Thermal transport of air pollution from regulated industries: stakeholder consultation

Chief Scientist's Group report

February 2026

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Published by:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH

www.gov.uk/environment-agency

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Keywords:
Air quality, thermal flows, stakeholder consultation, questionnaire

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Project number:
SC240014/R3

Citation:
Environment Agency (2026). Thermal transport of air pollution from regulated industries: stakeholder consultation. Environment Agency, Bristol.

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Dr Robert Bradburne
Chief Scientist

Contents

List of abbreviations

AD	Anaerobic Digestion
ADMLC	Atmospheric Dispersion Modelling Liaison Committee
ADMS	Atmospheric Dispersion Modelling System
AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model
AQUM	Air Quality Unified Model
AURN	Automatic Urban and Rural Network
CALPUFF	California Puff Model
CEDA	Centre for Environmental Data Analysis
COMAH	Control of Major Accident Hazards Regulation
Defra	The department for environment, food and rural affairs
DSTL	The department for environment, food and rural affairs
ECMWF	European Centre for Medium-Range Weather Forecasts
EfW	Energy from Waste
EPR	Environmental Permitting Regulation
LIDAR	Light Detection and Ranging
NAE	North Atlantic European
NAME	Numerical Atmospheric-dispersion Modelling Environment
NIEA	Northern Ireland Environment Agency
NRW	Natural Resources Wales

NWP	Numerical Weather Prediction
SEPA	Scottish Environment Protection Agency
SHPI	Sites of high public interest
TAPRI	Thermal Transport of Air Pollution from Regulated Industries
TOMPS	Toxic Organic Micro Pollutants
UKCEH	UK Centre for Ecology and Hydrology
US EPA	US Environmental Protection Agency
WOW	Weather Observations Website
WRF	Weather Research and Forecasting model

Acknowledgements

We thank the project steering group who imparted their valuable expertise, advice and constructive comments throughout the lifetime of this project, as well as commenting on various iterations of this report.

We also thank our stakeholders we consulted who completed the questionnaire and answered further questions and imparted their knowledge.

Executive summary

The Thermal Transport of Air Pollution from Regulated Industries (TAPRI) project aims to enhance the understanding of thermal air flows and their impact on air pollution dispersion from regulated sites. Traditional air pollution assessments often rely on simplifying assumptions, such as uniform terrain and temperature profiles, which do not always hold true in real-world scenarios. This report, the third in the TAPRI series, focuses on assessing current awareness and practical experiences of thermal wind effects among Environment Agency staff, other UK regulators, and key experts. The goal is to identify the types of information and tools needed to better account for thermal winds in regulatory practices.

A comprehensive stakeholder questionnaire was developed and distributed to a broad audience, including regulators, operators, land use planners, consultants, and modellers. 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. Follow-up communications were conducted to gain additional detail and nuance.

The questionnaire received 23 responses, 14 of which (61%) from internal Environment Agency staff. The responses highlighted a range of expertise and perspectives on thermal winds and their impact on pollution dispersion. Key findings include:

- Varying background understanding

  Respondents demonstrated varying levels of awareness of thermally driven air movements, including sea-land circulations, anabatic and katabatic flows, and urban heat island effects. Some respondents noted the importance of differential heating due to land use and other factors.

- Current regulatory practices

  There was uncertainty about the number of sites potentially impacted by thermal flows. Specific examples of thermal wind impact on local populations were provided, and some respondents noted that thermal wind effects are occasionally raised by stakeholders during public consultations.

- Data and Scenarios

  Respondents identified key meteorological and ground-level conditions associated with thermal winds, such as low synoptic wind speed conditions, stable boundary layers, and differential surface heating. Various sources of long-term weather and pollution data were suggested.

- Modelling

  Tools currently used for assessing thermal winds include Gaussian-based models (AERMOD, ADMS), non-steady state models (CALPUFF), and mesoscale numerical models (WRF, Met Office's Unified Model). Respondents emphasized the need for tools that match the objectives of the assessment, with appropriate scales and resolutions.

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 a robust, science-based consideration of the evidence and clear guidance on tools and indicators for assessing thermal wind impacts. The need for targeted monitoring and the importance of providing accessible information to the public were also highlighted.

The TAPRI project underscores the importance of understanding and accounting for thermal air flows in air pollution assessments. Engaging with key stakeholders has provided valuable insights into the current state of knowledge and the tools needed to address thermal wind impacts. There is a desire to develop and disseminate clear guidance and fit-for-purpose tools to ensure that thermal wind effects are effectively considered in regulatory practices.

1. Introduction

1.1 Background

This report is the third in a series produced for the Thermal Transport of Air Pollution from Regulated Industries (TAPRI) project, and part of our investigation to better understand what is already known about thermal air flows (Figure 1). The rationale and background to the TAPRI project are described elsewhere (Environment Agency, 2025a). Briefly, much of the Environment Agency's current air pollution assessment work relies currently on simplifying assumptions, such as terrain being relatively flat and surface temperature and temperature profile of the atmosphere above it being uniform over the area of interest. However, there are real-world situations where these assumptions do not hold; there is evidence – both published and anecdotal - that local air pollution movements can consequently differ from those predicted. 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 during assessments and decision-making.

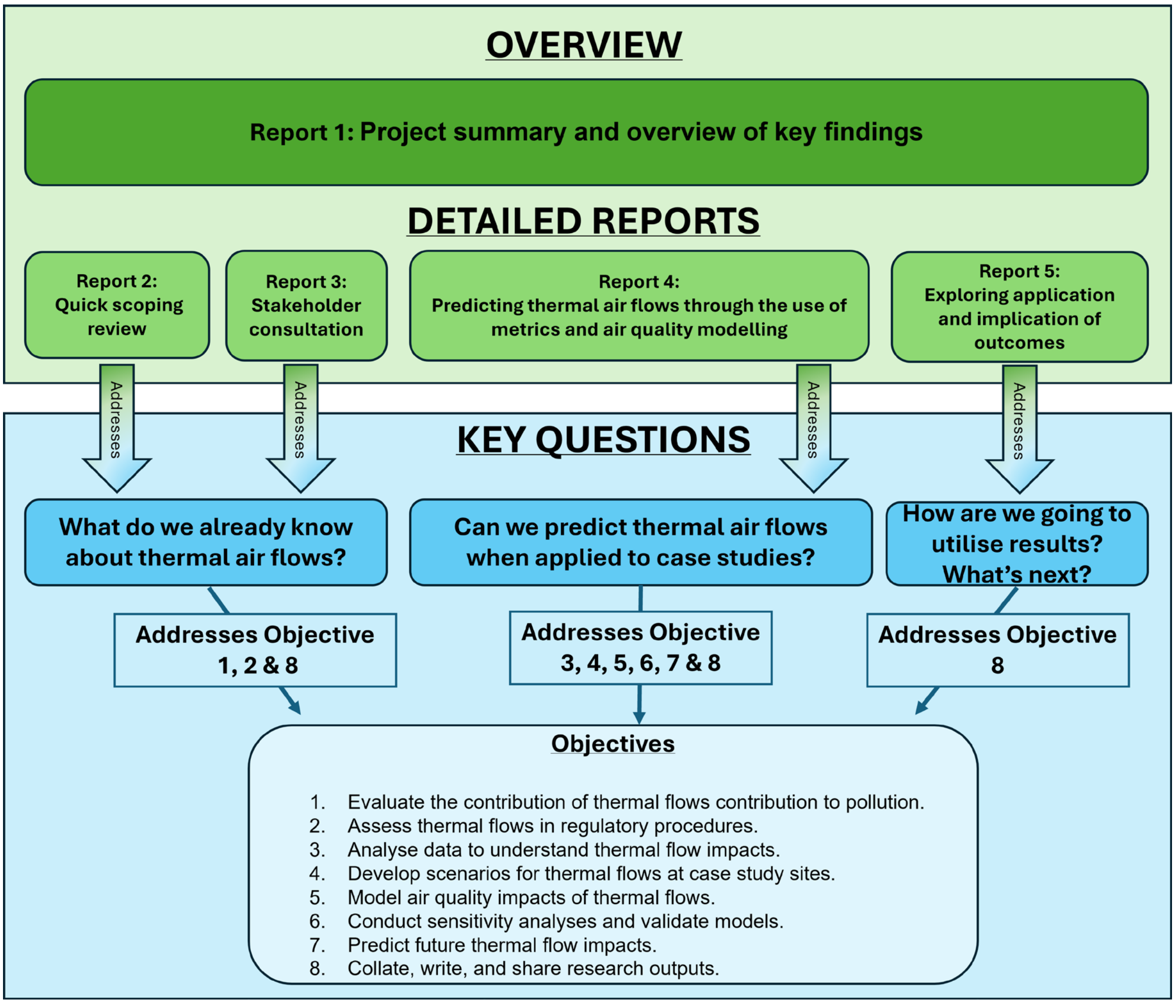

Figure 1. An overview of the different aspects of the TAPRI project, how they interlink and the key questions and objectives they address.

TAPRI engages a broad, multidisciplinary audience that includes regulators, operators, land use planners, consultants, modellers. These diverse stakeholders bring varied perspectives, priorities, needs, experiences, and differing levels of air quality expertise, which can be both complementary and conflicting. Understanding these differences is crucial to ensure that the outputs of this work are useful and fit for purpose. Engaging with stakeholders is therefore critical, as it helps to avoid duplicating efforts, and ensures that the work is relevant and effective. Additionally, this engagement fosters transparency and builds trust by demonstrating a commitment to considering the interests, needs and concerns of all affected parties.

This report describes work we carried out to assess current awareness of thermal wind effects amongst Environment Agency staff, other UK regulators, and key academic experts, to gather practical experience of thermal wind effects impacting on our regulatory and wider environmental duties, and to gauge the types of information and tools that would be welcomed to enable thermal winds to be better accounted for operationally. The purpose of this is to help us learn about how thermal flows may be currently informally considered if thermal flows need to be considered more formally in the future, and provide insights into what procedures, tools and knowledge would be best suited to account for them, all within a UK regulatory context. Given the multidisciplinary nature of TAPRI, knowledge exchange and collaboration between these groups is critical, we shared the findings from the TAPRI project as a whole via a webinar, and also held a face-to-face workshop to explore the application and implications of TAPRI outcomes; these are reported elsewhere (Environment Agency, 2025b).

1.2 Aims

The overarching aim of TAPRI is to assess the impacts of thermal air flows on the movement of air pollutants.

The specific aims for this element of the TAPRI work are to conduct a stakeholder consultation to:

1. Assess knowledge of thermal flows and their potential practical implications.
2. Gather lived experience of thermal flows impacting on stakeholders as they carry out their responsibilities.
3. Gauge whether there are any other aspects, tools, or relevant datasets we may have overlooked which may be relevant to the project.
4. Gain a better understanding of our stakeholder requirements for assessing thermal air flows.

2. Approach

To elucidate knowledge from stakeholders a questionnaire was developed. This was delivered and responses collated using Microsoft Forms. The research team and project advisory group (see (Environment Agency, 2025a) for details)) compiled the list of questions, which were compiled into key themes to create a template for the questionnaire. The research questions and key themes are provided in Appendix 1.

Key stakeholders (n=79) were identified by the research team and project advisory group, and consisted of internal staff (including representatives from area, permitting, regulatory resilience, operations and incident teams)), external experts from devolved administrations (Natural Resources Wales (NRW), Scottish Environment Protection Agency (SEPA), Northern Ireland Environment Agency (NIEA)), other government bodies (The department for environment, food and rural affairs (Defra), The Met Office, the Defence Science and Technology Laboratory (DSTL), the UK Centre for Ecology and Hydrology (UKCEH)), academics and commercial air quality consultants.

Stakeholders were given two weeks to complete the questionnaire; the questionnaire was sent out and completed in August 2024.

By way of gaining addition detail and nuance, some stakeholders were followed up via email and/or a virtual meeting, throughout October and November 2024.

3. Results

Twenty-three responses to the questionnaire were submitted; the majority of responders (14 (61%) were internal Environment Agency staff, and the remaining 9 responses included academics, air quality consultants and staff from other public bodies. The respondents represented a cross-section of expertise, from inexperienced, through experienced non-specialists to highly experienced specialists. Answers reflected this range of expertise but also benefitted from the diverse perspectives the various respondents brought.

Responses are summarised by key themes (as per the structure of the questionnaire, see Appendix 1).

3.1 Background understanding

3.1.1 Awareness of types of thermally driven air movements

Answers covered all of the categories expected, with reference to sea-land circulations, thermally driven internal boundary layer growth, anabatic and katabatic flows including cold air drainage, and urban heat island effects. Other situations with differential heating due to land use were also mentioned, specifically irrigated crops and extensive solar farms, and also the effects of wildfires.

Due to the wording of the question some respondents included mention of buoyant hot plumes from point source releases and from vehicles. While not of direct relevance to this work they may be of indirect importance since they add to the effects of solar radiation balance in determining temperatures in built-up or industrialised areas. Street-level thermally driven circulations were also mentioned by more specialist respondents and could be of relevance for the same reasons.

Some responses mentioned thermal stratification without advection, particularly in the context of “cold pooling” and vertical transport of pollutants. This is out of scope for the current project, though is adjacent in that cold air pooling can be a consequence of katabatic flows when these reach low points in local topography.

Some respondents expressed their lack of knowledge of this topic, and this should be considered if any briefing material concerning thermal flows is produced.

The meteorologists who responded pointed out that the term “thermal wind” has a specific, synoptic scale meaning for them. Using the term “thermal flow” would help differentiate synoptic wind from the small scale deviations that are the focus of this work , as would clarifying whether synoptic, mesoscale or local effects are being referred to.

3.1.2 Awareness of situations where thermal winds have played a role in pollution dispersion and/or on deposition of pollutants

A number of specific sites and situations were mentioned by name with no further context or explanation; Immingham, Teeside, Runcorn, Port Talbot, and Cwmfelinfach.

Some respondents went on to outline the issues at specific sites as follows:

- The 1957 Windscale fire, a nuclear accident which occurred at a site now known as Sellafield on the north-west coast. During this incident, the plume was lofted to upper-level winds and widely advected across the country.
- Walleys Quarry (a landfill site located in Newcastle-under-Lyme) and a similar landfill site at Redhill (located to the south of London) as having a suspected issue with cold air drainage winds advecting excessive releases of landfill gas towards particular local populations
- Coastal fumigation with sulphur dioxide in the vicinity of Stanlow oil refinery in the northwest of England, and a plume from a recent silo fire in the northeast of England which was seen to be carried out to sea by a land-sea breeze. Newcastle-upon-Tyne was also given as an example of sea-land circulation effects with "elevated transport to sea during day 1, mixing down into onshore sea breeze on day 2".
- Problems arose with odour from a pig farm above a residential area and from a landfill located on a mountain above a residential area (locations were not specified).

More generically, respondents referred to emissions from Medium Combustion Plants in London and other major urban areas being influenced by urban heat island effects. Sea breezes were described as "well-known to affect wind rose and hence dispersion patterns close to coastlines" and "common features of coastal cities", while another commented that in England "the sea breeze can sometimes stretch so far inland it converges with sea breezes from other coasts". There was mention of airsheds (such as Los Angeles) being subject to cold air pooling of katabatic flows draining into them, and the suggestion that this might be a common problem. Katabatic winds were mentioned a number of times as impacting on dispersion, over scales from "a small-scale landfill to a mountain valley", with dense air being described as flowing down a slope even against a light wind.

3.1.3 Descriptions of situations where air pollution and temperature have been seemingly linked

There was some overlap between the responses to this and the previous question. Most frequently mentioned were katabatic drainage from elevated landfill sites which it was recognised could advect odour from problematic sites to particular receiving environments under some meteorological conditions. One respondent from the Environment Agency referred to "a number of landfill investigations ongoing where temperature, time and air pressure appear to be linked to pollution". Another describes coming across "pools" of landfill and odour from anaerobic digestion (AD) in dips in the road and on a road located on a valley floor. The tendency for such odour to be associated with hot days was linked with the nature of "smelly biodegradable waste" rather than a particular flow.

The role of high temperatures, in one response described more specifically in terms of temperature differentials rather than absolute temperature, is recognised as driving sea to land breezes. Great Yarmouth power station was mentioned as a high NOx-emitter which is “located in the town and impacted by this type of dispersion”. Another response described elevated levels of particle-bound radioactivity in the air around the Sellafield site during summer, which is believed to be due to increased resuspension of previously deposited material but also the lower wind speeds associated with high pressure systems such that onshore breezes can develop more readily. Several respondents allude to the association of thermal winds becoming of significance under anticyclonic conditions, characterised by low winds and a capping inversion, favouring sea breezes and ‘topographically forced downslope flows’. One respondent mentioned the circumstance of plumes of emission released into ambient conditions warmer than the emission temperature consequently behaving as a dense gas subject to downhill drainage.

There is some conflation in responses of thermal winds and more static effects arising from surface temperature, with temperature inversions mentioned several times in the context of boundary layer height. In one example a capping inversion in a valley traps pollution emitted from a 110 m stack, at a height in line with housing on the side of the valley.

One response asks whether noise and vibration should be considered along with particles, gases and odours, describing experiences of “wind moving noise from an existing industrial source towards local residents and causing pollution/complaints”. Another raised the issue of plumes from cooling towers, which can be dense under certain weather conditions and block sunlight from adjacent properties. While this may not in itself be a thermal wind effect it might conceivably result in temperature differentials at ground level that could influence air flow.

3.2 Regulatory practices

3.2.1 Regulatory sense of the number of sites that might be impacted by thermal air flows

There was uncertainty amongst the nine regulators who responded. Six responded that they had little or no feel for the number, one felt it was a “significant number” and two felt that all of their sites were potentially affected. The regulator for an industrial cluster responded that “all of the industrial emitters in my cluster, and the local residents and habitats, could potentially be impacted”.

Of the non-regulators who responded to this question all felt that most sites, and especially those near the coast, in complex topography or potentially coupled to urban or industrial heat islands had the potential to be affected by thermal winds under certain conditions.

3.2.2 Situations where thermal airflows that have impacted on local populations (other than Walleys Quarry)[1]

Various specific examples were offered with various levels of detail:

- “Stanlow oil refinery plumes at Thornton le Moors (a village located to the south of the refinery)”
- “Plumes from industries at Avonmouth can impact on houses that overlook the coast (from slightly elevated terrain) under sea breeze conditions”
- “A highly protected habitat is downwind of our proposed industrial cluster [Teeside]. The habitat relates to soil of poor nutritional value. Any nitrogen[2] emitted by the new cluster could enrich the soil and damage this habitat.”
- “two brickworks … suffer from thermal airflows across ridgelines, mainly in mornings where a strong inversion existed.” (location was not specified)
- “The Windscale fire in 1957 provides an example of this situation.”
- “Blaydon Quarry Landfill Northeast. Some sewage treatment works creating odour from coastal easterly winds (inland).”
- “Stanlow SO_2 issue from suspected sea breeze, coastal fumigation.”

3.2.3 Situations where thermal wind effects been raised as an issue by others (such as protesters or other stakeholder groups)

Responses to this question were sparse.

One respondent asserted that “It is common for sites of high public interest (SHPI), e.g. energy from waste (EfW) applications, for members of the public to raise anecdotal issues

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[1] Walleys Quarry is a former quarry and now a landfill site located in Newcastle-under-Lyme in Staffordshire an area with topography allowing cold air drainage. In 2020-2021 the Environment Agency received a marked increase in reports relating to odour problems arising from excessively high landfill gas emissions, which led to our off-site mobile monitoring facilities being installed in 2021 (Environment Agency, 2025c). Katabatic drainage flows have been observed at Walleys Quarry (Timmis and Moncreiff, 2023) and it was deemed possible that this was exacerbating odour complaints under some conditions as odour-laden flows were channeled towards particular receptors. As it is already a well-known and well documented site in the Environment Agency, we wanted to learn about other potential examples of thermal air flows.

[2] “nitrogen” in this context refers to reactive nitrogen compounds which can lead to nutrient enrichment when deposited and hence change in ecosystem status.

during public consultation of inversions or microclimates in areas where topography is more complex”.

Another gave the specific example of residents who opposed a proposed EfW plant in Keighley raising dispersion and plume impacts as potential issues, though the thermal wind influence there was not specified.

A third stated that “Inversions rather than thermal wind effects are occasionally raised in public meetings”.

3.2.4 Are thermal flows currently considered in current regulation/permit/assessment?

The majority of respondents were unsure or felt that thermal flows were not considered.

Reasons for this fell into three categories:

- Assessors were unaware of the issues or unclear as to whether/under what circumstances they were significant or not with respect to pollution dispersion

- Assessors considered current regulatory tools as lacking capabilities for assessing thermal flow effects

- Assessors believe that the conservative assumptions used in current evaluations, which focus on "worst-case" scenarios regarding the highest ground-level concentrations for a specific level of emissions, are adequate to encompass any effects that thermal winds might contribute

3.2.5 Have thermal air flow topics been raised when visiting/assessing sites?

Nine respondents indicated that this question was not applicable to them. Of the remainder, six responded with a no, one of them adding that the Environment Agency “has not trained staff in waste on this matter”.

Of the other respondents, one considers urban heat island effects in urban areas, especially with respect to Medium Combustion Plant in London, while another “often considers them with “landfill and AD sites where there is topography and also land and sea breezes”, and once raised an issue with bioaerosols.

A non-Environment Agency technical manager responded that they do consider thermal flow effects, and that these would “influence consideration of appropriate meteorological data to use in an assessment and any modifications to an existing dataset”.

Other responses mentioned sea breezes and cold air drainage without further elaboration.

One Regulatory Specialist pointed out the need for thermal flow discussions “to be discussed at the planning application, Environmental Permitting Regulation (EPR) application and Control of Major Accident Hazards Regulations (COMAH) safety report stages. Once the plant is built and site inspections have commenced, it is too late”.

3.2.6 Are there any protocols or guidance that has been developed to forecast thermally driven flows of air pollution?

The possibility of guidance within US Environmental Protection Agency (US EPA) appendices was mentioned, as was Atmospheric Dispersion Modelling Liaison Committee (ADMLC) guidance for dispersion in complex terrain. One (non-Environment Agency) technical manager provides guidance to emergency assessors about caution in low wind speed conditions where flow may be thermally driven rather than mechanically driven by large scale weather systems.

A respondent referred to our access to the Met Office Numerical Atmospheric-dispersion Modelling Environment (NAME) chemical dispersion model (driven by flow fields generated by Weather Research and Forecasting model (WRF)) for use in major incidents.

Anecdotally one respondent described how residents of Teeside are aware that “often a ‘smog cloud’ that formed yesterday and was carried offshore by a nocturnal land breeze, will return the next day on sea breeze (unless weather pattern changes overnight).

3.2.7 Should thermal wind effects be considered as part of air quality impact assessments?

With the exception of three “don’t know” responses all agreed that this is probably the case. Several added caveats that this should only happen routinely under certain conditions of risk, if the science supported the need, if appropriate tools/guidance existed to do so and if the impacts of thermal flows on pollution impacts were not already subsumed in the conservative approach to assessment currently taken.

3.2.8 Information needed to help assess the impacts of thermal air flows for permitting/regulatory/assessment purposes

Respondents asked for additional knowledge and training, including “basic education that they are a thing” and how they might influence air pollution behaviour. What do sites need to be aware of, and perhaps integrate into their management systems, to mitigate or adapt to the effects of thermal flows?

Several asked for guidance on recognising when thermal air flows are likely to occur, including rules of thumb such as “sea breeze trigger temperatures”, and what tools are available for assessing sites that “screen in” as being at risk of thermal wind impacts.

In terms of data respondents identified a need for meteorological data at sufficient temporal and spatial resolution from relevant locations, including those which might be affected by thermal flows such as low-lying spots and “spill points”. Several mentioned topographic data and land use/land cover data. There was no mention of cloud cover or stability indicators such as Pasquill category.

3.3 Data and scenarios

3.3.1 If any, what meteorological conditions/parameters do you associate with thermal wind occurrence, or do you think could indicate likelihood of the magnitude of a thermal wind?

Most respondents mentioned an association of thermal winds with low synoptic wind conditions and a stable boundary layer temperature profile.

3.3.2 If any, what ground-level conditions/parameters do you associate with thermal wind occurrence (e.g. land use, topography)?

Surface heating was mentioned several times as a parameter. Some went further to describe the importance of differential surface heating to drive temperature, and hence density, differences in the air above. Factors described as leading to differential heating included differences in albedo, thermal mass, moisture balance and angle of surfaces to insolation.

The surface factors influencing these properties included topography (one respondent suggested that any slope above 1/100 could lead to a “thermal (i.e. density driven) acceleration), contrasting land uses, presence of water bodies, differences in surface (e.g. soil) moisture, the presence or absence of buildings, anthropogenic heat emissions and presence/absence of vegetation.

One respondent pointed out that “drainage” flows of cold, dense air can be very shallow - in the order of a few metres - and so may be most important for true surface or very near-surface sources. On these scales, even features like trees and tall hedges can trap or steer flow. Buildings may be on a similar depth scale so likely have a strong impact but also help deepen the cold layer and hence reduce its impact. Even moderately elevated sources may not 'see' the flow.

As with other questions some respondents included comments on static thermal effects on pollution dispersion, how topography can impact on these and how they can trap pollutants or lead to surface fumigation by pollutants as inversions break down.

3.3.3 Are you aware of thermal flow situations overseas that may become more prominent or frequent in the UK due to climate/land use/population changes?

The only direct effects mentioned were the possibility of changing temperature gradients due, for example, to greater surface heating and impact of sea temperature change, and the possibility of major climatic impacts such as slowing of the gulf stream.

Indirect effects of climate change mentioned included changes in land use, changes in rainfall, more frequent haze from wildfires, urban adaptations to greater heat and expansion of urban areas.

3.3.4 Can you suggest and places/scenarios/data source that will have long-term weather and/or air pollution monitoring data?

Many sources of long-term meteorological data were suggested, including:

- European Centre for Medium-Range Weather Forecasts (ECMWF, 2025).
- Centre for Environmental Data Analysis (CEDA, 2025).
- UK sea buoy data (NDBC, 2025)

Other sites suggested are run by or for enthusiasts or in support of specific activities, including:

- Ant Veal's GreatWeather! (2025), which collates and provides links to a wide range of weather information sources, including the National Highways monitoring network for adverse driving conditions.
- Windy (2025) which provides weather information aimed at sailing enthusiasts.
- Met Office (2025) Weather Observations Website (WOW) where weather enthusiasts can submit their own data allowing “crowd sourcing” of weather estimates across an area.

Sources of long-term sources of weather data for particular locations included airports (though concerns were raised about how long smaller airports might retain information), and measurements taken at regulated industrial sites. One suggestion was the historic data collected by coal-fired power stations, used to balance their sulphur dioxide emissions in real-time. Peterborough Brickworks has a weather station; being located in the Fens it is likely to be subject to sea breeze effects. Some sites, such as Port Talbot steelworks, collect meteorological data in order to adjust on-site operations under certain meteorological conditions to minimise pollutant impacts.

A key source of long-term pollution information is the UK’s statutory monitoring networks such as the Automatic Urban and Rural Network (AURN), Toxic Organic Micro Pollutants (TOMPs), Heavy Metals, Black Carbon and Ammonia Network. Other information might be available from specific regulated sites managing site activities, or through monitoring undertaken by regulators in order to determine compliance. However, the latter is less likely to be over a long duration.

3.4 Modelling

3.4.1 What tools are you currently using, or aware of, for assessing thermal winds and their impact on pollution dispersion?

The Gaussian-based models American Meteorological Society/US EPA Regulatory Model. (AERMOD) and Atmospheric Dispersion Modelling System (ADMS) are named in five responses. Two respondents mention the latter's capability to include internal boundary layer growth at the sea land interface but one adds the caveat that using that option "involves switching off other options that often have a more significant influence on dispersion". Another adds that "ADMS 6 can model the katabatic flows on a large scale much better than ADMS 5.2 due to improvements in the terrain module". Two respondents were uncertain that this type of model was suitable for this type of flow modelling.

Two responses suggest that non-steady state models such as the California Puff Model (CALPUFF) which are "said to have the capability for near-field impacts in complex flow or dispersion situations (complex terrain, stagnation, inversion, recirculation and fumigation conditions, overwater transport and coastal conditions, light wind and calm wind conditions)".

The KLAM_21 cold air drainage model was mentioned by one respondent, who did not elaborate on its use. Another suggested that 2D models have to make big approximations to the physics that we do not fully understand

The Met Office's NAME model was mentioned by several respondents, with one adding that "NAME can use full 3D wind fields but the spatial resolution of these can limit their usefulness for short-range air quality assessments".

Three respondents use mesoscale numerical models at resolutions down to 50 m, including the Met Office's Unified Model and WRF. Advantages given in one response include "the ability to embed the modelled region of interest within the much larger area of changing meteorological conditions. This can be performed in both hindsight (after incidents) and in forecasting mode", however with the caveat that "the number of sites/locations which would potentially need modelling would be unreasonable".

3.4.2 What are your requirements from such tools, or what do you think the tools should deliver?

Responses highlighted the need for tools to match the objective for which they were being used, ranging from simple screening of sites for possible thermal flow risks, through screening of routine meteorological data to identify thermal wind impacts up to an ability where necessary to model in detail the dispersion of pollution in thermal winds and so predict risk at receptors. One response wanted the ability to include impacts of thermal flows during emergencies, for example in guiding personnel conducting environmental monitoring". Another wished for the ability to "accurately predict the spread of pollutants in a meteorologically realistic (and meteorologically evolving), geographically complex environment, and predict concentrations of pollutants in the region of interest" since "common dispersion models at present cannot do this"

3.4.3 What scales and resolutions do/should these tools work at?

There was a consensus that "scales and resolution should be appropriate for the application". Given the diurnal variation a temporal scale of an hour or less was thought to be appropriate. Choice of spatial scale should be informed by the type of thermal flow thought to be occuring for example tens of metres for cold air drainage flows and other katabatic flows in stable nighttime conditions, and hundreds of metres for sea breeze effects. No particular scale was suggested for heat island effects, though one respondent suggested 1 m scale if building-resolved flows were required in urban areas.

One respondent gave the following detailed discussion:

"Mesoscale numerical weather prediction (NWP) models run at horizontal grid spacing O (10 km), vertical grid spacing O (100 m) and temporal resolution O (15 mins) have been operational for about 20 years. For example, the Met Office North Atlantic European (NAE) (12 km grid spacing) was introduced around 2001 and the current Global model (10 km grid spacing) has been operational since 2012 I think. These models can capture larger scale thermal circulations such as land and sea-breezes. NWP models with horizontal, vertical and temporal resolution O (1 km, 10 m, 1 min) can capture smaller scale thermal circulations such as slope winds and convection. High resolution NWP models have been operational for about 10 years. For example, the Met Office UKV (1.5 km grid spacing) was introduced in 2014 replacing the NAE. To capture local topographic effects such as cold air drainage flows requires very high horizontal resolution O (300 m) and temporal resolution (30 s) have been in development since around 2017. Currently they are expensive to run and so are run on demand over limited area domains. Online pollution models, such as the Air Quality Unified Model (AQUM), integrate atmospheric chemistry into the Met Office NWP model. This model has a 12 km horizontal resolution covering the UK and has been operational since 2006. It produces a 5-day air quality forecast. Offline dispersion models, such as NAME, use output from NWP models at varying resolution (10 km, 1.5 km) and are largely used for emergency response forecasting. Thus, there are existing air quality models that are run routinely and can capture some mesoscale flows (land- sea-breezes, convection, urban circulations, larger slope and valley winds) but air quality studies of smaller-scale thermal flows such as cold air drainage flows are typically only produced for field campaign or short duration simulations."

3.4.4 What information does/would a thermal winds-capable model require to operate? Is it available?

Topographic information is readily (and freely) available from Light Detection and Ranging (LIDAR) surveys carried out by the Environment Agency and from mapping sources such as Ordnance Survey.

Meteorological data are available at a range of resolutions from sources mentioned previously. The Environment Agency's Air Quality Modelling and Assessment Unit has UK-wide meteorological data ready for use by the CALPUFF model.

No mention was made of land use/land cover data.

3.4.5 Are there currently gaps in achieving that capability, or limiting performance of models?

Responses indicated that modelling tools are available to estimate thermal flows, but that their use is limited by a) availability of the models and specialist knowledge to operate and interpret them and b) the time and computational power to use them routinely. Nonetheless one respondent commented that "we believe that only a full numerical weather prediction model can form the basis of an accurate dispersion model".

The issue of scale was raised: "There will be significant limitations on modelling small-scale thermal winds such as katabatic flows on a small scale such as Walley's Quarry. The key is understanding these limitations and associated modelling uncertainty, and using them appropriately. Monitoring is likely to be the best option in many cases."

The continued importance of targeted monitoring was raised, both for model validation/verification, for detecting variation at scales below the resolution of the model and for assessing uncertainties on model outputs.

3.5 Other thoughts and comments

Several responses raised the need for basic awareness of issues around thermally driven flows and the importance of providing "a simple and accessible narrative that the public can understand"

The value was flagged of the 25-year archive of data collected by the Environment Agency Ambient Air Monitoring service as a resource to be "mined" for evidence of the occurrence and impacts of thermal flow effects. Complaint logs were also mooted as a source of information.

One respondent raised that "adding more complexity to an environmental assessment is often counterproductive in that the reliability of the output is not improved".

4. Discussion

Responses demonstrated a broad range of understanding of thermally driven air flows and their potential impacts on pollution behaviour, ranging from little or no knowledge of them to a high level of technical expertise. A number of examples where thermal flow effects were thought to have contributed were identified. There was clearly an appetite for more information, pitched at levels appropriate for operational staff who are not air pollution specialist, both for their own sake in understanding potential risks and as an aid to communicating with stakeholders such as public interest groups, some of whom are themselves aware of thermal flows as a potential issue. A key point arising was the need for consistent terminology; this was found to differ between stakeholders. For example, for meteorologists all winds are “thermal”. The term “thermal flow” is therefore a more useful term in a pollution dispersion context, and adding a description of scale (local or mesoscale as opposed to regional or synoptic) adds further clarity.

Responses indicated desire for a proportionate approach when considering any incorporation of thermal wind impacts into air quality impact assessments, pointing out the need to relate any increase in complexity to the likelihood that it would improve the assessment process and ultimately reduce risk of adverse outcomes. There was no consensus on how many Environment Agency-regulated sites might be impacted by thermal flow effects.

Another consideration raised was how significant thermal flow effects were in comparison to other factors at a site that could influence exposure at nearby receptors. For example, a number of responses conflated thermal flow effects with static effects arising from thermal stratification and inversion, with the implication that even in flat terrain the conditions associated with colder air at the surface will lead to higher pollution concentrations in areas around a source, due to the low capping inversion. “Cold pooling” – collection of cold air in hollows - was cited in several responses, highlighting the need to consider the static and dynamic aspects dispersion together.

As a starting point respondents wanted a robust, science-based consideration of the evidence as to whether thermal winds are ever an issue with respect to Environment Agency air quality responsibilities. If they are, then there is need for a set of indicators that would flag them up as a potential issue for a given source(s)-pathway(s)-receptor(s) situation. This might be as simple as a screening checklist against a set of criteria.

Should thermal winds be flagged as a risk then respondents wanted clear guidance on fit-for-purpose tools to assess their impacts, specifically any deviation they might bring about from the “non-thermal wind” baseline case. These should be proportionate to the risks they would mitigate.

There was a view that under most circumstances the tools routinely used for regulatory assessment at present do not have thermal flow modelling capability. A “second tier” of models (Gaussian puff models) were considered more appropriate for the variable conditions associated with thermal winds, and both the models and the requisite meteorological data are available within the Environment Agency, though resource to allow wider use of such models may be limited. A “2D” model was also mooted specifically for cold air drainage flow but it was not clear that this was routinely available nor what the scope and limitations are of its applications and performance.

The atmospheric science specialist respondents described their routine use of mesoscale numerical weather models such as WRF to measure thermal flows down to tens of metres resolution and seemed confident that such models predict flows over time in complex settings. Performance is dependent on availability of appropriate input meteorological data and information concerning surface properties. Some respondents mentioned the NAME model, which couples mesoscale numerical weather modelling with a pollution dispersion model. It is used by the Met Office to provide air pollution dispersion modelling during major incidents.

Users of these models noted that the additional complexity associated with them was justified to meet those users' modelling objectives. Such levels of complexity would probably be considered "overkill" operationally for all but the highest risk situations. There was concern around the scalability of these models down to individual installation levels and this needs to be addressed in developing advice on model selection.

There was uncertainty amongst respondents as to the practicality of using the different tiers of model. A useful product would be a realistic assessment of what is required to run each type and how feasible or desirable it might be for a given circumstance.

There was little in the responses regarding what might be done differently if thermal flows were found to be having a significant impact in a given situation. It was suggested that consideration of thermal flow risks should be included at the planning stage, before new or amended activities are approved or housing is constructed in areas that might be impacted. Retrospectively the key element of control remains emissions management where this can be achieved (for example, the influence of katabatic flows at the high profile Walleys Quarry is secondary to the main issue of excessively high levels odorous gas emitted from the regulated site resulting from it receiving inappropriate waste). There may be some adaptations that can be made to timing of activities leading to emissions where this is controllable. Where this is not possible then for smaller scale katabatic flows there is the possibility of channelling them away from sensitive receptors, but it is difficult to identify mitigations on greater scales that do not involve reducing or relocating emissions.

5. Conclusions

The stakeholder questionnaire allowed us to gauge knowledge amongst those whose duties might be impacted by thermal flows and to gain a greater understanding of what we know currently about their occurrence.

- Thermal flows are generally recognised as a potential issue when considering pollution dispersal, though it is not currently clear how many regulated sites might be affected in practice, nor how significant these effects may be compared with other factors such as topographic or static thermal stratification effects.
- Thermal flow assessment should therefore be carried out within a wider assessment considering these other factors.
- Stakeholders' knowledge of thermal flows is currently variable and there is a wish amongst them for communications that will give them an appropriate level of understanding for their own operational needs and for dialogue with the general public.
- Practitioners are supportive of a hierarchical approach to assessment, using a level of complexity proportionate to the risk being assessed. Implicit in this is a requirement for clear guidance and training on gauging that risk and selecting the right level of assessment.
- There is a need to test whether explicit thermal flow modelling highlights additional risk or whether the conservatism already applied to assessment modelling leads to sufficiently precautionary conclusions.
- Perhaps the main use of thermal flow prediction is pre-emptively, for example during planning or permitting. Retrospectively, thermal flow consideration may help to explain movements of air pollutants leading to unacceptable impacts, and it may support the case for mitigation of emissions.

It is hoped that information and analysis carried out in other parts of the TAPRI project will address some of the evidence gaps and concerns highlighted by stakeholders.

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Appendix 1.

Stakeholder questionnaire

The stakeholder questionnaire was split into 6 sections. The sections, and questions under each section are summarised in Table A . All questions required free-text answers. Stakeholders were asked to contribute as much or as little as they wished, and assured that ‘no’, ‘don’t know’, and ‘not applicable’ were valid responses.

Table A 1. The questions asked in the stakeholder questionnaire

Question no.	Question
Section 1: About you ***The purpose of this section was to gauge different stakeholder needs and perspectives***	
1.	Full name
2.	Email address
3.	What department/group/team do you work in?
4.	What is your job title/role?
Section 2: Background understanding ***The purpose of this section was to gauge the general awareness of thermal wind effects and what currently matters to our stakeholders.***	
5.	What types of thermally driven air movements are you aware of?
6.	Are you aware of any situations, specific or in general, where thermal winds have played a role in pollution dispersion and/or on deposition of pollutants?
7.	Can you recall any sites or situations where colleagues have commented (even if anecdotally) on links between air pollution and temperature? If so please describe (e.g. where, when, what).

Question no.	Question
Section 3: Regulatory practices	
The purpose of this section was to explore whether, if at all, thermally driven air movements have been a consideration or concern in regulation of air pollution-emitting activities, whether you feel they should be and if so what support might be of use.	
8.	If you are a regulator, do you have a sense of how many sites in your area might be impacted by thermal air flows?
9.	Are you aware of situations where thermal airflows have impacted on local populations (other than Walleys Quarry)[3]?
10.	Have thermal wind effects been raised as an issue by others, for example protesters or other stakeholder groups?
11.	How much/well do you think thermal flows are currently considered in current regulation/permit/assessment?
12.	When assessing/visiting a site, have thermal air flow topics been raised (e.g. 'cold air drainage', 'shoreline fumigation', 'rural airflows into urban heat islands')?
13.	Are you aware of any protocols or guidance that has been developed to forecast thermally driven flows of air pollution to warn/protect people?
14.	Do you think the possibility of thermal wind effects should be improved/considered as part of air quality impact assessments?

[3] Walleys Quarry is a former quarry and now a landfill site located in Newcastle-under-Lyme in Staffordshire an area with topography allowing cold air drainage. In 2020-2021 the Environment Agency received a marked increase in reports relating to odour problems, which led to our off-site mobile monitoring facilities being installed in 2021 (Environment Agency, 2025c). Katabatic drainage flows have been observed at Walleys Quarry (Timmis and Moncreiff, 2023) and it was deemed possible that this was exacerbating odour complaints under some conditions as odour-laden flows were channeled towards particular receptors. As it is already a well-known and well documented site in the Environment Agency, we wanted to learn about other potential examples of thermal air flows.

Question no.	Question
15	What information would you need to help assess the impacts of thermal air flows for permitting/regulatory/assessment purposes? (Feel free to be creative here - what do you wish for?)
Section 4: Data and scenarios ***The purpose of this section was to gauge if there are any parameters we have not considered which may influence thermal flows, and be made aware of any datasets which may be useful to this project.***	
16.	If any, what meterological conditions/parameters do you associate with thermal wind occurance, or do you think could indicate likelihood of the magnitude of a thermal wind?
17.	If any, what ground-level conditions/parameters do you associate with thermal wind occurance (e.g. land use, topography)?
18.	Are you aware of thermal flow situations overseas that may become more prominent or frequent in the UK due to climate/land use/population changes?
19.	Can you suggest and places/scenarios/data source that will have long-term weather and/or air pollution monitoring data?
Section 5: Modelling ***The purpose of this section was to understand requirement for modelling thermal wind effects, current capabilities and the input data required.***	
20.	What tools are you currently using, or aware of, for assessing thermal winds and their impact on pollution dispersion?
21.	What are your requirements from such tools, or what do you think the tools should deliver?
22.	What scales and resolutions do/should these tools work at?
23.	What information does/would a thermal winds-capable model require to operate? Is it available?

Question no.	Question
24.	Are there currently gaps in achieving that capability, or limiting performance of models?

Section 6: Anything else

The purpose of this section was to provide the responders with the opportunity to add anything else that may be relevant that was not already captured elsewhere in the questionnaire.

25.	Do you have any other thoughts or comments that may be relevant?

Appendix 1. References

Environment Agency (2025e) Welcome to Walleys Quarry Landfill Site. Available at: https://engageenvironmentagency.uk.engagementhq.com/hub-page/walleys-quarry-landfill

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