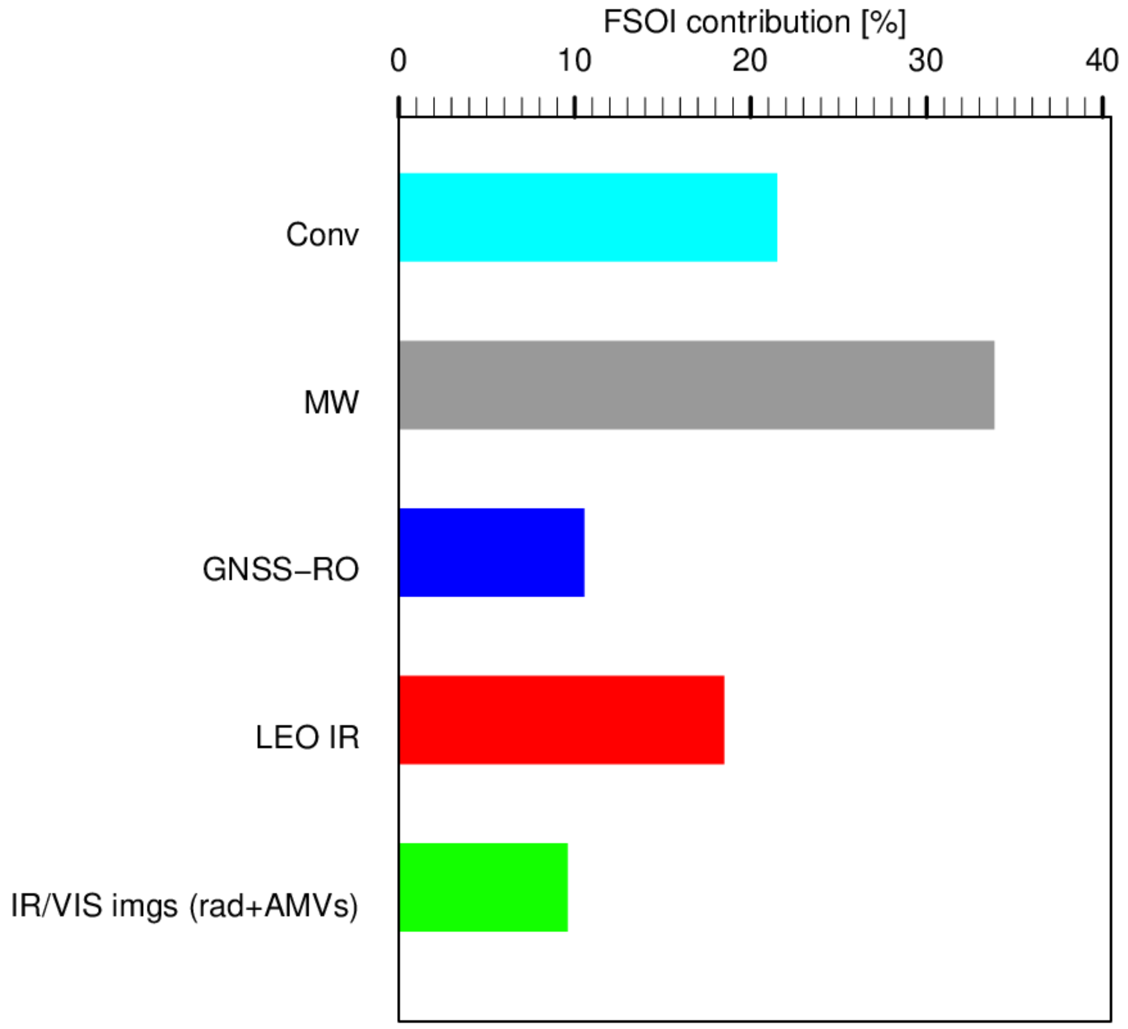
Verified against operational analyses, 3 periods combined



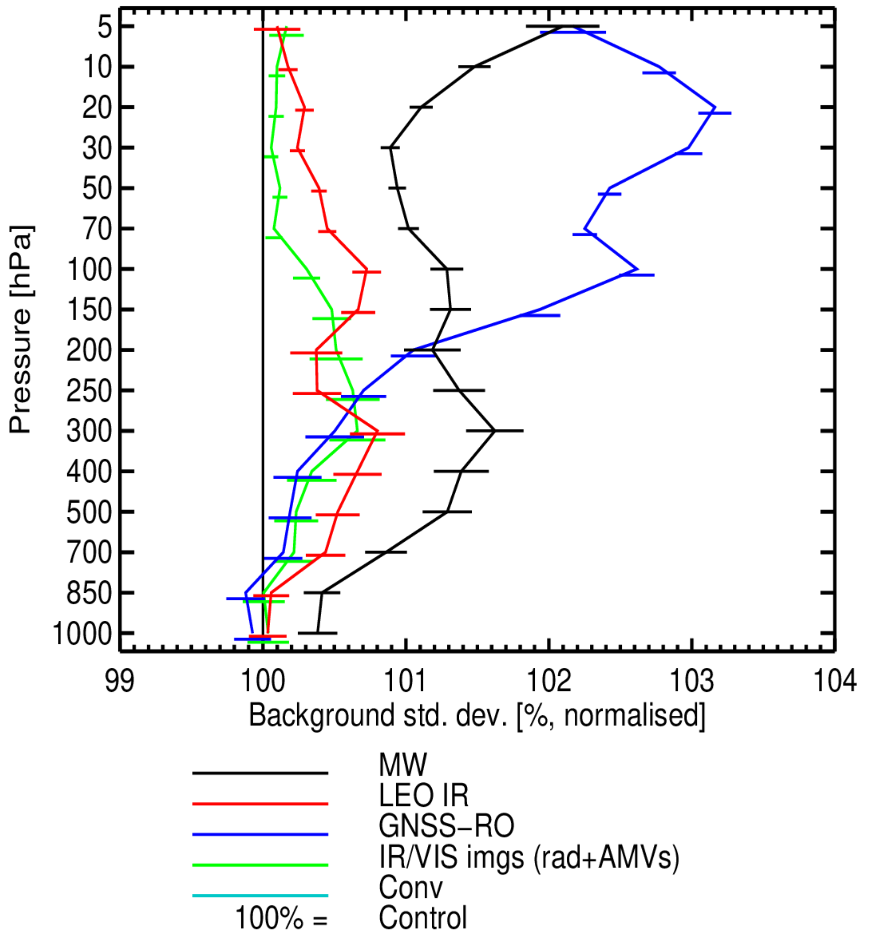


Short-range impact as estimated by FSOI

3 periods combined, operational ECMWF system



For comparison: global short-range wind impact vs in-situ observations from OSEs



Short-range impact as estimated by FSOI

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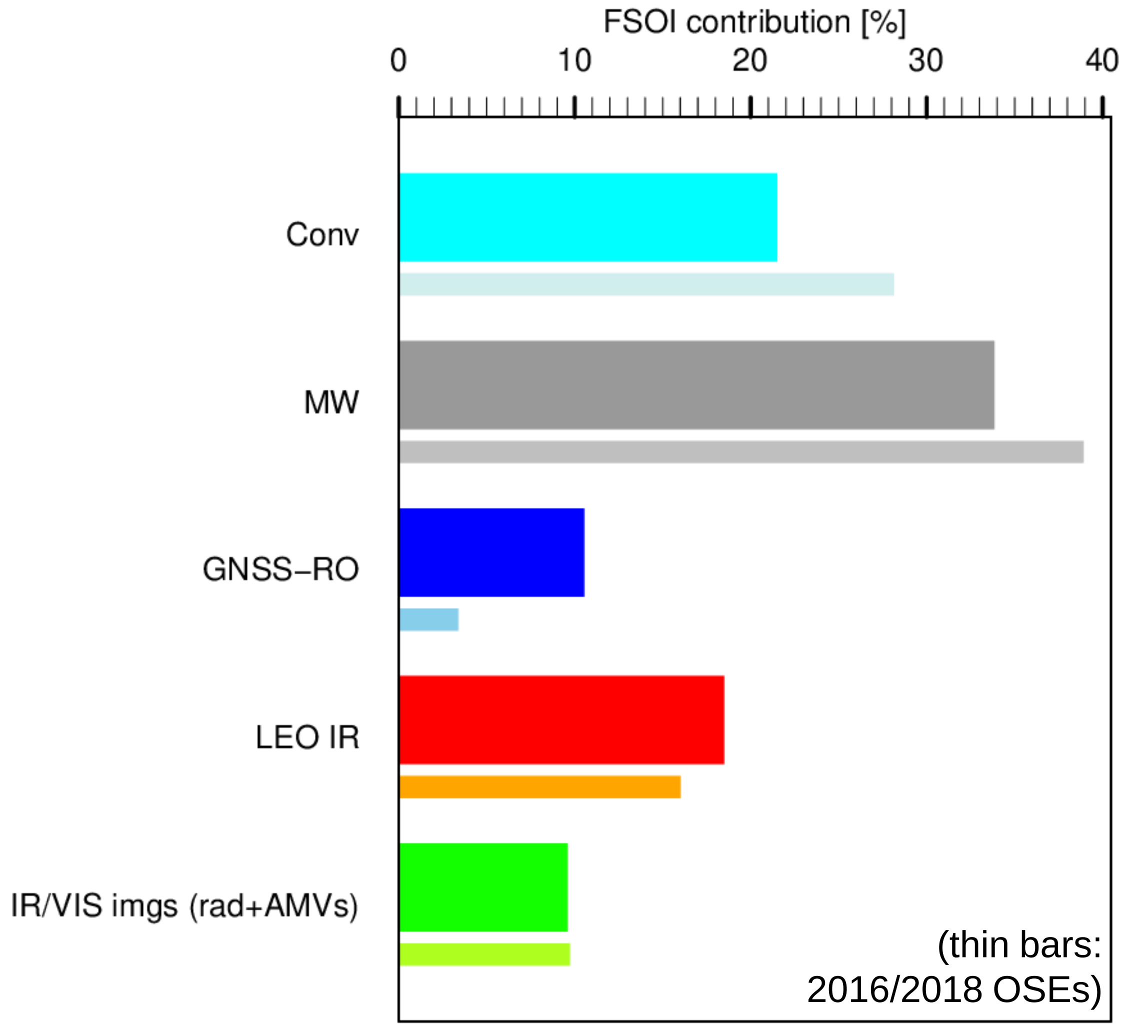
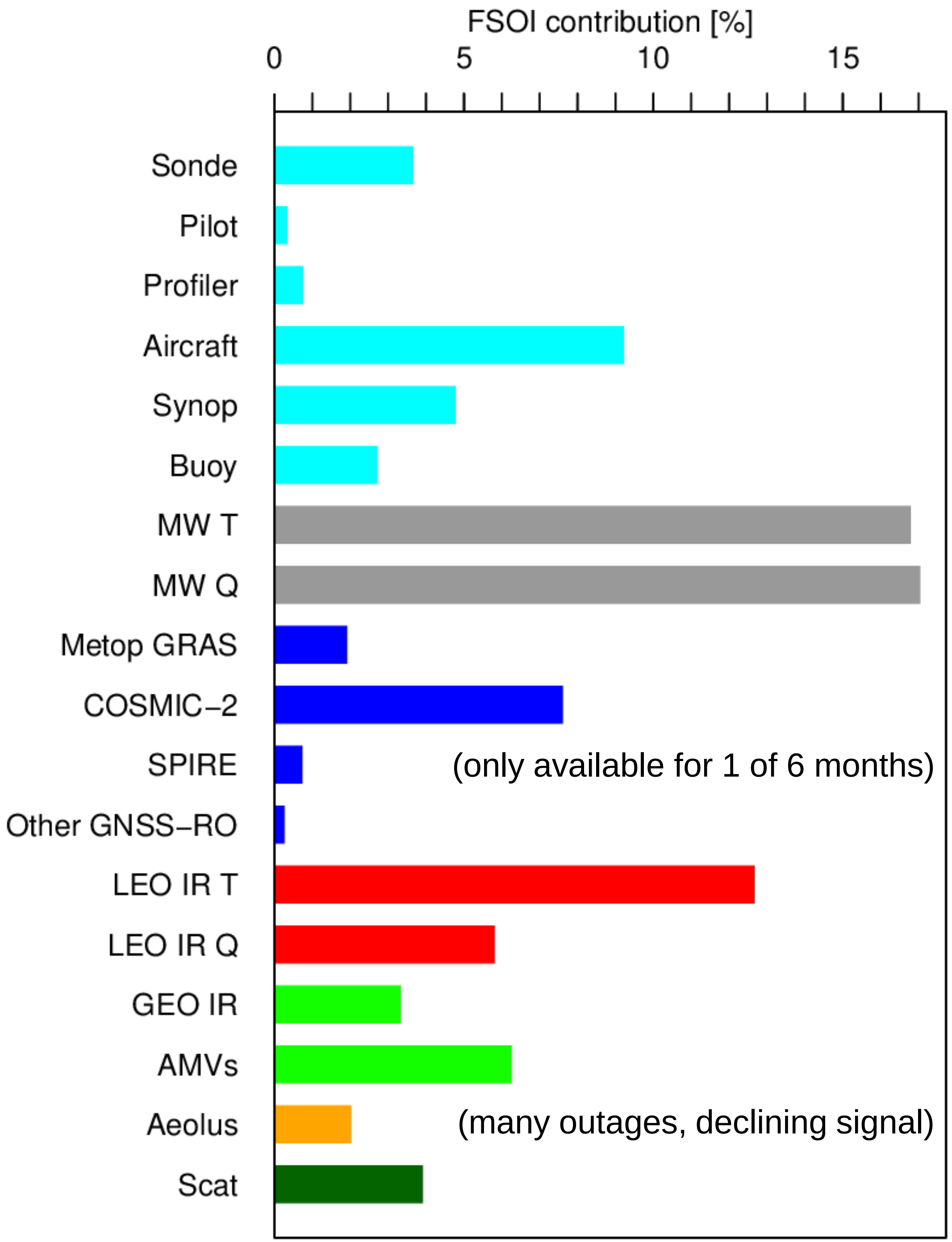


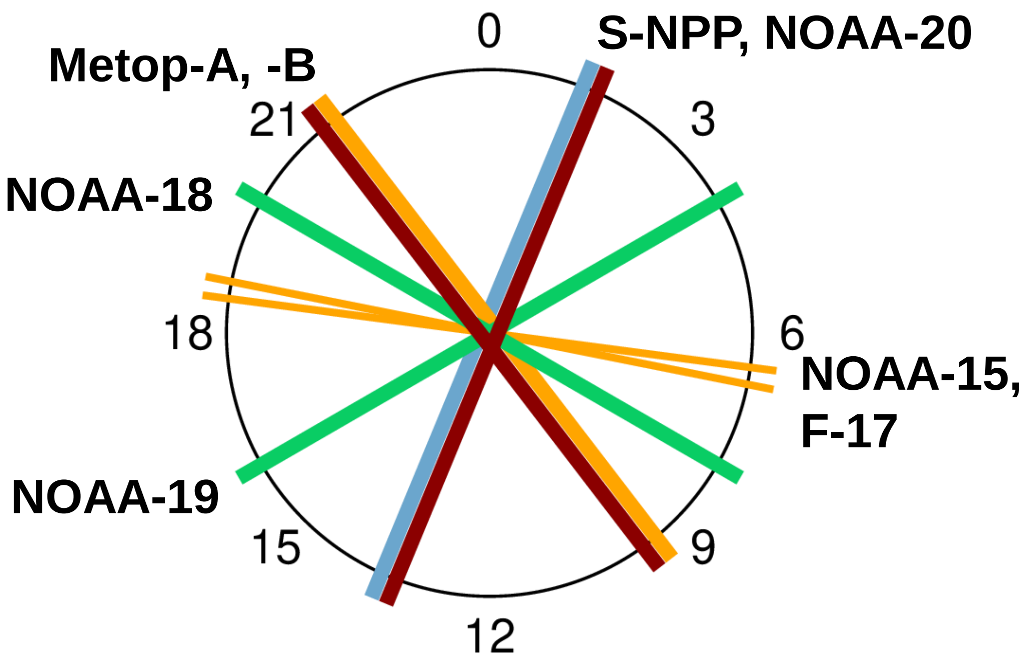


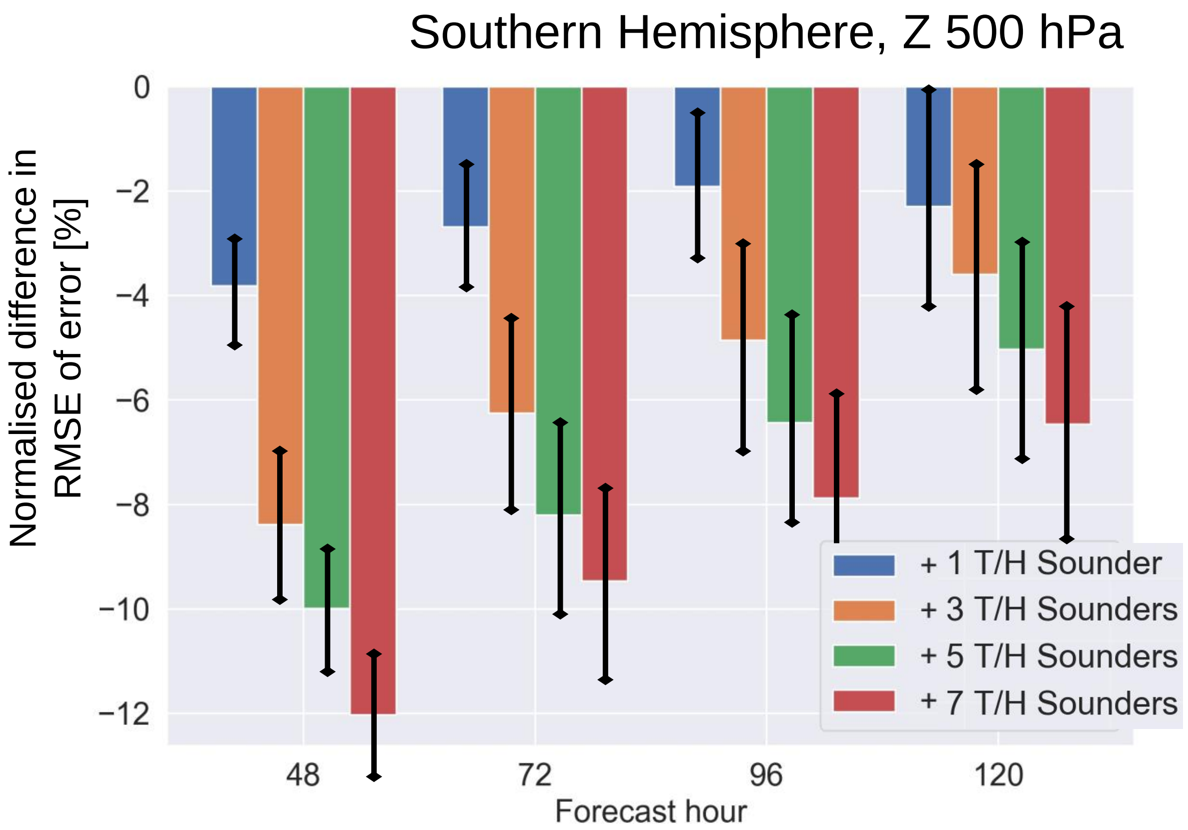
Using DA systems to guide the evolution of the global observing system

- OSEs, OSSEs, EDA simulations

Impact of MW sounders from multiple orbits/instruments

(Duncan et al 2021)





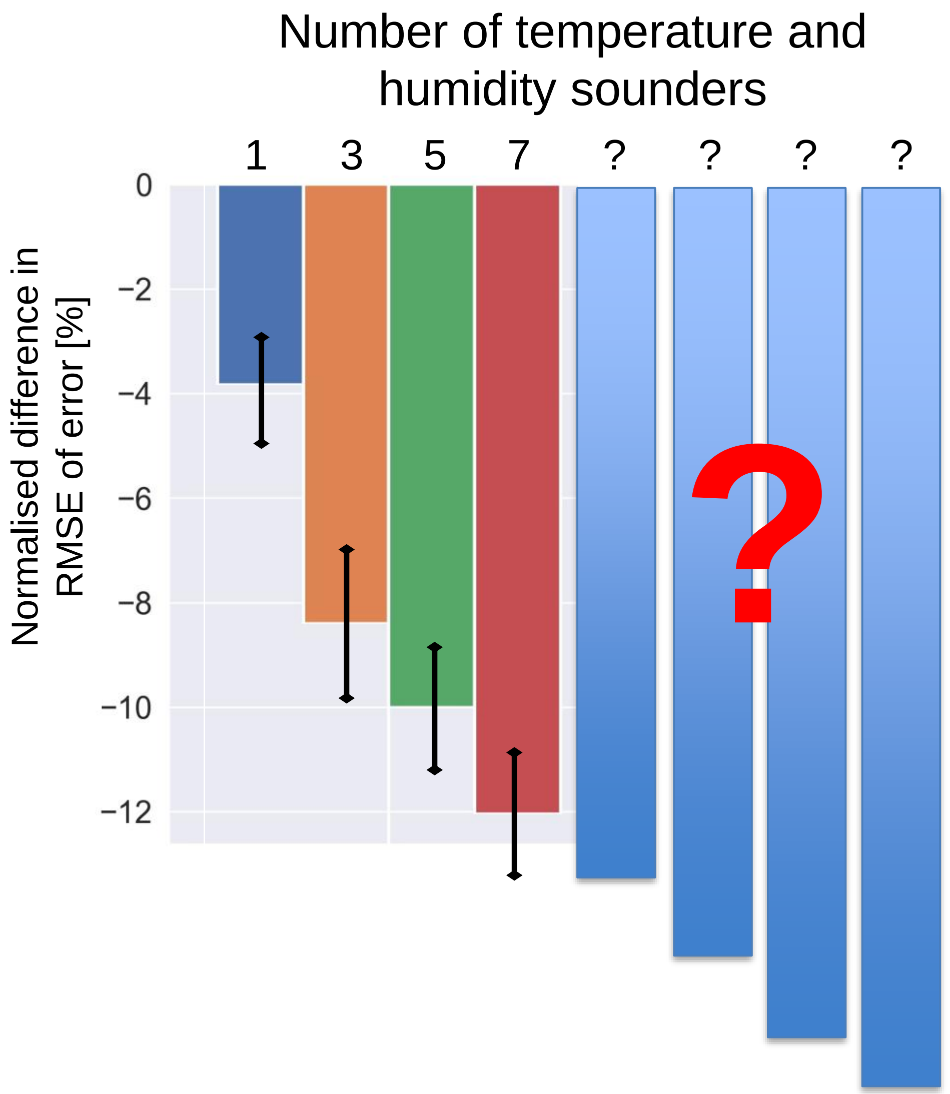
Control: Full observing system, **but no microwave sounding data**
Experiments: Control + either 1 / 3 / 5 / 7 MW sounders
Period: 1 June – 15 September 2018

Continued benefit from adding further MW sounders.

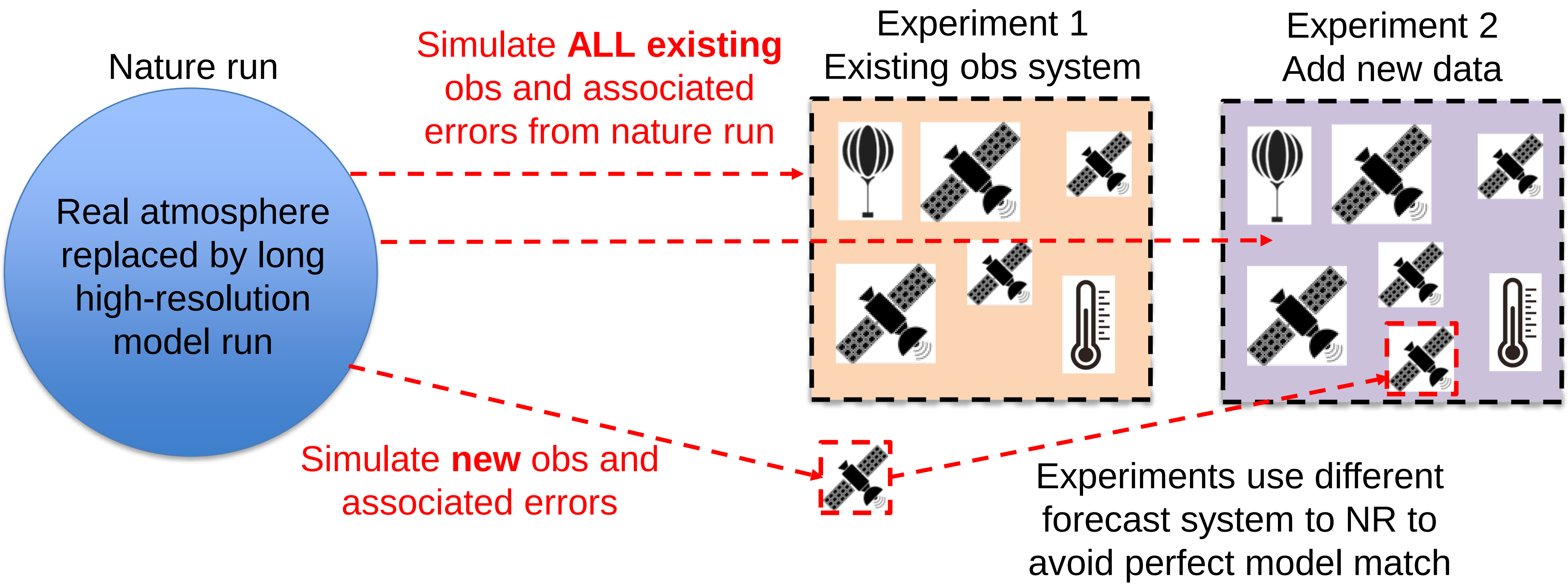
How much further benefit could we expect from more MW sounders?

- **While OSEs may give some guidance on aspects of the global observing system, they cannot estimate the benefit of observations that do not exist yet.**

- **Methods to investigate impact of future observations:**
  - **Observing system simulation experiments (OSSEs)**
  - **Simulations with Ensemble of Data Assimilations**



Observing System Simulation Experiments (OSSEs)

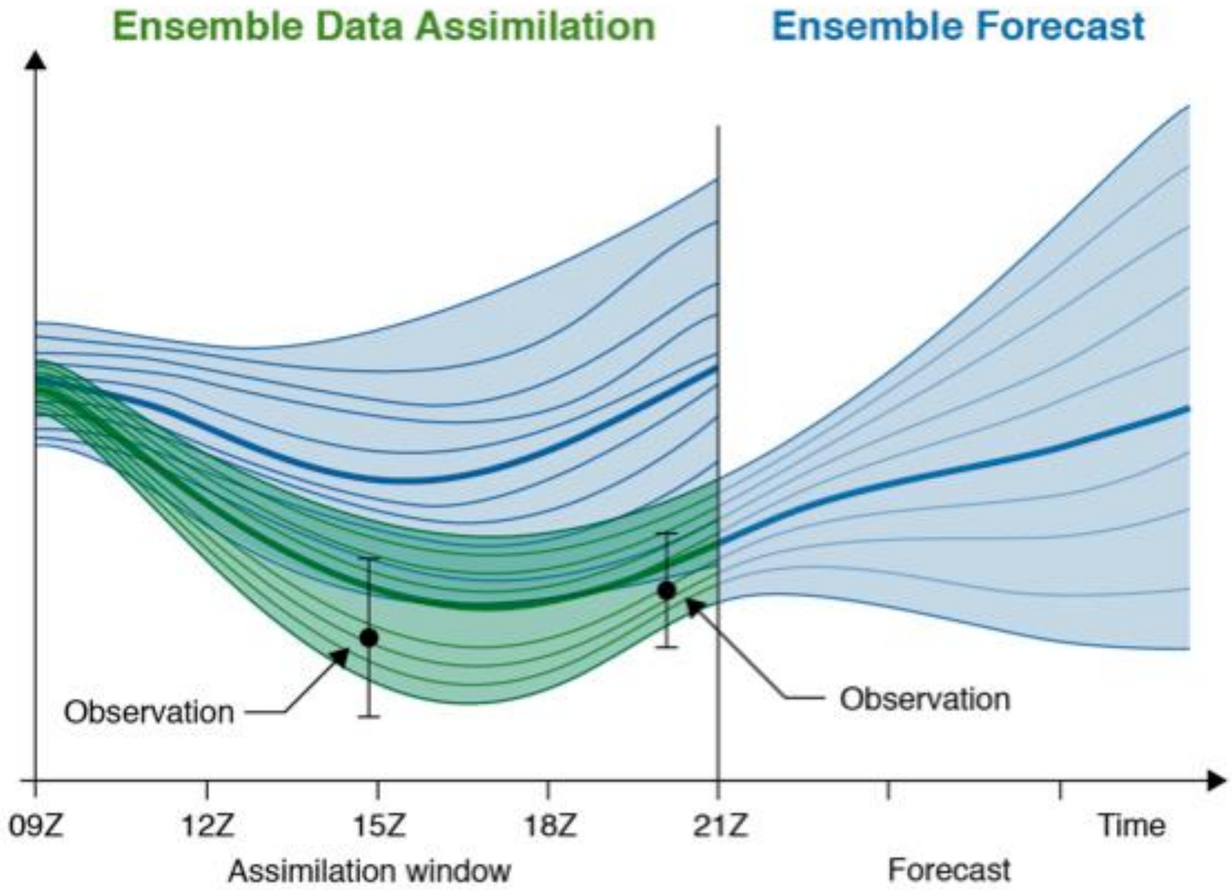


- Extension of OSEs but experiments verified against nature run “truth”
- Analysis/forecast error computed over experiment period

Ensemble of Data Assimilations (EDA) method

- EDA: Ensemble of 4D-Vars with observations, surface fields (SST) and model parameterisations perturbed according to their random error characteristics.
  - The ensemble spread is a measure of the random error in the analysis and short-range forecast.
  - Used operationally to specify flow-dependent background errors.

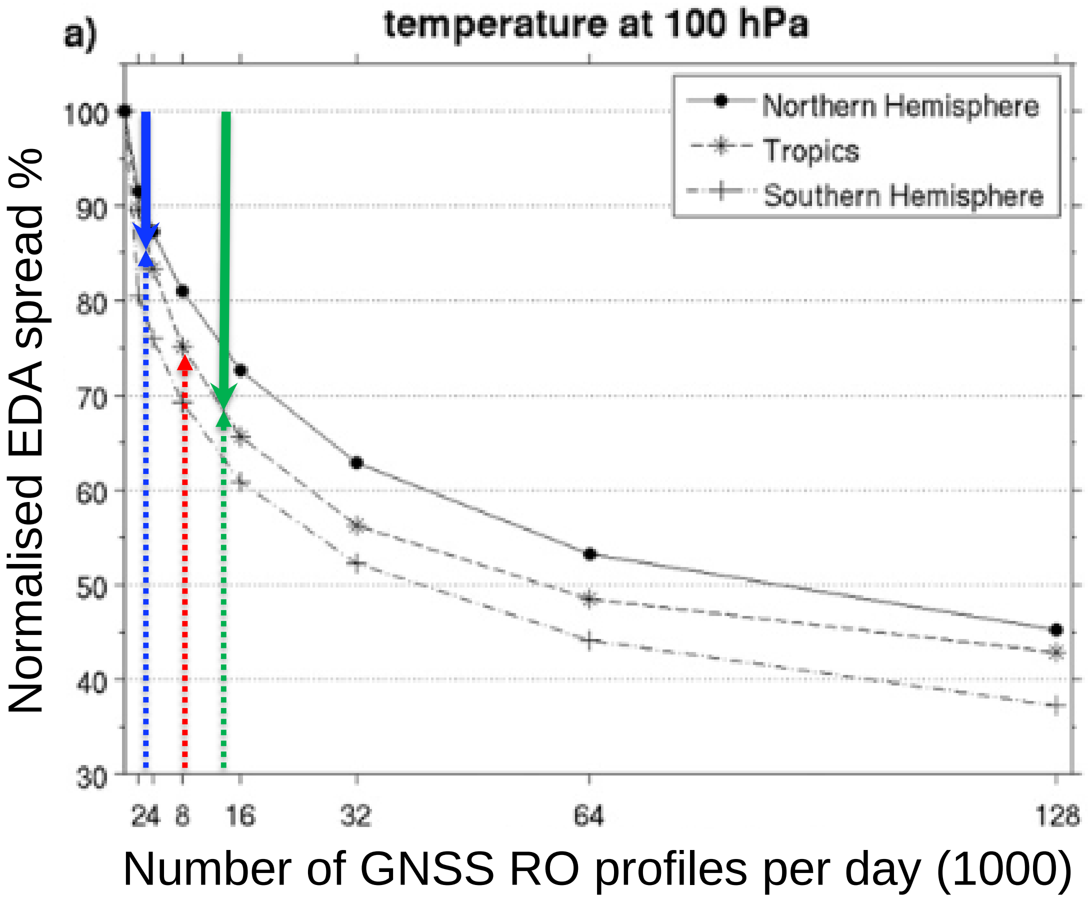
- To estimate the impact of **future observations**, we can use the EDA with **existing real observations plus simulated future observations**.
  - Measure of impact: change in ensemble spread (provided the errors are realistic)
- Used in the past for Aeolus and GNSS RO.



Example of using the EDA method: GNSS RO

- 8 years ago: How much further benefit could we expect from more GNSS RO observations?

Prediction with EDA: Harnisch et al (2013)



Reality in 2020

Significant increase in the number of assimilated GNSS RO profiles in 2020:

- Start of 2020: ~ 3000 profiles per day
  (from Metop, KOMPSAT-5, TanDEM-X,TerraSAR-X)
- March: + ~5000 profiles per day from COSMIC-2
- May: + ~5000 profiles per day from Spire
  (until 30 Sept 2020)

Example of using the EDA method: GNSS RO

(Chris Burrows, Katrin Lonitz, Sean Healy)

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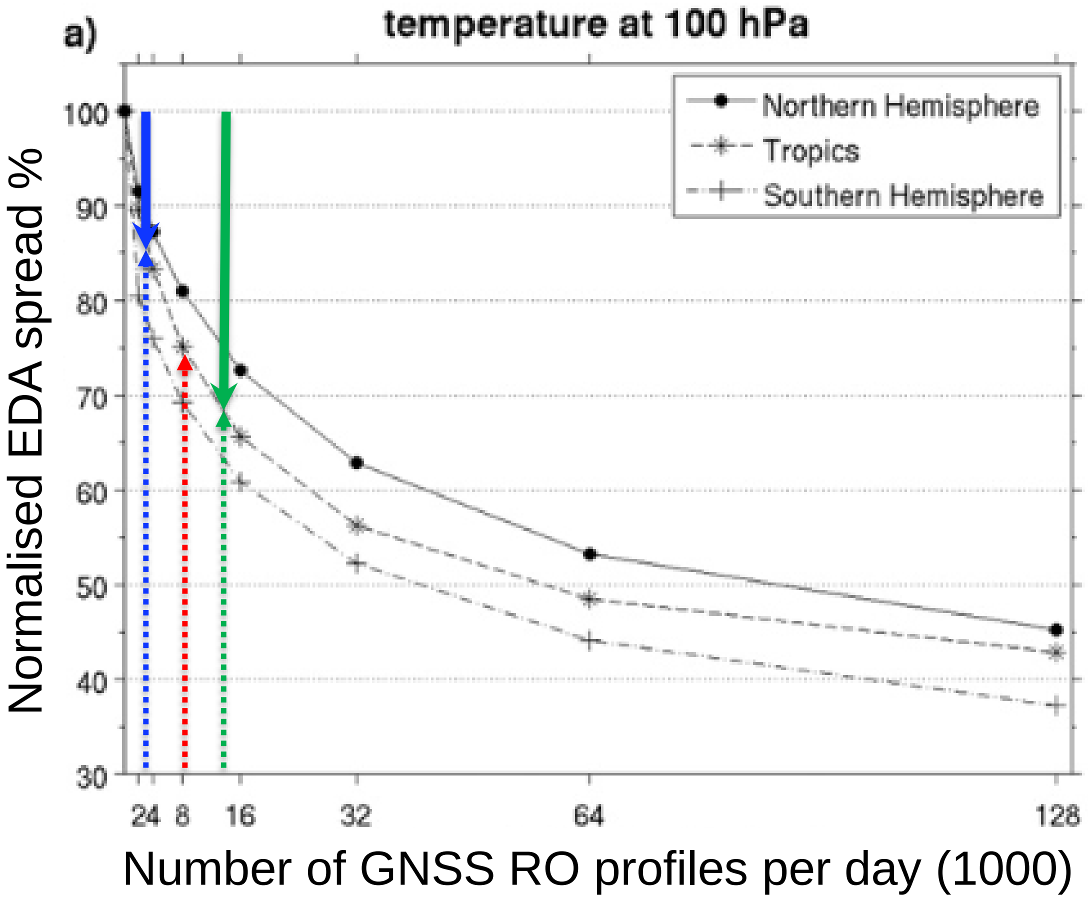
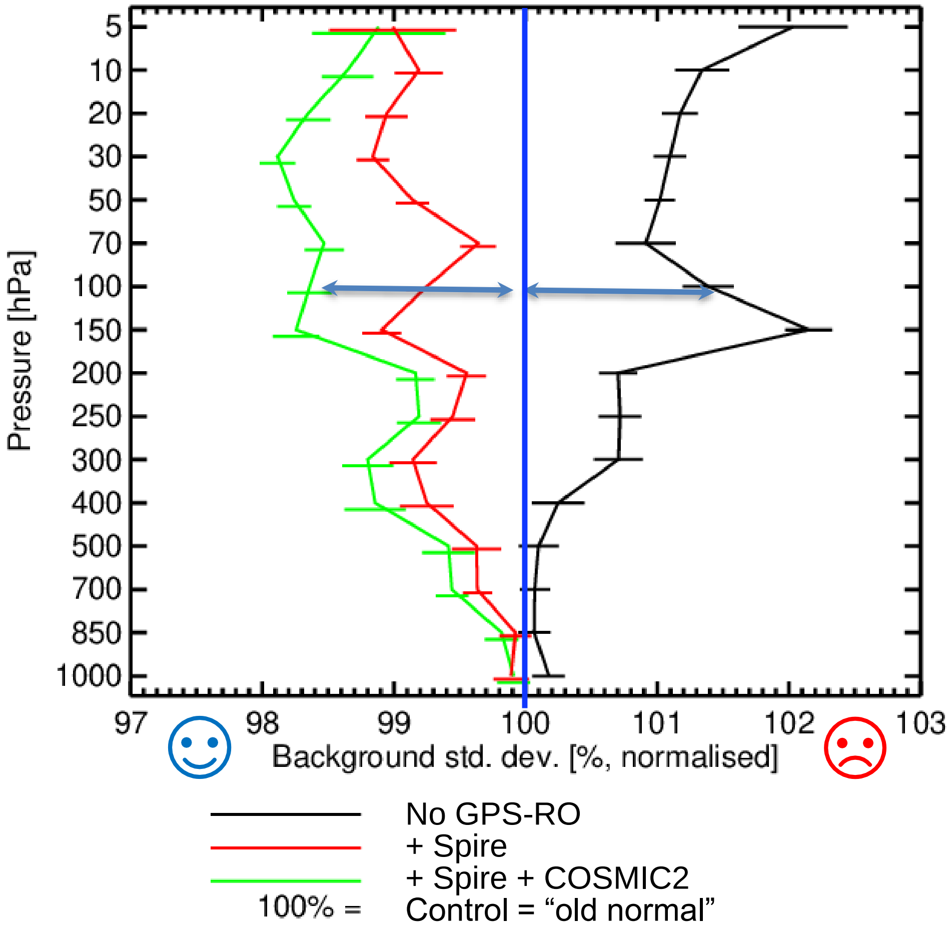


Reality in 2020

Radiosonde temperatures, global, (1 Jan – 31 March 2020)



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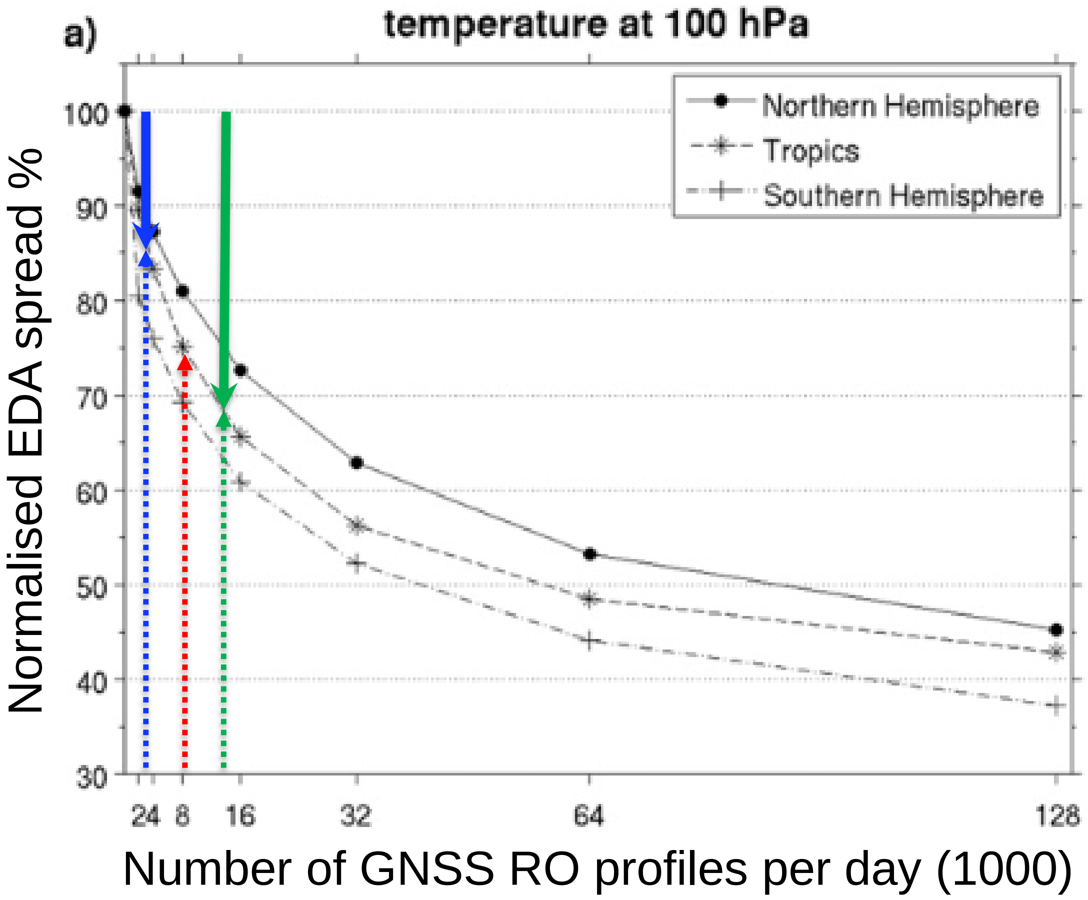
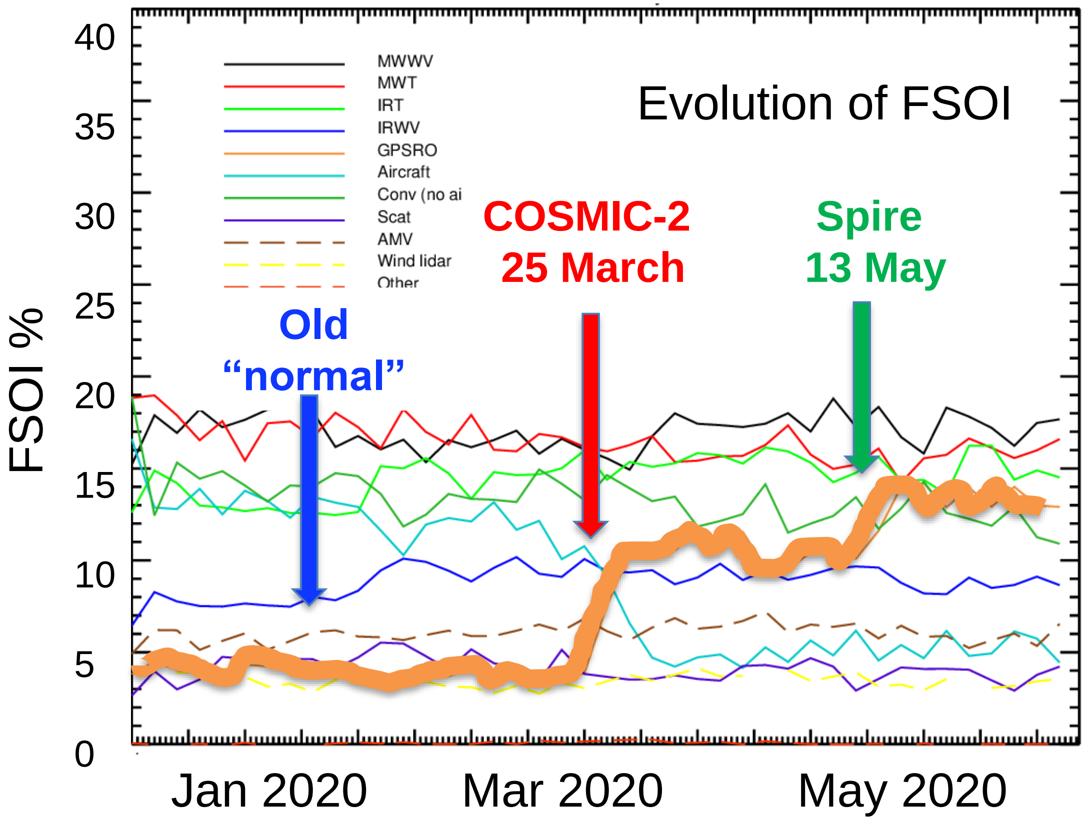
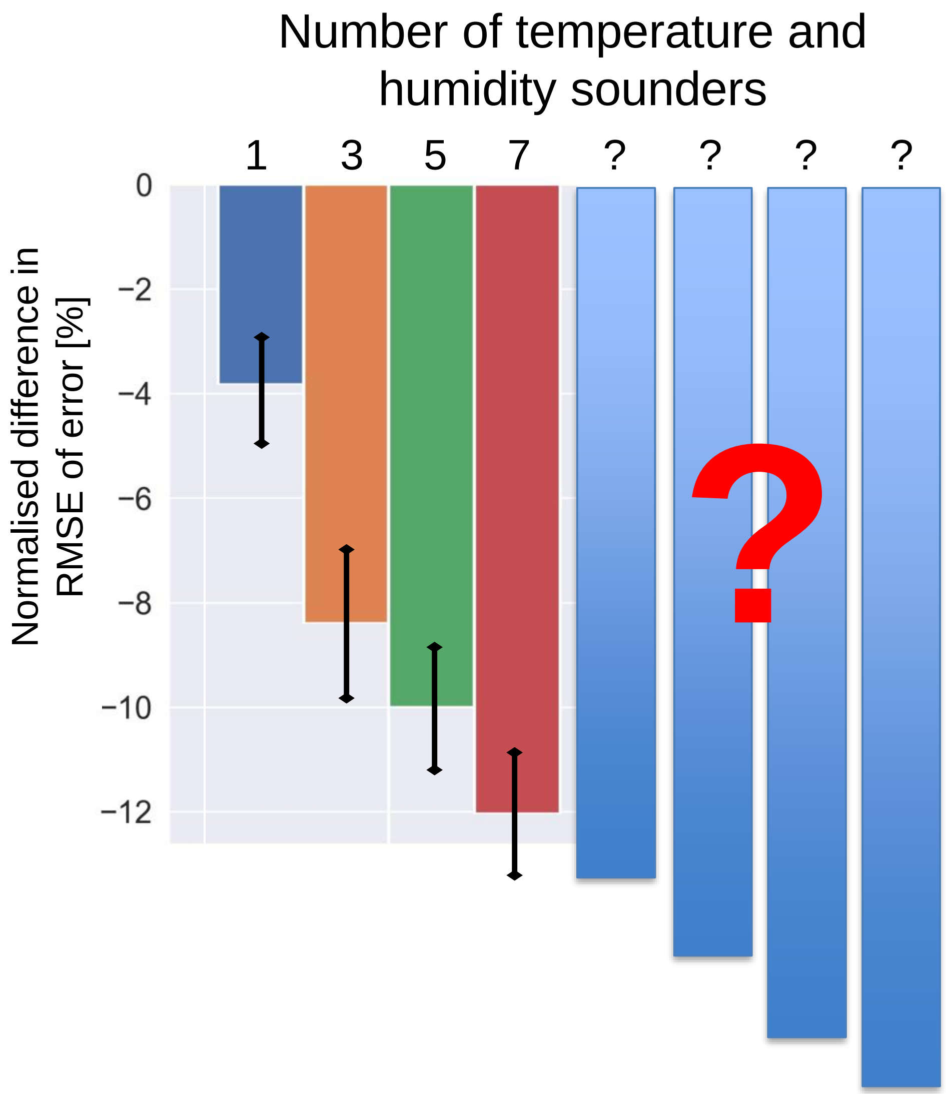


Reality in 2020



New ESA study: Applying the EDA method to MW sounding

- **EDA method is now being applied to assess NWP-benefit of a constellation of MW sounders to complement the backbone system:**
  - **Motivated by possibilities offered with small satellites.**
  - ***<u>Key questions:</u>***
    - How many and what type of additional orbits (polar/low-inclination)?
    - What is the influence of instrument capabilities (e.g., **humidity** sounding vs **humidity+temperature**? instrument noise performance?)?



(Katie Lean)

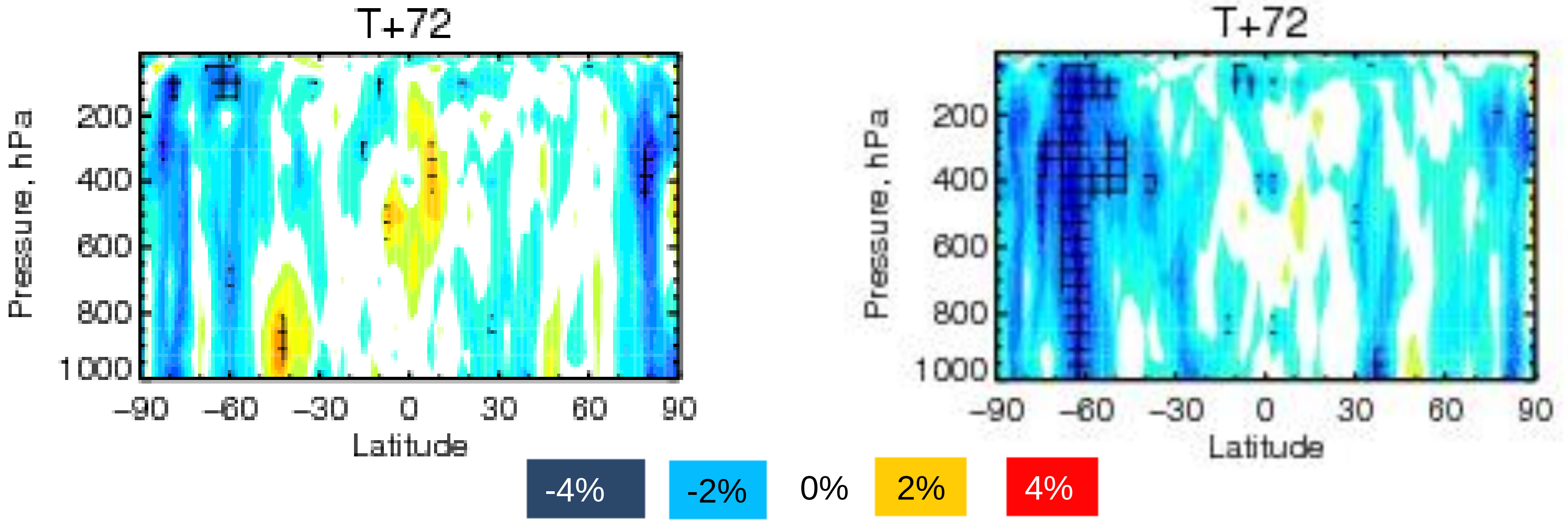
Increased impact due to advances in how the data are used

Reminder: changes in the impact on an observing system can also arise through advances in the data usage.

- E.g., all-sky assimilation of humidity-sensitive MW observations

T+72 Vector Wind RMS difference normalised by RMS of control

Clear-sky MHS impact | All-sky MHS impact



(Geer et al 2014)

Other aspects of forecast impact - what else can OSEs tell us?

- Examples from recent polar OSEs

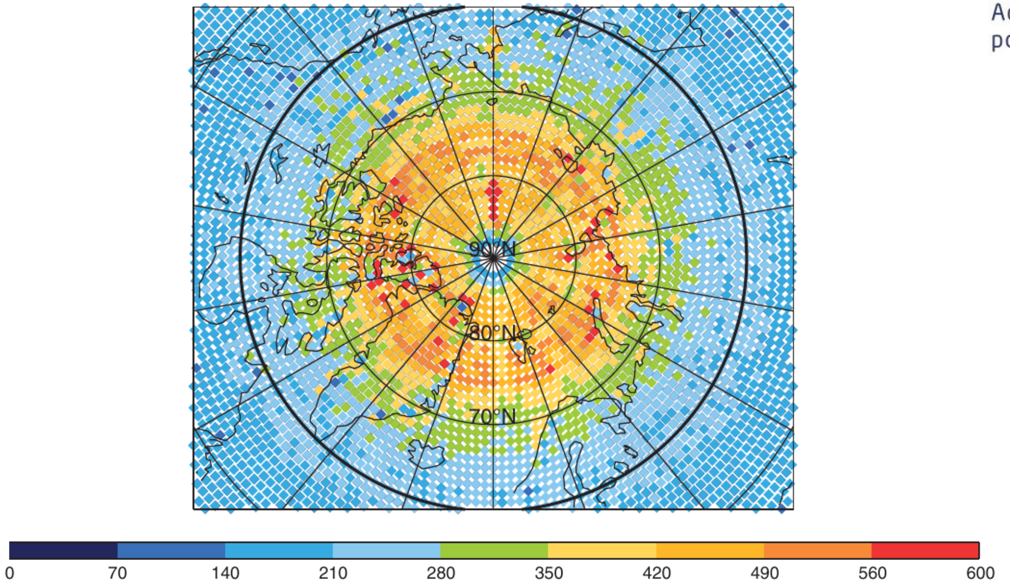
Polar observing system experiments

APPLICATE.eu
Advanced prediction in polar regions and beyond

- Polar regions:
    - Data-rich for satellite observations; data-sparse for conventional data
    - Extreme climate; snow/ice, etc
- Remove selected observing systems over lat>60N and lat<-60S.
- Periods:
  June – September 2016
  December 2017 – March 2018

See also Lawrence et al, QJRMS, 2019

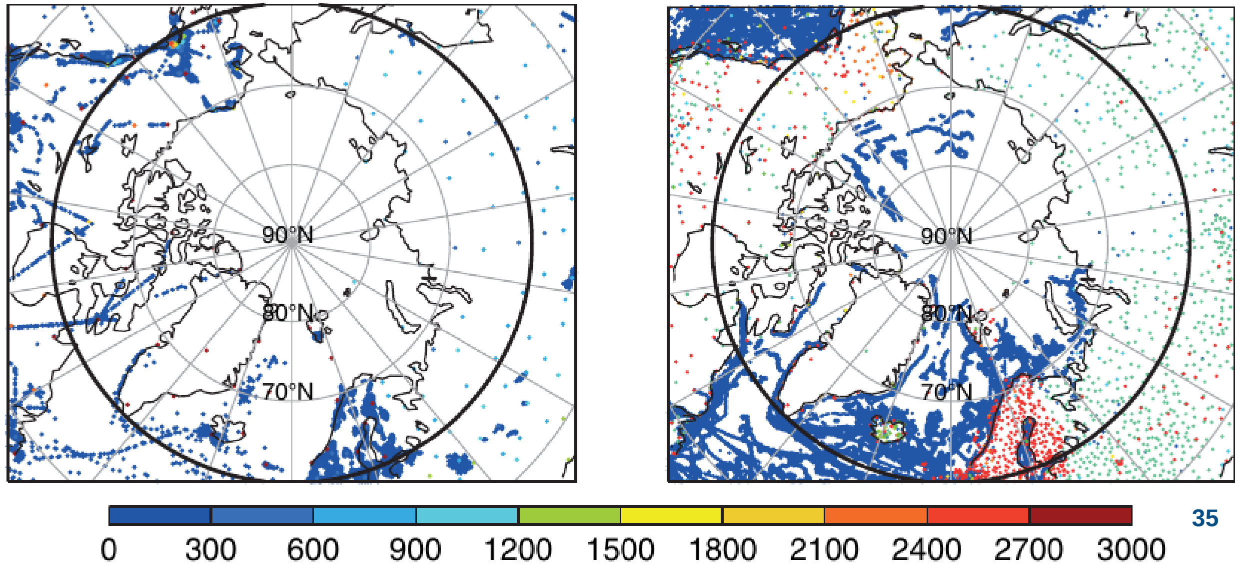
Satellite radiances from AMSU-A, winter



Conventional data

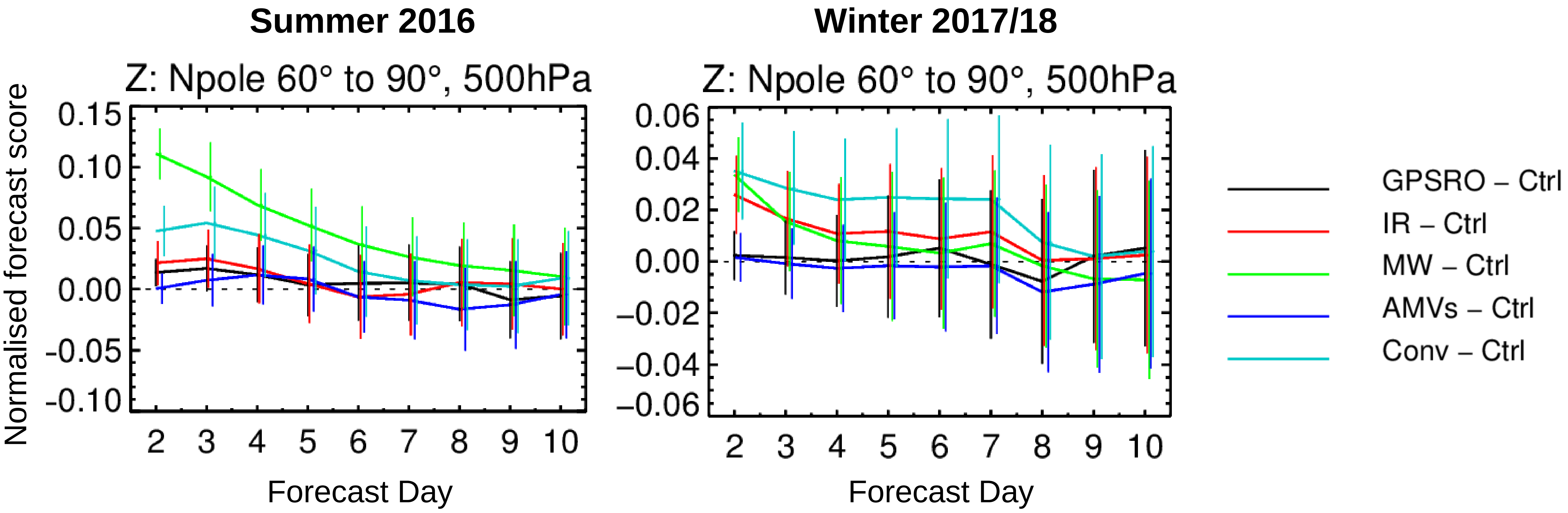
Temperature 400 – 600 hPa, winter

Surface pressure data, winter



ECMWF

Strong seasonal dependence of the relative forecast impact over the Arctic



(Lawrence et al 2019)

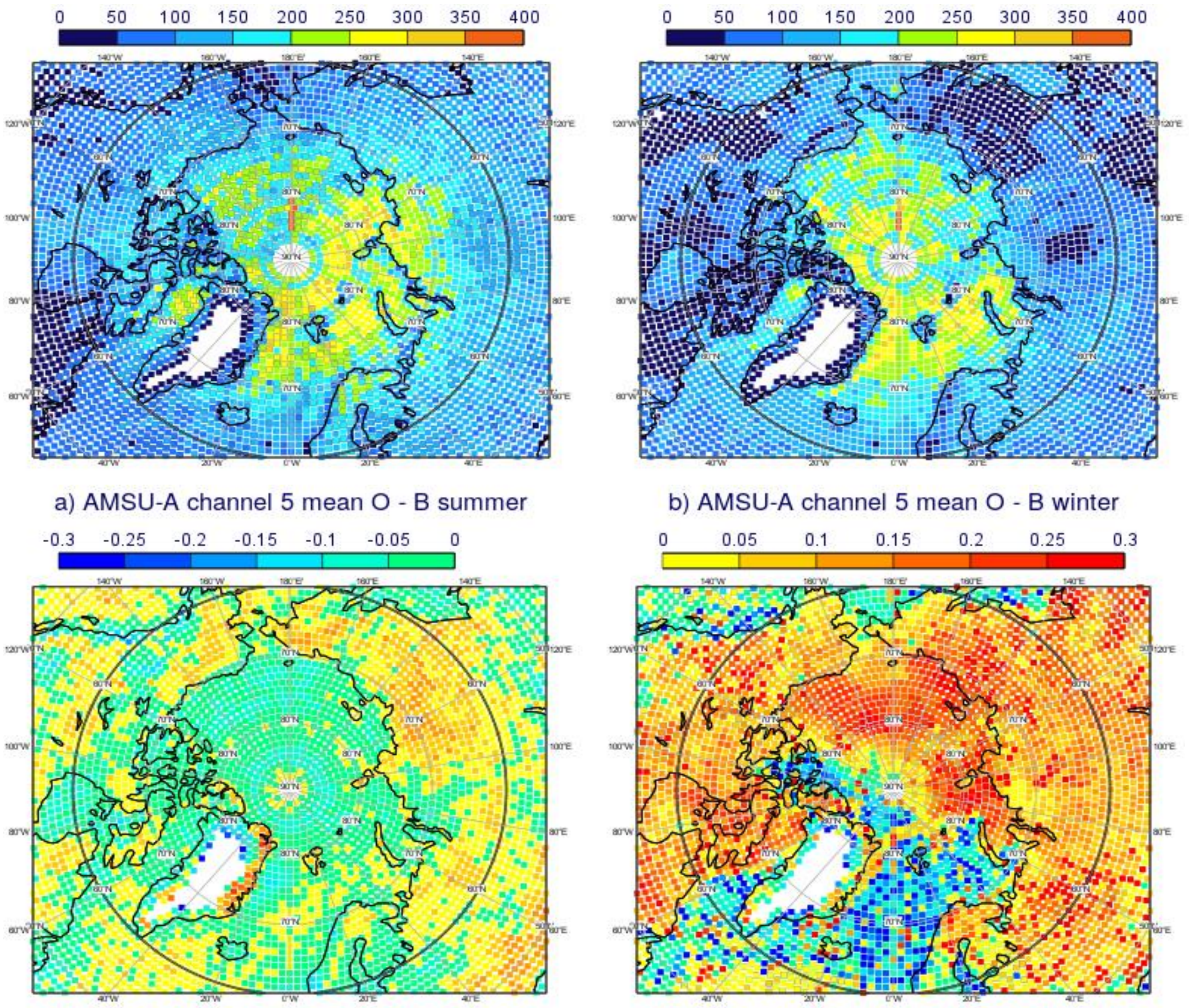
Summer/winter differences of the impact of passive MW data linked to usage over snow/sea-ice

Summer 2016 | Winter 2017/18

Nb obs

NOAA-15
AMSU-A channel 5
(peaks 500-700hPa)

Mean(o-b)



- More challenges with using surface-sensitive MW sounding data over snow and sea-ice (model errors, radiative transfer modelling)

OSEs can tell us where to put development effort for improved data usage.

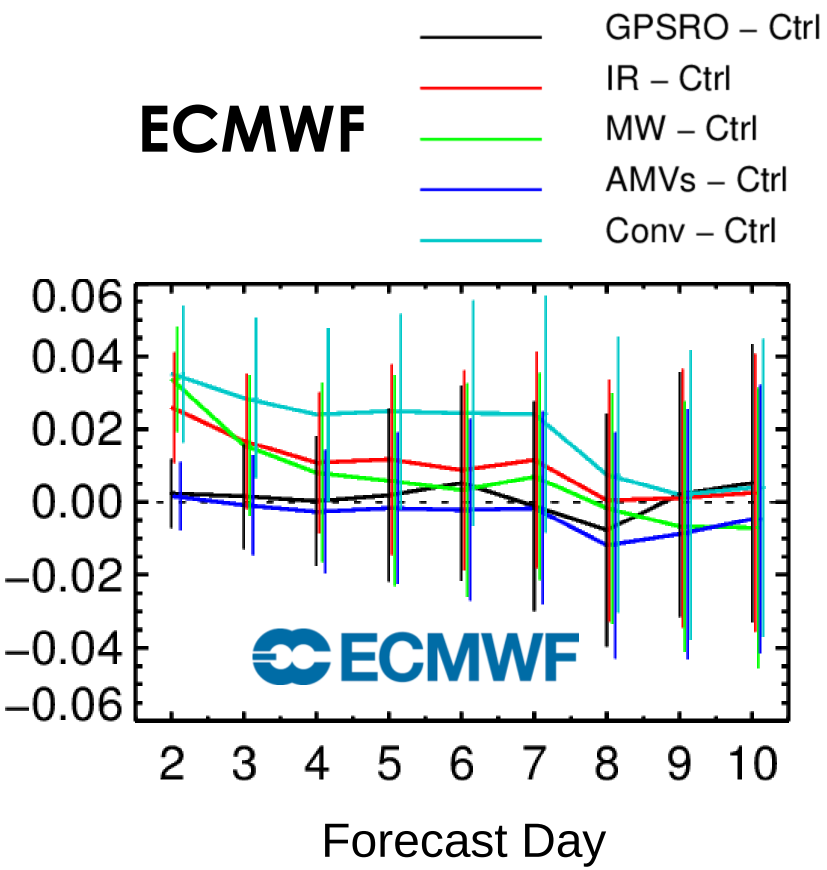
Different OSE results for different assimilation systems

APPLICATE.eu
Advanced prediction in polar regions and beyond

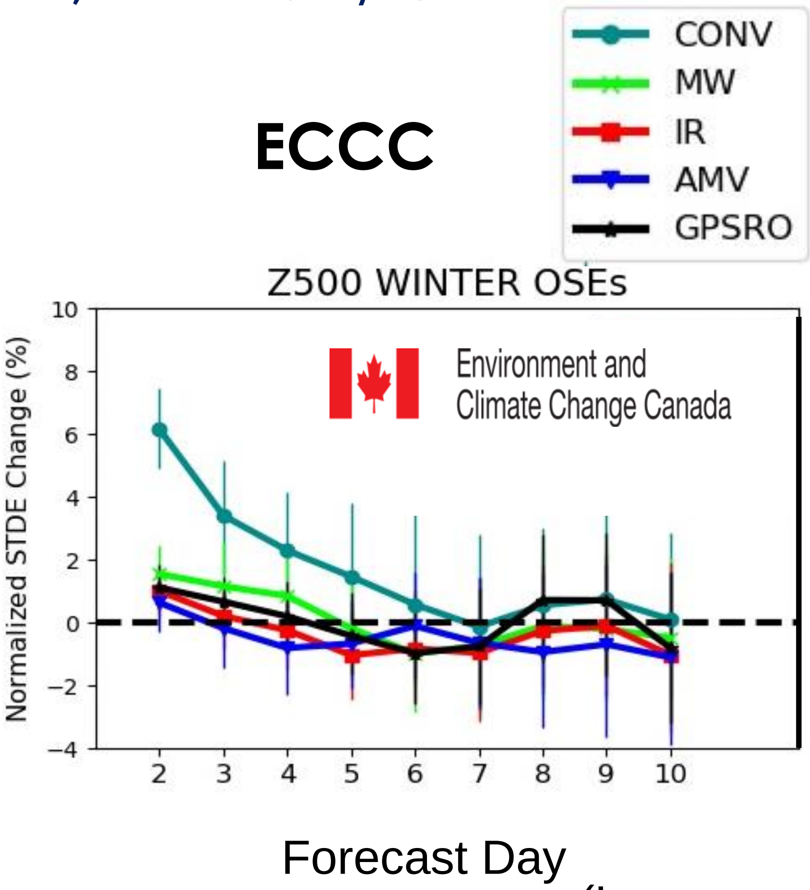
Environment and Climate Change Canada

Normalized STD Differences of Z500 Forecast Error
North Polar region, winter 2017/18

ECMWF



ECCC



Different impact in different systems due to different observation usage.

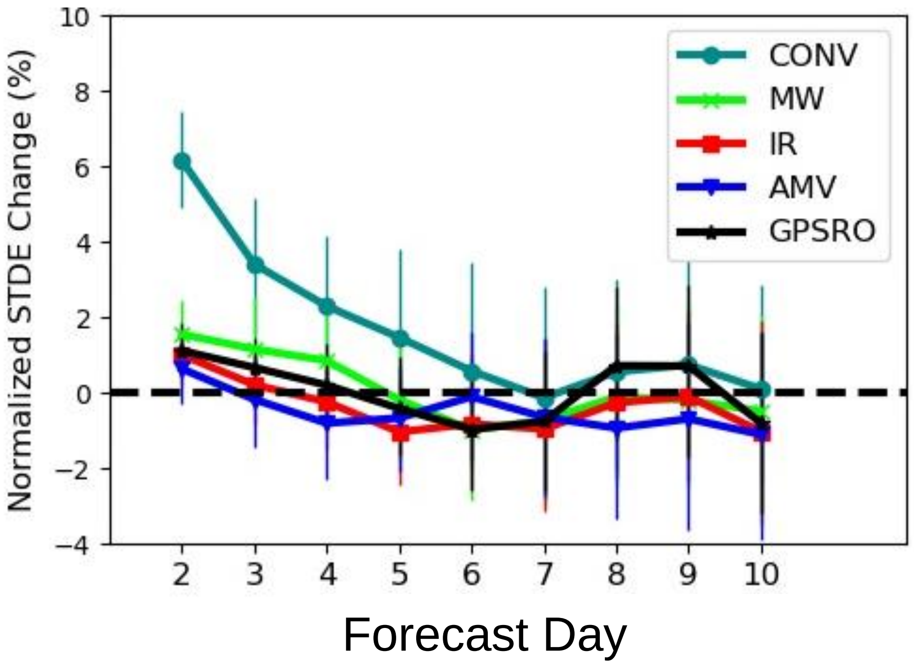
(Lawrence et al 2019, Laroche et al 2021)

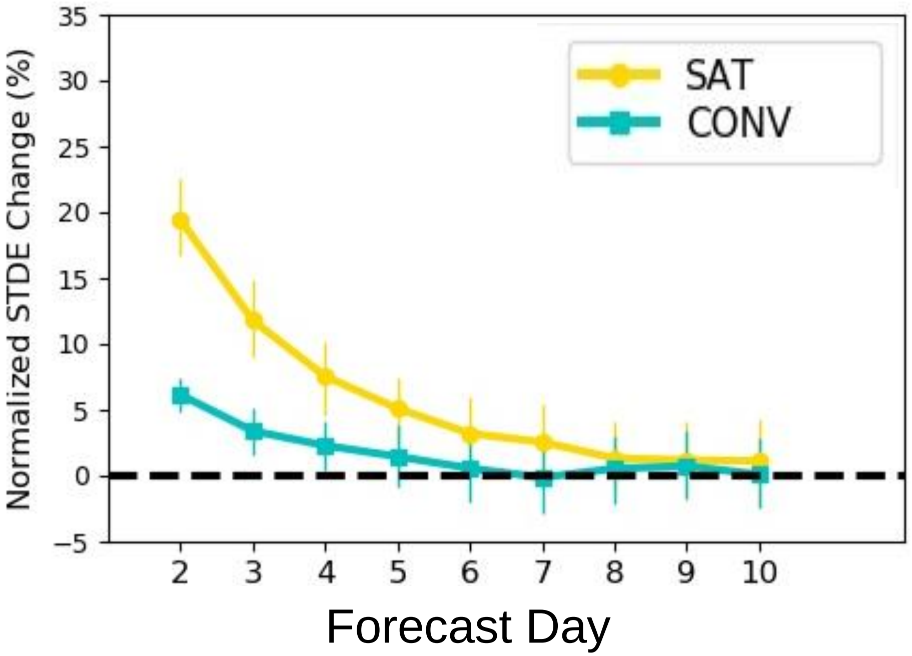
Polar OSEs at Environment Canada:
Large impact from denying ***all*** satellite data in the polar region

Environment and Climate Change Canada

(Stephane Laroche, Emmanuel Poan)

Normalized STD Differences of Z500 Forecast Error
North Polar region, winter 2017/18



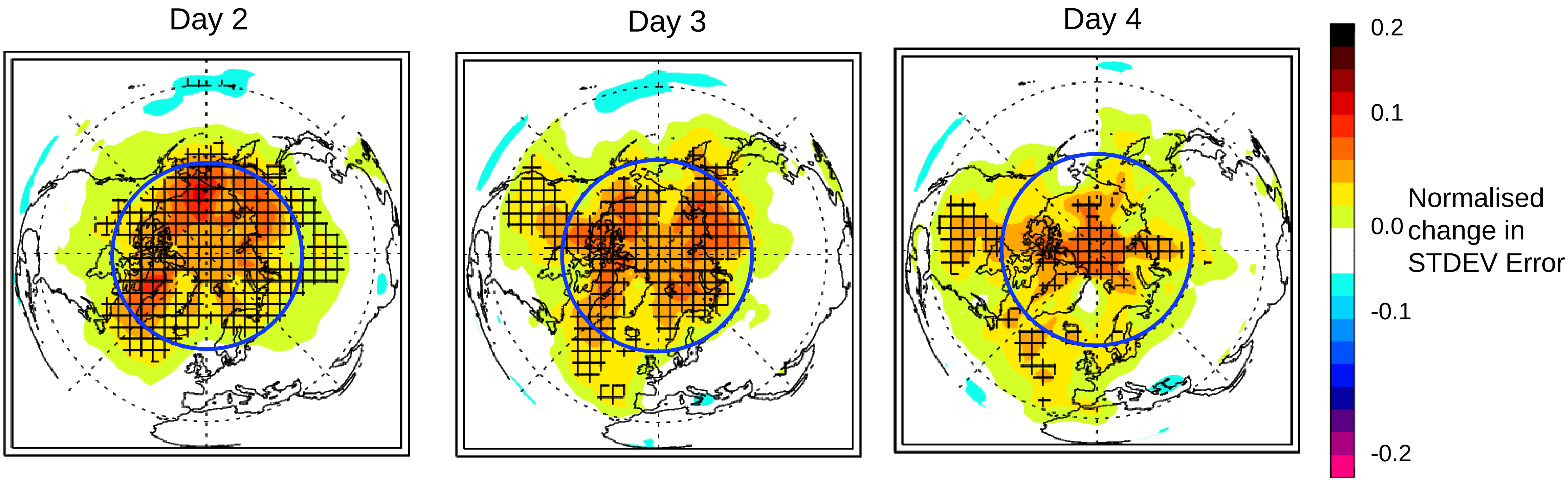


Impact of denying several observing systems is **larger** than the sum of the individual impacts.

(Laroche et al 2021)

Propagation of observation impact: Mid-latitude impact from Arctic observations

ECMWF MW OSE: Normalized STD Differences of Z500 Forecast Error, summer 2016



Medium-range impact depends on observations upstream.

See also Day et al (2019)

Observing system experiments in a regional assimilation system

Norwegian Meteorological Institute

- In a regional system, observations impact through:
  - Assimilation in the regional domain
  - Assimilation in the global system providing the boundary conditions

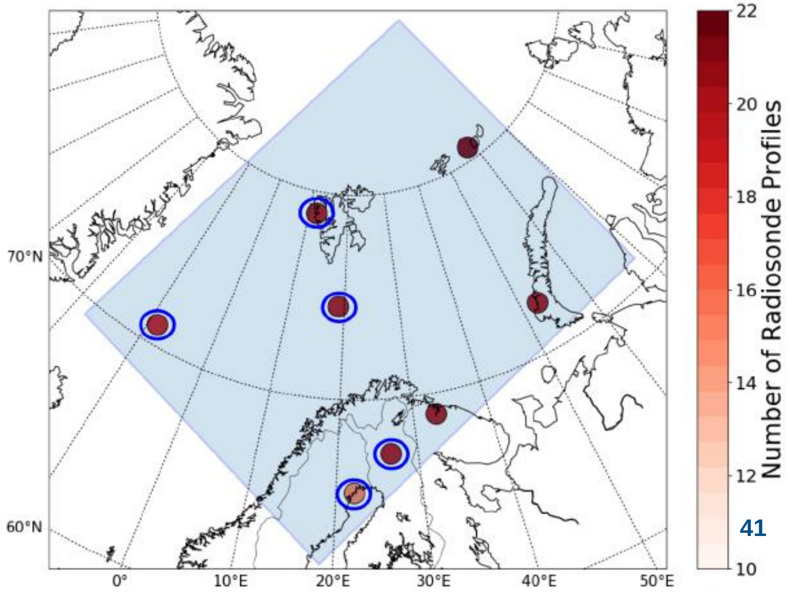
- Experiments with AROME-Arctic at Met Norway to investigate different contributions:
  - **Control:** Assimilation in regional and global system
  - **Reg-denial:** Observations denied in regional system, but assimilated in global system
  - **Reg+Glob-denial:** Observations denied in regional and global system

    In global system: denial of polar observations only

- Periods: 10 Feb – 31 March 2018; 1 – 25 July 2018

- *See Randriamampianina et al (2021)*

Domain of ARMOE-Arctic



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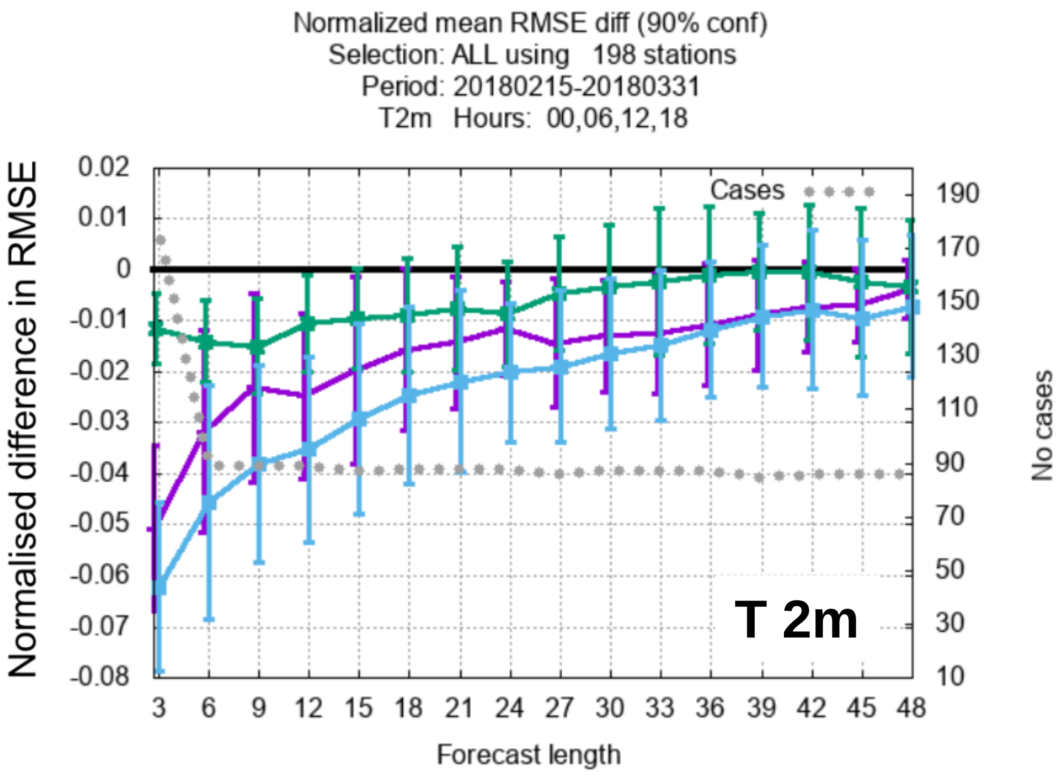
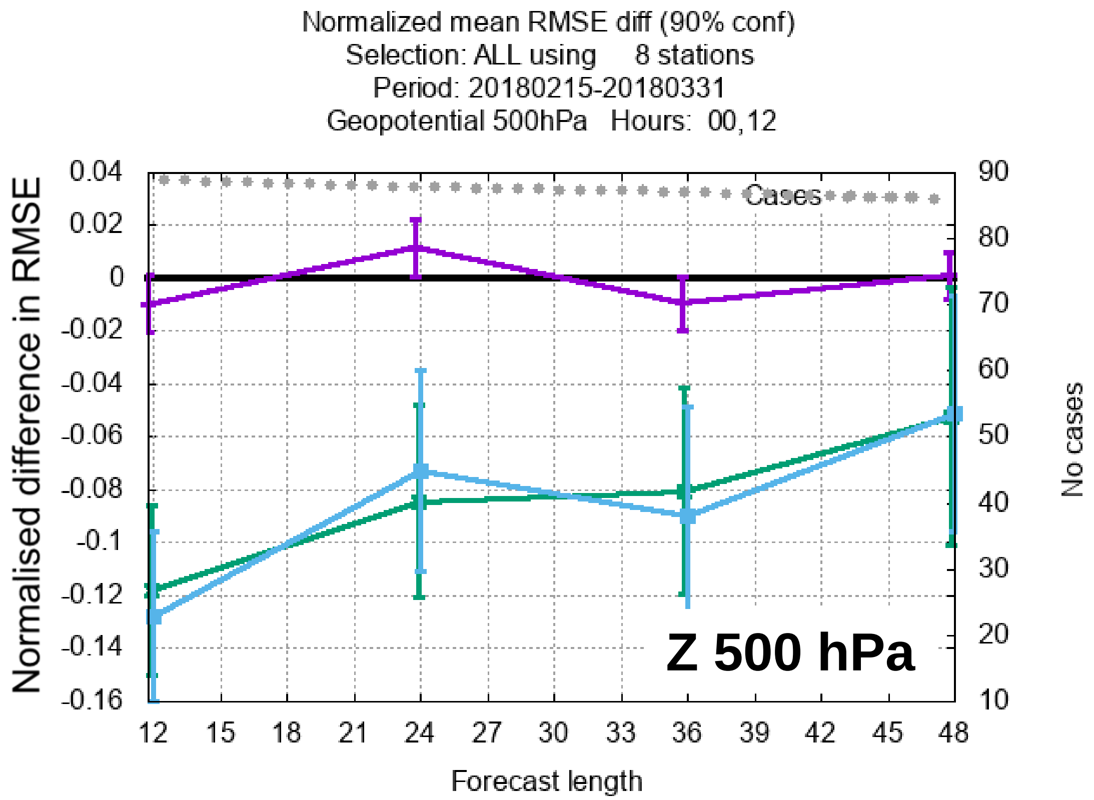
Total observation impact is the combination of regional and global DA

Impact from conventional data, winter period
10 Feb – 31 March 2018

- Impact through regional DA (Control vs Reg-denial)
- Impact from global DA only (R-denial vs Reg+Glob-denial)
- Total impact (Control vs Reg+Glob-denial)



Impact through regional DA dominates for near-surface variables.



Impact through global DA dominates for upper-air variables.

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Summary

- **OSE/FSOI confirm significant forecast benefits from conventional observations, MW, GNSS-RO, hyperspectral IR, and IR/VIS imagers in the ECMWF system**
  - Strong increase in impact from RO – incl. for short-range wind forecasts in the tropics
  - Combined, satellite data dominate forecast impact
- **Impact of observations can change over time:**
  - Due to advances in the use of the observations
  - Due to changes in the observing system
- **OSEs can tell us about:**
  - Assimilation mechanisms
  - Non-local impact of observations in the medium range
  - Areas in need of development effort
  - Evolution of the global observing system
- **DA systems are successfully being used to inform about the future evolution of the observing system**
  - E.g., EDA spread simulations for GNSS-RO constellation, Aeolus; MW sounder constellation

Further reading

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Duncan, D, Bormann, N, Holm, E, 2021: On the addition of microwave sounders and numerical weather prediction skill. Q J R Meteorol Soc, 147, accepted, doi: 10.1002/qj.4149

Geer, AJ, Baordo, F, Bormann, N and English SJ: 2014: All-sky assimilation of microwave humidity sounders. ECMWF Technical Memorandum 741, 57pp, doi: 10.21957/obosmx154

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Healy, B, Polichtchouk, I., Horányi, A., 2020: Monthly and zonally averaged zonal wind information in the equatorial stratosphere provided by GNSS radio occultation. Q J R Meteorol Soc., 146: 3612– 3621. https://doi.org/10.1002/qj.3870

Langland, R.H. and Baker, N., 2004: Estimation of observation impact using the NRL atmospheric variational data assimilation adjoint system. Tellus A, 56, 189– 201.

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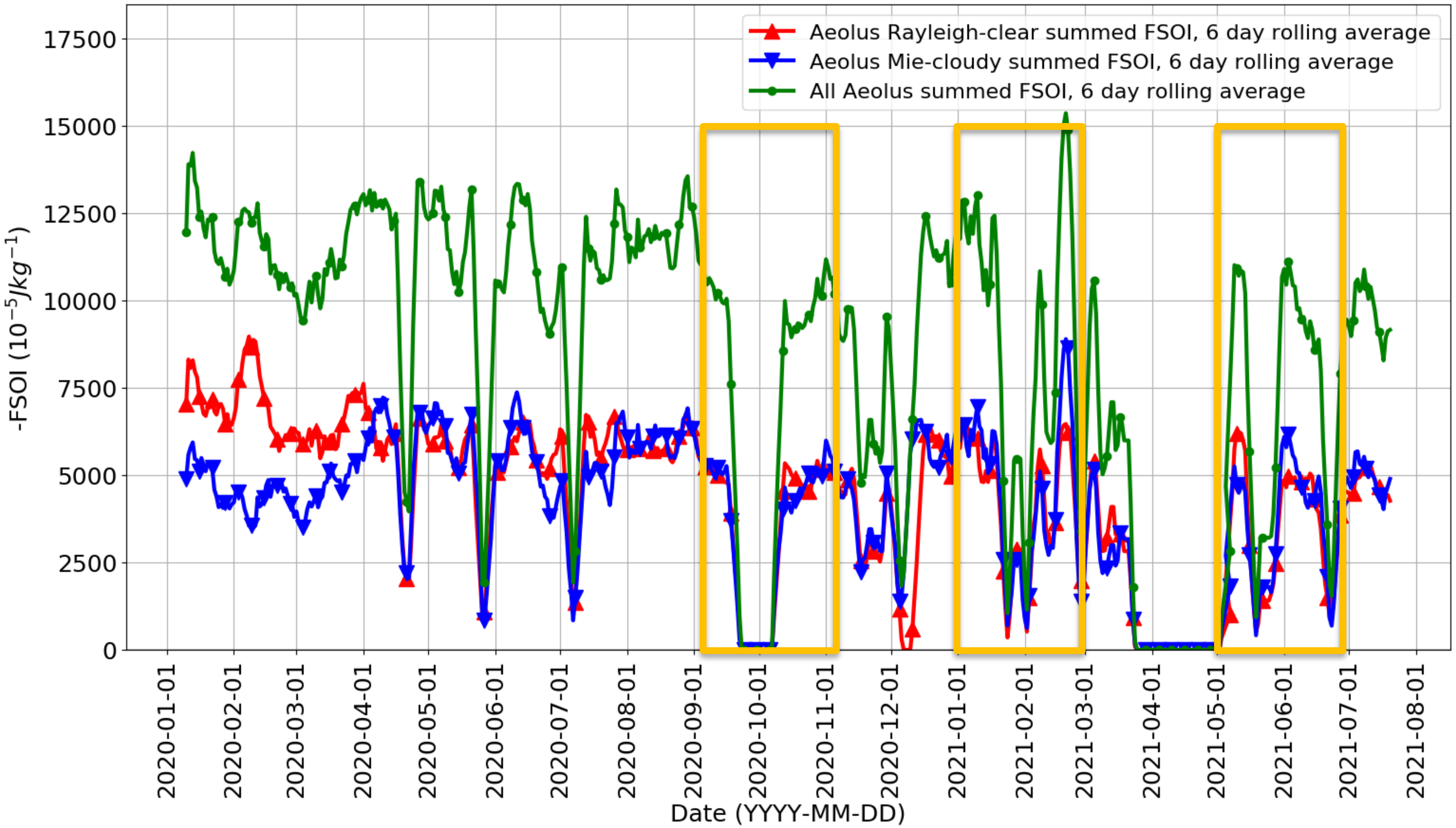
Peubey, C and McNally, AP, 2009: Characterization of the impact of geostationary clear-sky radiances on wind analyses in a 4D-Var context. Q J R Meteorol Soc. 135, 1863-1876.

Randriamampianina, R, Bormann, N, Køltzow, MAØ, Lawrence, H, Sandu, I, Wang, Z., 2021: Relative impact of observations on a regional Arctic numerical weather prediction system. Q J R Meteorol Soc., 147: 2212– 2232. https://doi.org/10.1002/qj.4018

Backup slides

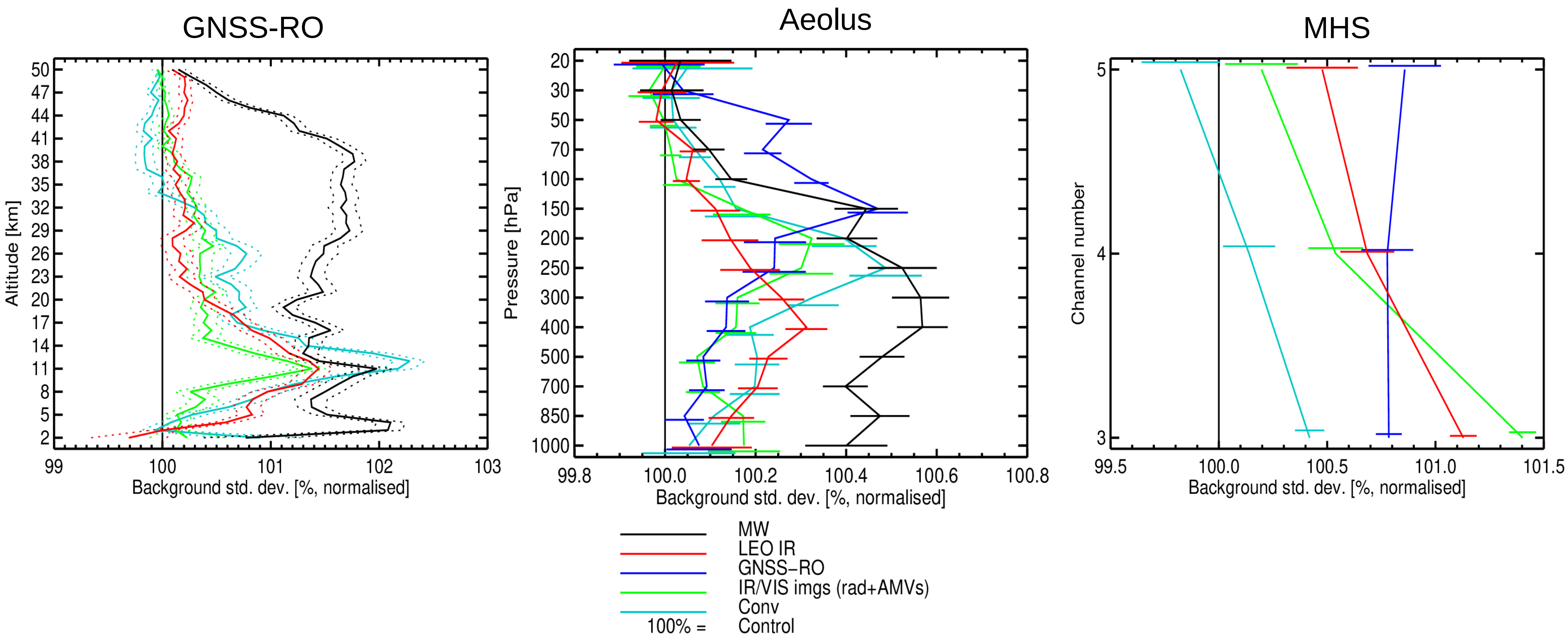
Aeolus FSOI

Aeolus is affected by outages and loss of signal during the experiment period.



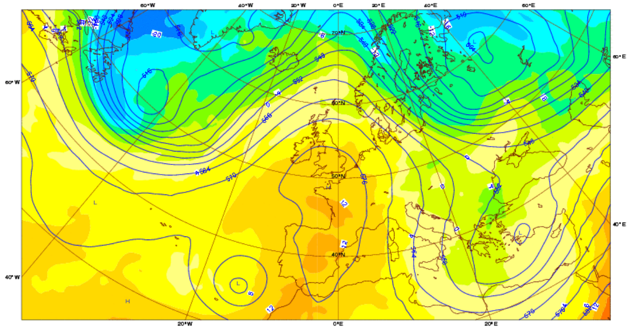
Short-range impact evaluated against satellite observations: Stdev(o-b)

Global, 3 periods combined



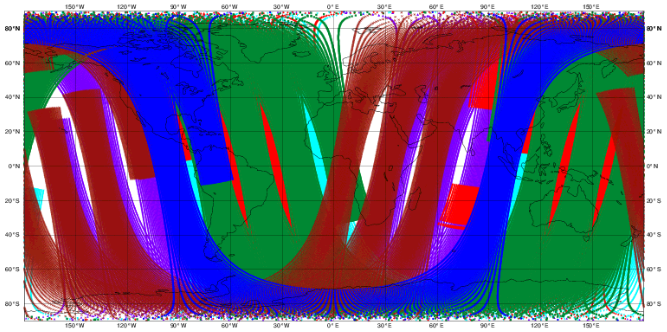
Simulation of new observations

ECMWF NWP analysis
→ proxy for the ‘truth’ for the new observations



interpolate

Observation time and location



Observation operator RTTOV-SCAT
(channel specs, within MWS channel set)

add realistic observation errors
(instrument noise, calibration/pointing errors, other errors)

Simulated MW sounder radiances

ECMWF