Thermal transport of air pollution from regulated industries: project summary and overview of key findings

Chief Scientist's Group report

February 2026

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Dr Robert Bradburne
Chief Scientist

Contents

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Executive summary

This report presents the findings of a research project to investigate the role of local thermally driven atmospheric flows, such as sea breezes, slope winds, and urban heat island (UHI) circulations, in the transport and dispersion of air pollutants emitted from regulated industrial sites in England.

Air quality is a critical environmental and public health issue in the UK. While the Environment Agency regulates emissions from major industries, current assessment tools often assume flat terrain and uniform atmospheric conditions. However, real-world conditions frequently involve complex thermal flows that can significantly alter pollutant dispersion, leading to unexpected exposure patterns. These flows are likely to become more significant due to climate change, urbanisation, and evolving land use.

The project aimed to assess the frequency, significance, and implications of local thermal flows on air pollution from regulated sites. It was structured around four work packages, each resulting in a detailed report:

1. **A quick scoping review.**
   A literature review to understand the current state of knowledge regarding local thermal winds, including the range of impacts and assessment methods used.
2. **Stakeholder consultation.**
   We sent out a questionnaire to key stakeholders, including regulators, academics and consultants, to engage with and gauge current understanding and needs around thermal air flows.
3. **Predicting thermal air flows through the use of metrics and air quality modelling.**
   We commissioned contractors to (i) develop metrics and indicators to estimate the likelihood and strength of thermal air flows using meteorological and topographical data and (ii) conduct dispersion modelling on some case study examples.
4. **Exploring the application and implication of outcomes.**
   This part of the project focused on engaging stakeholders to translate scientific findings into practical regulatory tools to gather input to inform future guidance and applications.

Key findings:

- Thermal flows are relevant under UK conditions, particularly sea breezes and katabatic winds. The former in particular can dominate local wind fields for hundreds of hours annually.

- Standard Gaussian plume dispersion models are not capable of explicitly capturing recirculating or fluctuating thermal flows. While Gaussian puff and Eulerian models offer improvements, they require more data and expertise.

- Simple screening tools such as slope and land-use analyses, which are already implemented on Environment Agency Geographical Information Systems (GIS), can help identify sites where thermal flows may be significant.

- Stakeholders support a proportionate, risk-based approach, ranging from basic screening to advanced modelling, depending on site sensitivity and emission characteristics.

- Workshops and engagement activities fostered a shared understanding and generated actionable ideas, including the development of a “traffic light” risk assessment framework.

Local thermal flows can significantly influence how air pollution disperses and therefore warrants consideration in regulatory assessments. This report highlights the value of:

- Conducting routine screening for thermal flow potential using available GIS and meteorological tools.

- Advancing and validating metrics and models to better estimate flow frequency, depth, and impact.

- Expanding the use of case studies to evaluate model performance and refine practical guidance.

- Maintaining active stakeholder engagement to support the effective use of findings and tools.

Together, these actions support more accurate, proportionate, and evidence-based air quality assessments that are better equipped to protect public health and the environment in a changing climate.

List of abbreviations

CAD	Cold Air Drainage
CFD	Computational Fluid Dynamics
GIF	Graphics Interchange Format
GIS	Geographical Information System
LIDAR	Light Detection and Ranging
UHI	Urban Heat Island

Glossary

Term	Definition
Anabatic flow	An upslope wind driven by heating of the surface, causing warm air to rise along a slope.
Dispersion model	A tool used to predict how pollutants spread in the atmosphere. Common types include: • Gaussian plume/puff models. They assume that the concentration of pollutants forms a bell-shaped distribution both horizontally and vertically as the plume moves downwind. These models use wind speed, emission rate, and atmospheric conditions to estimate pollutant concentrations at different locations. They are more simple models that are widely used for regulatory purposes. • Eulerian models are more complex. They divide the air into a fixed 2D or 3D grid and predict how pollutant concentrations changes in each part of the grid over time, based on wind, turbulence, chemical reactions, and other processes. • Computational Fluid Dynamics (CFD) uses physics-based equations to model how air moves around objects, through spaces, or in the atmosphere. These are high-resolution complex models, often used in research or for more detailed assessments.
Katabatic flow	A downslope wind driven by cooling of a surface, causing cold, dense air to drain downhill under gravity. Also called cold air drainage (CAD) flow.
Light Detection and Ranging (LIDAR)	A technique for measuring distances to create high-resolution maps of terrain and surface features, by targeting a surface or object with a laser and measuring the time it takes for the reflected light to return.
Metrics	A simple, quantitative method to indicate the likelihood and strength of an event occurring. In this context, the event is a thermal air flow, and the metrics are made up of various meteorological, surface and flow characteristics (e.g. slope angle, vertical temperature profile, potential temperature difference, synoptic wind speed etc.)

Term	Definition
Numerical weather models	Computer-based mathematical models that predict the weather based on current weather conditions.
Recirculating flows	Air movements that loop back on themselves, often occurring in thermal circulations such as sea breezes or urban heat island flows. These can trap pollutants and lead to unexpected concentration patterns.
Sea breezes	Local winds caused by temperature differences between land and sea. Typically, during the day, cooler air from the sea moves inland, while warmer air rises over land; at night, the flow reverses. Can transport pollutants inland or offshore and create recirculating flows.
Sensitivity analysis	A method to test how changes in input parameters affect model outputs. Helps identify which factors most influence predictions.
Synoptic wind	The regional-scale wind driven by large-scale pressure systems, unaffected by local terrain or thermal effects. Often determines how air pollutants disperse unless local thermal flows are strong.
Thermal wind	A local wind driven by temperature differences at the surface (e.g., between slopes, land and sea, or urban and rural areas). Secondary effects include changes in humidity and chemical reactions that can influence pollutant formation.
Urban Heat Island (UHI)	The phenomenon where urban areas are warmer than surrounding rural areas due to heat retention by buildings and human activities.

1. Introduction

1.1 Background and rationale

Poor air quality has been described as the top environmental risk to human health in the UK. Long-term exposure to air pollution in the UK is estimated to be responsible for up to 43,000 premature deaths per year (Mitsakou *and others*, 2022). The Environment Agency is responsible for regulating major industry and waste management sites in England, ensuring that permitted industrial processes prevent or minimise emissions that have the potential to cause harm to human health and the natural environment (Environment Agency, 2025a). Duties include assessing industrial emissions to the air to determine their impact on pollution levels in the atmosphere, regulation of emissions through a system of permitting, overseeing monitoring for compliance with permit conditions and for reporting on the condition of the atmosphere and investigation of air pollution incidents.

Much of the Environment Agency’s current air pollution assessment work relies on simplifying assumptions, such as terrain being relatively flat, uniform surface temperature and a simple temperature profile in the atmosphere above the area of interest. However, there are real-world situations where these assumptions do not hold, and where there is evidence, both published and anecdotal, that local air pollution movements can consequently differ from those predicted. A recent review of Environment Agency air quality evidence gaps identified a need to better understand and quantify the impacts of local thermal wind effects to assess their scale and significance for our air quality assessment work (Environment Agency, 2023). Several types of local thermal flow were identified in that review as having potential significance for the Environment Agency. These included cold, dense air flowing down slopes under gravity, coastal winds arising from the difference in temperature between land and sea, and winds generated through differences in surface temperature between urban and rural areas.

For example, sea breezes arising from the difference in temperature between land and sea have been seen to carry pollutants inland from coastal industry. Some major industrial activities, many regulated by the Environment Agency, are located on coastal plains which offer flat land, access to ports for import and export, and ready availability of water for use in cooling systems. These include petrochemical sites, steelworks, and electricity generation, and there are plans for clusters of new industrial activities associated with decarbonising our energy supply, including ammonia import, production and storage, and carbon capture and storage.

Elsewhere, pressure to increase housing stocks has meant an increase in the proximity of housing to potential sources of air pollution including dust and odour. Under such circumstances it is crucial to understand local factors which might lead to unacceptable local-scale episodes of poor air quality. For example, during a recent high-profile case in which a landfill site had received inappropriate waste and was consequently emitting excessively high levels of odorous gas, it was suspected that a thermal flow might at times be exacerbating the situation; the odour impact on certain nearby residential areas was reportedly worse under weather conditions associated with such local thermal flows. Examination of local topography and patterns of odour complaints under these conditions suggested it was plausible that cold, dense air was flowing downhill from the area of odour emission to nearby housing. Such effects need to be borne in mind when considering the siting of new houses and assessing of polluting processes.

Urban areas are generally warmer than surrounding rural areas. This "urban heat island" (UHI) difference, on its own or in combination with other flows, can be sufficient to generate air movements that carry pollutants from industrial and waste sites located on the edge of a city into the populous urban centre. Many of the sites we regulate are in such areas; examples include waste handling facilities and arrays of diesel generators that provide emergency power to data centres or that bridge shortfalls in energy entering the national electricity grid.

The significance of thermal flows and their air quality impacts are likely to increase, due to factors such as global warming, increased urbanisation, growing population, and changes in land use that alter the reflective, evaporative, and thermal characteristics of the land surface. By better understanding these thermal effects under present and future scenarios we will better understand the circumstances under which they may confound standard predictions of local pollution levels.

There is therefore a pressing need for research into the frequency, significance and circumstances of air quality impacts arising from thermal flow effects at regulated sites, and if their significance warrants it, into methods by which they can be considered routinely and proportionately during assessments and decision-making.

1.2 Aim and objectives

The aim of this project was to assess the impacts of local-scale thermally driven processes in the near-surface atmosphere on the movement of air pollutants. To do so we identified eight key objectives:

1. Evaluate how thermal flows might contribute to air pollution from regulated sites and identify key methods and data required to simulate their impacts.
2. Assess the consideration of thermal flows in regulatory procedures.
3. Interrogate data (e.g. terrain, meteorological, air pollution) to better understand the number of Environment Agency regulated sites potentially affected by thermal flows and frequency of thermal flows.
4. Develop generic (i) existing scenarios and (ii) predictions of future case scenarios for the thermal flows in each environment at Environment Agency regulated sites.
5. Explore how effectively the air quality impacts of thermal flows can be modelled in case studies.
6. Conduct sensitivity analyses and validate model outputs.
7. Use modelling to predict how air pollution from thermal flows can be mitigated, assessing risks, and evaluating how their impacts may be altered in future scenarios.

8. Collate, write and share the outputs from the research and engage with stakeholders to get feedback on how they might be used.

Research activities to address these objectives were grouped into four work packages, each of which generated a detailed report. The links between these and the eight objectives are shown in Figure 1.

In addition, we produced this overarching report to give an overview of the various work packages and how they fit together, a summary of their key findings, and a synthesis of these to give overall conclusions.

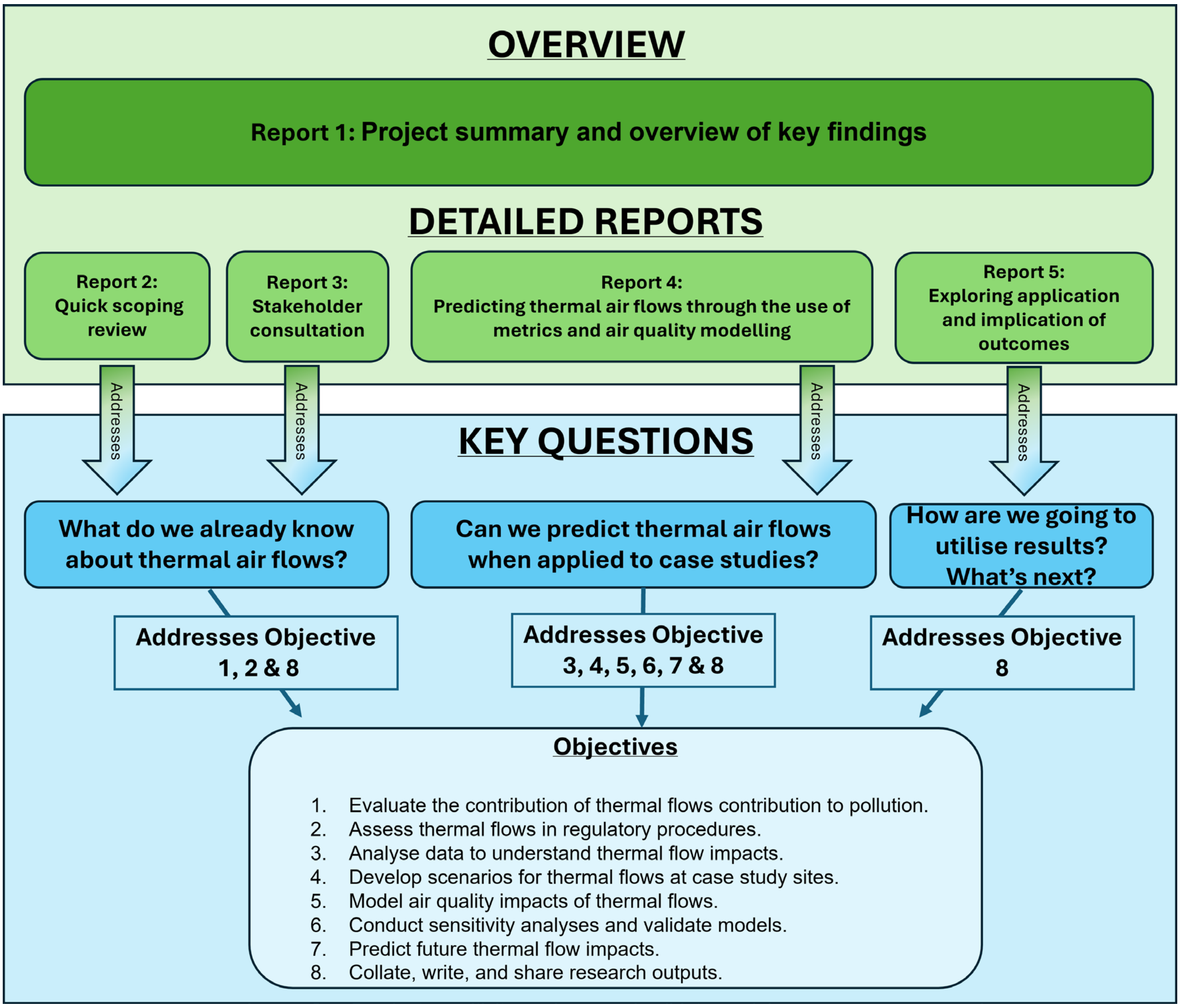

Figure 1. An overview of the different aspects of the Thermal Transport of Air Pollution from Regulated Industries project, how they interlink and the key questions and objectives they address.

2. Technical background

2.1 Small scale, thermally driven atmospheric flows

Flows of air in the atmosphere across all scales are thermally driven. Warm air is less dense than colder air. Consequently, air that is warmer than surrounding air rises while cooler air sinks. The differences in air pressure that result from this mean that air will flow between warmer and cooler areas. Over distances greater than a few kilometres the influence of the Earth's rotation becomes significant; this property of flows on rotating surfaces, termed the Coriolis effect, gives rise to the familiar patterns of air circulation around, rather than directly between, high- and low-pressure areas as seen in synoptic weather forecasts. These processes are involved when interpreting and forecasting weather, down to a resolution of tens of kilometres horizontally and tens to hundreds of metres or more vertically.

The focus of this work is on the influence of heating and cooling of air on a more local scale (of metres to a few kilometres horizontally and metres to tens of metres vertically and driven by differences in temperature of the underlying surface on these scales) to better understand their influence on movement of air pollutants from sources regulated by the Environment Agency.

Temperature differences on this scale can come about for several reasons:

- **Air is heated or cooled by the underlying surface.**
  Surface materials differ in the amount of solar radiation they reflect or absorb, and in thermal capacity (the amount of heat energy that must be absorbed to raise a material's temperature by 1 $^{\circ}$C). For example, water has a high thermal capacity and so temperature variations arising from its heating in sunlight and cooling at night are minimal. The land surface tends to have a lower heat capacity, meaning that temperature fluctuations are greater. Consequently, air temperatures above land can become higher than those above water bodies during the day, resulting in daytime surface level air flows from over a water body onto the shore, which penetrate inland. The reverse can occur at nighttime, creating a land-to-water air flow. In both cases a counterflow of air at a greater height above the surface completes a local circulation of air (Figure 2).

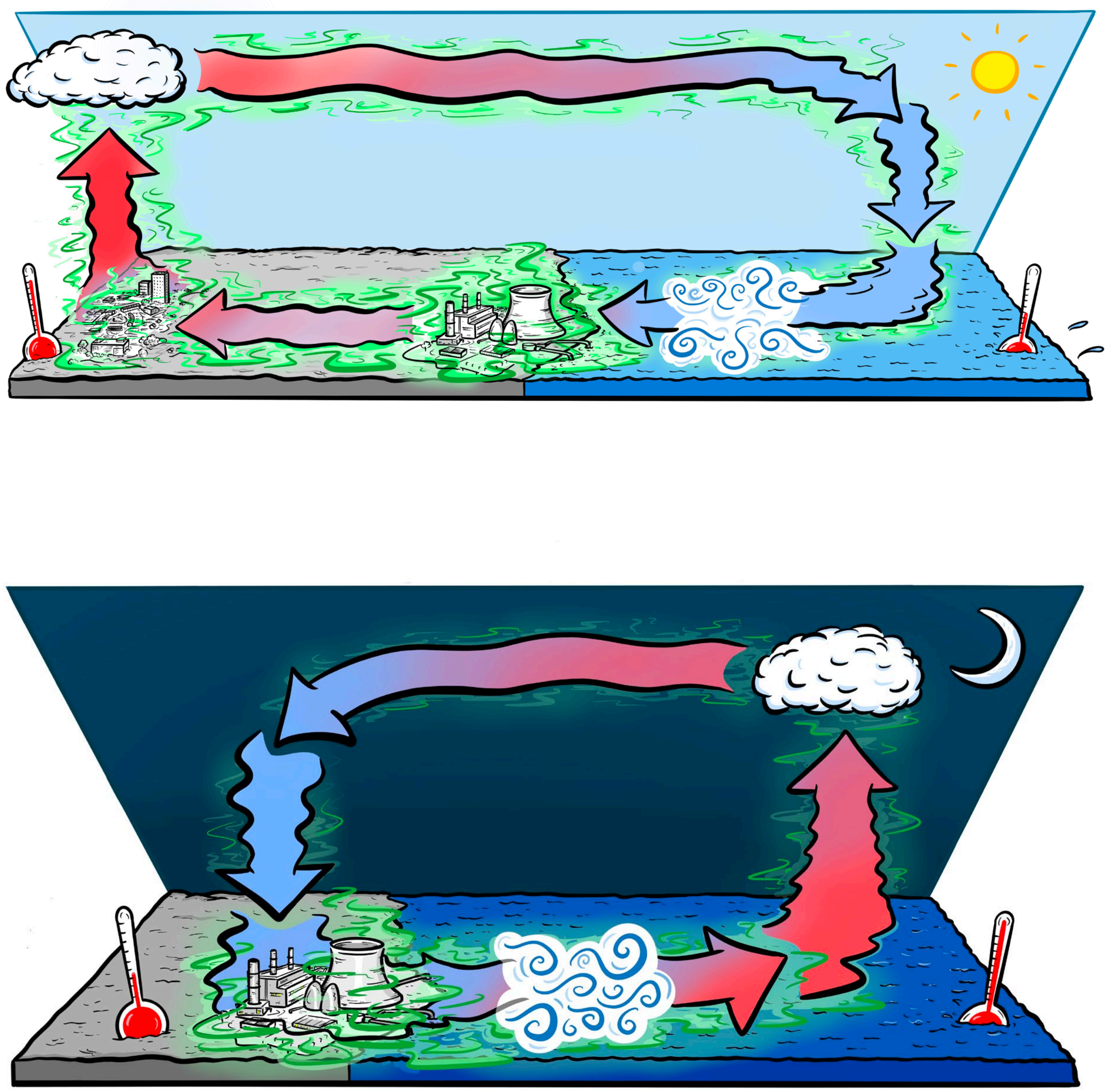

Figure 2. An illustration of a sea breeze thermal air flow during the day (top) and at night (bottom) (visualised by ScribeySense).

- **Differences in land cover can also produce temperature gradients.**
  A particular example is the transition from rural to urban areas. The built surfaces of the latter heat up more rapidly than the agricultural or semi-natural surfaces of the former. This difference is extended by the addition of thermal energy from a concentration of human activities in the urban area, such as driving, cooking and indoor temperature regulation, and by cooling in vegetated rural areas through evaporation and water loss from plants resulting in a net reduction in warming for a given energy input. The resulting mass of relatively warm air rises over the urban centre, creating an area of lower pressure that 'draws in' cooler surface air from surrounding rural areas as illustrated in Figure 3.

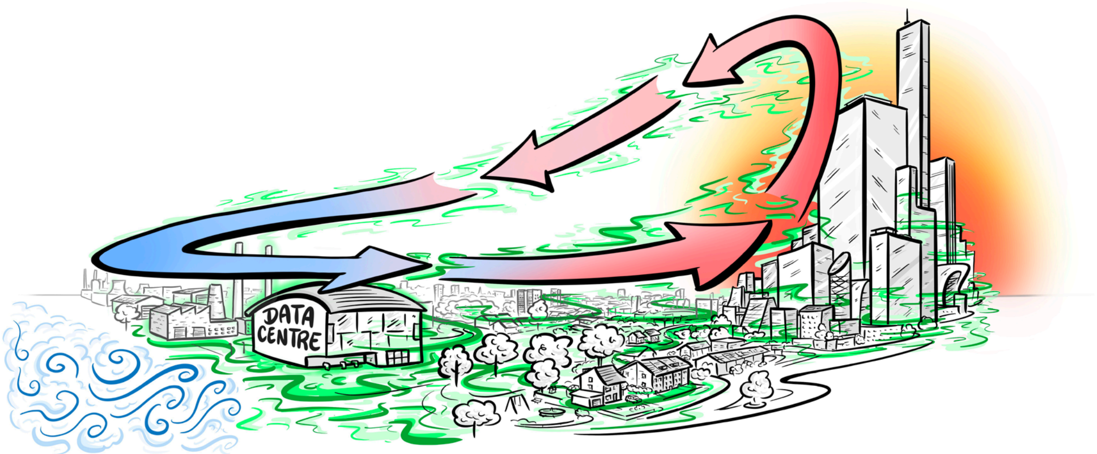

Figure 3. An illustration of an UHI thermal air flow (visualised by ScribeySense).

- **Temperature differences due to different orientations of surfaces relative to the sun**.
  A surface facing directly towards the sun (i.e. at a perpendicular angle) will receive more solar radiation per square metre than a surface facing it obliquely (i.e. at non-perpendicular angle), because in the oblique case the same incoming solar energy is spread over a greater area. Moreover, a slope facing away from the sun will receive less radiation than a flat surface. An example of this would be a valley running east-to-west. The south facing side of the valley is heated more than the north-facing side during the day (in the northern hemisphere), and this can result in a cross-valley circulation of air from the north-facing side to the south-facing side at the surface with a counterflow aloft.

- **Surface temperature affecting the vertical distribution of heat in the overlying air.**
  This can lead to air movement because, in the absence of external heating or cooling, air temperature drops with increasing height, due to its expansion as air pressure drops with height. In dry air this happens at a rate (known as the dry adiabatic lapse rate) of about 1^{o}C per 100 m increase in height. If air near a surface is cooled by contact with that surface (which might, for example, have lost heat by longwave radiation on a clear night) then the rate of temperature change with height differs from the adiabatic lapse rate, with the consequence that any "parcel" of air carried upwards by turbulence will be surrounded by warmer air and so will sink again. In this way a layer of colder, and hence denser, air can form at the surface. If the surface is not flat then the cold, dense surface air will begin to flow down the slope under gravity. Such a flow of cold air down a slope is termed a katabatic flow (sometimes referred to as a cold air drainage (CAD) flow) (Figure 4). The flow will increase in speed until drag forces cancel out acceleration due to gravity. Similarly, air heated at a surface

will be more buoyant than air above it, and this can lead to an upslope flow of air (termed an anabatic flow).

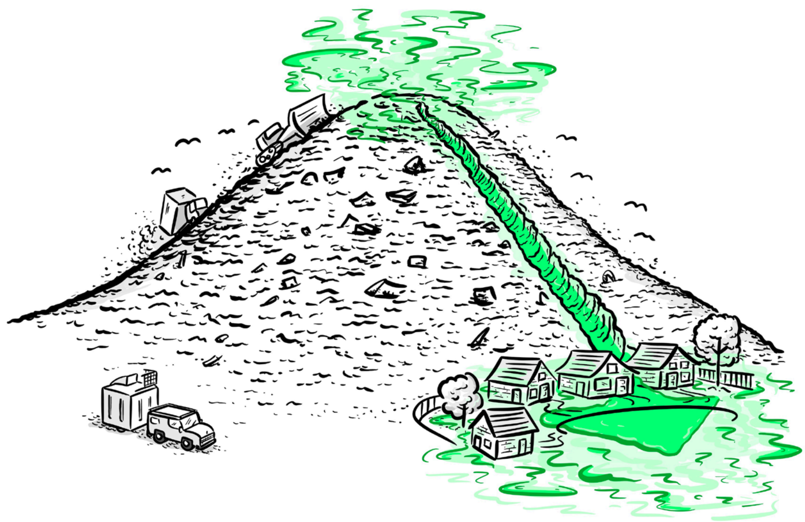

Figure 4. An illustration of cold, dense air moving downslope from an area on a landfill where noxious gases are being generated and escaping into the air. In this example the flow carries the emissions towards housing and away from a mobile monitoring station as shown by van with trailer (visualised by ScribeySense).

Under certain conditions these local thermally driven flows can become strong enough relative to the regional air flow to become significant, moving air in directions other than those that might be inferred from the prevailing wider scale meteorology (as might be taken from national weather forecasting or collected at a regional weather station). Such locally altered flows have implications for understanding local exposure to pollutants, and for the placement of monitors to ensure that they collect representative data.

2.2 Impacts on air quality

As discussed in Section 1.1, the occurrence of local thermally driven air flows has the potential to affect the transport and dispersion of air pollutants resulting in patterns of exposure, spatially and over time, that differ from those that would occur in the absence of thermal winds. More complex secondary effects can arise; for example, incoming humid air in a sea breeze can affect chemical and physical processes in the atmosphere, while transport and mixing of pollutants into areas of background air can enhance production of secondary pollutants (those formed through chemical reactions in the atmosphere rather than emitted directly) such as ozone.

There is therefore a need to consider the potential impact of thermal flows in our assessments. This needs to be carried out in a manner proportionate to the hazard that they may represent. For example, it might prove possible to screen out thermal winds as an important factor when assessing an occasional, low-toxicity emission in relatively flat and unpopulated inland terrain quite simply and inexpensively. By contrast, a site handling toxic material in a coastal location might justify much more detailed assessment to determine potential worst-case scenarios. Where air pollutant monitoring is required (reasons for this include "ground-truthing" predicted pollutant concentrations, enforcing regulatory compliance and interpreting air pollution episodes) consideration of potential local thermal flows should be included when deciding where monitors should be located.

2.3 The research questions

These fell under the following categories:

Scale of the issue: are local thermal winds relevant to UK conditions? If we are to achieve a proportionate approach to inclusion of local thermal flow effects in our air quality assessments then we need to understand their significance under UK conditions, particularly with respect to their frequency and the extent of their impact on pollution dispersion.

Changing perceptions of the issues and response needed: if local thermal winds are found to be of potential significance generally then we need to understand under what specific circumstances. What features of a particular site might indicate that it is at risk from them? In determining this it was important to engage closely with those responsible for designing, implementing and interpreting site assessments operationally to ensure that they are aware of the issue. By working with these stakeholders, we were better able to consider the implications and real-world practicalities arising from these findings and identify ways in which they could be taken into account during operational assessments.

Options for meeting those needs: the complexity of air pollution assessments can vary according to the risks involved. What tools are available to support consideration of local thermal winds at different levels of assessment? These might range from simple guidance and checklists to sophisticated atmospheric flow modelling.

Strengths and limitations: as with any scientific study this work was constrained by the resource and time available for its completion, as well as by the state of knowledge that it is available to build upon. What are the gains from this work, uncertainties and caveats around findings and conclusions drawn from them? What lessons can we learn from the project that might be applied to future work?

Key evidence gaps: what do we still need to learn to achieve the desired outcome of proportionate and practicable consideration of local thermal winds in air quality assessment? What further work is needed to generate the new knowledge needed to address those gaps?

3 Summary of approach and key findings

Section 3.1 summarises the scoping review in Report 2, and Section 3.2 summarises the Stakeholder Consultation in Report 3. Report 4 covers work that was led by our contractors and is summarised in 2 parts for clarity: Part 1 covers metrics and is summarised in Section 3, and Part 2 covers modelling and is summarised in Section 3.4.

3.1 Quick scoping review

3.1.1 Rationale and summary of approach

We carried out a literature review to understand the current state of knowledge regarding local thermal winds.

We used a quick scoping review methodology rather than a full systematic review. This was within the resource and timescale available for the project and was considered proportionate to its needs, in that our objective was to inform our understanding of the range of impacts and assessment methods rather than to provide detailed parameterisation of quantitative operational assessment tools.

Details of the process and findings of the review are reported in Environment Agency (2025b).

3.1.2 Findings

Our search identified 3,084 papers. After applying a clear and auditable screening process, we reviewed 149 and extracted and synthesised information from them.

Collectively these demonstrated that thermal flows such as sea breezes, slope winds, and UHI circulations can play a significant local role in the transport and transformation of air pollutants. Although only one study was conducted in the UK, the other studies reviewed indicate that thermal flows do occur in climatic conditions similar to those found in the UK, particularly in coastal regions. The UK's temperate maritime climate shares many features with regions where thermal flows are well documented, suggesting that such processes are also relevant here.

Sea breezes were the most frequently studied and were commonly observed at locations in northern Europe and under similar climatic situations in North America and Asia. These flows were seen to carry pollutants inland or offshore and could recirculate them, contributing to the formation of secondary air pollutants such as ozone. Katabatic and anabatic slope flows were less frequently studied in isolation but were shown to facilitate upward and downslope pollutant transport. UHIs were shown to induce circulations that draw in pollution from surrounding areas and potentially influence their long-range transport by injecting them upwards into faster moving winds.

In many cases, different types of local thermal flow were found to exist simultaneously and to interact, resulting in complex pollutant behaviour. For example, several studies described cases of sea breezes combining with UHI and valley winds to produce unexpected levels of air pollution inland.

The studies reviewed included modelling as well as monitoring. A variety of assessment methods were employed to simulate thermal flows and their effects. These varied in complexity, spatial resolution, and data requirements, ranging from simple observation of landscape for indicators of potential for thermal flows (such as slopes and water bodies) through to various categories of numerical dispersion model. The widely used regulatory models based on the evolution of a Gaussian plume were considered unsuitable for thermal wind assessment since they are inherently unable to reproduce recirculating flows. Gaussian puff models do allow for recirculating flows, are routinely used, and are not overly demanding computationally. The majority of the studies that involved modelling used the more complex Eulerian models. These were better able to represent the physical realities of flows and dispersion. Moreover, they can integrate the effects of multiple local factors that influence dispersion, including combined thermal effects and impacts of topography. Their performance was sensitive to the quality and resolution of input data, with common challenges including under- or overestimation of air pollutant concentrations, and inadequate representation of boundary layer structure and flow interactions. High temporal and spatial resolution can improve model accuracy, but these enhancements are often computationally expensive and limited by resolution of input data and the inherent variability of the atmospheric system. A key decision in model selection is balancing benefits of various levels of uncertainty with computational costs and availability of data, including the consequences of decisions made under different degrees of uncertainty. No clear intercomparison of model performances and suitability in a real-world situation was found, and the monitoring data available for validation appears to be sparse.

Accurate simulation and understanding of thermal flows depend on sufficiently high-quality meteorological data, such as wind, temperature, humidity, and radiation flux. The data available for the studies reviewed varied but were often sparse or inconsistent. Land use characteristics (e.g., vegetation cover, building height) and topography (e.g., valleys, coastlines) significantly influence flow development. This information was often readily available from open information sources.

3.1.3 Conclusions

Both monitoring and modelling indicated that thermal flows can significantly alter local pollutant dispersion patterns and should be considered in air quality assessments, especially in coastal, valley, and urban environments. Failure to account for these flows can lead to underestimation of worst-case exposure scenarios. Diurnal variability and chemical transformations must also be integrated into assessments to align emissions with actual exposure risks. There is a need for more work considering flows under UK conditions, and on the interactions of combined flows in complex terrain, including monitoring designed to measure the magnitude and frequency of thermal wind effects and for model performance testing.

A few mitigation strategies such as urban greening, cool roofs, and changes in surface materials were found to influence local atmospheric thermal dynamics and pollutant behaviour. However, these interventions may also have unintended consequences and should be evaluated in the context of their interactions with thermal flows. A practical measure to avoid future thermal flow issues would be to include screening for potential effects at the planning or permitting stage, for both emitters and for potential sensitive receptors (such as housing) that may be proposed in the vicinity of an air pollution source. A critical step towards achieving this is raising awareness of thermal flows amongst stakeholders.

A key need identified from the review is for assessment of, and where necessary development of, proportionate screening and forecasting tools that can be used under realistic scenarios and considering what input data might feasibly be available. Intercomparisons of performance of the different model types against standardised test cases, with plausible availability of data would be informative. As in other areas of forecasting and assessment the development of probabilistic modelling approaches would improve prediction, and hence the possibility of accounting for local thermal flow impacts on air quality.

3.2 Stakeholder consultation

3.2.1 Rationale and summary of approach

The issues being explored in this project are of significance to a broad constituency of end-users, including regulators, planners, consultants, modellers, business operators, and local communities. These come with a variety of perspectives and needs, and different levels of air quality expertise. The purpose of this consultation was to establish a baseline of current understanding and needs amongst stakeholders, including the extent to which they are aware of local thermal winds, what, if any, means they use to account for them. The purpose was also for us to learn from stakeholders' "lived experience" of local thermal wind effects. We also sought information on any extant data sets that might be used as case studies during the project.

This information has provided us with a "line of sight" from our scientific analysis through to end-users, helping to ensure its practical relevance. Early stakeholder engagement such as this encourages a sense of co-ownership of the issues which encourages uptake of findings, while understanding the range of experience and expertise is critical for communicating those findings effectively. Full details of the process and findings of the consultation are reported in Environment Agency (2025c).

A comprehensive stakeholder questionnaire was developed and distributed to a broad audience, including regulators, operators, land use planners, air quality consultants, and academic researchers. The questionnaire aimed to gather insights on the awareness of thermal flows, their practical implications, and the tools and data required to assess their impacts. The questionnaire elicited 23 responses. Respondents ranged from permitting officers with field and regulatory experience, to academics with a deep understanding of atmospheric flow modelling.

3.2.2 Findings

Respondents demonstrated various levels of awareness of local thermal flow effects. Many identified key meteorological and ground-level conditions associated with local thermal winds, such as low synoptic wind conditions, stable boundary layers, and differential surface heating, with some awareness of how these factors were influenced by season and time of day. Some were able to share anecdotal accounts of local thermal flow effects. A number described experience of static thermal effects (non-moving accumulation of cold air near the surface. These may occur in isolation, such as when pockets of cold air form in hollows from which they are unable to spread, or be the end point of a katabatic flow where further movement of the flow is physically blocked). Other respondents shared commentary on more rigorously measured or modelled studies.

In response to the call for sources of long-term weather data sets, pollution data sets and potential case studies, several were suggested. Specific examples of thermal wind impact on local populations were provided. Some respondents noted that thermal wind effects are on occasion raised by stakeholders during public consultations, and so are an issue we need to be prepared to respond to authoritatively. There was uncertainty about the number of sites potentially impacted by thermal flows. The Environment Agency's archive of air pollution monitoring data, gathered for purposes such as compliance checking and troubleshooting around regulated sites, was endorsed as a source of case study material, and patterns of complaints under different conditions were also seen as potentially informative. Environment Agency Light Detection and Ranging (LIDAR) data, giving topographical information down to a few centimetres' vertical resolution, are freely available; for rapidly changing topography, such as that of a land fill site, up-to-date information can be obtained through additional deployment of Environment Agency LIDAR resources. No additional sources of land use/land cover information were suggested by stakeholders to supplement those identified in other work packages.

Tools currently used in assessing thermal winds were named and discussed. Gaussian-based models were considered unsuitable except in limited circumstances. Non-steady state "puff" models were considered capable of modelling flows in complex flow situations and are currently available and used by regulators. Eulerian models are routinely used down to resolutions that capture larger local thermal wind features, such as sea breezes, urban circulations and larger topographic effects. Finer scale (sub-kilometre resolutions horizontally, metres vertically) implementations are also well-established and used routinely by some respondents for research purposes and for dispersion modelling during emergencies. However, these require a greater degree of operator skill and computational power, and their accuracy is limited by the resolution of the data available to initiate and verify them. Given these challenges their use is likely to be justified operationally only in "high stake" situations. Respondents emphasised the need for use of tools that match the objectives of the assessment, with appropriate scales and resolutions. They also stressed the need for new monitoring data, further comparison of models with data and with each other, assessment of uncertainty, and measurement of variation below the lowest resolution modelled. Respondents recognised the role that modelling has in identifying appropriate locations for representative monitoring,

The responses revealed a broad range of understanding and an appetite for more information on thermal flows. There was a desire for a proportionate approach to incorporating thermal wind impacts into air quality assessments, with a focus on improving the assessment process and reducing risks. Respondents called for robust, science-based consideration of the evidence and clear guidance on tools and indicators for assessing thermal wind impacts.

3.2.3 Conclusions

Engaging with key stakeholders has provided valuable insights into the current state of knowledge and the tools and capabilities needed by different users to address thermal wind impacts. There was a clear desire to develop and disseminate both clear guidance and fit-for-purpose tools to ensure that thermal wind effects are effectively considered in regulatory practices. The benefits were flagged of developing a clear narrative around local thermal flows to inform stakeholders and the wider public, particularly those who are already affected by such flows, or those who are concerned that they might be in the future.

3.3 Metrics and indicators

3.3.1 Rationale and summary of approach

The objectives of this part of the project were:

i. To explore the conditions under which local thermal flows occur.
ii. To identify readily accessible parameters (properties that can be measured to determine the state of a system, in this case the local environment) and metrics representing them that could be used to determine whether a local thermal flow is likely in a given situation.
iii. If such a flow could occur, to indicate its likely duration, speed and direction of travel.

Having identified metrics appropriate for the different types of thermal flow, value ranges were determined, from the literature and theoretical considerations, that indicate their likely presence or absence, and if present the likely magnitude of the flow. Examples of sites which could experience such flows (coastal, sloping, urban and rural interface) were chosen and annual hourly meteorological data sets obtained for them. From these data, values of the metrics identified could be calculated for each hour and an estimate made of the number of hours during the year when thermal flows were likely.

A comparison was then made between the strength and direction of any predicted thermal flows and those of the synoptic wind (the regional wind, whose speed and direction of which are not influenced by local factors such as topography or small-scale fluctuations in surface temperature) in the same hour. Carrying out such comparisons over a full year of hourly meteorological data gave an indication of the frequency with which local thermal flows may be absent, insignificant, comparable to, or dominant compared to regional winds.

Full details are reported in Environment Agency (2025d).

3.3.2 Findings

A key driver for thermal flows is the difference in temperature (and hence density) of the air above areas of different surface, and so a parameter embodying this was identified for each category of thermal wind. However, the way in which air temperatures change with height above a surface (known as the vertical temperature profile) means that use of a single temperature from, say, a fixed height above a surface, is insufficient.

For slope-mediated flows, the temperature-related parameter chosen was the difference between average potential temperature across the air influenced by local surface temperature and that of the air above this region. (Potential temperature is the temperature a parcel of air from any height above the surface would have if it were moved to sea level (usually assuming a standard pressure of 1000 millibars there) without gaining or losing heat. This makes it possible to compare temperatures at different heights by removing the effect of pressure changes.) Vertical temperature profiles can be estimated in a variety of different ways. The simplest example would be an observer estimating this based on cloud cover and prevailing wind direction and associating these with different atmospheric stability classes. More complex methods involve using meteorological pre-processor tools commonly used in regulatory models.

For flows driven by the difference in surface temperature between adjoining areas, the temperature-related metric used was the difference in potential temperature between air sufficiently high up to be unaffected by local surface temperature, and the averaged potential temperature across the layer influenced by the surface. For example, a lower average potential temperature over a water body than over a land surface results in a density difference that causes air near the surface to flow from water to land.

The synoptic wind strength and direction relative to the local thermal flow are other key parameters. A strong synoptic wind component will dominate dispersion of pollutants, and the greater turbulence generated in faster moving air mixes the air vertically, diminishing the differences in potential temperature with height that are needed to drive local thermal flows.

The gradient of the slope affects the downslope acceleration of cold air under gravity, so that the acceleration is greater where the slope is steeper. The acceleration will be opposed by the frictional drag of the surface on the moving air, which is dependent on the aerodynamic roughness of the surface and increases as air speed increases, eventually reaching a point on the slope where the acceleration and drag are equal and opposite so that there is no net force. Windspeed becomes constant from that point onwards so long as the slope gradient and roughness remain the same, and so long as the temperature difference between the surface and the air aloft remains the same. The gradient of the slope also influences the quantity of direct heating it receives from the sun, a factor also influenced by the orientation of the slope relative to the sun. Slope, orientation and ground cover are therefore important parameters to consider.

Aerodynamic drag will impact on the speed of sea-land and urban-rural thermal flows. For example, as a sea breeze penetrates inland away from the coastal temperature change that drives it, its momentum will be lost due to drag and eventually the thermal flow will cease. The point at which this occurs defines how far inland a sea breeze may penetrate. The complex and variable built environment associated with rural to urban transition means that a simple parameter for aerodynamic roughness is unlikely to be informative, and the three-dimensional impact of buildings on airflow (by, for example, blocking, channelling or diverting flows) may need to be considered.

No parameters were suggested by which the likely height of the thermally driven flow might be easily estimated in a given situation. This indicates that more detailed modelling might be required to determine whether an elevated source of pollution, such as a stack emission, might or might not be within the local thermal flow. The effects of the “return legs” of thermal flow circulations on pollution dispersion were not considered.

A simplified model of the flow physics allowed estimates to be made of the magnitude of local thermal flows that might occur in a number of real situations for which meteorological data were available. By setting some arbitrary but plausible parameter values and thresholds it was possible to compare local thermal winds and synoptic winds hour-by-hour over a full year and so estimate the frequency with which the local thermal flow might feasibly be of significance relative to the synoptic wind. This treatment was applied with respect to anabatic and katabatic flows and sea-land breezes but not for UHI breezes, for which the uncertainties were considered too great and appropriate meteorological data were not available.

This process indicated that sea/land breezes were by far the most significant type of local thermal flow, both in terms of frequency of occurrence (being the dominant wind component for over a hundred hours across the year and influential for several hundred more) and speed (predictions of speeds exceeding 6 ms^{-1} for sea to land flows and up to 3 ms^{-1} for land to sea flows, which were consistent with measured values found in the literature).

Down-slope flows showed the expected dependency on slope, with negligible occurrences at the lowest angle considered (11 hours in a year for a 0.34º slope), again rising to several hundred hours a year of influence for steeper slopes. Speeds were generally less than 1 ms^{-1}. Up-slope flows were far less frequent (a few tens of hours per year) across the cases examined, and with speeds of less than 0.5 ms^{-1}.

3.3.3 Conclusions

Parameters associated with thermal wind, and corresponding metrics to quantify them, included angle of slope, length of slope, vertical temperature profile, Accounting for local thermal wind effects in air quality assessments can be broken down into a series of stages, at any of which they may be "screened out" as negligible or may indicate the need for more detailed assessment stages.

The first stage is to look for features that may allow them to occur in principle – primarily slopes and land-water interfaces. Other drivers of surface temperature difference may also be found to be of significance, such as solar farms adjacent to arable crops, irrigated versus non-irrigated areas and pasture versus forest.

The second stage is to consider whether the locations and heights of pollution sources intersect with possible thermal flows and what the consequences of this might be, especially with respect to nearby receptors.

The third stage is to consider how often thermal flows may be having an influence. Despite relying on simplifications and assumptions the scheme used here to estimate the frequency with which the various flows might be of significance delivered results that varied in line with expectations and broadly with the sparse measured values available in the literature.

The fourth stage involves case-by-case decisions regarding the need for more detailed modelling assessment. This will involve consideration of: (i) possible consequences that might arise from the impact of a local thermal flow on pollution transport and fate, (ii) the likelihood of it arising (based on estimates of frequency of such flows for the given case) and (iii) the likelihood of the thermal flow and pollution release occurring concurrently.

The findings here indicate sea-land breezes and downslope winds as being of the greatest potential significance, while the relative infrequency and slow speeds indicated for upslope flows under UK conditions suggest that these are less likely to be significant. No conclusions could be drawn on the frequency or significance of UHI-induced airflows, primarily because of a lack of flow measurement data for UK situations.

Key uncertainties include lack of information concerning the height above the surface to which the local thermal flow may grow, the distance over which equilibrium speeds are reached for thermal flows, and the likelihood of sea breezes penetrating a given distance inland. It is important to remember that the surface wind arising from a local thermal flow is one "leg" of a circulating flow, with a returning flow occurring aloft and regions of convective lift and subsidence completing the circulation. Not considered here are potential impacts of the return flow; an indication of the typical range of heights and speeds of these flows would be informative. For coastal breezes, consideration is needed of the impact of flow reversal on pollution transport during the diurnal cycle of land warming or cooling while sea temperature remains relatively constant. Analysis of existing meteorological data and collection of new data where this is not yet available would add confidence to the estimates of frequency and other key parameters of local thermal flows indicated by this study. There is a lack of flow monitoring data along transects of rural, suburban, urban, and city-centre situations and between rural and industrialised areas. which is needed to assess potential urban heat island (UHI) flows, and to validate modelling of UHI flows.

3.4 Case study modelling

3.4.1 Rationale and summary of approach

The objective of this work package was to explore the performance of different modelling approaches in reproducing the impacts of local thermal flows on pollution dispersion. Case studies thought likely to exemplify each type of local thermal flow were identified from an archive of around three hundred monitoring campaigns conducted around regulated sites by the Environment Agency's Ambient Air Monitoring Team. These campaigns included local measurements of meteorology and measured concentrations of air pollutants. Chosen cases included two landfill sites (indicative of slope flows) and two coastal locations (indicative of sea-land breezes). Cases indicative of UHI driven flows were sought but no clear UK case studies were identified.

Due to constraints of time and resource, model assessment was mainly restricted to a comparison of the performance of a standard commercial regulatory assessment model. This model comprised a meteorological preprocessor to model the local air flow field from meteorological data inputs, which were measured or else derived from numerical weather models, and a Gaussian dispersal model to predict air pollutant concentration across the model domain. Concentrations were predicted under conditions where local thermal flows were plausible, and under those where they were unlikely. Modifications to the commercial model were made to take into account factors identified in the earlier stages of the project and additional predictions were made using this. A 2D Eulerian model was also evaluated on the two landfill cases, and a simple topographical analysis of drainage lines was carried out at one landfill site.

Details are reported in Environment Agency (2025d).

3.4.2 Findings

One of the two landfill sites examined included terrain with a slope of up to 3.7^{o}. Here the regulatory model showed satisfactory performance under conditions not conducive to katabatic flows. However, under conditions where significant or dominant local thermal flows were predicted to occur (around 15% of the time), the model underpredicted concentrations measured at downslope monitoring sites. The other landfill case study site had shallower slopes, up to 1.5^{o}. Again, katabatic flows led to underestimates of concentrations at downslope monitoring sites. In this case such flows were predicted to occur over only a few hours in the year, and so while peaks may be missed, concentrations averaged over time were better predicted. Adjusting the underlying meteorological preprocessor to include thermal flow parameters improved performance over that of the "off the shelf" version of the model in both cases under katabatic flow conditions, though concentrations were still underestimated for the steeper case while in the shallower case they were overestimated. The 2D Eulerian model, which was developed specifically to model drainage of cold air from elevated areas, predicted elevated pollutant concentrations near the measurement site that showed the strongest katabatic flow influence. However, the model exhibited limited sensitivity to meteorological parameters and so is presumably insensitive to the impact these many have on estimated pollution concentrations.

Topographic analysis of drainage lines was simple to execute, and the lines obtained were consistent with flows indicated by the two models.

The two coastal case studies demonstrated the influence of sea/land breezes on pollution concentrations at monitoring sites, and on wind speed and direction across the model domain. Both cases involved multiple pollution sources and complex coastline geometry, one including an estuary as well as coastline, so that generalisable conclusions are difficult to draw. Unsurprisingly, best results were obtained when using observed meteorological data from close to pollution sources, or data from a numerical weather prediction model of sufficiently high resolution, since such data would incorporate the effects of thermal winds.

3.4.3 Conclusions

Both categories of thermal flow scenario for which case studies could be found showed the influence of local thermal flows on pollution dispersion, and hence the need for them to be considered during modelling for air quality assessment. In the two coastal cases there were indications that coastal breezes can reduce local concentrations of pollution emitted by sources close to (within a few kilometres of) the coast. The katabatic flow cases illustrated how elevated concentrations of pollution might be missed if models do not take such flows into account.

Comparison of the two landfill case studies points to the importance of the frequency of local thermal flow on model performance. Over longer averaging times the influence of infrequent thermal wind events becomes “diluted”, and standard regulatory tools may remain appropriate. However, where infrequent events may nonetheless have substantial impacts, for example recurring episodes of exposure to unpleasant odours, then tools should be used which are capable of explicitly modelling them. Similarly, when local thermal flow effects are likely to be frequent, they should be accounted for since their impact on average results will be more significant.

The regulatory model used here was modified to better account for thermal wind effects (by adjusting the meteorological preprocessor to take account of some of the metrics – see Section 3.3 above) with some improvement in these specific case studies. However considerably more work is required to assess the changes required to make such modifications more generally applicable, including refinement of those metrics through means such as an exploration of their sensitivity to the assumptions used (for example regarding the depth of the thermal flow) and sensitivity to factors such as slope and surface roughness.

The category of model evaluated here cannot represent non-steady state flow fields and recirculating flows, and no comparison with models that could represent them was possible within the resources available to this project. On the other hand, a simple consideration of slope direction was shown to identify possible routes that katabatic flows would be likely to follow, helping to identify potential issues and inform monitor siting. Further model intercomparison is required to assess the most appropriate tool for a given situation.

It should be borne in mind that the Environment Agency's interests in air pollution modelling extend beyond routine assessments for statutory permitting and include other statutory responsibilities such as incident response, assessment of and preparedness for incidents at potentially hazardous sites, and design of regulatory frameworks.

3.5 Report 5: Exploring application and implication of outcomes

3.5.1 Rationale and summary of approach

This part of the project involved engagement between the project team and the stakeholder communities previously identified, to share findings and explore together how they can be translated into practical regulatory tools and guidance where appropriate.

We adopted a co-designed, professionally facilitated approach to ensure that stakeholder engagement was meaningful, inclusive and aligned with the project's scientific goals. A series of planning sessions between the project team and a facilitator shaped the structure and content of two complementary workshop components. The first of these was a virtual session to disseminate and discuss findings with a broad cross-section of the air quality community, from academics to those directly involved with operational delivery. After several weeks to allow the new information to be digested and commented upon a more regulatory focussed, face-to-face workshop was held to explore practical applications of the new knowledge, and future needs.

The workshops made use of a professional facilitator to co-design and take part in delivery of them. We found that drawing upon this specialist expertise enabled us to maximise the information we could collect and record.

We were also supported by a graphic illustrator to enhance accessibility and engagement, and the digital platforms like Padlet and Session Lab were used to coordinate design, planning and capture outputs. The illustrator was able to produce drawings that translated complex ideas into a form that communicated them concisely and clearly.

Details are reported in Environment Agency (2025e).

3.5.2 Findings and conclusions

The virtual workshop was open. It reached a broad audience of 68 live attendees and was recorded for offline engagement. The virtual workshop received positive feedback for its content and structure and was an efficient way to communicate findings in advance of the subsequent in-person workshop, freeing time during that to work collaboratively.

The in-person event was by invitation to ensure a good mix of relevant participants. It enabled deeper, collaborative exploration of risk assessment, application and development of findings, discussion of future unknowns and research directions. Structured sessions, including scenario-based discussions and prioritisation exercises, helped identify actionable insights and a shared understanding of how thermal air flows can be better integrated into environmental assessment. Key conclusions included the need for improved modelling tools, improved access to relevant data, and clear practical guidance for use in operational settings. Participants supported ranging from simple indicators to sophisticated modelling, to be used as proportionate to a given situation.

Participants agreed that consideration of thermal wind effects should be included routinely in assessments. They endorsed the "hierarchy of tools" approach summarised in Section 3.3.3 above, and proposed several actionable ideas at different levels within this, ranging from the development of a "traffic light" risk assessment scheme and integration of Geographical Information Systems (GIS) to overlay thermal flow models with complaints data, to more detailed modelling where risk justified it. There was a strong emphasis on bridging the gap between science and regulation, fostering cross-disciplinary communication, and proactively addressing the emerging air quality challenges that are being driven by technological, environmental, and societal shifts.

The workshops concluded with a clear call for more robust assessment frameworks, policy and business support to apply them (with due impact assessment), and collaborative approaches to ensure thermal flow considerations are embedded in future air quality management strategies.

3.5.3 Conclusions

From feedback at the time and subsequently we have evidence to show that the workshops have encouraged stakeholders to consider thermal flow evidence and insights when assessing regulated sites. Open discussion and structured exercises enabled us to link our research findings to the contexts in which they may be used, and to consider them from the perspective of different potential end users.

The success of these workshops underscored the value of collaborative, multidisciplinary engagement in translating research into practice. Embracing similar approaches across government agencies and the wider scientific community could foster innovation, inclusivity, and the development of impactful partnerships, leading to more effective regulation that protects public and ecosystem health and promotes environmental recovery.

4 Synthesis and discussion

We consider here how the work carried out in the various components of this project may be used to address the five overarching research questions (Section 2.3).

4.1 Scale of the issue

From the scoping literature review local thermal flows can have a profound influence on air quality. They can result in increased or decreased levels of pollutants and changes in their patterns of dispersion, with implications for exposure and its consequences. They can, for example, lead to channelling of pollutants towards or away from sensitive receptors, influence the location, magnitude and extent of maxima in pollution concentration, and impact on how representative any monitoring data truly are of local air pollution levels. Diurnal variation in local thermal flows can lead to different patterns of dispersion across the day. For example, pollutants have been observed being carried out to sea and later carried back to shore, as described in several reviewed papers, and recounted from first-hand experience by an Environment Agency officer in the project's stakeholder group.

As well as their impact on the speed and direction of surface winds the 3-dimensional structure of local thermal flows is of significance. Their depth relative to the height at which pollutants are being released affects whether pollutants are incorporated within or remain above the surface flow. Cold air flows not only transport pollutants released within them, but the suppression of turbulent exchange at the top of the surface layer effectively traps the pollution, so that higher near-surface concentrations can be maintained over longer distances. For the same reason, air pollutants released above a cold air flow will be held aloft until the cold layer breaks down, when they may result in sudden surface fumigation events. If sufficiently elevated, releases of pollutants near coastlines can become entrained in the return flow of a thermally driven circulation and subsequently give rise to unexpected fumigation events as they are transported downwards within the downflowing (subsiding) region of the circulation. Within any local thermal circulation pollutants can accumulate, and the literature contained reports of cases where this was thought to explain episodes of high pollution.

Few papers included in the scoping review, or cited in the metrics study, involved UK measurements, raising the question of whether they are of relevance here. While some papers discussed extreme environments, such as deserts or glaciers, others involved temperate maritime climates more similar to the UK, including studies in Japan, Northern France and the New England region of the USA. These provided evidence indicating the likely occurrence of thermal flows in the UK, and a number showed how flows of the scale produced under such conditions could impact on air quality. The small number of UK-focused papers did also confirm their occurrence here.

Anecdotal accounts collected during stakeholder engagement activities also indicated that the effects of thermal flow were at times significant. Regulatory officers responsible for specific sites gave accounts of patterns of odour complaints associated with wastewater treatment and landfill sites that could be accounted for if cold air flows were considered. Another described observing the passage to sea and then subsequent return to shore of smoke from a fire (the Environment Agency has a responsibility for assessing the transport of emissions during major incidents, such as large fires and accidental releases, that impact on air quality).

The exploration of metrics also indicated that local thermal flows are plausible, and indeed probable, under UK conditions. It demonstrated that where, and how often, they occur was sensitive to local conditions, and that local thermal flows can affect how air pollution moves but only become significant if they grow to a strength similar to that of prevailing regional winds. Again, the frequency with which this occurred was found to vary according to local factors, ranging from occasional to hundreds of hours each year.

An examination of the performance of standard regulatory tools at several case study sites showed that they performed well when compared with monitoring data collected under conditions not conducive to local thermal flows, but that their performance deteriorated when these flows were most likely to be occurring. For time-averaged data the performance of the regulatory tool lessened as local thermal flows occurred over a greater proportion of the averaging time. Local thermal flows are therefore a potential source of error and should be considered in air quality assessments.

The UK case studies in this project could only assess the significance of the surface wind components of thermal flow circulations, so that the significance of the upper wind components of circulations remains unresolved.

4.2 Changing perceptions of the issues and response needed

Research at the Environment Agency is ultimately intended to generate new knowledge that will improve our ability to carry out our duties. Stakeholder engagement throughout the project played a valuable role in ensuring that we understood the practical challenges and experience of those responsible for fulfilling those duties and how local thermal flows might be impacting on them in practice. It also helped us to understand the baseline level of knowledge in the organisation and explore which ways of communication worked best to share new knowledge. We were able to work collaboratively to determine how best this new knowledge might be applied. Expanding the stakeholder group to other UK organisations with similar or overlapping roles to those of the Environment Agency facilitated additional insights and helped add value to our findings by disseminating them further.

Including academic and other meteorological specialists in the dialogue throughout enabled us to add their contributions to the pool of new knowledge, and to receive their support in resolving technical and scientific questions. Many were experienced users of the atmospheric models that were used in many studies found in the scoping review, which models were more sophisticated than current regulatory tools. These users were able to confirm the capabilities of sophisticated models and what their use entails, showing that while powerful and flexible they are also data-hungry and more complex to operate. Both the literature and current users provided insights as to where and how, if at all, sophisticated models might be used to support Environment Agency needs, either directly or through the insights they might provide into pollution movements under different scenarios.

By the final stages of the project, stakeholder feedback indicated a "levelling up" in understanding of local thermal flows and their potential impacts, from the diverse starting point indicated by responses to our initial questionnaire. We have built up a selection of communication resources, ranging from technical and scientific reports to slide packs, graphics, animations and Graphics Interchange Format (GIFs), and used these in a variety of ways. At the final stakeholder workshop participants appeared to share a common understanding of the nature and relevance of local thermal winds and engaged enthusiastically and collaboratively in developing ideas for ways in which they might be better able to include consideration of local thermal flows in their work.

Throughout the project stakeholders identified and expressed several needs. A clear explanation of the issue and its potential consequences was deemed important; this should stem from a firm evidence base, with a convincing narrative as to why consideration of local thermal flows is important and what we are doing to account for it proportionately. There was agreement on the need for a range of ways to consider local thermal flows for specific sites and scenarios, and that these should be proportionate to the level of risk involved, with the lowest risk situations being screened out from further consideration and a progression of methods appropriate to increasing levels of risk.

4.3 Options for meeting those needs

Through a detailed review of the evidence in the scientific literature and by testing under conditions relevant for the UK we have provided the evidence base asked for. By communicating this in various forms to a range of audiences we hope that we have provided tools that stakeholders can use to explain the issues persuasively to others.

We have identified a hierarchy of questions and tools to use while assessing if and how local thermal flows might impact significantly on the movement of air pollutants. Some of these can be used immediately while others require further development and validation.

4.3.1 Landscape features

An obvious first step is to look for features in the landscape under assessment that are prerequisites for local thermal flows, including slopes and changes in surface characteristics that might indicate differences in properties that affect rates of heating and cooling.

Slopes may be obvious to the eye, or clear on Ordnance Survey mapping, though they can also be subtle. The presence of a river also implies a slope. GIS map layers highlighting topography (including orientation relative to the sun and mapping of slope gradient) are readily available to the Environment Agency and other regulators, including LIDAR coverage giving high vertical resolution.

Changes in surface characteristics may also be seen during site visits or in standard mapping. Coastlines are obvious and are likely to have an influence that can persist several tens of kilometres inland, while the literature shows that smaller water bodies such as lakes and rivers can also affect local air movement. Other contrasting surfaces might include farmland, and expanses of asphalt or concrete. It should be borne in mind that such contrasts can involve changes in surface roughness, which themselves can influence air movements near the surface, and give rise to recirculating flows; sufficiently large three-dimensional roughness elements, such as buildings, can interfere substantially with local thermal flows.

4.3.2 Sensitive receptors

If the potential for local thermal flows is identified, the next question is whether they matter. Could they intersect with locations that might be adversely affected by any consequent increment in pollution exposure, perhaps because of the presence of sensitive ecosystems and/or people? Might they account for intermittent episodes of exposure (for example, resulting in a pattern of odour complaints)? Should they be considered when selecting locations for, or interpreting data from, monitoring? Such considerations may be applied to existing situations or when considering the siting of new sources or receptors of air pollutants. Consideration may be aided by GIS tools. For example, Environment Agency GIS resources include a tool that highlights “fall lines” – the lines down which water would flow preferentially; cold dense air might be expected to follow these lines. When applied to a case raised at the final stakeholder workshop the GIS tool highlighted the link between a wastewater treatment plant and housing that had experienced intermittent odour exposures. (Note that these tools can also identify low points in a landscape where cold air may accumulate or “pool”).

4.3.3 Meteorological context

Simple indicators of conditions conducive to thermal flows on specific occasions include extent of cloud cover and synoptic windspeed, and occurrences of such indicators can be compared with, for example, those of odour episodes without the need for modelling.

If the need for more detailed assessment is indicated, then a useful step in selecting appropriate methods is an estimate of how often conditions conducive to local thermal flow formation are likely to occur. An approach to this was proposed and explored in the metrics section of this project. The possibility of even a single episode may be important in hazardous or disruptive situations, such as potential accidental release of an acutely harmful or noxious substance. Examination of case studies showed that the performance of the modelling approach used in current regulatory tools decreases under local thermal flow conditions. On the other hand, where assessment using these models was based on longer-term averaged exposure the impact of local thermal flows on model performance depended on the proportion of the averaging time that the local thermal flow was predicted to be significant (see sections 3.3 and 3.4). The case study work provided an opportunity to explore whether modifications to account for local thermal wind effects could be made in the process for converting meteorological inputs into the wind and turbulence representations driving the Gaussian plume dispersion component of these models. One approach was tested (detailed in the full case study report); this did improve performance but with varying degrees of success. Use of local meteorological data, reflecting conditions at source, and at potential receptors, was found to improve performance in the sea/land breeze case studies. Data from Numerical Weather Prediction models can also be used; the resolution of data readily available is such that it can represent larger local thermal flows such as strong sea breezes, and finer data can also be obtained. This type of Gaussian-based dispersion model cannot account for fluctuating or recirculating flows, so it was not possible to assess the impact of these in our case studies or more generally under UK conditions.

4.3.4 Model options

Gaussian puff models, a related class of dispersion model also routinely available to regulators, were proposed to better account for the movements of pollutants in variable and recirculating flows. However, these are still reliant on an underlying air flow representation that can model such features. They were not tested during this project.

The two-dimensional Eulerian model that was tested on the landfill case studies is a research tool and not widely available. It did indicate the path that cold air might follow but was found to be insensitive to meteorological parameters (see Environment Agency (2025d)), perhaps reflecting the compromises in representation of physical processes needed in such a model, as commented upon in the scoping review. It is not clear that such a model adds anything beyond what can be concluded from current Environment Agency GIS tools.

Most literature reviewed, and the meteorological specialists in the stakeholder group, use three-dimensional Eulerian models designed for the purpose (see Environment Agency (2025b)) to generate flow fields. These models are well-validated, and sources of input data, such as larger scale Numerical Weather Prediction data, surface topography models, surface temperature and land use data are readily available. Surface layer sub-models can be incorporated to better represent UHI effects. Pollution movements can be modelled by tracking the movement of “packets” of pollutant through the flow field, with multiple repeats of this building up a probability distribution of pollution concentration that may be set up to include the effects of atmospheric chemistry over time. Resolution can be varied, and different scales “nested” so that finer scales can be used over points of particular interest or concern. They can also represent multiple and interacting local thermal flows, such as combined coastal and UHI-induced flows, as well as other influences such as direct effects of topography on flows. They are widely used for modelling pollutant movement during major incidents, including by the UK Met Office on behalf of the Environment Agency. They have also been used to pre-prepare representations of complex flow fields for an area under different meteorological scenarios, which can then be used subsequently to determine pollution dispersion in the conditions prevailing during pollution releases.

These capabilities must be offset against the greater skill levels required to operate them, the time they take to set up and their computational intensity and run time, particularly at fine resolutions. Again, we were unable to apply them to our case studies due to resource constraints and so are currently unable to comment on the benefits they might offer us to offset any increase in effort and/or resource required to deploy them.

The least constrained Eulerian models, general Computational Fluid Dynamics (CFD) models, are readily available and can be used to model extremely complex flows. Their resolution can be varied across the model domain, allowing the highest resolution in areas of greatest interest, for example where rates of change in the flow are likely to be the greatest. These models are deceptively easy to configure and operate, but this belies the level of expert knowledge required to do so in order to deliver meaningful results. Critical decisions include choice of boundary conditions (for atmospheric studies, determining the properties of the flows entering the model domain, such as profiles of speed and temperature) and choice of appropriate scheme for the type of flow involved to represent turbulence at scales smaller than the model's explicit resolution. These models are successfully used in complex three dimensional situations, such as built environments, and the Environment Agency has used them in such settings (for example, to explore how representative monitoring data taken such locations is likely to be) but other than in sub-models for UHI-driven flow modelling it is harder to envision their use in local thermal flow modelling when more bespoke and well-tested and validated Eulerian tools are available.

4.4 Strengths and limitations

Work carried out under this project has provided a systematic consideration of local thermal wind effects and their relevance to air quality assessments. It has examined and checked our understanding of the fundamental processes involved, for real-world manifestations of these processes and for their impacts on air quality in a range of situations.

The literature review was conducted according to scoping criteria rather than those for a full systematic review, meaning that it cannot be taken as a definitive, quality-assessed summary of all knowledge in this field. However, it was proportionate to the aims, and resources, of this project, resulting in a broad overview of knowledge from which defensible conclusions about the impacts of thermal winds on air quality and the availability, strengths and limitations of means to account for them.

Data and analyses specific to the UK were sparse. The project addressed this by making use of an extensive archive of ambient air quality measurements taken for operational purposes around sites regulated by the Environment Agency. As well as being representative of cases relevant to the Environment Agency, these studies were carried out under well-defined conditions and followed clear protocols for measurement and reporting. A limitation is that they were not designed with detection of local thermal flows and their impacts in mind. Another limitation was the type of cases available to examine. For example, the cases identified as useful for exploring potential for flows of cold air were all landfill sites. These are of great significance to the Environment Agency, and it has previously been hypothesised that local cold air flows may have contributed to some odour complaints – a hypothesis that this project does not rule out. However, stakeholders described other situations where channelling of odour-bearing cold air flows by topological features was thought to contribute to complaints. A wider range of case studies would have helped give a broader perspective on when such flows might be significant. No clear-cut studies for local impacts from differential heating on land were identified in the data archive, so it has not been possible to test the circumstances under which thermal flows of this type may be significant. Similarly, no clear case studies for upslope flow effects were identified to test their relevance under UK conditions and the inferences around their likely frequency derived during the metrics analysis.

The modelling and metrics work did not provide parameters that might help determine the height of local thermal flows, either in absolute terms or relative to the boundary layer thickness (the height beyond which effects of the surface on local flow become less significant, and which acts as a "cap" restricting further upward movement of pollutants). This is of significance since it determines which pollution sources are within or above the local thermal flow. Moreover, low boundary layer heights are associated with the same meteorological conditions that promote local thermal flows; elevated pollution levels under these conditions may therefore be a consequence this "lower cap" as well as thermal flows. Some distinction may be seen in the spatial variation of monitored concentrations, though monitoring location density is generally low.

The project did not much consider "second order" effects which might influence a local thermal flow's behaviour and impacts. For example, for cold air flows it must be borne in mind that all of the local surface, not just the sloping part, will be subjected to similar cooling, so that a local cold air flow will encounter a layer of cold air on the flat area it "drains" onto with implications for subsequent mixing and dispersion. The displacement of cold air from the top of a slope can draw down warmer air from above, breaking down the flow, while the tendency of cold air layers to level out ('pool') under gravity means that elevated areas might protrude above the local boundary level or flow level.

While the literature and stakeholder accounts indicate that the full local thermal wind circulation (rather than just the surface winds) can be significant for pollution behaviour under UK conditions, it was not possible explore this further within the timescale and resources of this project. Data were not available within the data archive searched, and the category of model used for the case study analyses was unable to model such recirculating flows. Through the stakeholder engagement process we were able to identify and engage with groups using models that could represent these flows, putting us in a position to explore them in future work.

The literature demonstrated that local thermal flows could interact to produce flows involving otherwise unexpected air movements. Exploration of the significance of such effects in the UK were beyond the resources of this project to study. Similarly, while the literature indicated the importance of topography on the behaviour of local thermal flow movement, the study of metrics and parameters in this project was restricted to simplified cases involving constant slopes and straight coastlines. One of the sea-land breeze case studies involved a location with a complex coastal geometry but lack of data and of access to an appropriate modelling tool meant that the impacts of this could not be determined.

The project was able to identify a range of techniques to use during assessments and data interpretation thermal wind impacts, and these can be put into a hierarchy in terms of their potential capabilities. A limitation of the project was that we were unable to carry out any systematic comparison of model performance under different scenarios, and in particular an assessment of incremental effort involved versus benefits delivered.

Overall, despite its limitations this project has at the very least provided an increased awareness of local thermal flows, and their potential for significant impacts on air pollution movements under UK conditions, across a wide stakeholder community. By working with that community, we have been able to provide some simple questions that they can begin immediately to ask for every site under their consideration, helping them to screen sites in or out for more detailed consideration. While we have not been able (nor set out) to give definitive guidance on how to carry out that further consideration we have raised awareness of what standard regulatory tools can and cannot do and have provided a set of additional tools that can be further explored for what additional value they might add under different scenarios.

4.5 Main evidence gaps

Height and circulation of flows: There is a requirement for metrics and parameters that will give an indication of the local thermal flow's depth, including its change over distance and time, in order that the concentration of any pollutants released into it can, where necessary, be estimated. The impact of the full flow circulation is of potential importance according to the literature and anecdotal accounts from stakeholders; a systematic analysis is required to assess if, when, where, and in what way are such flows of significance in the UK. Modelling tools are available to support such an analysis, and engagement with academic and meteorological specialists may be a means by which to access expertise, as well as resources such as previously completed modelling studies and measured meteorological data.

Sensitivity analysis: the current metrics study was restricted to idealised conditions and was able to yield little information on sensitivity to variations in those conditions, nor to assumptions such as temperature profile and equilibrium between accelerating and decelerating forces. Such sensitivity analyses are required to inform choices such as what degree of slope is significant in a given CAD situation.

Case studies: Four case studies were possible within the constraints of the project. While they were informative, confirming the probable involvement of local thermal flows on pollution movements, additional case studies are required to test predictions for different situations and to better understand sensitivities to specific circumstances. Case studies needed include a longer slope or valley, coastal sites with less complex geometry and richer monitoring data, and simple cases of flows arising from adjacent surfaces of different temperature. The case studies in this study used available monitoring data that was not collected with thermal flow processes in mind; future case studies should use monitors that are located and instrumented with thermal flow processes and model validation in mind.

Hierarchy of assessment: It was not possible within the project to carry out a comparison of performance and needs of the different models identified in comparison with the improvement in information that they deliver, and this gap remains. A potential approach to addressing it might be to identify a set of test cases of increasing complexity and with increasing hazard, and to test the performance of the different levels of the assessment hierarchy against them. For each case, one could determine the level of complexity at which needs are met, or indeed whether lack of data means that more complex tools are limited in any performance increment they can offer.

Complexity: The literature review demonstrated the importance of interactions between local thermal flows, but the project was able to consider only isolated flows. It is not clear as to how significant these interactions might be under UK conditions. Nor was consideration given to topographical factors other than as a slope down which dense air can flow under gravity. Consideration needs to be given to other topographical interactions, notably the effect of constraining a down-slope flow in a channel, such as a gulley or valley. The literature indicated the role that coastline geometry could play in determining flow direction, for example pollutants carried to sea could be returned some distance further along the coast from where they were emitted. Consideration of these complexities and their relevance remains a knowledge gap.

Stationary thermal effects: A number of accounts included descriptions of “cold air pooling” events, where low points in a landscape became pockets of cold, dense air. While not strictly a thermal flow effect in themselves, such static thermal events are linked to them in that they can be fed by cold air and so accumulate pollutants, while in other circumstances they can protect an area from contamination in the air above until breakdown of the cold layer results in a downward pollution “fumigation” event. The impact of static cold air layers on downslope cold air flows has been mentioned as potentially impacting on dispersion of air pollutants. Several studies in the scoping review concerning UHIs described how surface heating and cooling respectively raised and lowered the height of the air volume in which pollutants were confined, in effect diluting or concentrating them irrespective of any advection. Such stationary thermal effects might be regarded as one end of a continuum of local thermal flow effects and so might usefully be considered in future work.

5. Conclusions

Local thermal flows can influence movements of air pollution under certain circumstances in the UK, and they should be considered during any air quality assessment process.

Sea-land breezes are the most commonly occurring, followed by downslope flows. At present we have insufficient information to assess the frequency and significance of up-slope flows and flows arising from differences in surface temperature in inland situations like urban-rural heat islands.

Simple tools are already available within the Environment Agency to support initial appraisal of whether thermal flows are a possibility and whether they may intersect with pollution sources and sensitive receiving environments (people or habitats), including GIS layers representing mapping, topography, drainage lines, pollution sources, sensitive habitats and population distribution.

Estimates of a local thermal wind’s probable frequency of occurrence can be made relatively simply; taken together with the potential for harm arising from such flows over different averaging times these can be of value in identifying where outputs of current regulatory models may become less dependable and where more detailed quantitative assessments are required.

Should more detailed analyses be indicated then more sophisticated tools are also available. However, further work is required to understand their strengths and limitations under different situations, their requirements, and hence to determine the balance between incremental benefits and their increased operational and resource requirements.

Tracking the outcomes of active stakeholder engagement shows the study has improved understanding of local thermal flows, particularly in the context of Environment Agency duties and responsibilities. Those responsible for air quality assessments are already more aware of the need to consider the possibility of these flows, of the means available to help them do so, and of the impact they may have on air quality impact assessments.

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