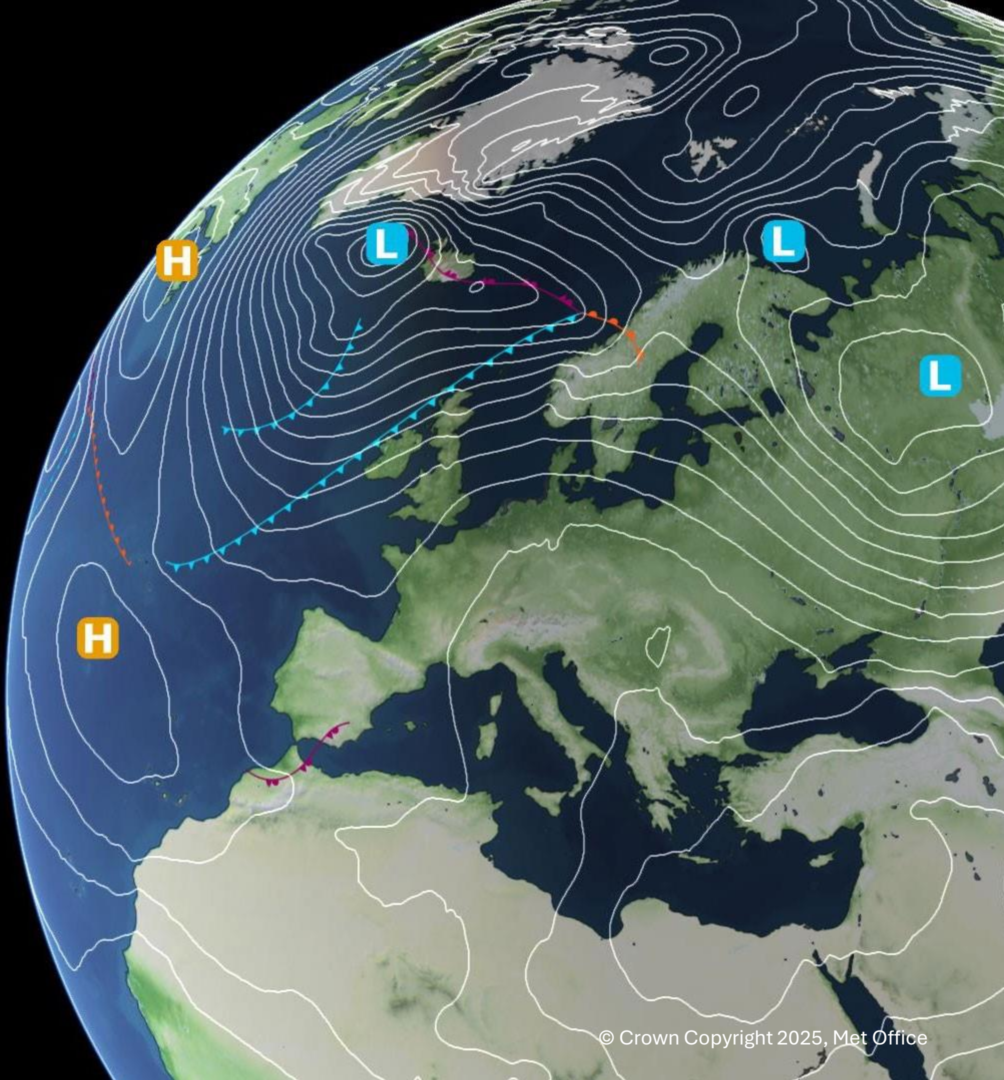
Met Office

Data assimilation for numerical weather prediction

Chris Thomas (Met Office)

9 June 2025



Many thanks to Jo Waller, Lee Hawkness-Smith, David Rundle and other members of the Surface and Satellite Assimilation group for material use in these slides

Contents

- Overview of DA for numerical weather prediction
- Observation processing
  - Surface-based observations
- Challenges

Met Office atmospheric NWP

Model

- Unified Model used for prediction across a range of timescales.
- Dynamical core solves the compressible non-hydrostatic equations of motion.
- Sub-grid scale processes represented by parameterizations.

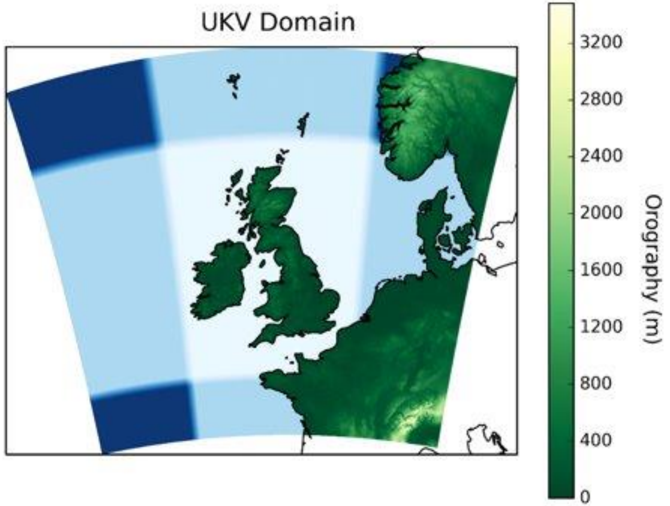
Deterministic Global NWP

- O(10) km resolution
- 70 vertical levels - the model top has an altitude of 80 km
- Forecasts t+168h

UKV NWP

- Variable resolution 4km (outer region) to 1.5km (inner region)
- 70 vertical levels - the model top has an altitude of 40 km
- Lateral boundary conditions are updated every 6 hours from the Global deterministic model.
- Forecasts to t+120h (2/day), t+54h (6/day) and t+12h (16/day)

Met-Office Regional Domain



Met Office atmospheric NWP

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Approximately 350 million grid points

- Forecasts t+168h

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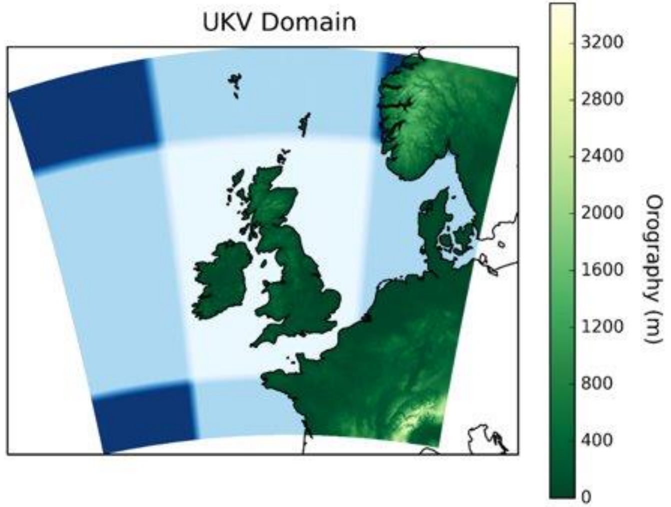
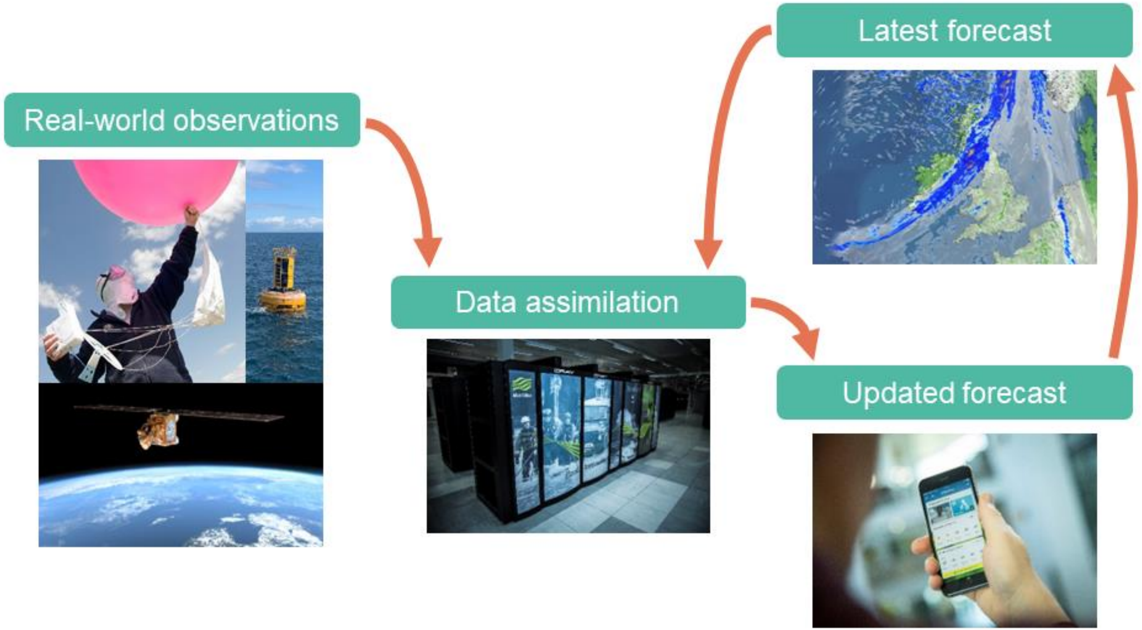


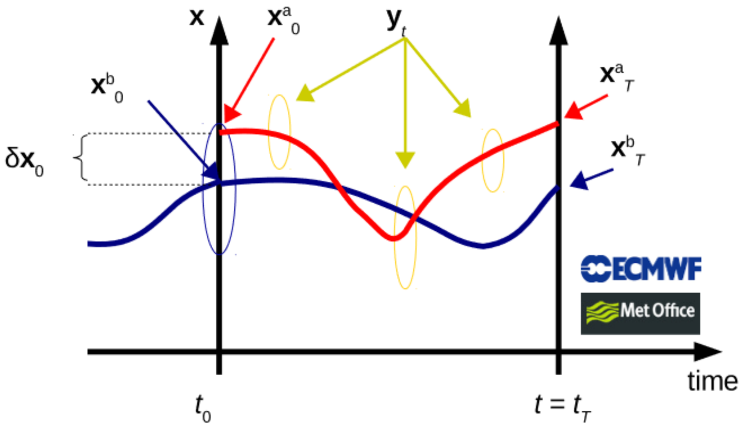
Data assimilation

- Data assimilation combines observations with a previous forecast to provide initial conditions to the current forecast. This helps keep our forecasts on track with reality.
- The model and observations, along with their respective uncertainties form the key ingredients of data assimilation.



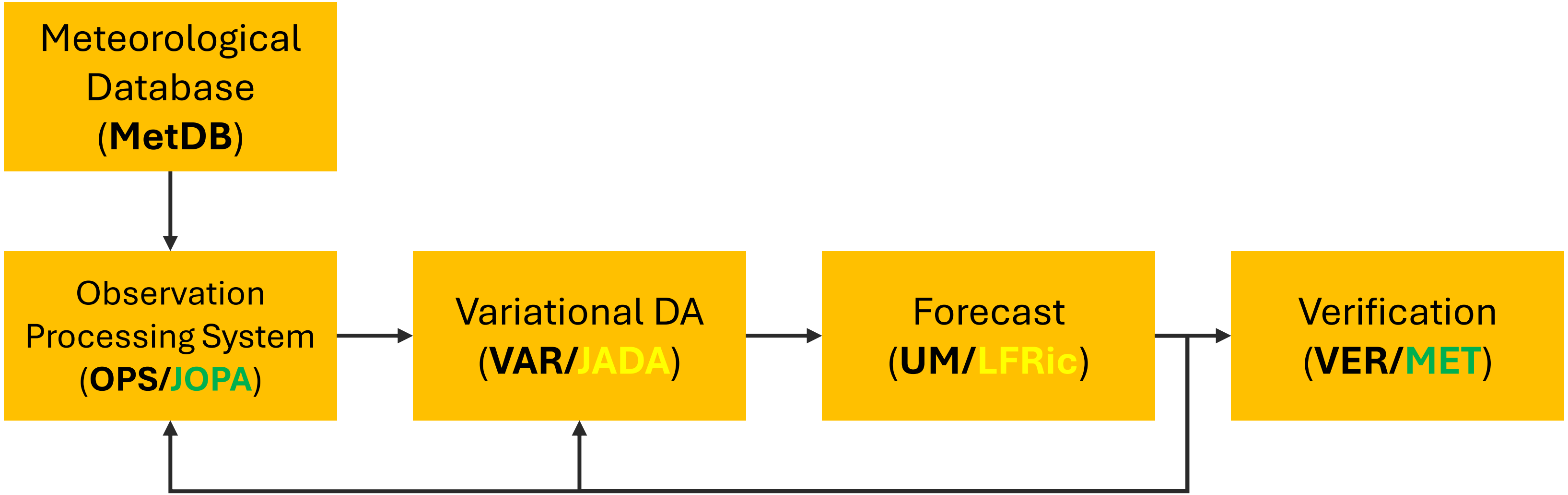
Met Office global and regional DA

- Assimilation carried out using a 4D incremental variational data assimilation scheme
  - Hybrid of parameterised and ensemble-based covariances.
- Global data assimilation is run every 6 hours using observations in a 6-hour window around analysis time.
- Regional (UKV) data assimilation is run every hour using observations in an hour window around analysis time.
  - Boundary conditions from global DA.

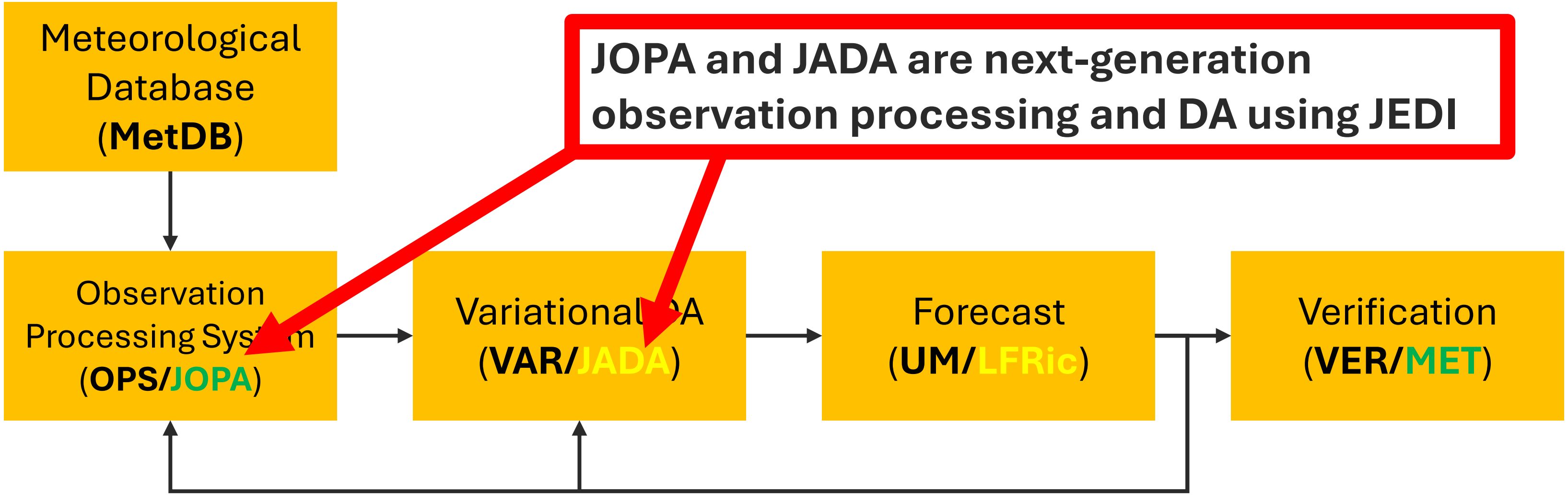


Global: Rawlins *et al.* 2007, Clayton *et al.* 2012
UKV: Milan *et al.* 2019, Milan *et al.* 2023

From observations to forecast



From observations to forecast



Observations in data assimilation

The observing system

- There are many ways to get information about our environment
- Typically, we consider them in two broad categories:
    - Satellite
    - Conventional (surface-based)

Image from Levizzani & Cattani (2019)

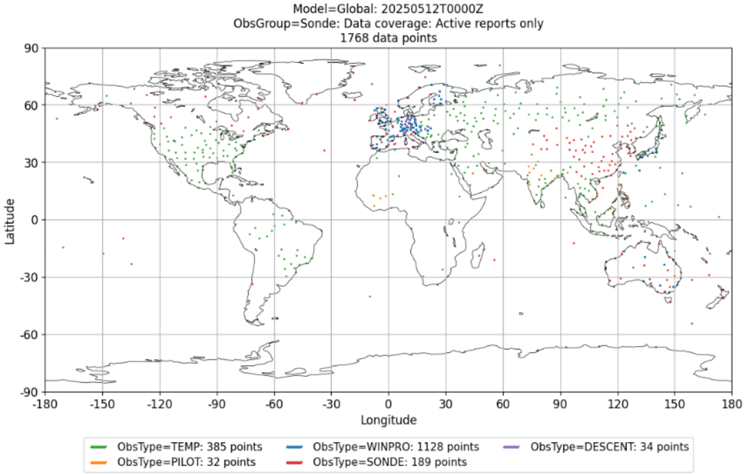
The observing system

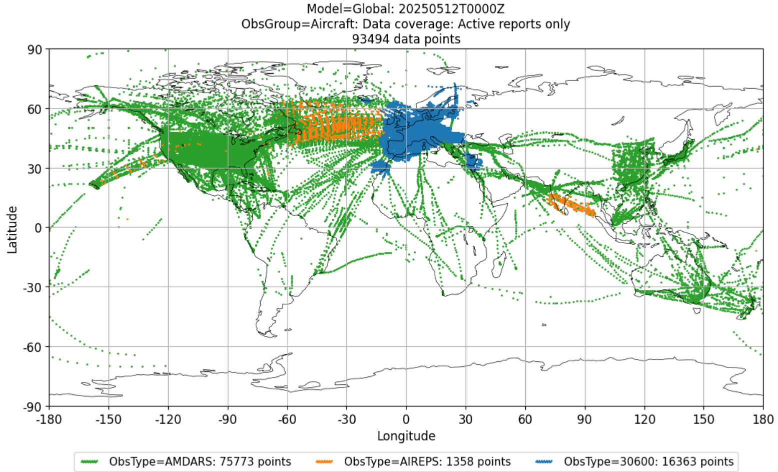
- Conventional observations
  - Aircraft (including Mode-S)
  - Radiosondes (weather balloons)
  - Land stations
  - Ships & ocean buoys
  - METAR (airport observations)
  - Bogus TC observations
  - Radar (regional only)

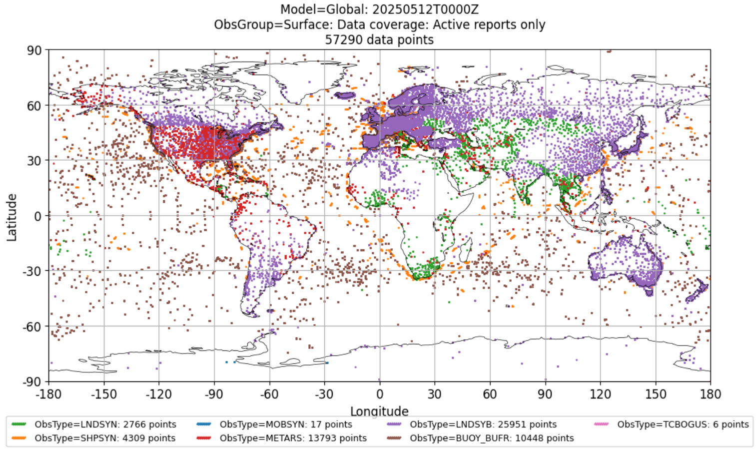
Image from [Levizzani & Cattani (2019)]

Conventional obs

- Direct measurement
- Non-uniform coverage
- Difficult to ensure consistency







The observing system

- Satellites (remote sensing)
  - Microwave and infra-red radiance measurements (polar-orbiting and geostationary satellites)
  - Remotely sensed winds (cloud tracking & sea-surface winds)
  - GNSS-RO
  - Ground-based GNSS
  - Dust measurements

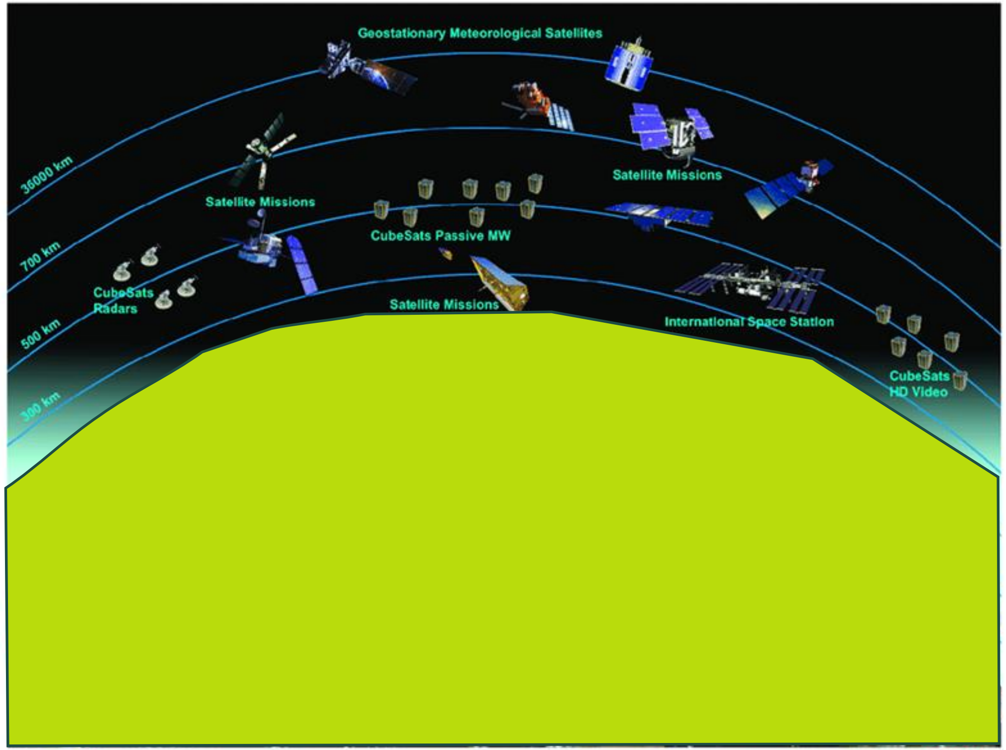
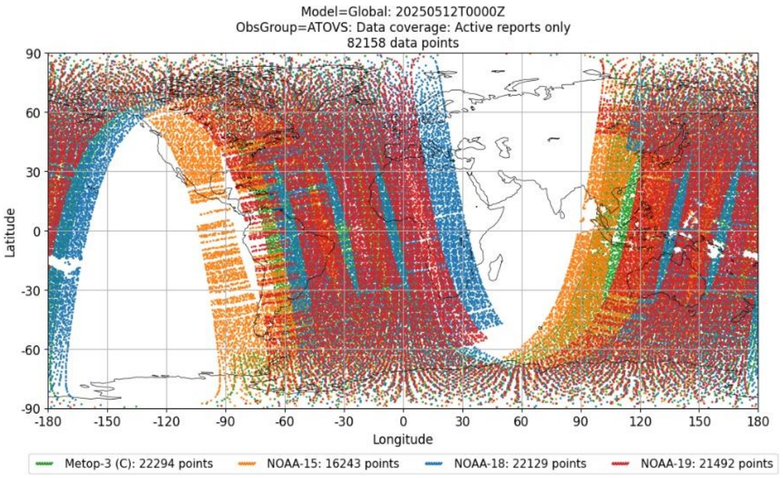
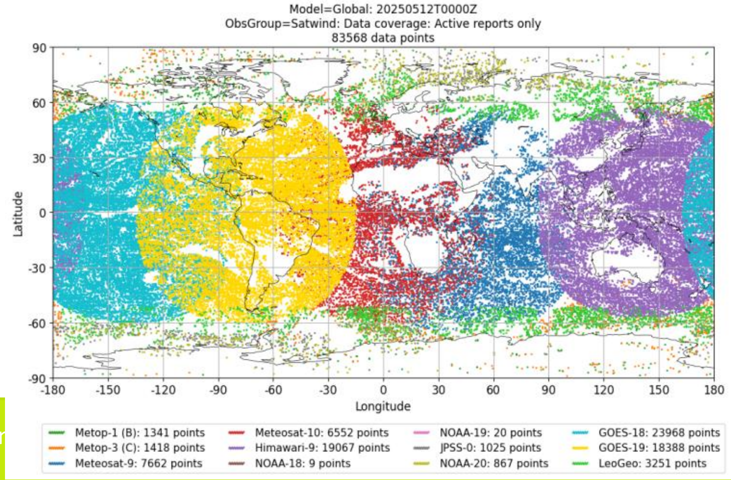


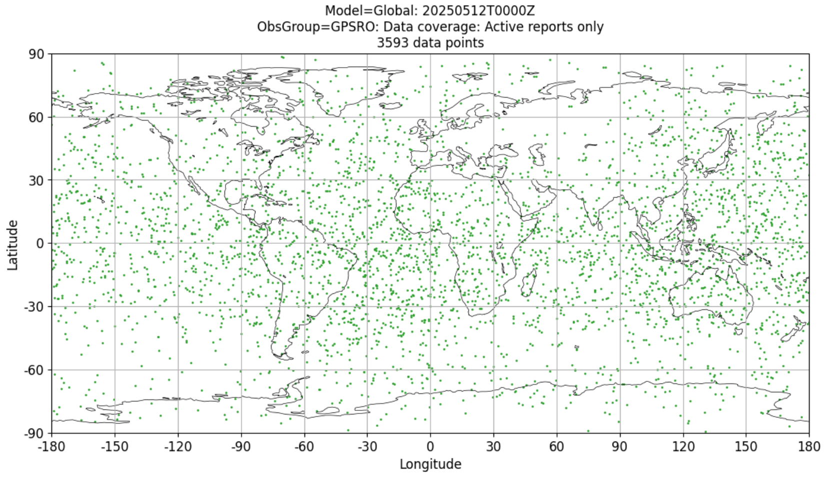
Image from Levizzani & Cattani (2019)

Satellite obs

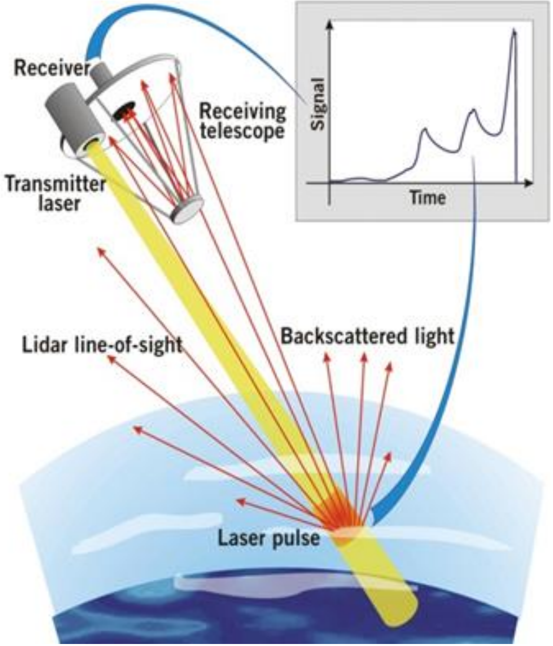
- Uniform coverage
- Indirect measurement
- Mostly biased







Pros and cons of different observing systems



- Quality
- Coverage
- Timeliness
- Consistency
- Reliability
- Direct or indirect measurements
- Estimation of uncertainty

The complementarity of observations

- Satellites are important – they helped close the gap between NH and SH forecast performance in the late 1990s
- Although satellites account for 90 – 95% of all assimilated observations (for the global system), conventional observations are crucial in 'anchoring' the system
- Conventional observations account for about 20% of the impact on forecasts (FSOI)

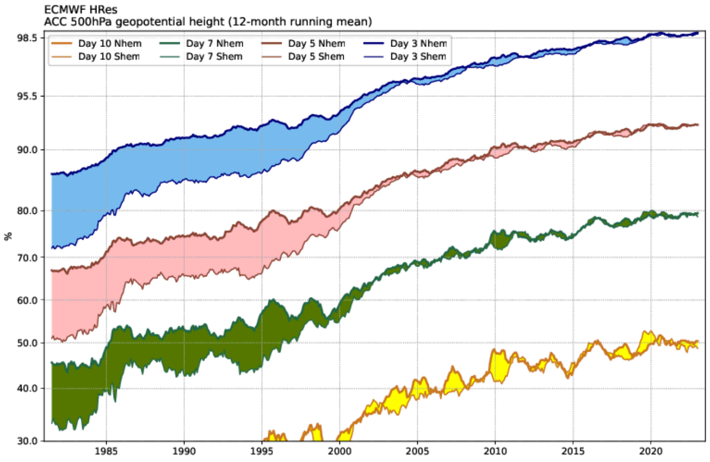
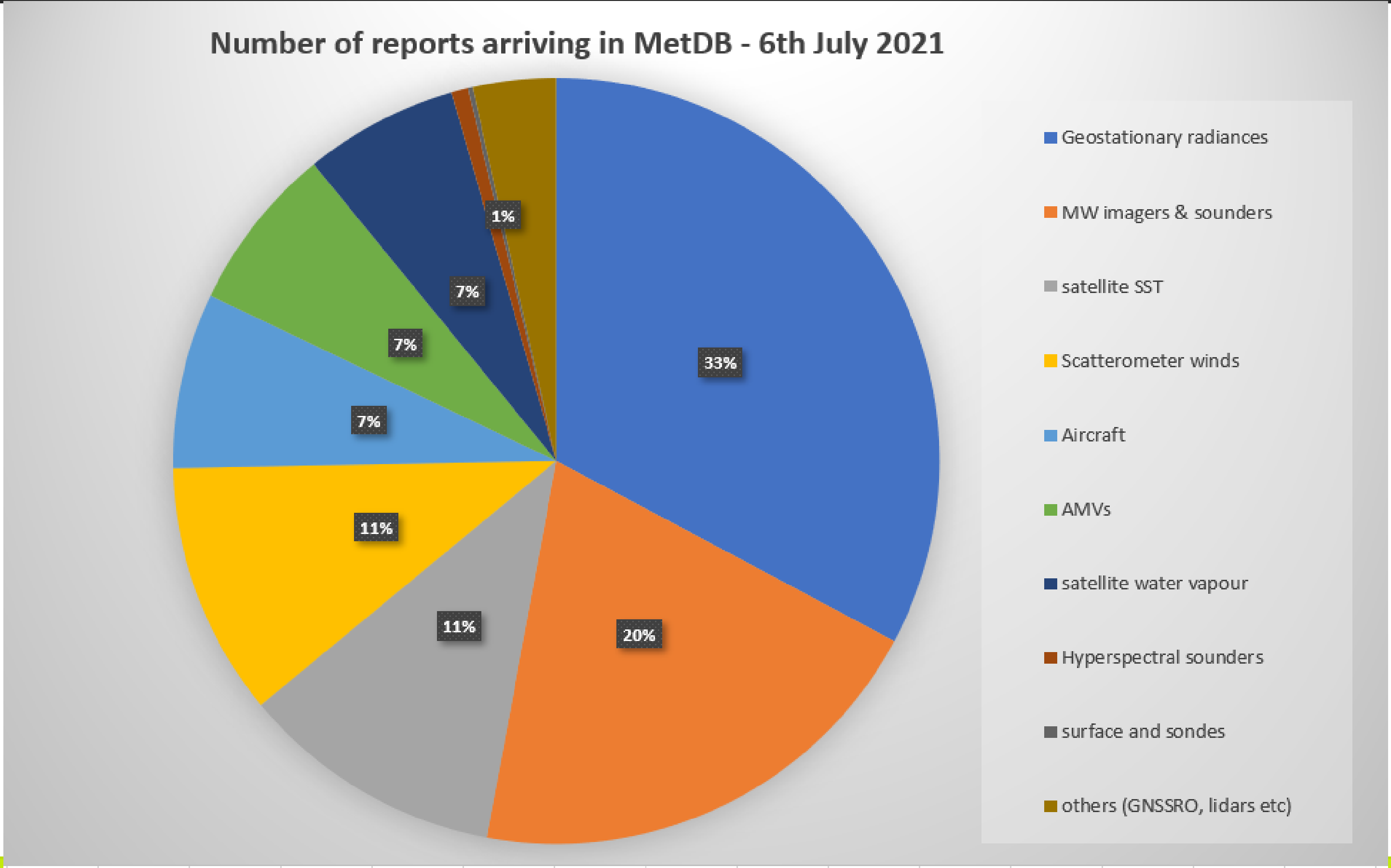


Image from ECMWF

Number of observations collected

Total per day
~385million



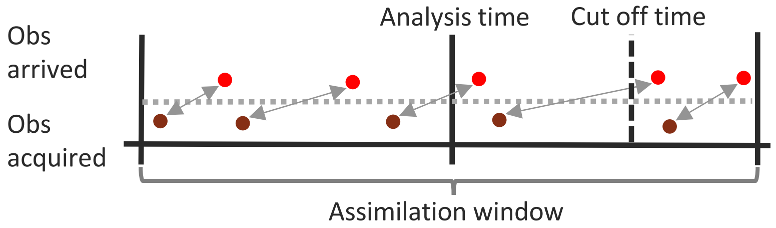
Computational resources

Component	Nodes	Time
OPS (all observation categories combined)	135	~ 5-6 mins
VAR (stage 1)	48	5 mins 42 seconds
VAR (stage 2)	128	15 mins 56 seconds
NEMOVAR (ocean DA)	11	16 mins 5 seconds
7-day forecast (coupled)	414	58 mins 13 seconds

- All DA tasks (including OPS) combined use about the same computational resources as running the forecast model for 1 day

Timeliness

- When producing forecasts can only process observations that have arrived within a certain time.



- Global: obs must be received within 2h 20min of the analysis time.
  - Main and update cycles
- UKV: obs must be received within 45min of the analysis time.

Observation processing

- Certain types of observations are bias corrected
- Then each category of observations goes through a sequence of quality controls (QC) to **determine which of those are assimilated**
  - Common reasons for observation rejection:
    - Thinning
    - Missing or bad data / blacklisted stations
    - Out of physically plausible bounds / out of domain (e.g. ships over land)
    - O-B (‘observation minus background’) checks
    - Satellites: channel selection

Pre-H(x)
Prior
Post-H(x)

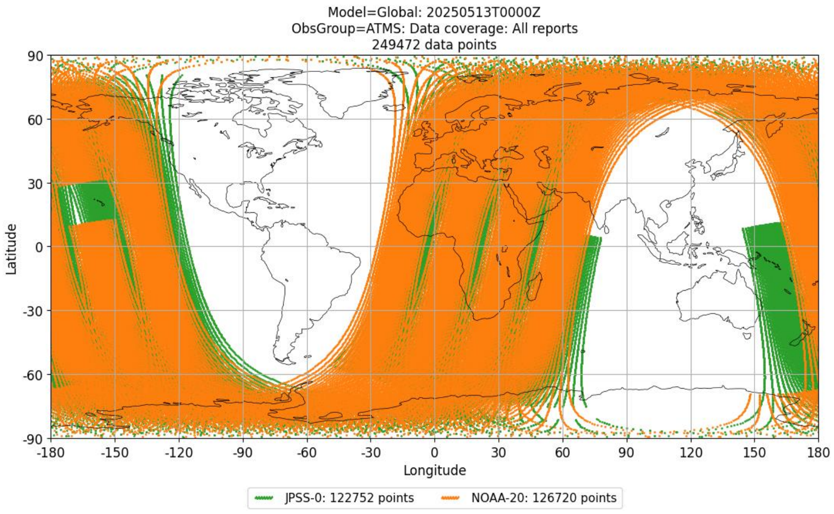
O-B checks

- Comparison with the latest short-range (6-hour) model forecast
- Need to compute the model equivalents of the observations, using the observation operator $H(x)$ (e.g. vertical interpolation, RTTOV)
- $H(x)$ includes 3 stages:
  - Model forecast (time interpolation)
  - Spatial interpolation
  - Conversion from model variables to the observed variable
- Reject observations that are too far from the background (e.g. absolute value of O-B greater than specified threshold, Bayesian treatment)

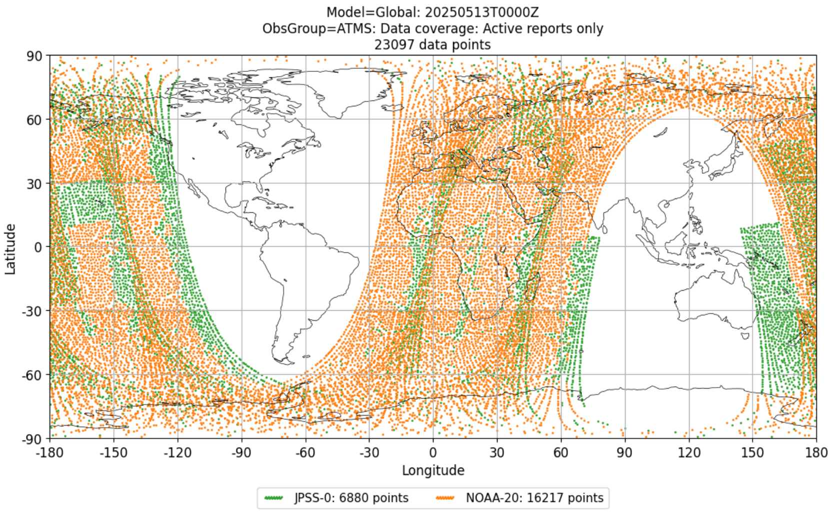
Thinning: Rejecting >90% of observations!

- Some observations (satellite, some conventional) are spatially too dense
- There could be multiple observations within a grid box
- Observation error characteristics are correlated, but existing variational DA systems do not always handle this
- Running the observation operators is expensive – we can't afford the (time) cost of assimilation if we retain too many observations
  - The linearised version of these operators need to be run for O(10) times operationally
- So… the data need to be 'thinned'

Thinning: Rejecting >90% of observations!

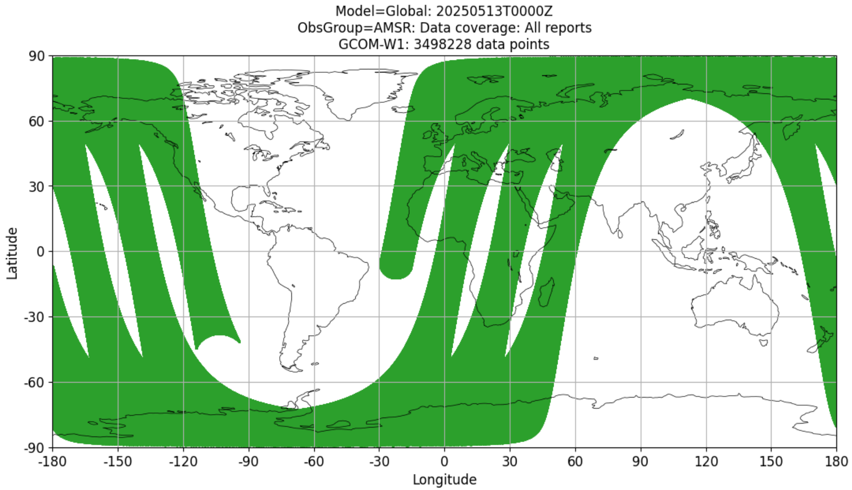


Raw observations

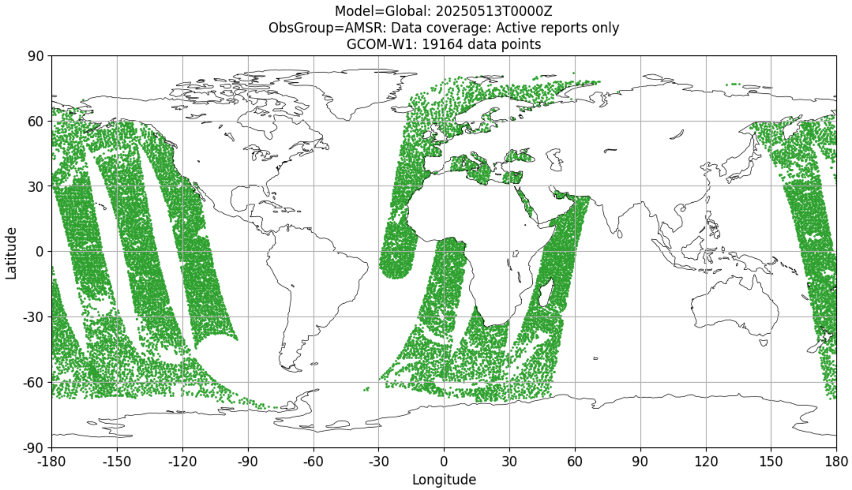


Active observations (after all QC stages)

Thinning: Rejecting >99.5% of observations!



Raw observations

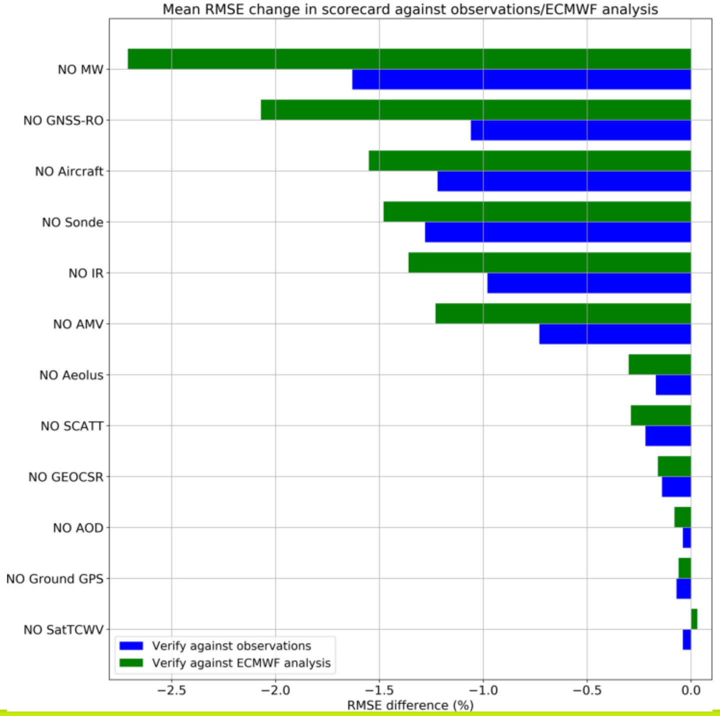


Active observations (after all QC stages)

Impact of assimilating observations

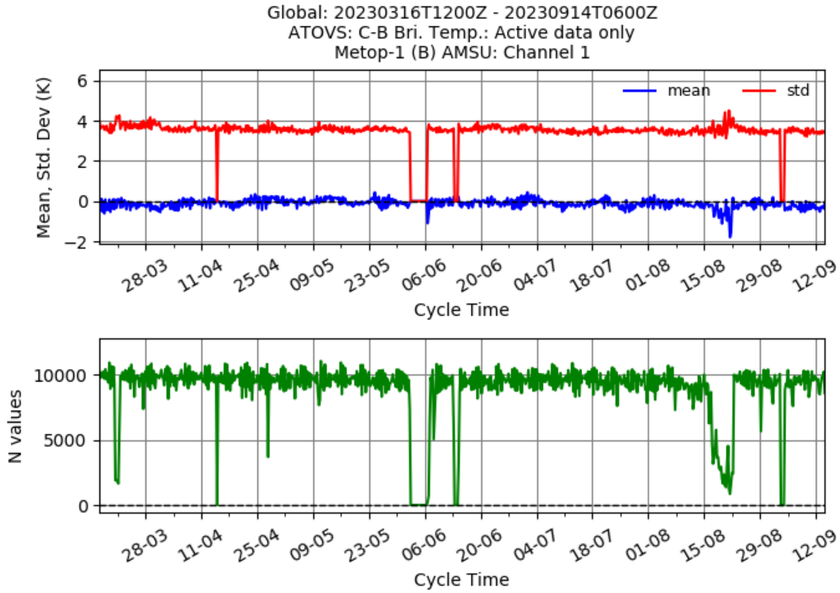
- Two primary ways to quantify the impact of assimilating observations
  - Data denial experiments (DDE)
  - Forecast Sensitivity to Observation Impact (FSOI)

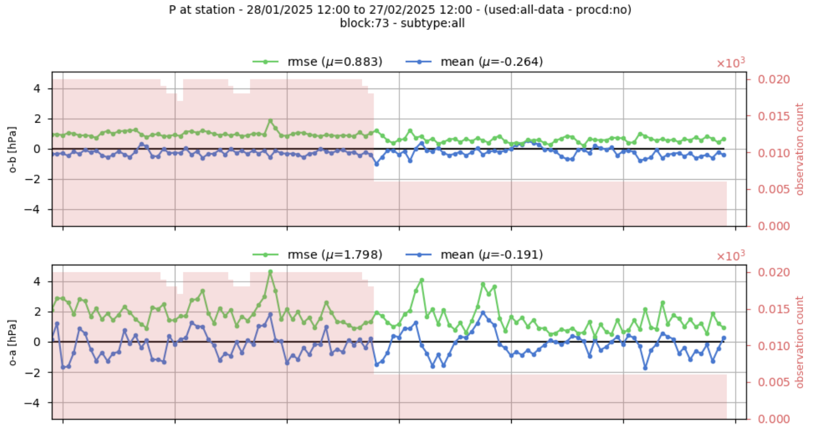
- DDE: re-run the assimilation system by discarding specific categories of observations, and see how much the analysis and forecast degrade
- Very expensive; impossible to run routinely
- Reduction of aircraft movements during COVID-19 had an impact on forecast accuracy

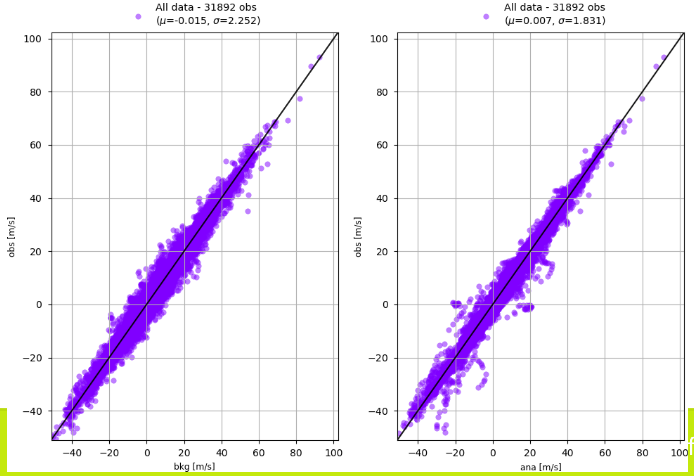


Observation monitoring

- Do things look reasonable?
- Are there any (automatic) alerts?



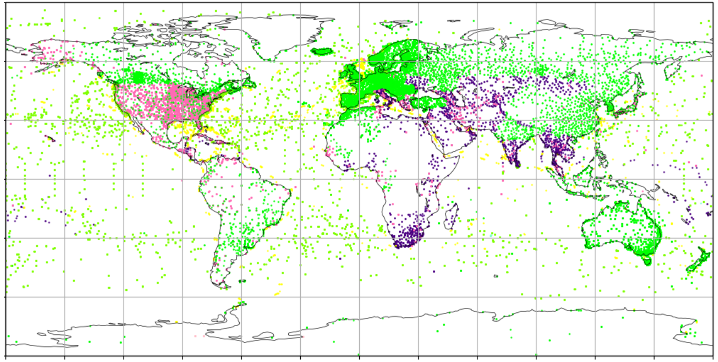




Surface-based observations

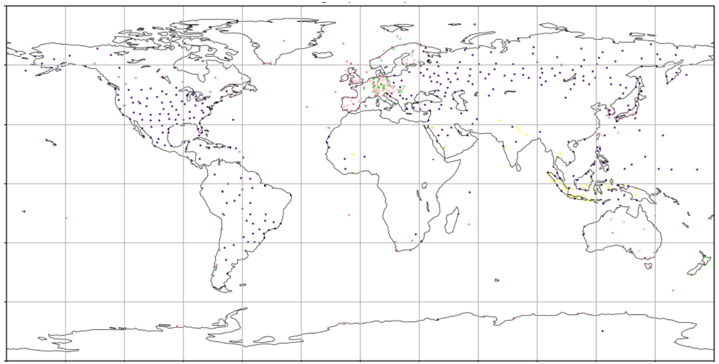
Surface-based observations

Surface



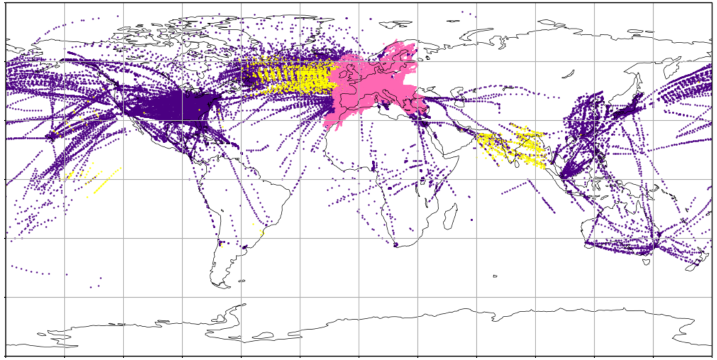
- Global and UKV
- 7 types
- 11 variables
- Only source of pressure obs

Profile



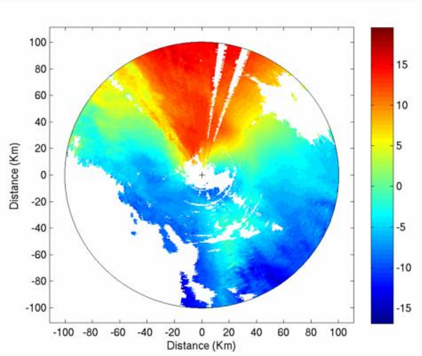
- Global and UKV
- 5 types
- 4 variables

Aircraft

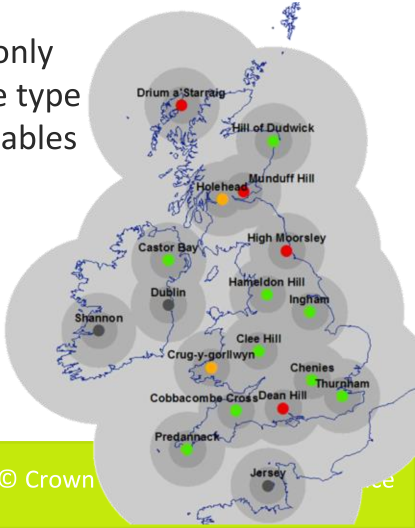


- Global and UKV
- 3 types
- 3 variables
- Dense data, but not evenly distributed

Radar



- UKV only
- Single type
- 3 variables



Met Office

Treatment of radar reflectivity observations

Information from radar reflectivity observations, in the form of a surface precipitation product, has been incorporated into the UKV via latent heat nudging (LHN) for over 25 years.

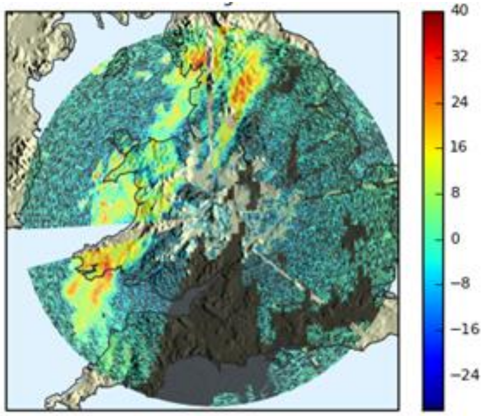
Determine if moving to direct assimilation of radar reflectivity observations is more beneficial than latent heat nudging.

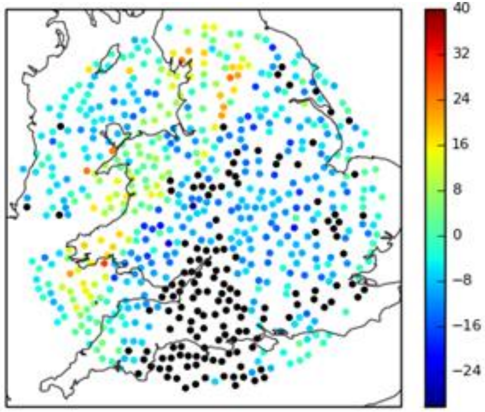
Quality control

- Reject non-hydrometeorological echoes.
- Reject obs where background T < 3°C, to avoid bright band melting layer.

Super-observations and Poisson thinning

- Super-Observation size: 15º by 15km
- Thinning: 15km for precip, 30km for dry obs.





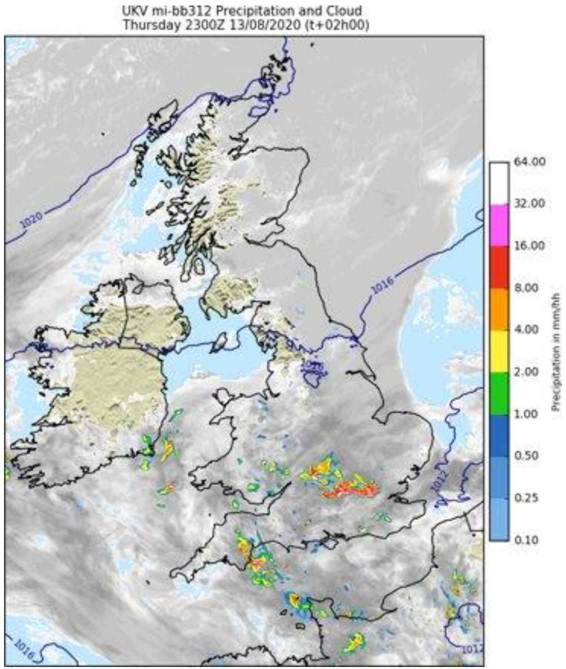
Hawkness-Smith, LD, Simonin, D. Radar reflectivity assimilation using hourly cycling 4D-Var in the Met Office Unified Model. Q J R Meteorol Soc. 2021; 1516– 1538.

Results

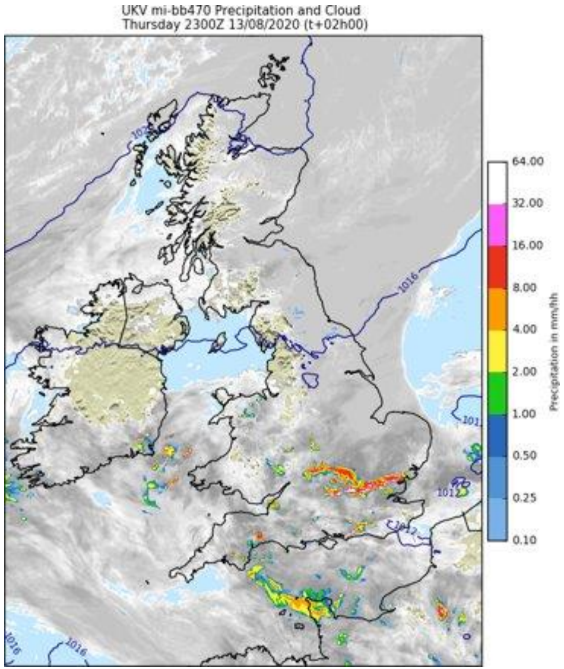
13 Aug 2020, T+2 2300

Improved organisation of bands of convection across southern England and Channel

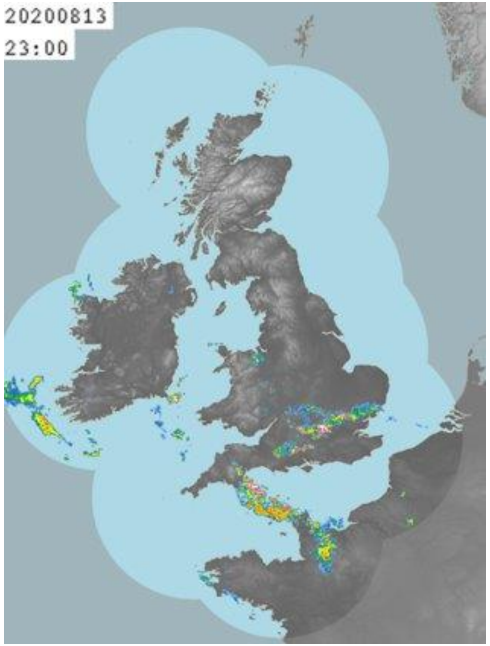
Control



Radar reflectivity experiment



Radar composite

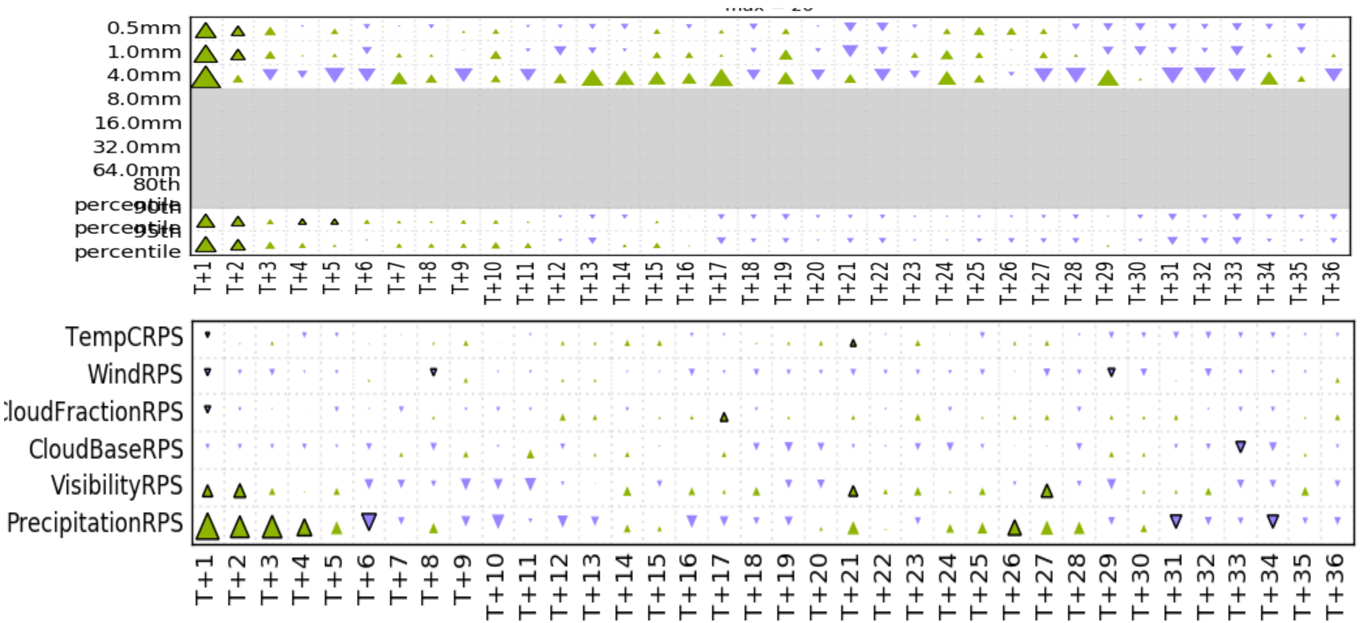


Hawkness-Smith, LD, Simonin, D. Radar reflectivity assimilation using hourly cycling 4D-Var in the Met Office Unified Model. Q J R Meteorol Soc. 2021; 1516– 1538.

Results

Improved Fractions Skill score at all thresholds in the first few hours.

Improved Precipitation Rank Probability Score, and neutral impact on other scores.



- Direct assimilation of radar reflectivity now operational for UK & Ireland radars.
- Extension to French and German radars planned for 2025

Hawkness-Smith, LD, Simonin, D. Radar reflectivity assimilation using hourly cycling 4D-Var in the Met Office Unified Model. Q J R Meteorol Soc. 2021; 1516– 1538.

Observation Uncertainties

In data assimilation the observation error statistics consists of a <u>measurement uncertainty</u> and a <u>representation uncertainty</u>, **R = E + F.**

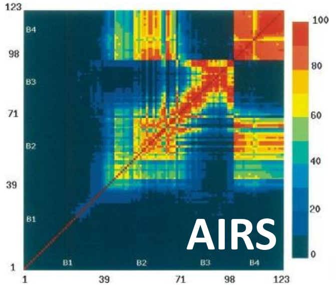
In practice to satisfy the current assumption of uncorrelated observation error:

- the observations are thinned,
- the error variances are inflated

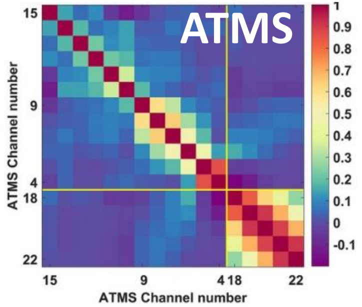
This reduces the observation usage to approximately 5%.

In global NWP, inter-channel error correlations are accounted for as the use leads to:

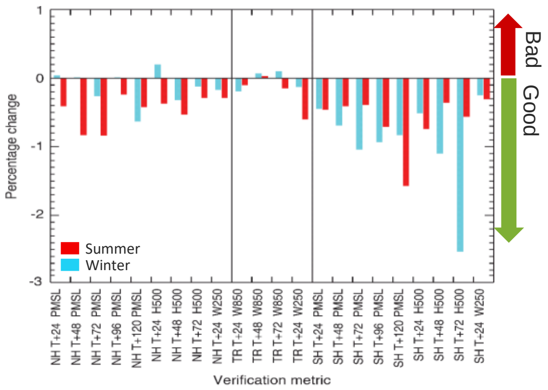
- Increase in the analysis accuracy.
- Improved fit of background to observations.
- Improvement in the forecast skill score.



Inter-channel error covariance matrix for AIRS
[Figure from Garand et al 2007]

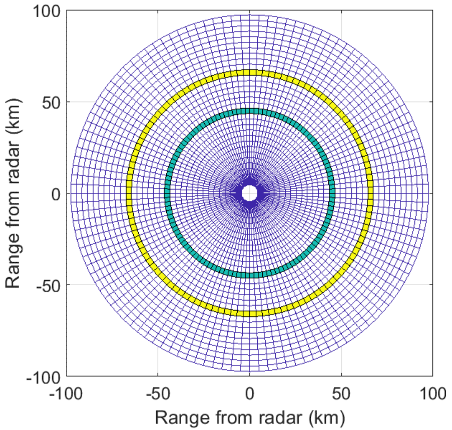


Inter-channel error covariance matrix for ATMS
[Figure from Campbell et al. 2017]

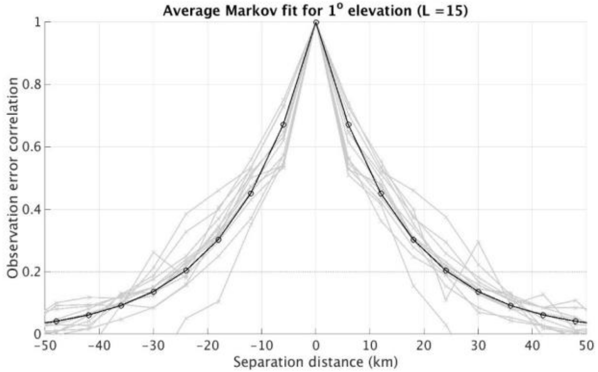


Change in RMSE and weighted skill against observations when accounting for IASI correlated errors. [Figure from Weston et al. 2014]

Correlated errors for radar winds



- UK radar network provides very high resolution observations that are under exploited in assimilation.
- Radar wind errors shown to have considerable correlation (Waller et al. 2016b).
- Use family method to include correlation and allow increased assimilation density Simonin et al. 2019.



Doppler radar radial wind error correlations

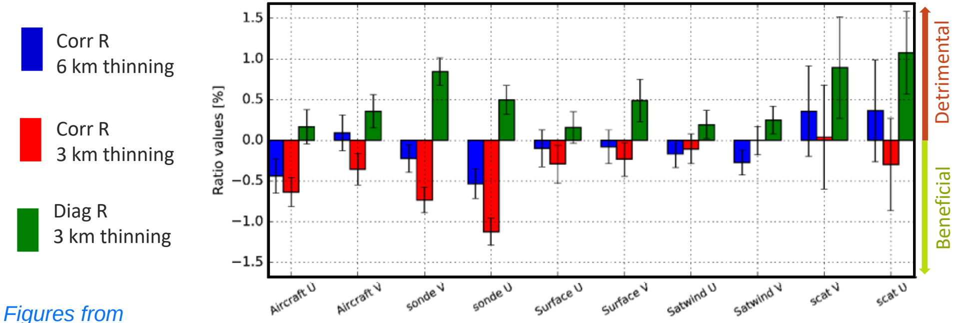
Very important! Additional cost of using error correlations not significant.

Experiment	Doppler wind observation error matrix	Observation thinning distance	Average time (s)
Control	Diagonal ***R*** (Operational)	6 km (~2000 rad obs. per cycle)	272
Corr-R-6km	Correlated ***R***	6 km (~2000 rad obs. per cycle)	293
Corr-R-3km	Correlated ***R***	3 km (~8000 rad obs. per cycle)	288
Diag-R-3km	Diagonal ***R*** (Operational)	3 km (~8000 rad obs. per cycle)	-

Simonin, D. Waller, JA. et Al. A pragmatic strategy for implementing spatially correlated observation errors in an operational system: An application to Doppler radial winds Q J R Meteorol Soc. 2019; 2772–2790

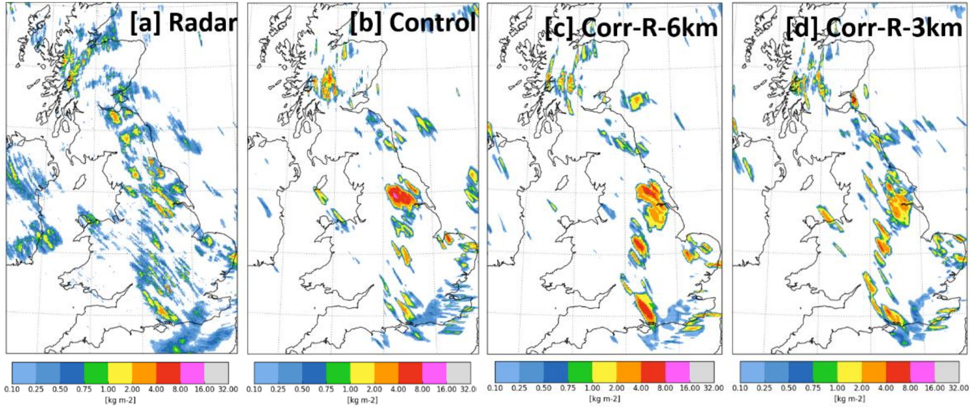
Results

- Improved fit to observations when observations assimilated with correlated errors.
- Further when observation density is increased.
- Increasing observation density without accounting for error correlations is very detrimental to fit to observations.
- Precipitation forecast has more small-scale information in when assimilating observations with correlated errors.
- Radar observations now assimilated with correlated errors in regional model.



[Figures from Simonin et al. 2019]

Trial average standard deviation ratio between the experiments and the Control



Hourly accumulated precipitation forecasts for 1500 UTC on 7 April 2016 at T+3.

[Simonin, D. Waller, JA. et Al. A pragmatic strategy for implementing spatially correlated observation errors in an operational system: An application to Doppler radial winds Q J R Meteorol Soc. 2019; 2772–2790]

Challenges for DA in NWP

Novel observations

Affordability

Coupled systems

Multiscale

Non-Gaussianity

Error representation

Non-linearity

Efficiency

Observation usage

Data volume

Machine learning

Scalability

Next-generation HPC

Summary and Conclusion

- Data assimilation is one of the contributors to the increase in forecast skill in recent decades.
- Operational DA is complex as it requires:
  - Complex processing of millions of heterogeneous observations.
  - Unification and communication between multiple observations and modelling systems.
  - An efficient and robust DA scheme that can ingest observations quickly.
- Next generation data assimilation systems are being developed that benefit from shared code and expertise.
- One of the challenges in DA is extracting the maximum amount of information from all the available observations. Forecasts have been improved by:
  - Introducing new observation types.
  - Making better use of existing observations.
- There are many upcoming challenges for operational data assimilation.