Assessing the impact of thermally driven flows on regulatory air dispersion modelling

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Harmo 23

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Motivation

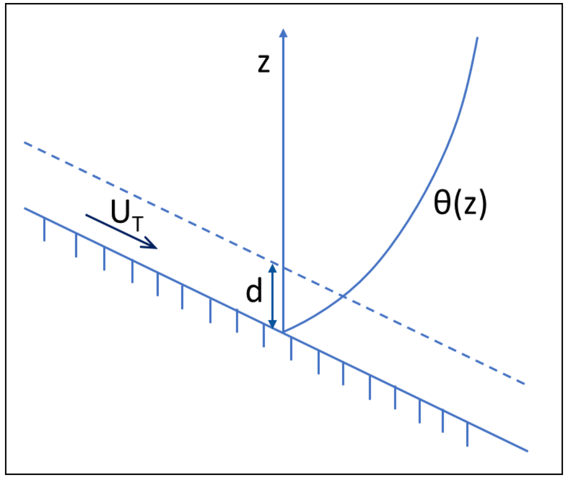
- Air quality assessments for environmental permits do not typically consider how variations in air temperature near the ground can cause local thermal air flows, which incorporate and transport air pollutants.
- Flows can occur in areas of sloping terrain, varying land cover, or at the coast.
- Many sites regulated by the Environment Agency in England are in such areas, and recent experience of thermal air flows at a high-profile site prompted this study into their potential impacts.
- Cold air drainage of air pollutants was identified as an EA-relevant priority evidence gap in the Environment Agency's air evidence review[1]

[1]https://assets.publishing.service.gov.uk/media/6571a2a3809bc3001330821b/Options_for_air_quality_research_-_drivers_of_future_changes_-_report.pdf

Thermal flow types

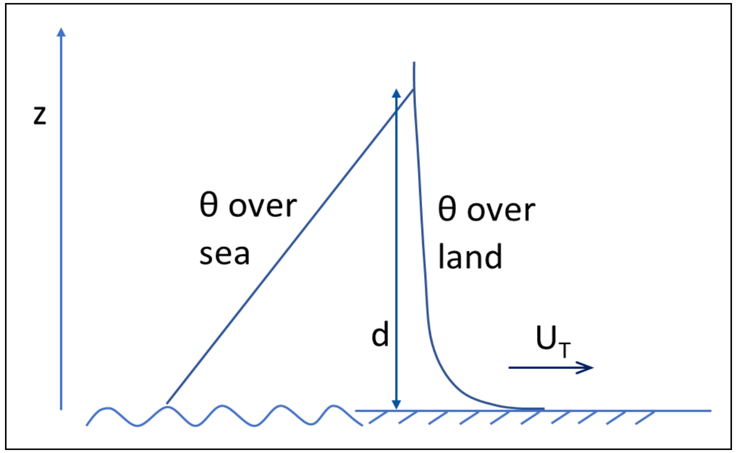
Sloping terrain

- Katabatic winds (cold air drainage)
  - Downslope flow
  - Night time, stable conditions
- Anabatic winds
  - Upslope flow
  - Day time, convective conditions



Coastal

- Sea breeze
  - Onshore wind (towards land)
  - Day time, land warmer than sea
- Land breeze
  - Offshore wind (away from land)
  - Night time, land cooler than sea

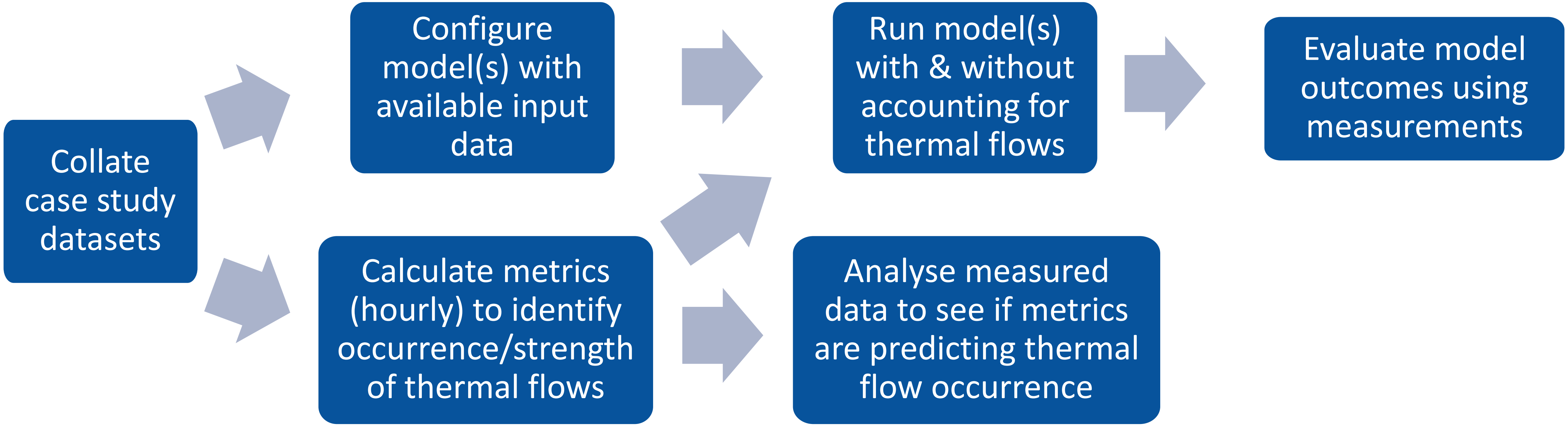


Land use

- Temperature difference due to changes in land use
  - Urban heat islands
  - Wetlands
- Potential for competing effects with other flow effects
  - Changes in surface roughness

d = layer depth, θ = temperature, U_T = thermal flow

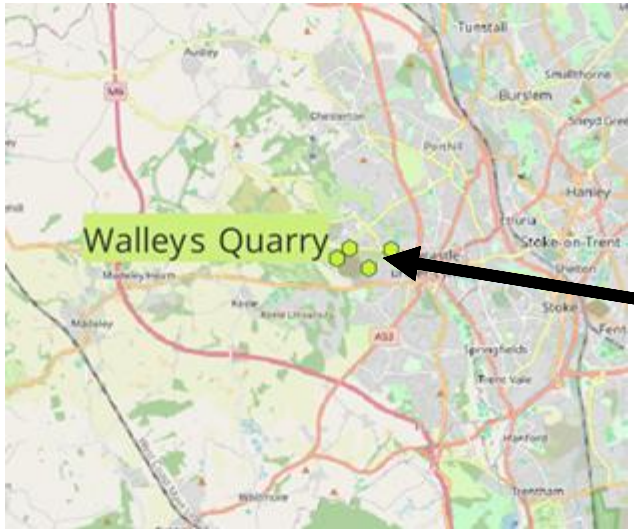
Case Studies: Overview of main tasks

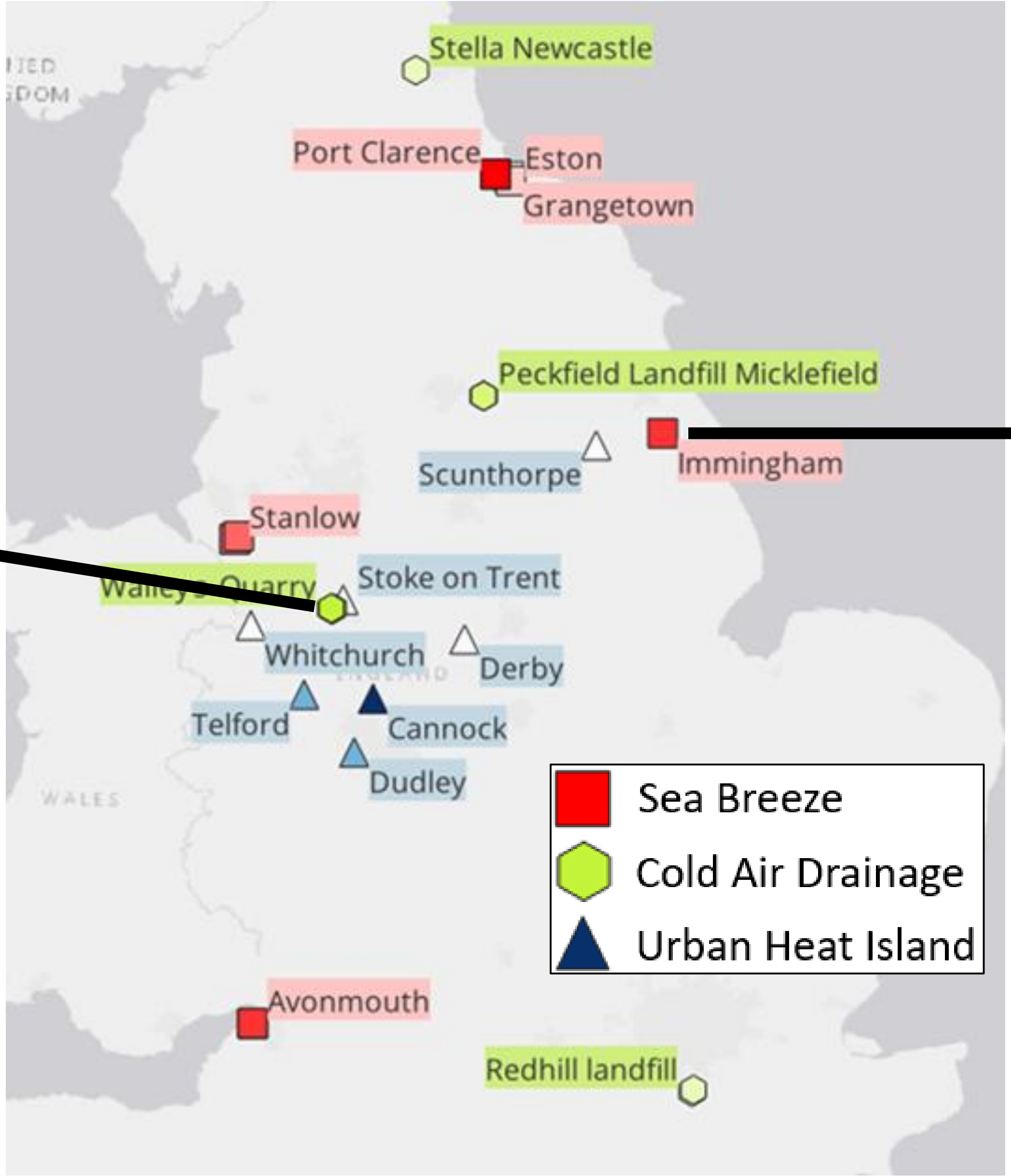


Caveat: Case study datasets not compiled for assessing thermal winds so some uncertainty in model inputs

Case studies: Choice of datasets (England)

Katabatic example





Coastal example

Screening criteria

Thermal flow type	Source height	Source location	Impacted receptors	Required meteorological conditions
Katabatic	Within cold near surface air layer (≤ 10 m)	Surface gradient (> 0.34°)	Downslope from source	Weak/calm synoptic wind; stable conditions, typically occurring at night with little cloud cover
Anabatic	Within warm near surface air layer (≤ 10 m)	Surface gradient (> 5°)	Upslope from source	Very weak/calm synoptic wind and strong solar heating, during daytime
Sea breeze	All source heights	Close to coast (within 15 km)	All receptors	Light synoptic wind. Temperature over land significantly greater than sea surface temperature, during daytime
Land breeze	< 50 m	Close to coast (within 10 km)	All receptors	Weak synoptic wind. Sea surface temperature significantly greater than temperature over land, during night time
Land use*	All source heights	Large contrasts in land type	All receptors	Weak/calm synoptic wind, with large temperature contrasts over land

***Urban heat island:** effects not readily detectable in cases examined

Thermal flow metric

$$U_T = \begin{cases} \left(\frac{dg\Delta\theta \sin\alpha}{2C_d\theta} - \frac{1}{2}{U_S}^2\right)^{\frac{1}{2}} & \text{if } \frac{dg\Delta\theta \sin\alpha}{2C_d\theta} > \frac{1}{2}{U_S}^2 \\ 0 & \text{otherwise} \end{cases}$$

d = layer depth

α = slope angle ($\sin\alpha$ = 1 for sea breeze)

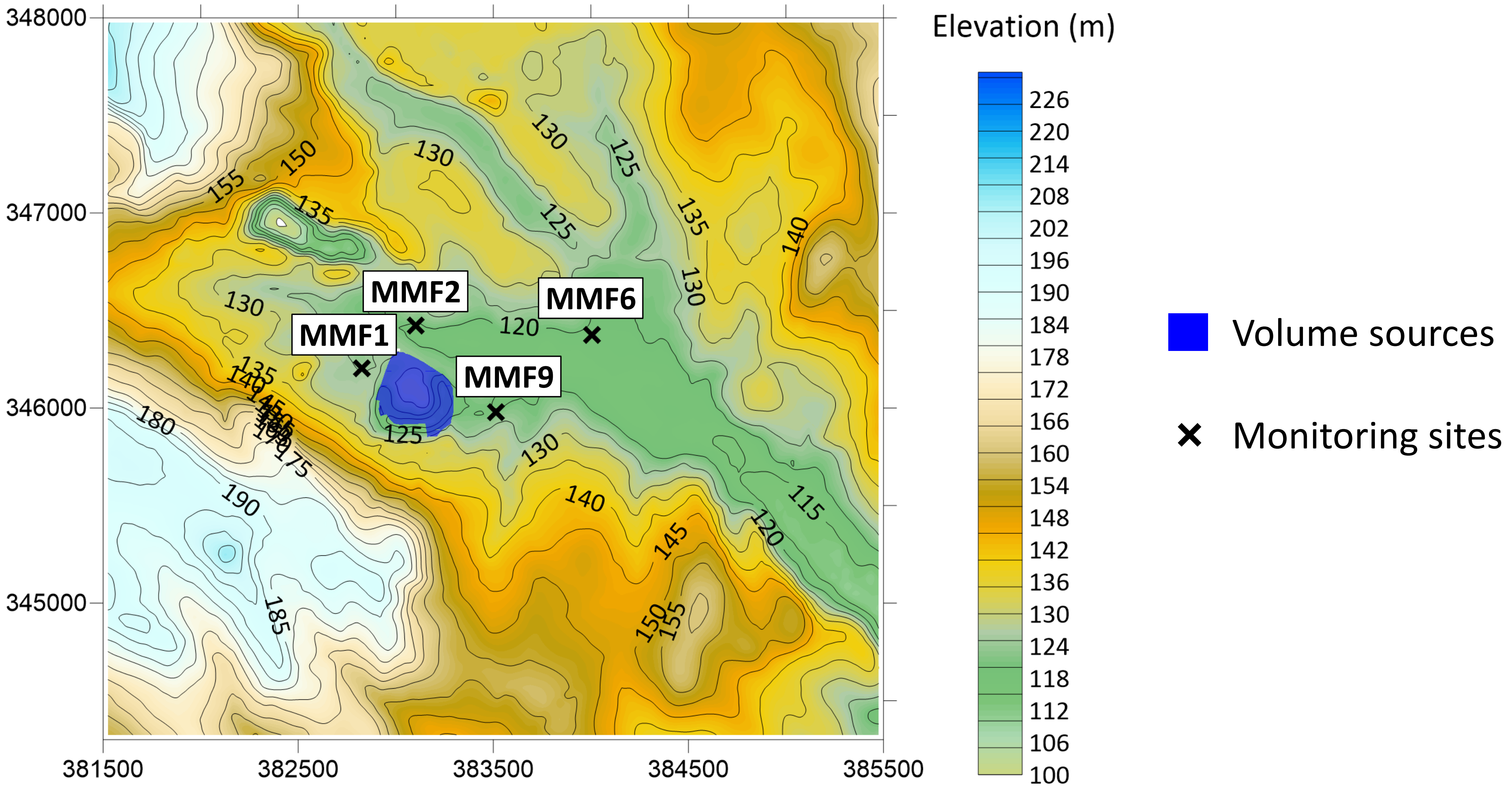
U_S = synoptic wind speed

$\Delta\theta$= temperature difference

- *over layer depth* for katabatic
- *Land surface – sea surface* for sea breeze

Wind criterion	Category	Description
$U_s > 2U_T$	Synoptic dominates thermal	Synoptic flow suppresses development of thermal flows
$2U_T > U_s > 0.5U_T$	Some thermal influence	Thermal flows will have an impact on the overall flow
$U_s < 0.5U_T$	Thermal flow dominates	Thermal flows dominate the flow

Katabatic: Site and measurement locations



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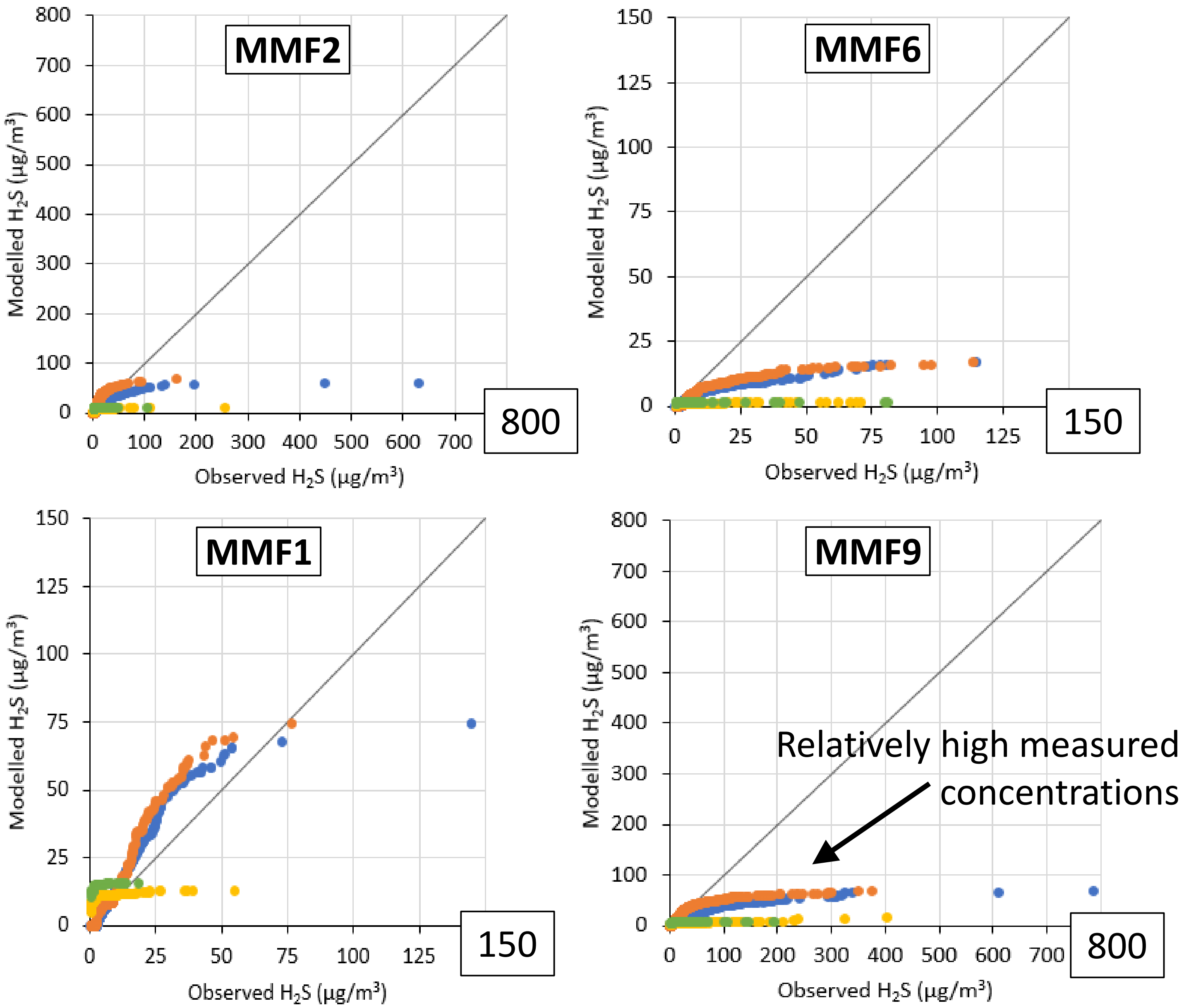
Katabatic: Thermal flow counts

Thermal flow type	Hill slope angle (°)	Number of hours with potential for thermal flows	Split between number of hours with potential for thermal flows			Average U_T for thermally dominated flows (m/s)	Average $\Delta\theta$ for thermally dominated flows (°C)
			No thermal flow	Some influence of thermal flow	Dominant thermal flow		
Katabatic	0.4	2766	2676	70	20	0.15	2.41
Katabatic	1.8	2766	2490	217	59	0.34	2.70
Katabatic	3.7	2766	2159	513	94	0.48	2.66
Anabatic	0.4	1027	1027	0	0	n/a	n/a
Anabatic	1.8	1027	1027	0	0	n/a	n/a
Anabatic	3.7	1027	1027	0	0	n/a	n/a

Shawbury meteorological data:29/04/2021 to 27/06/2023 (total 18937 hours).

Katabatic: Base model against observations (Quantile-Quantile, QQ plots)



Base model: *standard ADMS dispersion model*

- Model agreement with observations changes depending on thermal flow type:
  - No thermal flow & synoptic flow show same pattern
  - Some/strong thermal influence show a different pattern

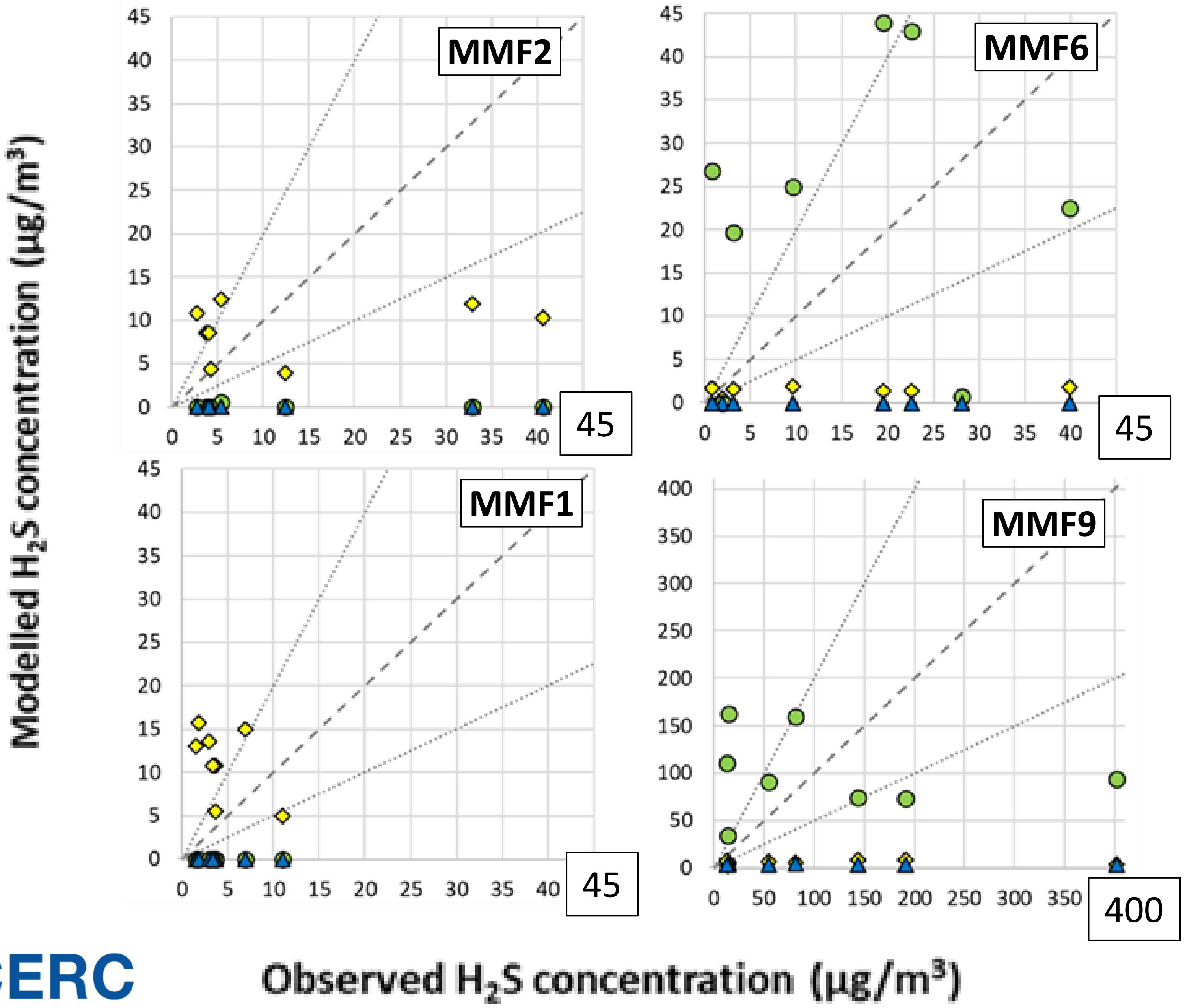
- No potential for thermal flow
- Synoptic dominates thermal
- Some thermal influence
- Thermal flow dominates

Katabatic: modelling approaches

- Standard ADMS
  - Including radial calms module
- ADMS, 3D flow field
  - Katabatic flow field combining mean synoptic flow with katabatic flow profile
- KLAM_21
  - Two-dimensional cold-air-drainage model

- Within katabatic layer
  - Downslope flow direction
  - Thermal flow wind speed
- Transition layer
  - Ensure smooth profile
- Synoptic layer
  - Wind speed and direction from synoptic flow

Katabatic: All models against observations (Thermally dominated hours)

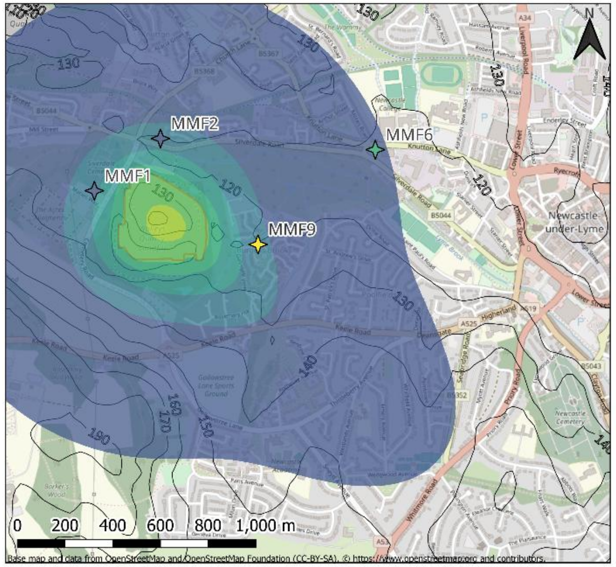


- Models performance for thermally dominated hours:
  - Upslope monitors show better agreement using the ADMS radial calms solution
  - Downslope monitors show better agreement using ADMS modified katabatic wind profile where concentrations are higher
  - The KLAM_21 plume 'misses' the monitors

ADMS, calms module
ADMS, katabatic wind profile
KLAM

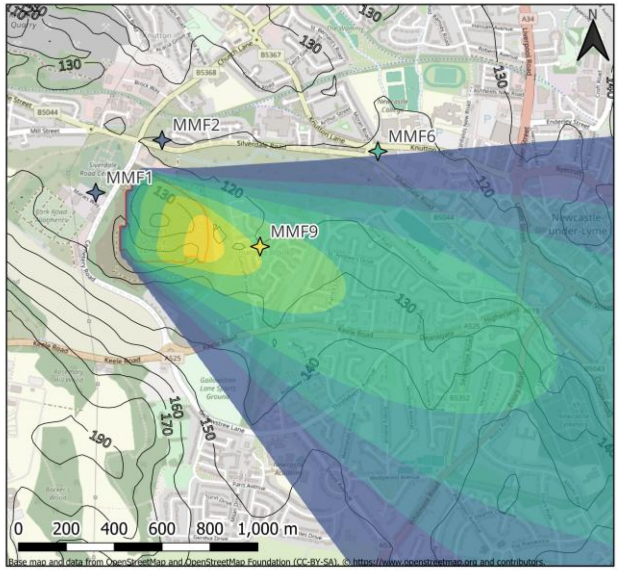
Katabatic: Example pollution map for a thermally dominated case

Standard ADMS



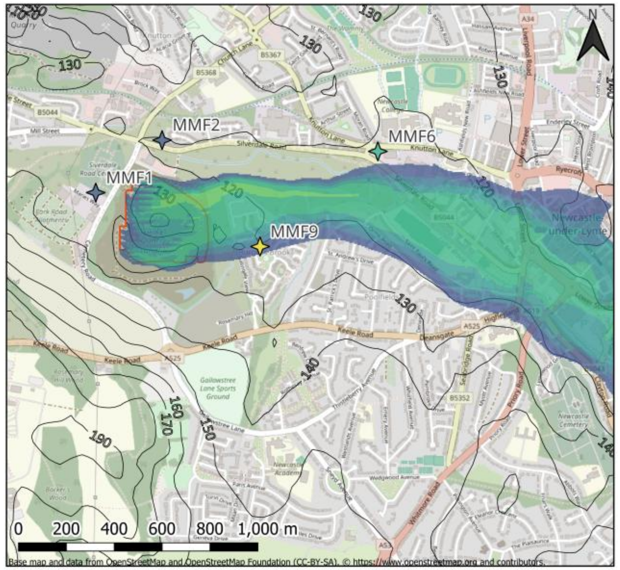
- Radial plume dominated, concentrations based on source-receptor distance

ADMS 3D flowfield



- Downslope flow allows plume to reach downslope monitor

KLAM_21

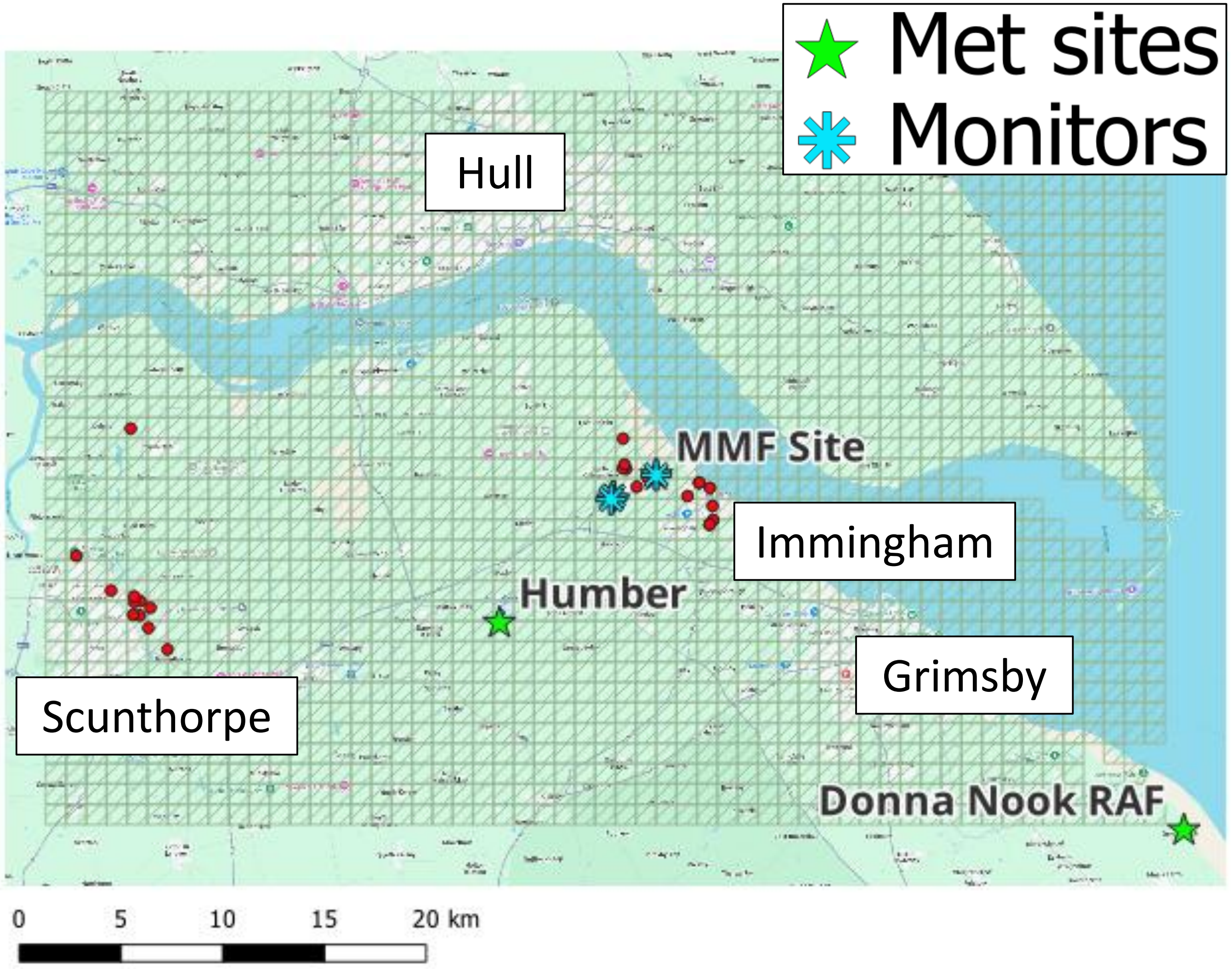


- Downslope flow, but narrow plume goes between monitors

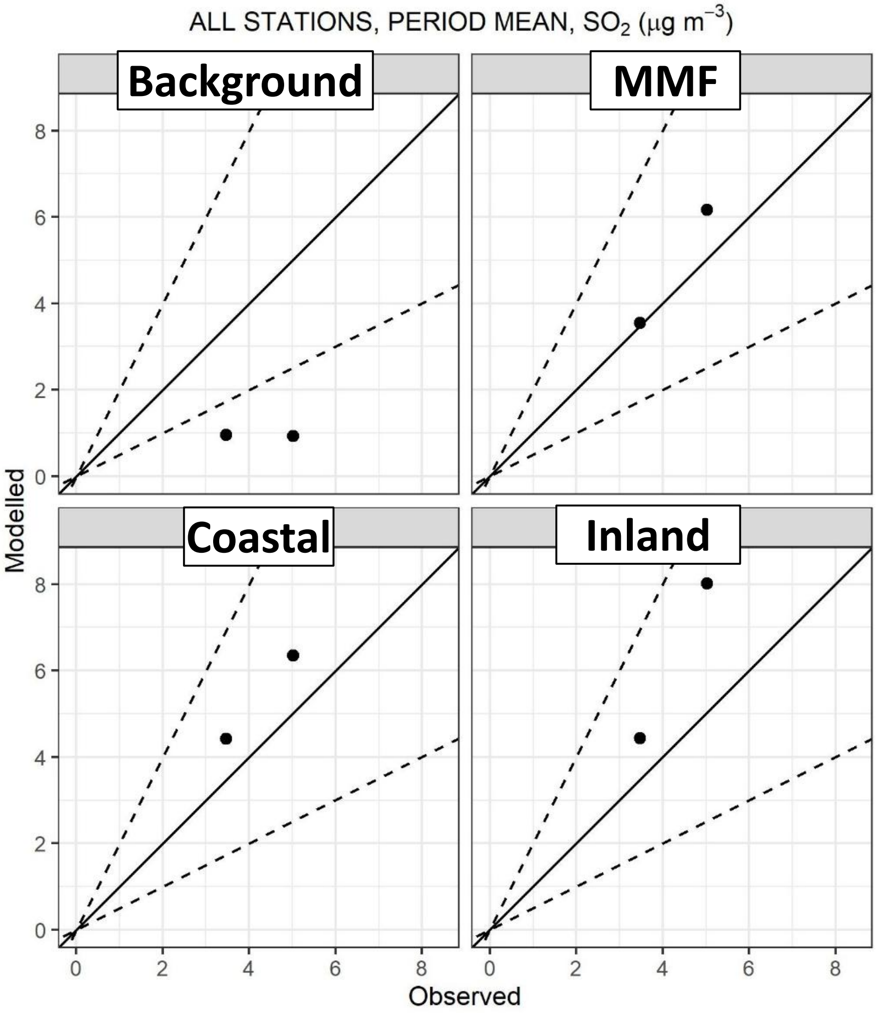
Monitors
Topography (m)
Walleys Quarry
H_2S concentration ($\mu g/m^3$)
<= 1
1 - 5
5 - 10
10 - 20
20 - 50
50 - 100
100 - 150
> 150

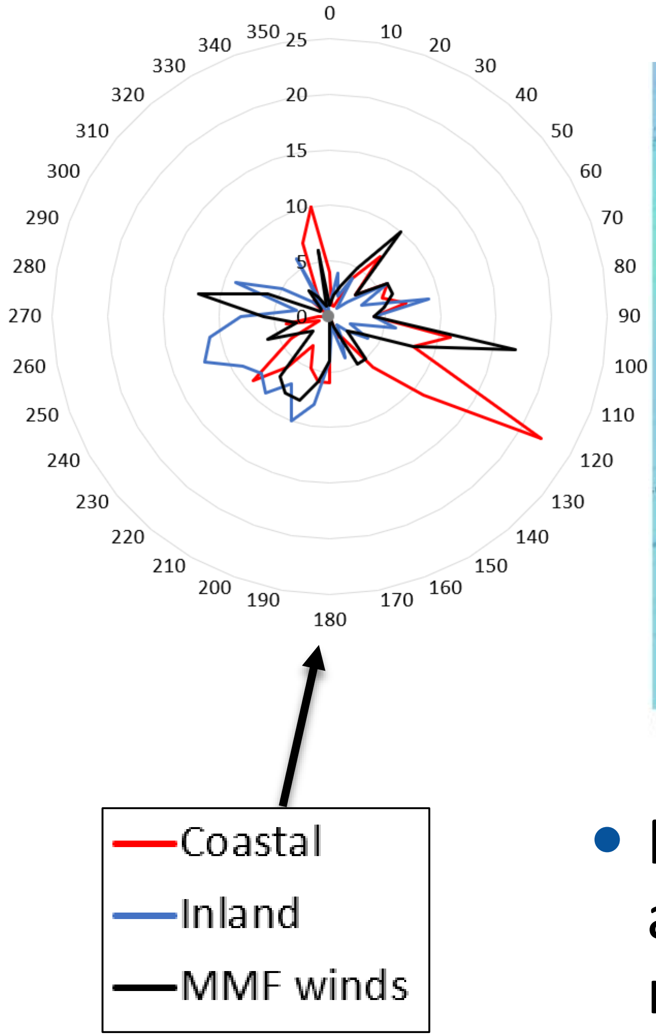
Coastal: Model configuration (ADMS)

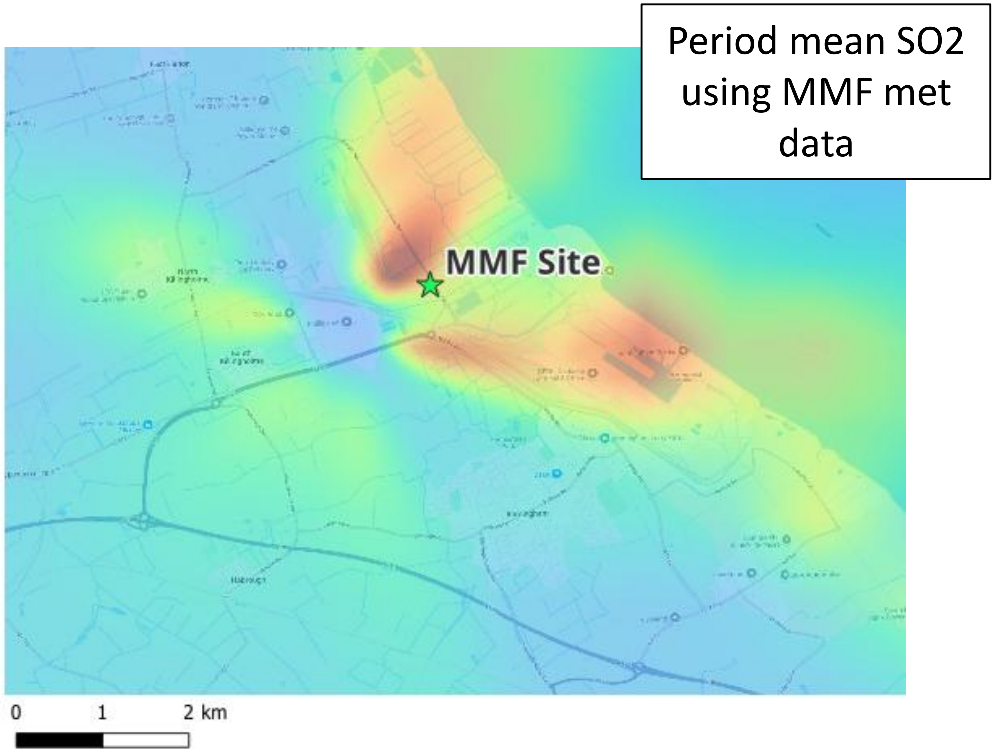
- Data for modelling & evaluation:
  - Meteorological data:
    - Humber (inland)
    - Donna Nook (coastal)
    - MMF (on site)
  - Monitoring data:
    - MMF (on site)
    - Killingholme School
- Metric calculations (April 2021 - June 2023):
  - **Sea breezes**: dominate flow for 92 hours, significant influence for 201 hours
  - **Land breezes:** dominate flow 16 hours, significant influence for 59 hours



Coastal: Results for different meteorological data







- Period average has good agreement for all meteorological data sets
- Onsite data (MMF) shows best performance

Generalisations

- **Metrics:** simple metrics can be used to determine if:
  - Thermal flows are likely
  - Thermal flows will significantly affect dispersion and pollutant concentrations.
- **Katabatic flows:**
  - Dispersion models which include explicit representation of the airflow can be modified in a simplified way to account for the effect of katabatic flows on the overall airflow.
  - This results in improvements in model predictions of pollutant concentrations at downslope locations, when katabatic flows are significant.
- **Sea and land breezes:** Dispersion models can be used with observed or NWP meteorological data representative of the source location

Acknowledgements

- **KLAM_21:** KLAM_21 cold air drainage model was provided by Deutscher Wetterdienst (DWD), the German weather service (available for research)
- **MMF data:** supplied by the Environment Agency

Thank you for listening

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