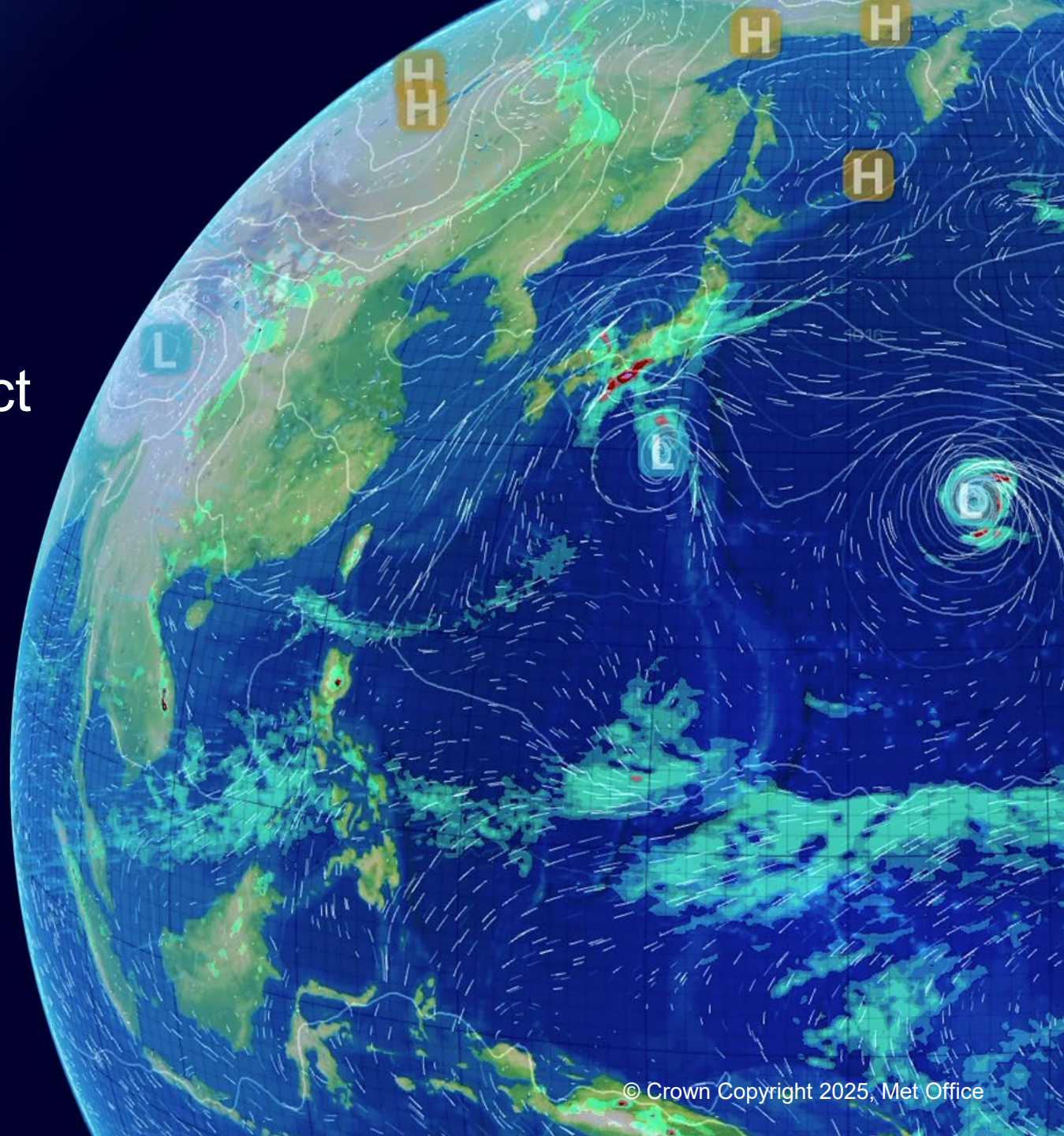
New tools and visualisations developed and planned to transform the way Met Office operational meteorologists interact with ensemble data

Brent Walker

Steve Willington

September 2025



This session

- Current forecast process and the barriers preventing greater ensemble integration
- Novel tools developed to address these challenges
  - Ensemble sensitivity analysis and ensemble sub-setting
  - Feature-based clustering
- Using these tools in the forecast process
- Plans for further development

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STRATEGIC ACTION Exploiting ensembles

What do Op Mets require from an ensemble?

(considerations as we continue to develop ensemble systems and improve the science)

- To bring something **extra** - in competition with other sources of data competing for Op Met attention.
- Offer **realistic** spread and confidence.
- **Consistency**: retain **focus** on area of concern – not **distracting** from the main threats.

Met Office

STRATEGIC ACTION Exploiting ensembles

What do Op Mets require to fully exploit ensembles?

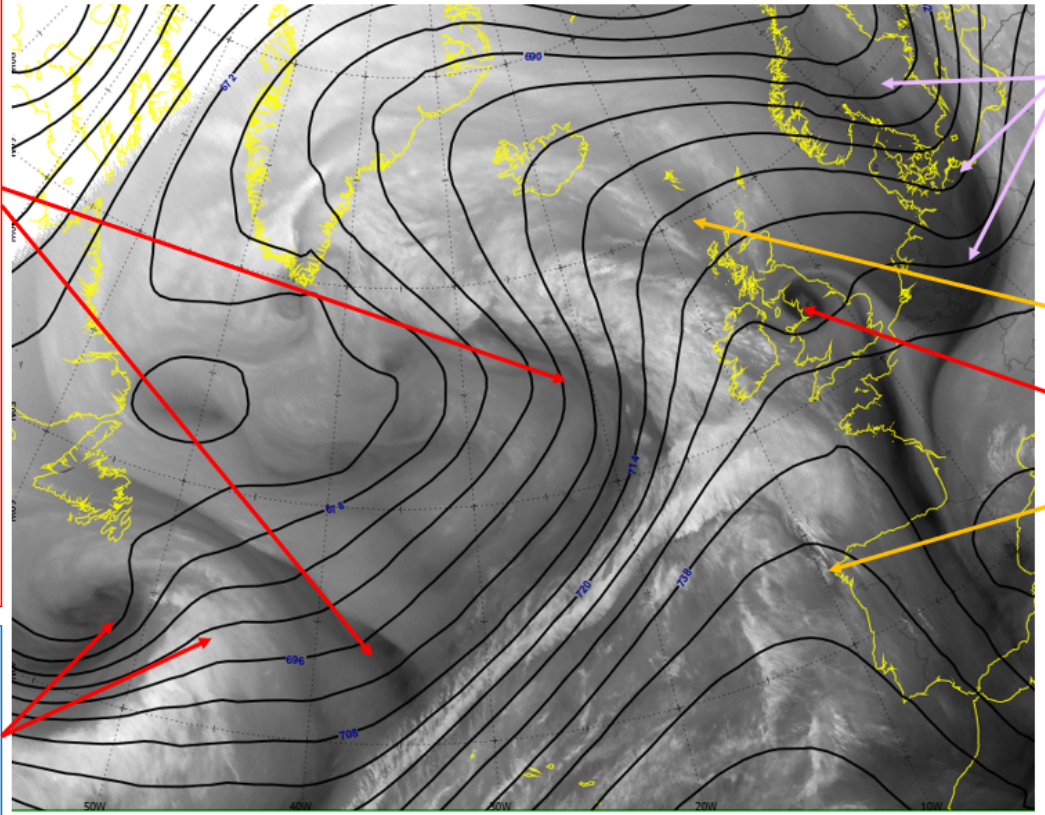
- Ability to **access** and **actively investigate** the information relevant to the challenge(s) of the day.
- The means to **identify** extremes or their precursors as **emerging risks**.
  - → Low probability extremes matter.
- Presented to complement Op Mets' **'top down'** working processes - exploring ensemble forecasts in a way that is **investigative** rather than **passive**.
  - → Otherwise, decisions are made by the time ensembles enter the process.

The ‘top-down’ forecast process

04Z MSG WV imagery (with 400hPa GPHs overlaid) is a reasonable fit to GM expectations in the broadscale. In the short term the ridge and embedded trough crossing the UK also look good. Further the southwest there remain concerns over the analysis of the jet entering the Atlantic and the downstream trough that is influential in the developments and uncertainty on Sunday.

Broad upper trough. The forward diffluent curvature maximum is taken towards the north of the UK while the rearward, travelling more quickly in the lower latitude flow, catches it up as it approaches the southern half of the UK. The forward trough looks reasonably well analysed, perhaps a little fast, while the rearward looks a little west and south of UM expectations, especially the more dynamically influential southern part. This is where the more active shortwave in ECs solution for Sunday derives from. The imagery mismatch highlights the uncertainty.

Shortwave on forward side of jet propagating into the Atlantic influences the development of the ridge and hence the downstream trough. Both look too progressive in GM.



Friday’s upper trough continuing to move way to the east

Upper ridge coming east across the UK so that its axis will lie over the North Sea by 18Z Saturday. Upper ridge is ‘contaminated’ by the trough running through it. This has a notable lens (red arrow), a result of barotropic shear instability, which will slide ESE to lie over the southern North Sea by 09Z Saturday. UM has a good handle on this feature and its southern flank has been interacting with the NE’ward moving occlusion plume to generate some occasional showery bursts from shallow elevated instability.

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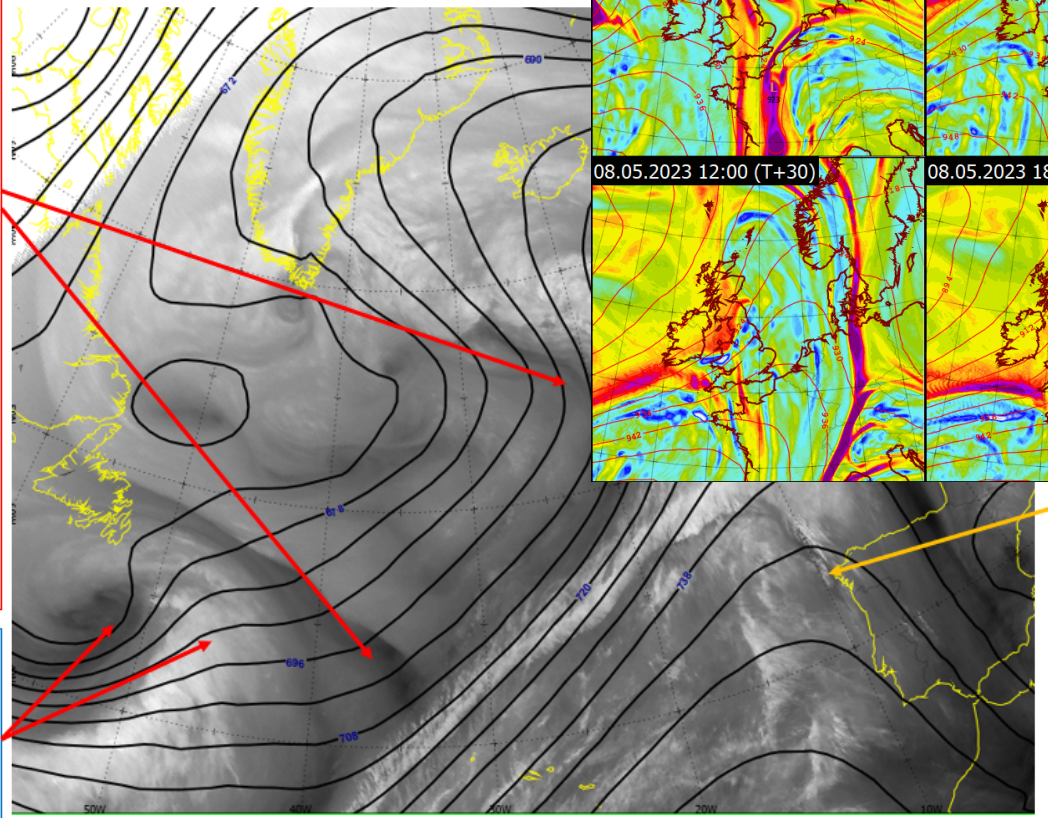

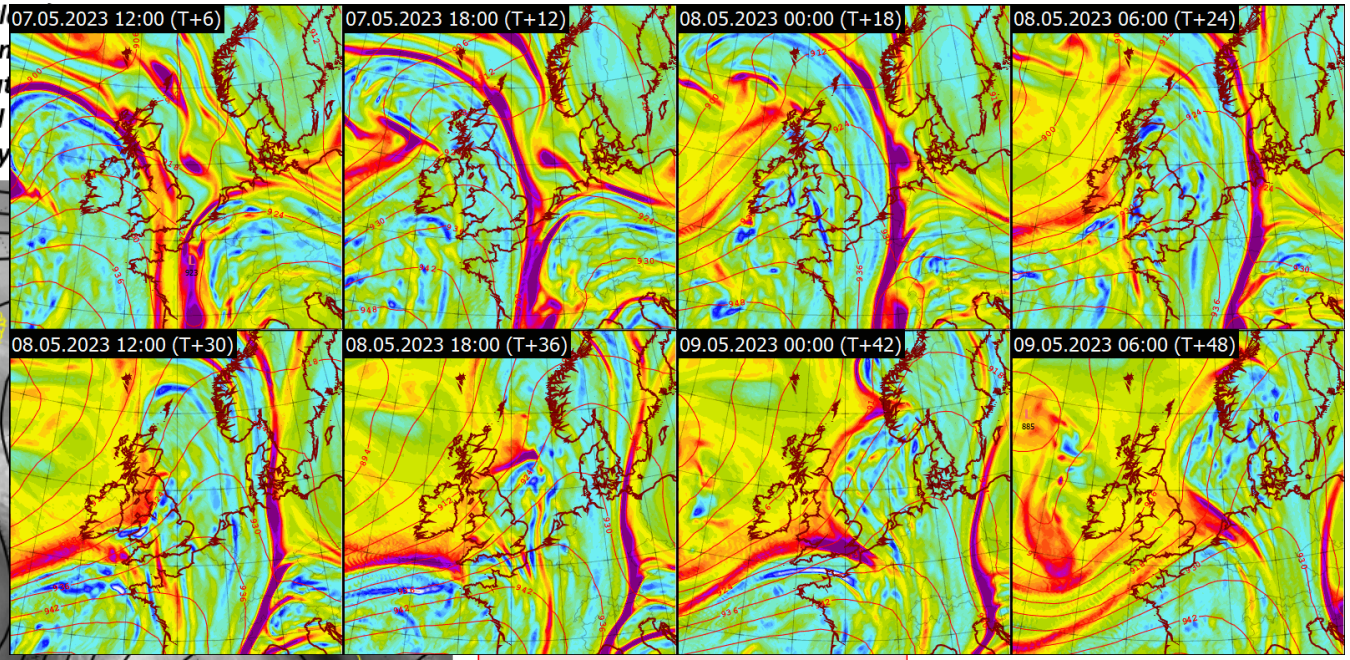

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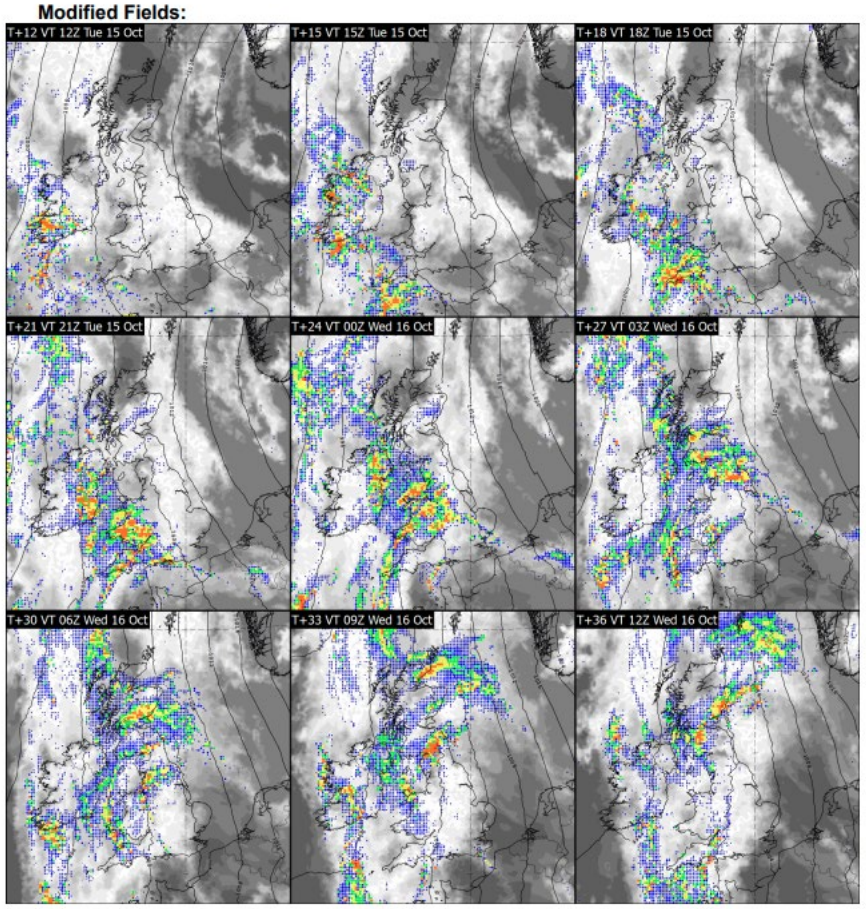

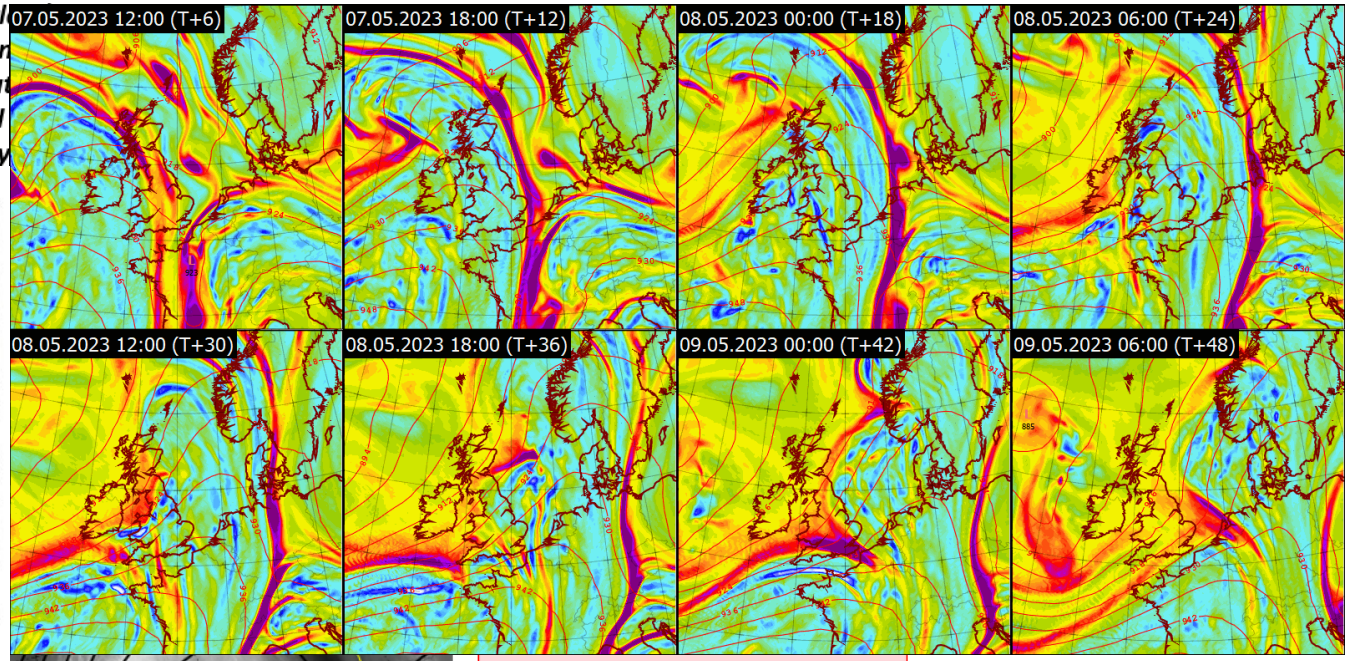

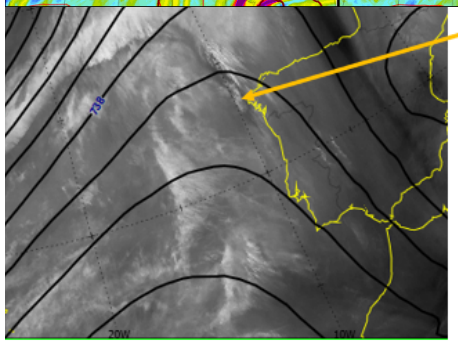

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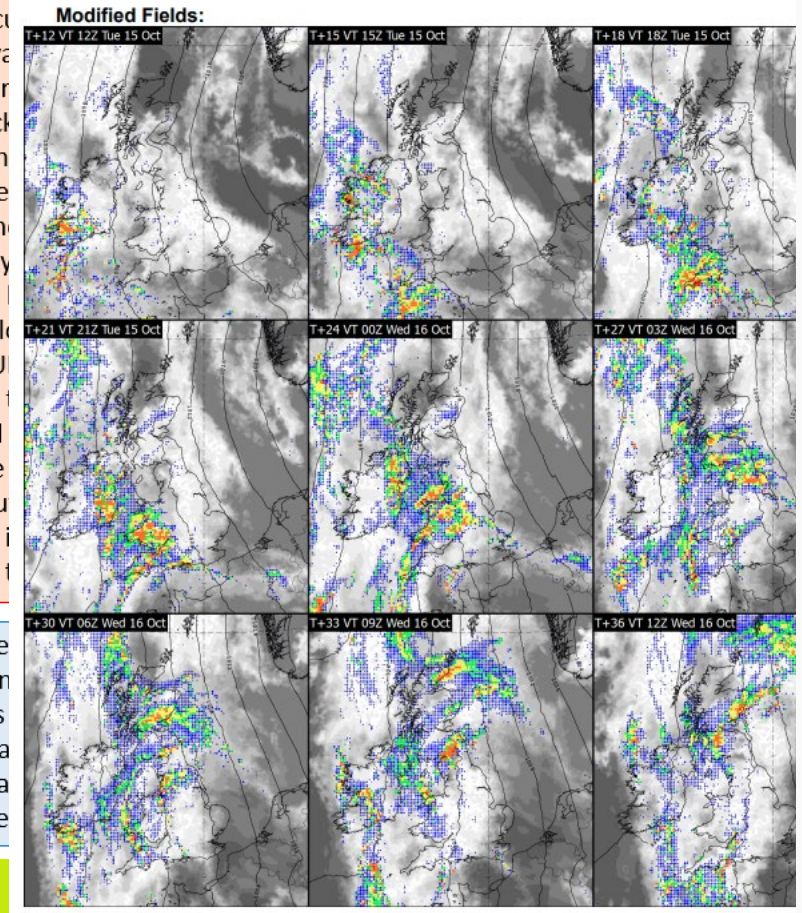

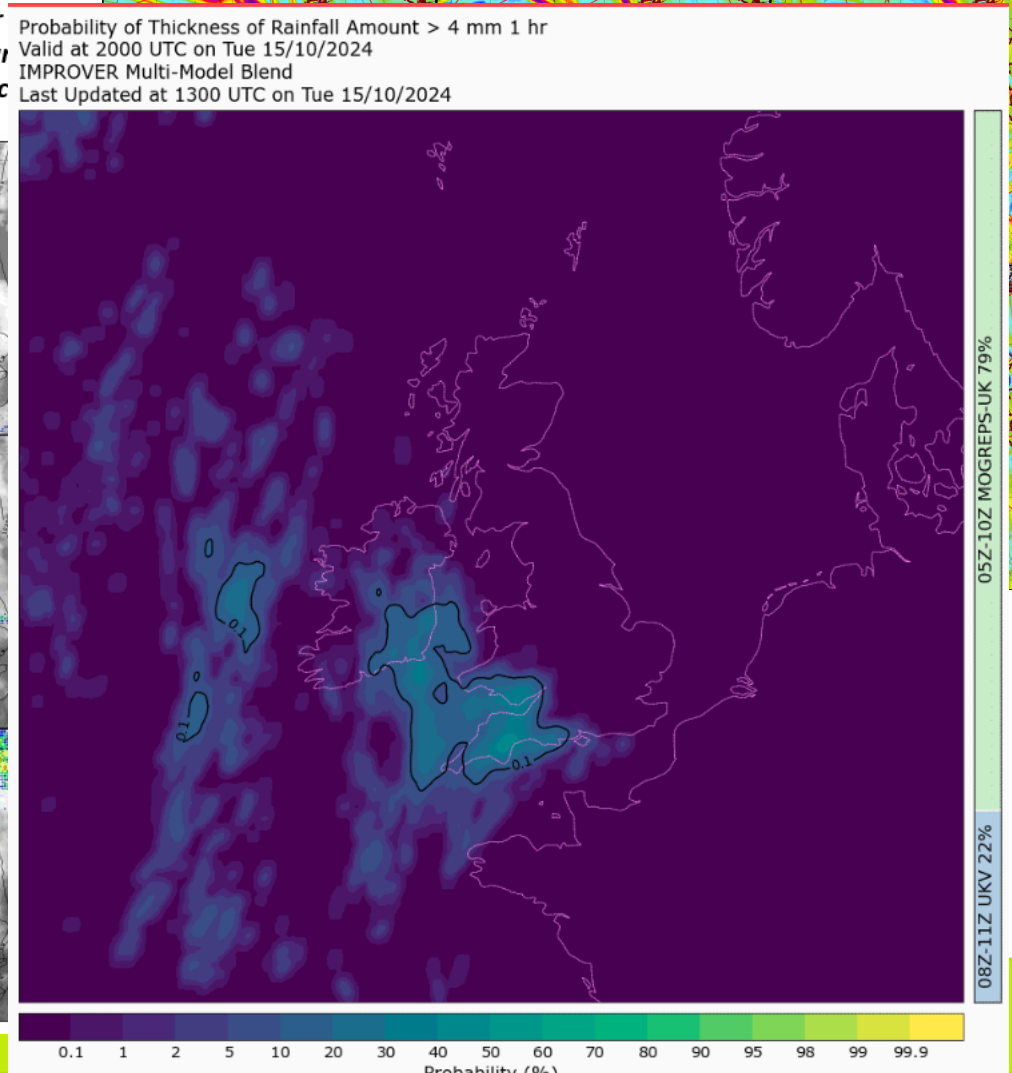

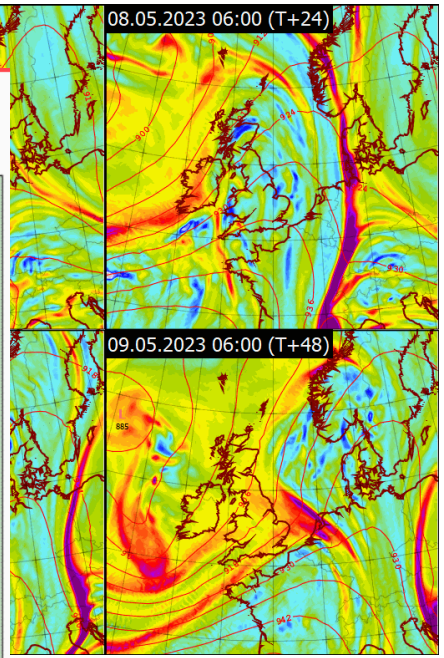

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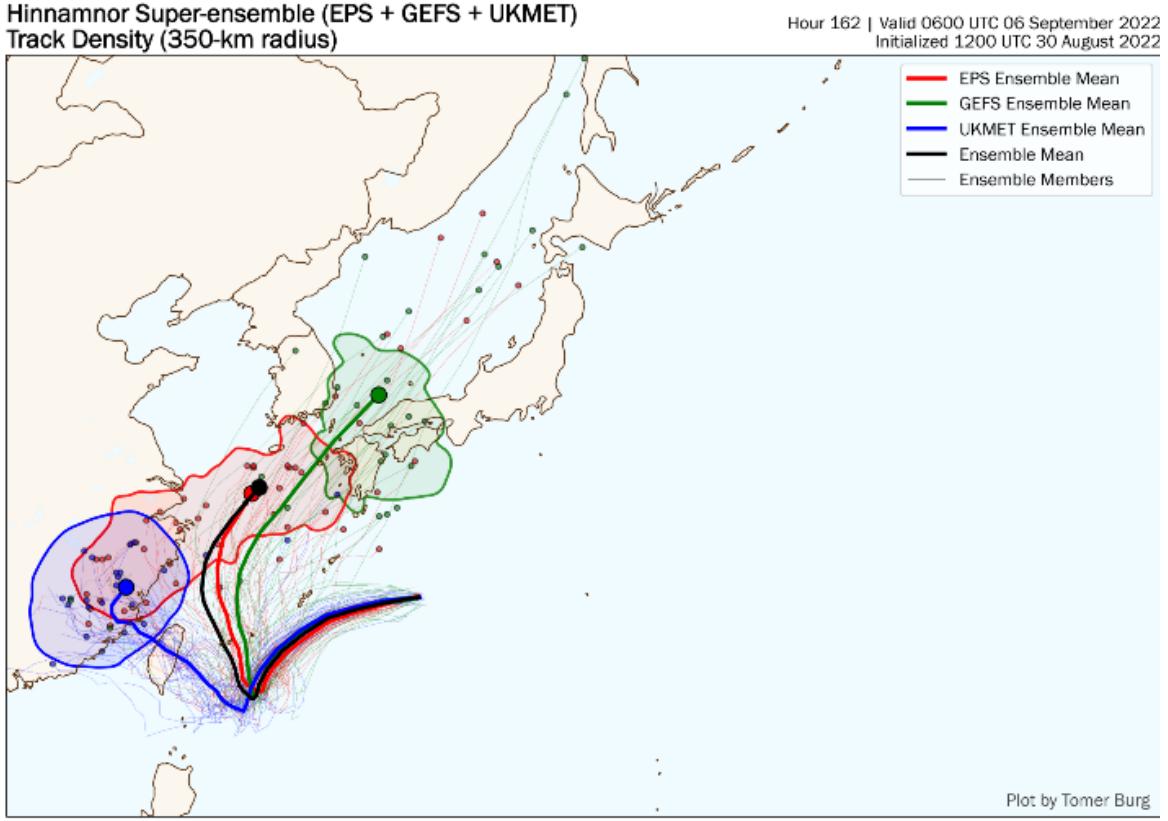
STRATEGIC ACTION Exploiting ensembles

The challenges facing Op Mets?

- Over confidence (clustering too tightly around control).
- Missing events.
- Excess complexity in presentation hinders interpretation (i.e. when evaluating model performance, understanding the evolution and sensitivities/key drivers).



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STRATEGIC ACTION Exploiting ensembles

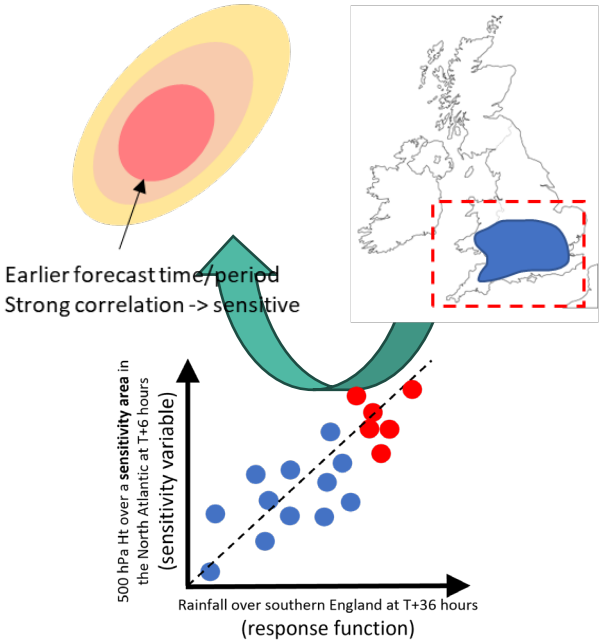
So how do we:

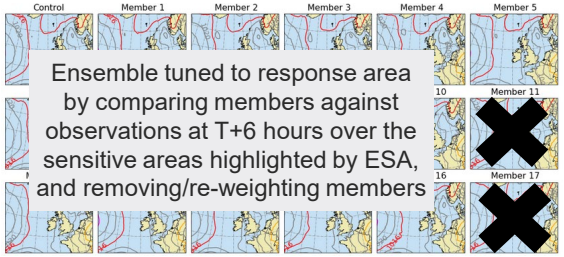
- Gain the most from the current ensemble systems?
- Mitigate lack of diversity and overconfidence issues?
- Tease out the ‘hidden’ information offered by ensembles i.e. the wealth of synoptic and contextual information that is, as yet, largely untapped?
- Support providing storylines, guidance and advice to customers?
- Focus effort on impacts relevant to our customers?

Ensemble Exploitation Work Package 1 tools

Ensemble Exploitation Work Package 1 tools

1. Ensemble Sensitivity Analysis (ESA) and Ensemble Sub-Setting (ESS)



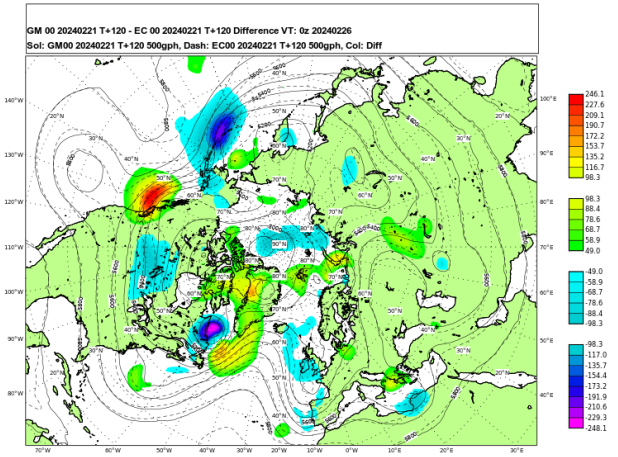


Ensemble tuned to response area by comparing members against observations at T+6 hours over the sensitive areas highlighted by ESA, and removing/re-weighting members

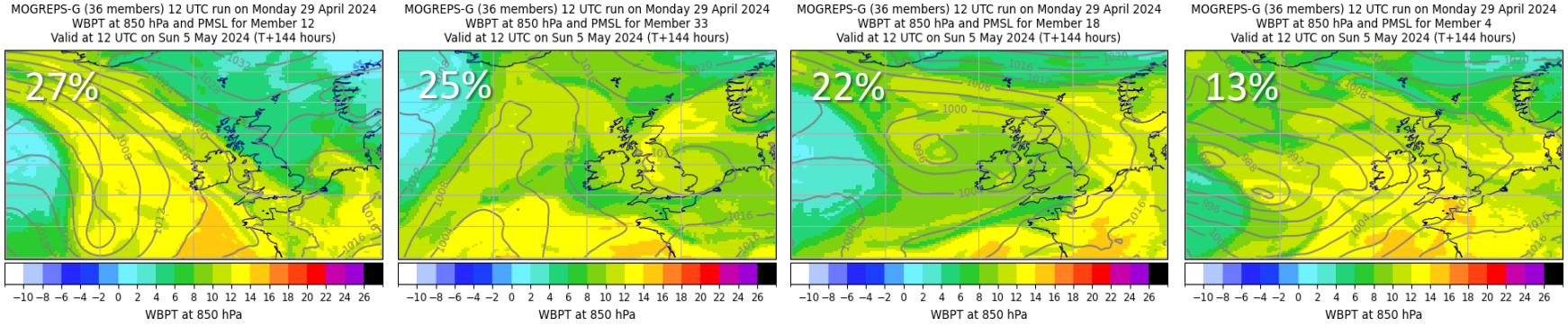
WP1 has:

Developed novel research prototype tools to allow active investigation of ensembles by Expert Weather Hub

3. Feature tracking applied to ensembles



2. Feature-based clustering



Ensemble Sensitivity Analysis

Thanks to Steve Willington, Helen Titley, Brian Ancell, Caroline Jones, Daniel Etheridge, Phil Relton, Adrian Semple, Brent Walker, Rebekah Hicks and Nigel Roberts.

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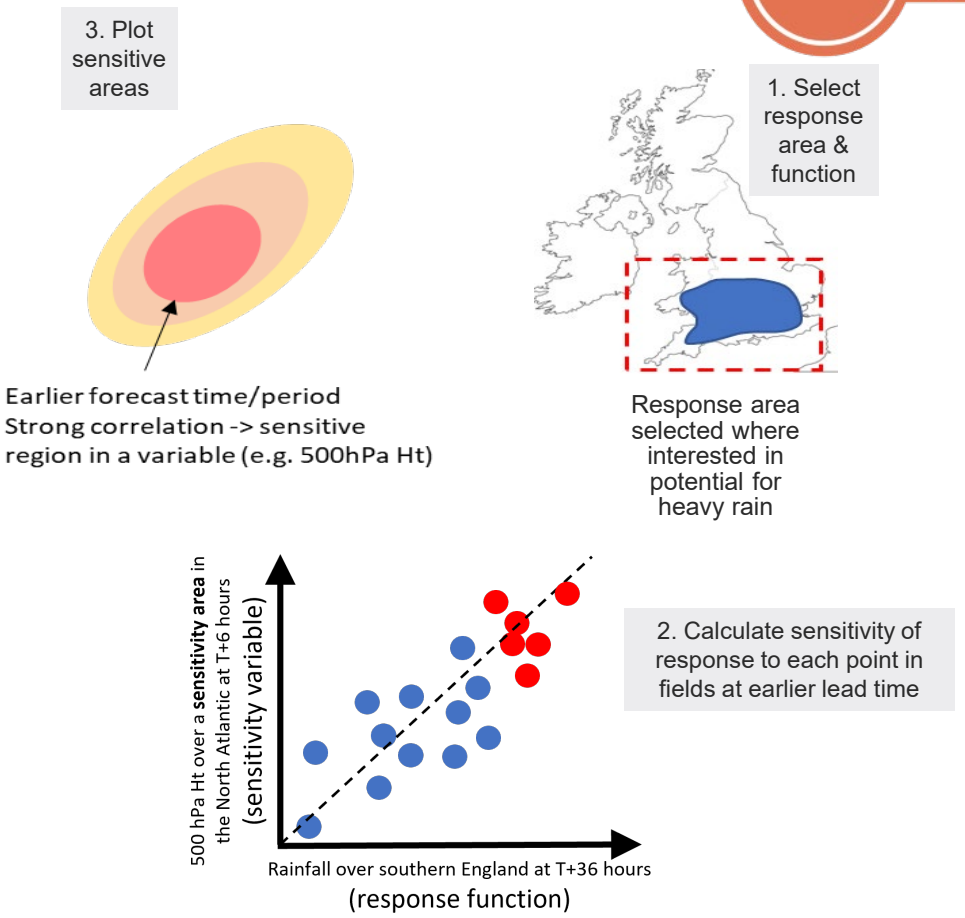
STRATEGIC ACTION Exploiting ensembles

What is Ensemble Sensitivity Analysis?

- Reveals how the evolution of a chosen forecast feature (response function - impact) is linked to meteorological conditions earlier in the forecast (sensitivity variable).
- Calculated through a simple linear regression between the forecast feature and early environmental condition at each model grid point

Torn and Hakim 2008



Ensemble Sensitivity Analysis (ESA): “ESA on the day”

Met Office

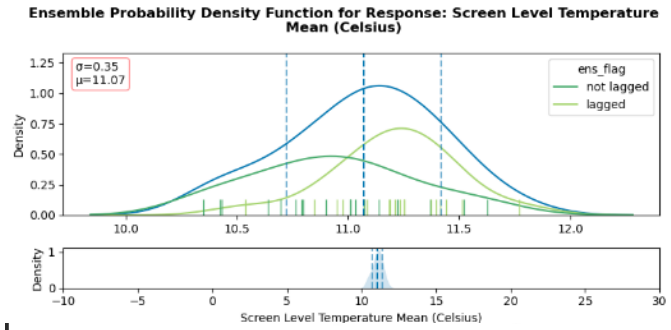
[Prototype] Ensemble Sensitivity Analysis output

Model Initialisation: 2024-06-24 12:00 | View response postage stamps | Response Time: 2024-06-27 12:00 | Response Function: temperature_at_screen_level percentile95 | Response Area: UK_Small

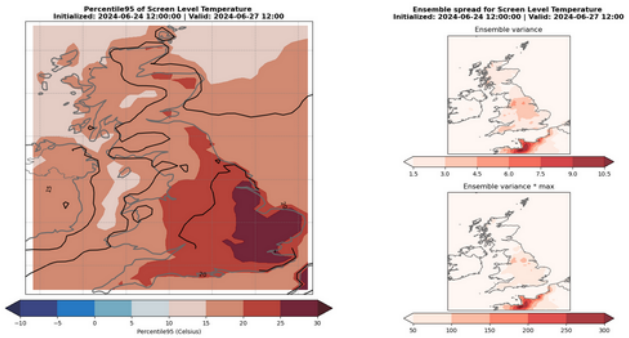
Sensitivity Variable: gph_300_hPa | Sensitivity Time: < << stop >> >

ESA run time: 20240624T2140Z, using ensemble: MOGREPS-G

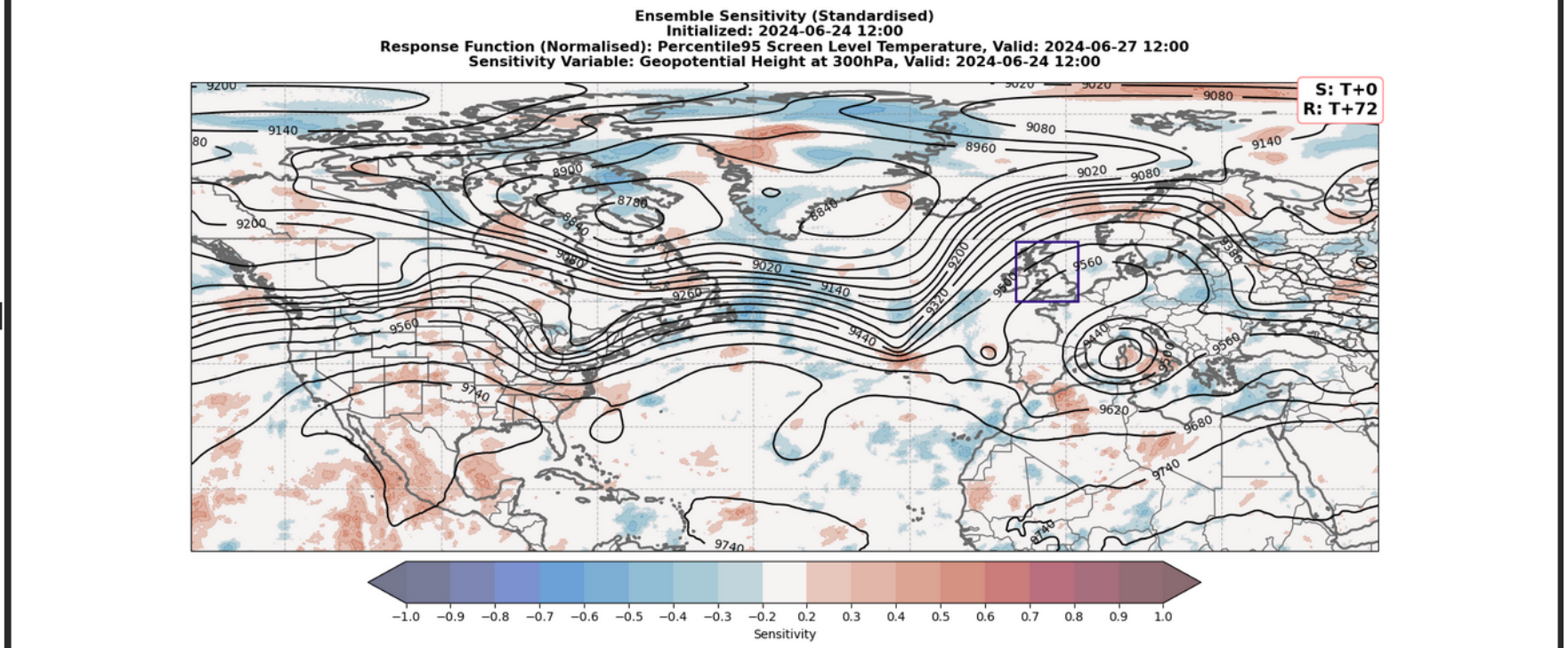
Response



Meteorological Context at Response Time



Sensitivity (Standardised)

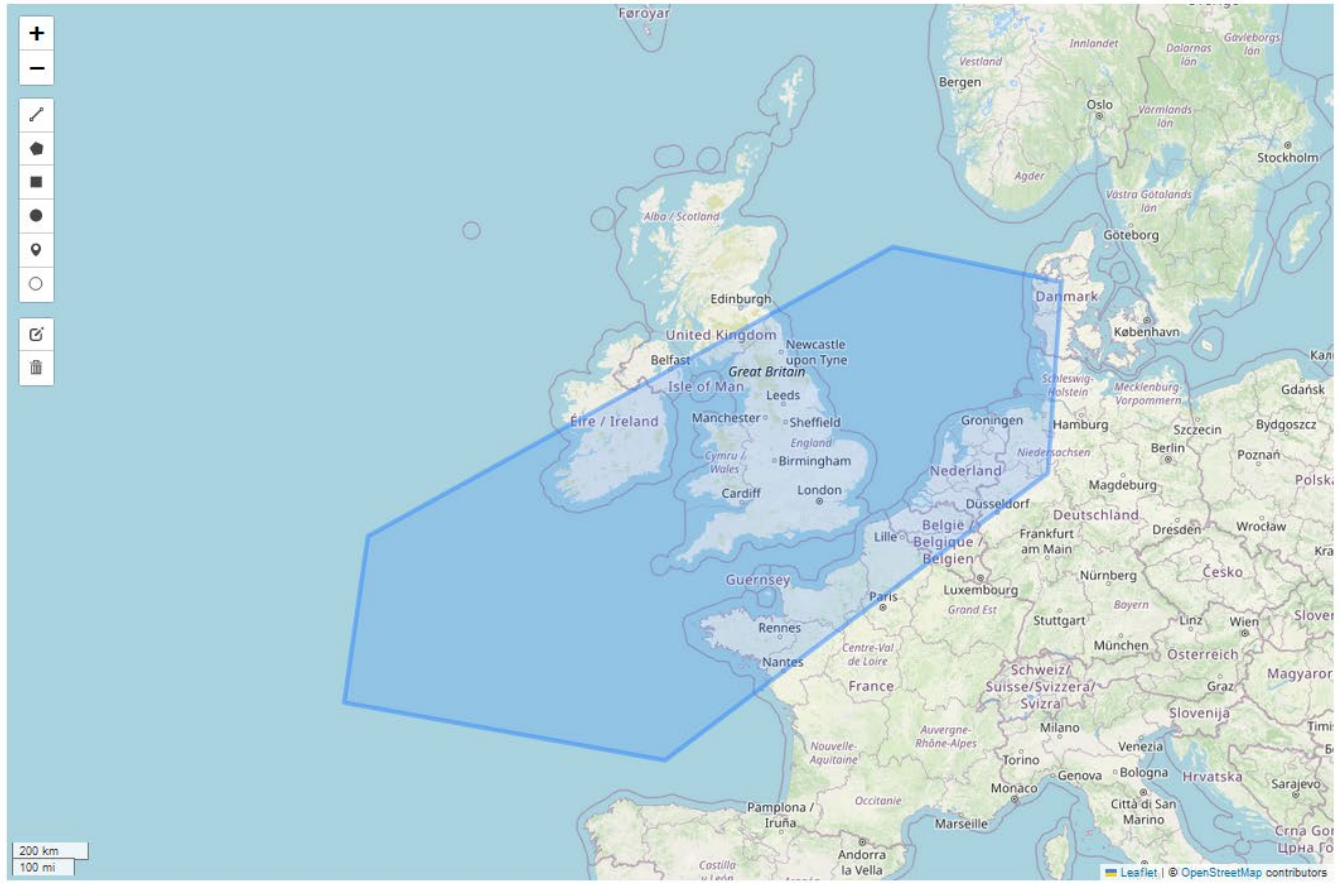


ESA on demand

Met Office

Ensemble Sensitivity Analysis: Bespoke user runs (TESTING)

Please select your response variable, function and area, and your sensitivity variable in the form and map below



Name of submitter:

Run date/time: 20240510T0000Z

Response forecast period: T+12

Response variable: Wind speed at 600m

Response function: Maximum

Value (leave blank if n/a):
For percentile give number between 1-99.
For threshold give in following units:
Wind (m/s); Temperature: (deg C);
Precipitation (mm); Snowfall (cm); PMSL (hPa)
Visibility (m); GPH (m)

Sensitivity variable: 500hPa GPH

Set off ESA run now

- Op Mets can select what they want to see given the current forecast challenges:
  - Response area
  - Response function
  - Sensitivity variable

Opportunities for improved prediction?

- Ensemble Sensitivity Analysis reveals the atmospheric features relevant to the predictability of the chosen weather of interest
  - Op Met awareness of key precursors.
  - Op Met awareness of 'tipping points' in the evolution.

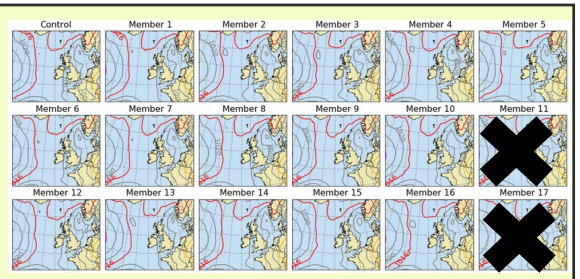
  } **c.95-98%**

- Sensitivity-based Ensemble Sub-Setting **c.2-5%**

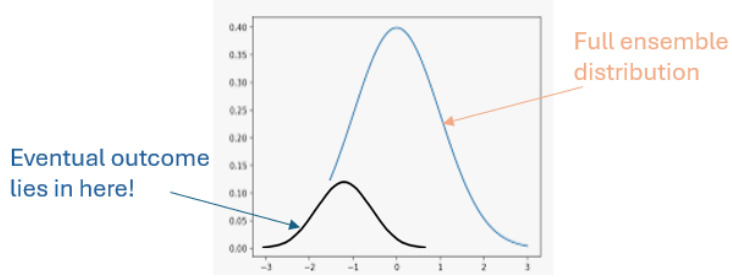
We are evaluating Ensemble Sub-Setting:

Ensemble tuned to response area by comparing members against obs (analysis and imagery) at early lead times over the sensitive areas highlighted by ESA, and removing/ re-weighting members

Caroline Jones is leading on this work.



Can we identify an emerging event?



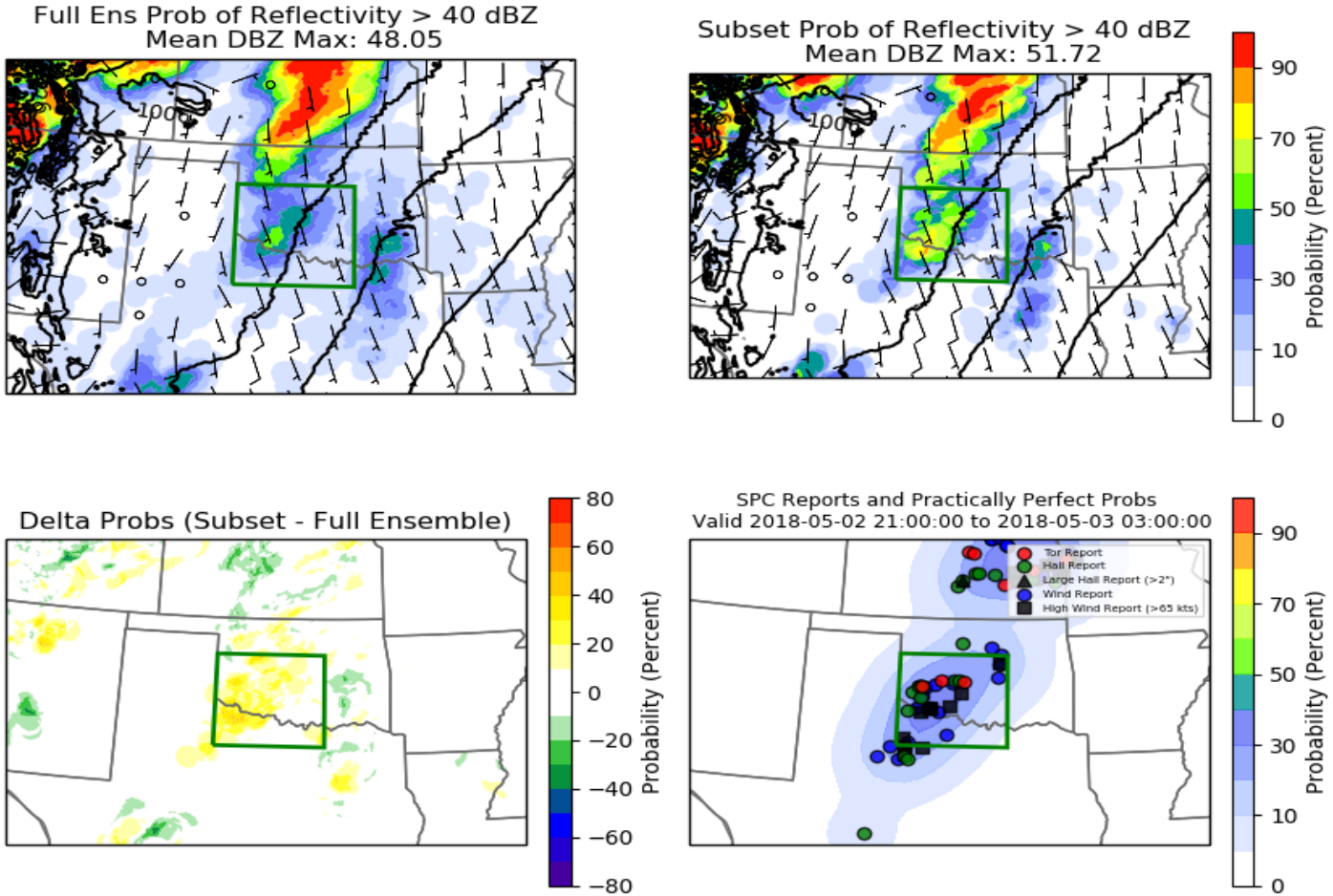
- **Multi-model** ensemble ESA, i.e. adding ECMWF ensemble data is a high priority recommendation in final report.

Can it be applied to the convective scale?

- **A research topic, it should be but more challenging as:**
- Evolution is more nonlinear than on synoptic scale.
- Requires a relatively large ensemble (TTU WRF EPS: 52-member) as:
  - Sub-set must contain sufficient members (5 to 25 optimal, Ancell 2016) and….
  - Require sufficient spread to capture the event….
- Requires greater observational density/quality

How would it work?

Response = Simulated Reflectivity Coverage > 40dBZ



2nd May 2018

Figures thanks to Brian Ancell and Austin Coleman

Next steps

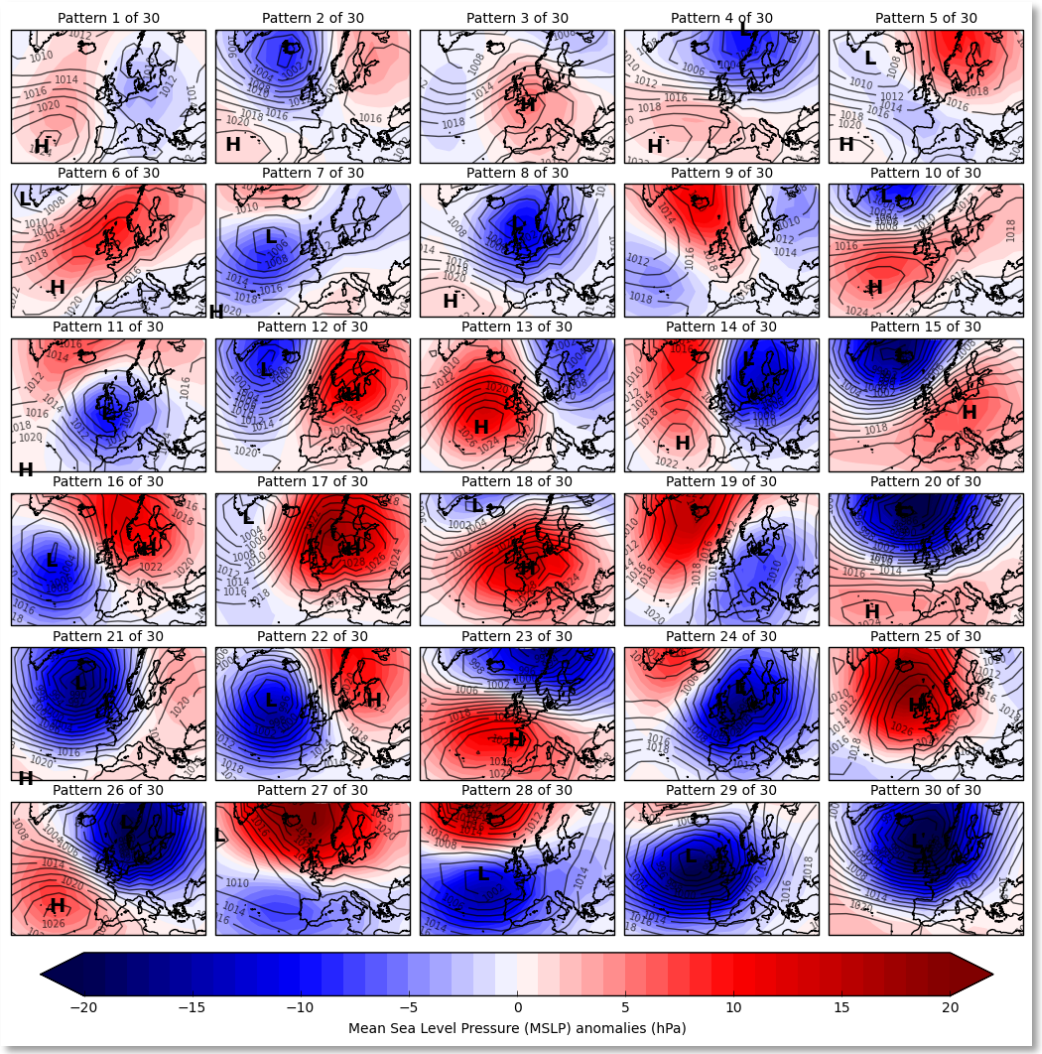
- Ensure support, non-operational, for the ESA prototype to allow further evaluation and development in the short term.
- Develop a prototype of the ESS proof of concept.
- Add other centres' ensembles.
- Expand to global coverage.
- Introduce convection allowing ensemble capability.
- Investigating future collaborations.
- Bring the 'family' of tools together into a single visualisation capability.
- **Ensure pathway to future operational support, sustainability and development…..**

Met Office

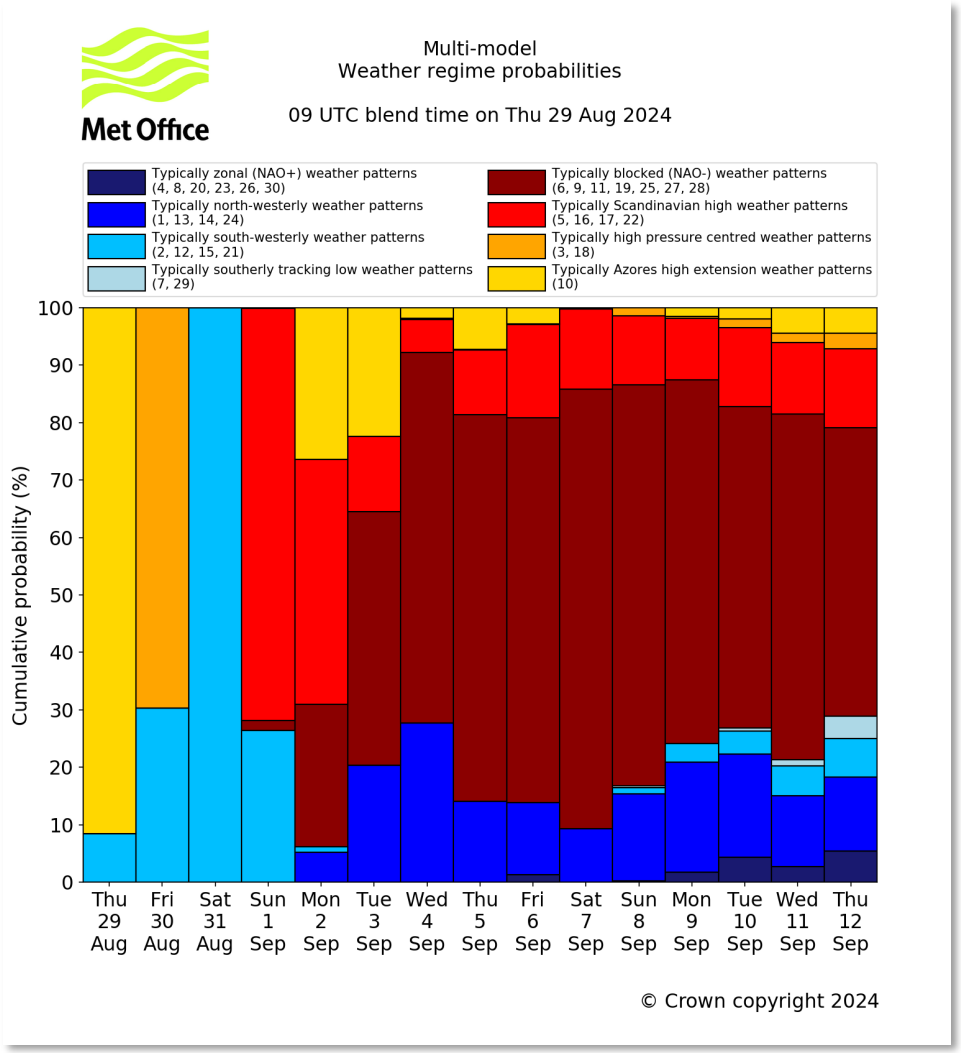
Feature-based clustering

Thanks to Rob Neal, Kris Boykin, Adam Gainford and Rebekah Hicks

Clustering by weather pattern



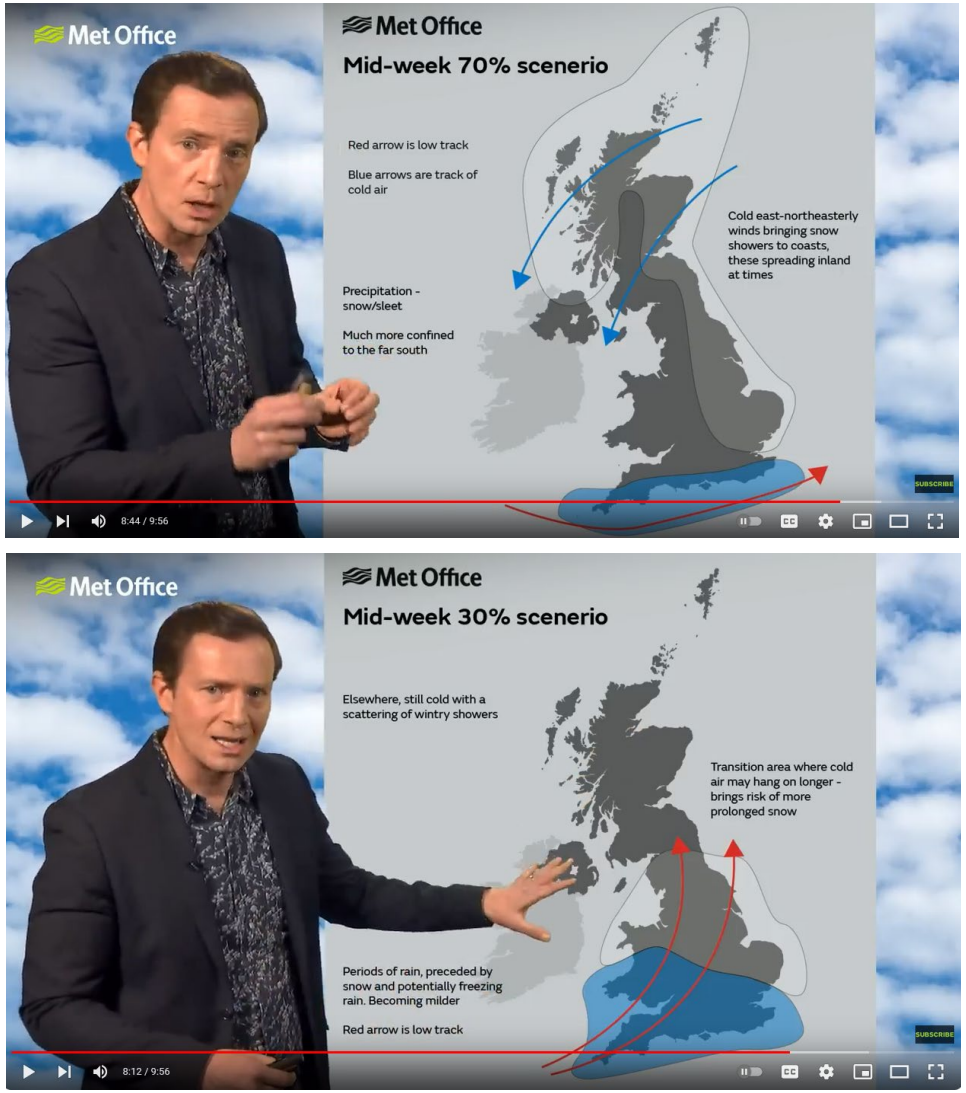
The set of 30 Met Office weather patterns used by Decider (Neal et al., 2016)



Top-level multi-model weather pattern forecast probabilities from Decider (Neal et al., 2024)

Clustering directly on the ensemble

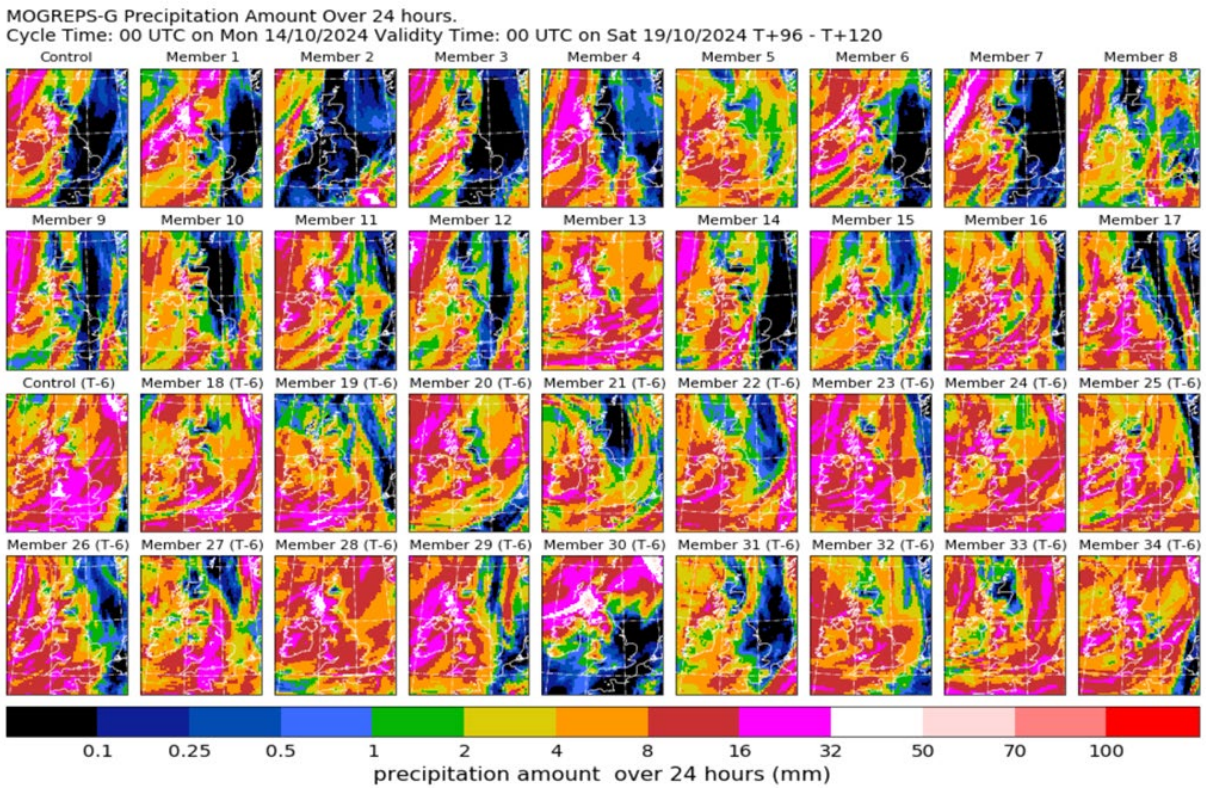
- The Met Office is trialling a **new feature-based ensemble clustering approach** based on methods initially developed by Boykin (2022).
- Features may represent **areas of hazardous weather**.
- Uses **k-medoids clustering** to group members with similar evolving features over **windows of interest**.
- Identifies a **Representative Member (RM)** for each cluster to provide distinct forecast evolutions with associated probabilities.
- Clustering products **aid the communication of forecast scenarios**.



Example snow forecast scenario communication from 7th December 2022

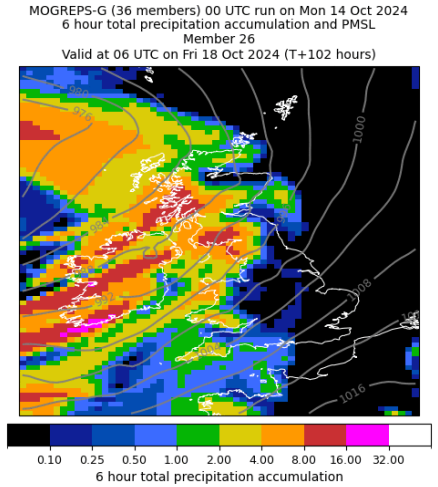
Clustering directly on the ensemble

In this example, clustering provides four distinct forecast evolutions with associated probabilities.

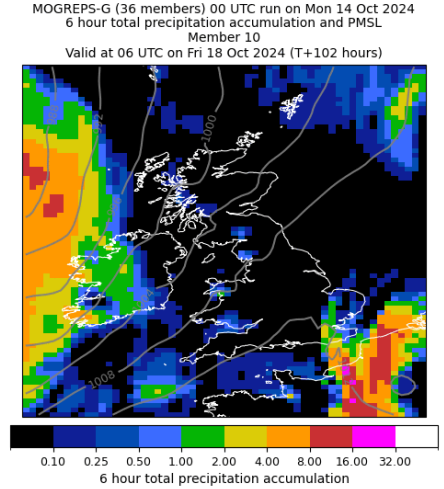


36-members from MOGREPS-G showing 24-hour precipitation accumulations.

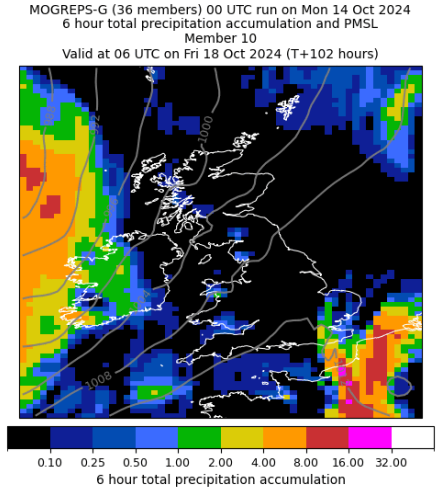
Scenario 1
42% probability



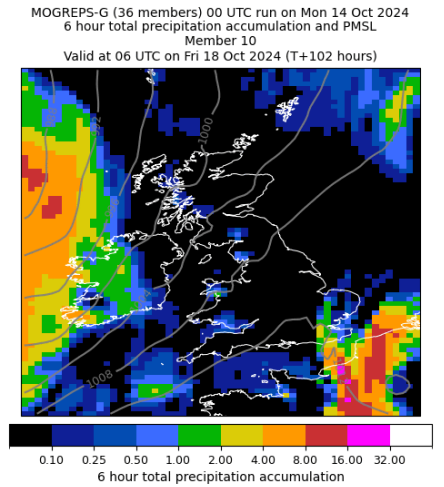
Scenario 2
31% probability



Scenario 3
17% probability

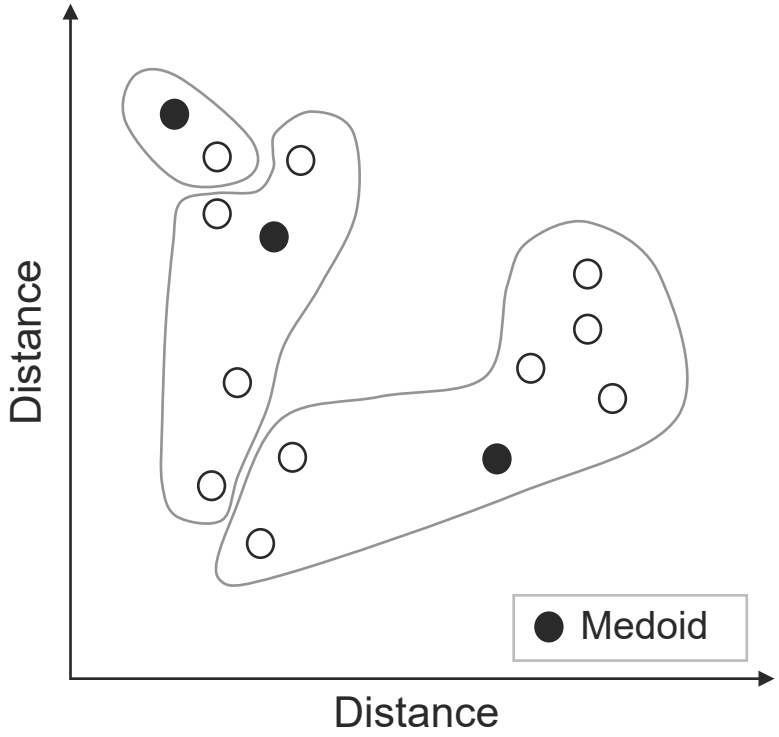


Scenario 4
11% probability



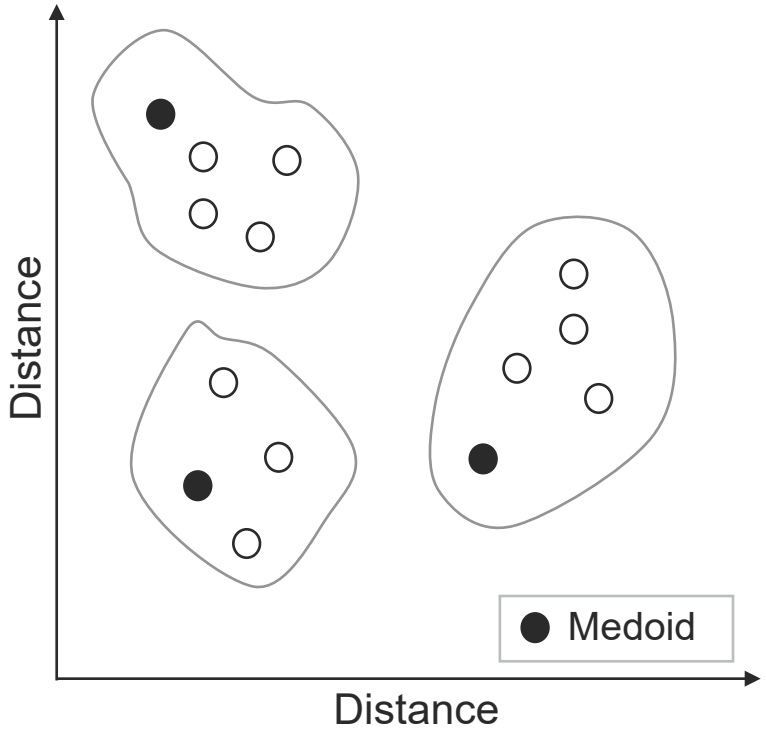
K-medoids clustering schematic

Step 1 (k=3)



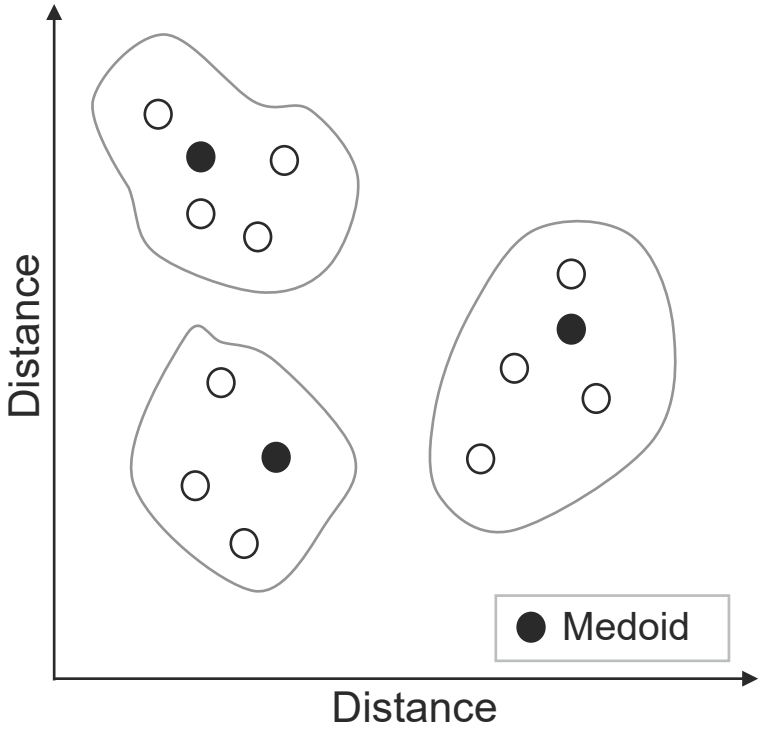
- Choose 3 members as initial medoids.
- Allocate each remaining member to its nearest medoid, based on the medoid-member pairing with the smallest distance (using the Fractions Skill Score as a neighbourhood distance measure).
- Calculate cluster sum distances between each member and the medoid.

Step 2 (k=3)



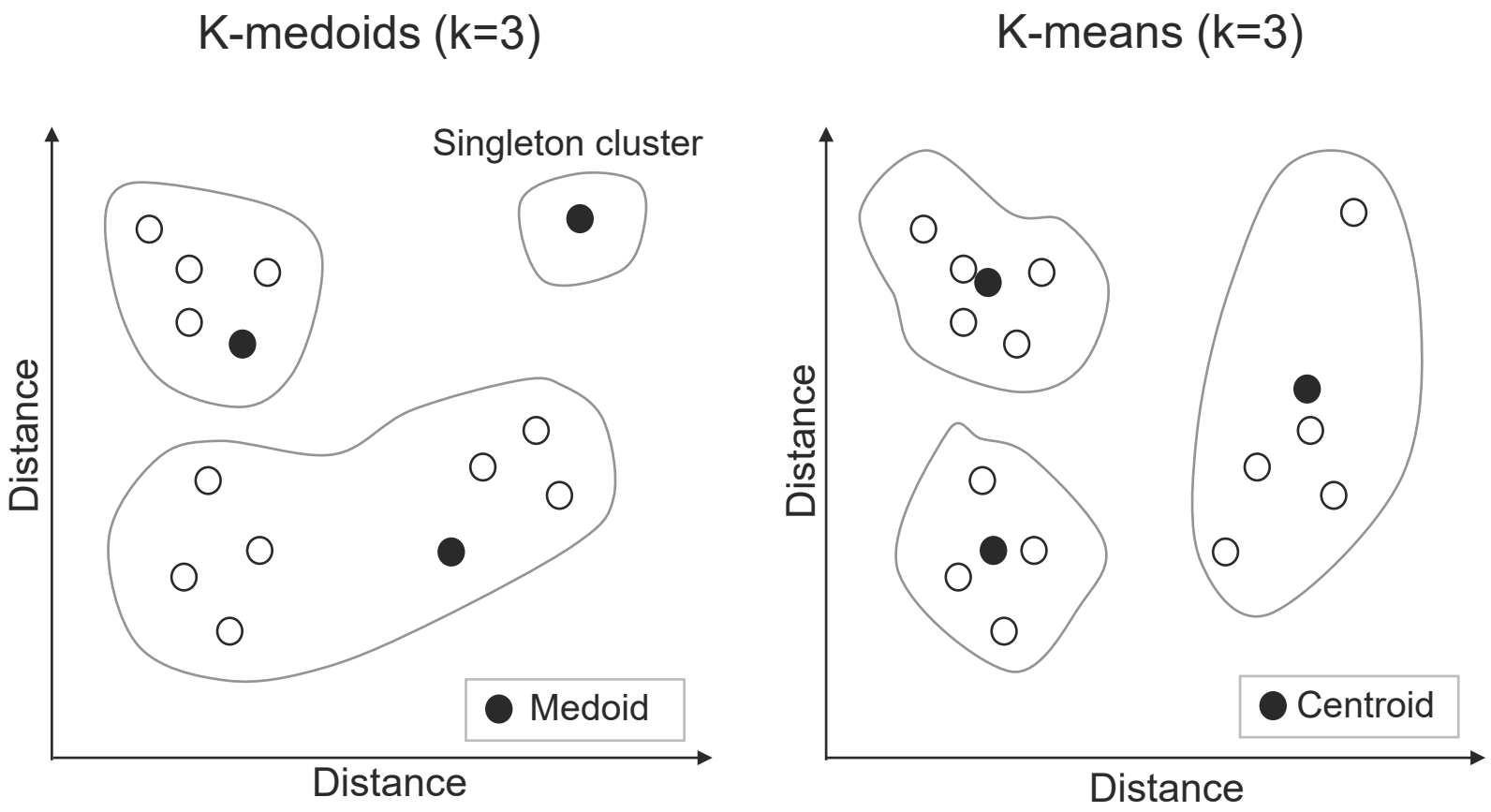
- Change one of the medoid objects.
- Re-allocate members to their closest medoids.
- Calculate cluster sum distances between each member and the medoid.

Step 3 (k=3)



- Continue the loop started in **Step 2** until the cluster sum distances bottoms out.
- Note: For k-medoids, the number of loops (iterations) is limited by the number of members (= quick to run, *mostly*).
- Note: Cluster membership remains unchanged in this final iteration, but the medoids change.

K-medoids and k-means clustering



A schematic comparison of clustering output from k-medoids and k-means where the input ensemble members are the same and k=3.

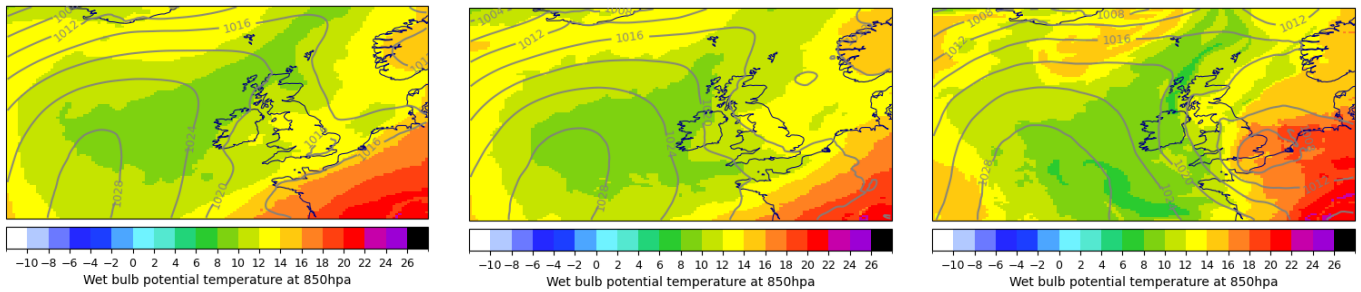
Why choose k-medoids?

- The centre point (medoid) is a member of the cluster instead of a mean of members (centroid) – this works better for fields like precipitation where it is less appropriate to assign members to their closest "smoothed" centroid.
- K-medoids is more likely to recognise an outlier as a singleton cluster if it is significantly different to other members.
- K-medoids is quicker to run due to less iterations required (capped by the number of members). K-medoids also produces the same solutions when run more than once on the same data set.

Drill down approach

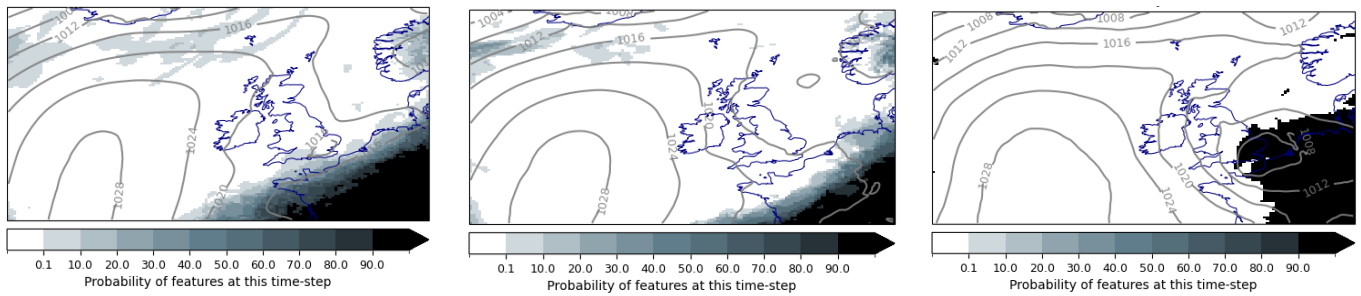
Forecasting products are available as a summary for each window of interest, and for each time-step within each window of interest.

Cluster means



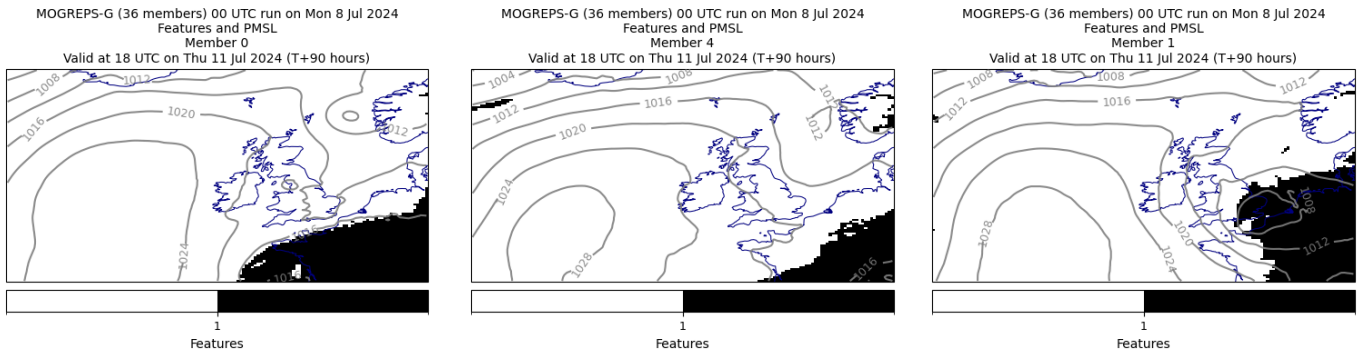
A quick way to assess the main differences between clusters.

Cluster feature probabilities



Useful for assessing ensemble spread within a cluster.

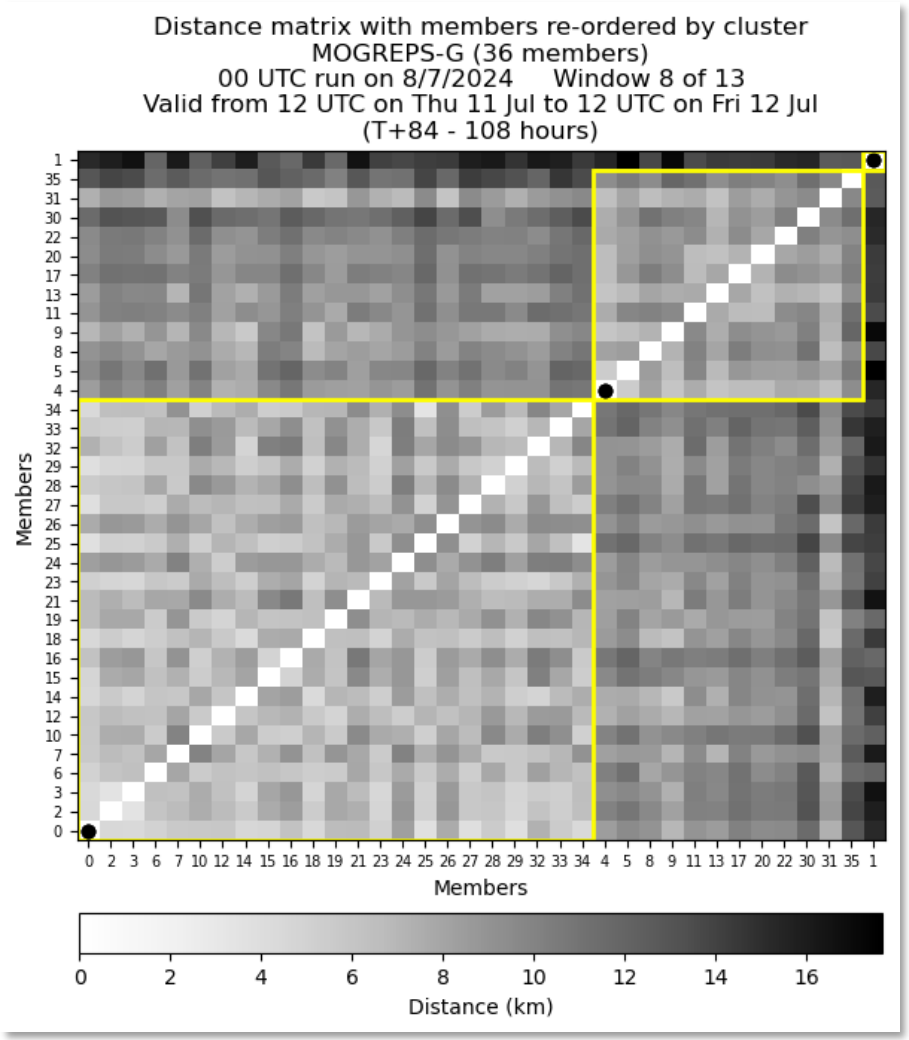
Cluster RMs (continuous field and feature presentation)



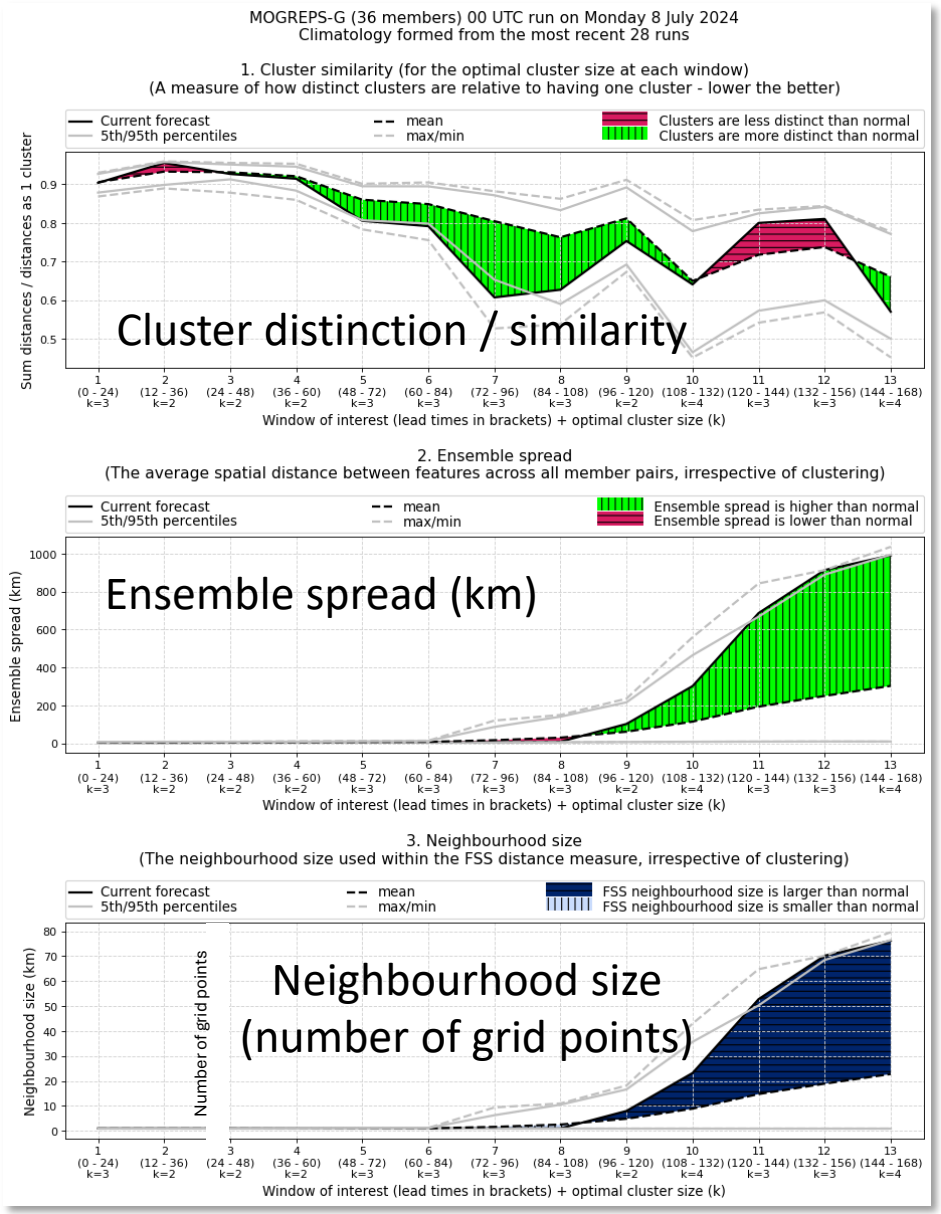
Useful for presenting forecast scenarios, alongside their probabilities.

Clustering diagnostics

How useful are today's clusters?



Distance matrices will ideally show distinct clusters (lighter shading within yellow boxes).



Colour-coded line graphs help us infer how useful today's clusters are relative to previous runs.

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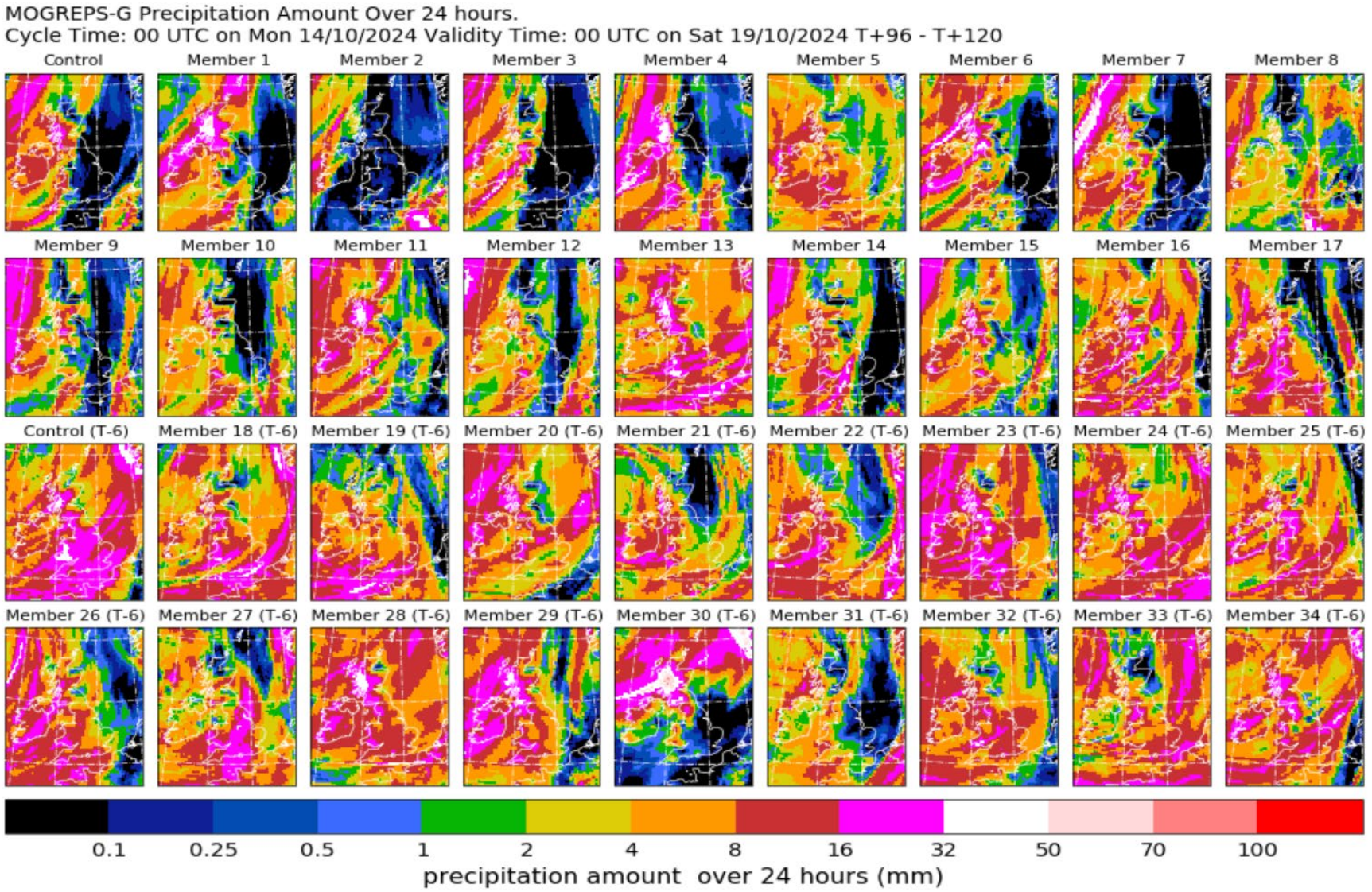


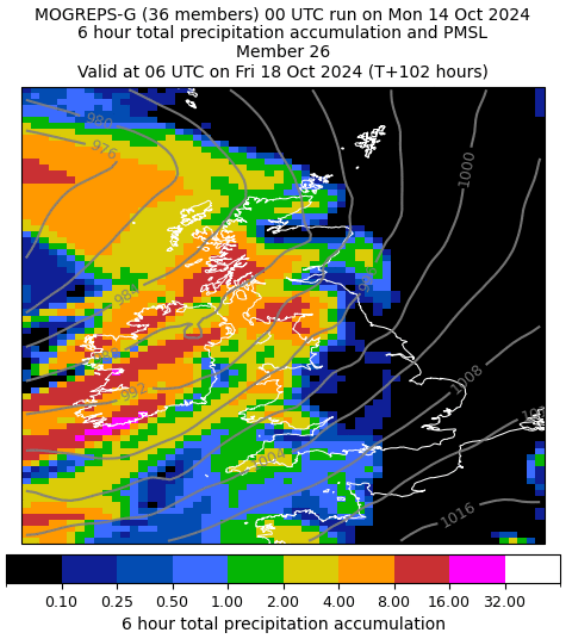
MOGREPS-G 24-hour rainfall accumulations valid 00Z Friday – 00Z Saturday (T+96 – 120-hour forecast).

"I am interested in the different rainfall scenarios for Friday and their probabilities. How can the clustering help?"

Communicating the story

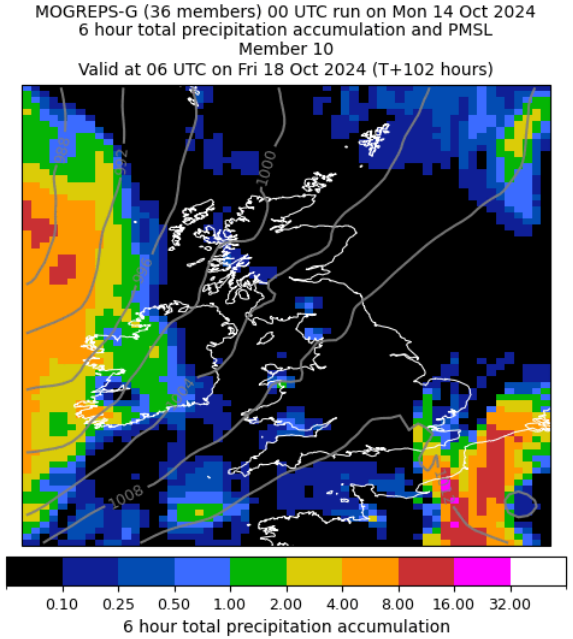
"There are four main forecast scenarios for the expected rainfall on Friday – some are more likely than others…"

Scenario 1
~40% probability



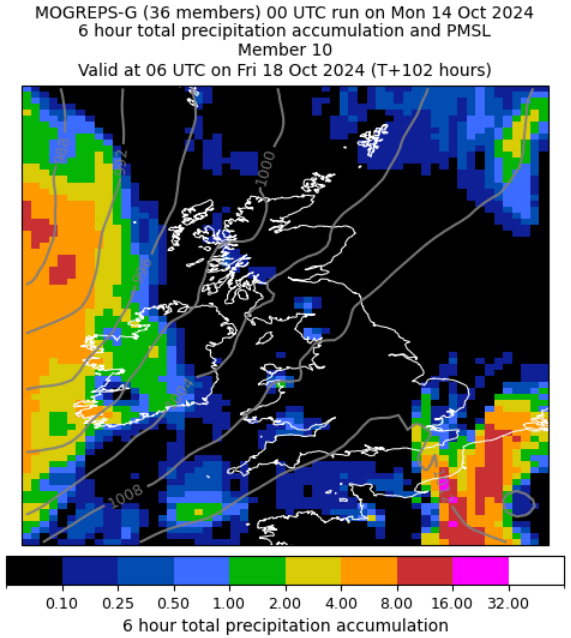
Heavy rainfall in western and southern areas during the middle part of the day.

Scenario 2
~30% probability



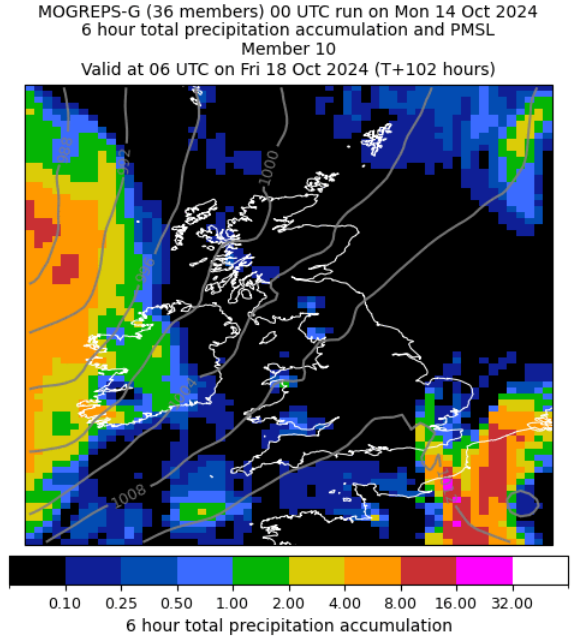
Heavy rainfall arriving into western areas later in the day.

Scenario 3
~20% probability



Moderate rainfall arriving into western areas later in the day.

Scenario 4
~10% probability



Heavy rainfall clearing central and southern areas early on, leaving a predominantly dry day for most.

(Or a ~50% probability of **moderate to heavy** rainfall arriving into western areas later in the day.)

Next steps

- Real-time clustering of MOGREPS-UK rainfall accumulations
- Refinement of the logic identifying the optimal number of clusters
- Refinement of the configurations used by MOGREPS-G clustering
- Identify the best distance measure
- Look into objective verification of clusters – any ideas?
- **Ensure pathway to future operational support, sustainability and development…**

Summary

ESA/ ESS/ feature-based clustering tools have been developed with the expectation (but no guarantee!) of addressing some of the challenges discussed. Specifically, they should:

- Provide access to, and the ability to investigate, the huge wealth of data ensembles generate.
- Help mitigate overconfidence and lack of spread (sub-sets/ multi-centre).
- Aligned with Op Met forecast process.
- Allow development of ensemble characteristics to build awareness of strengths, weaknesses, biases etc to help informed use and guide science development. *With a focus on verification/ evaluation when it matters.*
- Supports building storylines.

Met Office

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