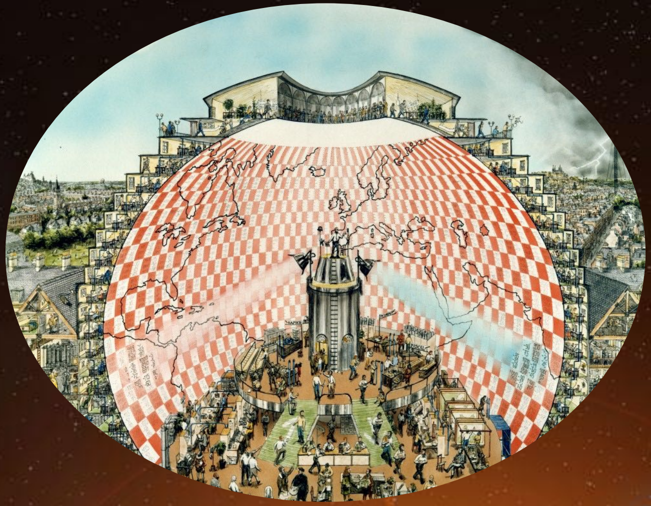
Operational NWP



CSU, Fort Collins

Jon Petch

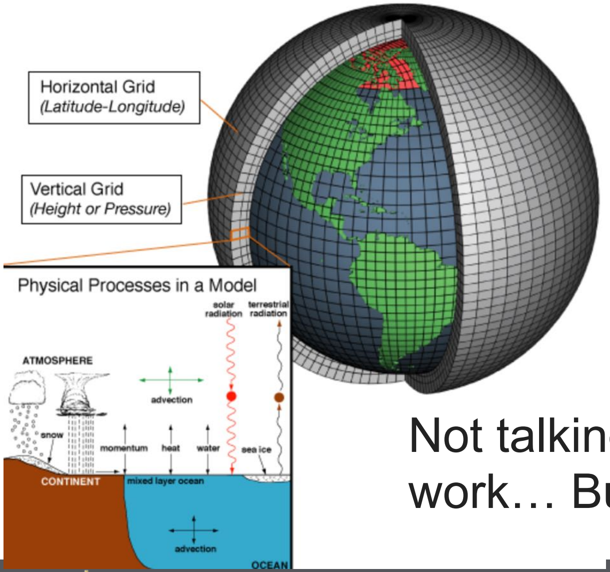
November 14th 2024

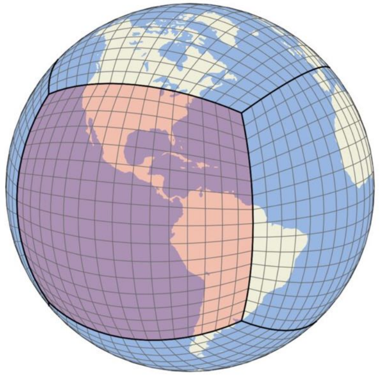
Contents

- What is purpose of operational NWP?
  - What is purpose of an operational center
  - What does NWP deliver vs other capacities
  - NWP ensembles; post processing and services…
- The components of an NWP system
  - What an NWP system looks like (Regional and global)
  - Challenges of a real time system
- Research and development for NWP

NCAR is not an operational center

This talk is based on my time at the Met Office 1997-2023





Some slides from my seminar here but mostly different stuff…

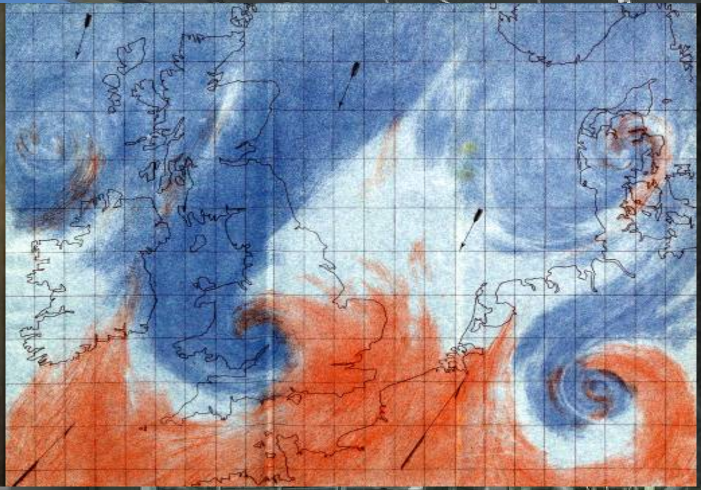
Not talking about how atmospheric, ocean or land models work… But how they are used and developed for NWP

The purpose of NWP

A potted history of the Met Office

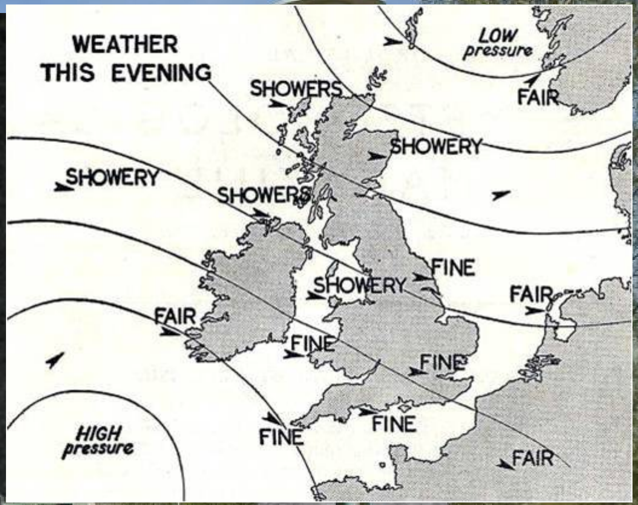
1854: Founded

1859: FitzRoy's interprets October storm



1922: Director: Lewis Fry Richardson

1949: First televised weather chart



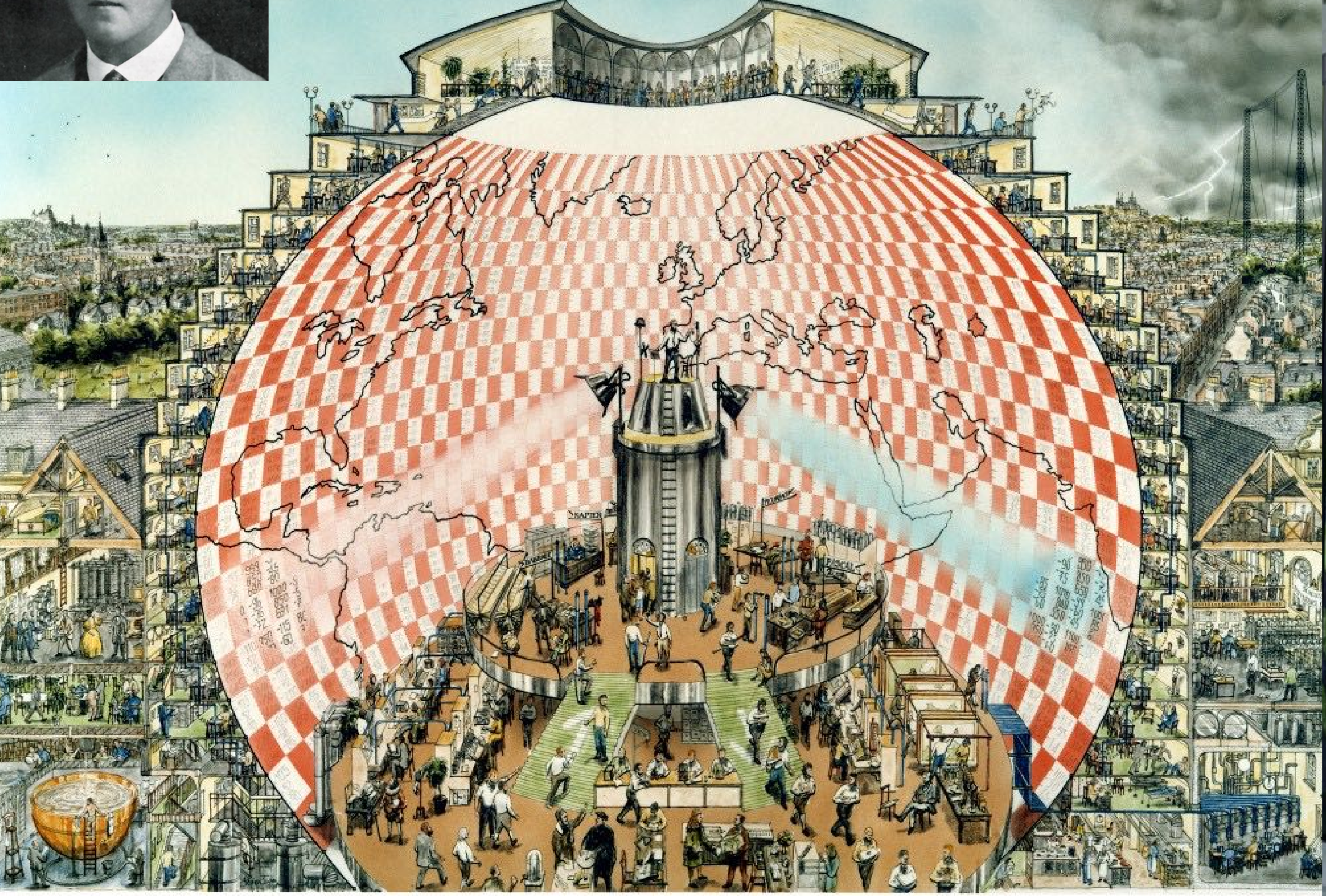
1959: First computer

1987: The "hurricane"

1990: Met Office Hadley Centre opens

2021: $1.6B investment in Microsoft HPC

Richardson was the first not only to suggest numerical integration of the equations of motion of the atmosphere, but also to attempt to do so by hand, during the First World War.



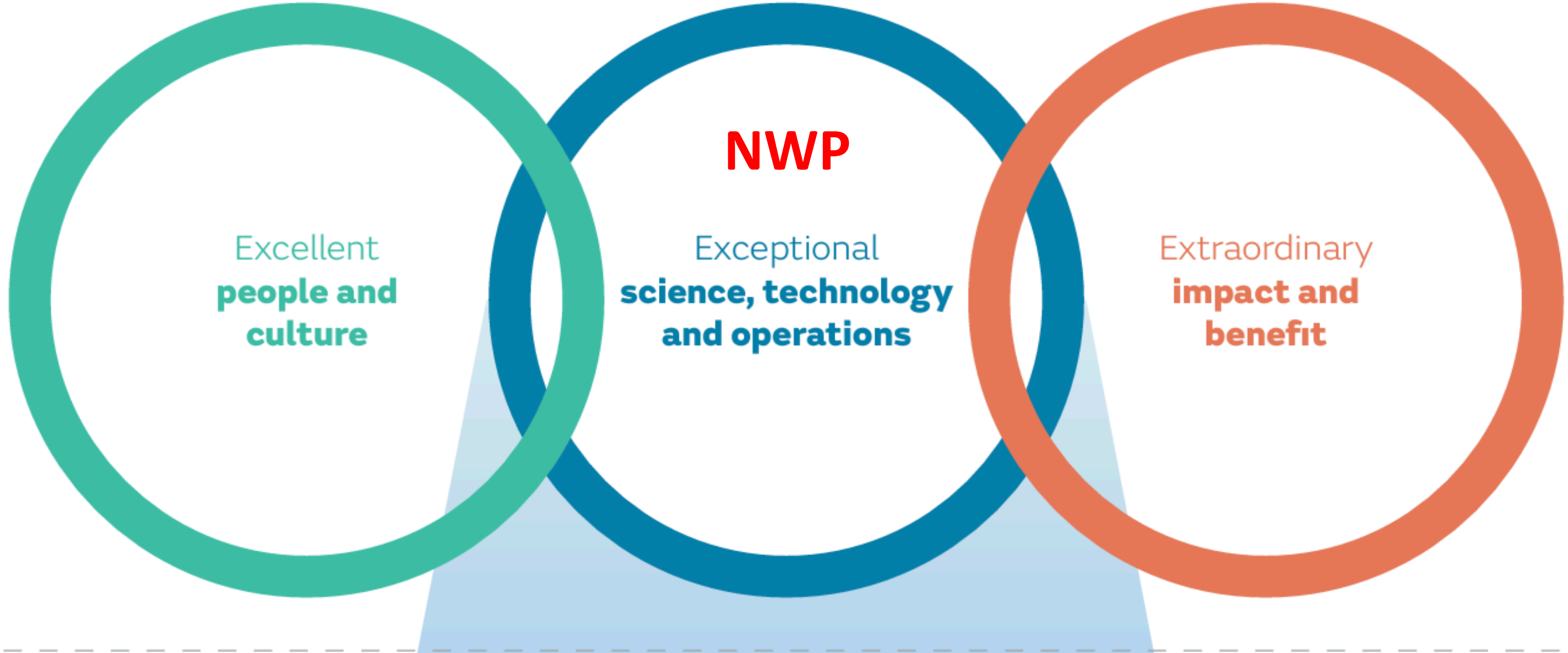
Our purpose - Why we exist

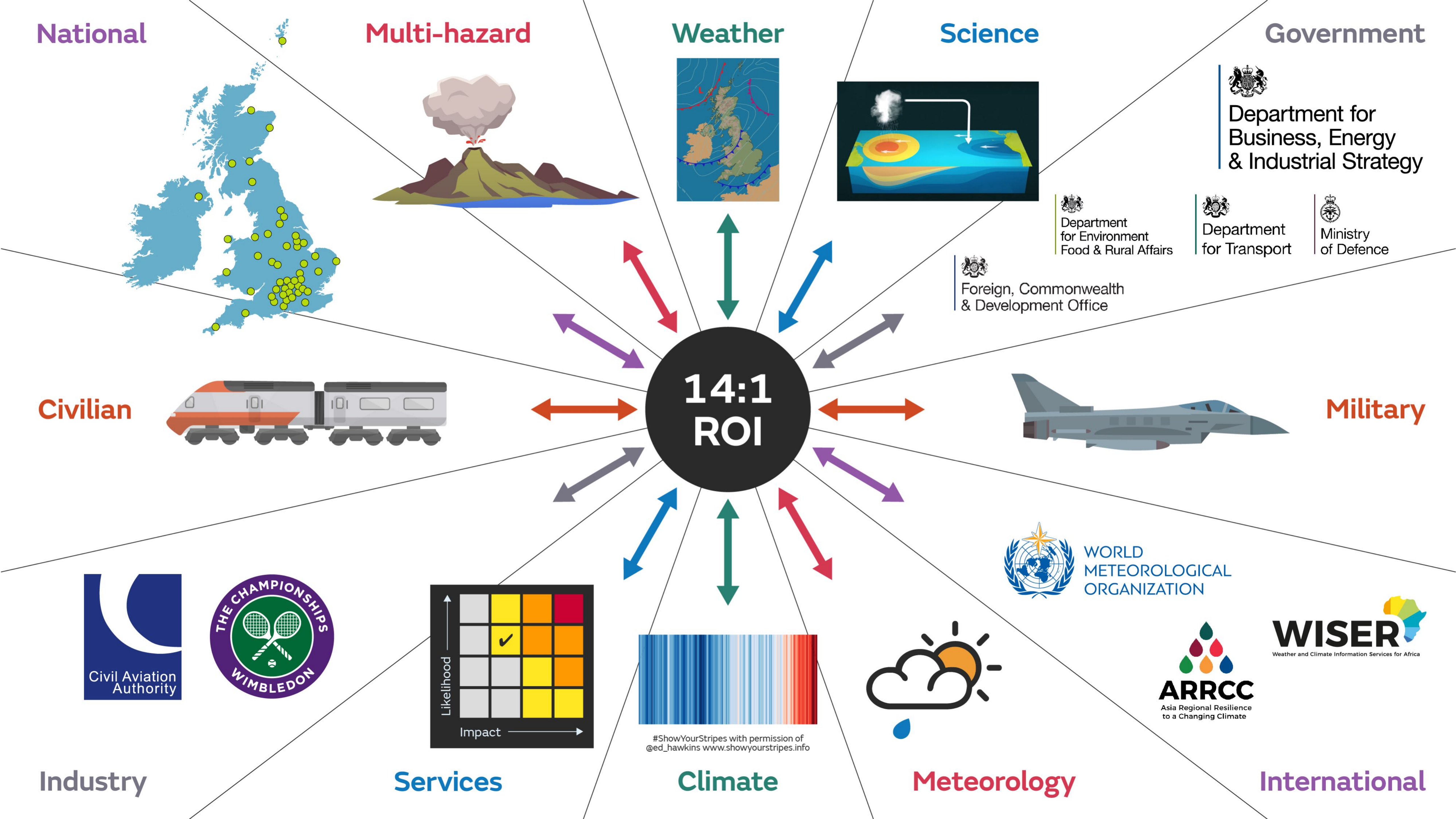
Helping you make better decisions to **stay safe and thrive**

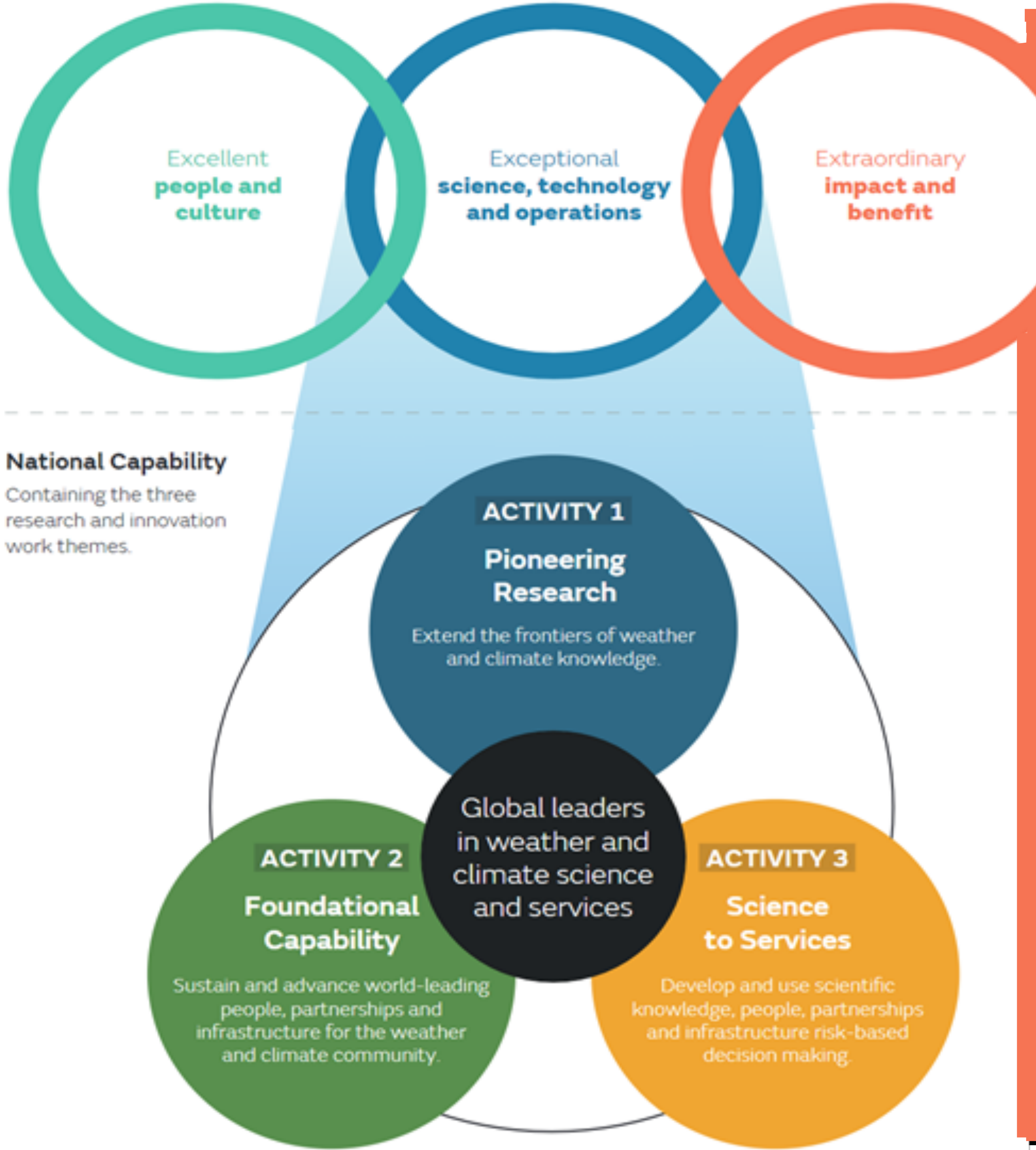
Our vision - What we want to achieve

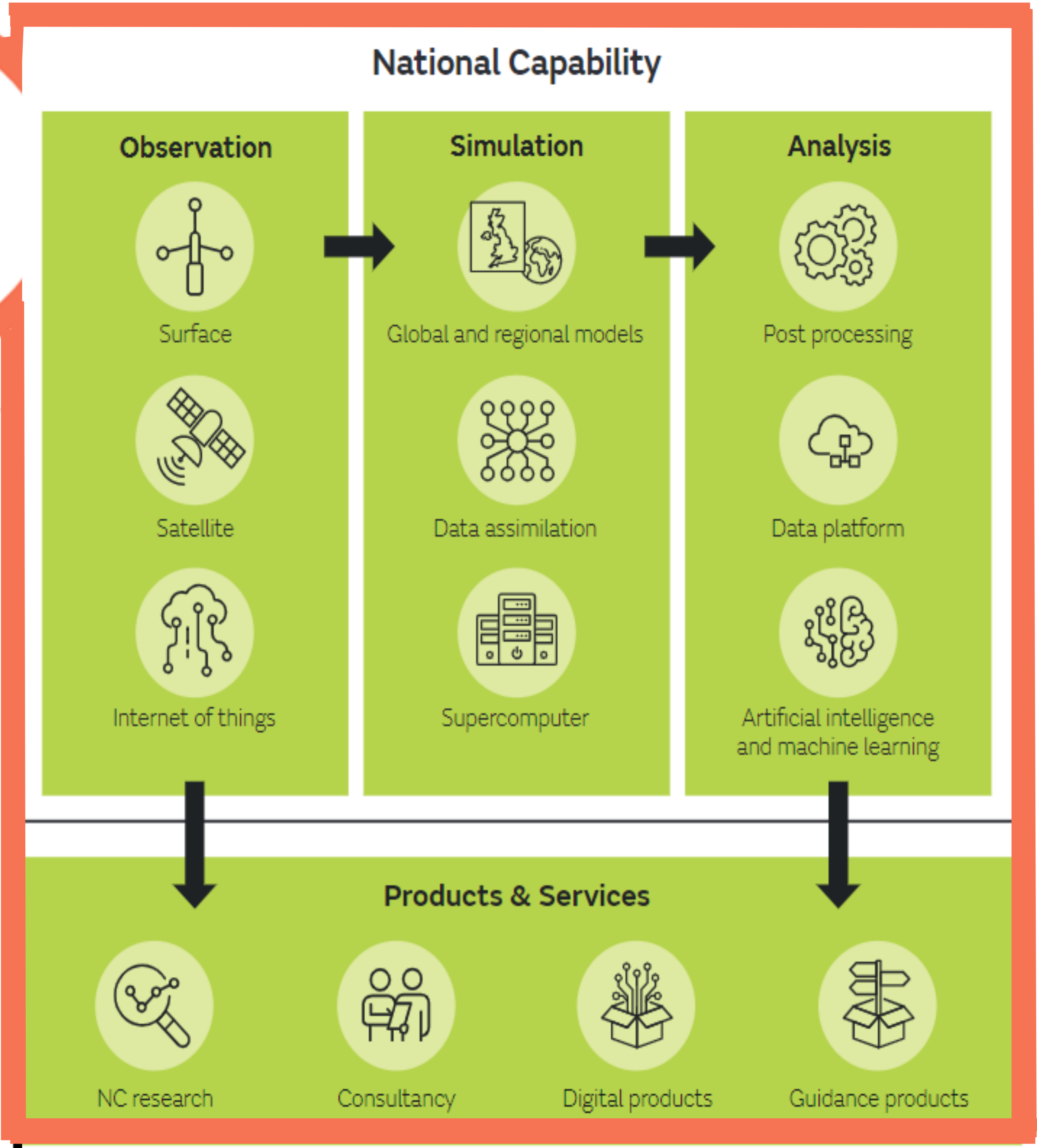
Recognised as global leaders in weather and climate science and services in our changing world

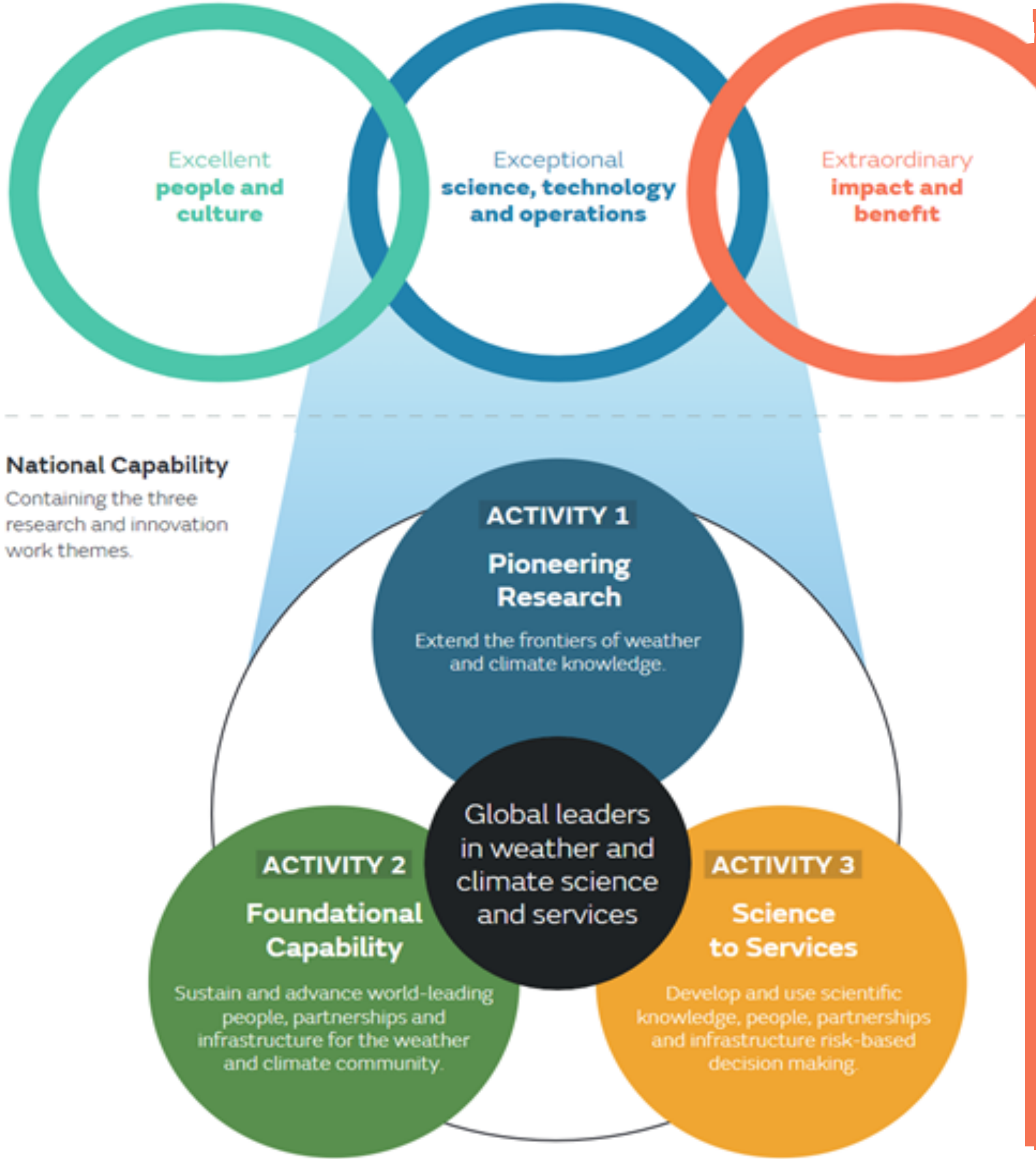
Strategic anchors - These are the areas we will focus on. The three areas overlap and complement each other.

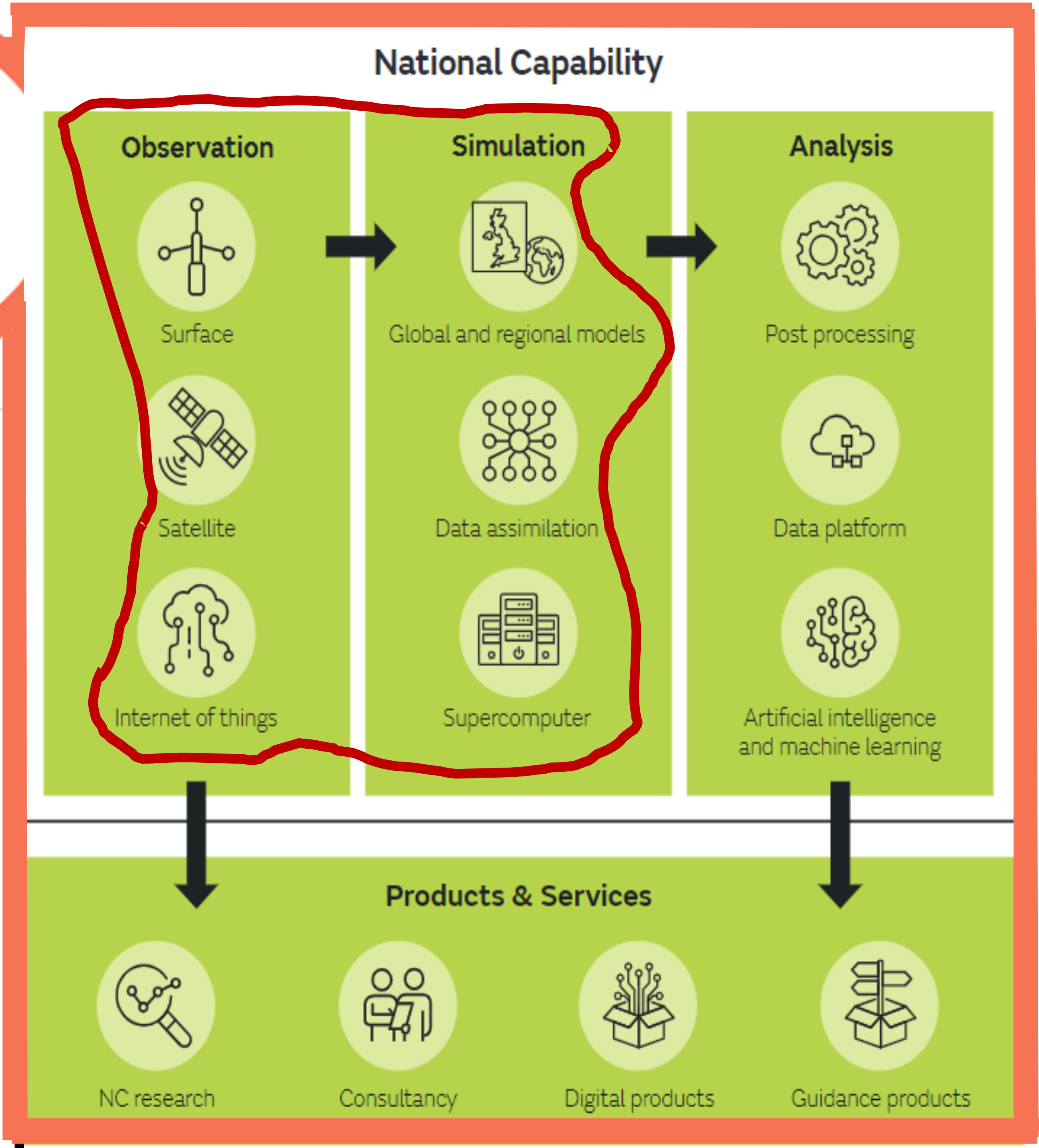



National
Multi-hazard
Weather
Science
Government
Department for Business, Energy & Industrial Strategy
Department for Environment Food & Rural Affairs
Department for Transport
Ministry of Defence
Foreign, Commonwealth & Development Office
Civilian
14:1 ROI
Military
WORLD METEOROLOGICAL ORGANIZATION
WISER
Weather and Climate Information Services for Africa
ARRCC
Asia Regional Resilience to a Changing Climate
Civil Aviation Authority
THE CHAMPIONSHIPS WIMBLEDON
Likelihood
Impact
#ShowYourStripes with permission of @ed_hawkins www.showyourstripes.info
Industry
Services
Climate
Meteorology
International


Excellent
people and
culture
Exceptional
science, technology
and operations
Extraordinary
impact and
benefit
National Capability
Containing the three
research and innovation
work themes.
ACTIVITY 1
Pioneering
Research
Extend the frontiers of weather
and climate knowledge.
Global leaders
in weather and
climate science
and services
ACTIVITY 2
Foundational
Capability
Sustain and advance world-leading
people, partnerships and
infrastructure for the weather
and climate community.
ACTIVITY 3
Science
to Services
Develop and use scientific
knowledge, people, partnerships
and infrastructure risk-based
decision making.

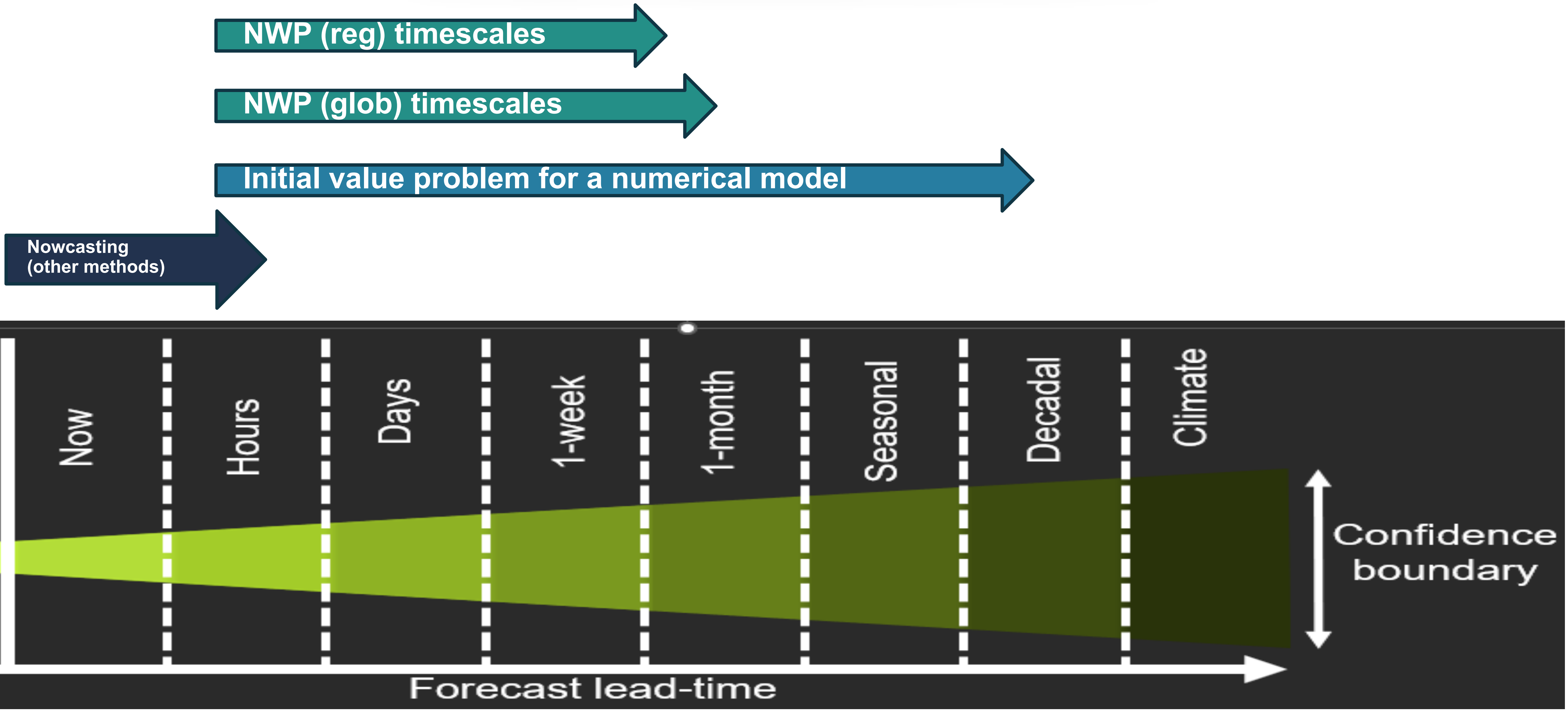

National Capability
Observation
Surface
Satellite
Internet of things
Simulation
Global and regional models
Data assimilation
Supercomputer
Analysis
Post processing
Data platform
Artificial intelligence
and machine learning
Products & Services
NC research
Consultancy
Digital products
Guidance products


Excellent
people and culture
Exceptional
science, technology and operations
Extraordinary
impact and benefit
National Capability
Containing the three research and innovation work themes.
ACTIVITY 1
Pioneering Research
Extend the frontiers of weather and climate knowledge.
Global leaders in weather and climate science and services
ACTIVITY 2
Foundational Capability
Sustain and advance world-leading people, partnerships and infrastructure for the weather and climate community.
ACTIVITY 3
Science to Services
Develop and use scientific knowledge, people, partnerships and infrastructure risk-based decision making.

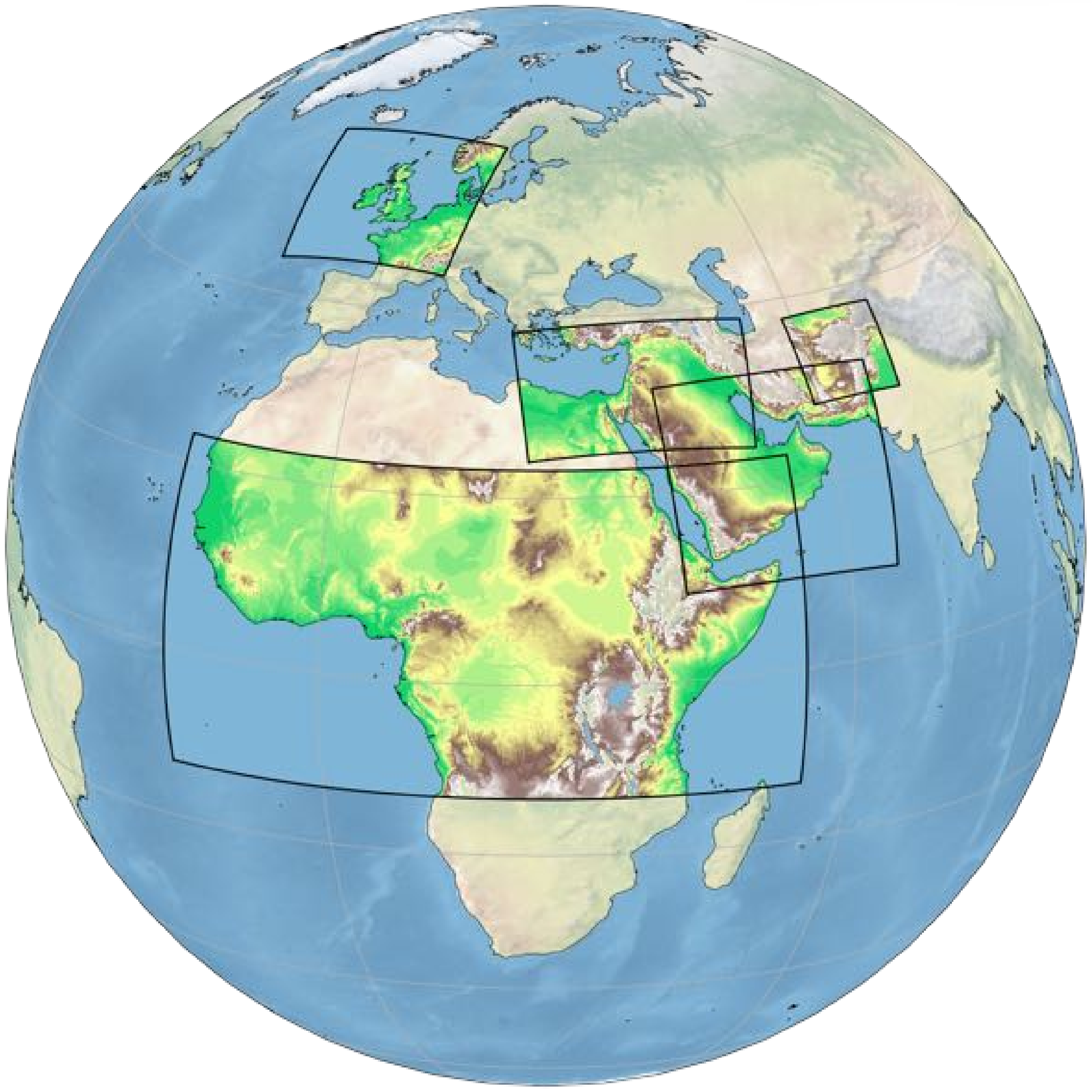

National Capability
Observation
Surface
Satellite
Internet of things
Simulation
Global and regional models
Data assimilation
Supercomputer
Analysis
Post processing
Data platform
Artificial intelligence and machine learning
Products & Services
NC research
Consultancy
Digital products
Guidance products

Timescales for NWP and a “seamless” model

What timescale is NWP?



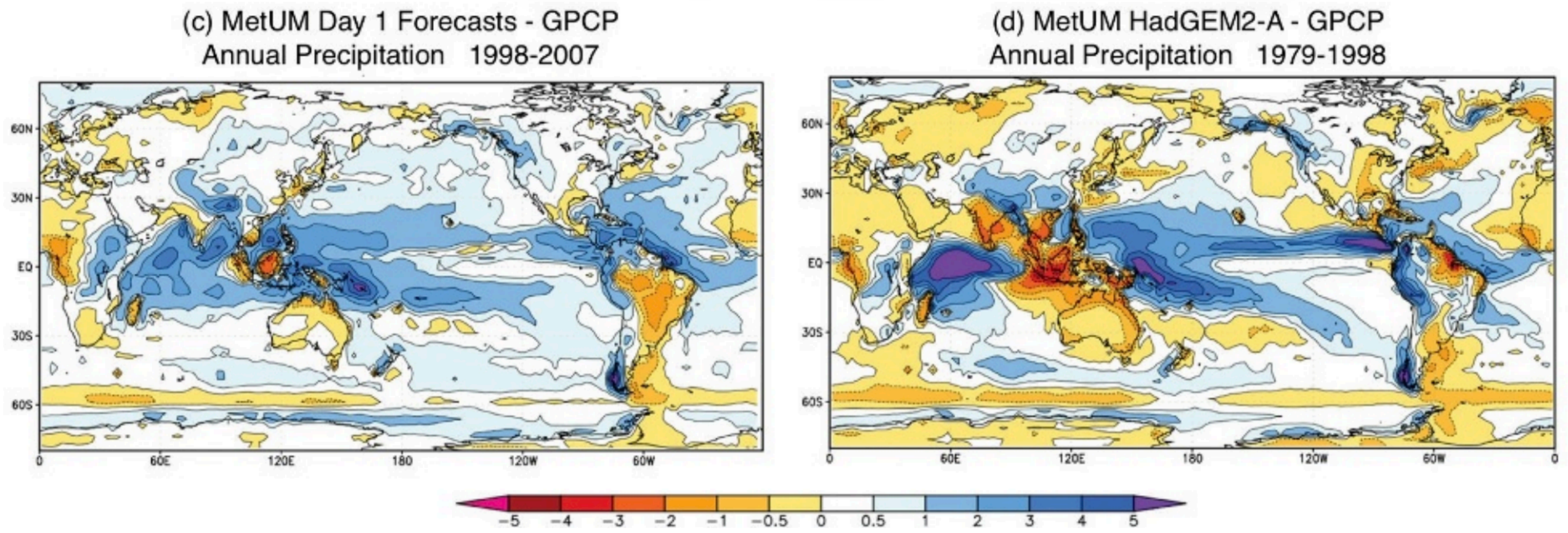
“Unified” modeling



A “common” modelling framework for use:
- Across time scales (hours to centuries)
- Global and regional
- Representing fine scales or courser scales to allow increased complexity etc…

Unified modeling
- Have things the same unless you need them to be different
- Know the differences
- Have a reason for them
  - I do not need/cannot afford that level complexity
  - I do not need a global configuration
  - I need to represent the carbon cycle and long runs but cannot afford convective scale
  - *My global land scheme doesn’t work well at high res regional scales – I will work on it…*

Why: “Unified” modeling

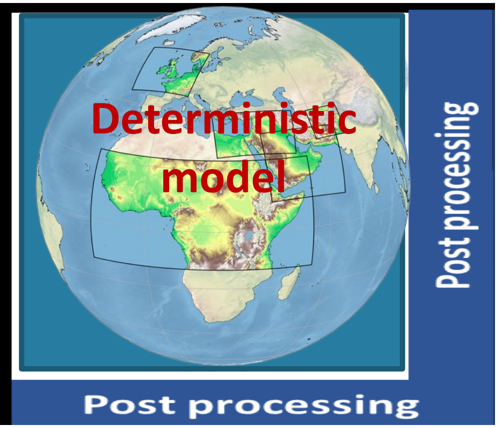


- Capture and analyze biases in short runs
- Model looked at in detail every day (in forecasts)
- Consolidation of effort in development of the system

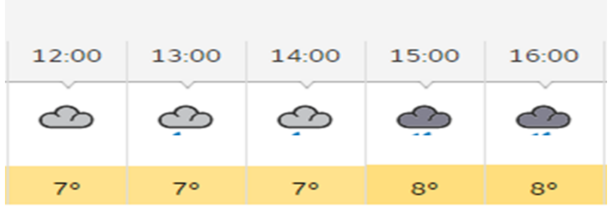
Ensembles in NWP to support services

NSF NCAR

Product “narratives” from a single realization



1 Single narrative products



Added uncertainty info from Postprocessing such as neighbourhood processing

Flood Risk Matrix
(River, tidal, coastal, surface water and groundwater flooding)

Likelihood				
High				
Medium				✓
Low				
Very Low				
	Minimal	Minor	Significant	Severe

Potential impacts

In this example I will assume a lagged ensemble is just an ensemble…

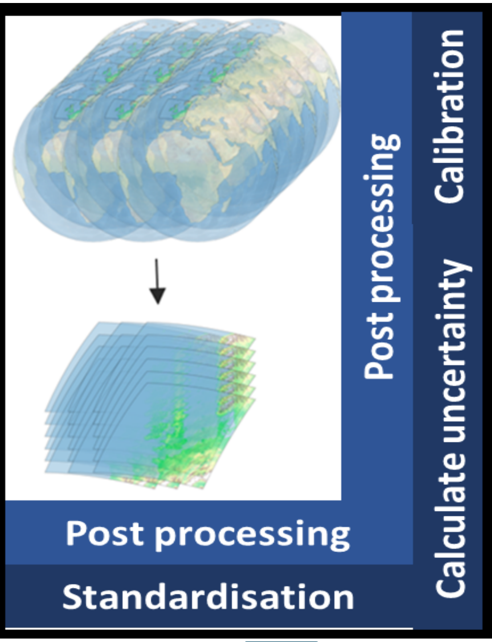
Added uncertainty info from Op met “climatological” knowledge of typical model uncertainty

Flood Risk Matrix
(River, tidal, coastal, surface water and groundwater flooding)

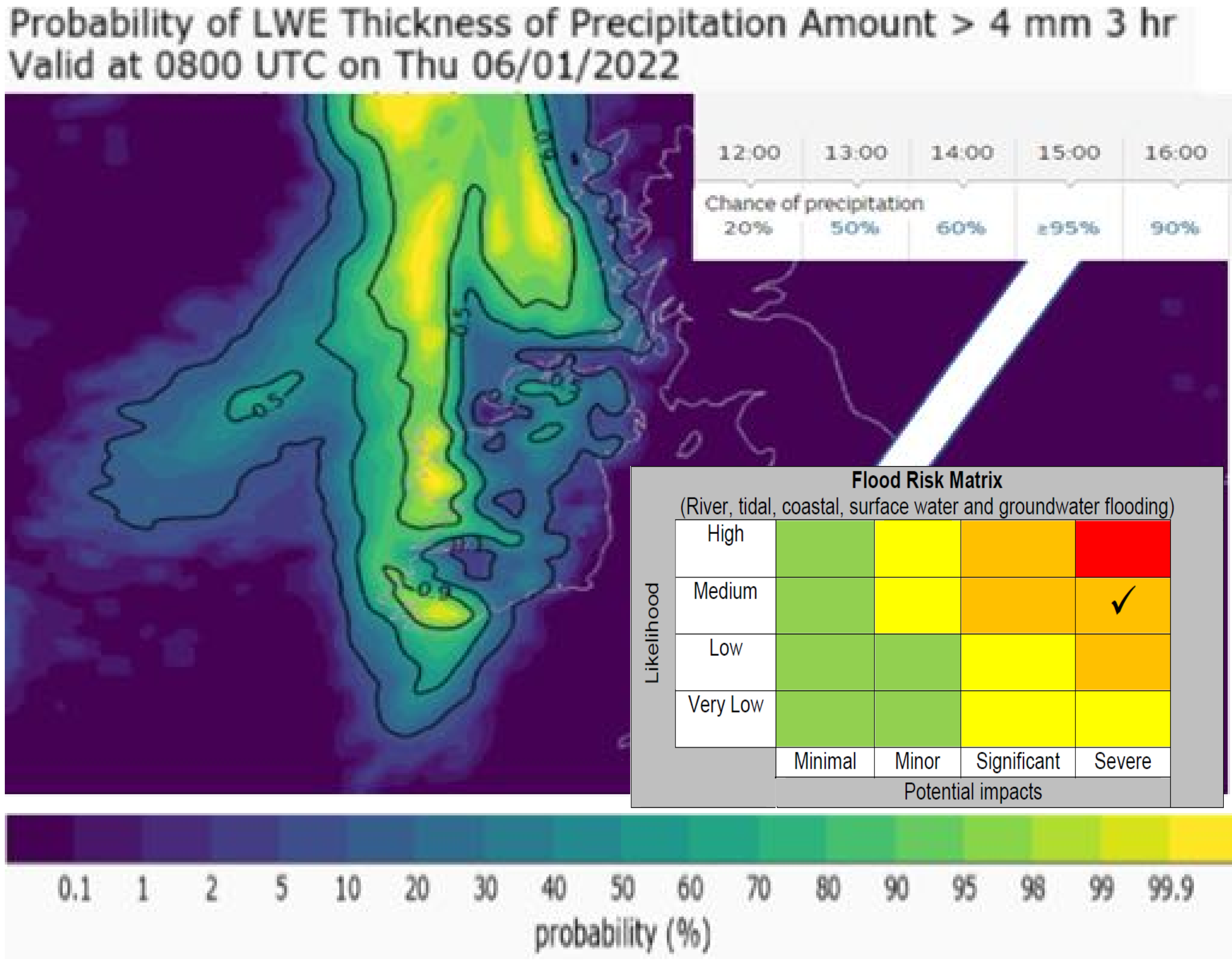
Likelihood				
High				
Medium				✓
Low				
Very Low				
	Minimal	Minor	Significant	Severe

Potential impacts

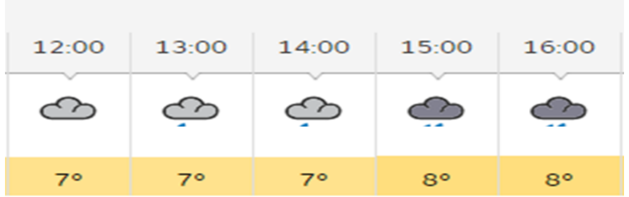
Four ways to use an ensemble



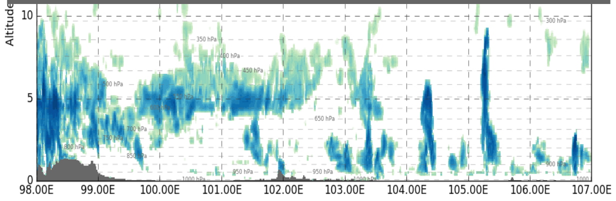
4. Narrative and products with likelihood, risk, extremes etc…



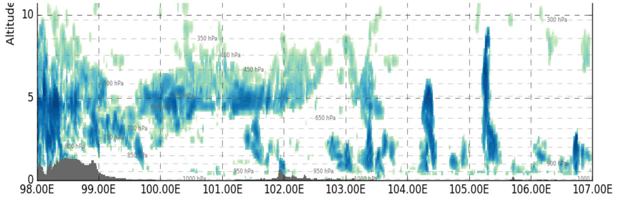
2. Single narrative products using processed ensemble



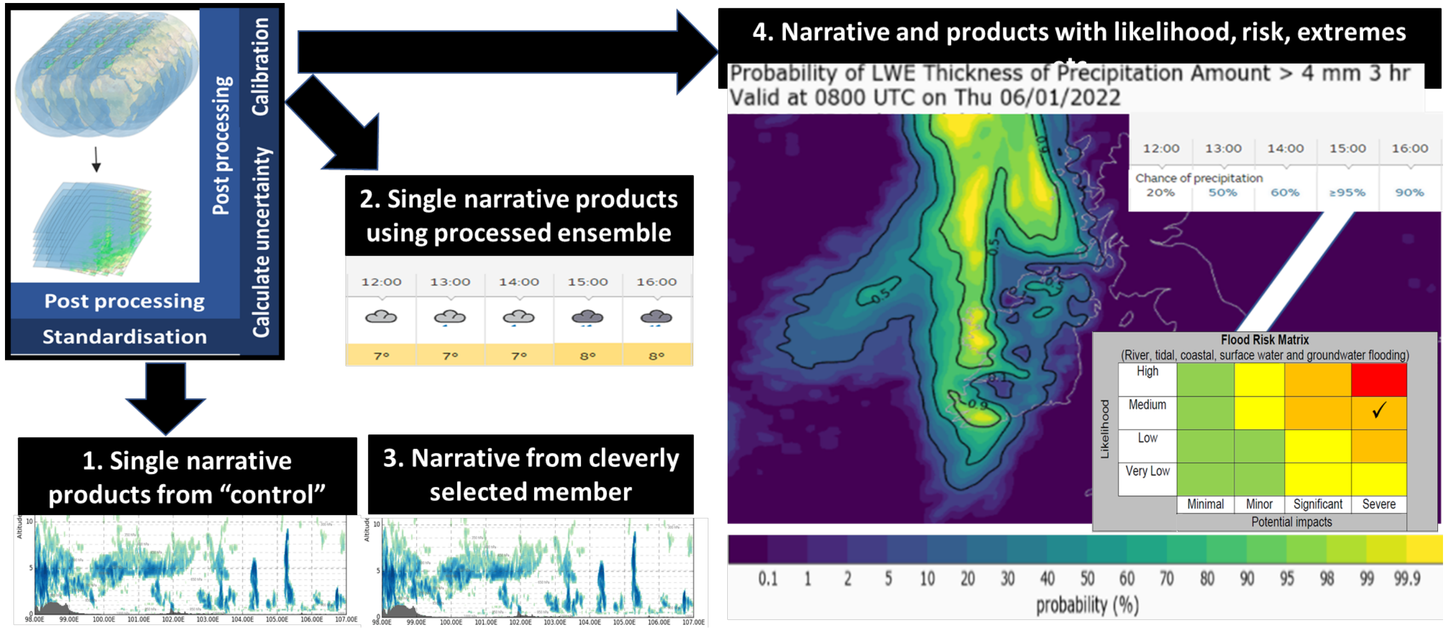
1. Single narrative products from "control"



3. Narrative from cleverly selected member

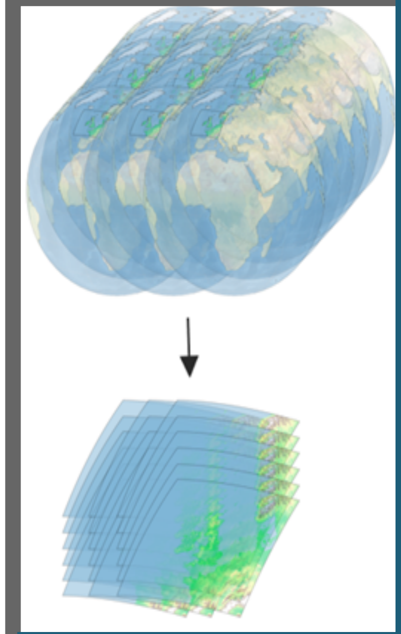


Four ways to use the ensemble



1 is not exploiting an ensemble. However, it allows us to use an ensemble system to deliver existing services without (much) work.
2 is exploiting ensembles. From end user perspective its just a more accurate single narrative.
3 is exploiting an ensemble. This is not really something we know how to do automated at this point.
4 is exploiting ensembles in perhaps the way we most commonly think of.

Challenges of ensembles from service (downstream) perspective



Post processing

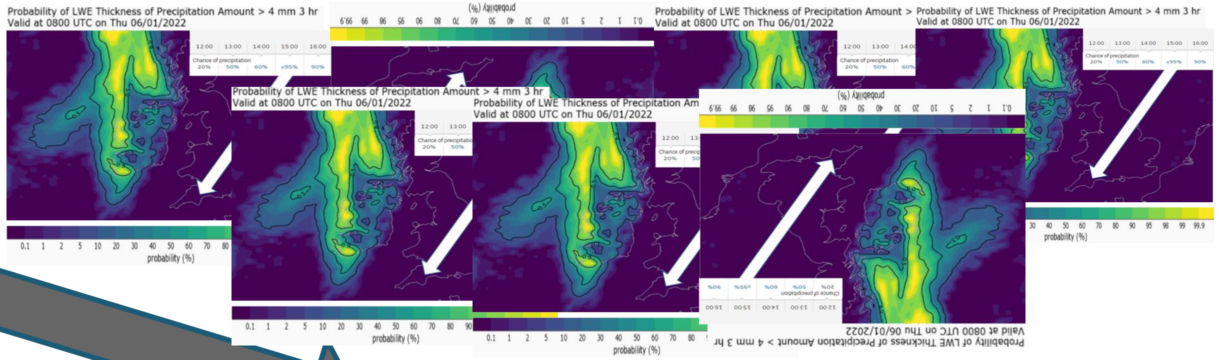
Calibration

Calculate uncertainty

Post processing

Standardisation

Large amounts of information to deal with in the forecasting process related to risk/uncertainty etc…



Influencing users to take information on uncertainty

Lots of data:- management and processing of it all

Getting the usable products/data to users that want uncertainty info

Defining an NWP system

Through the chain

Science to Services

Long term weather and climate science underpinning modelling capabilities

Delivering fundamental NWP capabilities to underpin our forecasting services

Translating our NWP data into services and advice

Global Coupled Ensemble NWP

Regional UK Ensemble NWP

Post processing: standardization, calibration and extraction of decision-relevant information

Weather services and advice for UK and beyond underpinned by probabilities and best deterministic narrative

Data Assimilation ingest as many observations as we can for best initial conditions

Physical model modelling systems representing the atmosphere, ocean and land as well as we can

Services: Taking the NWP data, making it more accurate, usable and then providing the advice

Prediction

Process observations
Gather, quality control and process observation ready for assimilation

Assimilate Observations
Data Assimilation (DA): Make analysis by combining model background and observations

Run forecast
Run ensemble systems for days ahead

Process NWP output
Post processing: Standardise, calibrate and extract decision relevant information.

Advise users
Utilise tools to deliver user specific advice

Understand
Advance our knowledge of fundamental processes. Develop novel and new methods.
Science and social sciences.

Develop and optimize
Translate understanding into systems and tools that are used above. Improve the systems for performance and efficiency.
Science, software engineering.

Evaluate and engage
Test and understand systems. Engage users to understand user needs. Identify areas for improvement.
Science; social science, testbeds.

Research & development

Prediction

Process observations	Assimilate Observations	Run forecast	Process NWP output	Advise users
Gather, quality control and process observation ready for assimilation	Data Assimilation (DA): Make analysis by combining model background and observations	Run ensemble systems for days ahead	Post processing: Standardise, calibrate and extract decision relevant information.	Utilise tools to deliver user specific advice

Understand	Develop and optimize	Evaluate and engage
Advance our knowledge of fundamental processes. Develop novel and new methods. Science and social sciences.	Translate understanding into systems and tools that are used above. Improve the systems for performance and efficiency. Science, software engineering.	Test and understand systems. Engage users to understand user needs. Identify areas for improvement. Science; social science, testbeds.

Research & development

Met Office

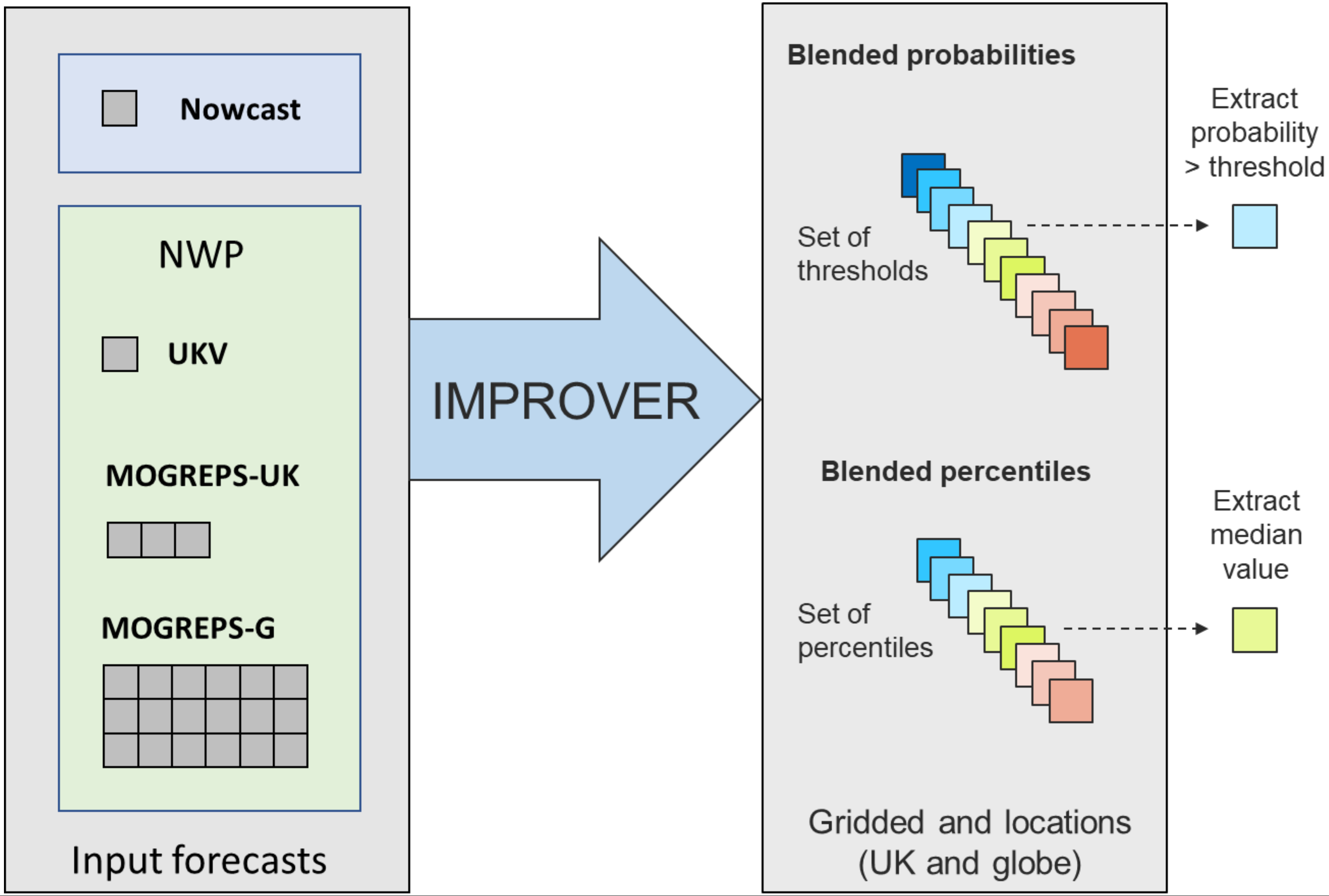
Postprocessing our ensemble

Process NWP output

Post processing: Standardise, calibrate and extract decision relevant information.

IMPROVER

Inputs	Input forecasts from individual NWP models / ensembles / nowcast
New variables Physical adjustments	Calculate new variables and apply physical adjustments including downscaling
Create probabilities Combine members	Convert to binary probabilities and combine ensemble members
Process probabilities Time-lag	Apply spatial post processing methods and include older forecasts (time lag)
Statistical calibration	Apply statistical post processing methods
Blend models	Blend probabilities from different models
Weather types Spot forecasts	Generate weather types and spot forecasts Output gridded and spot



Running an NWP system

Some nitty gritty

Operational NWP systems

OS45 – Operational June 2022

Global NWP:

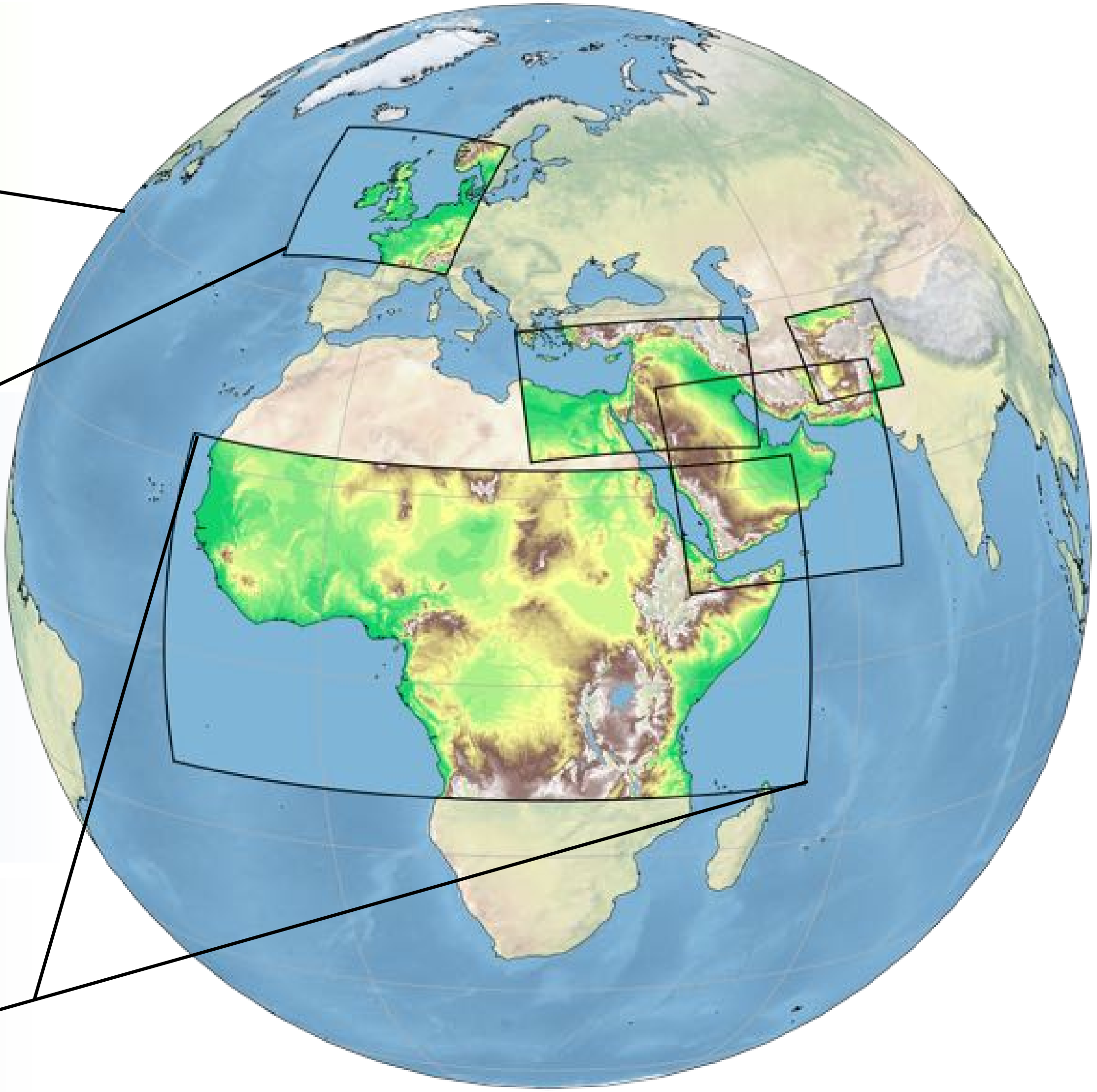
- 10/20km deterministic/ensemble
- 70 vertical levels (80km top)
- Hybrid 4D Variational Data Assimilation (DA)
- Forecasts to T+48 or T+192hr every 6 hours
- Coupled to ¼ degree ocean (weakly coupled DA)

UK NWP:

- 1.5/2.2km deterministic/ensemble
- 70 vertical levels (40km top)
- Hourly 4DVar DA + Radar via Latent Heat Nudging
- Forecasts to T+12 - 120hr every hour
- Hourly updating ensemble (up to T+120hr)
- Time varying SSTs from 1.5 km regional ocean model

Other Models:

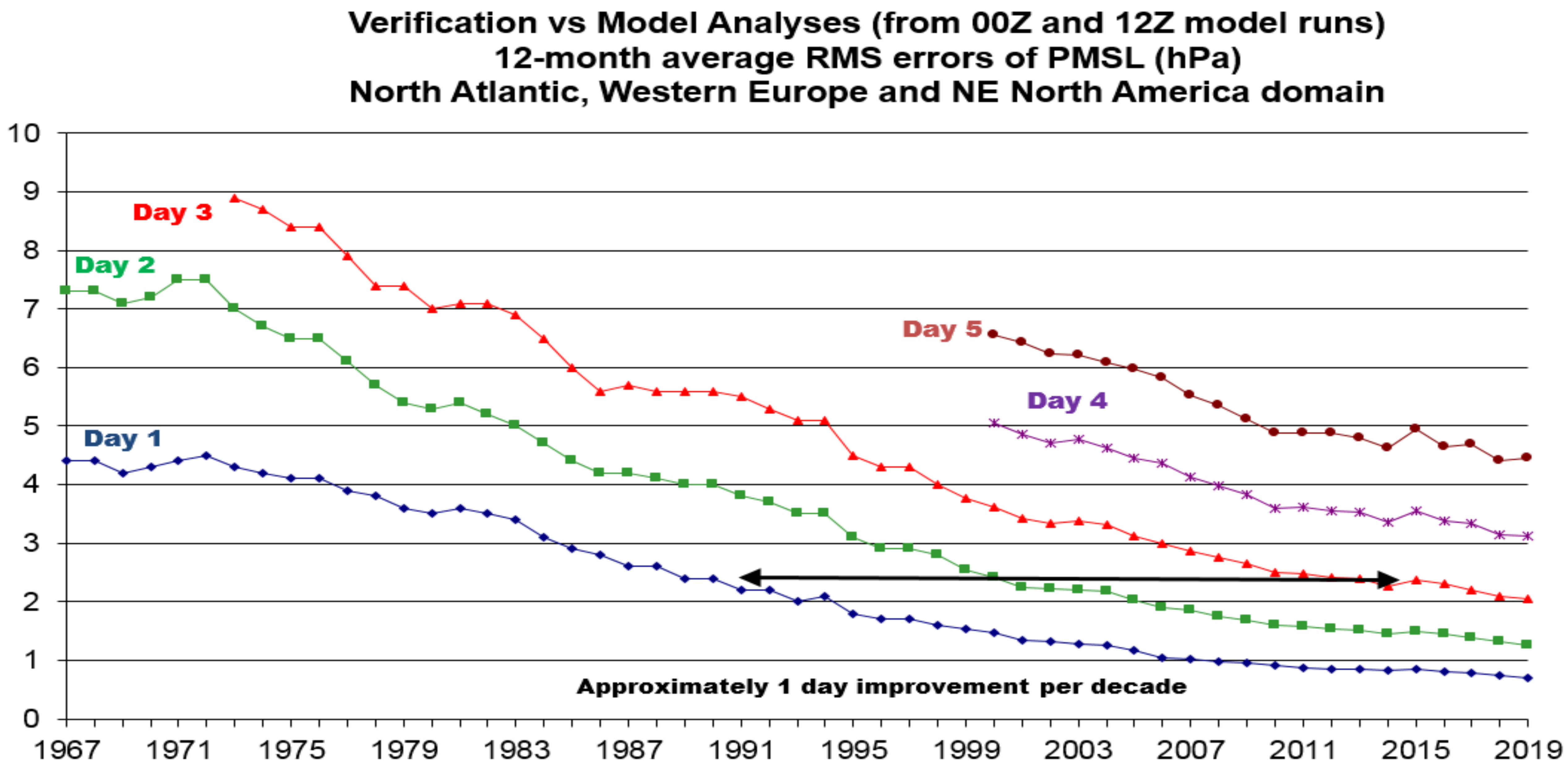
- 4.4km (without DA)
- 70 vertical levels (40km top)



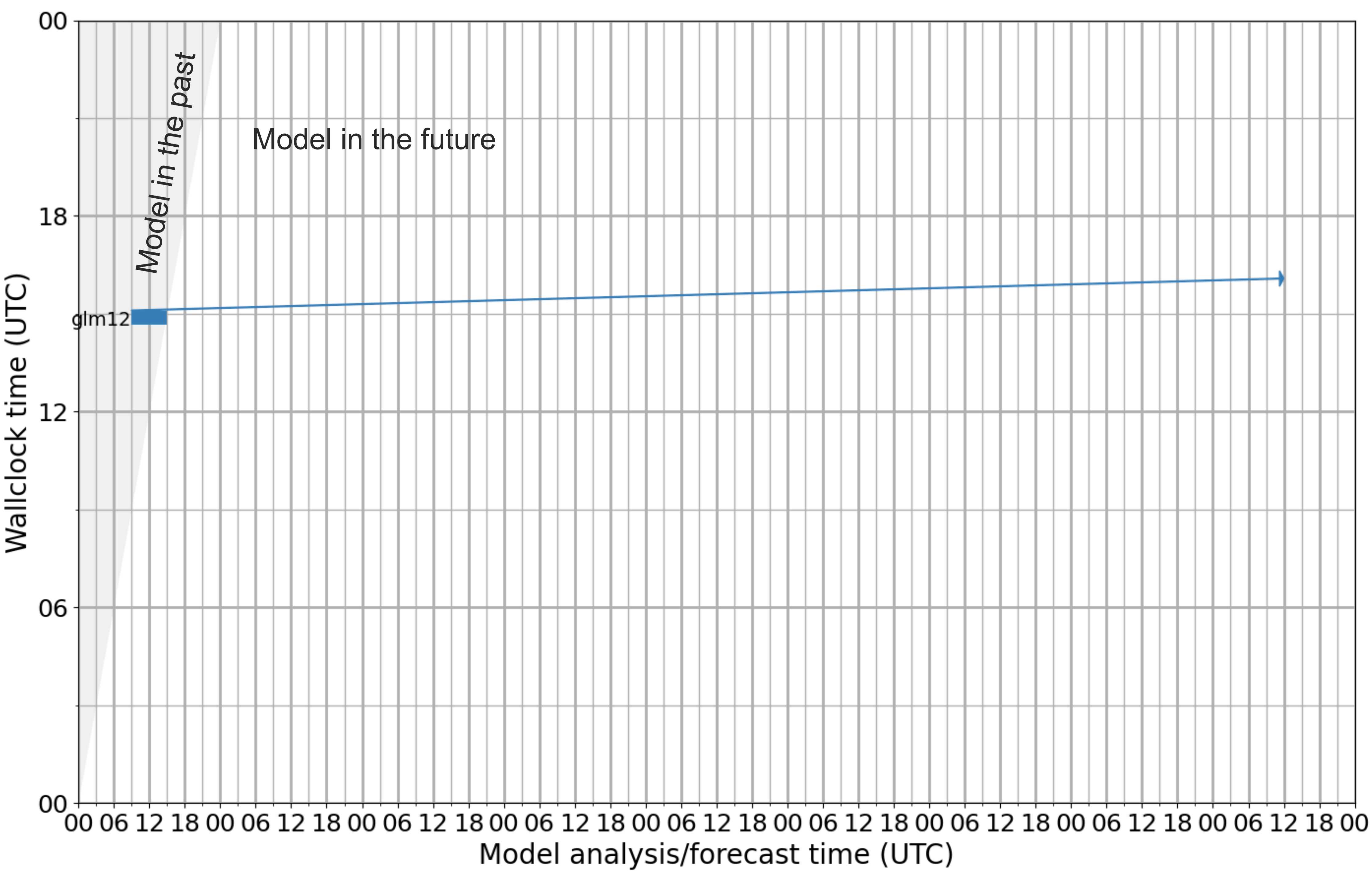
Why regional and why global?

- A regional model can give be run at higher resolution
  - There are step changes in impact information as we approach 1 km grid length
  - We can run more them far cheaper so we can afford to have
    - The finer scales
    - More ensembles
    - More rapid refresh (1 hour vs. 6)
    - Assimilate more/different obs (more locally available obs such as from ground based radar)
  - Regional DA is not good at constraining larger scales so links to global DA are needed
    - In UK this is done by blending global and regional tendencies
    - IN US a regular (e.g. daily) reset is done to use global analysis as Ics (cold start)
- But a global model is needed to provide the drivers of the regional model
  - So you either have it as part of your system or use someone else's
    - Note that the scheduling becomes delayed and you have less flexibility if it is not your's
  - Global ensembles and spread are needed as regional model moves to longer lead times
    - depends on domain size but let's say 2 days

- Regional models are usually run out to 2-3 days (US) but as far as 6 days (UK)
  - Beyond this detail loses any relevance
- In terms of global models – most skill is lost between 5 and 7 days now but we improve at a days lead time every 10 years of development


Verification vs Model Analyses (from 00Z and 12Z model runs)
12-month average RMS errors of PMSL (hPa)
North Atlantic, Western Europe and NE North America domain
Day 1
Day 2
Day 3
Day 4
Day 5
Approximately 1 day improvement per decade
10
9
8
7
6
5
4
3
2
1
0
1967
1971
1975
1979
1983
1987
1991
1995
1999
2003
2007
2011
2015
2019

DA cycling and the forecast



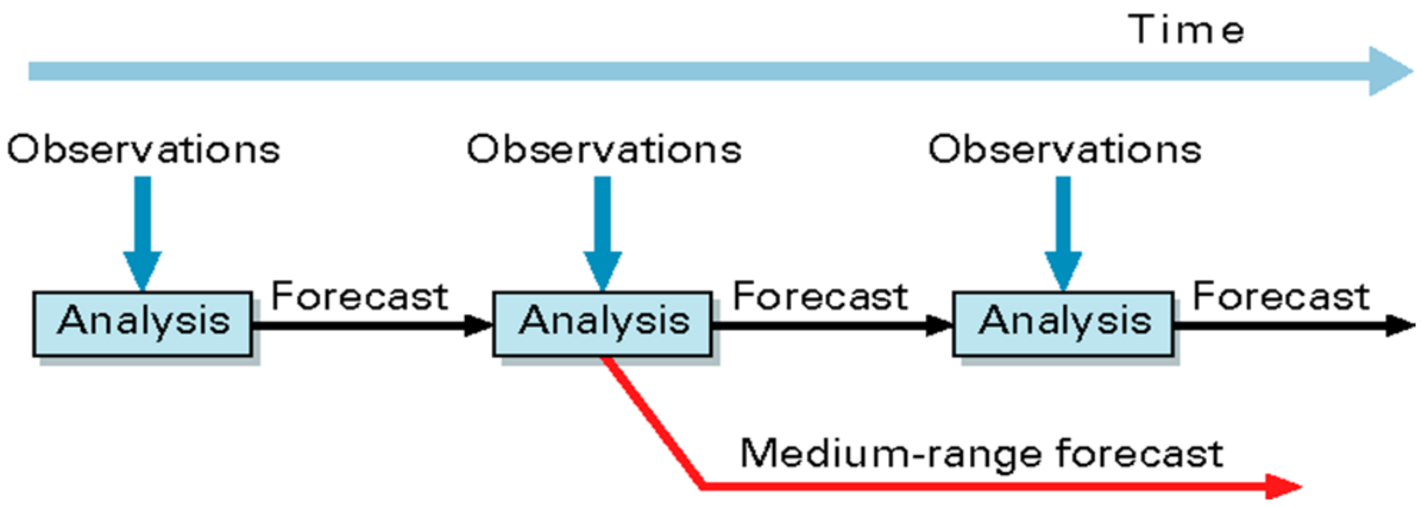
Model in the past
Model in the future
glm12
Wallclock time (UTC)
00
18
12
06
00
00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00
Model analysis/forecast time (UTC)

Met Office

Data Assimilation cycle

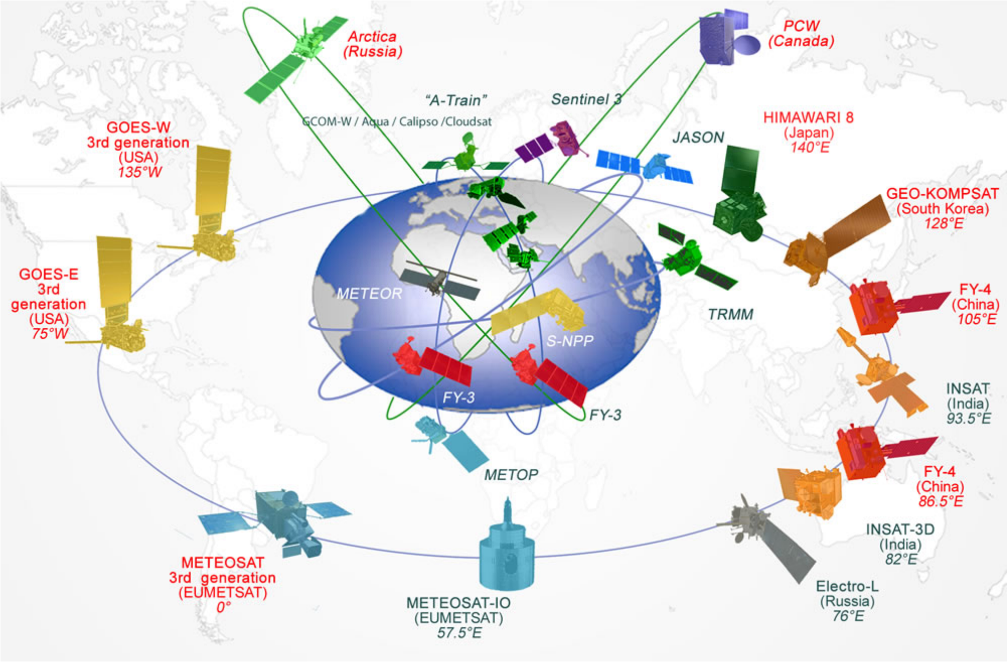
Data Assimilation is the process of absorbing and incorporating observed information into a prognostic model

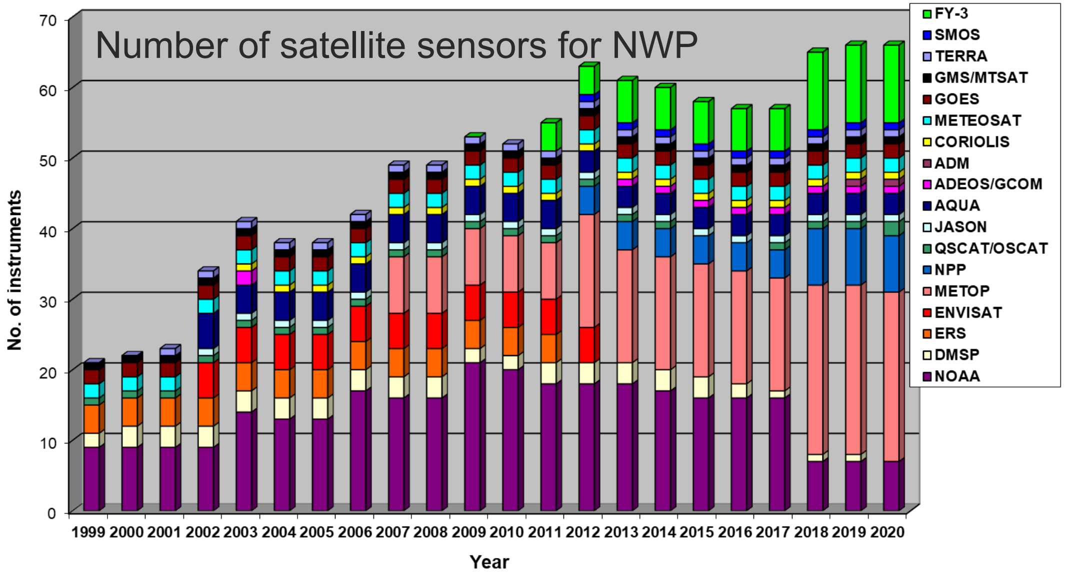
NWP definition:
process to estimate "optimal" initial conditions (or best analysis) that lead to best numerical forecast

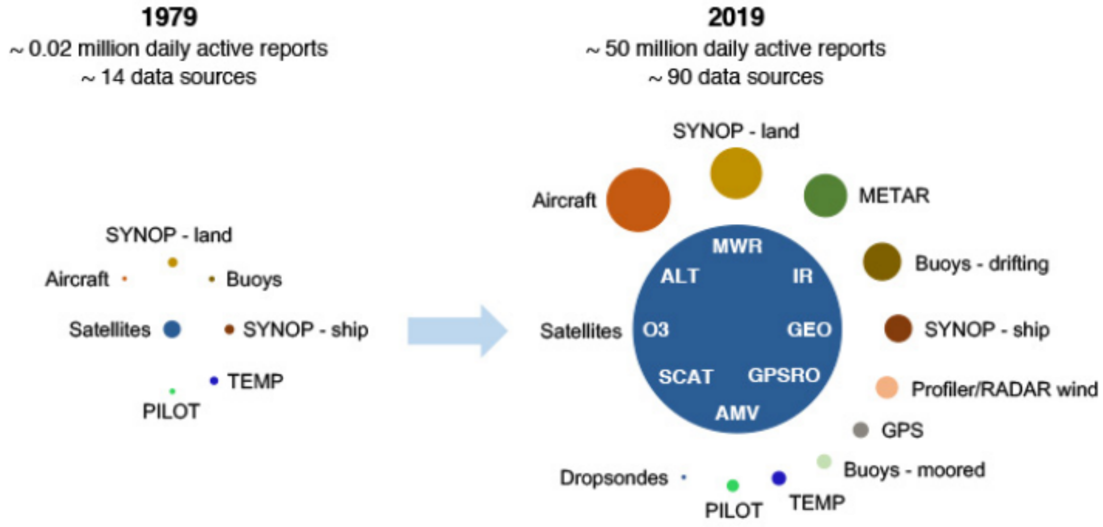


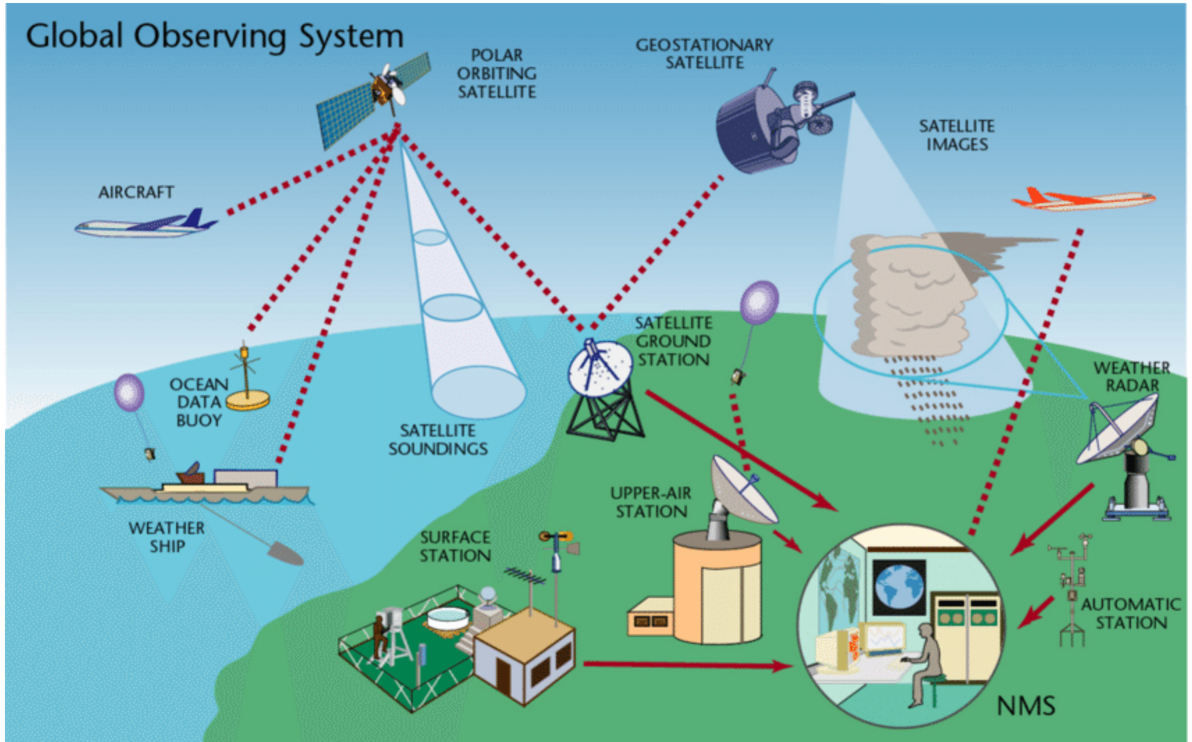
- The observations are used to correct errors in the short forecast from the previous analysis time (every 6 hours for global NWP, more frequently for higher resolution limited areas models)
- Every 6 hours about ~5 millions of observations are used to correct ~10^9 variables that define the model's atmosphere
- This is done by 4D-Var, a 4-dimensional adjustment in space and time
- The model is an integral part of the analysis algorithm, it carries information from past observations into the current analysis – the better the model the more accurate the background trajectory!

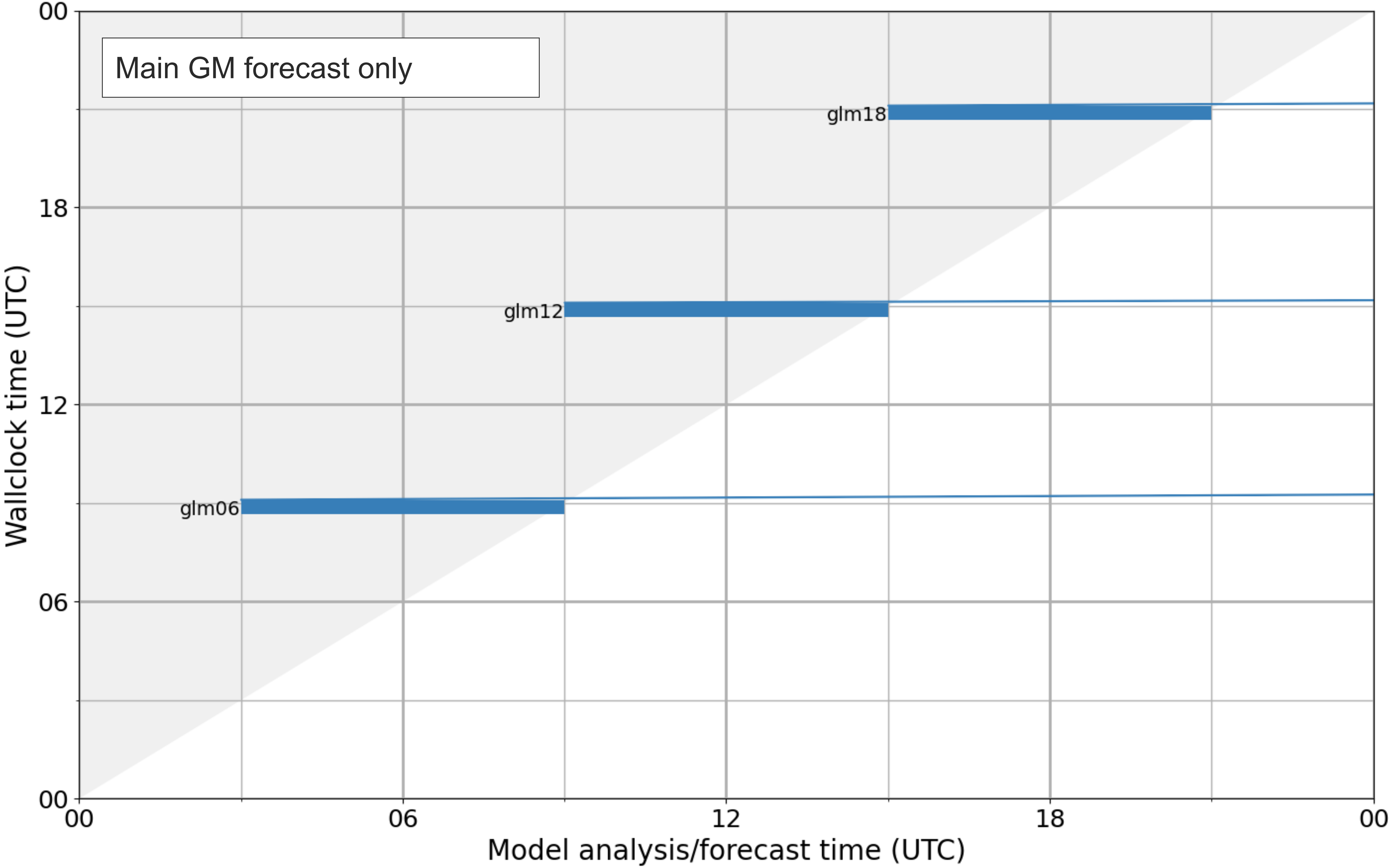
WMO Integrated Global Observing System



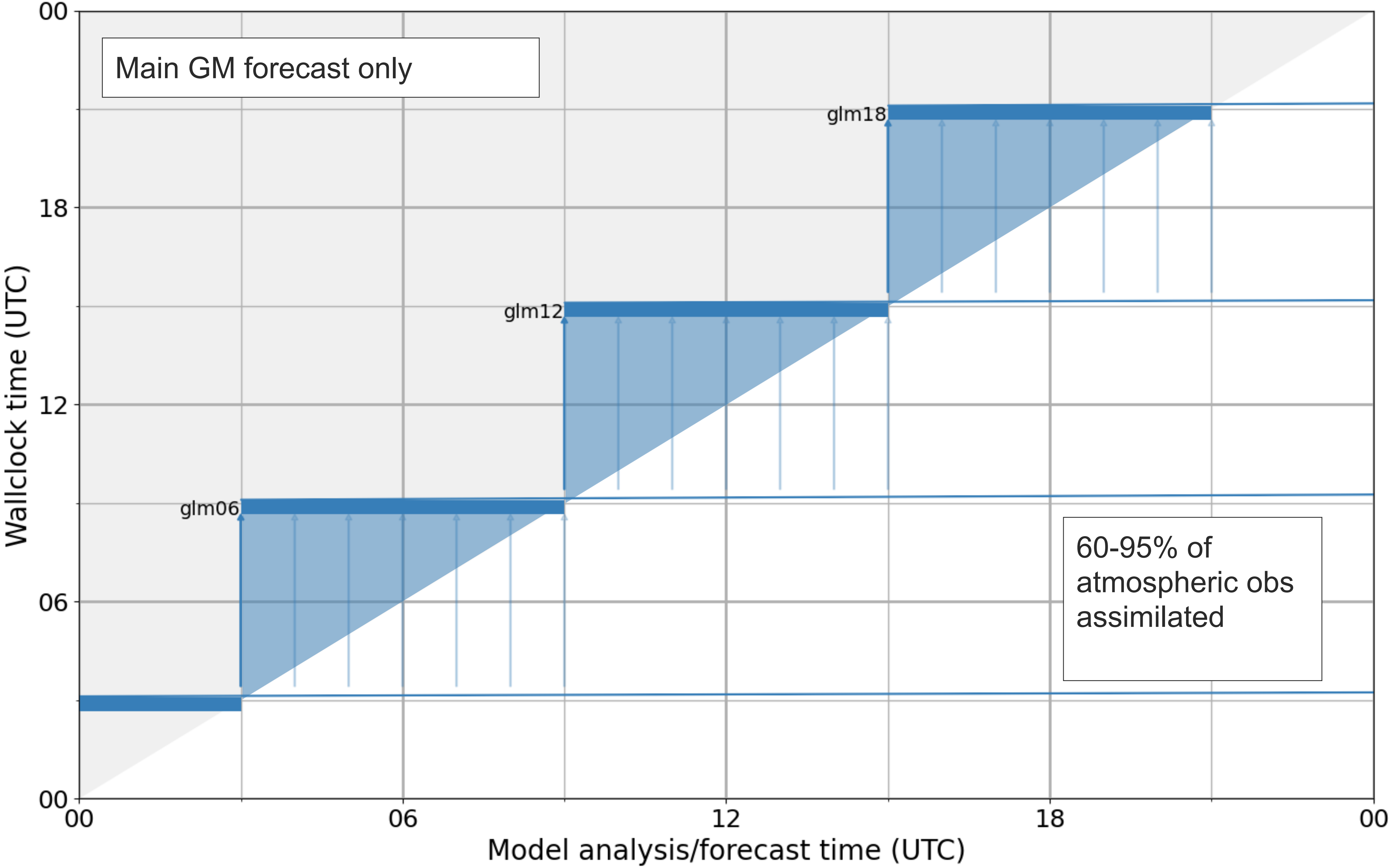




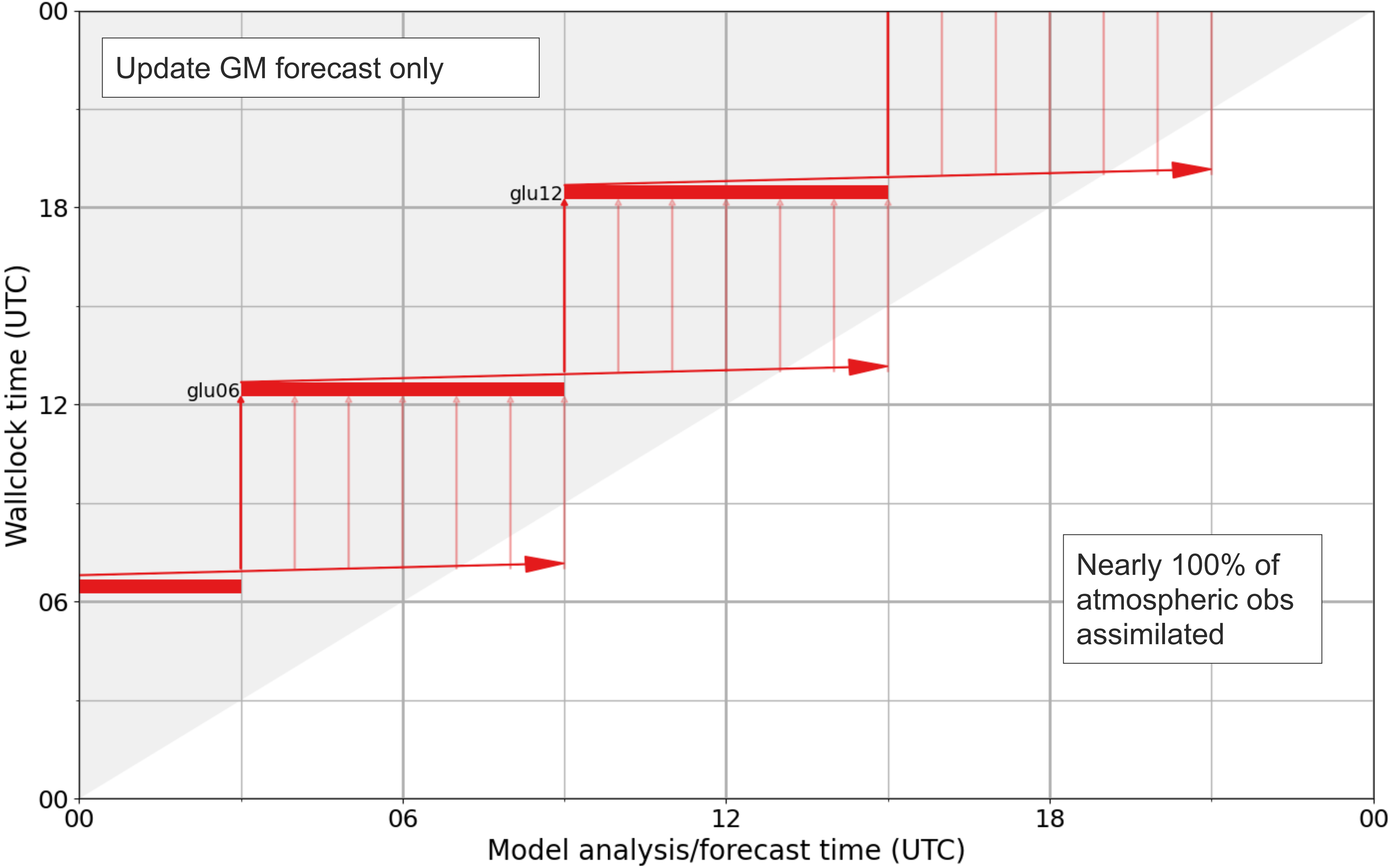




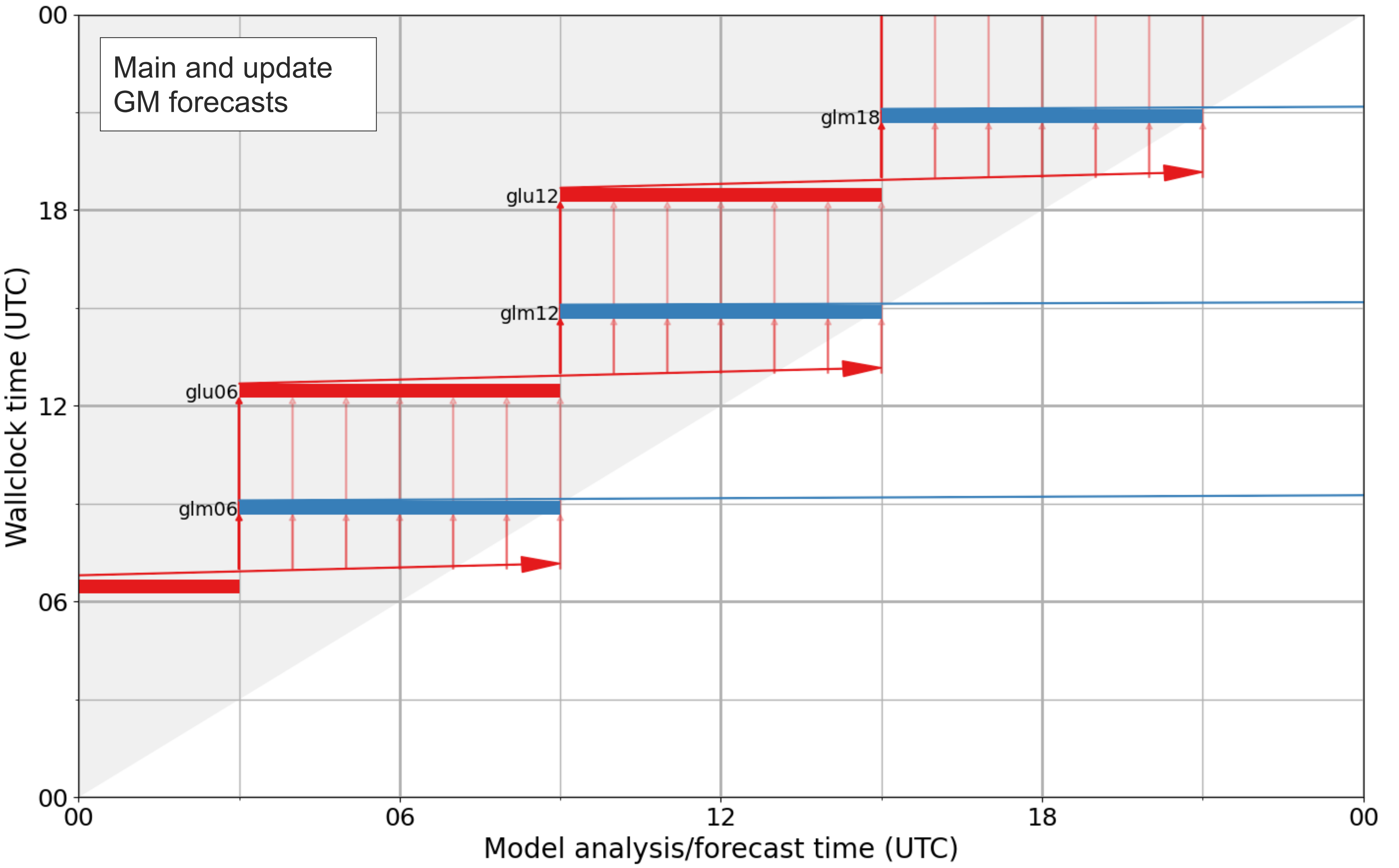
Main GM forecast only
glm06
glm12
glm18
Wallclock time (UTC)
Model analysis/forecast time (UTC)
00
06
12
18
00
00
06
12
18
00



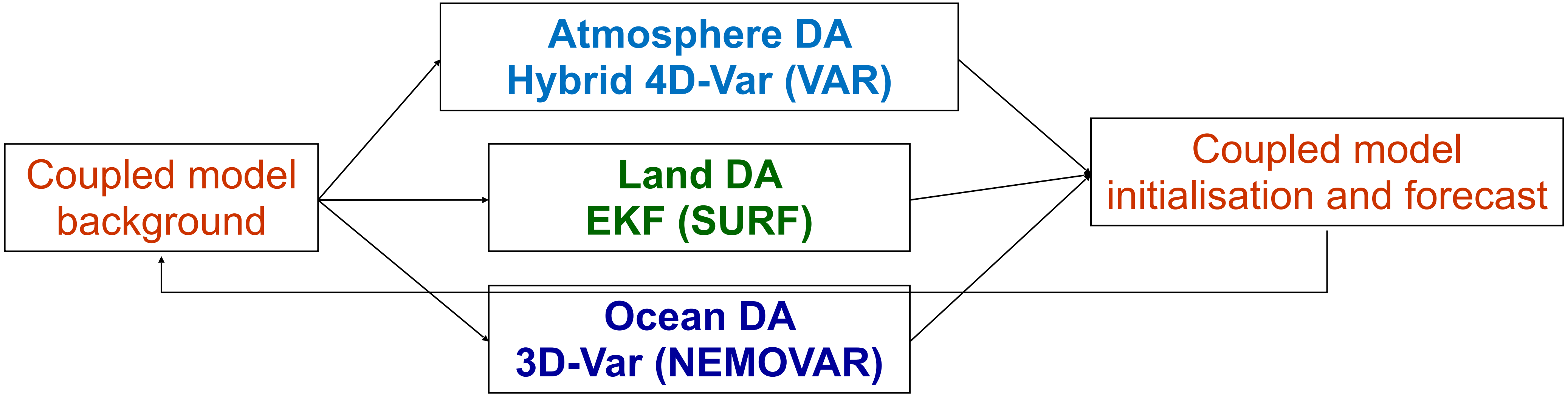
Main GM forecast only
glm06
glm12
glm18
60-95% of atmospheric obs assimilated
Wallclock time (UTC)
00
18
12
06
00
00
06
12
18
00
Model analysis/forecast time (UTC)

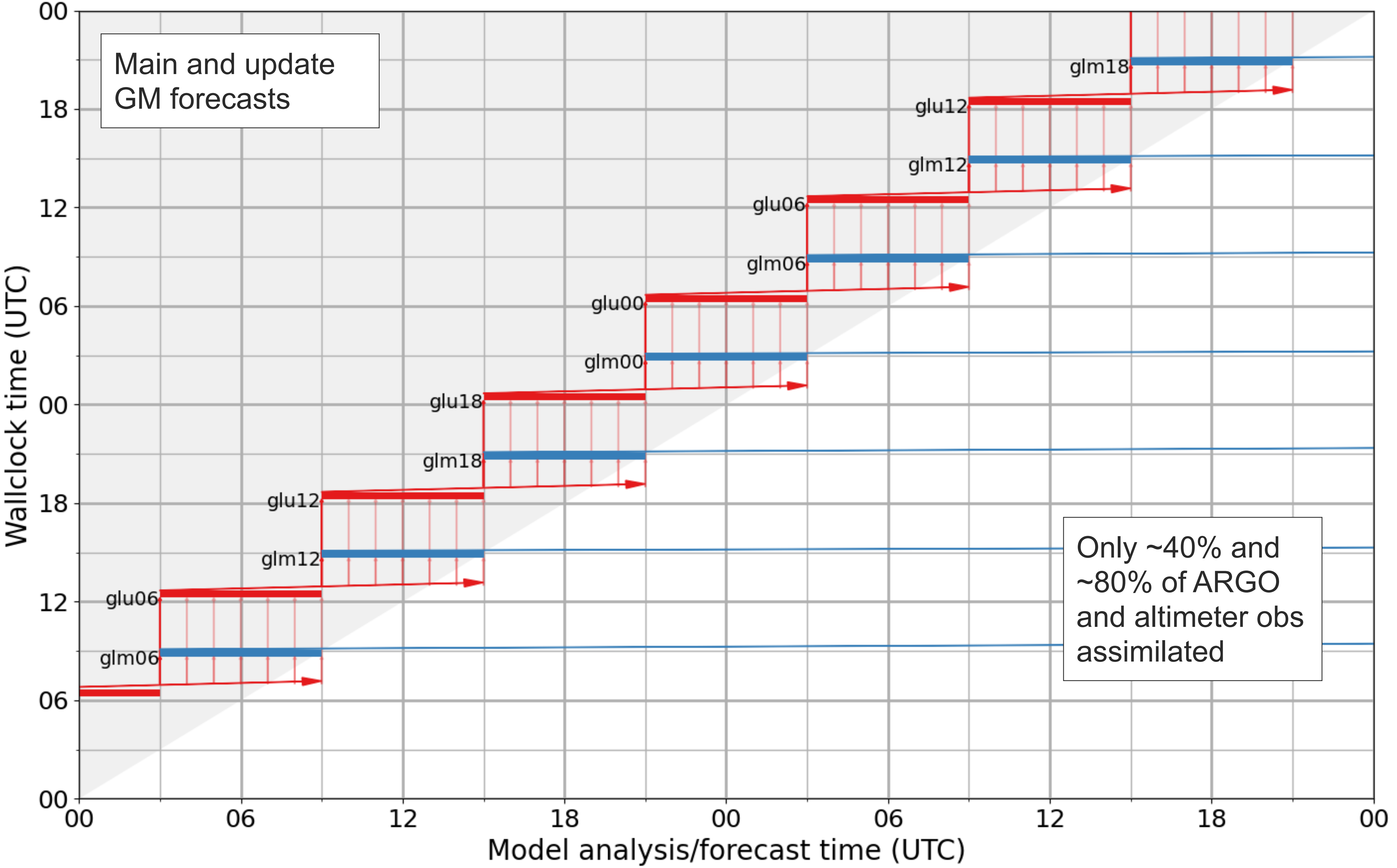


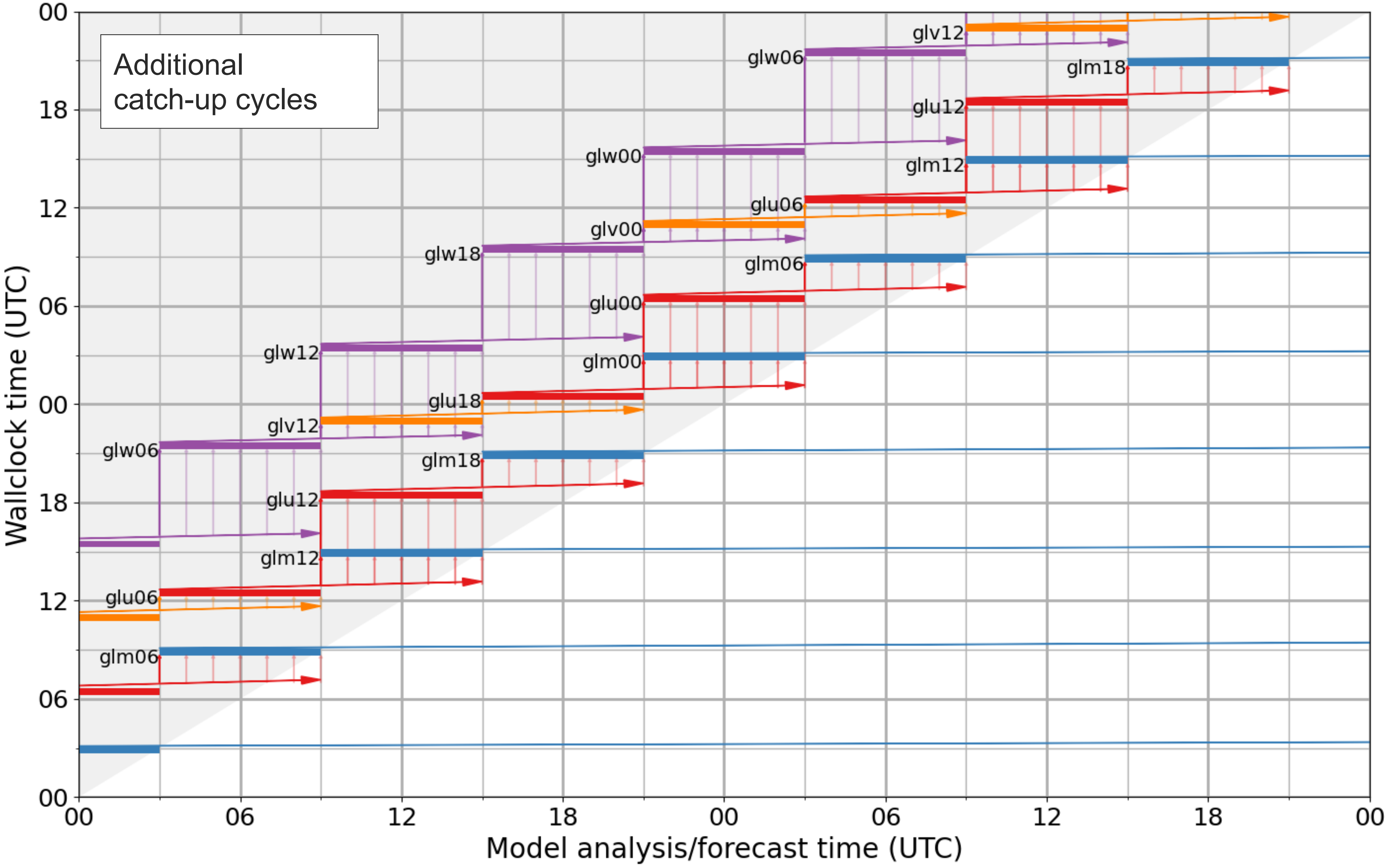
Update GM forecast only
glu06
glu12
Nearly 100% of atmospheric obs assimilated
Wallclock time (UTC)
00
18
12
06
00
Model analysis/forecast time (UTC)
00
06
12
18
00


Main and update
GM forecasts
glm18
glu12
glm12
glu06
glm06
00
18
12
06
00
Wallclock time (UTC)
00
06
12
18
00
Model analysis/forecast time (UTC)

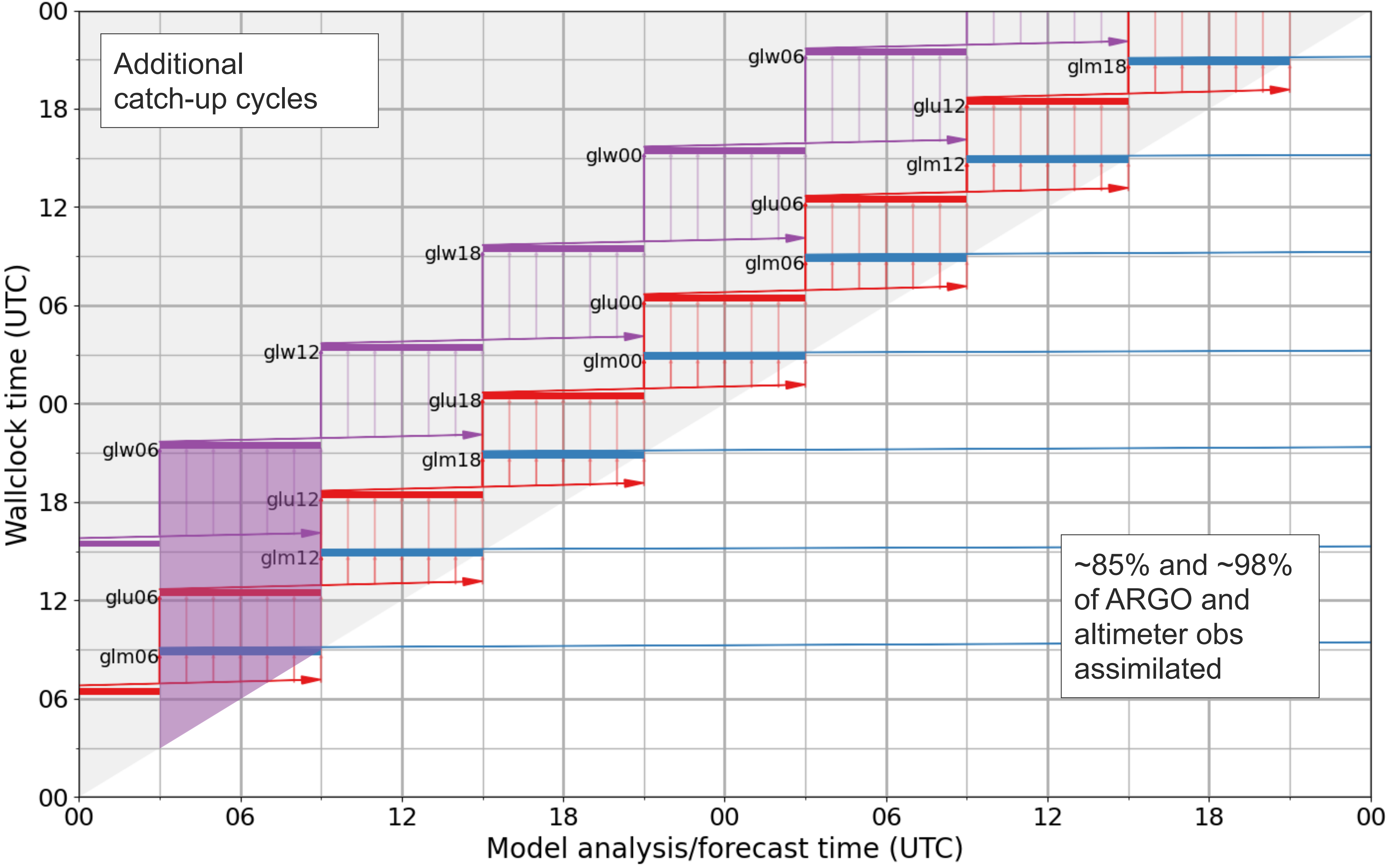
- **The ensemble system relies on the deterministic model**
- **The global model is coupled ocean-atmosphere and needs to ingest Ocean obs with come in slower than the atmospheric obs**
  - We use weakly couped DA…



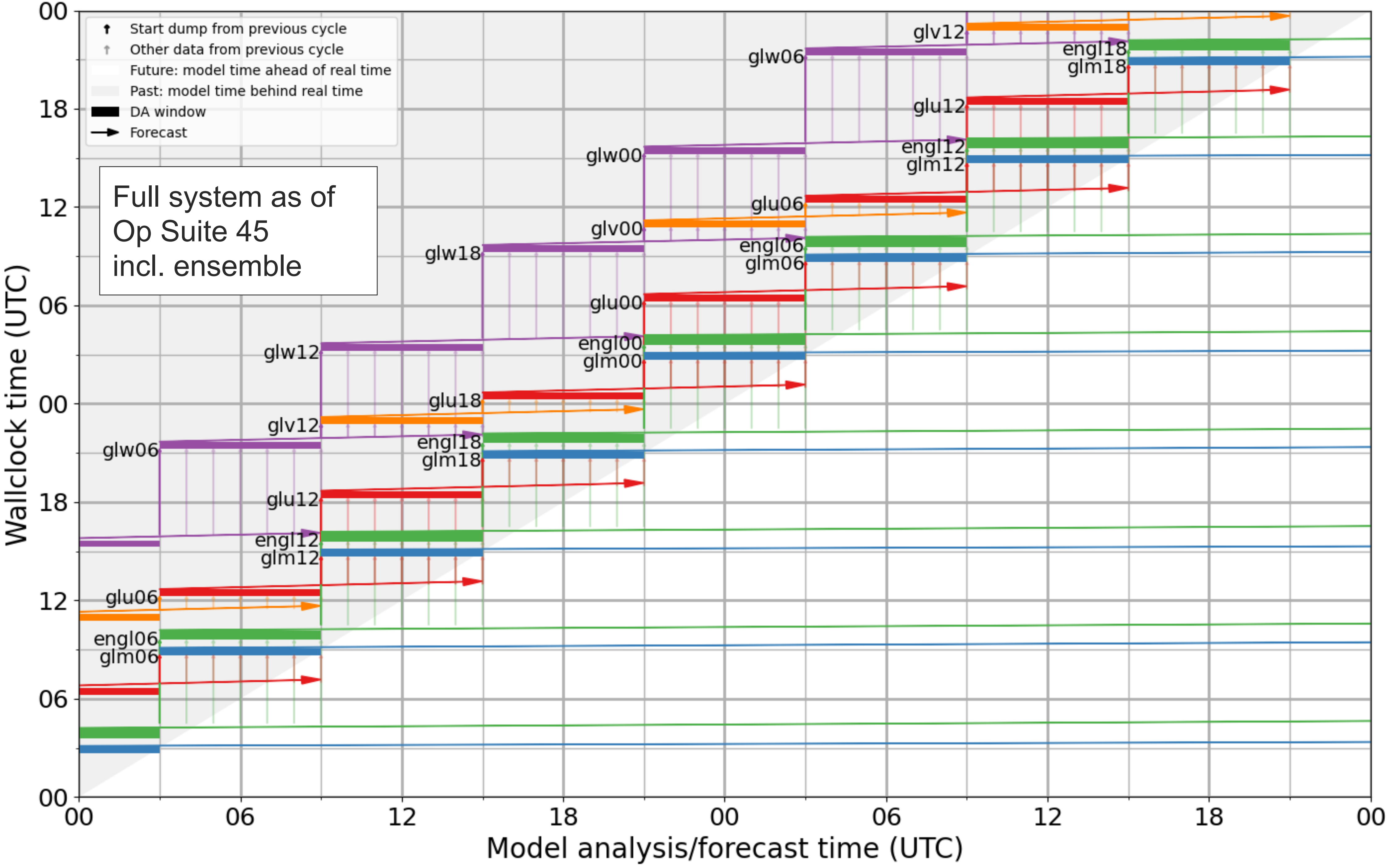

Main and update
GM forecasts
Only ~40% and
~80% of ARGO
and altimeter obs
assimilated
glm06
glu06
glm12
glu12
glm18
glu18
glm00
glu00
glm06
glu06
glm12
glu12
glm18
Wallclock time (UTC)
Model analysis/forecast time (UTC)
00
06
12
18



Additional
catch-up cycles
Wallclock time (UTC)
Model analysis/forecast time (UTC)
00
18
12
06
00
18
12
06
00
00
06
12
18
00
06
12
18
00
glw06
glu06
glm06
glw12
glv12
glu12
glm12
glw18
glu18
glm18
glw00
glv00
glu00
glm00
glw06
glu06
glm06
glv12
glu12
glm12
glm18



Additional catch-up cycles
~85% and ~98% of ARGO and altimeter obs assimilated
Wallclock time (UTC)
Model analysis/forecast time (UTC)
00
06
12
18
glw06
glu06
glm06
glw12
glu12
glm12
glw18
glu18
glm18
glw00
glu00
glm00



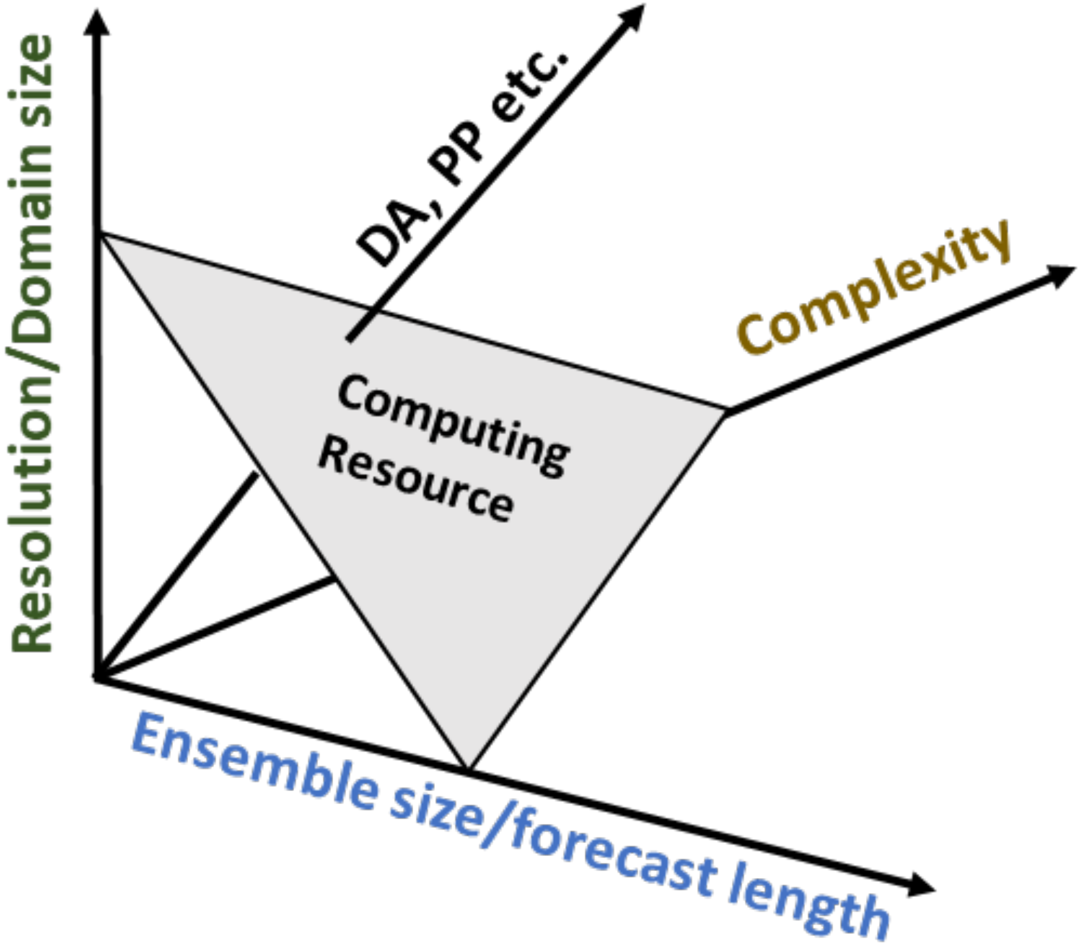
Start dump from previous cycle
Other data from previous cycle
Future: model time ahead of real time
Past: model time behind real time
DA window
Forecast
Full system as of
Op Suite 45
incl. ensemble
Wallclock time (UTC)
Model analysis/forecast time (UTC)
glw06
glw00
glw18
glw12
glv12
glv00
glu12
glu06
glu00
glu18
engl18
glm18
engl12
glm12
engl06
glm06
engl00
glm00
00
18
12
06

Developing an NWP system

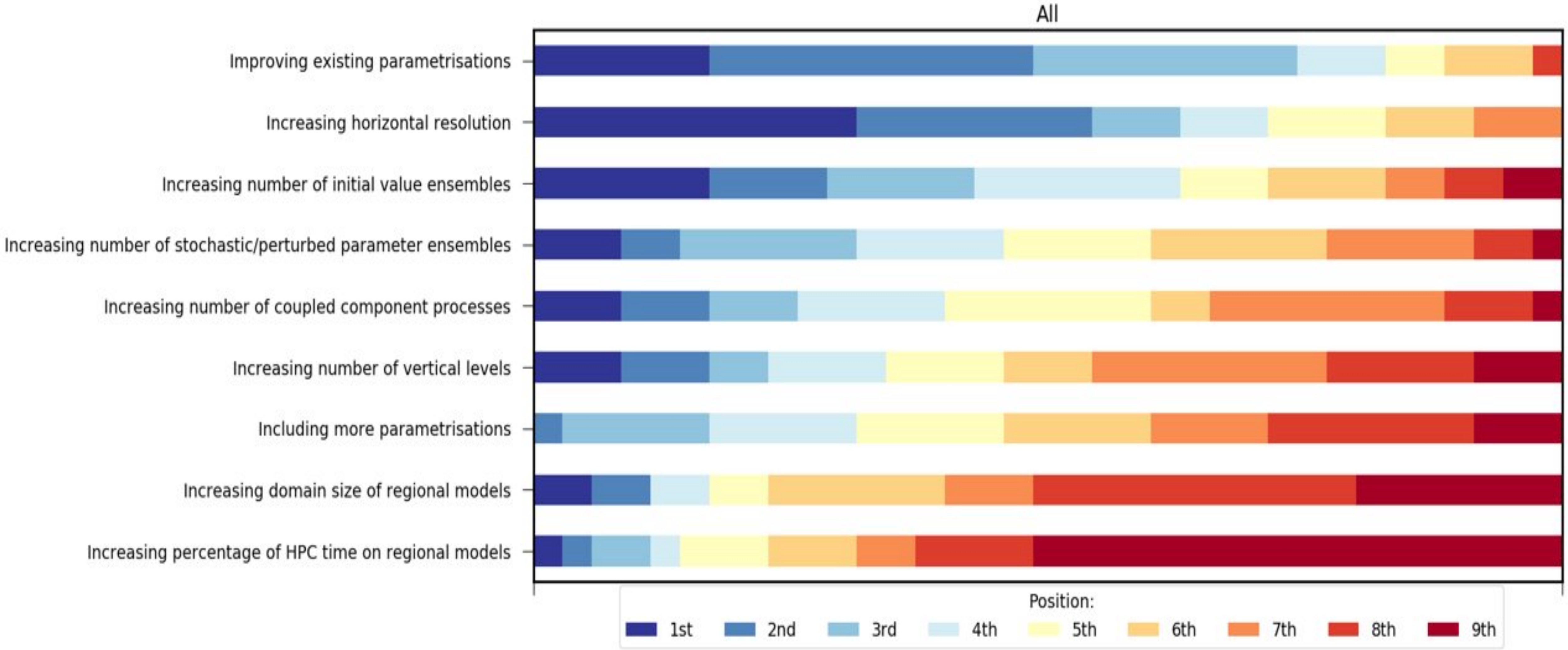
Balancing the HPC demands

Weather vs.
Seasonal vs.
Climate

Research vs
operations



Survey of users/developers in weather and climate



Ensemble exploitation

Science push vs user needs

SUPPLEMENT ARTICLE

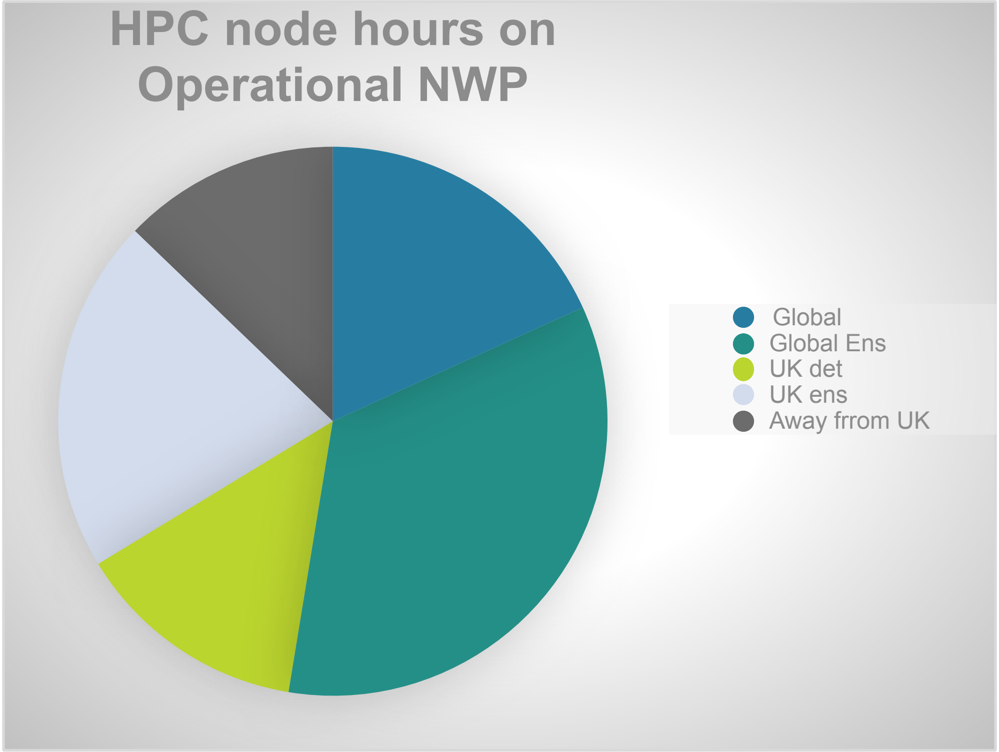
Quarterly Journal of the Royal Meteorological Society RMetS

Introduction to the special issue on "25 years of ensemble forecasting"

Roberto Buizza

25yrs ago the first operational, ensemble forecasts were issued ... a paradigm shift in weather prediction: for the first time, **forecasters and users could have reliable and accurate estimates of the range of possible future scenarios, and not just a single realization of the future**. … Their use will continue to increase, provided that we can help users to take decisions using probabilistic information…

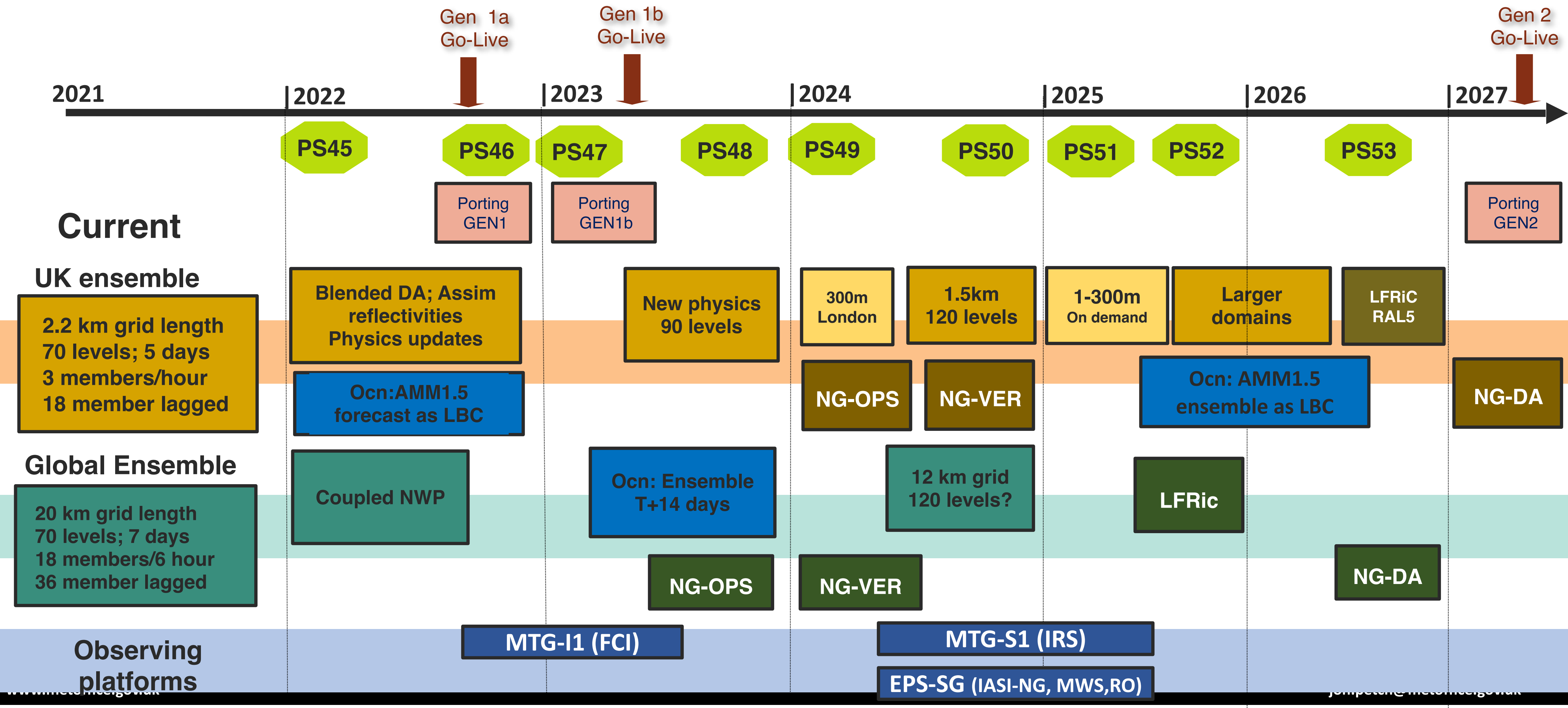
- Errors and uncertainty at all lead times and scales
- Show likely scenarios and less likely ones (but all possible)
- Show variations in predictability beyond the obvious
- More reliable single story
- Provide uncertainty in a range of useful ways



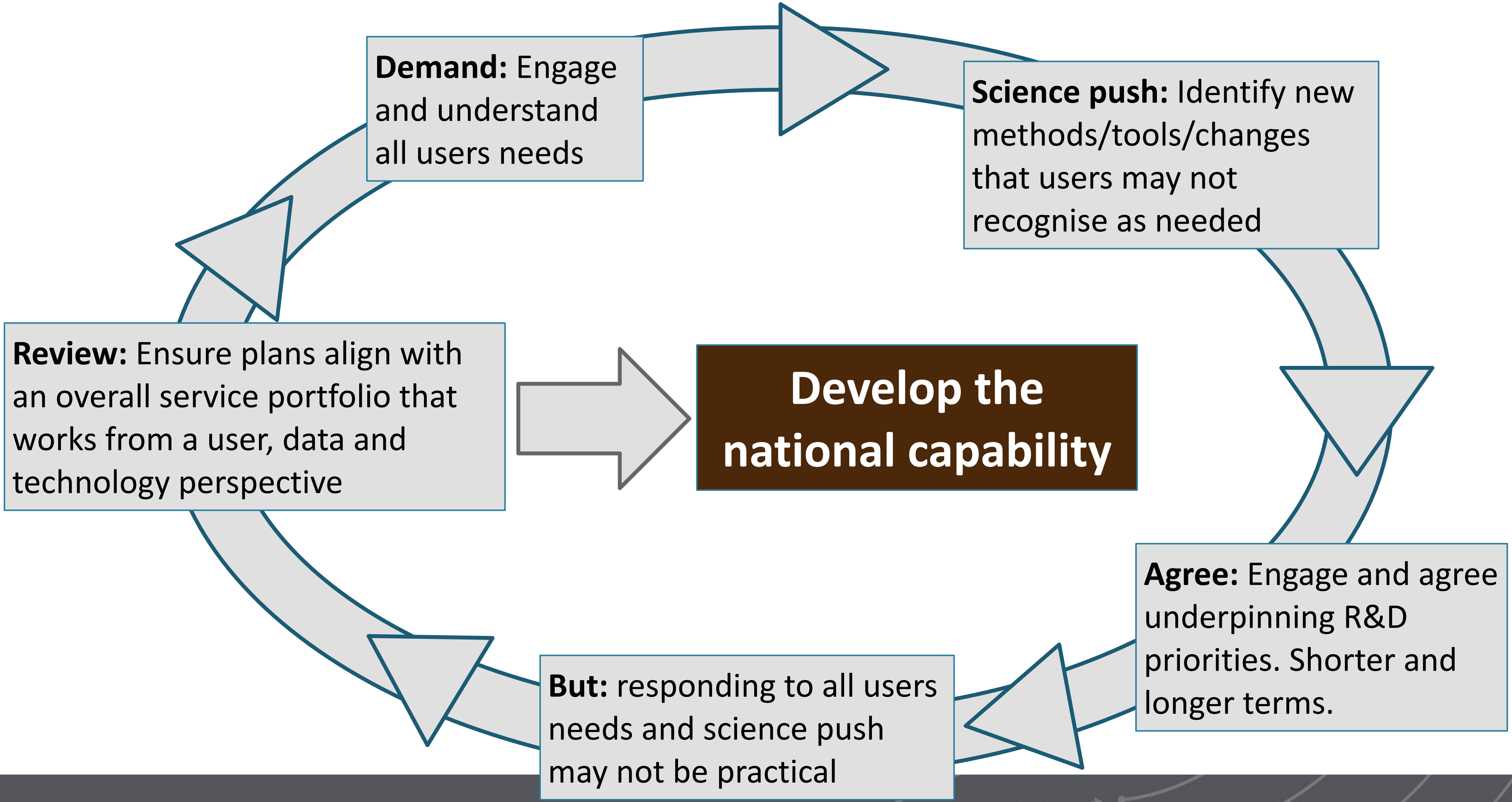
Met Office

Development timeline

A focus on our ensemble systems for weather prediction



Demand and science push



Recap

- Today I have focused on delivering services with an NWP system.
- This included
  - What NWP systems are for
  - They key role of ensembles now and in the future
  - The components of an NWP
  - Scheduling a system
  - How we make development decisions
  -