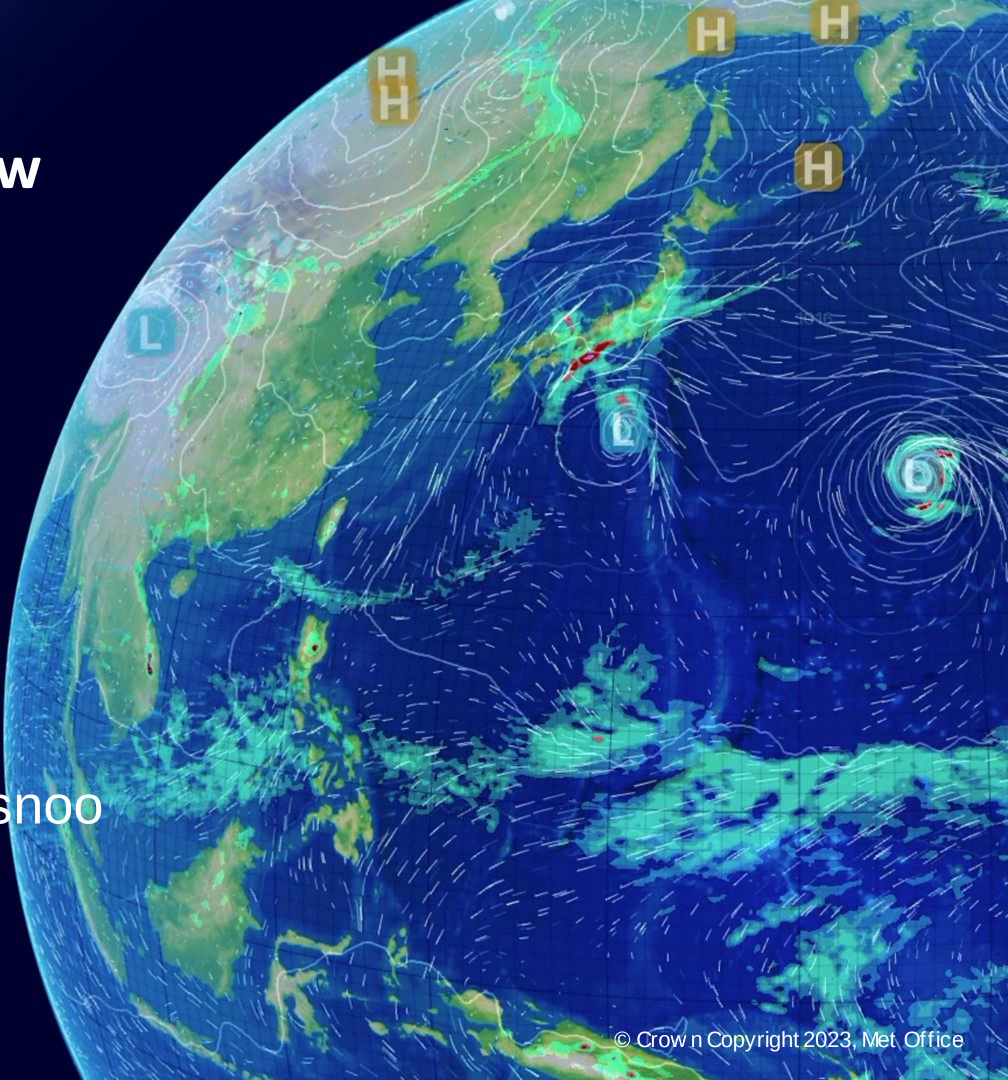
Steps towards assimilating a new observation type: Radar reflectivities



Lee Hawkness-Smith,

David Simonin, Jo Waller, Nawal Husnoo

9 May 2023

MetOffice@Reading

Content

- Motivation: what is the forecast we are trying to improve for?
- Understanding the model and observations
- Monitoring and quality control
- Development of assimilation scheme
- Implementation and verification
- Continued development

Motivation

Warning of flash flooding impacts

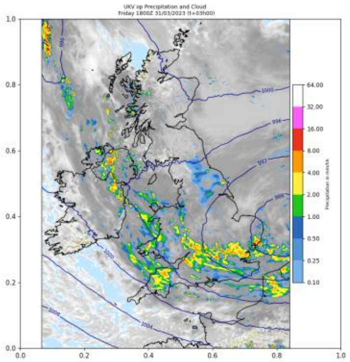
University of Reading campus, 31 March 2023

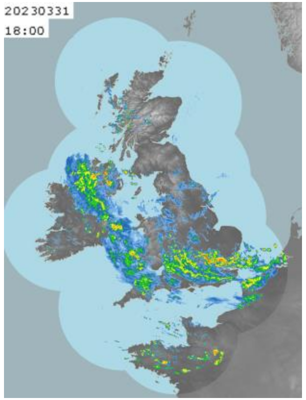
On my way home, I saw a car in a roadside ditch, and an underpass was blocked for 4 days

Nowcasting: forecast hazardous weather and precipitation *quantitatively* and *promptly*

~ to T+6 within 15 minutes of data time

Comparison of nowcasting techniques





Extrapolation

✓ Quick and simple technique

× What about orographic enhancement, mesoscale dynamics, etc. ?

Numerical Weather Prediction (NWP)

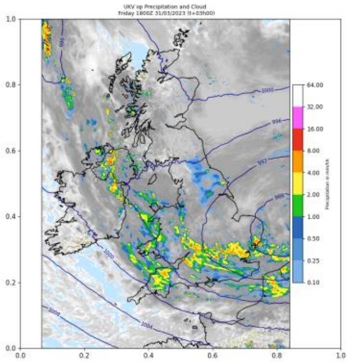
✓ More physically realistic modelling of the evolution of weather events

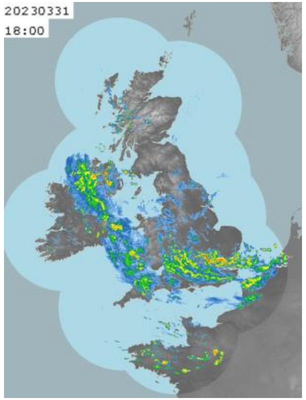
× Requires high spatial and temporal resolution modelling and data assimilation
→ Rapid collection, processing and dissemination of large data volumes
→ Takes time to compute and to spin-up

Blended forecast

- Use a blend of best available data at given forecast time

Data assimilation techniques used for radar data at Met Office





Latent heat nudging (soon to be retired)

- Rescale model latent heat profiles by the ratio of observation / model precipitation ratios. Separate process only used for radar derived precipitation observations

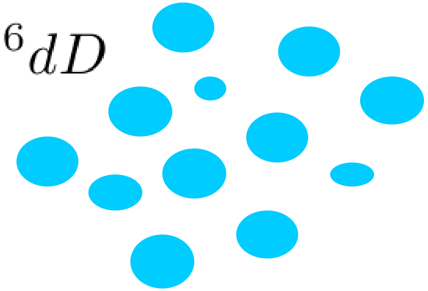
4D-Var (subject of this talk, now active and under development)

- Minimise the differences between the model and **ALL** observations as the model evolves

Understanding the model and observations

Radar observations: What are they and what do they tell us?

$$Z = \int_0^\infty N(D)\, D^6 dD$$



Reflectivity factor in Rayleigh scattering regime

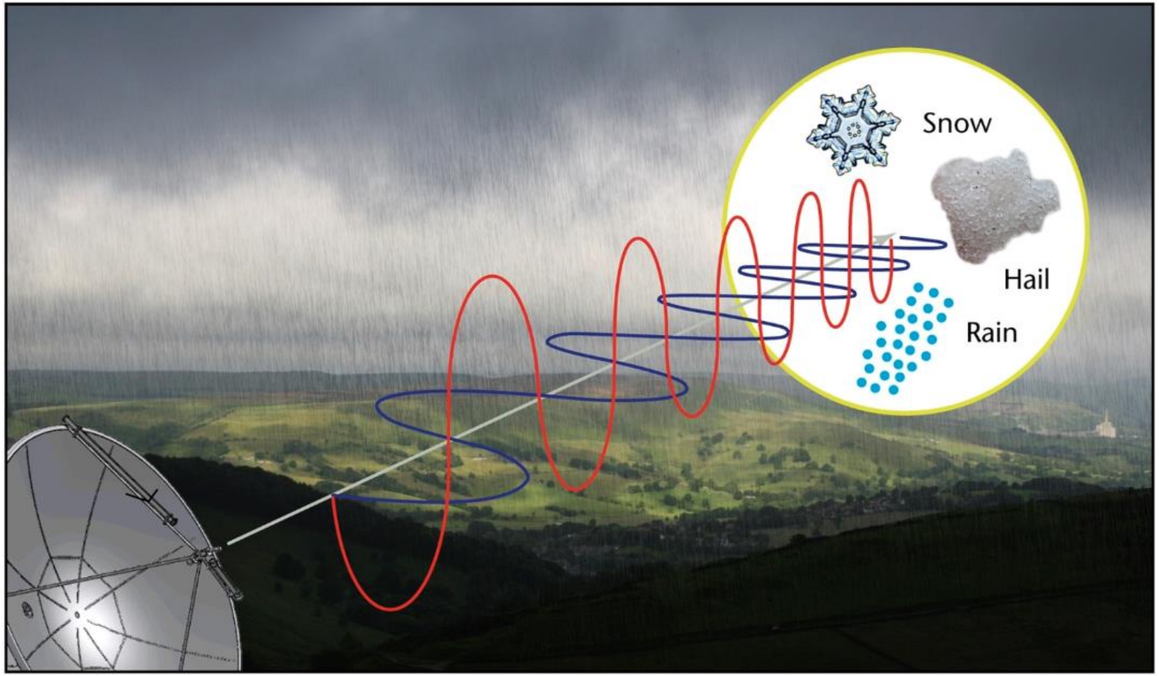
$$\Delta f = \frac{2V}{\lambda}$$

Radial velocity from Doppler shift

$$\Delta N \approx \frac{c}{4\pi f_t} \frac{10^6}{G_{ij}} \quad \text{with} \quad G_{ij} \approx \frac{\Delta\phi(d_j) - \Delta\phi(d_i)}{d_j - d_i}$$

Refractivity changes

Radar observations: What are they and what do they tell us?

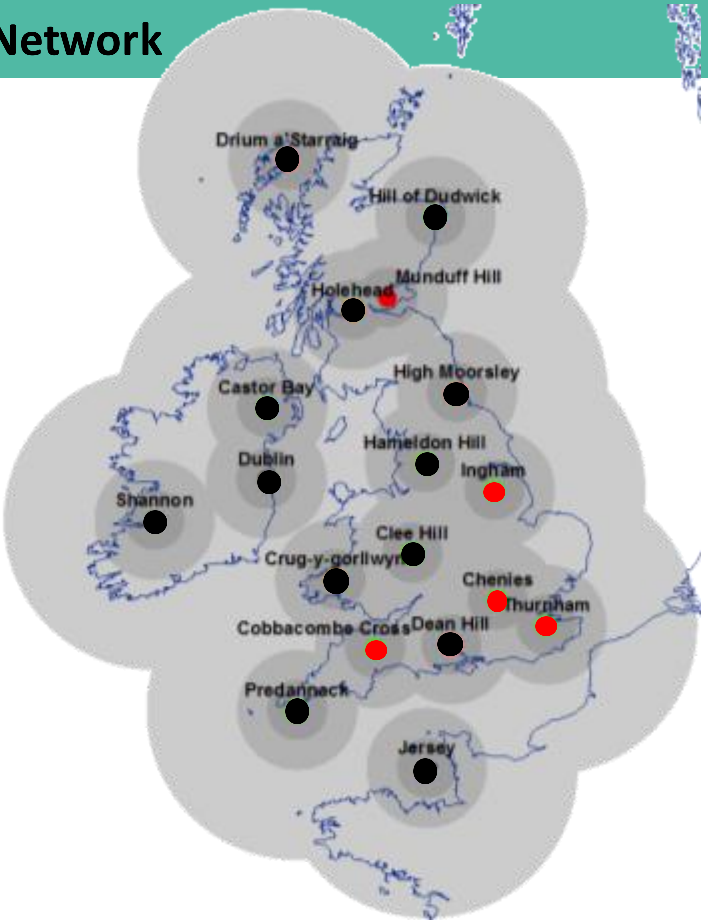


Dual-polarization gives information about particle size and shape, and can be used for quality control

Understanding the model and observations

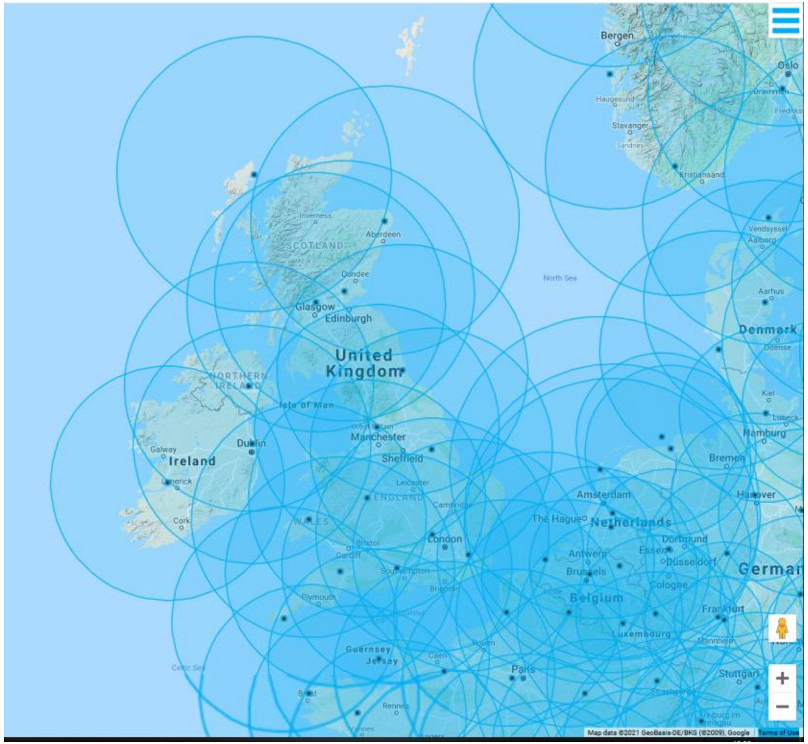
Radar observations: UK Radar Network

- 18 operational C-band weather radars in the British Isles
- All UK radars now Doppler and dual-polarization capable
- Up to 5 long-pulse reflectivity scans every 5 minutes out to 250 km
- Doppler scans every 10 minutes

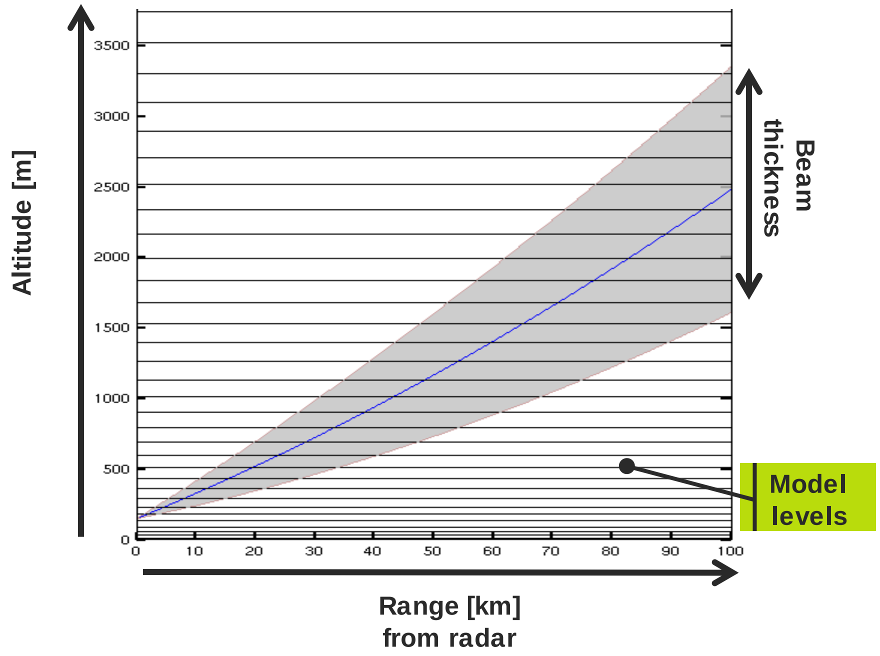


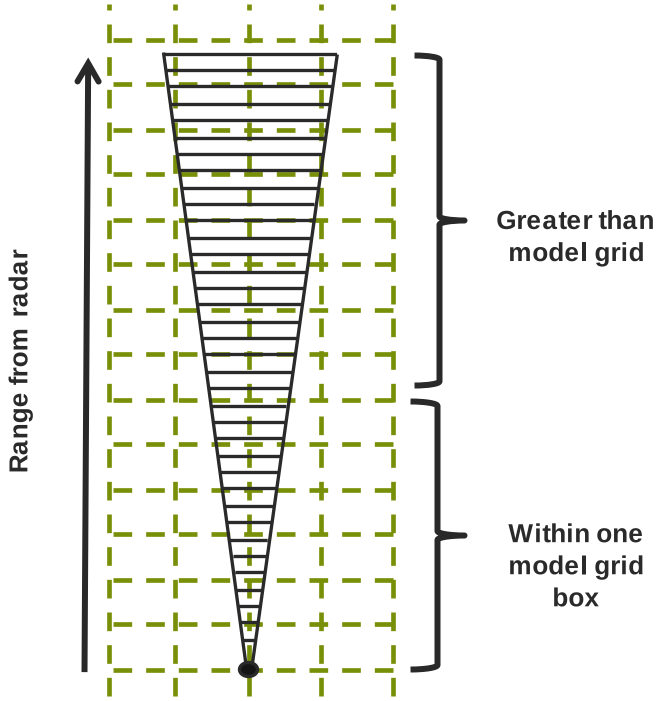
Radar observations: OPERA Radar network

- OPERA: 'Operational Programme for the Exchange of Weather Radar Information' has been exchanging European radar data for 20 years
- French and German radar scans also now available for assimilation in UK regional model



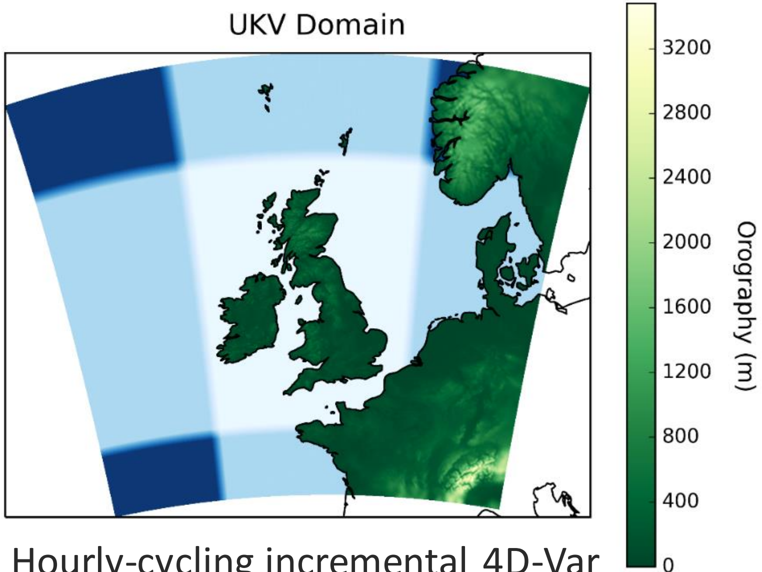
Radar observations: How are they distributed vertically?

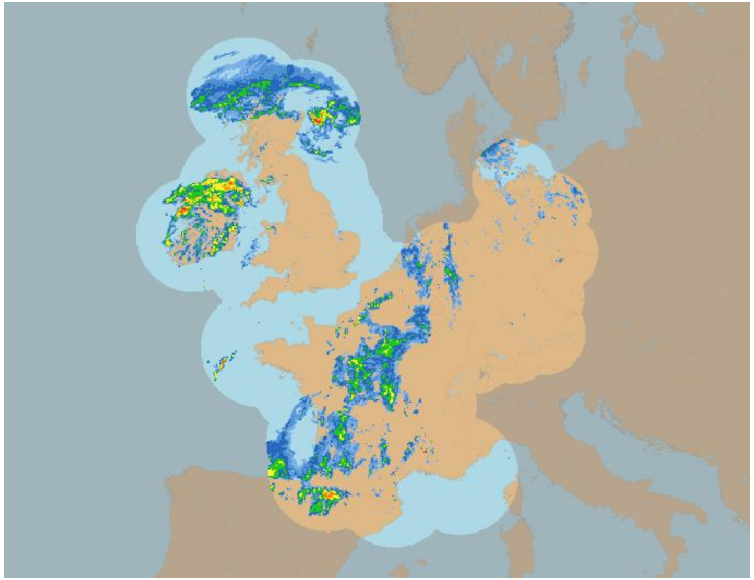




Understanding the model and observations

Regional model domain and radar-derived rainrate product

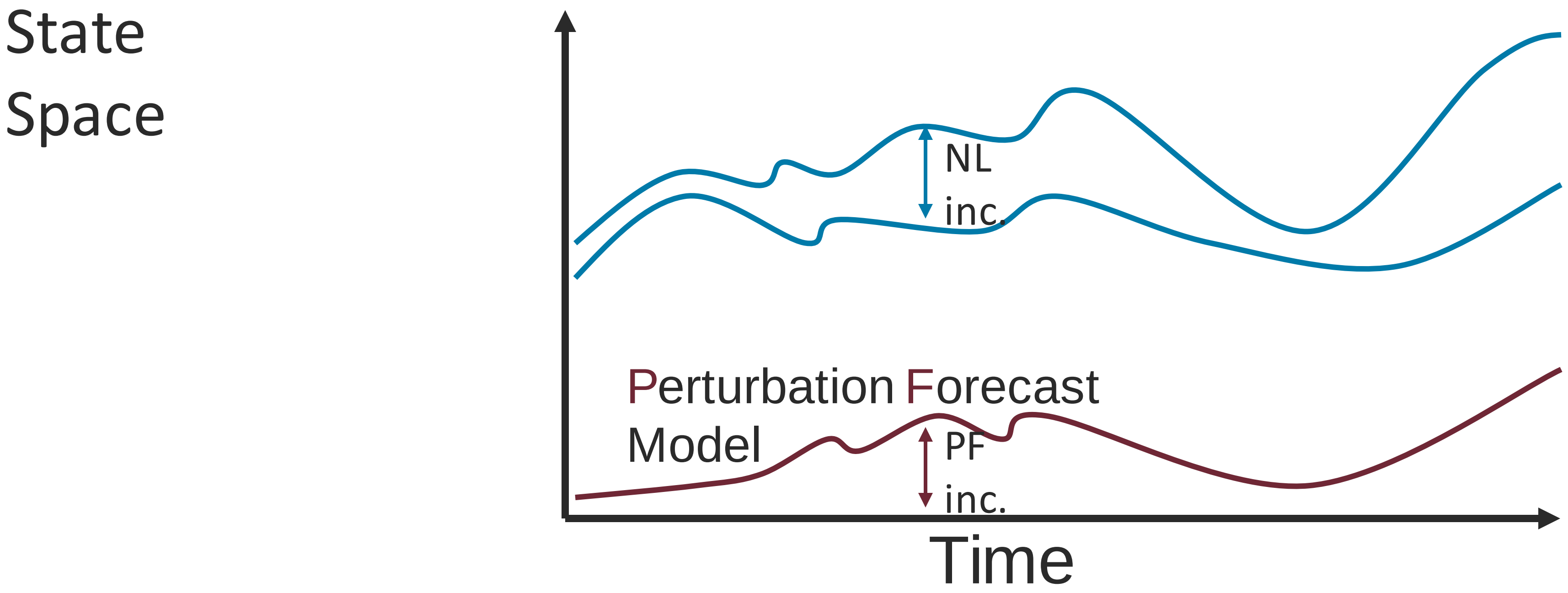




Hourly-cycling incremental 4D-Var
Single outer-loop
Milan et al. 2019

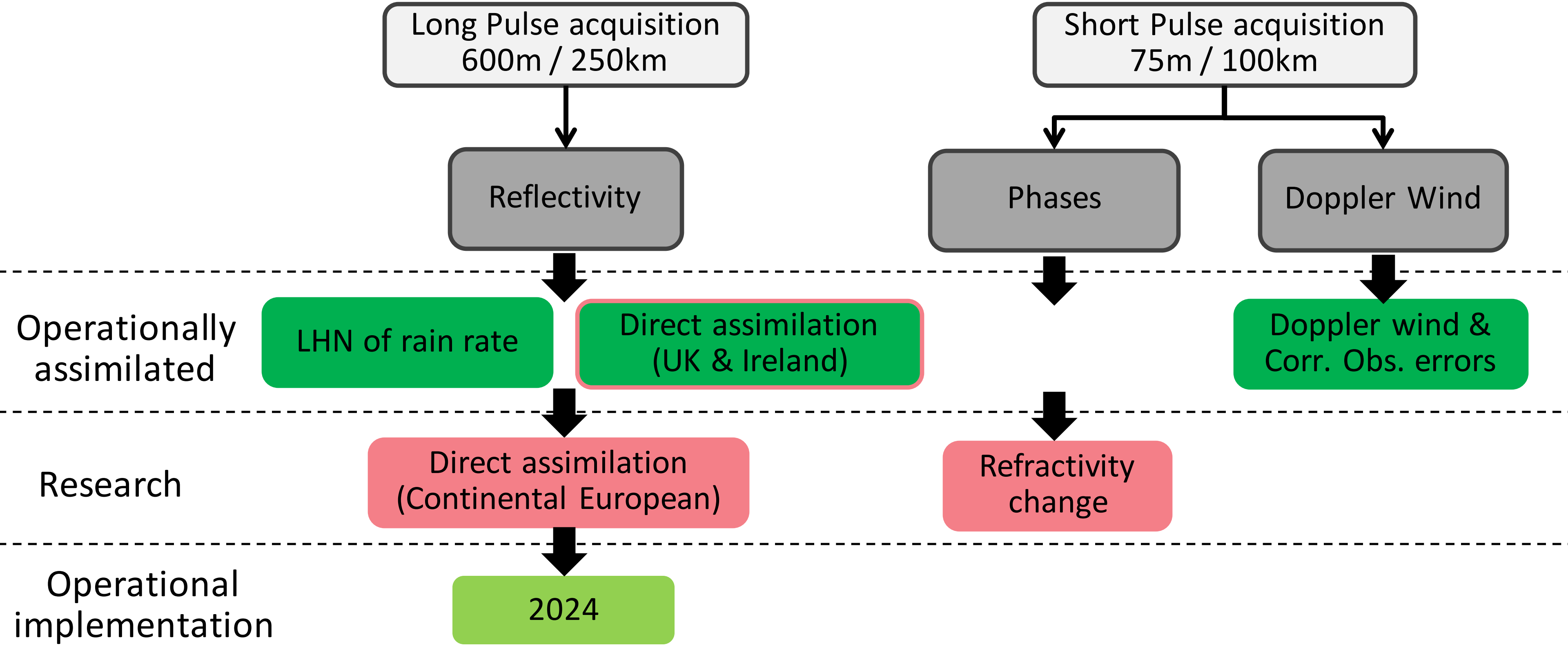
Understanding the model and observations

A preview of incremental 4D-Var…



For incremental 4D-Var we need a linear numerical model (and its adjoint) that approximates the dynamics and physics of nonlinear NWP model.

Current usage of radar data in NWP



Met Office

- Monitoring and quality control

Monitoring and quality control

Use of radar scans

P rti l beamf ll ng

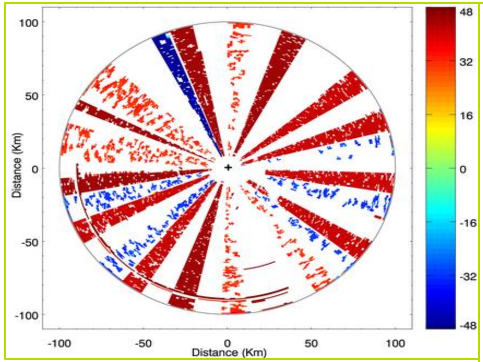
wet radome

attenuation

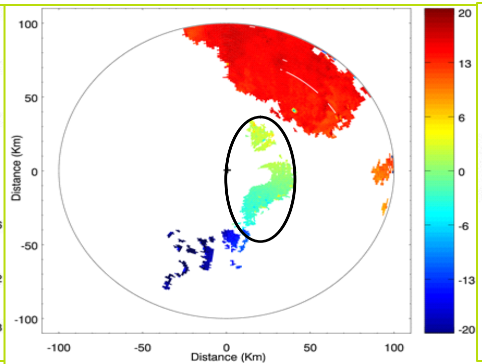
anomolous propagation

-NOISE-

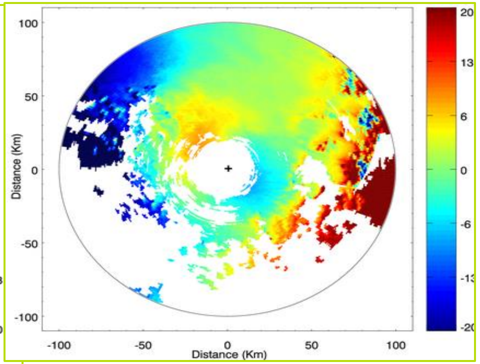
Radar failure



Sea clutter

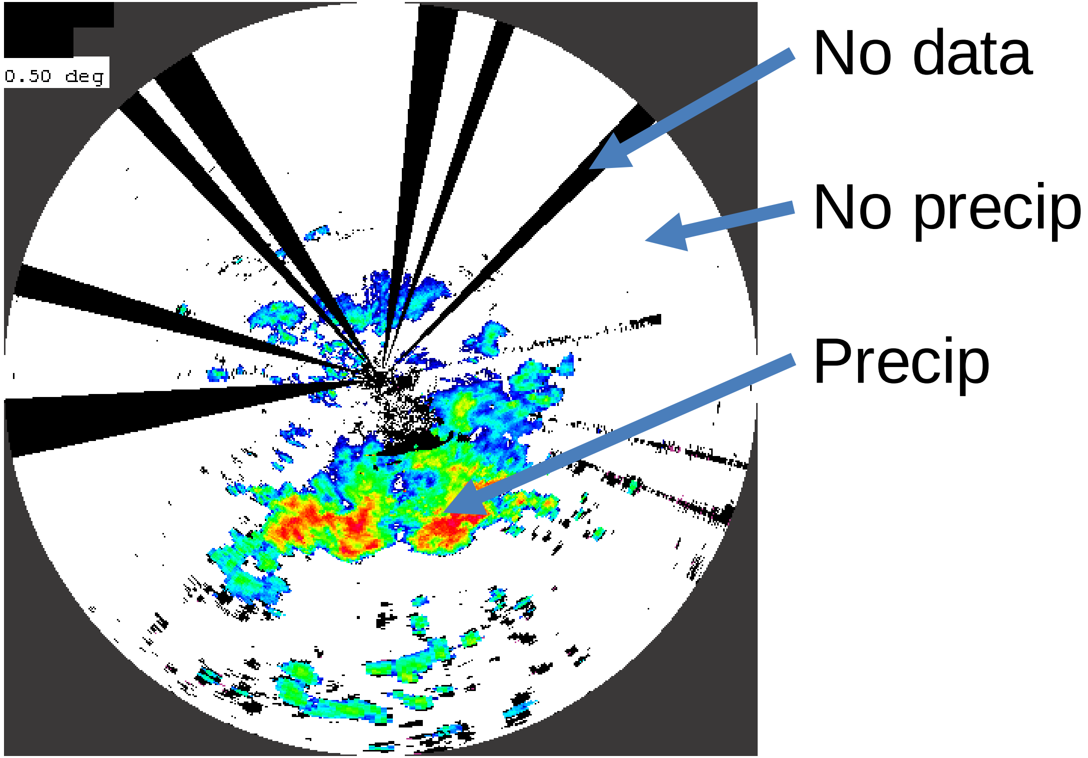


Unfolding



Monitoring and quality control

Use of radar scans



We can assimilate *Precip* and *No precip* observations

Monitoring and quality control

Observation operator: empirical relation

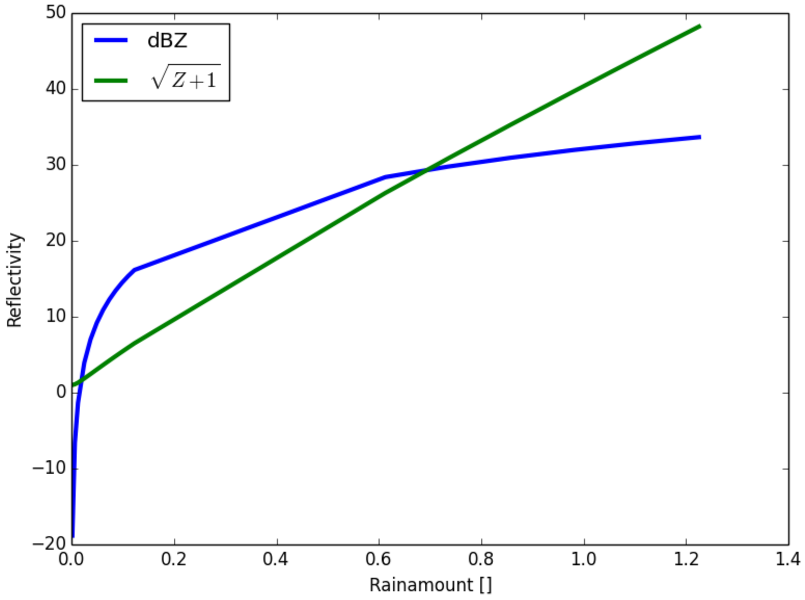
- Interpolation to a point – No beam broadening
- A simple empirical reflectivity (Z) -rain mixing ratio (q_r) relation (no ice assimilation):

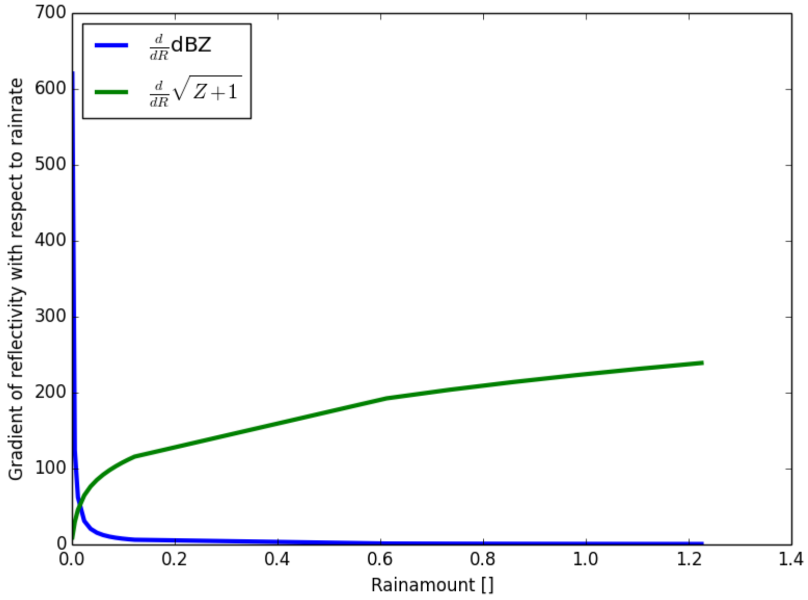
$$Z_R = 1.63x10^3 q_r^{7/4.0}$$

- BUT – range of Z_R spans many orders of magnitude! (Remember it scales with D^6)
- Reflectivity usually expressed in logarithmic units, dBZ ($10 \times \log_{10}Z$)

Monitoring and quality control

Observation operator: variable transform





- Unit of reflectivity are transformed from ZR [mm6 m-3] to $\sqrt{Z_R + 1}$

  → Compress the range and scale with the water mass

Monitoring and quality control

Reflectivity observation & QC

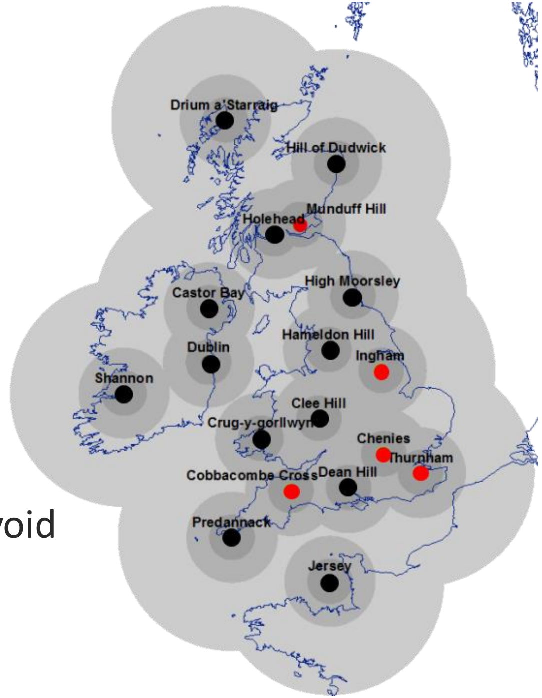
A replacement from the The Met Office latent heat nudging method to assimilate a radar derived surface precipitation product (over 25 years)

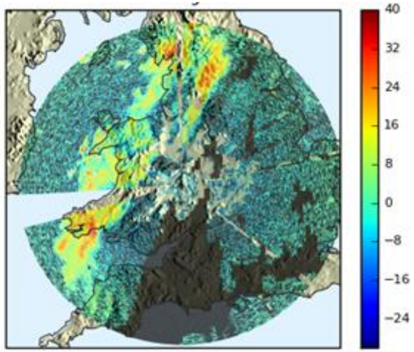
General information

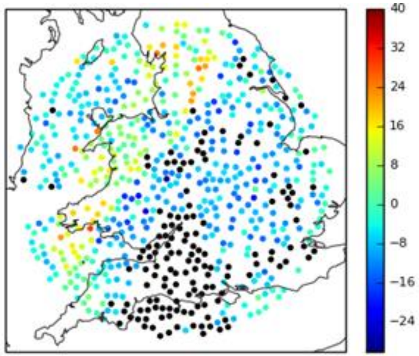
- 4D-Var hourly cycle / UKV.
- 3 volumes scans (0, 15, 30 minutes)
- Both dry and wet observations are used.
- Only apply so far to UK radar.
  → Outside the UK LHN

Quality control

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







Monitoring and quality control

Super-Observations and thinning

Super-Observations

It involves the combination or averaging of separate but relatively close observations into a single observation representing a larger spatial scale. The innovations are averaged and applied to the central location in the super-observation circle.

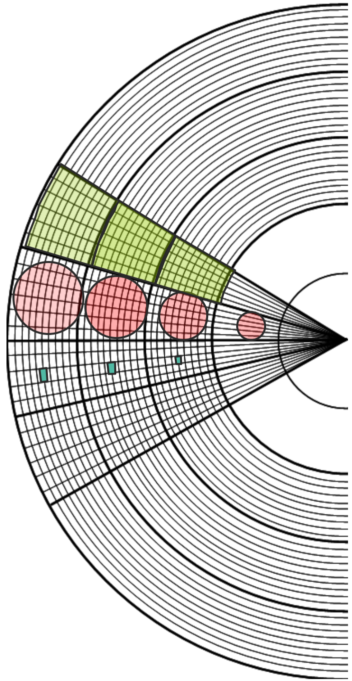
$$Y^{\mathrm{o}} = H(x^{\mathrm{b}})_{\mathrm{c}} + \sum_{i=1}^{n}[y_i^{\mathrm{o}} - H(x^{\mathrm{b}})_i]$$

It reduces data volume and uncorrelated observation errors.

Super-Observation size: 15° by 15km

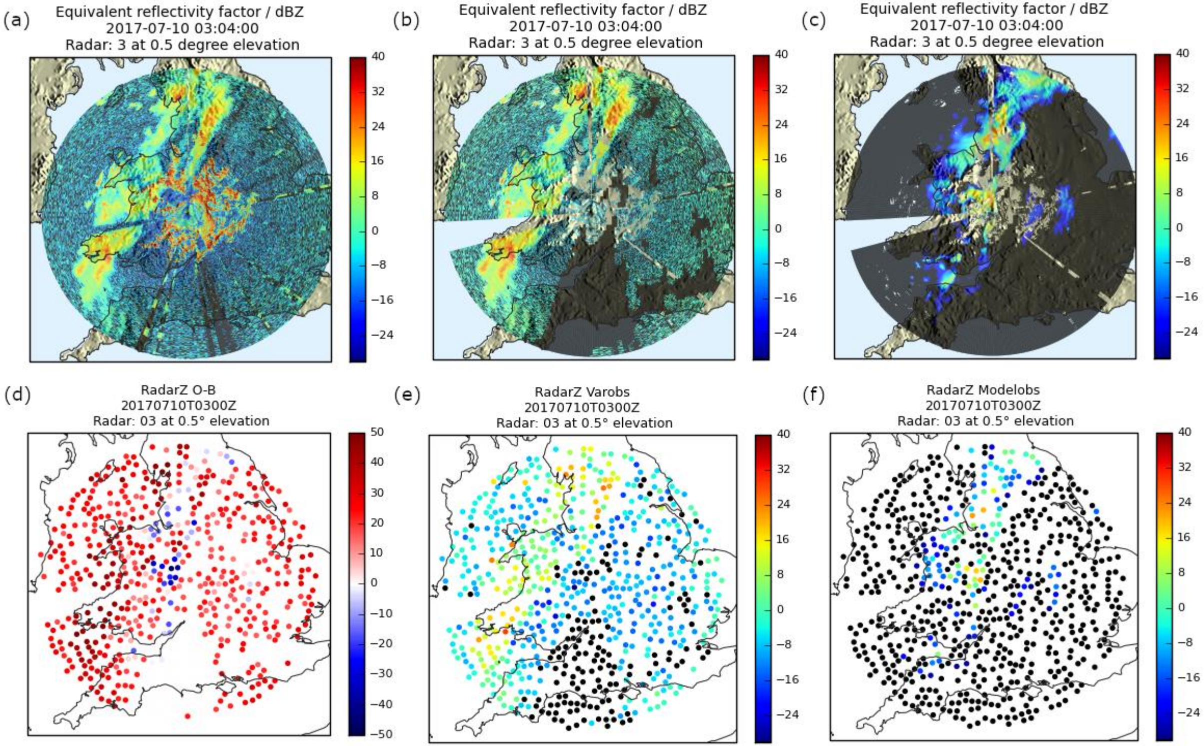
Thinning

Poisson disk thinning (constrained, uniform distribution)
15km separation for precipitation, 30km dry observations
Vertical thinning currently set to 15km → single layer



Monitoring and quality control

Monitoring



- Development of assimilation scheme

The next few slides were written when I started this project, about the same time as I was taking this course myself for the first time…

PF model development

Improvements in physical realism vs. linearity constraints

- Cloud microphysics
- Convection: Nonlinear/Triggered/On-Off
- Large scale precipitation (frontal rain)
- Boundary Layer

Compare PF model increment to NL model increment.

Challenges

- Scale

  How do we combine high-res local obs like radar reflectivity with large-scale extensive obs?

- Cycling

  Too slow and we don't capture the fast evolution of convective systems, too fast and spin-up dominates

- Control variables

  Which variables do we minimise with respect to? Currently use total water

More specific challenges…

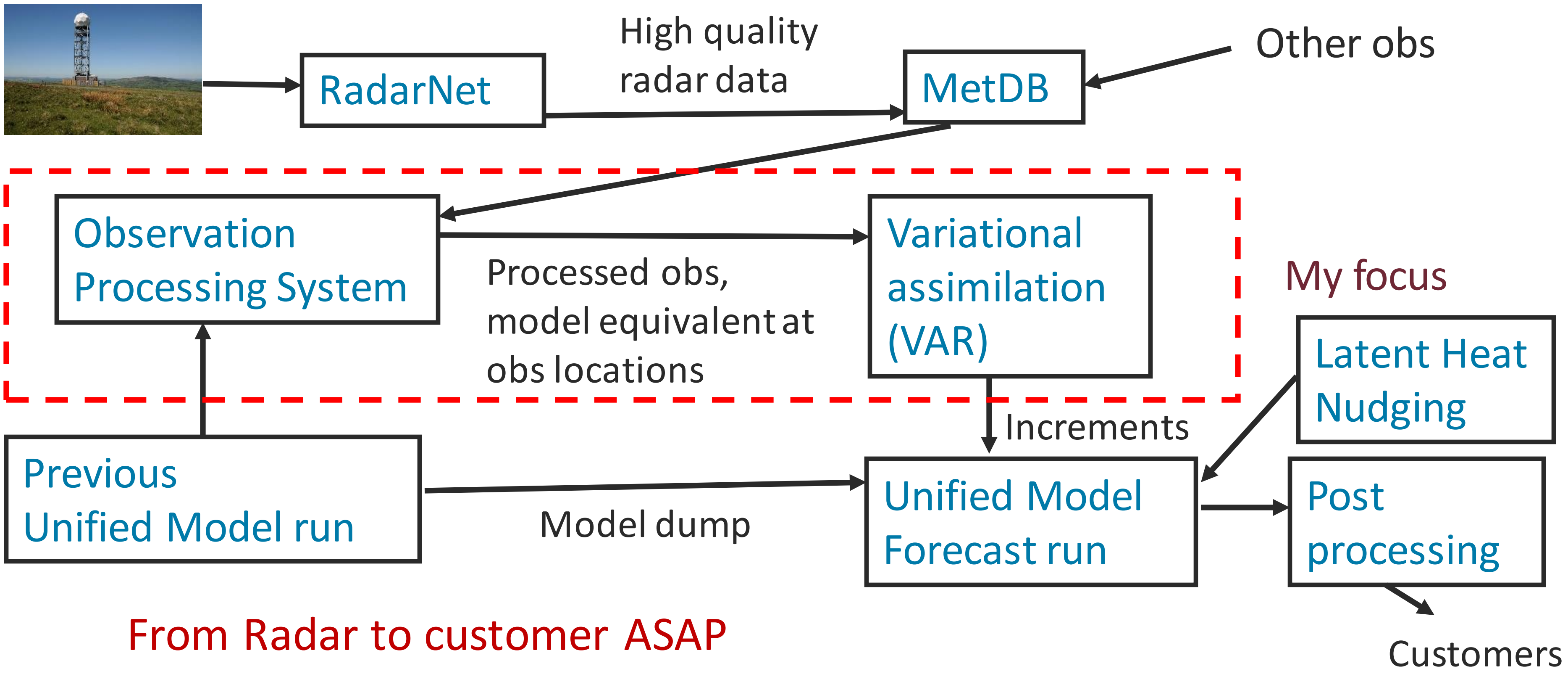
- Non-linearity
  - Clouds and precipitation are not linear!
- It gets worse
  - Reflectivity is *REALLY* non-linear – how will our minimisation schemes converge at all, let alone to a good solution?
- Spatial mis-match
  - What do we do when observed and modelled precip don't overlap?
  - Not so bad for frontal systems, convective showers more of an issue
  - How do you measure the cost of no rain compared to some rain?

Work so far

- Learning data assimilation
- Introducing reflectivity as a new observation
- Introducing large-scale rain rate at all vertical levels as a PF-model variable
- Debugging
    - Resistance *WILL* prove futile

Development of assimilation scheme

NWP Production process



From Radar to customer ASAP

Development of assimilation scheme

Method

Radar Reflectivity operator:

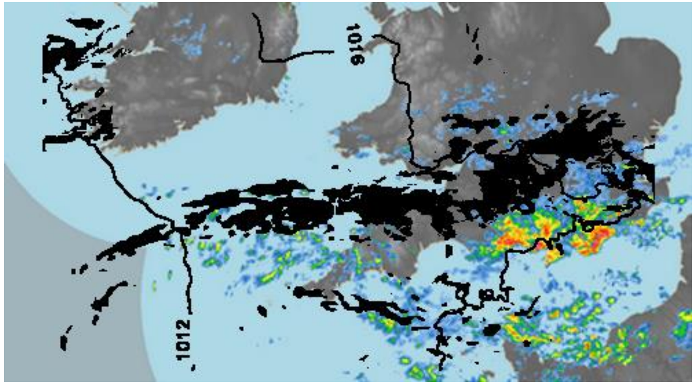
Current operator uses interpolation to a point and simple Z-q_r relation for rain (no ice assimilation yet)

Unified Model has reflectivity diagnostics, still need a simple relation for the PF & adjoint model

Innovations can be very large: reweight with Huber norm

Assimilate dry and rainy observations, reject non-hydrometeorological echoes

Fixed non-zero dZ/q_r where $q_r < q_{r\_CRIT}$ and precipitation observed to reduce zero-rain issue



Perturbation Forecast (PF) model:

Autoconversion-like term from diagnostic cloud water, rain falls out in single timestep (no evaporation)

No cloud and thus no rain increments where Zero cloud in LS state

Linearity assumption is poor for precipitation: only use Reflectivity obs in first 30 mins of window

Development of assimilation scheme

Observation error and Huber norm

Observation error:

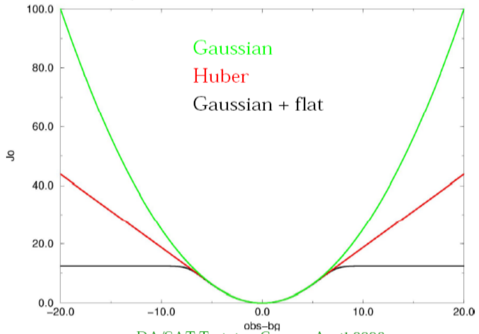
- 60 $[\sqrt{Z_R+1}]$ dry
- 30 $[\sqrt{Z_R+1}]$ one for precip.

(Use ½ (O-B) from first trials for precip.)

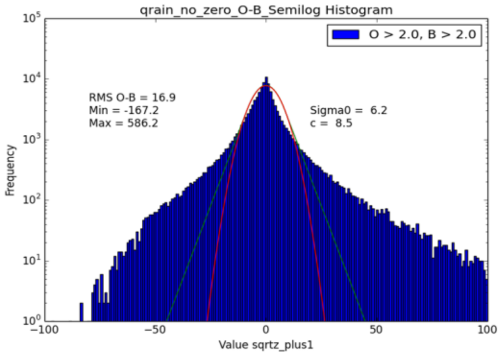
The Huber-norm – a compromise between the l_2 and l_1 norms

ECMWF

$$p^H = \begin{cases} x^2/2 & \text{if } |x| <= k, \\ k|x| - k^2/2 & \text{if } |x| > k, \end{cases}$$



DA/SAT Training Course, April 2008



Weights of large innovations reduced but not rejected

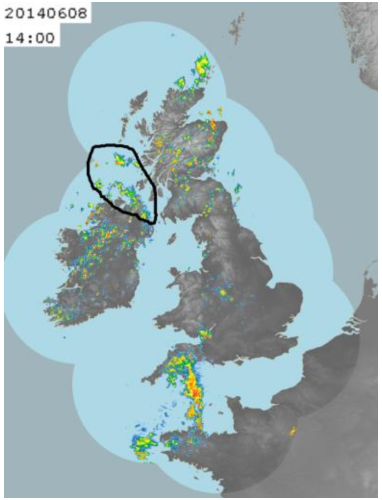
Alternative approach is to make a error a function of observation value (e.g. JMA)

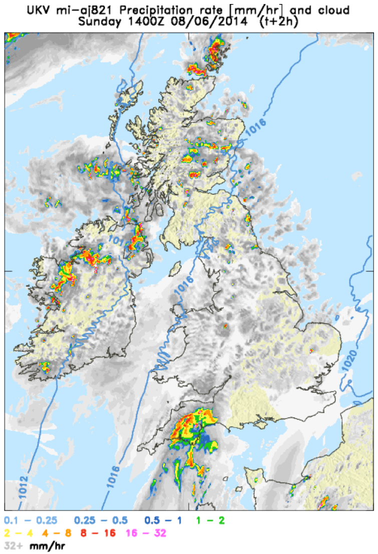
Met Office

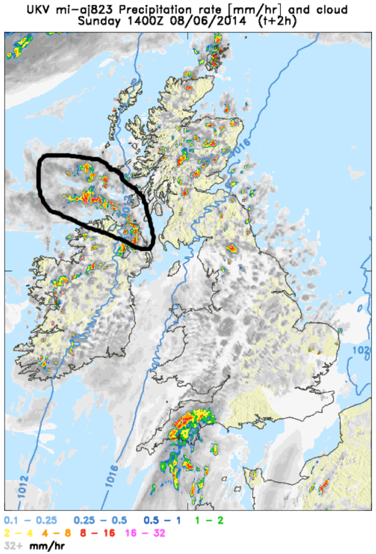
- Implementations and results

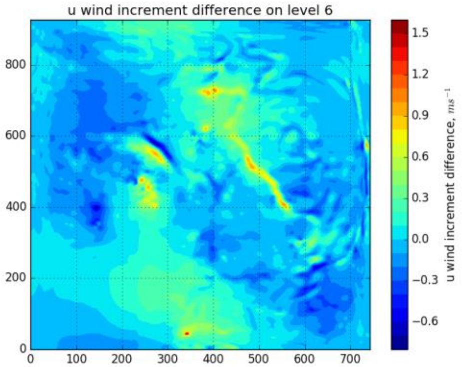
Implementation and results

Early experiments: version 0









Radar obs derived surface rain

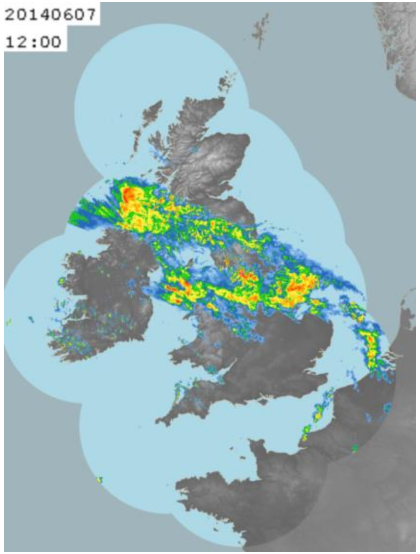
Control

RadarZ-NoLHN

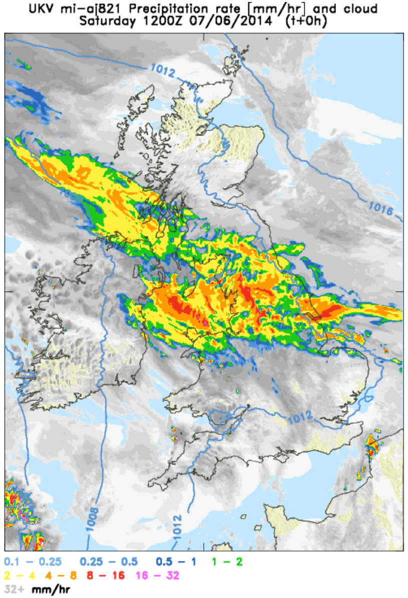
Level 6 u wind increment difference

Implementation and results

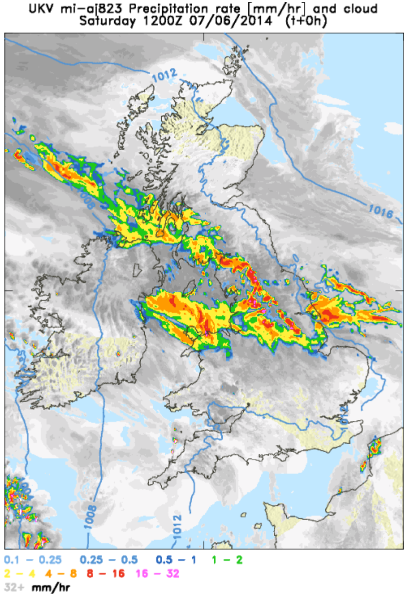
Early experiments: version 0



Radar obs derived



Control Analysis



RadarZ-NoLHN Analysis

Promising initial results but scheme had dry bias

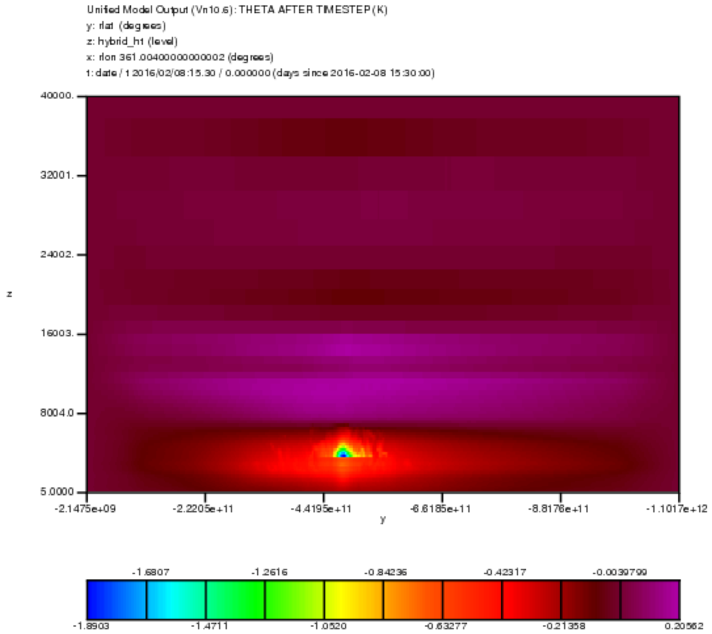
Early experiments: version 0.1…

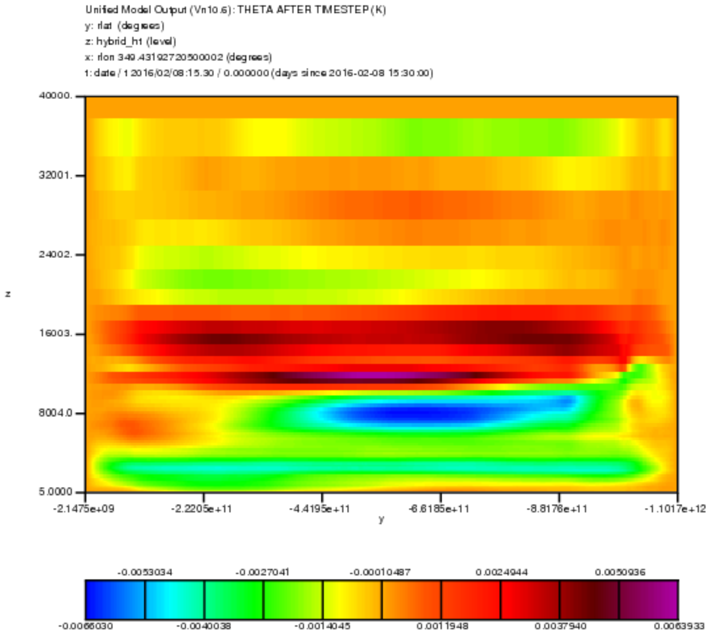
08 Feb 2016 16UTC: Theta increment

Analysing failed cycles from different trial periods in more detail showed evidence of:

stratospheric ringing

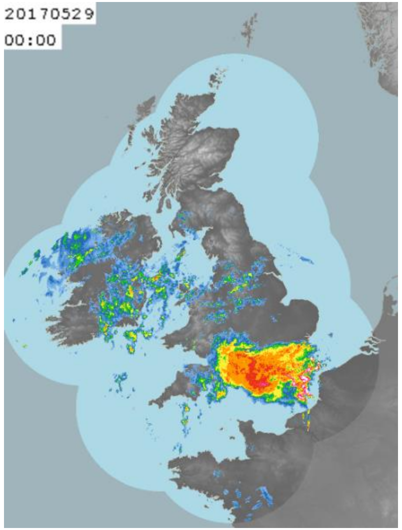
large qT and theta increments at ~5km altitude

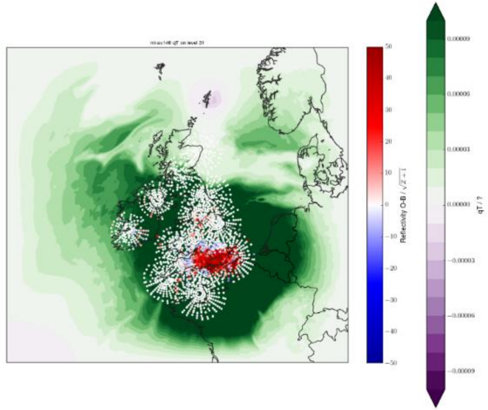


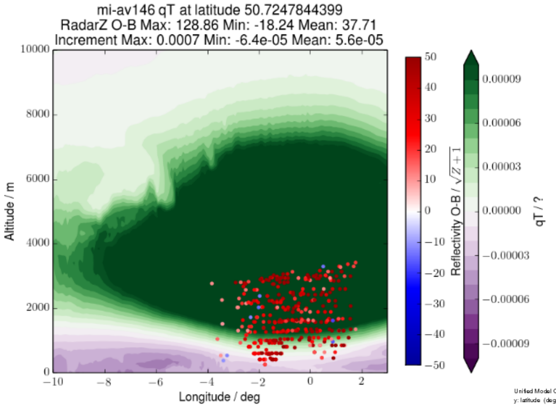


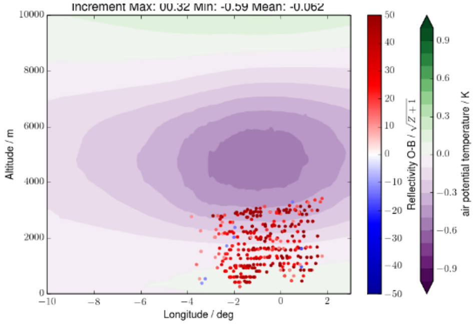
Implementation and results

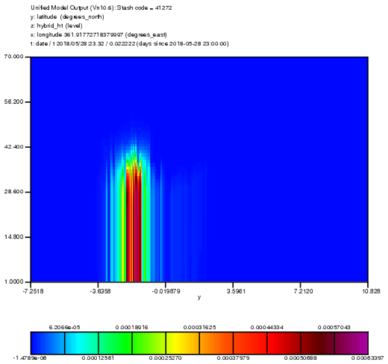
Early experiments: version 0.1…











Implementation and results

First attempt at implementation

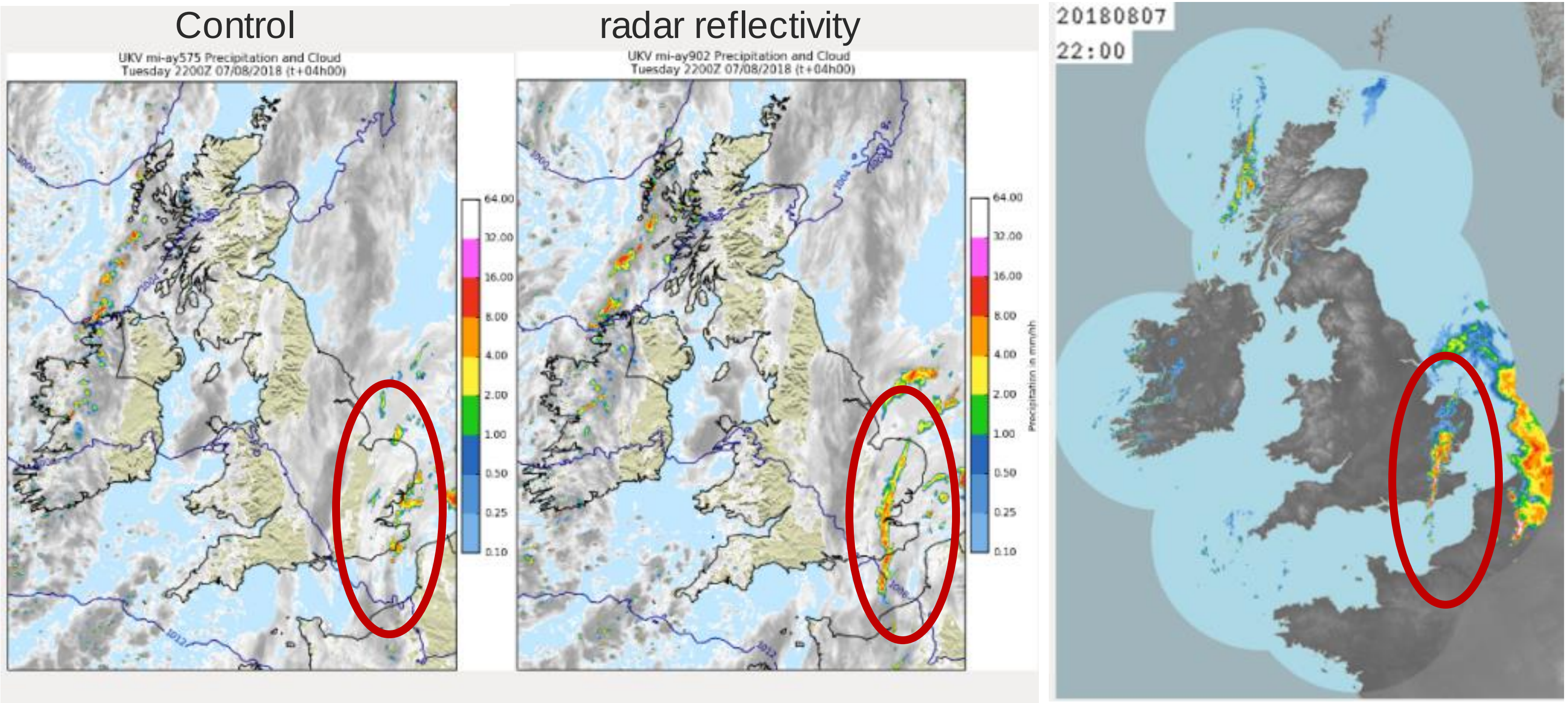
Two main components of Reflectivity package:

- Retune precipitation efficiency in linear PF model (from 0.0001 to 0.001) – for stability
- Enable direct reflectivity assimilation in UK/Ireland area using grib2 data (latent heat nudging remains for now, and includes data from France and Germany)

Implementation and results

07/08/2018 18Z T+4 Precipitation

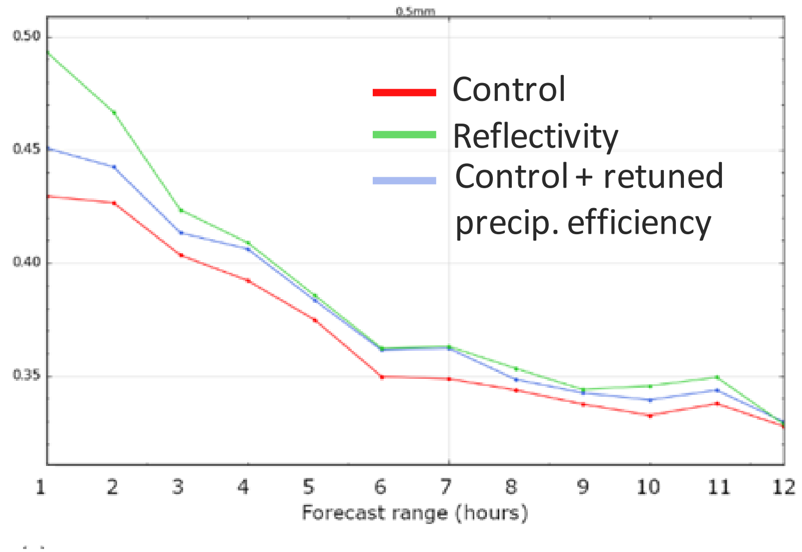
Direct reflectivity assimilation experiment has good organization of arc in South-East England

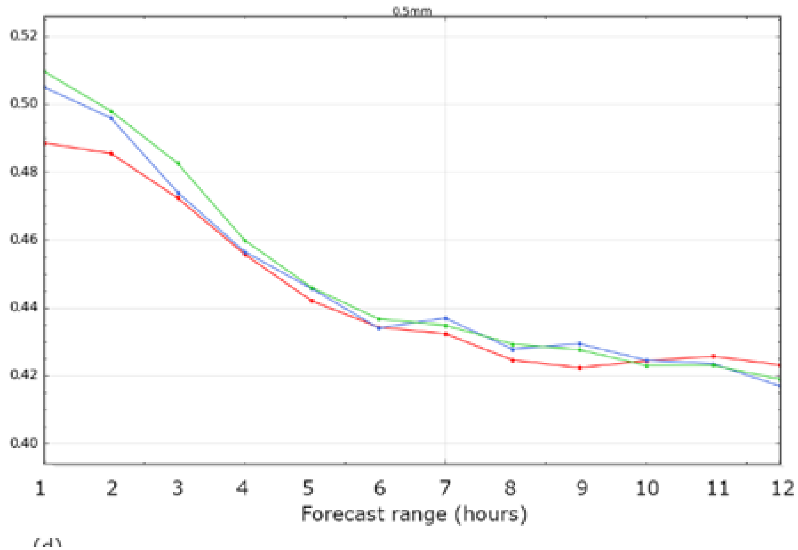


Implementation and results

Results

Fractions Skill Score – 0.5 mm – 35 km

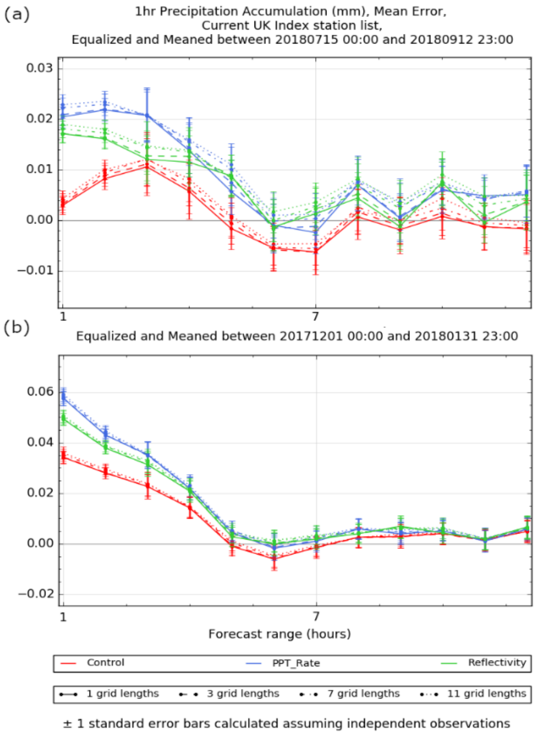




Implementation and results

Results

Precipitation accumulation bias measured against gauges



Summer 2018

Winter 2018

Implementation and results

First attempt at implementation

Precipitation efficiency alone has significant cloud and consequent T2m impact

- Cloud overthickened in mid level → excessive precipitation in first couple of hours
- Detriment to Summer T2m, with degradation to diurnal cycle

Additional impact of reflectivity assimilation beneficial

Largest benefit for mesoscale organized convection

Package rejected due to excessive precipitation and T2m degradation

Implementation and results

Second (successful) attempt at implementation

- Restore the default precipitation efficiency, and instead diagnostically scale the q_{rain} increment
- Implement bug fix to Poisson thinning routine (which gives greater thinning to dry observations than rainy observations, as originally intended)
- Retune reflectivity operator based on offline bias estimation using Desroziers (2005) method:

$$Z_R = 4.0x10^3 q_r^{2.1}$$

- Reduce observation error for dry observations to match rainy observations

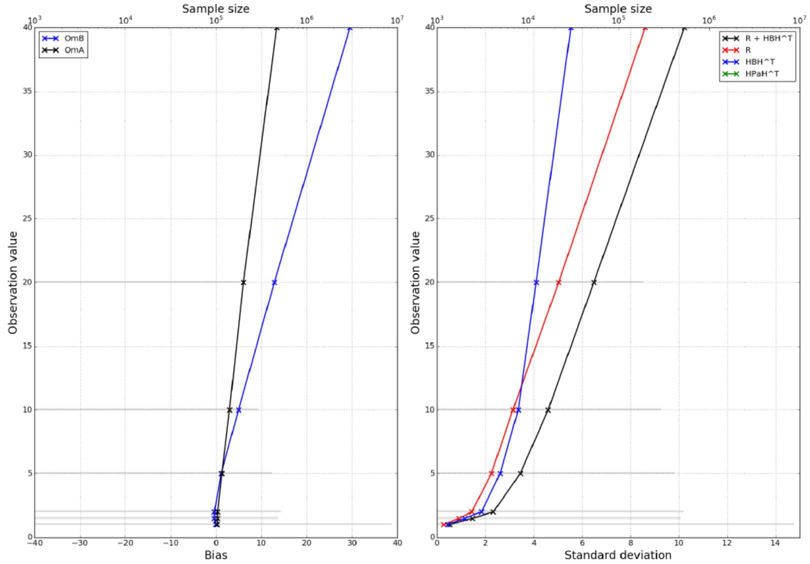


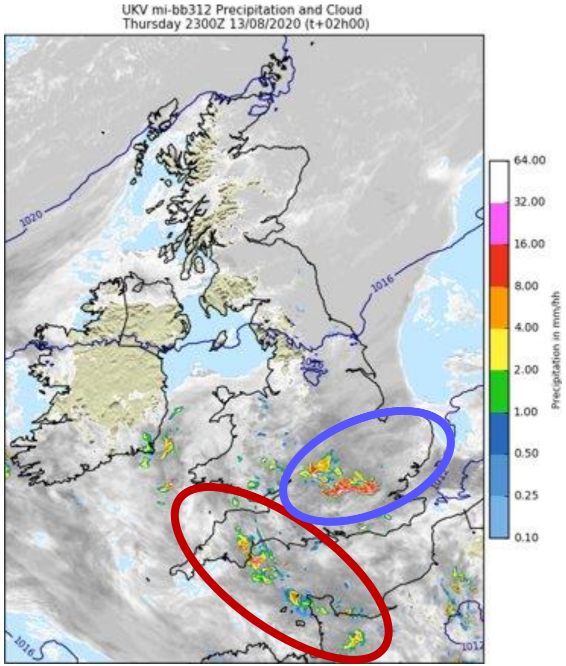
Figure 3 – Left panel) OmB and OmA bias for different observation values. Right panel) Estimated innovation $\mathbf{HBH}^T + \mathbf{R}$ (a), observation $\mathbf{R}$ and observation space background $\mathbf{HBH}^T$ standard deviations.

Implementation and results

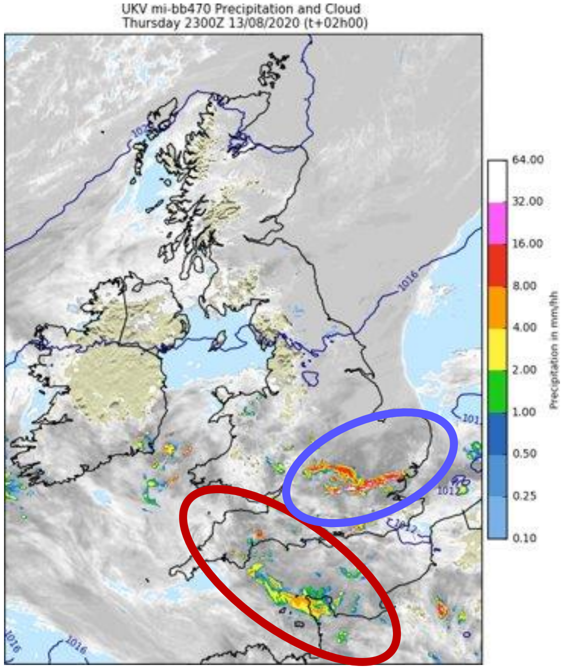
13 Aug 2020, T+2 2300

Improved organization of bands of convection across southern England and Channel

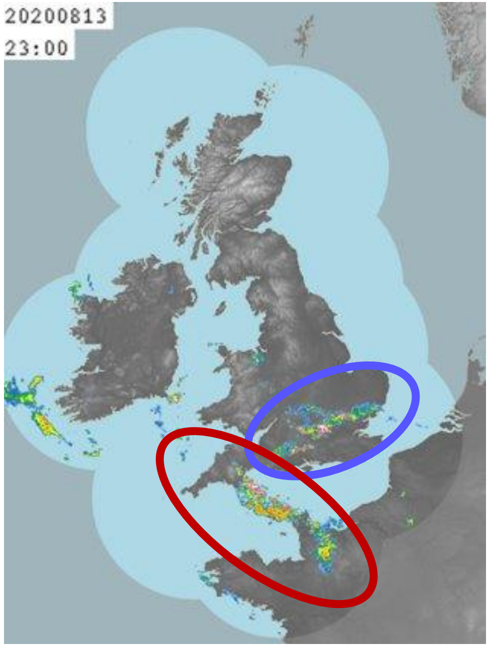
Control



Radar reflectivity experiment

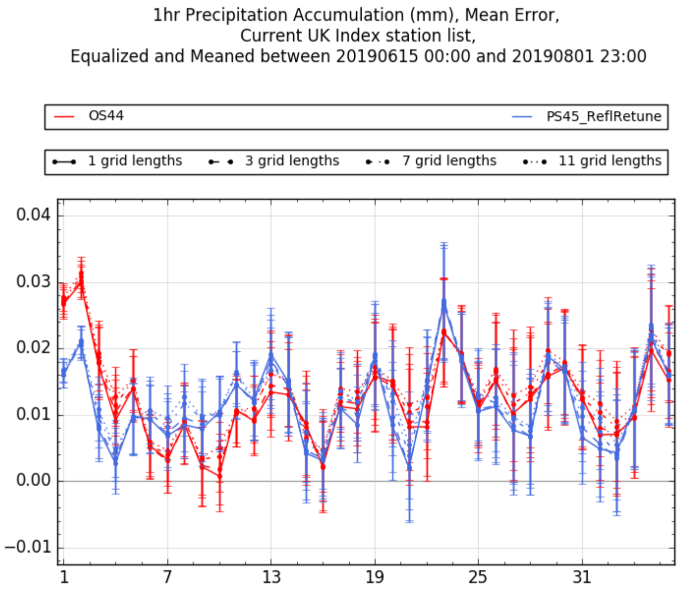


Radar composite

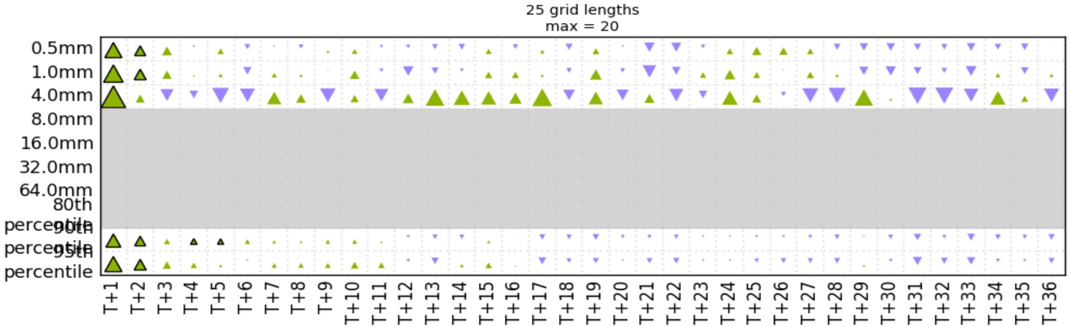


Implementation and results

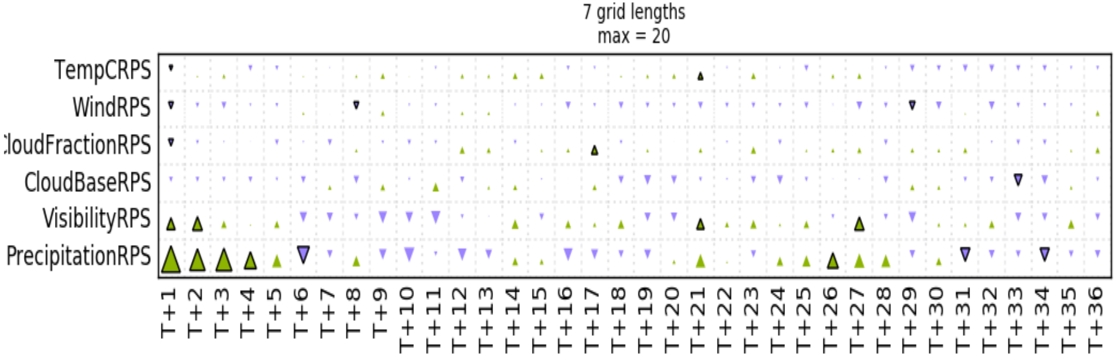
Trial results



Reduced 'spin-down' bias at model initialization



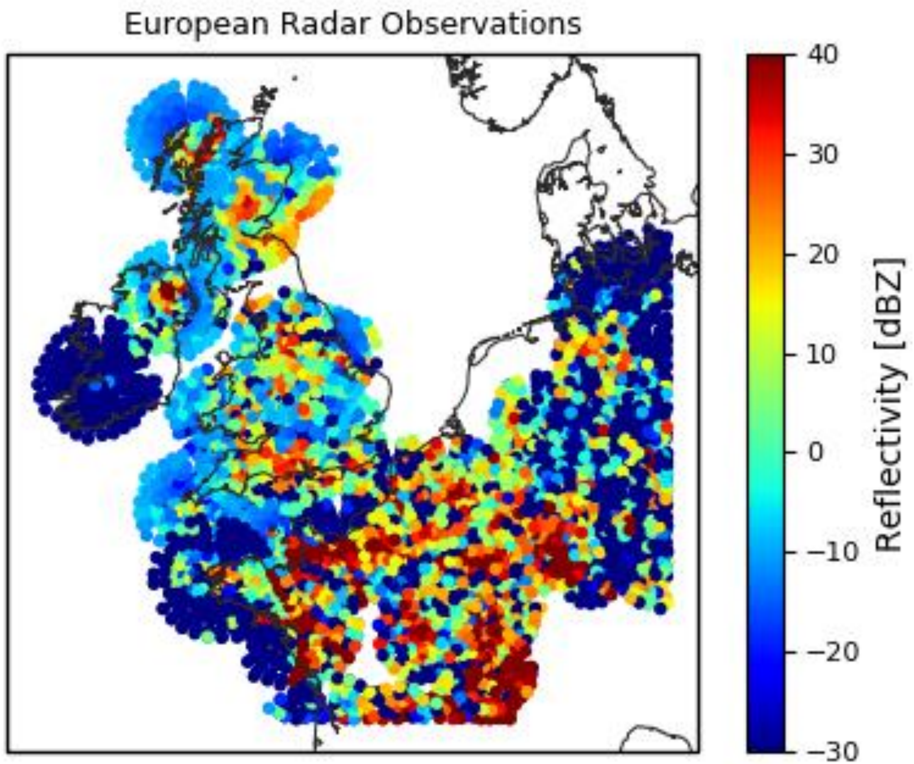
Improved Fractions Skill score at all thresholds



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

Continued development

Radar reflectivity super-observations



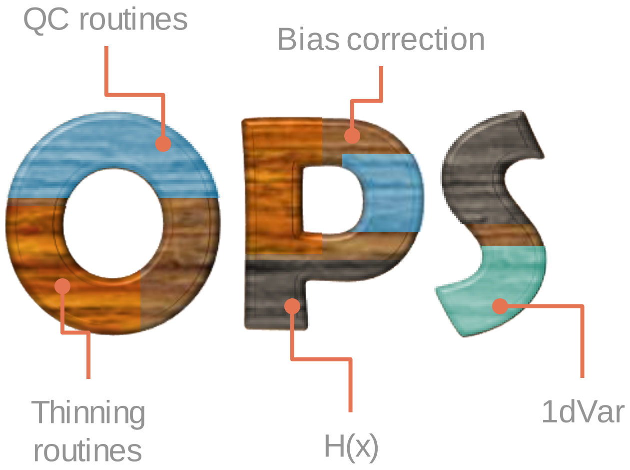
- Super-observations generated using lowest 3 elevations from C-band radars at T-30:T-25, T-15:T-10, T0:T5
- Some German scans with irregular number of rays – we reject this to simplify processing

Continued development

Re-code all observation processing: Joint Effort for Data assimilation Integration (JEDI)

Current system…

In our current system, the logical chain of processing applied to the observations is "**static**".



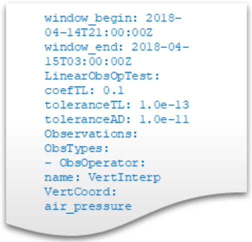
JOPA | JADA

The logical chain of processing is applied "**dynamically**".

→ Code free of any science

Collection of bricks
functions, methods, classes, procedures

Configuration file



Instructions
how to assemble the bricks

Assemble the bricks
using modern computation techniques

Direct assimilation of radar reflectivity

Summary

- What are you trying to predict?
- In what timeframe?
- Understand the structure of the observations and their information content and errors
- Understand the modelling system and its capabilities and errors
- Understand what the observations and the model can represent
- Need to monitor observations and apply careful quality control
- Consider which theoretical assumptions are valid, and how to reduce impact of invalid assumptions!

Reference

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.

Met Office

Many thanks

Questions?