

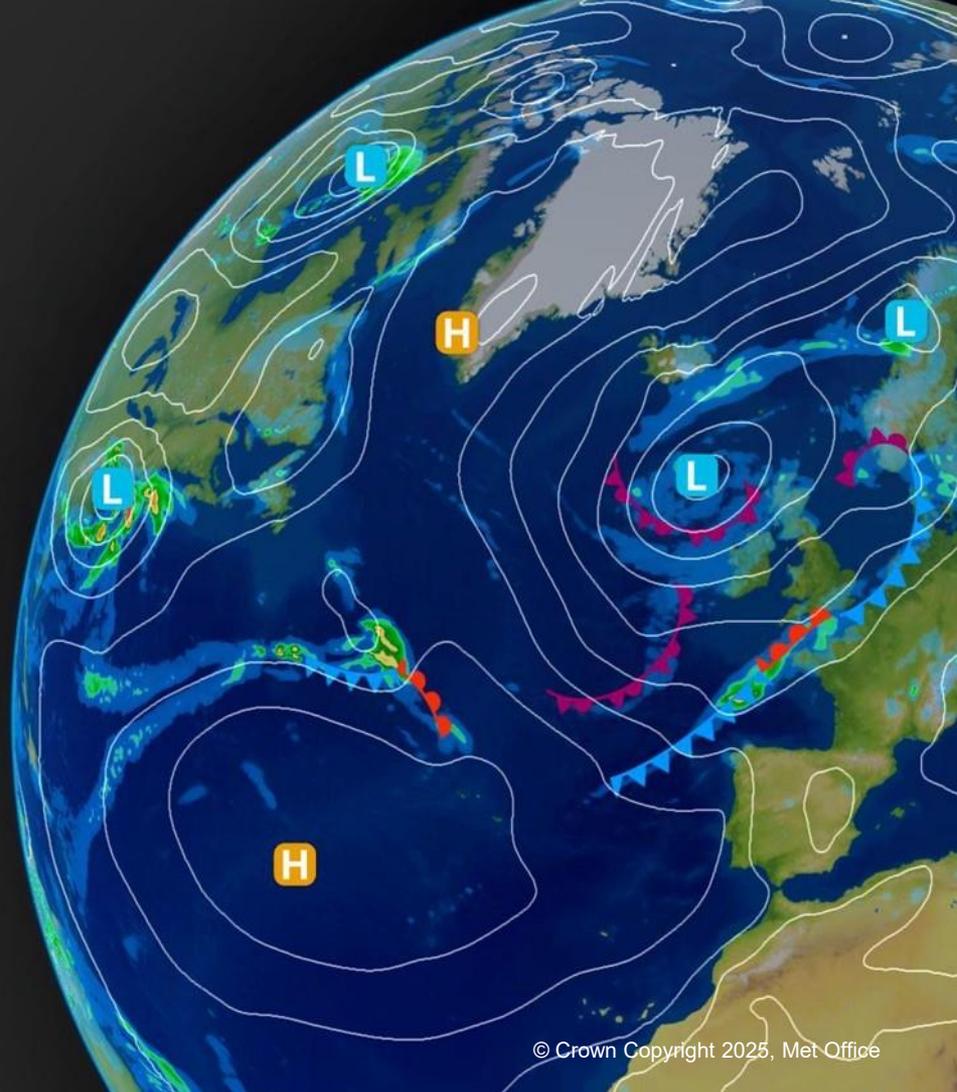
# Current status and future developments in Hectometric prediction

Humphrey Lean

Urban-scale Modelling Research  
RMED, MetOffice@Reading

Thanks to many. In particular:  
Natalie Theeuwes,  
My group: Lewis Blunn, Carol Halliwell, Kirsty Hanley, Jon Shonk, Alfie Bull Green.  
University of Reading colleagues  
ParaChute/WesCon colleagues  
Valery Masson and the RDP group

EWGLAM, SHMI Sept 2025

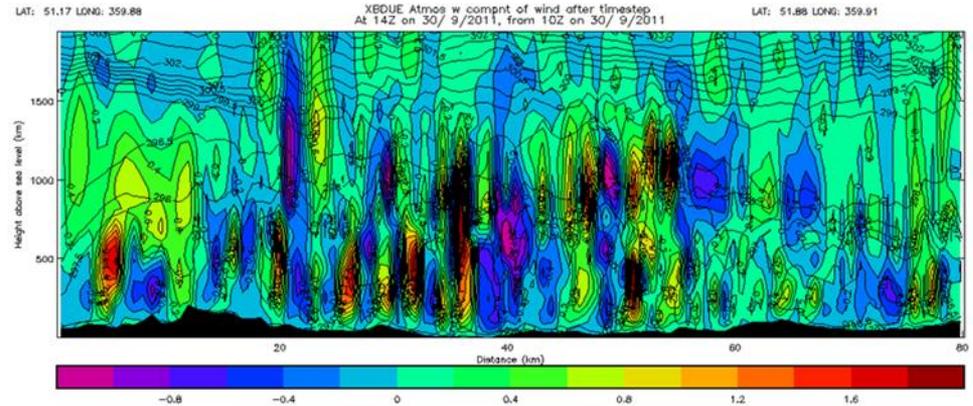


- Motivation
- Important examples of recent progress/projects
- What do we know so far?
- AI approaches



A complex city environment (Chicago)

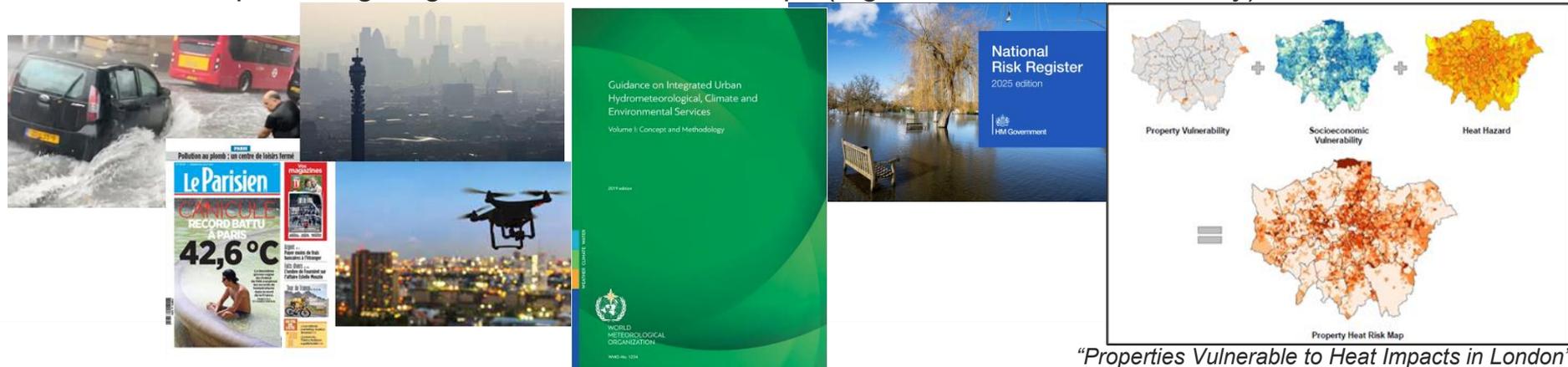
- Many groups have experimented with hectometric models for the last 20 years.
- Have found better representation of many phenomena: Convection, fog, valley pooling and downslope flows, convective boundary layers, urban temperatures etc.



Lean, H.W. et al <https://doi.org/10.1002/qj.3519>.

- Need now is to build on this to turn these into practical models.

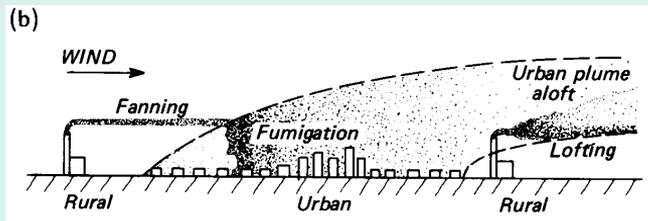
- At the same time growing demand for prediction of local scale hazards on both weather and climate timescales:
  - General awareness of heatwaves, flooding etc particularly impact on cities.
  - UK National Risk Register includes many local scale meteorological hazards.
  - Key pillar of UN Early Warnings for all (EW4ALL) is improved meteorological prediction much of which will need to be on hyper-local scales.
  - WMO Integrated Urban hydrometeorological, climate and environmental Services (IUS) call for services for urban hazards across time scales (weather to climate)
  - Cities producing neighbourhood scale risk maps (e.g. Greater London Authority).



*"Properties Vulnerable to Heat Impacts in London"*  
Greater London Authority commissioned report 2024

## Two potential benefits of high resolution

### Scope to give finer scale forecasts

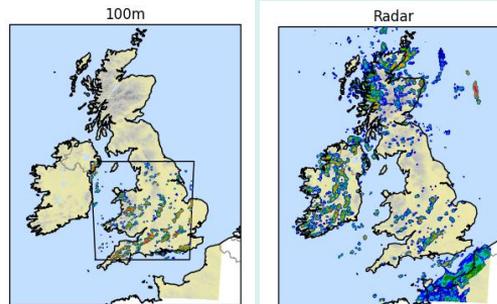


Can capture neighbourhood/hyper-local scale effects.

Potential for neighbourhood scale forecasts (within predictability constraints).

e.g. Good representation of boundary layer structure critical for AQ/Dispersion.

### Better resolved atmosphere/surface: Better meteorology

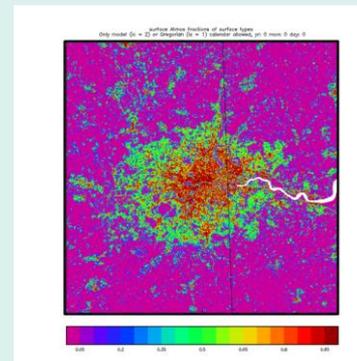


Model dynamics will better resolve some atmospheric processes such as convergence lines, entrainment, turbulence.

Benefits for convection, sea breezes, tornadoes

Better representation of underlying surface e.g. urban fraction, orography.

Benefits for orographic precipitation, cold-pooling in valleys, temperature distribution in cities.



# Hectometric modelling Challenge workshop (KNMI, 2022)

## **GAIN: Better representation of convection, turbulence, surface heterogeneity**

- > The high cost is the big obstacle
- > Post-processing essential to get the best out of these expensive runs
- > Sources of high resolution surface data (esp cities).
- > Steep slopes
- > Running physics and dynamics on different grids
- > Need for grey zone physics schemes
- > Some parametrisations get more complicated - Representation of 3D processes
- > Predictability decreases -> more need for ensembles
- > Almost no experience of DA in sub-km models
- > Need for non-conventional observations and new verification techniques



### **The hectometric modelling challenge: Gaps in the current state of the art and ways forward towards the implementation of 100-m scale weather and climate models**

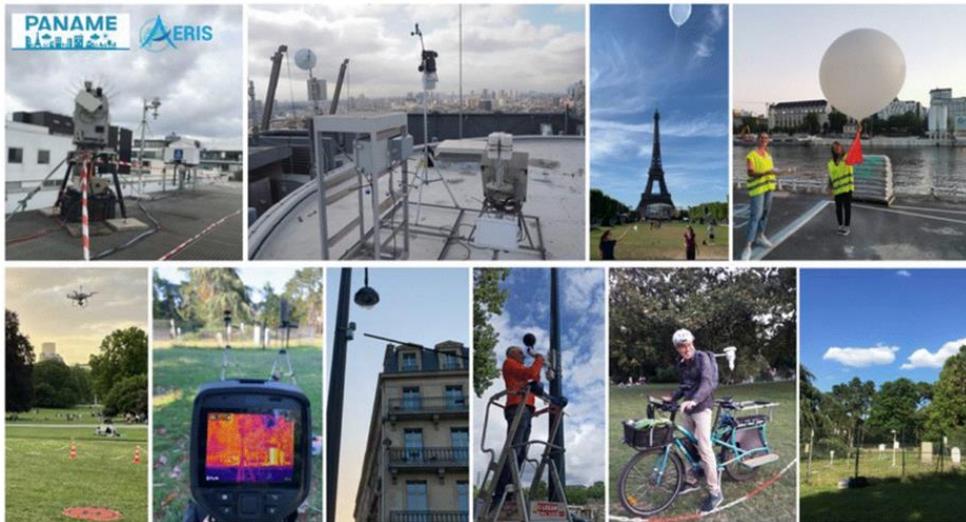
Humphrey W. Lean<sup>1</sup> | Natalie E. Theeuwes<sup>2</sup> | Michael Baldauf<sup>3</sup> |  
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Chiel van Heerwaarden<sup>11</sup> | Rachel Honnert<sup>12</sup> | Adrian Lock<sup>13</sup> |  
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Nigel Roberts<sup>1</sup> | Pier Siebesma<sup>1,14</sup> | Petra Smolikova<sup>15</sup> | Xiaohua Yang<sup>16</sup>

Lean, Humphrey W\*, Natalie E. Theeuwes\* et al. QJRM  
<https://doi.org/10.1002/qj.4858>.

\*Lean and Theeuwes equal contributions.

To advance research on the (future) meteorological forecasting systems at ~100m resolution for urban areas

Institutes from: France, Canada, USA, China, Sweden, Japan, Germany, Netherlands, Korea, UK, Australia

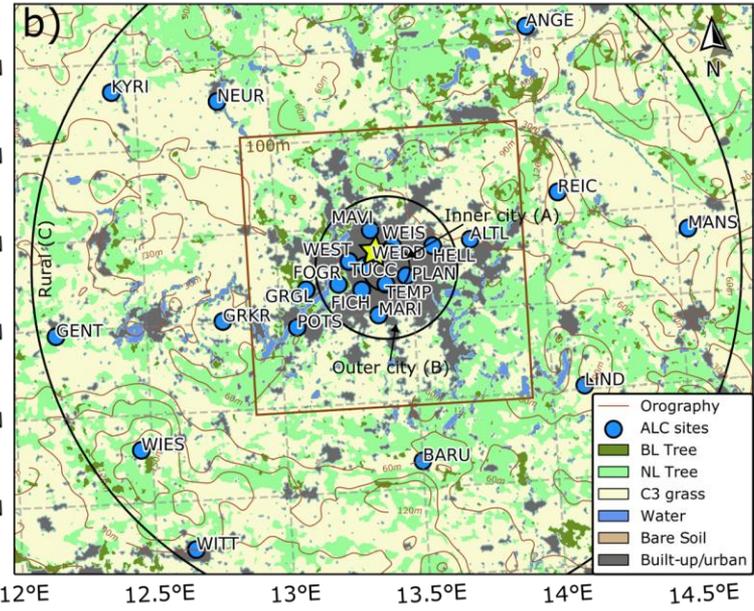


2019	Endorsement of the RDP by WWRP, Identification of the research questions by the partners
2020	Kick off meeting, scientific collaborations, identification of funding and project opportunities
2021	Modelling exercises at 100m scale
2022	Research activities continue; <b>observation campaign kick-start</b>
2023	Research activities continue; <b>observation campaign continues</b> <b>model intercomparison started</b>
2024	Routine running of 100m scale models for period of games.

Summary paper submitted to BAMS.

Led by Valery Masson (Meteo France)

# Met Office Berlin Field Campaign/Modelling



**BAMS**  
Article

**urbisphere-Berlin Campaign: Investigating Multiscale Urban Impacts on the Atmospheric Boundary Layer**

Daniel Fenner,<sup>a</sup> Andreas Christen,<sup>a</sup> Sue Grimmond,<sup>b</sup> Fred Meier,<sup>c</sup> William Morrison,<sup>a,b</sup> Matthias Zeeman,<sup>a</sup> Janet Barlow,<sup>b</sup> Jörn Birkmann,<sup>d</sup> Lewis Blunn,<sup>e</sup> Nektarios Chrysoulakis,<sup>f</sup> Matthew Clements,<sup>b</sup> Russell Glazer,<sup>b</sup> Denise Hertwig,<sup>b</sup> Simone Kotthaus,<sup>g</sup> Kai König,<sup>a</sup> Dana Looschelders,<sup>a</sup> Zina Mitrača,<sup>h</sup> Dimitris Poursanidis,<sup>i</sup> Dimitris Tsirantonakis,<sup>j</sup> Benjamin Bechtel,<sup>k</sup> Kit Benjamin,<sup>b</sup> Frank Beyrich,<sup>l</sup> Ferdinand Briegel,<sup>a</sup> Gregor Feigel,<sup>a</sup> Carlotta Gertsen,<sup>a</sup> Nimra Iqbal,<sup>a</sup> Jonas Kittner,<sup>h</sup> Humphrey Lean,<sup>a</sup> Yiqing Liu,<sup>l</sup> Zhiwen Luo,<sup>k</sup> Megan McGrory,<sup>b</sup> Swen Metzger,<sup>a,j</sup> Matthew Paskin,<sup>b</sup> Marvin Ravan,<sup>d</sup> Thomas Ruhtz,<sup>m</sup> Bethany Saunders,<sup>b</sup> Dieter Scherer,<sup>c</sup> Stefan Thor Smith,<sup>j</sup> Megan Stretton,<sup>b</sup> Katja Trachte,<sup>n</sup> and Melania Van Hove<sup>o</sup>

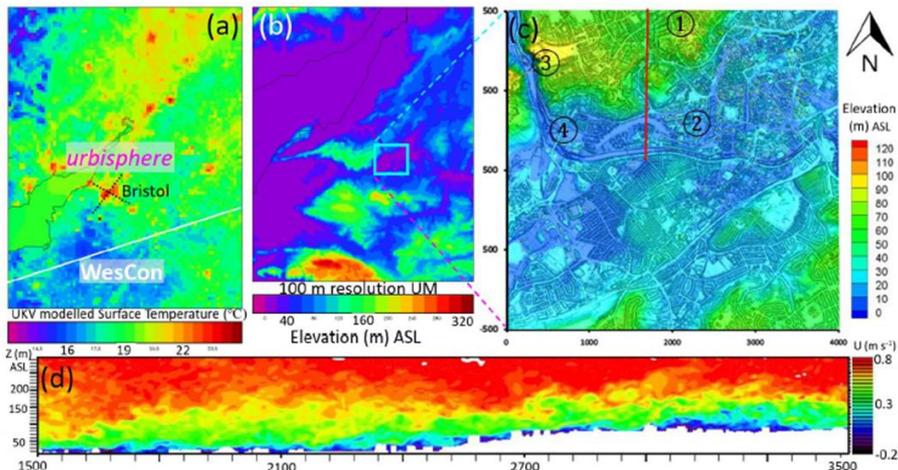
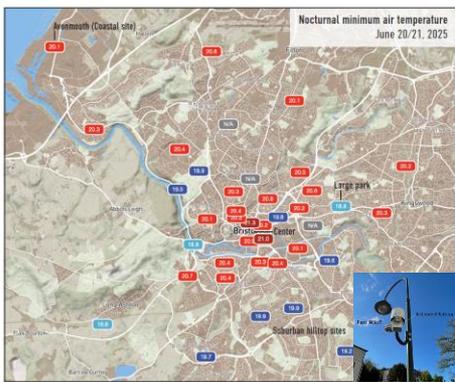
# Met Office urbisphere - ASSURE (Bristol):

Across-Scale processes in URban Environments; on our way to coupling dynamic cities and climate



Bristol, UK chosen because of

- Medium-sized city
- Topography
- Representative land-use heterogeneity
- Engaged stakeholders



# UrbanAir

(URBAN simulation for Air quality and heat Resilience strategies)



<b>Duration</b> 2025-2028	<b>Funding</b> €14.2 million - Horizon Europe	<b>Consortium</b> 18 partners, 11 countries	<b>Action Cities</b> Antwerp, Barcelona	<b>Learning Cities</b> Paris, Bristol, Rotterdam
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## UrbanAIR

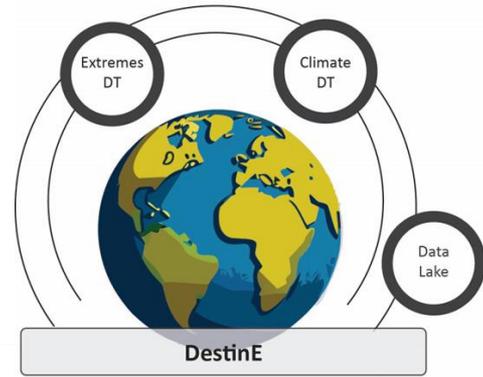
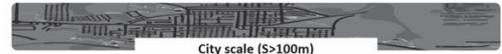


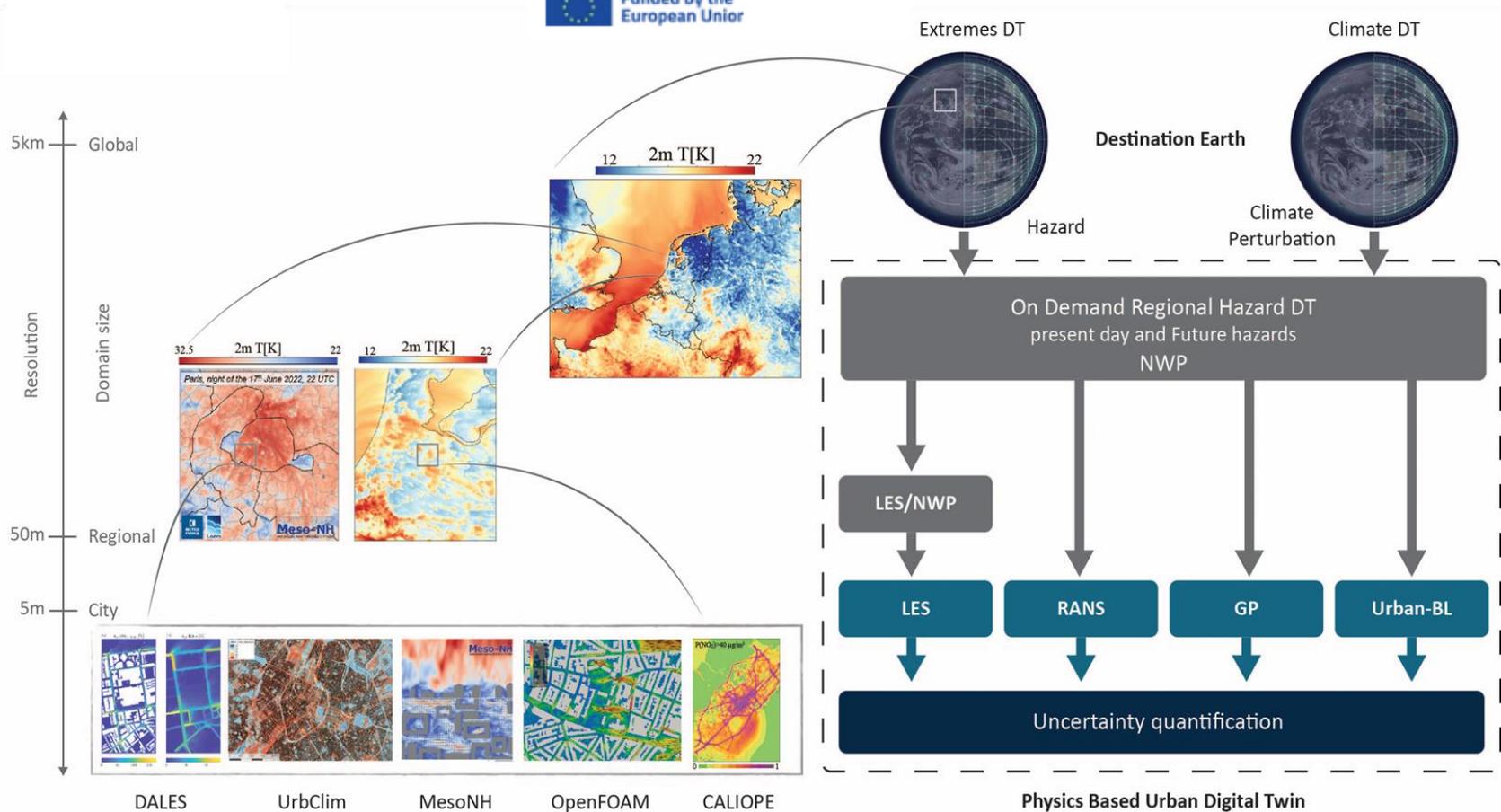
**Pillar 1**                      **Pillar 2**                      **Pillar 3**

DestinE Service Platform

Uncertainty quantification

Behavioural modelling





# ParaChute Programme

**Para**metrizing **C**onvective [turbulence] at **H**ectometric [and km] scales, and **U**nderstanding the **T**urbulent **E**nvironment



*Aim: To improve the understanding and representation of turbulent processes in km to sub-km scale models.*

Joint NERC/Met Office programme (Feb 2023-2027)

Using observational data from WesCon field campaign (2023) specifically designed to understand turbulence in convective clouds.



# Met Office Met office Variable resolution 300m ensembles

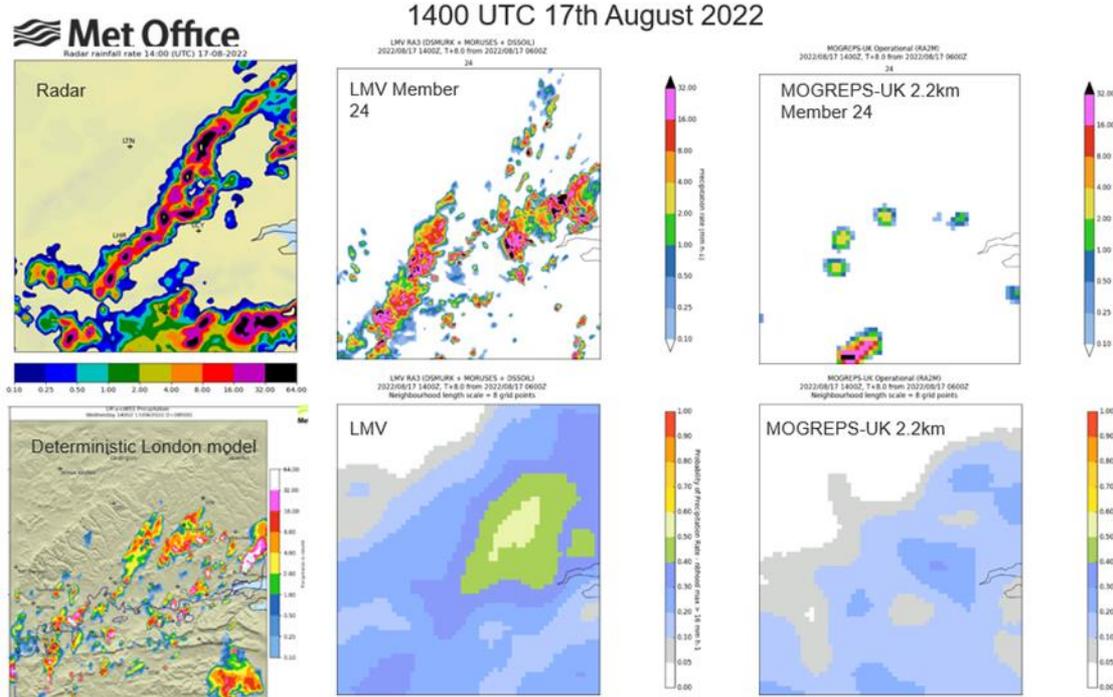
- In the Met Office we have designed the optimal 300m city forecasting system for convection including an ensemble of variable resolution models.
- Variable resolution essential to push edges of domain and spin up effects away at minimal cost.
- Ensemble essential because scales of unpredictability larger compared to the area being forecast (compared to km scale models).



LMV domain (London)



## 1. Good potential to improve forecasts of convection (with several caveats).



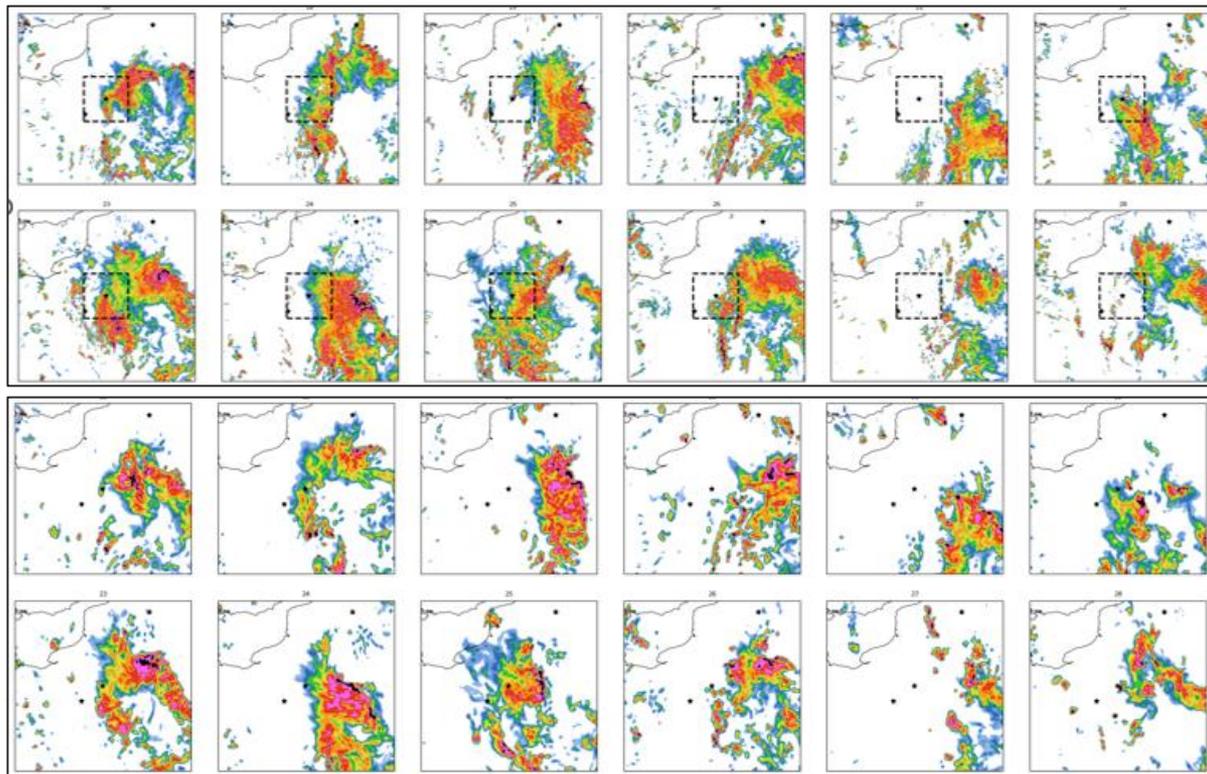
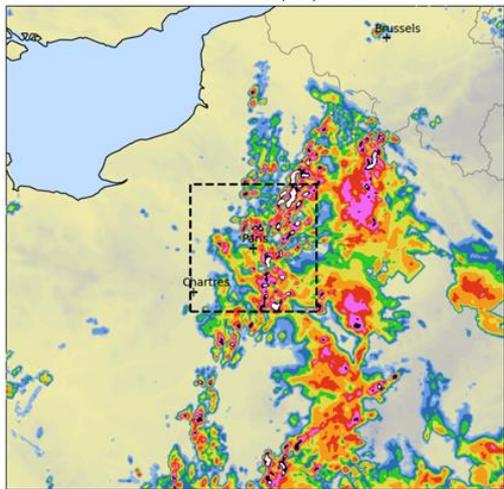
Better indication of chance of heavy rain – this case did result in flood impacts in London and the SE.

# What do we know so far?

## 1. Good potential to improve forecasts of convection (with several caveats).

First Caveat – works well in UK because we get many impactful convective events which are relatively small. Benefit of resolution not always as clear with larger systems such as often seen in Paris.

Radar rainfall rate 23:00 (UTC) 20-07-2024



300m

2.2km

N.B. 300m better than 500m

# What do we know so far?

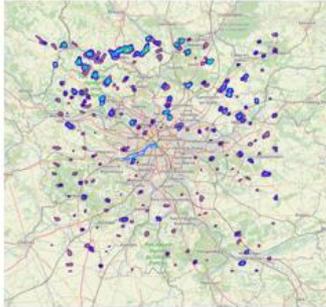
## 1. Good potential to improve forecasts of convection (with several caveats).

Second Caveat – “small showers problem” many spurious small showers – often seen when convection is initiating. RDP showed that this is seen in many models.

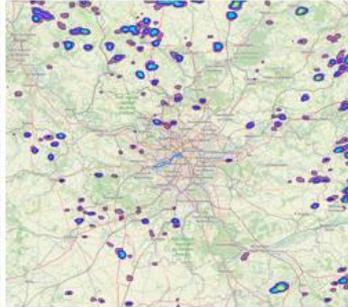
### Radar



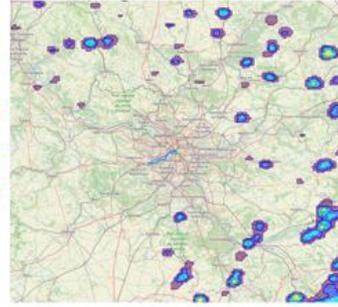
MESO-NH (100m)



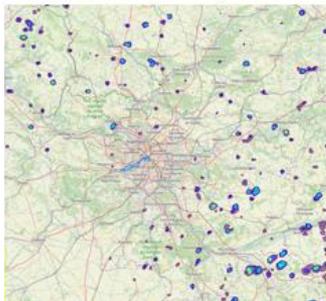
AROME-500m (500m)



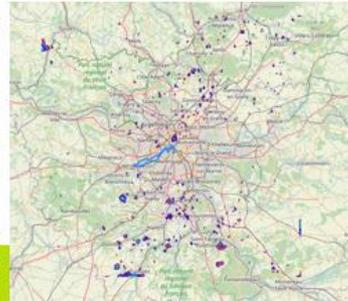
AROME-DBL (1.3 km)



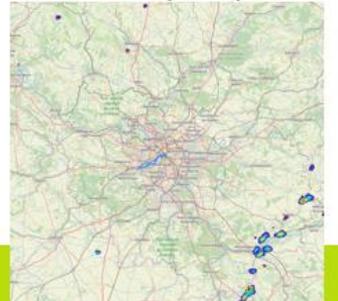
UM (300m)



GEM (100m)



ICON (500m)

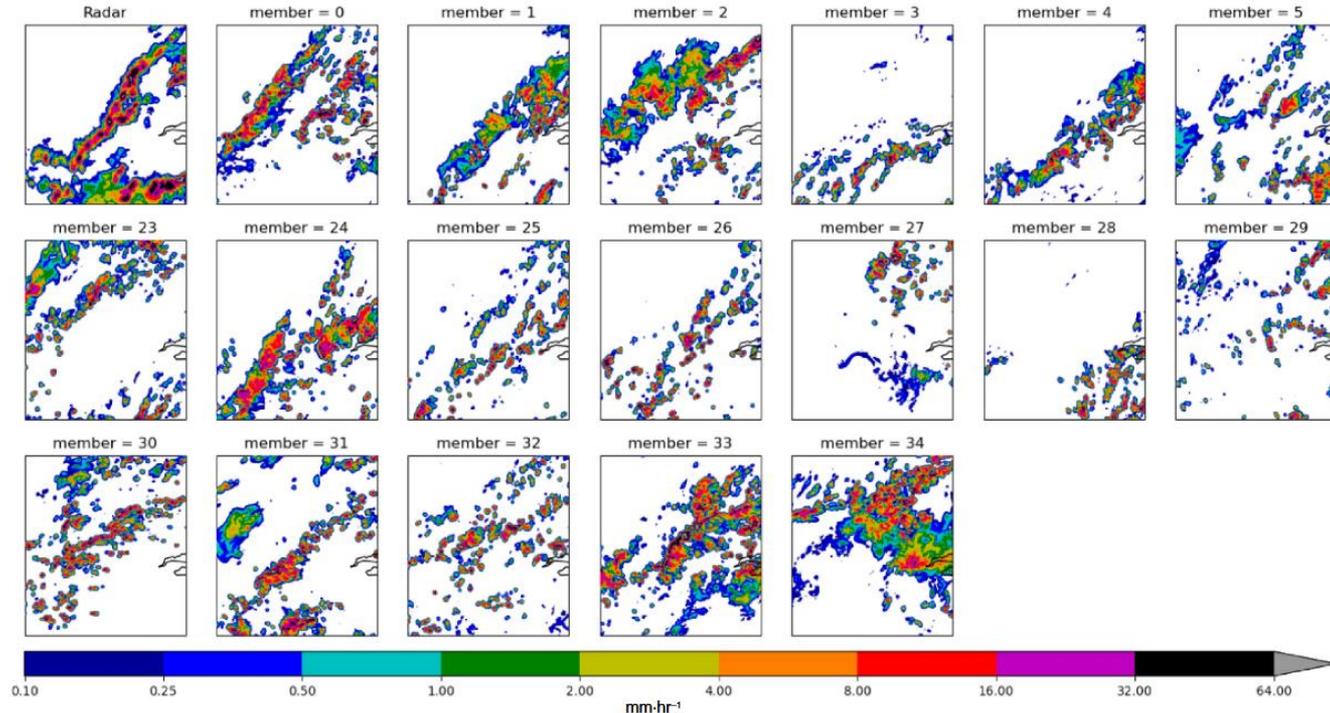


- Size scales unrealistically with gridlength.
- Thought to be due to clouds going too deep (often clouds in correct places but shouldn't be precipitating).
- May be solved by turbulence scheme or shallow convection scheme (ParaChute “HiFi” project making progress on this).

Paris RDP: 1200 UTC 2<sup>nd</sup> Aug 2024.

# What do we know so far?

2. **Need to use ensembles at hectometric scales** – particularly for less predictable elements like convection and fog. Particularly important because scales of predictability larger compared to the scales we are forecasting on.



Also true of fog

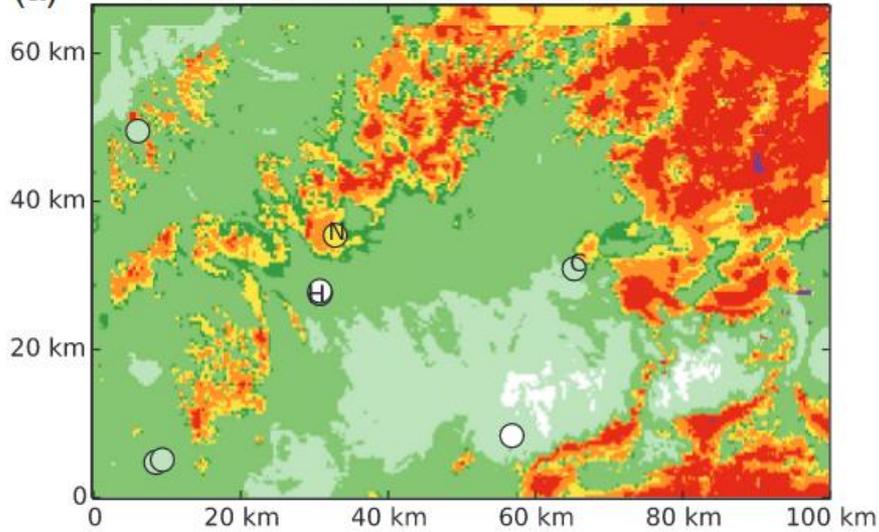
Caveat: Need better ensemble diagnostics e.g. clustering on storm characteristics.

e.g. in this case what percentage of members have a SE-NW oriented line of very heavy convection somewhere in domain.

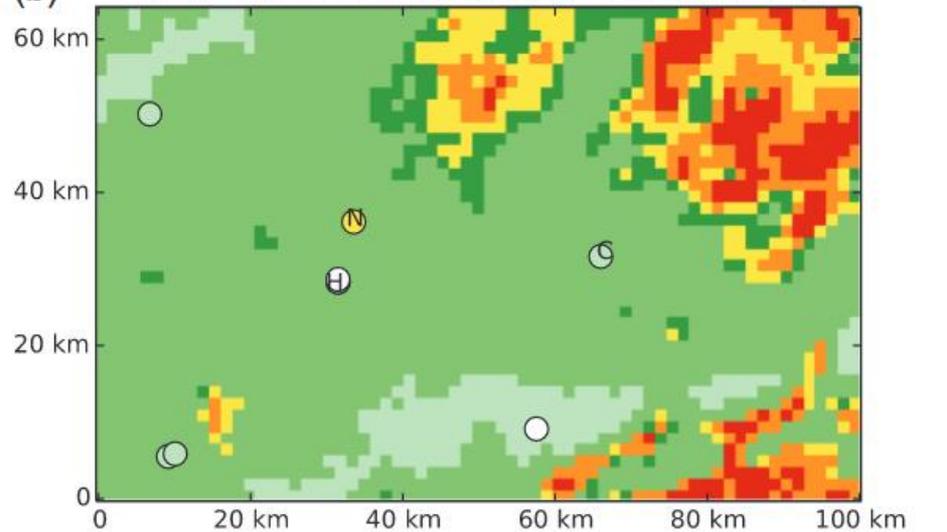
## 3. Forecasts of fog benefit from hectometric modelling.

Due to more detailed orography mainly but also evidence of benefit from improved representation of orographically induced turbulence.

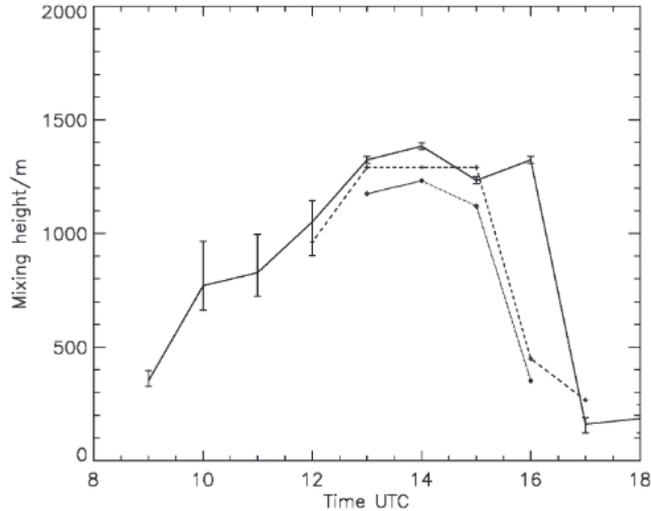
(a) LM Visibility at 1.5 m: 2013/10/18 07:00Z (T + 4)



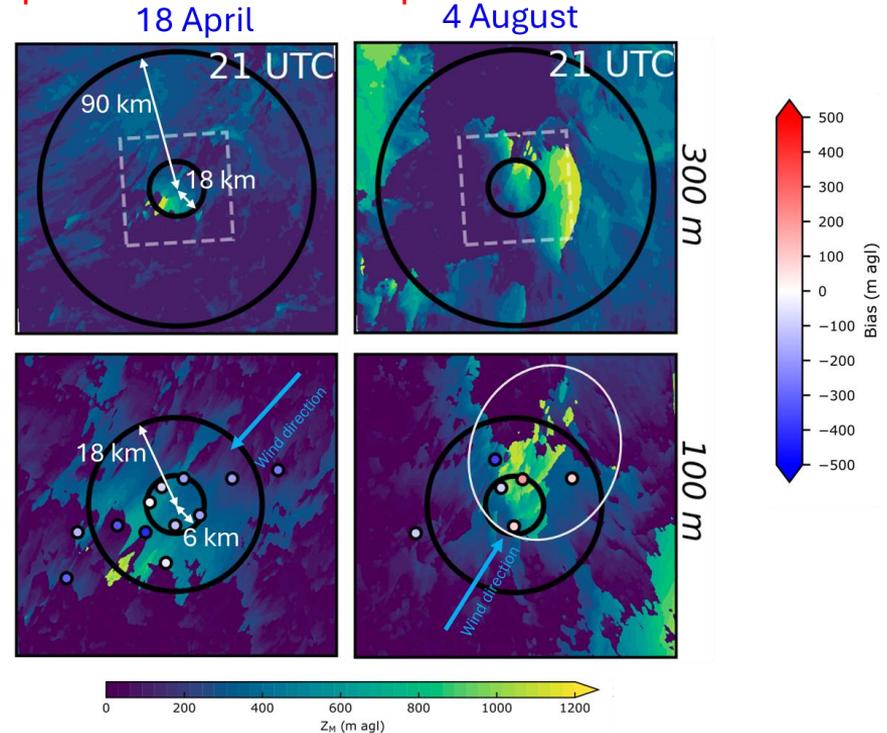
(b) UKV Visibility at 1.5 m: 2013/10/18 07:00Z (T + 4)



## 4. Mixed layer depths and variations in time and space over cities well represented



**FIGURE 7** Mixing height at WCC as a function of time from lidar observations, U100 and U50. The mixing height was calculated using a variance threshold of  $0.1 \text{ m}^2/\text{s}^2$ . The solid line is lidar data, circles/dotted U100 and plus signs/dashes U50. Error bars were calculated by perturbing the variance threshold up and down by 30%



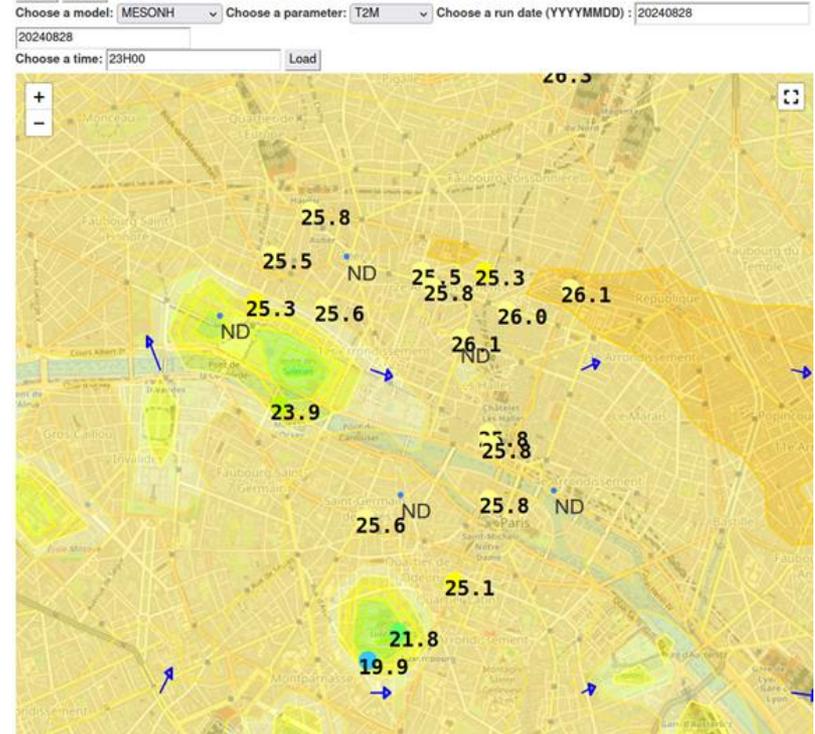
Lean et al 2019 <http://doi.wiley.com/10.1002/qj.3519>

Glazer et al (2025) <https://doi.org/10.5194/egusphere-2025-2064>

(Partly) resolved turbulence gives benefits in terms of being able to distinguish different measures of mixing height. Lean et al 2022 <http://dx.doi.org/10.1002/qj.4291>

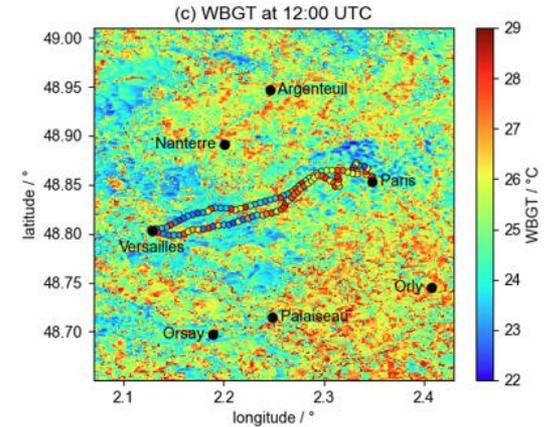
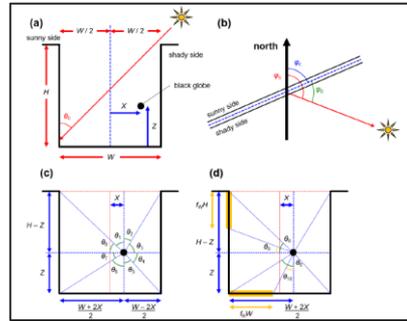
## 5. Temperatures across cities are complicated but in principle can add a lot of value.

- In principle models can capture heterogeneity across cities (rivers, parks, different sorts of buildings etc.)
- Need to consider different temperatures for different applications (surface temp, 1.5m temp, heat stress measures).
- Urban parameterisation crucial as is treatment of soil moisture as demonstrated by [Hall et al \(2024\)](https://onlinelibrary.wiley.com/doi/pdf/10.1002/qj.4669) <https://onlinelibrary.wiley.com/doi/pdf/10.1002/qj.4669> who compared surface temperatures over London with satellite data.

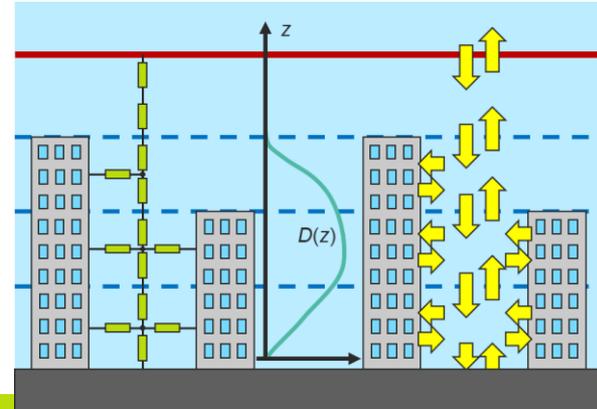


# City Temperatures.

- Need to bear in mind different temperatures.
  - Air temperature important for many applications.
  - Surface temperature relevant for heat load on buildings and human heat stress.
  - Various measures of human heat stress.
- To understand temperatures in urban canopy need a distributed canopy scheme.



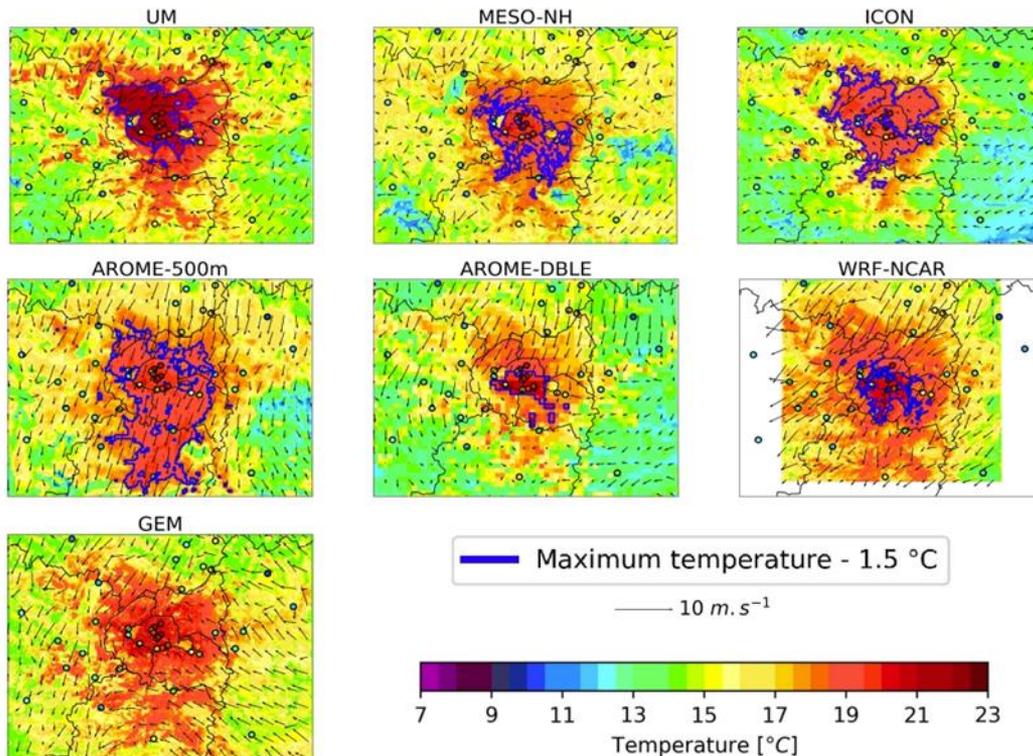
Wet Bulb Globe Temperature calculation. Shonk et al QJ in revision.



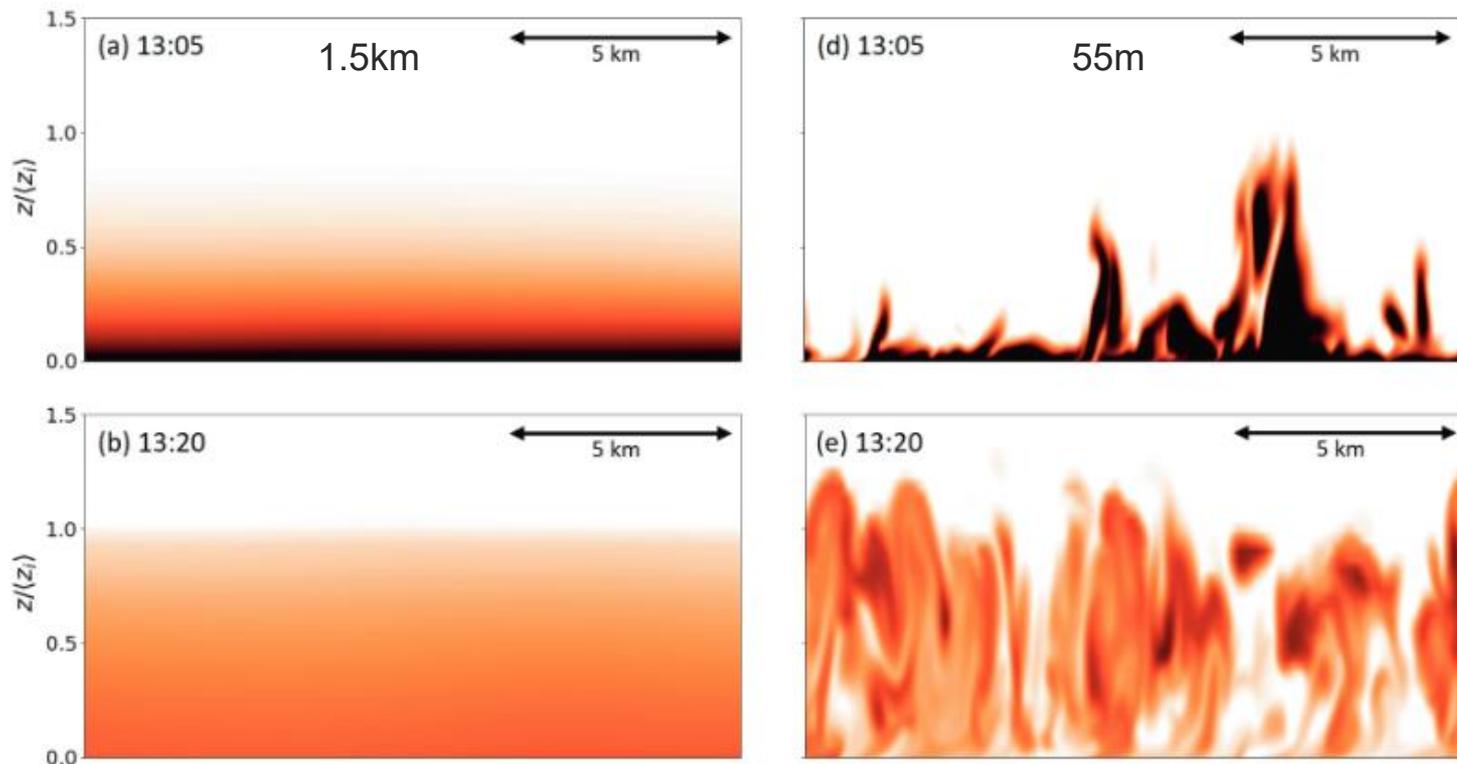
Urban canopy scheme schematic: Jon Shonk

## 5. Temperatures across cities are complicated but in principle can add a lot of value.

- Various intensities in UHI
- Models have a various behaviour concerning **urban heat plume** (some favor localized UHI, others heat transported in far suburbs)
- Need further analysis using crowdsourced stations data

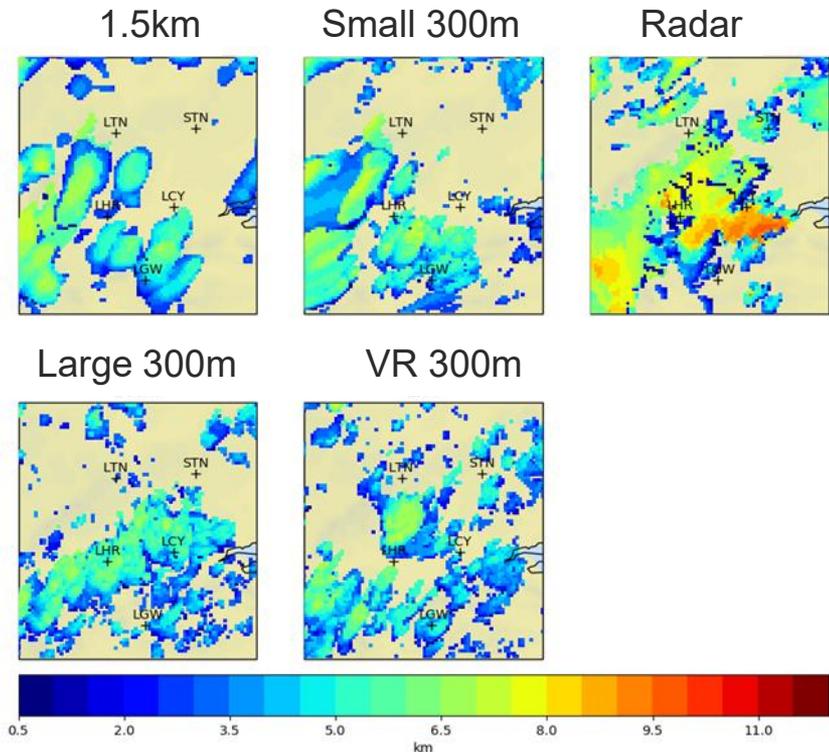


6. Dispersion/Air quality model has potential to benefit from partially resolved turbulence. More realistic structures and variation in pollutant.



**7. Spin up effects.** The need to use small domains (for cost reasons) means that spin up effects, particularly turbulence of convection are important. Can be mitigated by larger domains (expensive), variable resolution or stochastic noise on boundaries.

0 dBZ cloud top at T + 10.5 valid 14:00 (UTC) 18-08-2017 - RA2M



## Convection example

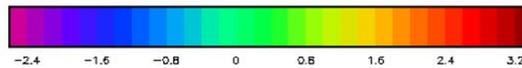
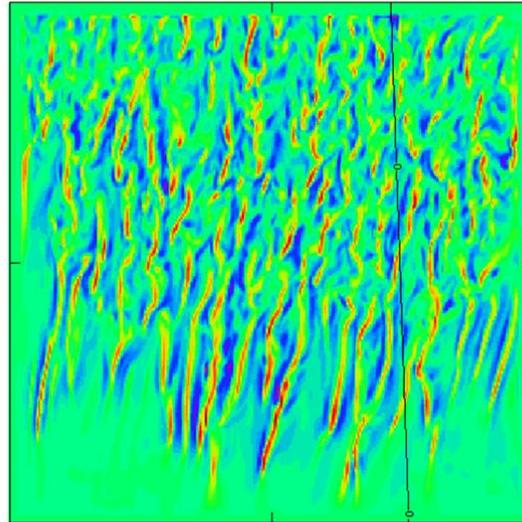
- Small (order 100km) domain 300m gives no advantage for convection over 1.5km model with much too smooth field.
- Large 300m model (only inner part of domain shown) gives much more realistic fields in terms of scales of variability.
- Variable resolution model (only inner fixed resolution part of domain shown) is as good as large 300m model much more cheaply.

**7. Spin up effects.** The need to use small domains (for cost reasons) means that spin up effects, particularly turbulence of convection are important. Can be mitigated by larger domains (expensive), variable resolution or stochastic noise on boundaries.

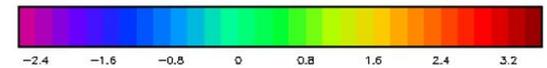
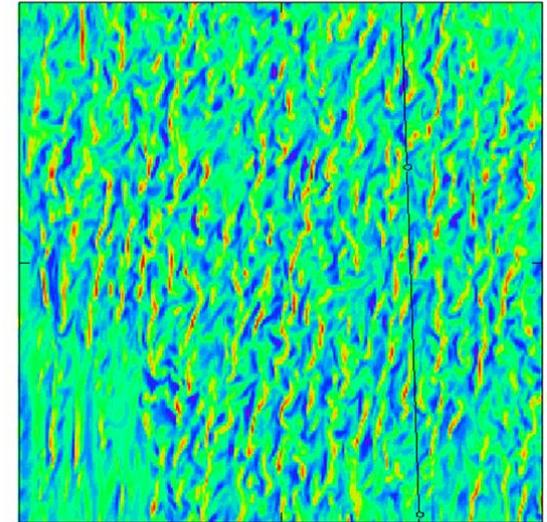
## Turbulence example

- Can see spin up of turbulence close to inflow (lower) boundary.
- Not physical because caused by boundary (doesn't occur at that location in larger model).
- Close to boundary see spurious roll structures – explained due to shallow mixed layer as explicit turbulence spins up.
- (Other boundary layer rolls seen in these models not caused by model boundary may be realistic).

Small 30x30km 300m domain

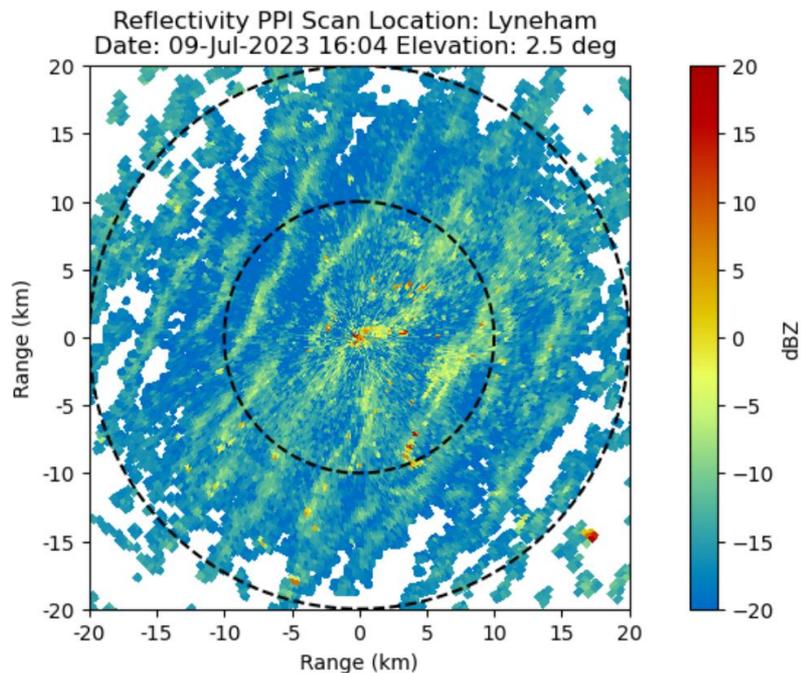
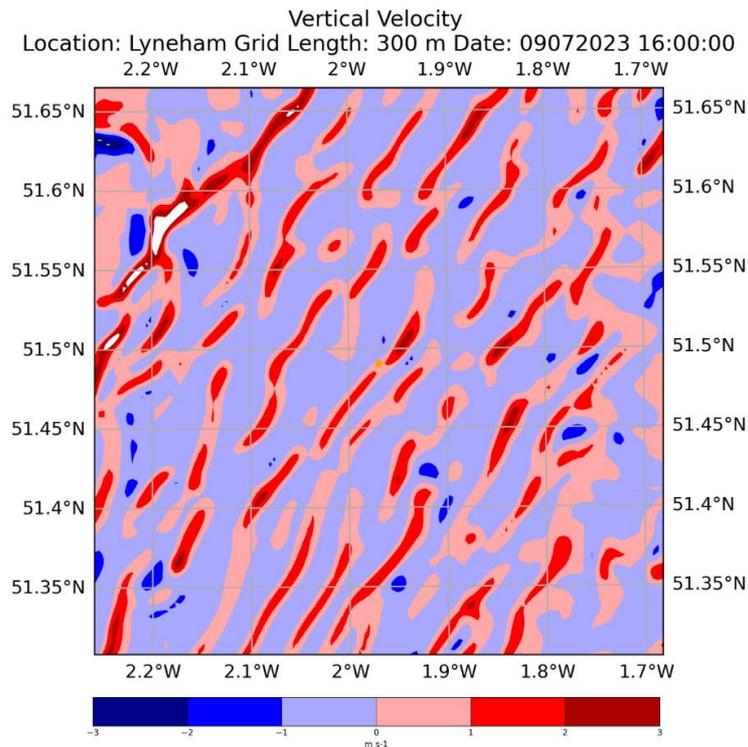


Subset of 80x80km 300m domain



Convective BL case. Vertical velocity at 300m height. Wind from south.

Boundary layer rolls in hectometric models are realistic in at least some cases.

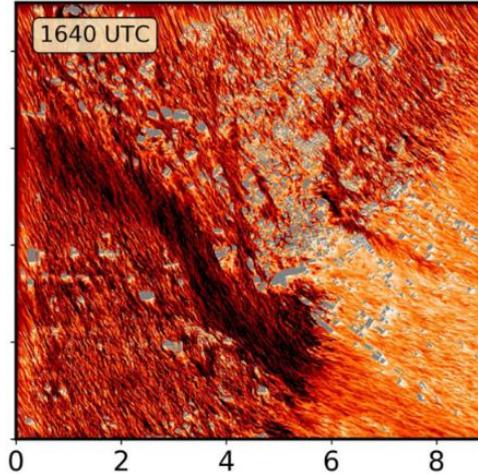


Isabelle Gorst (Reading PhD). Observations from WesCon/WOEST project.

## 8. For cities need to think about benefits of building resolving vs parameterised



100m grid on city of London



 FastEddy®

10m wind in downtown Dallas in 5m FastEddy domain during frontal passage. Munoz-Esparza et al (2025).

<https://doi.org/10.1016/j.uclim.2025.102334>

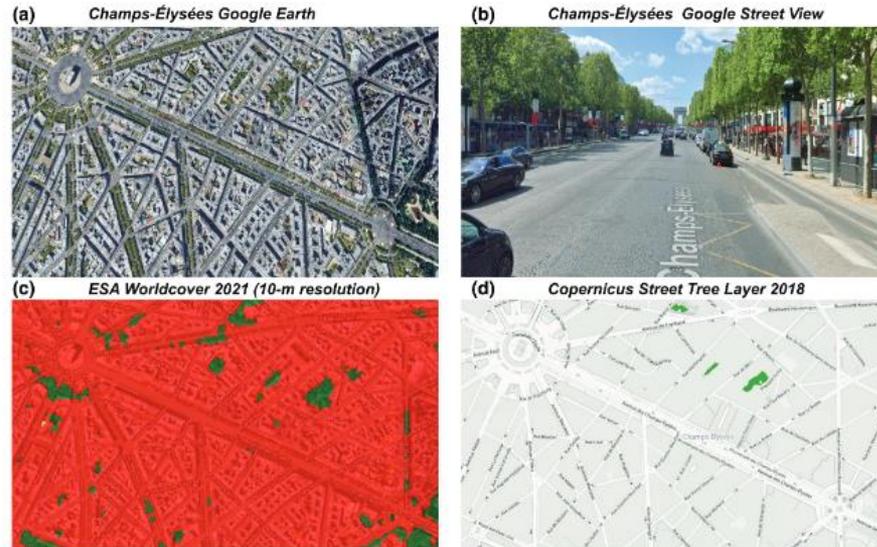
- Separately from the 100m scale modelling being discussed in this talk, there is a lot of activity on running building resolving LES/RANS models of cities for various applications. (PALM, FastEddy etc). These can be nested in km scale mesoscale models. Using GPUs can increase area of city simulated. This will become more important if ML emulators of these models become available.
- Key issue is to understand what applications require building resolving models and which can use 100m scale models with parameterised building effects. Key benefit of 100m scale models likely to be interactions with larger scale effects.

# What do we know so far?

## 9. Almost no experience of hectometric scales data assimilation.

Could be important for very short range/nowcasting applications. Also an issue with sources of observations at high enough densities.

## 10. Getting high enough resolution surface data (particularly cities) is a key issue.



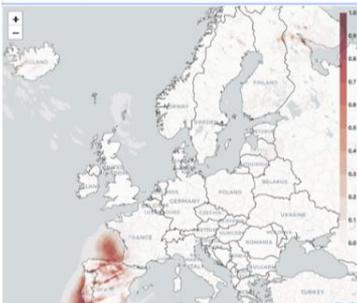
**FIGURE 4** Illustration of poor sub-hectometric land-cover description exemplified for the Champs-Élysées, France. The in-canopy vegetation represented in (a) Google Earth imagery and (b) Google street view is under-represented in both (c) ESA Worldcover v200 (Zanaga *et al.*, 2022) and (d) Copernicus Street Tree Layer 2018 (Copernicus, 2018).

- High computational cost is a big issue likely to limit practical use of Urban-scale models. Particularly important in the context of generally slowing increases in HPC capacity.
- E.g., like for like, a 100 m model is about 9000 times more expensive than a 1.5 km model
- Current approach is to only run models over small areas of particular interest/economic impact (.e.g models over big cities) or where there is extreme meteorology expected, facilitated by variable resolution to avoid spin up issues related to the small domain.
- Running over small areas a viable solution for some applications but the cost is still likely to limit what we can do.

## Destination Earth On Demand Extremes

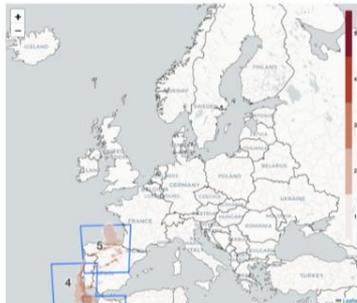
### Detection of extremes

10 metre wind gusts, probability of threshold crossing



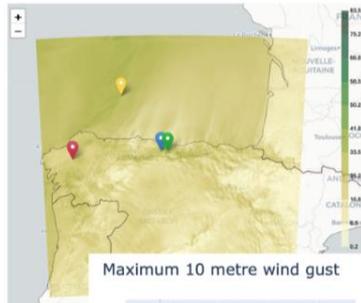
### Domain selection

Suggested domains for 'storm' events

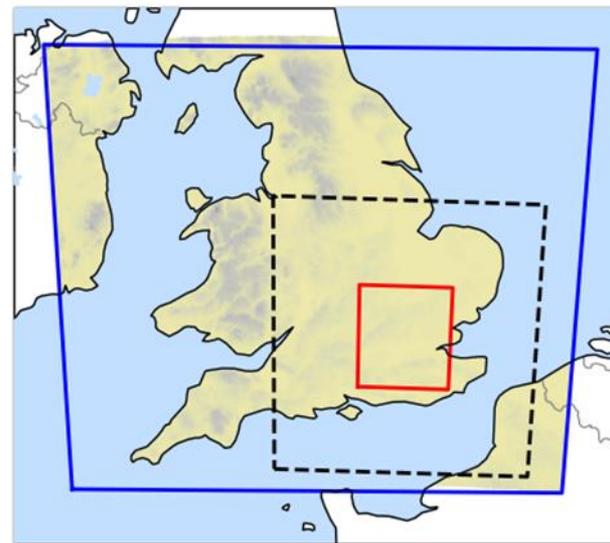


### Weather simulation

storm\_5\_2025-01-29\_HARMONIE\_AROME\_500m

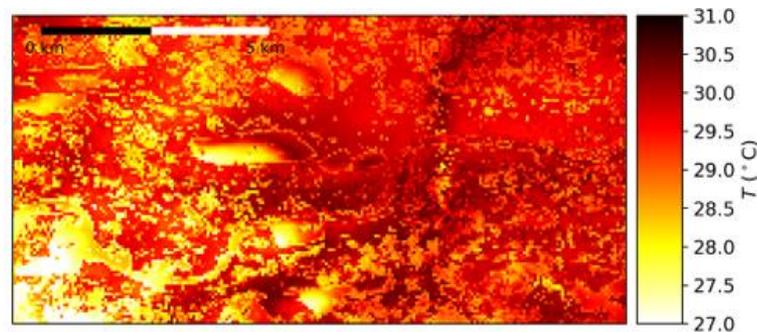
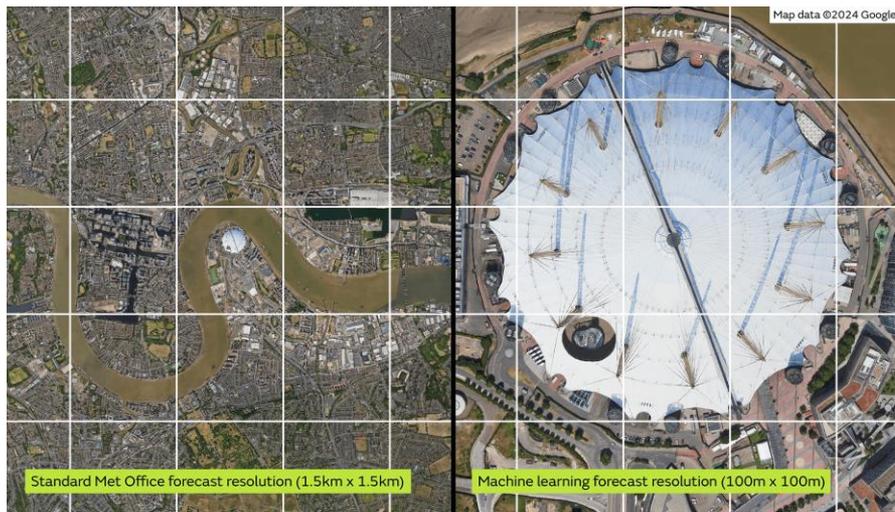


Example from 29 January, 2025



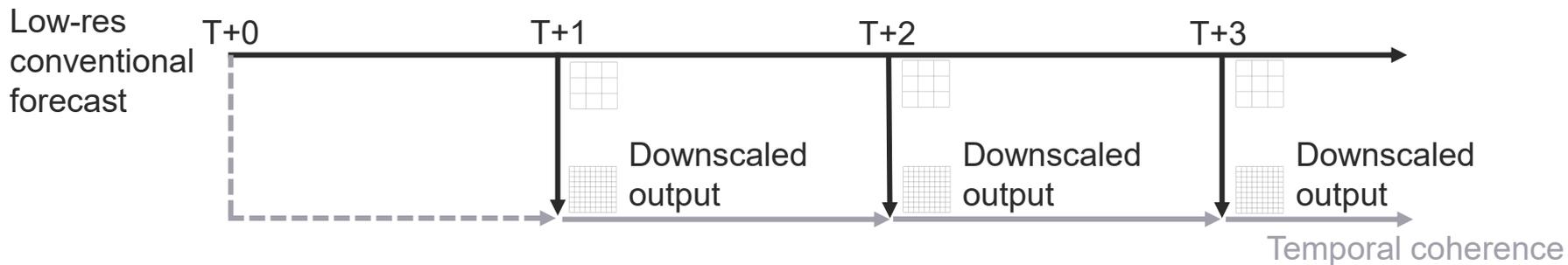
## Machine learning could offer the benefits of Urban-scale models at significantly lower cost, enabling practical Urban-scale predictions for weather and climate applications

- ML is currently changing how many centres are thinking about the future of atmospheric modelling.
- AI global models with more skill than physical models have been demonstrated (e.g. AIFS).
- These are computationally very cheap to run for a forecast but the training data, using physical models/analyses are, very expensive to produce.
- Already quite a bit of work on Urban-scale AI modelling.

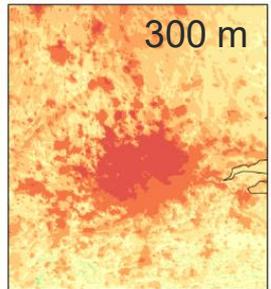
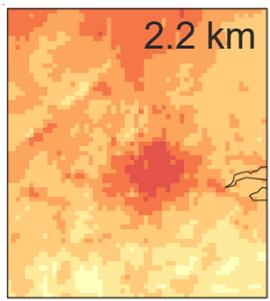


# First Approach: Downscaling

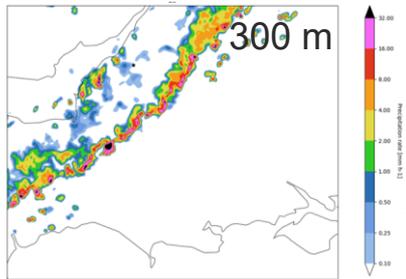
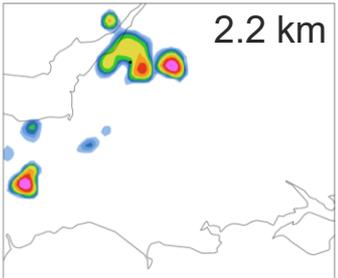
Take low resolution model output at a particular time and use ML to produce a high resolution (100 m scale) version.



**Screen temperature**

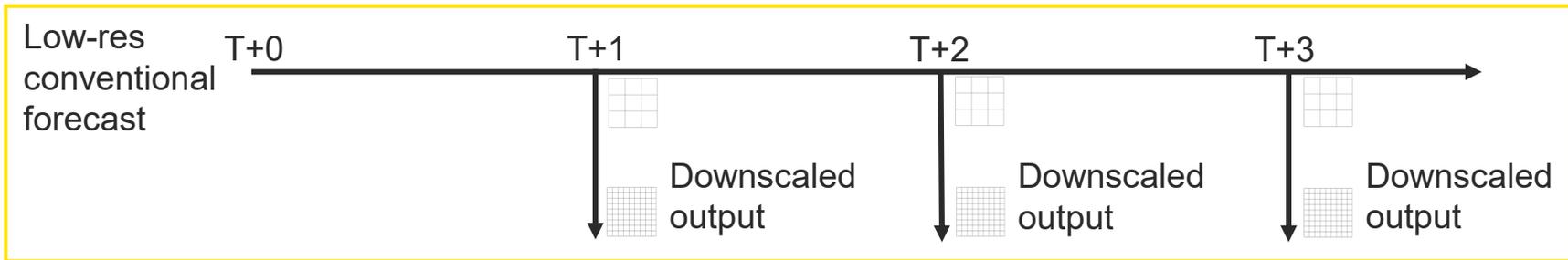


**Precipitation**

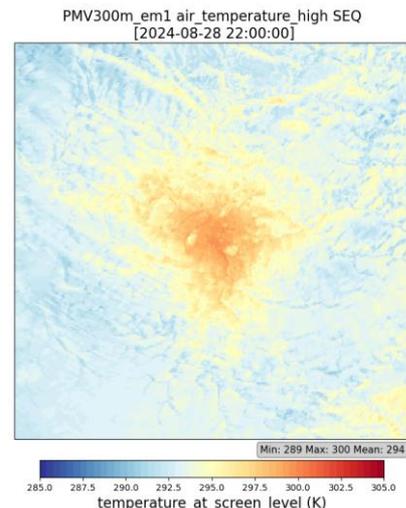
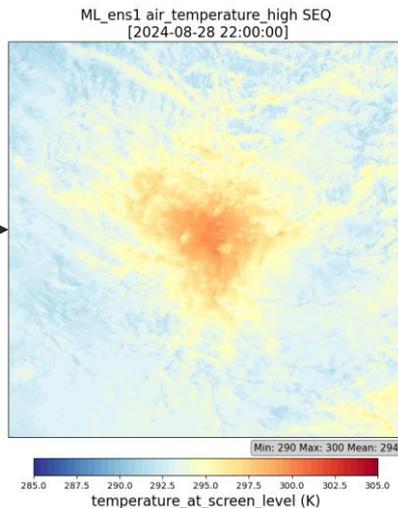
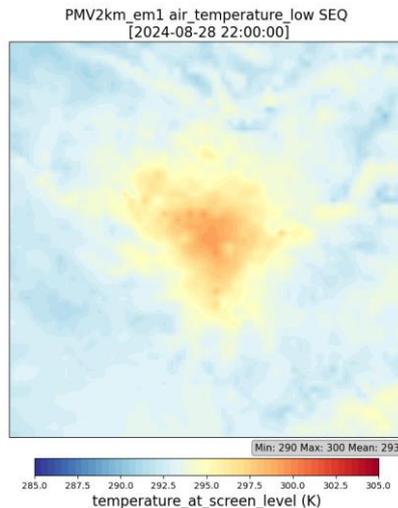


N.B. Fields shown are conventional model fields for illustrative purposes.

# Urban-scale ML Downscaling

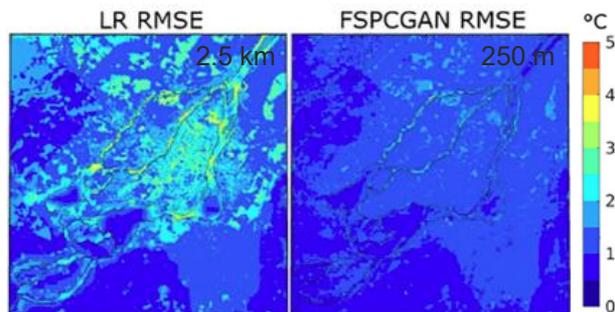
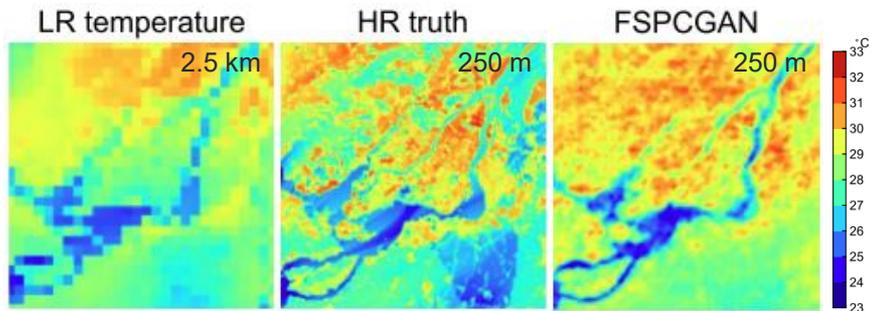


Paris Model  
Member 1



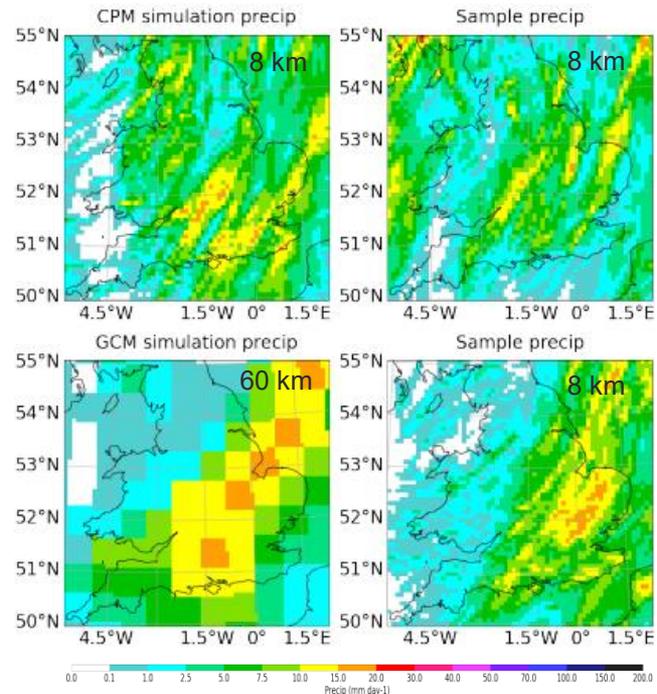
## Screen temperature

Montreal, Canada



Wu et al. (2021): <https://doi.org/10.1029/2021GL094737>

## Precipitation



Addison et al. (2024): <https://arxiv.org/abs/2407.14158>

# Addressing small domain question

Use previous conventional Urban-scale forecasts to train ML models capable of making fast, UK-wide Urban-scale predictions.

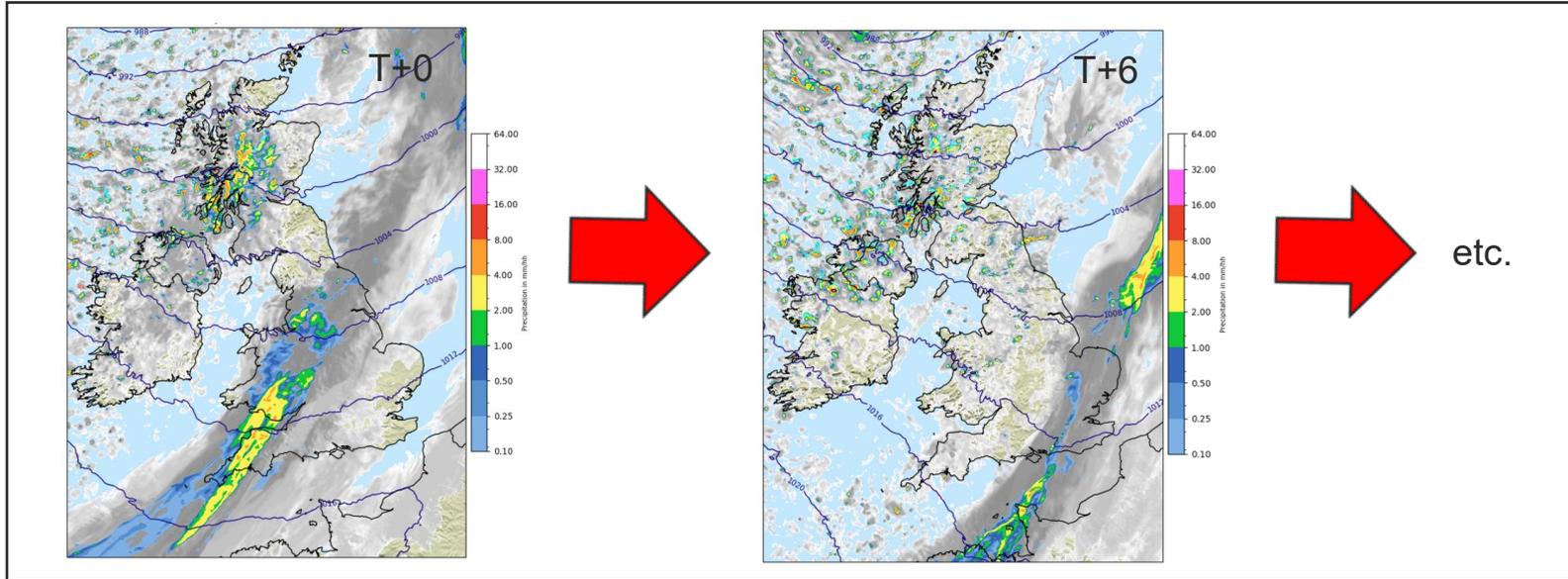
Could we train using several conventional Urban-scale models with small domains over different regions, chosen to encompass a wide variety of meteorology (e.g. a city, a plain, a coastal area, a mountain range etc.), such that the model can predict over the entire UK?

- Requires spatial transferability
- Requires physical process insight



# Second Approach: Data-driven Forecasting

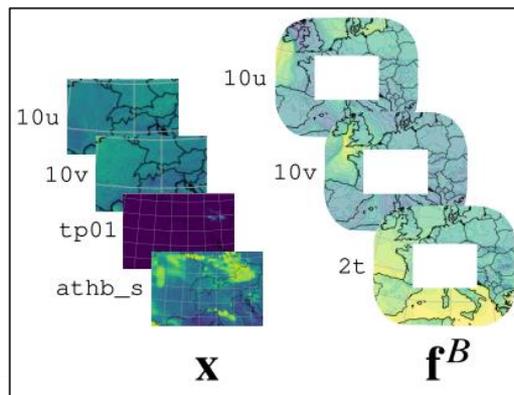
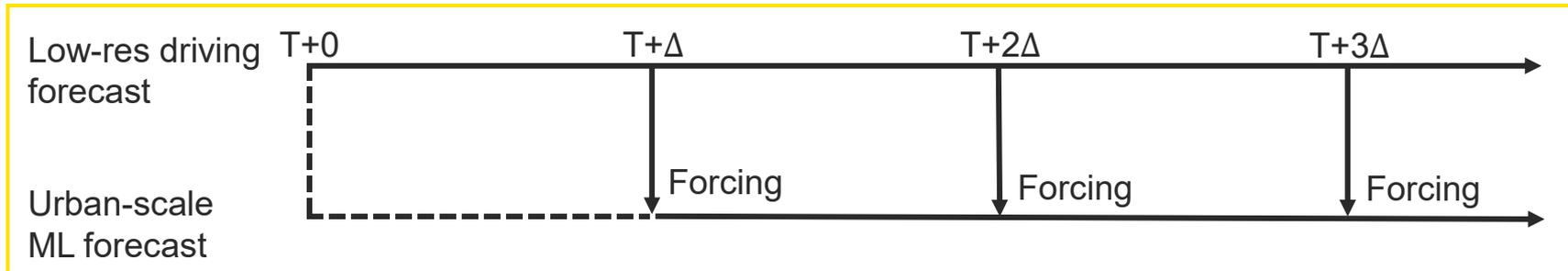
Given the full state of the atmosphere at a particular time on an Urban-scale grid, train an ML system to produce the state of the atmosphere at later times (i.e., analogous to conventional physical models).



N.B. Illustrative pictures from UKV

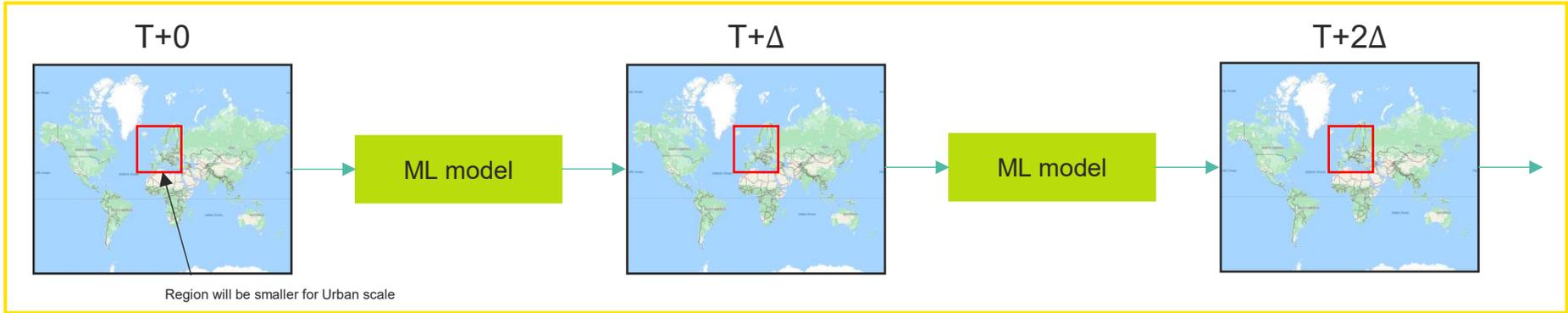
Much work has been done with global models (e.g., AIFS) and there is work starting on km scale, but not hectometric scale so far. Data-driven forecasting is more computationally expensive and technically challenging than downscaling.

Method 1 for Data Driven Forecasting: analogous to conventional **one-way nesting**



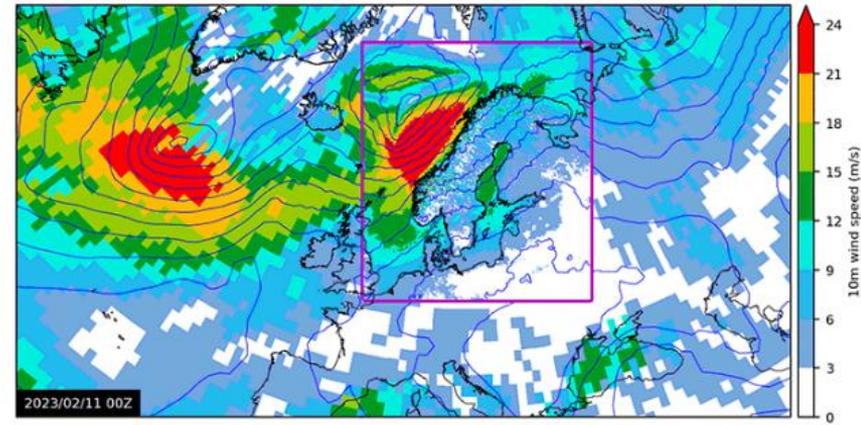
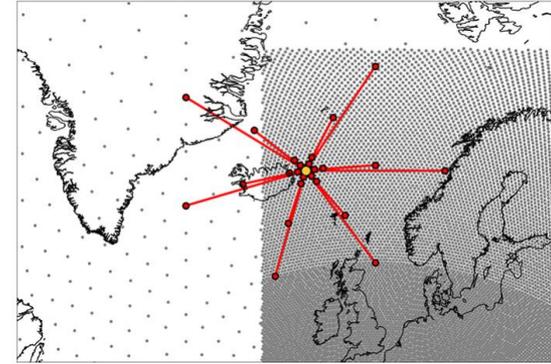
Adamov et al. (2025): <https://arxiv.org/pdf/2504.09340>  
"Building Machine Learning Limited Area Models: Km-scale Weather Forecasting in Realistic Settings"

Method 2 for Data-driven Forecasting: analogous to **variable resolution** – we will likely investigate this



- Training data: ERA5 / global data with Urban-scale data (from short forecasts) in domain of interest
- Variable resolution graph neural network
- No boundary conditions

- “Method 2” example
- Regional ML weather forecasts at 2.5 km
- Train using global ERA5 reanalysis (31 km) and Nordic regional analyses (2.5 km)
- Two-step training – global 43 years and regional 3.3 years
- Stretched grid graph neural network
- Performance:
  - For 2 m T, beats regional model control and mean
  - For precipitation and wind speed, competitive
- Collaboration between MET Norway and ECMWF
- Based on the Anemoi ML framework



- How much data do we need? Currently only have relatively short datasets (~2 months). For example only 1-2 heatwaves in each summer dataset. Routine running models will help?
- What data should we use for data-driven forecasting. Most global systems have used ERA5 but not appropriate regional analyses for Urban-scale ML. Could train using short physical forecasts but might not be deterministically correct.
- ML systems only as good as physical models they were trained on. Still need to solve “small showers” problem or develop urban parameterisations.
- One way round above is to train with observations e.g. use radar as target to downscale km scale model. Issues with predictability.
- Will predictions be temporally consistent (e.g. a big storm 6 hours ago should still exist).
- Which ML model architectures should we use?
  - Probabilistic? Generative vs deterministic
  - Loss function – move beyond RMSE (Sobel operator, Tweedie deviance).
- Is spread/skill maintained after downscaling

- Motivation for hectometric prediction is strong on both weather and climate timescales with forecasting local hazards (often in the context of cities) important.
- A number of projects/centres are exploring practical applications of hectometric models but it is clear the benefits depend on the particular application and the geography/meteorology of the area in question.
- As a community we already know a great deal about the potential benefits of these models as well as about practical considerations for their use.
- Cost is a continuing big issue with hectometric models and is likely to remain a major constraint given the slowing of increases in HPC capacity.
- In the context of the above there is a lot of work continuing and planned on developing ML approaches to provide similar benefits to hectometric modelling more cheaply.
- The two key approaches are downscaling coarser model outputs to hectometric scales and data-driven modelling.