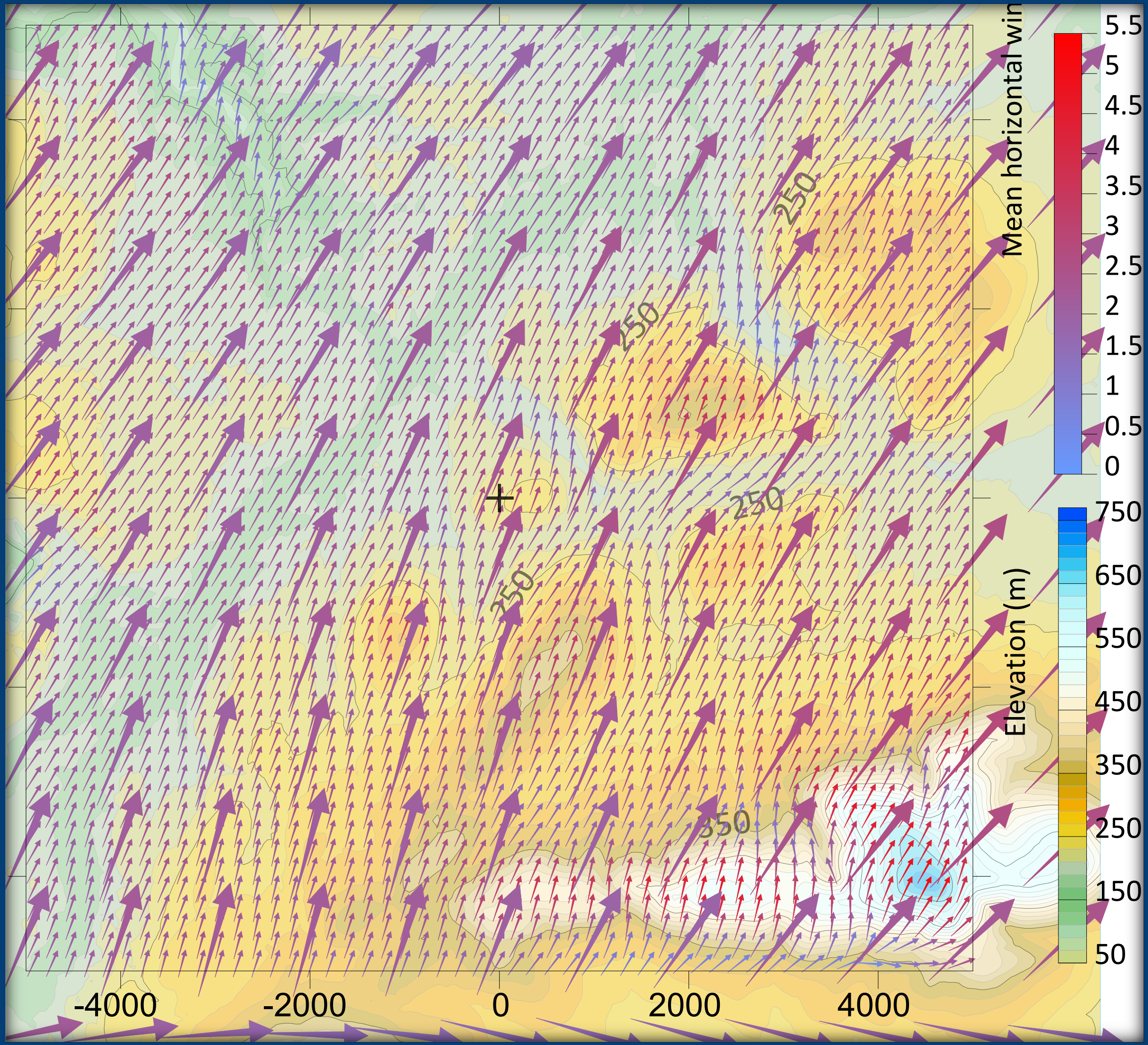

Investigating modelled meteorological data for local dispersion modelling

Dr Christina Hood

Dispersion Modellers User Group

25 April 2024, London

Project background

- Project funded by Atmospheric Dispersion Modelling Liaison Committee (ADMLC): 'Investigating the impact of applying different grid resolutions of Numerical Weather Prediction (NWP) data in atmospheric dispersion modelling'
- Project components:
  - Literature review of NWP models
  - Evaluation of modelled met variables
  - Comparison of secondary met variables
  - **Comparison of local dispersion model outcomes**
  - Investigation of local terrain modelling with NWP inputs
  - Comparison of probabilistic model outcomes (UKHSA)
  - Recommendations
- Full report is available online:

  https://admlc.com/wp-content/uploads/2024/01/d5.2-finalreport-jan2024.pdf

Project team

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Met Office

APS

AIR POLLUTION SERVICES

Lakes

Lakes Software

Presentation outline

- Evaluation of modelled primary meteorological data variables
- Comparison of modelled secondary meteorological data variables
- Comparison of dispersion model outcomes
- Investigation of terrain modelling with NWP inputs
- Recommendations

Numerical Weather Prediction (NWP) evaluation

- NWP datasets from
  - Met Office UM – 10 km and 1.5 km grid size
  - APS WRF – 9 km, 3 km and 1 km grid size
  - Lakes WRF – 3 km grid size
- Using measured data from 2019 from 8 sites, evaluation of:
  - Wind speed
  - Wind direction
  - Temperature
  - Cloud cover
  - Precipitation

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Uncertainty in measured met data

- From WMO "Guide to Instruments and Methods of Observation: Volume 1 – Measurement of Meteorological Variables"

Parameter	Measurement uncertainty	Unit
Air temperature	0.2	K
Wind speed	0.5	m/s
Wind direction	5.0	°
Cloud cover	2.0	Oktas (range 0 to 8)
Precipitation	5.0	mm/h

- Other sources of uncertainty when using measured met data for dispersion modelling:
  - Mis-match of met site and dispersion site characteristics
  - Periods of missing data

NWP evaluation relative to measurement uncertainty

Parameter	Measurement uncertainty	Typical NWP mean bias	Unit
Air temperature	0.2	0.2	K
Wind speed	0.5	0.4	m/s
Wind direction	5	4	°
Cloud cover	2	0.2	Oktas
Precipitation	5	0.01	mm/h

- Typical NWP mean bias ≤ measurement uncertainty for all parameters
- Wider analysis (see full report) showed:
  - Generally good agreement between models and observations for wind speed, direction and temperature
  - More uncertainty in observations and between model and observations for cloud cover and precipitation

➡ More variation between different NWP models/configurations than due to different model grid resolution for most metrics and sites

Presentation outline

- Evaluation of modelled primary meteorological data variables
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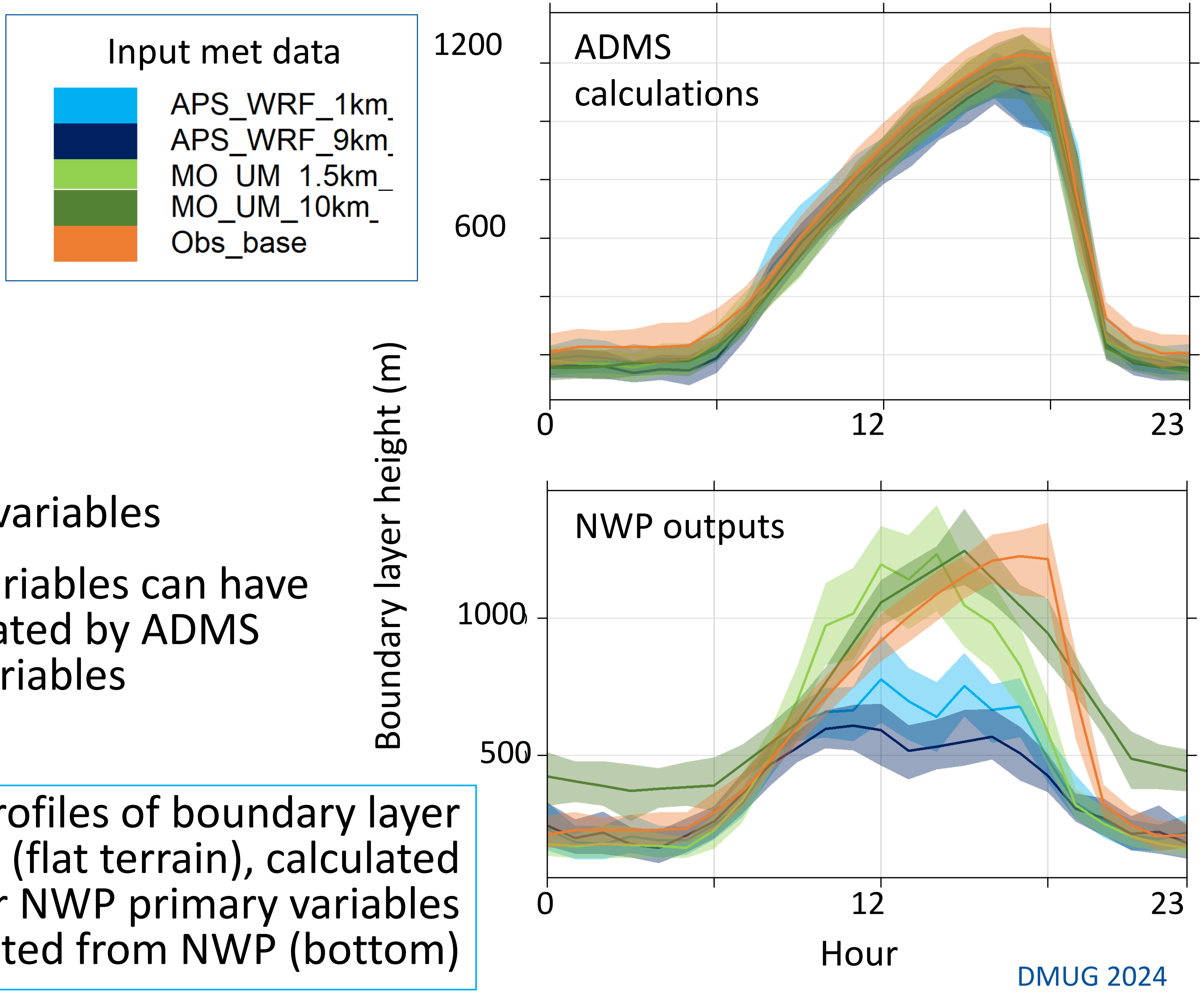
NWP secondary variables comparison

- Boundary layer properties which determine atmospheric stability are not routinely measured
- ADMS calculates solar radiation, heat flux and boundary layer height as secondary variables from input primary variables (wind speed, temperature, cloud cover, date and time)
- NWP models can also supply secondary variables
- Comparisons showed NWP secondary variables can have very different behaviour to values calculated by ADMS using input observed or NWP primary variables



July average diurnal profiles of boundary layer height (m) at Waddington (flat terrain), calculated by ADMS from observed or NWP primary variables (top) or extracted from NWP (bottom)

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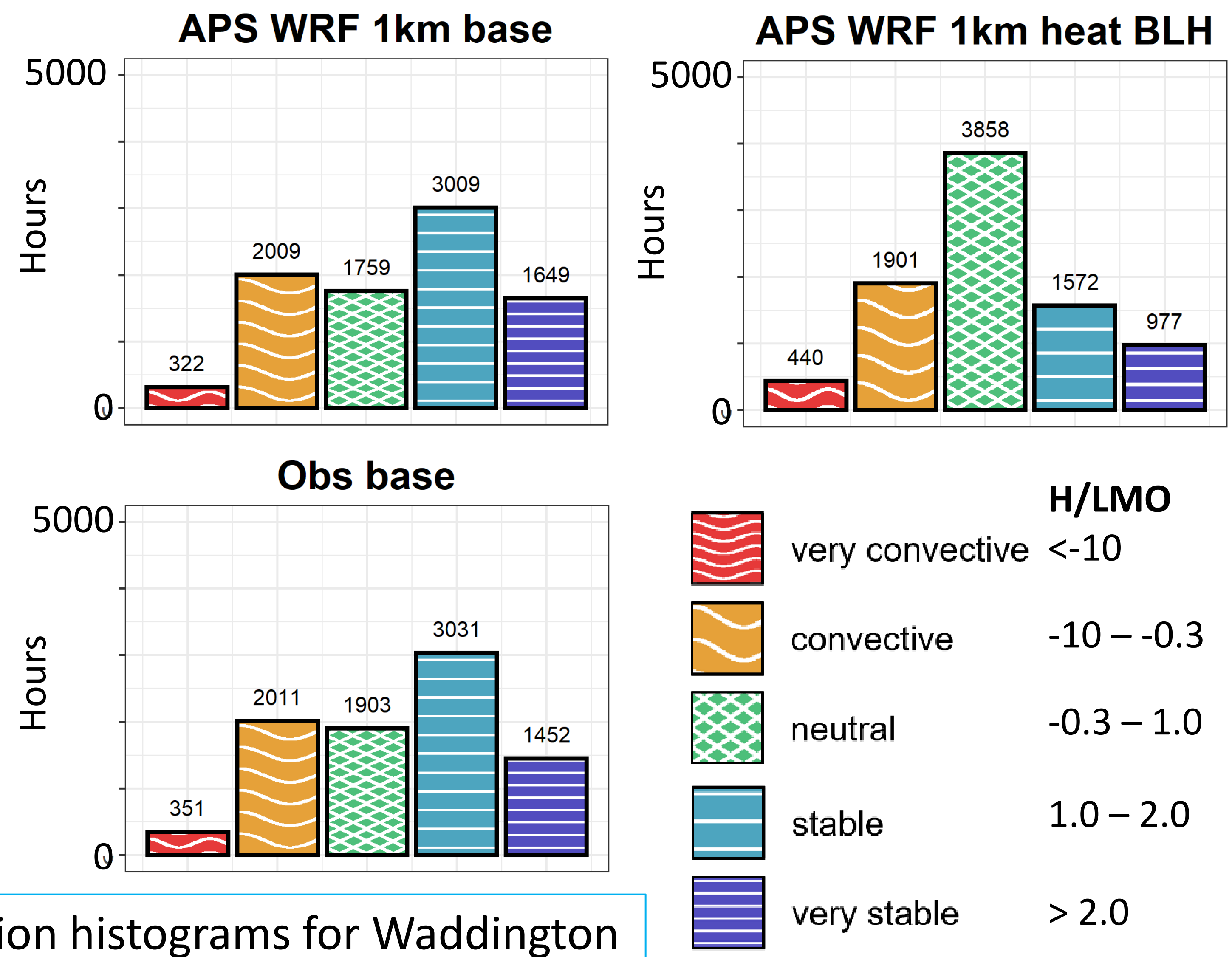
NWP secondary variables comparison

- Stability indicator: H/LMO (boundary layer height / Monin-Obukhov length)
- Different stability distributions calculated by ADMS with input observations and input NWP with secondary variables.
- Also different stability distribution in ADMS with different input NWP secondary variable datasets.

➡ **Recommend** NWP met data for ADMS should only include primary variables



Stability distribution histograms for Waddington with input observed and NWP met

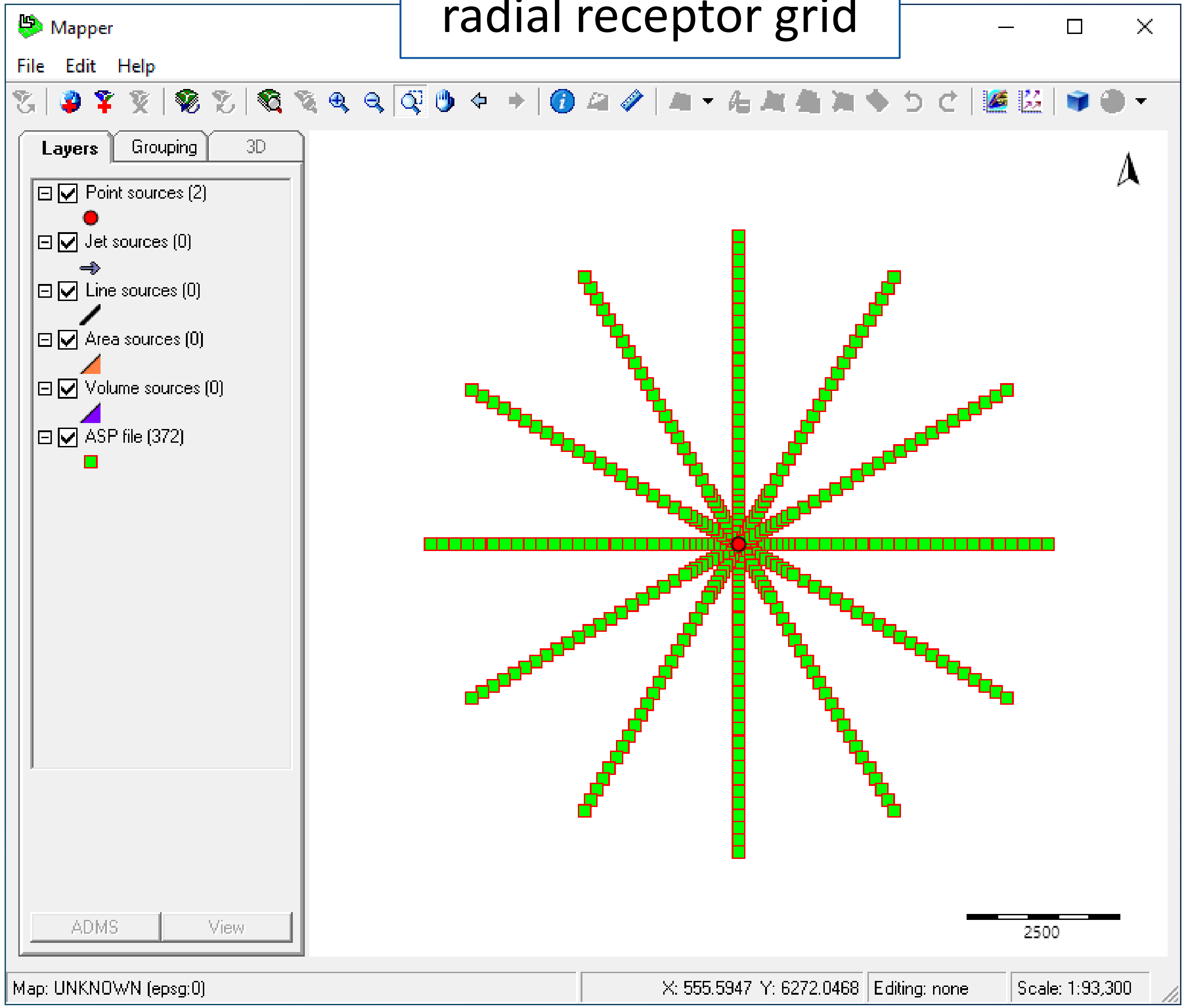
Presentation outline

- Evaluation of modelled primary meteorological data variables
- Comparison of modelled secondary meteorological data variables
- ➡ Comparison of dispersion model outcomes
- Investigation of terrain modelling with NWP inputs
- Recommendations

Dispersion modelling study

- ADMS and AERMOD annual average and high percentile hourly concentration outputs were generated for:
  - Idealised near-ground or elevated source, 1 g/s emission rate
  - 4 locations: Waddington (flat), Sennybridge (complex) Drumalbin (complex), Leuchars (coastal)
  - Met datasets
    - Observed
    - Met Office (MO) Unified Model (UM) 10 km and 1.5 km
    - Air Pollution Services (APS) Weather Research and Forecasting (WRF) 9 km and 1 km
    - Fine resolution NWP: base (primary) and 'extra' variables
  - Outputs on radial grids of receptors, 30 degree sectors

Dispersion modelling radial receptor grid



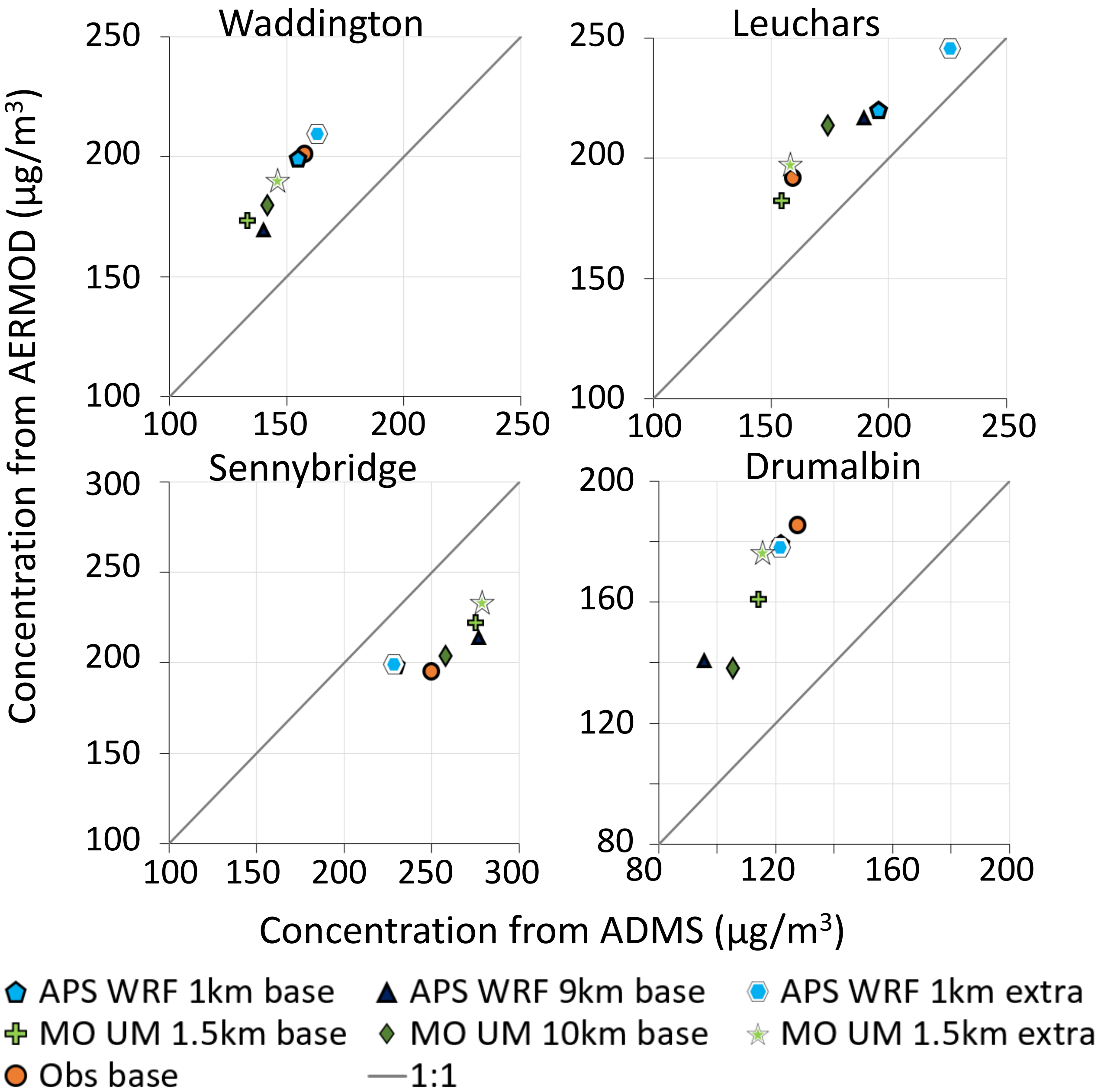
Dispersion modelling study

- Focus on overall maximum value and location for each output metric
  - Annual average, 98th percentile hourly and maximum hourly concentration
  - Annual average wet deposition (proportional to deposited mass): ADMS only

- **Key questions**:
  - What is the sensitivity of dispersion model outputs to choices of observed or NWP met data?
  - What is the importance of NWP model grid resolution for dispersion modelling?
  - How does the sensitivity to met data compare to the difference between ADMS and AERMOD with observed data?

Dispersion modelling: annual average, near-ground source

- Maximum **value** of annual average concentration from **near-ground source**
- More difference between ADMS and AERMOD with observed met than due to different base NWP met datasets input to the same model in most cases
- AERMOD predicts higher concentrations than ADMS at all sites except Sennybridge
- Relatively small differences due to NWP resolution alone
- **Location** of maximum annual average concentration from **near-ground source** consistent across all datasets



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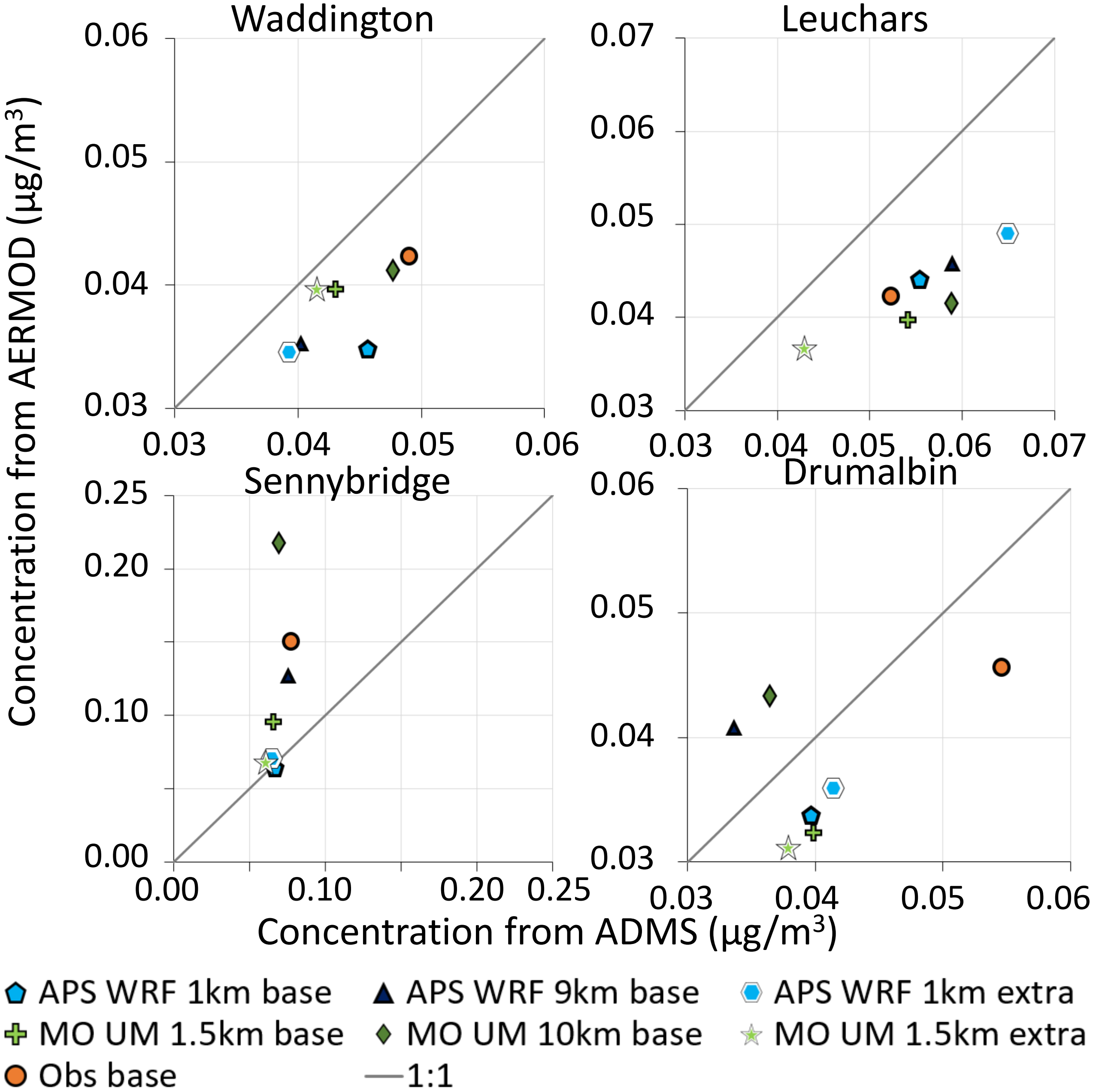
Dispersion modelling: annual average, elevated source

- Maximum **value** of annual average concentration from **elevated source**
- More variation due to different met datasets than local model at all sites except Sennybridge
- AERMOD predicts generally lower concentrations than ADMS at all sites except Sennybridge – opposite pattern from near-ground sources
- No consistent pattern of influence from NWP resolution
- Sennybridge and Drumalbin show variation of terrain modelling between ADMS and AERMOD – also clear in locations (next slide)
- Leuchars shows strongest influence of 'extra' NWP variables – coastal heat flux?



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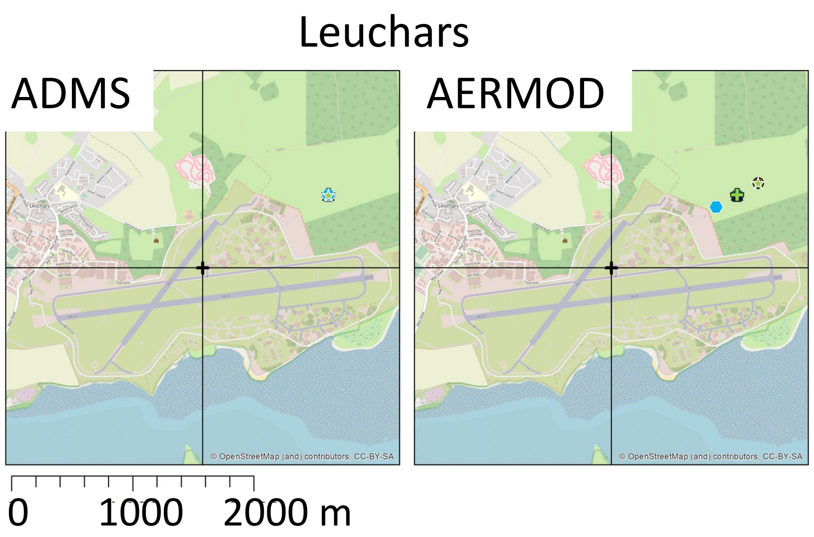
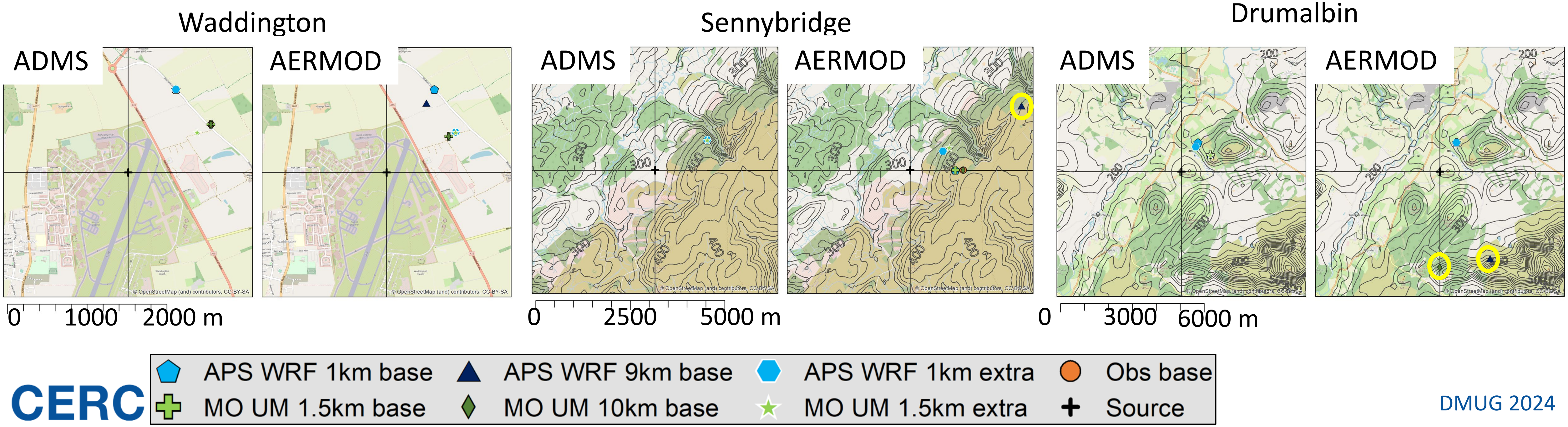
Dispersion modelling: annual average, elevated source

- **Location** of maximum annual average concentration from **elevated** source
- Broadly consistent location predictions for flat terrain: points overlay on maps
- Significant differences in complex terrain:
  - Fairly consistent locations from ADMS
  - Inconsistent locations from AERMOD: maximum annual average concentration predicted 4–5 km downstream for some met datasets: modelled plume centreline impacting on terrain (unphysical)





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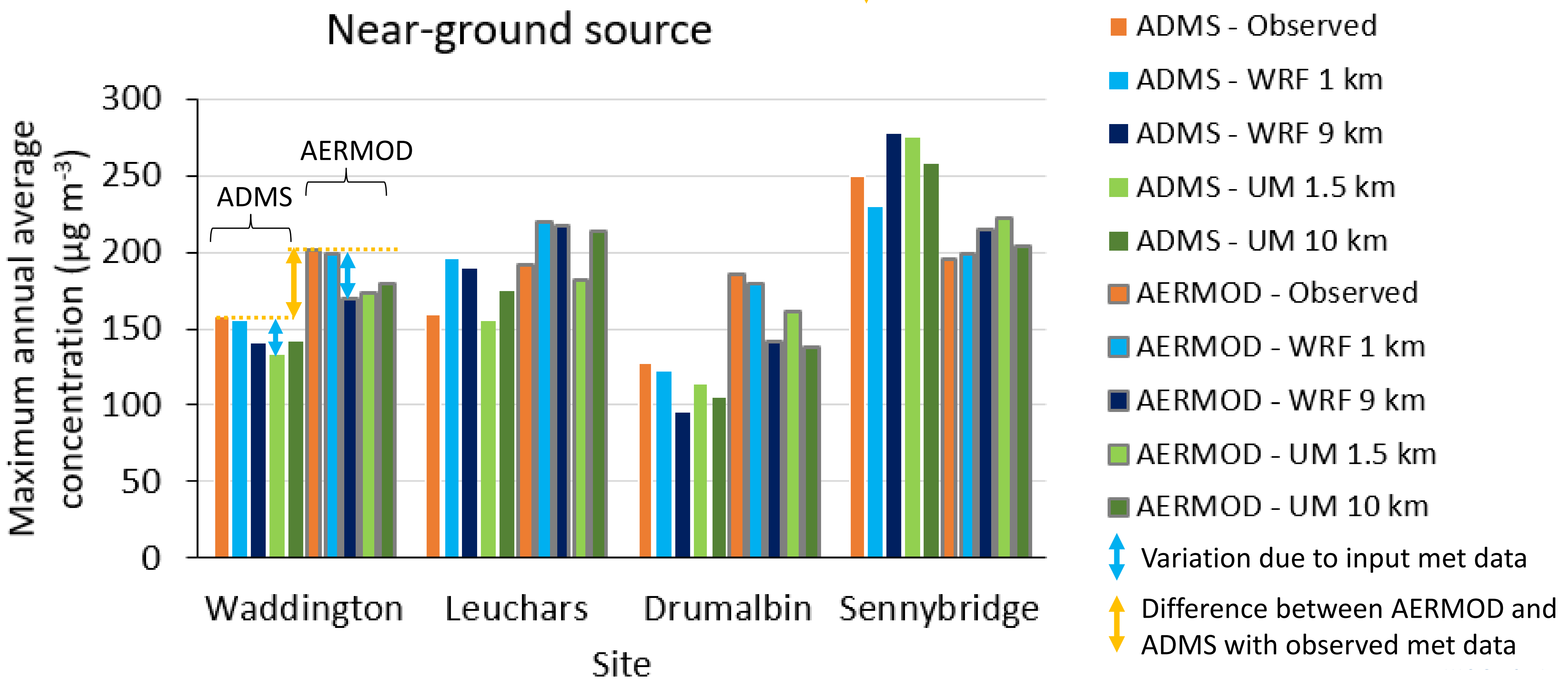
Dispersion modelling: sensitivity

- Compare range of values with observed or NWP met (↕) to corresponding value with observed met
- Compare ADMS and AERMOD values with observed met (↕)



Dispersion modelling: summary

Source type	Site type	ADMS 6 sensitivity			AERMOD 22112 sensitivity		
		AAve	P98	P100	AAve	P98	P100
Near-ground	Flat terrain	Low	Low	Medium	Low	Low	Low
	Coastal	Medium	Low	Medium	Medium	Low	Medium
	Complex terrain	Medium	Medium	Low	Medium	Low	High
Elevated	Flat terrain	Low	Low	Medium	Low	Low	Very high
	Coastal	Low	Medium	High	Low	Medium	High
	Complex terrain	Medium	Low	Medium	Very high	High	Medium

- Sensitivity of model outputs to choice of **input met dataset**
  - Based on ratio of range of outputs with observed and base NWP datasets (↕) to value with observed met ( )
  - Categories: **Low** < 0.2; **Medium** 0.2 – 0.4; **High** 0.4 – 1.0; **Very high** > 1.0
  - Low sensitivity for annual averages, flat terrain
  - Higher sensitivities for higher percentile outputs (P98, P100), complex terrain

➡ Likely to lead to higher uncertainties in these outputs

Dispersion modelling: summary

Source type	Site type	AERMOD - ADMS sensitivity		
		AAve	P98	P100
Near-ground	Flat terrain	Medium	Medium	High
	Coastal	Low	Medium	High
	Complex terrain	Medium	Medium	Very high
Elevated	Flat terrain	Low	Low	High
	Coastal	Medium	Low	High
	Complex terrain	High	High	Very high

- Sensitivity of model outputs to choice of **local model**
  - Based on ratio (AERMOD - ADMS)/(0.5(ADMS + AERMOD)), maximum across the two complex terrain sites
  - Categories: Low < 0.2; Medium 0.2 – 0.4; High 0.4 – 1.0; Very high > 1.0

➡ Sensitivity to local model choice similar to or greater than sensitivity to met dataset

Presentation outline

- Evaluation of modelled primary meteorological data variables
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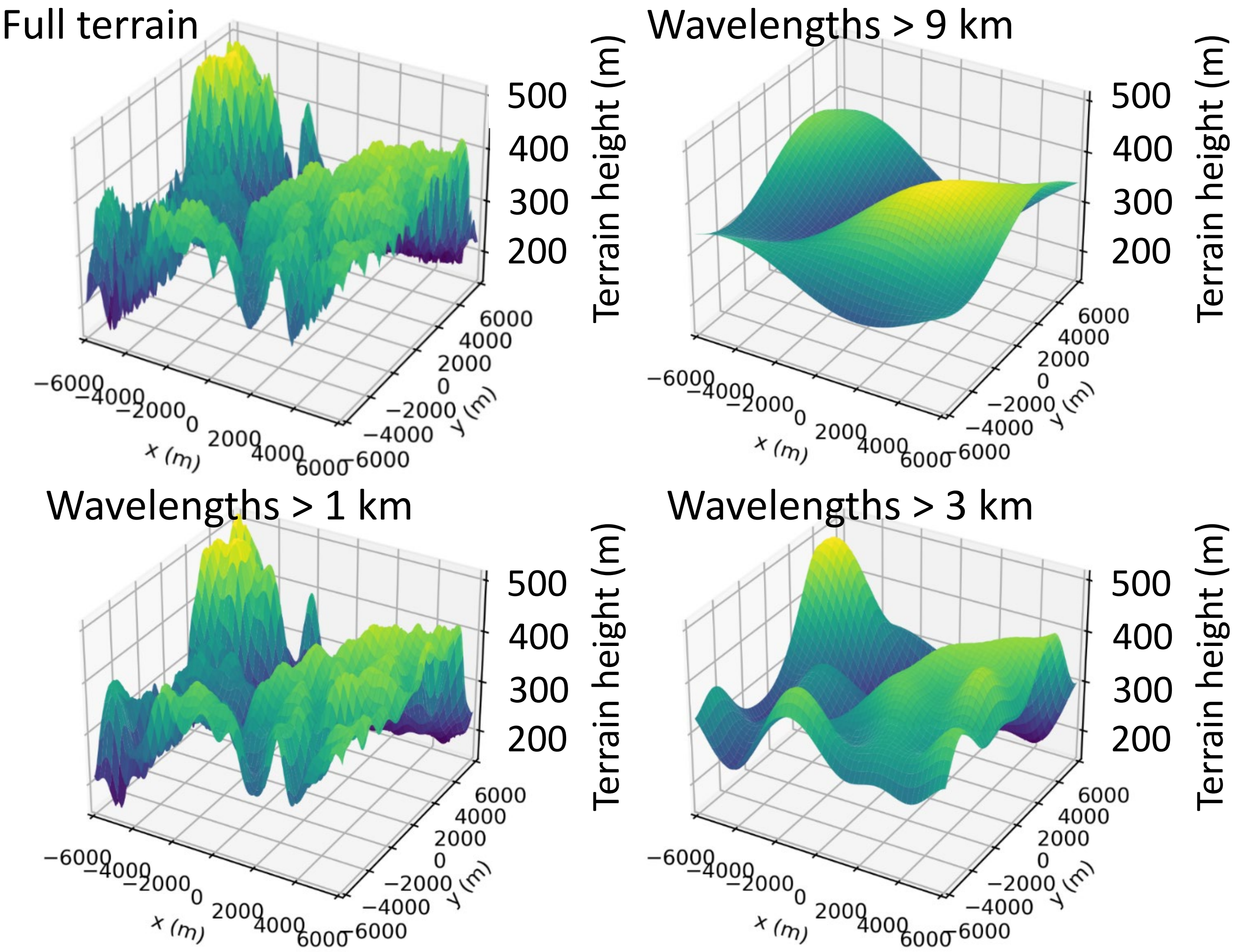
- ➡ Investigation of terrain modelling with NWP inputs
- Recommendations

FLOWSTAR modelling approach

- ADMS uses FLOWSTAR flow field modelling for dispersion in complex terrain
- FLOWSTAR assumes input met data represents upwind conditions, or the flow which would occur in the absence of the modelled terrain
- Input terrain data extents must cover all source(s) and output point(s) [modelling domain], with a margin [FLOWSTAR domain]
- FLOWSTAR calculates a 3D flow field using a solution of linearised equations of motion in Fourier space



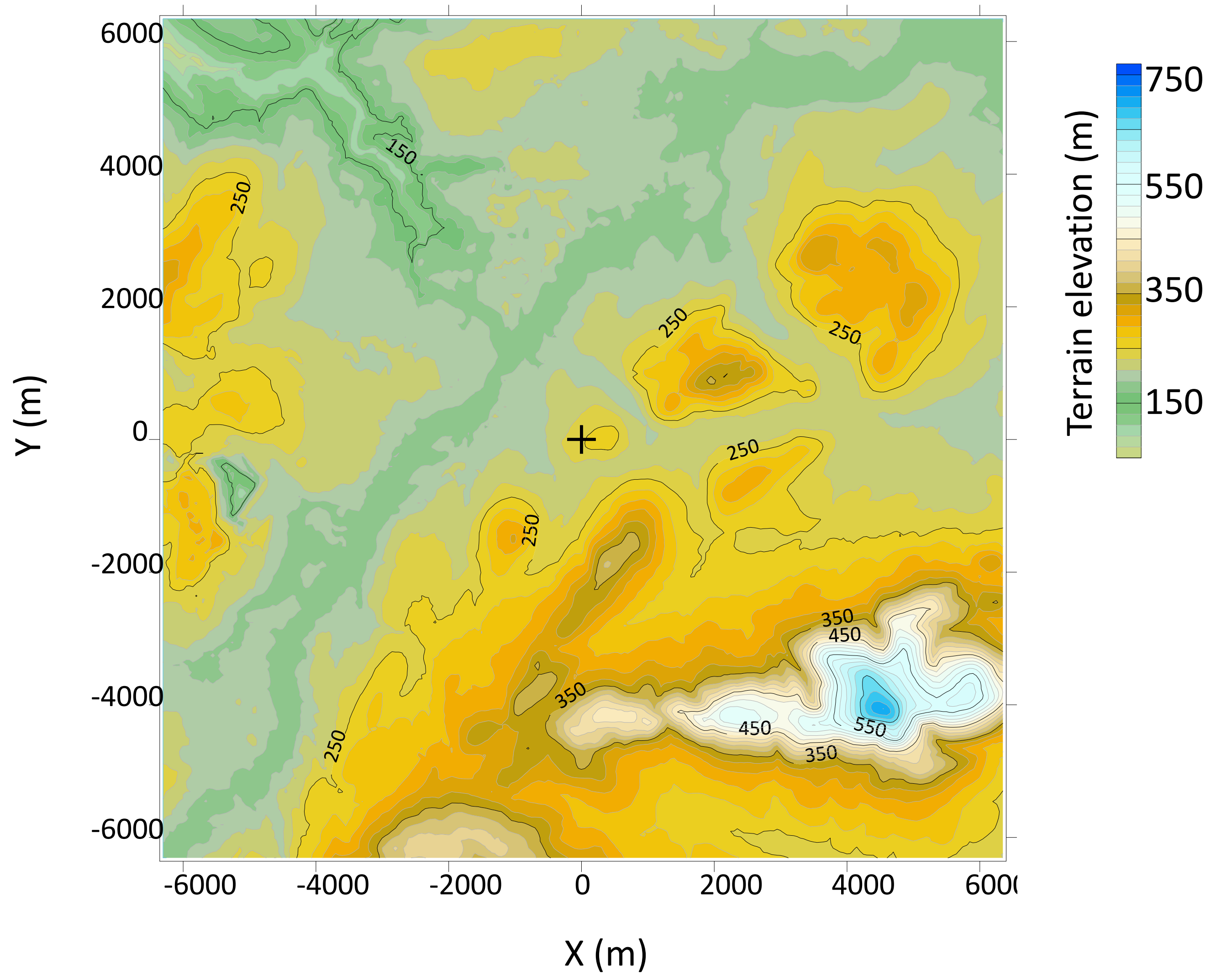
Sennybridge terrain
Underlying OS Terrain ® 50 data
Vertical variation exaggerated

AERMOD complex terrain plume dispersion uses a weighted average of terrain-impacting (horizontal) and terrain-following solutions, not a 3D flow field

➡ ***These investigations only apply to ADMS***

Investigation of ADMS terrain modelling with NWP

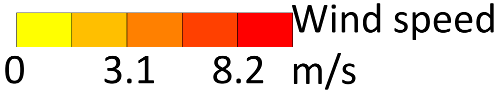
- **Key questions**:
  - How do FLOWSTAR flow fields compare to gridded NWP data?
  - Are terrain effects ‘double-counted’ between fine-resolution NWP and FLOWSTAR local modelling?
  - What is the influence of this ‘double-counting’ on concentration outputs?
  - How should NWP data be used with local terrain modelling?
- Investigations carried out for Drumalbin and Sennybridge



Drumalbin terrain
Data from OS Terrain ® 50

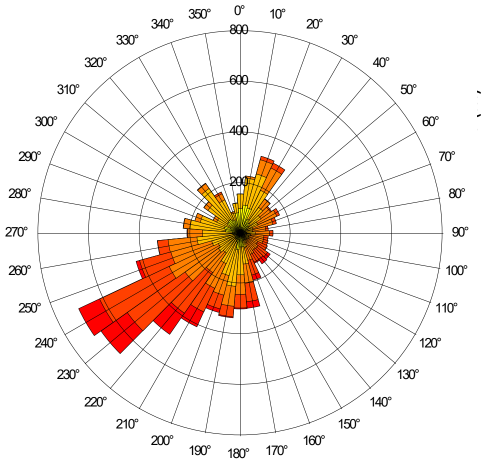
Terrain modelling: summary

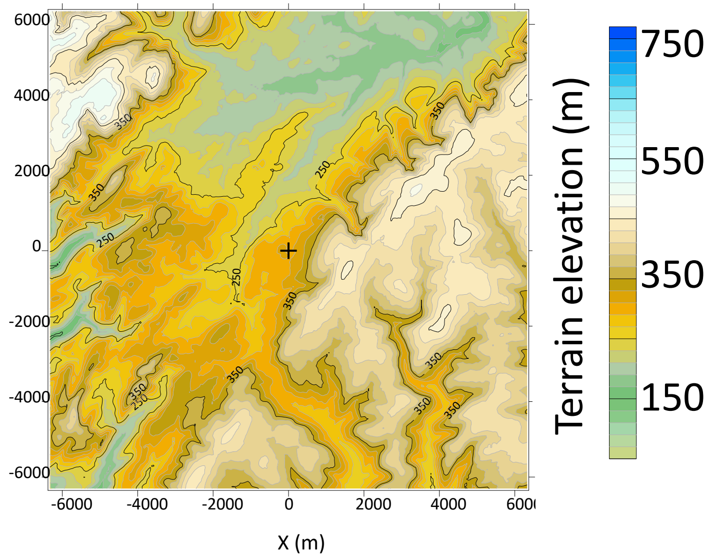
- Terrain features with length scales between modelling domain size and NWP grid resolution can be double-counted when running with single-cell fine resolution NWP
- Magnitude of impact is site-dependent
- Coarse resolution NWP or spatial average of gridded fine resolution NWP over larger domain can mitigate double-counting
- Change in maximum annual average concentration **magnitude** generally within ±10%
- Changes in **location** of maximum annual average concentration can be more substantial



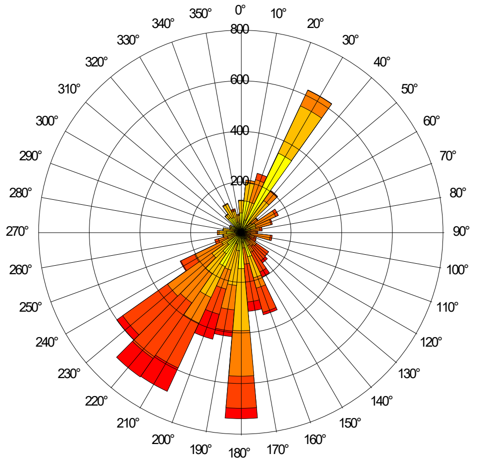
Sennybridge

Observations (input)

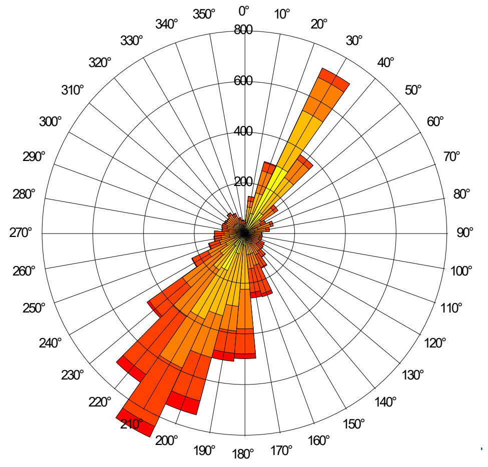




FLOWSTAR output at met site using observed input



FLOWSTAR output at met site using MO UM 1.5 km input



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Presentation outline

- Evaluation of modelled primary meteorological data variables
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Project recommendations

- Providers of modelled met data should provide supporting information about model configuration and evaluation
- High quality NWP data at horizontal resolutions of 1 – 9 km and hourly temporal resolution can be an adequate substitute for observed meteorological data for use in regulatory dispersion modelling, where locally representative observed data are not available
- Only use ‘base’ input variables when using NWP for ADMS: wind speed and direction, temperature, cloud cover, precipitation
- When using FLOWSTAR complex terrain modelling in ADMS, choose NWP data resolution similar to domain size where possible
- Consider using spatially-averaged fine resolution NWP data for larger domains (~10 km)
- Further investigation needed for very large domains (> 50 km) which may require spatially-varying meteorology: possible extension of Multi-model Air Quality System (MAQS) coupled system approach

Choosing met data for modelling

- Are locally representative observed data available with good data quality?
- What is the size of the modelling domain?
  - Single or multiple sources?
  - Near-ground or elevated source(s)?
- How complex is the local terrain?
- What is the acceptable uncertainty in magnitude and/or location of high concentrations?

Modelling domain length scale

Example modelling scenario and met options

1 km
- Single near-ground source
  - Local observations
  - Fine-resolution NWP

10 km
- Single elevated source, group of near-ground sources
  - Local observations (not affected by complex terrain)
  - Spatially averaged fine resolution NWP or coarser resolution NWP for sources in complex terrain

> 50 km
- Multiple sites with elevated sources
  - Spatially-varying meteorology

Discussion

Thank you for your attention!

Any remaining questions?

- Surgery 5: Accounting for uncertainty
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Acknowledgements

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NWP data: Met Office, APS, Lakes

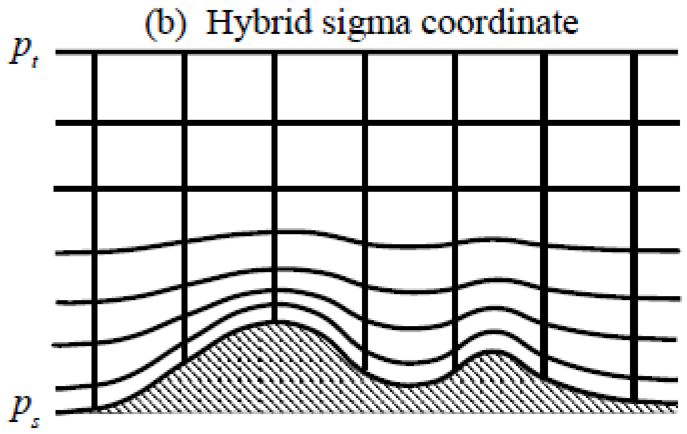
Project partners: UKHSA

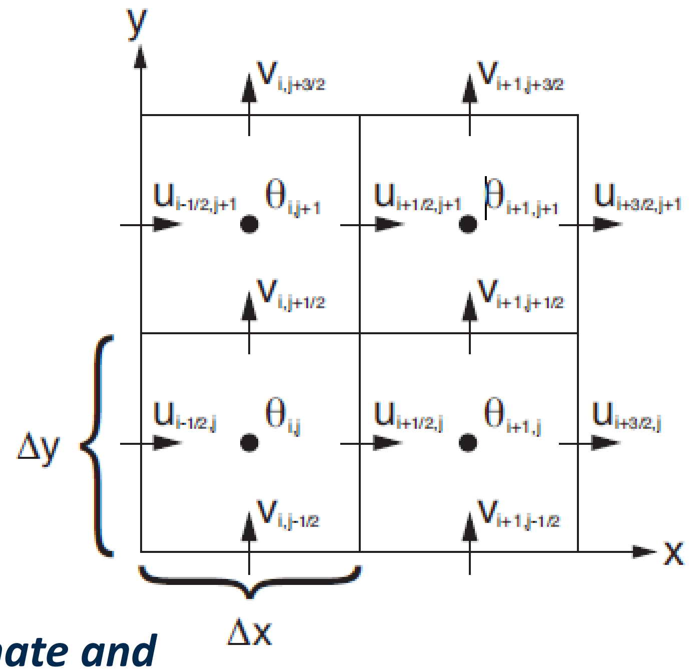
https://admlc.com/wp-content/uploads/2024/01/d5.2-finalreport-jan2024.pdf

Extra slides

Introduction to Numerical Weather Prediction (NWP)

- Numerical Weather Prediction: models used to calculate meteorological datasets, NWP models include Unified Model (UM – Met Office), Weather Research and Forecasting (WRF - NCAR), Integrated Forecasting System (IFS - ECMWF), Global Forecast System (GFS - NCEP)
- 3D gridded calculations of meteorological parameters
- Takes into account terrain, land use
- Fine-scale models driven by coarser resolution global models
- Can incorporate measured meteorology (data assimilation)
- Parameterisation of processes happening at length scales smaller than grid size, eg. convective cloud and precipitation
- Differences from measured meteorology due to:
  - Grid-cell average vs point data
  - Resolution and representation of input terrain and land use data
  - Specific difficulties with precipitation and cloud cover





horizontal grid

WRF v4 vertical coordinate and staggered grid definitions

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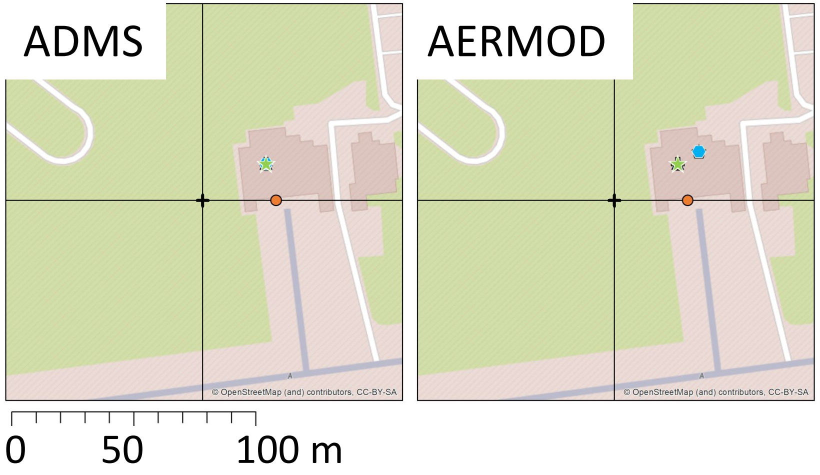
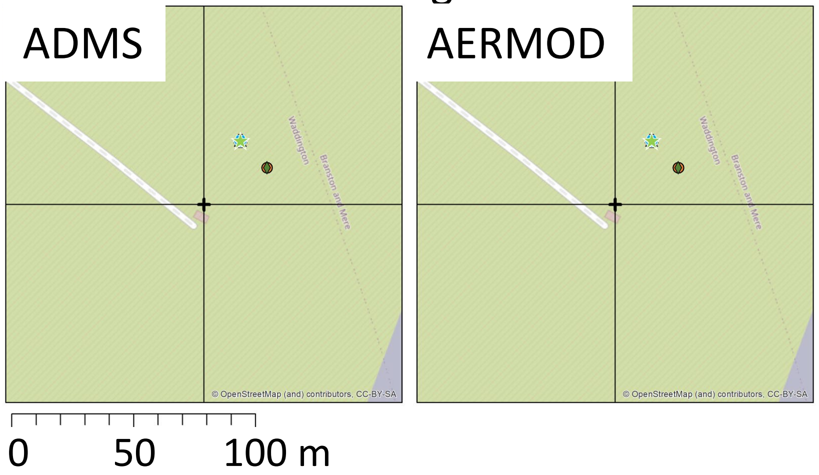
Dispersion modelling: annual average, near-ground

- **Location** of maximum annual average concentration from **near-ground** source
- All predictions 30 - 40 m from source
- Consistent locations at each site with different met datasets

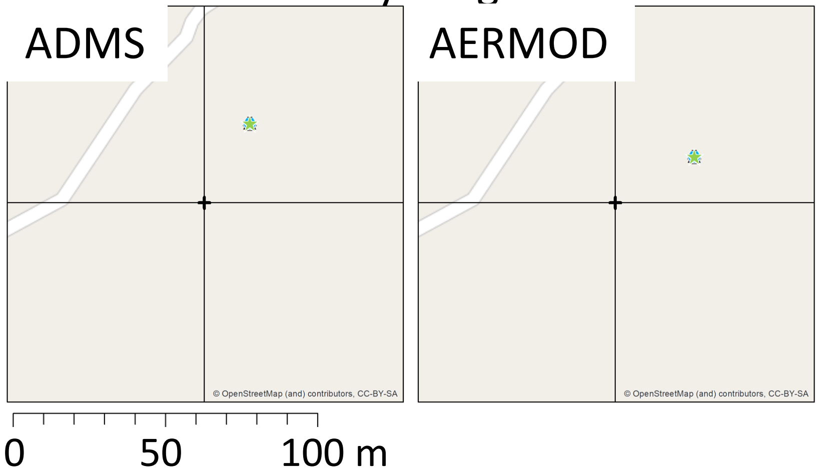
Leuchars



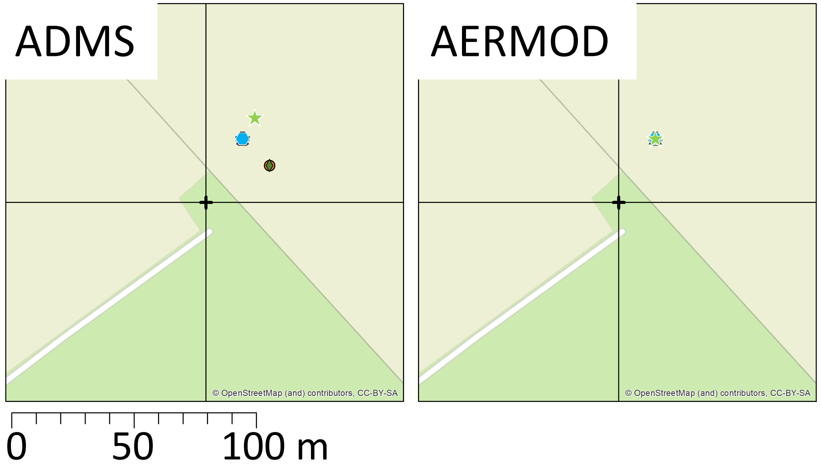
Waddington



Sennybridge



Drumalbin



APS WRF 1km base	APS WRF 9km base	APS WRF 1km extra	Obs base
MO UM 1.5km base	MO UM 10km base	MO UM 1.5km extra	Source

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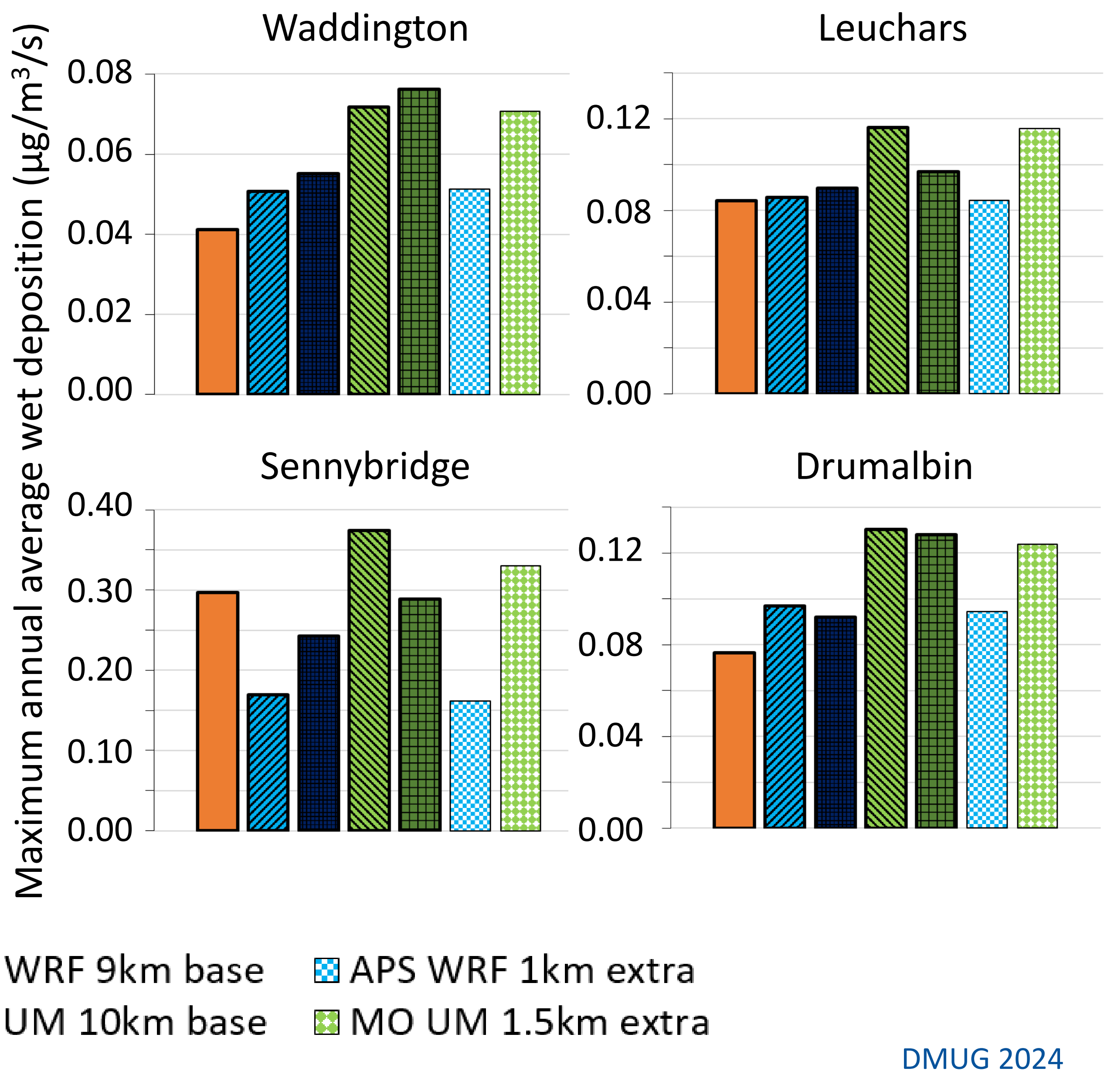
Wet deposition: near-ground

- Maximum annual average wet deposition values with observed and NWP input met
- NWP captures broad differences in deposition magnitude between sites
- NWP data leads to higher long-term wet deposition than observed input met in almost all cases
  - NWP over-predicts the prevalence of low-intensity precipitation
- Bigger range of wet deposition predictions with different NWP as a proportion of value with observed met than for concentrations
  - Affected by uncertainties in both precipitation and dispersion



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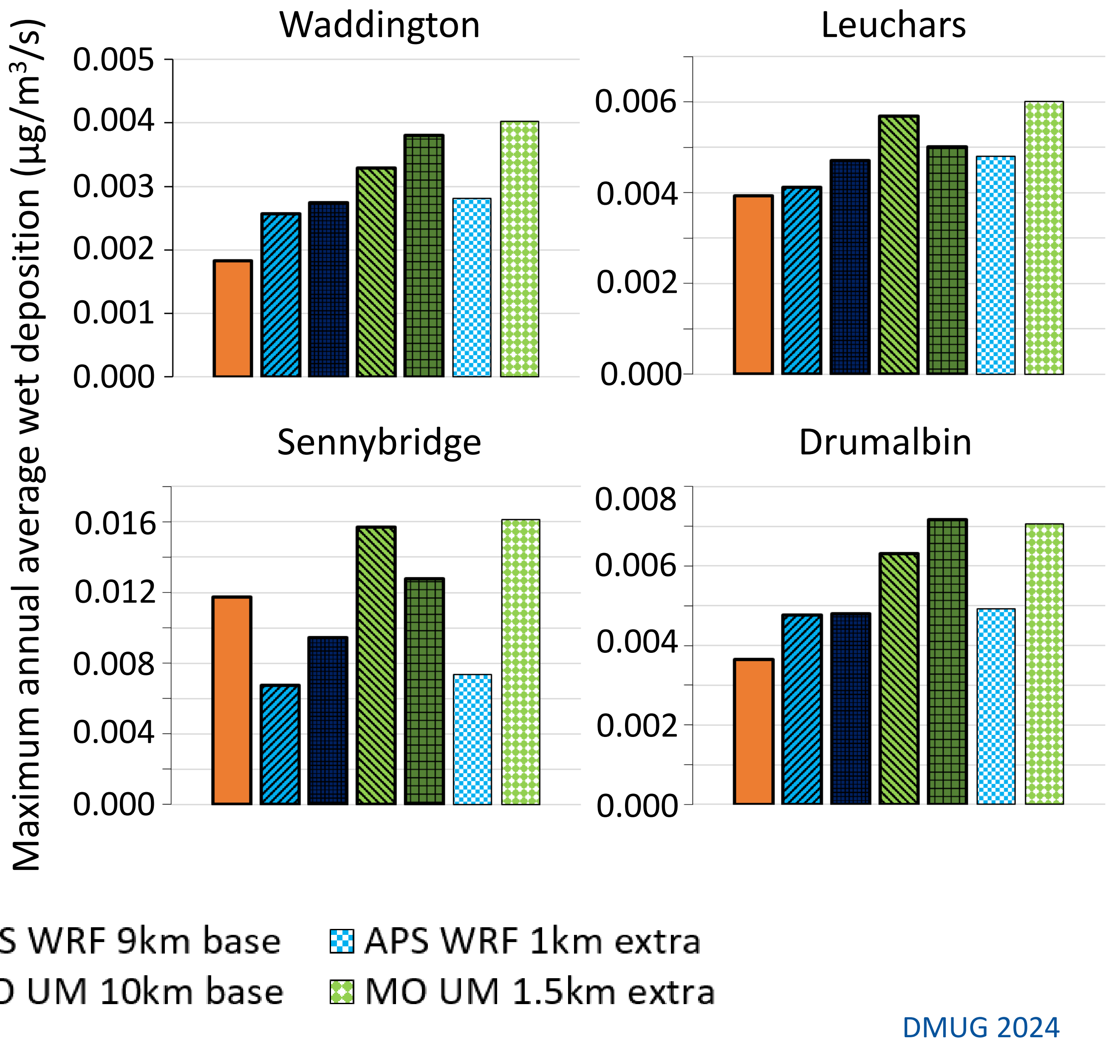
Wet deposition: elevated

- Maximum annual average wet deposition values with observed and NWP input met
- NWP captures broad differences in deposition magnitude between sites
- NWP data leads to higher long-term wet deposition than observed input met in almost all cases
  - NWP over-predicts the prevalence of low-intensity precipitation
- Bigger range of wet deposition predictions with different NWP as a proportion of value with observed met than for concentrations
  - Affected by uncertainties in both precipitation and dispersion



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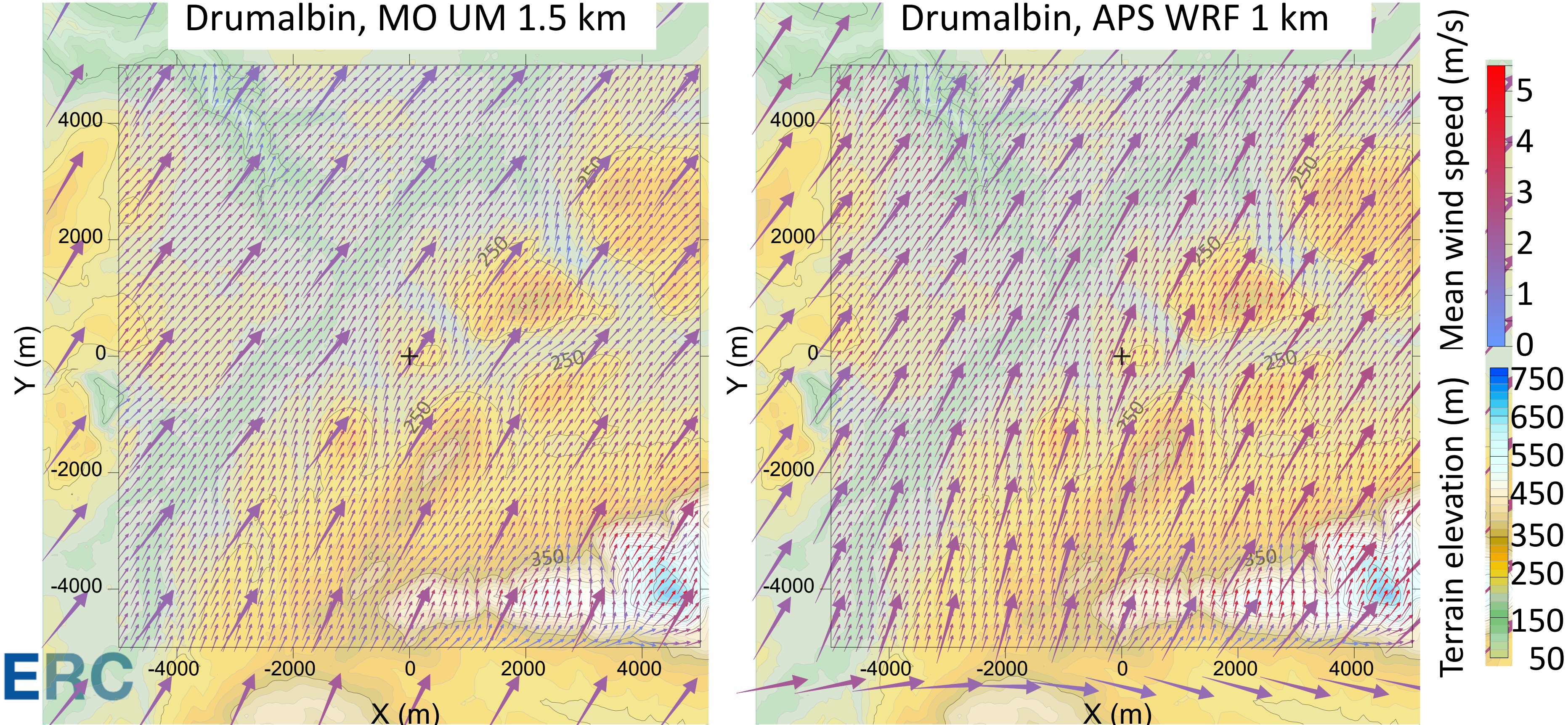
Comparison of FLOWSTAR and NWP flow fields

- **Long-term** (annual average) flow fields at 10 m above ground compared between FLOWSTAR and fine-resolution NWP
  - MO UM 1.5 km grid cells, modelling extent 10.5 x 10.5 km
  - APS WRF 1 km grid cells, modelling extent 11 x 11 km
  - FLOWSTAR driven by lower-resolution NWP (10 km MO UM, 9 km APS WRF)

Results:

- Similar overall flow field between NWP and FLOWSTAR but additional detail from FLOWSTAR around smaller terrain features
- Wider range of wind speeds from FLOWSTAR than NWP



- Large arrows: NWP flow field
- Small arrows: FLOWSTAR flow field (every 4th point for visibility)
- Arrow colours: wind speed
- Filled contours: terrain

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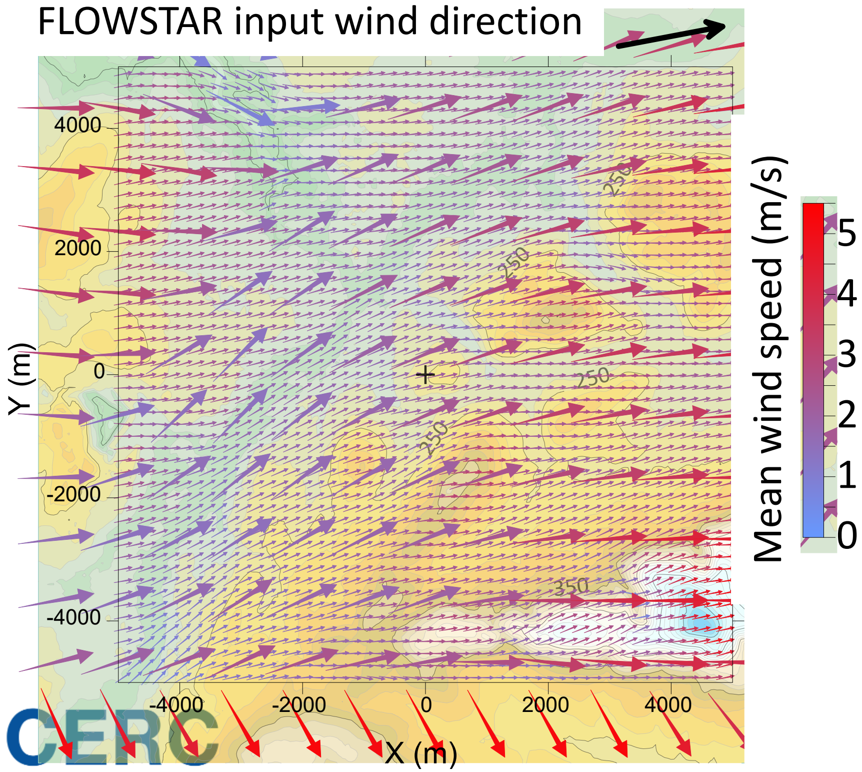
Comparison of FLOWSTAR and NWP flow fields

- **Short-term** (single hour) flow fields at 10 m above ground compared between FLOWSTAR and fine-resolution NWP
  - APS WRF 1 km grid cells, modelling extent 11 x 11 km
  - FLOWSTAR driven by lower-resolution NWP (9 km APS WRF)
  - Convective and stable examples shown, with broadly westerly winds

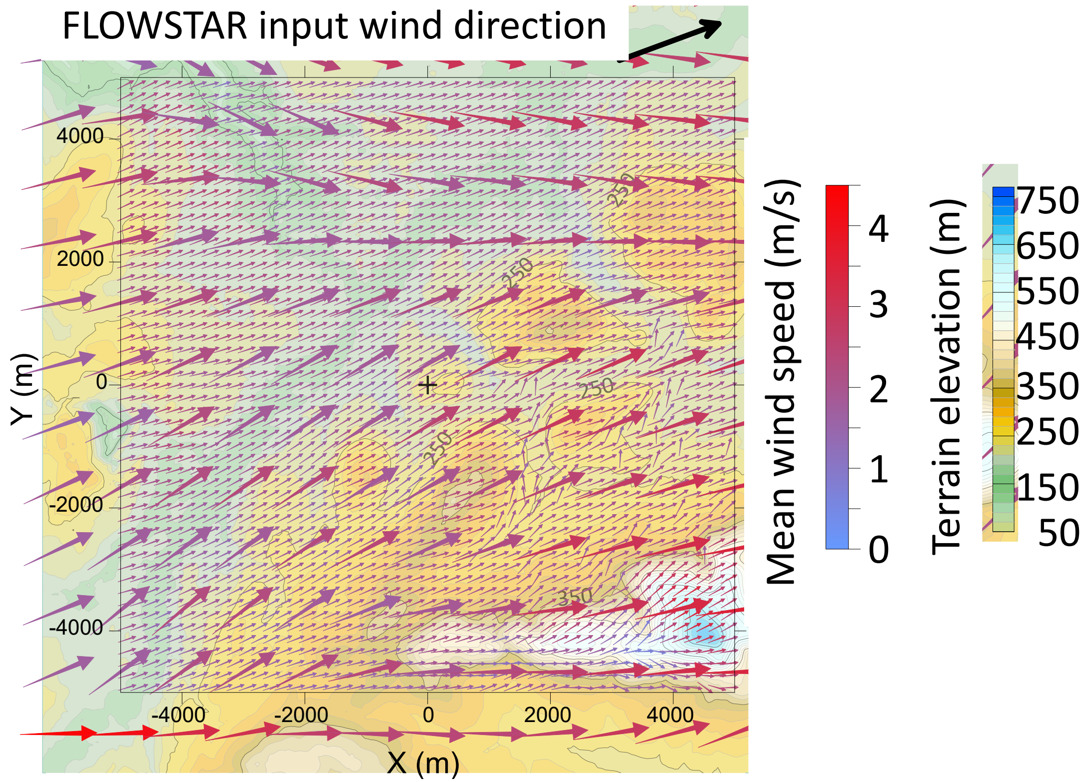
Results:

- Similar overall convective flow field between NWP and FLOWSTAR but additional detail from FLOWSTAR around smaller terrain features
- Bigger differences in stable conditions – larger scale terrain flow effects in NWP and different thermal flow effects between FLOWSTAR and NWP

Convective



Stable

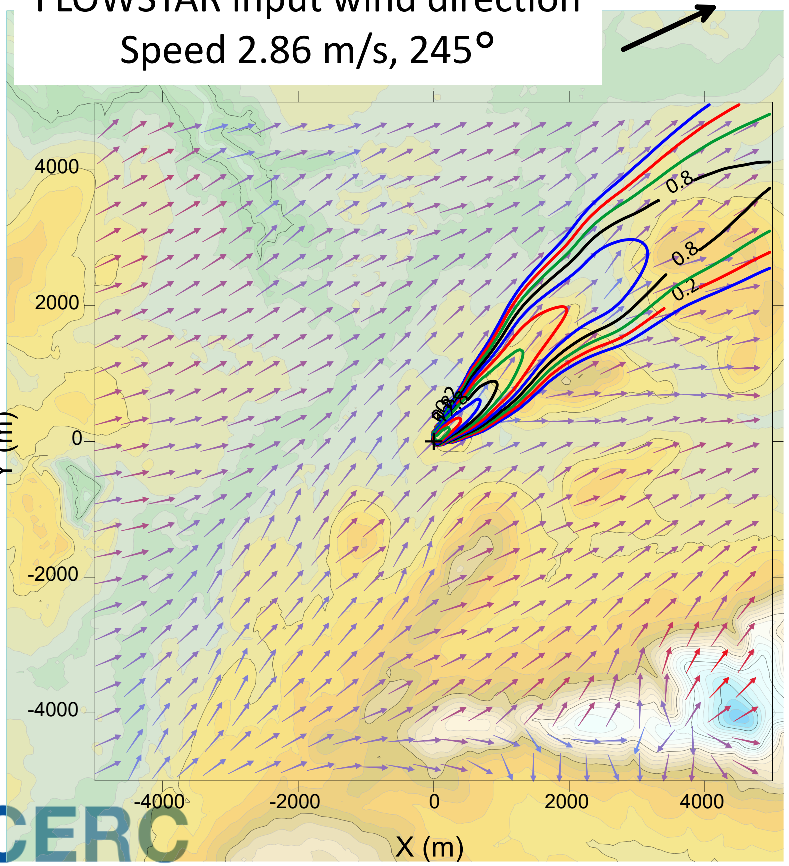


- Large arrows: NWP flow field
- Small arrows: FLOWSTAR flow field (every 4th point for visibility)
- Arrow colours: wind speed
- Filled contours: terrain

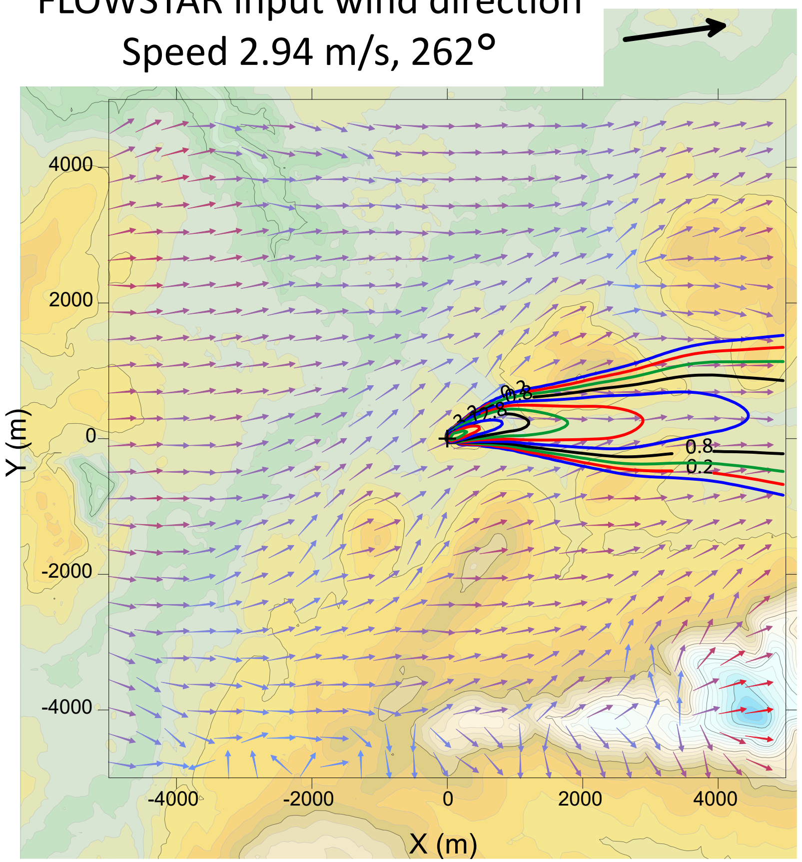
Short-term sensitivity

- Example of short-term flow and dispersion sensitivity to small changes in inputs

Single cell fine resolution NWP input (MO UM 1.5 km)

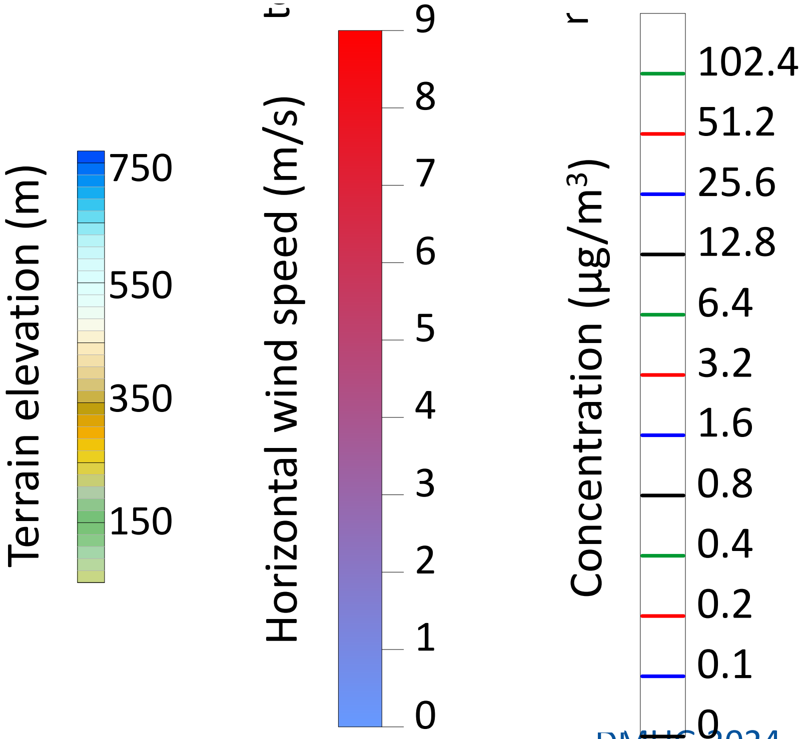


Spatially averaged fine resolution NWP input (MO UM, averaged from 1.5 km to 10.5 km)



Drumalbin flow and concentration contours, near-ground source

30 December 2019 21:00 (stable)



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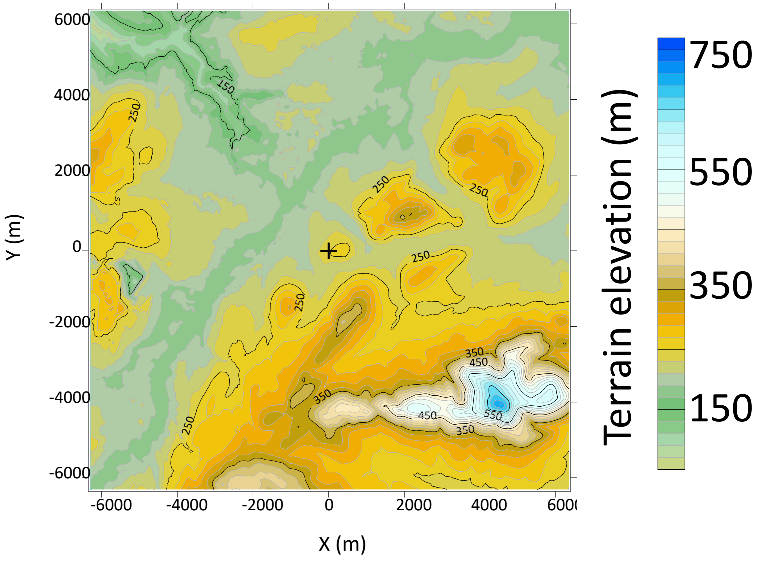
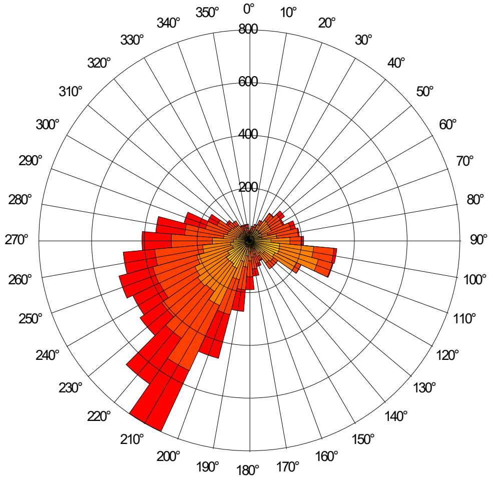
Double-counting terrain effects?

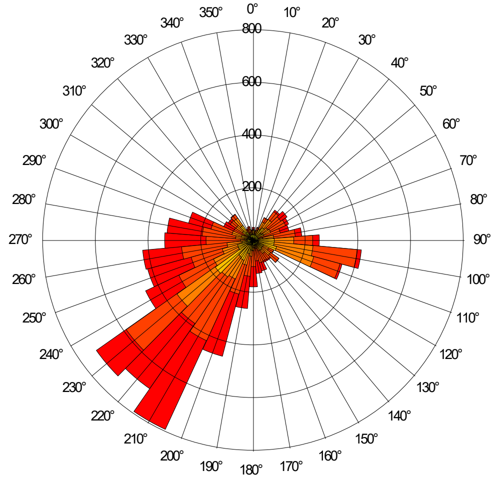
- Wind roses – summary of hourly wind speed and direction throughout year
- Weak signal of increased along-valley flow frequency from double-counting, when FLOWSTAR is driven with either observed input or single cell fine resolution NWP at Drumalbin



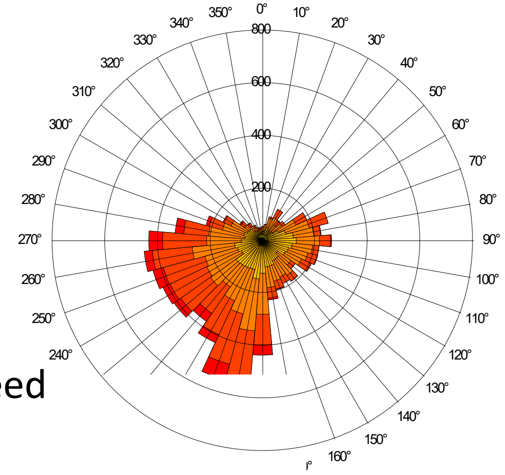
Observations (input)



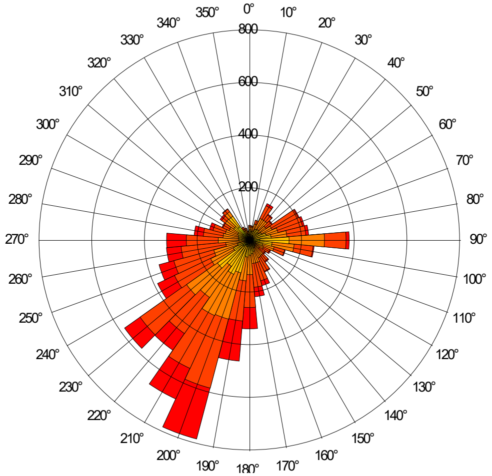
FLOWSTAR output at met site using observed input



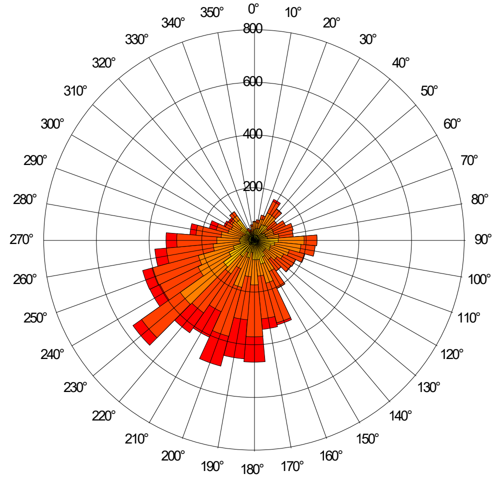
Fine resolution MO UM (input)



FLOWSTAR output at met site using single cell **fine** resolution MO UM



FLOWSTAR output at met site using single cell **coarse** resolution MO UM



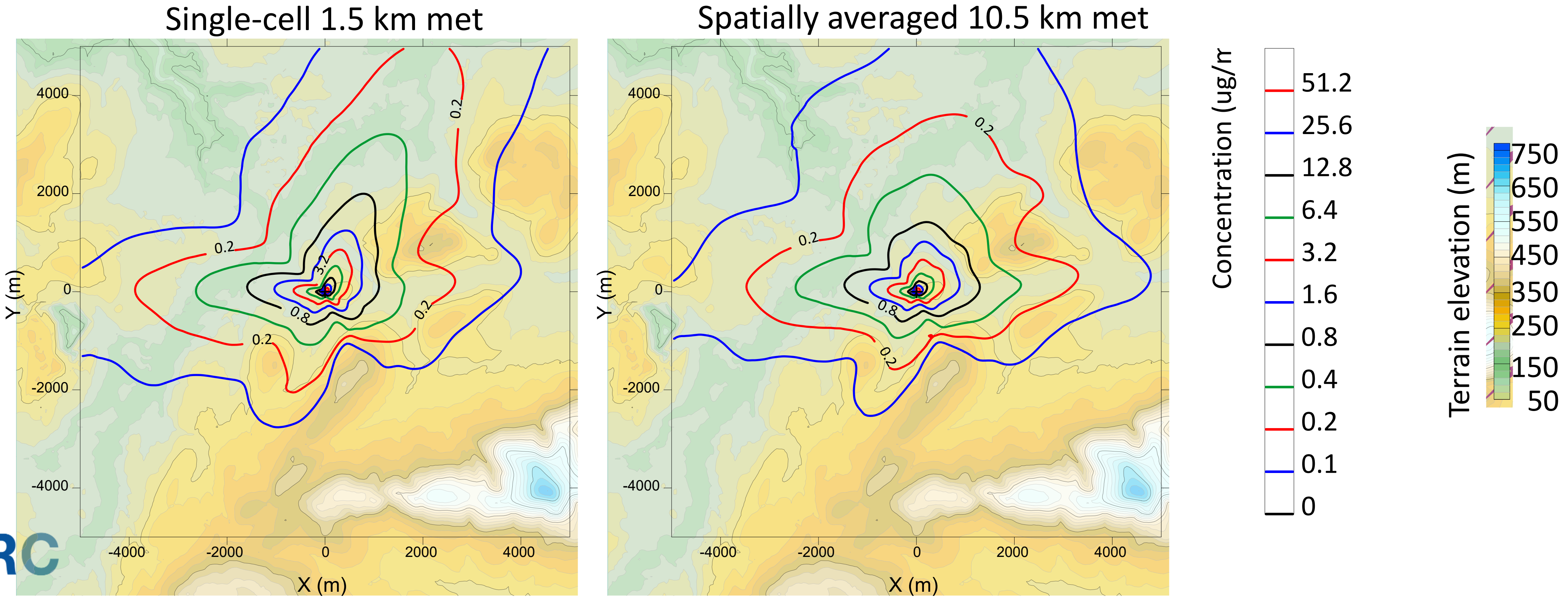
Wind speed
0 3.1 8.2 m/s

Long-term dispersion in terrain: near-ground source

- Comparing annual average concentration from **near-ground source**, using FLOWSTAR driven with input met:
  - Single cell fine-resolution NWP (1.5 km MO UM)
  - Spatially averaged fine-resolution NWP (10.5 km MO UM)

Results

- More channelling of concentrations along valley with single-cell fine-resolution NWP
- Maximum annual average concentration 8% higher with single-cell met than spatially averaged met, within general uncertainty
- Location of maximum concentration differs by 24 m between single-cell met and spatially averaged met



CERC

Long-term dispersion in terrain: elevated source

- Comparing annual average concentration from **elevated** source, using FLOWSTAR driven with input met: :
  - Single cell fine-resolution NWP (1.5 km MO UM)
  - Spatially averaged fine-resolution NWP (10.5 km MO UM)

Results

- Slightly more along-valley channelling with single-cell fine resolution NWP
- Maximum annual average concentration 8% higher with single-cell fine resolution NWP than spatially averaged NWP
- Location of overall maximum concentration moves from N to E of stack: change between local maxima; bistable flow pattern around small hill?

Single-cell 1.5 km met

Spatially averaged 10.5 km met