



Thermal transport of air pollution from regulated industries: a quick scoping review

Chief Scientist's Group report

February 2026

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Dr Robert Bradburne
Chief Scientist

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List of abbreviations

AROME	Application of Research to Operations at Mesoscale
ARPS	Advanced Regional Prediction System
ASL	Above Sea Level
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ASTGTM2	ASTER Global Digital Elevation Model version 2
CAD	Cold Air Drainage
CAP	Cold Air Pooling
CAPs	Cold Air Pools
CFD	Computational Fluid Dynamics
CLC	CORINE Land Cover
CMAQ	Community Multiscale Air Quality
COAMPS	Coupled Ocean-Atmospheric Mesoscale Prediction System
CORINE	Coordination of Information on the Environment
DEM	Digital Elevation Model
DOI	Digital Object Identifiers
DryARD	Dry Atmospheric Regional Demonstrations
FLEXPART	Flexible Particle dispersion model
GIS	Geographic Information System
HLAM	High Resolution Limited Area Model
HRRR	High-Resolution Rapid Refresh
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
LEAF	Land Ecosystem-Atmosphere Feedback
LES	Large Eddy Simulation
LIDAR	Light Detection and Ranging
LPDM	Lagrangian Particle Dispersion Model
LST	Land surface temperature
MAX-DOAS	Multi-Axis Differential Optical Absorption Spectroscopy
MEGAN	Model of Emissions of Gases and Aerosols from Nature
Meso-NH	Non-hydrostatic mesoscale atmospheric model
MM5	Fifth-Generation Penn State/NCAR Mesoscale Model
MODIS	Moderate Resolution Imaging Spectroradiometer
MOSAIC	Model for Simulating Aerosol Interactions and Chemistry
MOZART	Model for Ozone and Related Chemical Tracers
NO ₂	Nitrogen dioxide
NO _x	Nitrogen oxides
O ₃	Ozone
PALM	Parallelised Large-Eddy Simulation Model
PBL	Planetary boundary layer
PCA	Principal Component Analysis
PM	Particulate matter
PM ₁₀	PM with a diameter of 10 micrometres or less

PM _{2.5}	PM with a diameter of 2.5 micrometres or less
RAMS	Regional Atmospheric Modelling System
RANS	Reynolds Averaged Navier Stokes
RegCM4	Regional Climate Model version 4
SLUCM	Single Layer Urban Canopy Models
SODAR	Sonic Detection and Ranging
SO ₂	Sulphur dioxide
STILT	Stochastic Time-Inverted Lagrangian Transport
SUHII	Surface Urban Heat Island Intensity
TAPRI	Thermal Transport of Air Pollution from Regulated Industries
UHI	Urban Heat Island
UHIs	Urban Heat Islands
UHII	Urban Heat Island Intensity
US EPA	United States Environmental Protection Agency
USGS	US Geological survey
WRF	Weather Research and Forecasting Model
WRF-Chem	WRF model coupled with chemistry

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We thank Ricardo consultants who we contracted to aid us with extracting information from some of the studies.

Executive summary

This report is part of the Environment Agency's Thermal Transport of Air Pollution from Regulated Industries (TAPRI) project. Current regulatory assessments do not explicitly consider thermal air flows. TAPRI explores how thermally driven air flow, such as sea breezes, slope winds, and urban heat islands (UHI), can affect the dispersion of air pollutants.

This quick scoping review evaluates the existing evidence base to inform whether and how thermal flows should be considered in UK air quality assessments. The review aimed to determine; whether thermally driven flows significantly influence pollutant dispersion; what conditions they occur and how frequently; what tools and data are used to model them; their relevance to UK conditions; and implications for assessment, forecasting, and mitigation.

A quasi-systematic approach was used to search for and identify relevant literature from peer-reviewed and grey literature; 149 articles were assessed.

Thermal flows such as sea breezes, slope winds, and Urban Heat Island (UHI) circulations play a significant role in the transport and transformation of air pollutants. Among these, sea breezes are the most frequently studied and are commonly observed, including in northern Europe. These flows can carry pollutants inland or offshore and may recirculate them, contributing to the formation of secondary pollutants such as ozone (O₃). Katabatic and anabatic slope flows were less frequently studied in isolation but are known to facilitate vertical and downslope pollutant transport. UHIs can induce circulations that draw in pollution from surrounding areas and potentially influence long-range transport. In many cases, these flows interact, such as sea breezes combining with UHI and valley winds, resulting in complex and often unpredictable pollutant behaviour. Although only one study identified was conducted in the UK, the available evidence indicates that thermal flows do occur in climatic conditions akin to 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 similar processes are relevant here.

Only one article referred directly to the UK, but others described work in similar temperate, maritime climates.

In the studies synthesised, a variety of atmospheric model classes were employed to simulate thermal flows and their effects. These models differ in complexity, spatial resolution, and data requirements. Their performance is highly sensitive to the quality and resolution of input data, with common challenges including under- or over-estimation 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 different levels of uncertainty with computational costs and availability

of data. Only a small proportion of studies (n=24, 16%) made explicit mention of forecasting; the majority of these were in relation to katabatic flows.

Accurate simulation and understanding of thermal flows depend on sufficiently high-quality meteorological data, such as wind, temperature, humidity, and radiation flux, which are often sparse or inconsistent. Land use characteristics (e.g., vegetation cover, building height) and topography (e.g., valleys, coastlines) significantly influence flow development.

Both monitoring and modelling indicated that thermal flows can substantially alter pollutant dispersion patterns and should be considered in air quality assessments, especially in coastal, valley, and urban environments. Failure to account for these flows may 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.

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 step to avoid thermal flow issues *a priori* is to include screening for potential effects at the planning or permitting stage; a key step towards this is raising awareness of thermal flows amongst stakeholders.

There is a need for more research on flows under UK conditions, and on the interactions of combined flows in complex terrain. Proportionate advancements in screening and forecasting tools, access to high-resolution data where necessary, and the development of probabilistic modelling approaches are essential to improve prediction, avoidance and management of thermal flow impacts on air quality.

1. Introduction

1.1 Background

This report is the second 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, 2025b). 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.

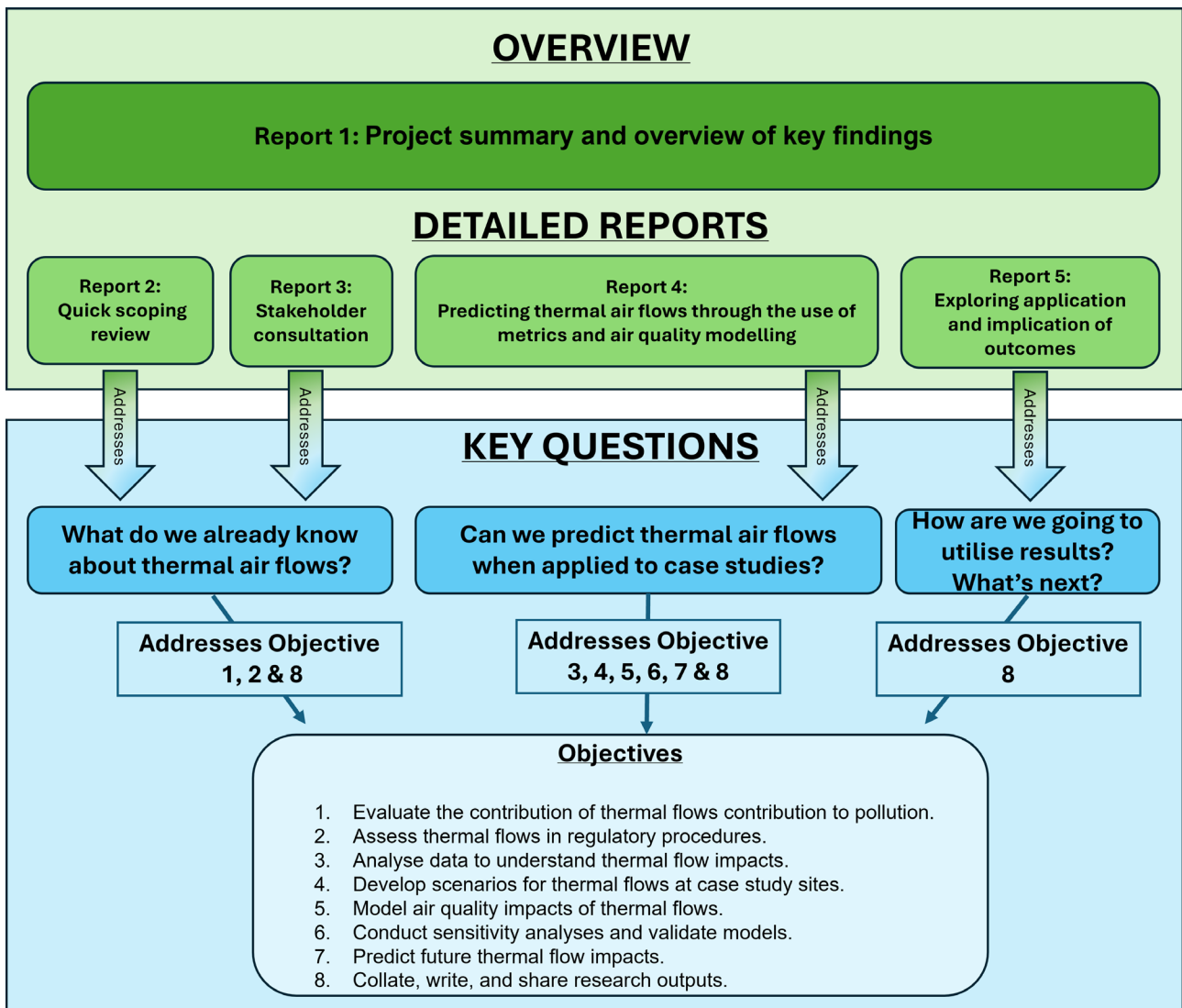


Figure 1. An overview of the different aspects of the TAPRI project, how they interlink and the key questions and objectives they address.

Understanding how thermally driven processes influence air pollution dispersion is essential for accurately assessing environmental impacts from regulated facilities. Reviewing existing scientific literature provides a means to assess the current state of knowledge on thermal air flows. Reviewing the literature allows examination of the types of thermal air flows that occur, the conditions under which they arise, and their potential to affect air pollution transport. It also informs where and when these flows are likely to develop, and whether these are likely to form in UK climatic conditions. Reviewing the literature is also likely to provide insights into the tools available to simulate or assess thermal flow processes (e.g. dispersion models, meteorological data) and their range of complexity, and collate any UK-relevant parameterisation information, for both current and future scenarios.

By reviewing the literature, key gaps can be identified, particularly in the context of the UK's regulatory and environmental landscape, which will ensure that TAPRI will address key gaps in knowledge. This report outlines the methodology used to conduct the review and presents findings that can inform future research, including assessment approaches, related to TAPRI.

1.2 Aims

The aim of this work was to conduct a quick scoping review of thermally driven processes influencing air pollution source, pathways and receiving environments.

This will help us to learn about how thermal flows may be informally considered in a UK regulatory context, inform whether thermal flows need to be considered more formally in the future, and assess what tools and knowledge would be required to account for them.

This is part of a wider project with an overarching aim to assess the impacts of thermal air flows on the movement of air pollutants. Other components of this work include characterisation of thermal flow metrics, case study identification and conducting dispersion modelling for the case study areas, which are reported separately (Environment Agency, 2025a).

2. Approach

Due to the short timescales of the project, a quick scoping review was conducted, which was able to provide an informed conclusion on the volume and characteristics of an evidence base in relation to the research questions. Where possible, guidance on how to conduct quick scoping reviews and rapid evidence assessments (Collins *and others*, 2015) was followed. An advisory group of air quality experts from across the Environment Agency was set up to advise on all stages of the project.

2.1 Research questions

The research questions we aimed to answer from this review were:

Primary:

- Do thermally driven processes influence air pollution dispersion? If so where, how often, and under what conditions?

Secondary:

- What tools are best for simulating thermally generated local air flows?
- What types of thermal wind effects can significantly impact air pollution dispersion?
- What parameters (e.g. meteorology, topography and land use) determine how and when they arise?
- How frequently do those sets of parameters arise?

2.2 Search strategy

The research questions were used to develop key research concepts, which were then used as the basis for developing search terms (provided in Appendix 1). These search terms were used to search peer-reviewed literature using the Scopus electronic database. As this is a quick scoping review, other electronic scientific literature databases were not examined. Search terms were reviewed by the advisory group.

Grey literature was identified by searching relevant grey literature databases, government websites (UK and internationally) and other relevant websites. The grey literature search strategy is provided in Appendix 2.

2.3 Study selection

Studies identified from the Scopus database search were imported into the citation and reference management tool, EndNote version 20. Duplicates were removed, using the 'find duplicates' tool in EndNote. Studies not in English were excluded by using 'language' field in Endnote (any studies that did not state a language in the field were included). Only studies where a full text was readily available were included (to identify full texts, the references

were updated using the 'find reference updates' tool (as some references did not have key identifiers such as Digital Object Identifiers (DOI) numbers), followed by the 'find full text' tool in EndNote).

Remaining studies were imported into Rayyan (Rayyan, 2025), a free web application intended to facilitate the literature review screening processes. Studies were screened based on their title and abstract. Studies were excluded if:

- They did not concern thermal flows
- They did not concern air pollutants
- They concerned indoor air
- They were on topics outside of scope (e.g. sub-surface thermal flows)
- They concern other research fields (e.g. geology, materials science, manufacturing toxicology etc.)

If the title and abstract of the study were vague, or if there were any other uncertainties, the study was excluded.

Studies were then assessed on their full text. The following information was extracted from the studies:

- Paper identifiers (authors, year of publication, title)
- Basic information (was the study a review, aim, study setting (e.g. coastal, urban, regional etc.), the region the study was conducted in, key conclusions)
- The type of thermal flow (katabatic, sea-breeze, UHI etc.)
- Whether air quality data was collected and if so brief details
- Whether an atmospheric and/or pollutant model was used, and if so brief details, including whether any meteorological pre-processing tools or models were used.
- Whether any statistical models or tools were used, and if so what
- What parameters were measured and how (meteorological data, topographical data and land use data)
- Whether wind and/or thermal flows were quantified
- Whether the studies made any commentary on the frequency of thermal flows, forecasting or mitigation

3. Results

The results of the searching and article screening process are summarised in Figure 1.

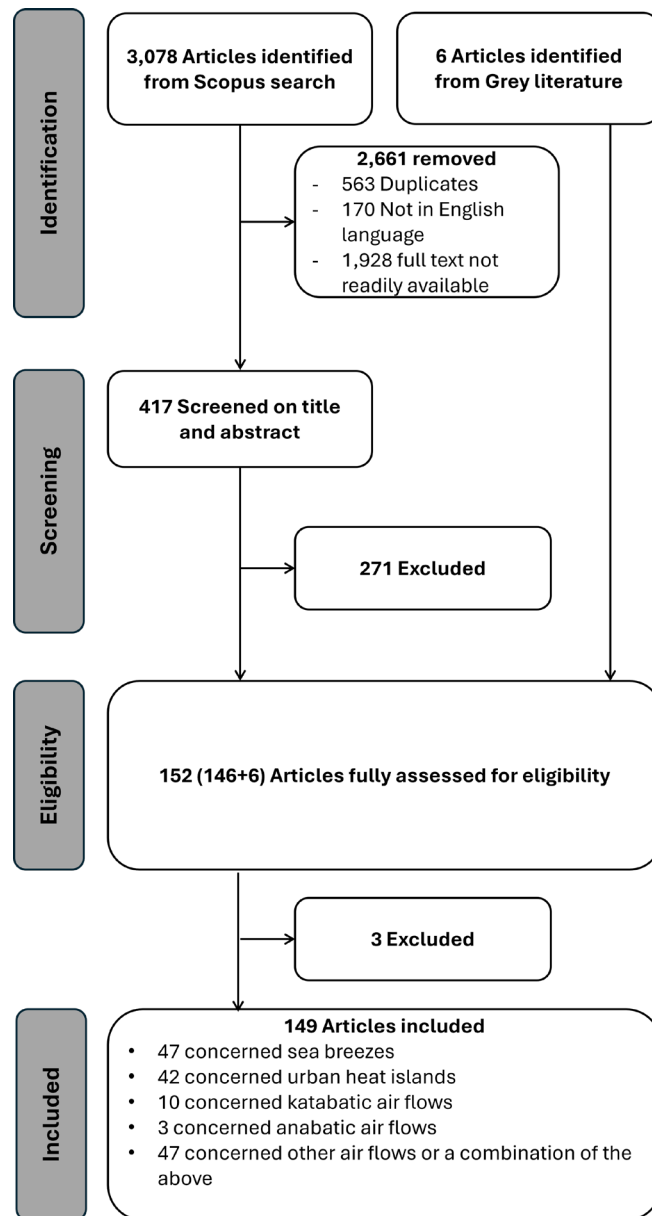


Figure 2. Flow diagram summarising the study selection and exclusion process

The majority of studies considered only sea breezes (32%, n=47), but often sea breezes were considered in conjunction with urban island heat effects or katabatic air flows and would have been captured as ‘Other’ (Figure 1)). Four studies were reviews. The studies were conducted from across the world, with the majority conducted in East Asia (30%, n=44), mostly in China, followed by Europe (23%, n=34) and North America (22%, n=32) (Figure 2). One study was focused on the UK (McHugh and Ellis, 2001).

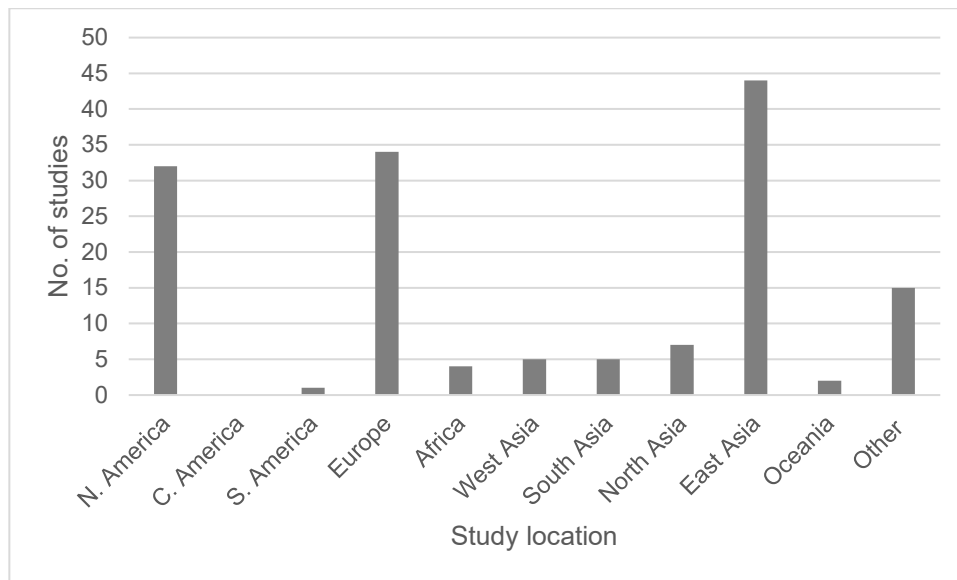


Figure 3. Locations that the selected studies were conducted in.

Eighty-six studies included air quality data; the majority of studies monitored or modelled O₃ (27%, n=40) and/or particulate matter (PM; PM with a diameter of 10 micrometres or less (PM₁₀) and PM with a diameter of 2.5 micrometres or less (PM_{2.5}) or other particulates) (25%, n=37). Most studies monitored air quality, either by using bespoke monitoring campaigns or utilising network monitoring data, although 17 studies used both. Eleven studies used aircraft data to monitor air quality, and five used remote sensing data. Three studies used remote sensing to detect aerosols using different techniques; Geddes *and others* (2021) used satellite-based remote sensing, Ou *and others* (2023) used a Multi-Axis Differential Optical Absorption Spectroscopy (MAX-DOAS) instrument and Pace *and others* (2015) used Light Detection and Ranging (LIDAR) backscatter. Two studies used LIDAR-observed O₃ data (Niwano *and others*, 2007; Werner *and others*, 2006). Twelve studies modelled air quality data; eight utilised both monitored and modelled data (Huszar *and others*, 2020; Li *and others*, 2017; McHugh and Ellis, 2001; Niwano *and others*, 2007; Ohashi and Kida, 2002b; Ryu *and others*, 2013; Zhang *and others*, 2020; Zhu *and others*, 2015), usually as a validation tool to test model performance. For example, Ohashi and Kida (2002b) utilised air quality data from an air quality monitoring system, which included concentrations of pollutants such as suspended PM and sulphur dioxide. This was used to validate the performance of a Lagrangian Particle Dispersion Model (LPDM) in simulating the transport and distribution of pollutants in the Osaka and Kyoto region in Japan, whereby local air circulations are influenced by sea-breezes, valleys and heat-island effects.

The quality of the studies identified were varied, but it was beyond the scope of a quick scoping review to assess overall study quality and assess study bias.

3.1 Defining thermal air flow events

Few studies explicitly defined what conditions need to be met to define a thermal flow event; sea breezes and cold air drainage (CAD) events were most defined.

Sea breeze events were mostly defined through examination of observed wind direction. Geddes *and others* (2021) aimed to analyse sea breeze conditions in Boston, USA, and examine impacts on local air pollution concentrations; the reversal of surface winds were deemed the most relevant features to identify. Therefore, 'sea breeze days' were defined as having at least 5 h of westerly (offshore) winds between 1am and 12pm, followed by at least 5 h of easterly (onshore) winds between 9am and 8pm. An average of 28.3 sea breeze days (31%) were identified each year between June and August 2010-2019. Hu *and others* (2019), a study conducted in Pingtan, China, defined sea breezes as when the absolute value of variation in wind direction ranged from 90-270° between 2am and 2pm, and both sea breeze and land breeze lasted longer than 3 h. McLaren *and others* (2010), conducted in the Lower Fraser Valley in USA, defined inflow sea breezes as having a wind direction of 180-330° and outflow land breezes as having a wind direction of 0-120°, sustained for several hours with wind speeds $>5 \text{ km h}^{-1}$ at six observation stations. Sea breezes were observed on 9 out of the 13 days studied. Only one study did not use observed wind direction to determine sea breeze events, but instead used satellite imagery and back trajectory modelling. Zhang *and others* (2020) used this method when assessing whether these events contributed to sharp spatial gradients in O_3 concentrations in the New York metropolitan area, USA. They did this in three steps: 1) Use daily visible satellite imagery to manually detect sea and shore breeze circulations; 2) Construct 24 h back trajectories using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model and using daily LIDAR vertical profiles generated using data from six profiler sites in the region; 3) visually inspect images to identify evidence of sea or shore breezes circulation. Authors concluded that a sea and/or shore breeze circulation has formed if there was a sudden shift in wind direction from offshore to onshore and/or a line of cumulus clouds parallel to the shoreline that did not form due to a synoptic frontal passage of gust front.

Glojek *and others* (2020) examined equivalent black carbon pollution in a rural mountainous region in Slovenia. They state that cold air pools (CAPs) are formed due to the influences of temperature inversions and calculated the number of days with a temperature inversion (26 days in 88 days across winter 2017-2018). Karl *and others* (2020) aimed to better understand air movements in Innsbruck, Austria, an urban area located in a valley and also calculated the frequency of temperature inversions (16% in 2016-2018), which peaked in December and January. They also provide the number of hours of foehn winds ($n=311.2$ in 2016-2018), but do not state how a foehn wind is defined (a foehn wind is a dry, warm, downslope wind which occurs on the lee side of a mountain range). Sekuła *and others* (2021) examined the impacts of foehn winds on PM_{10} concentrations in Kraków, Poland, and did clearly define a set of criteria to determine foehn occurrence. Periods of potential foehn were confirmed if at least one of the following criteria were fulfilled; a) wind direction of 90-270°, a wind speed of $\geq 5 \text{ m s}^{-1}$ and presence of altocumulus lenticularis clouds; b) wind direction of 90-270°, a wind speed of $\geq 5 \text{ m s}^{-1}$ and a relative humidity $\leq 70\%$; c) a relative humidity $\leq 70\%$ and the presence of altocumulus lenticularis clouds, checked by the analysis of measurement data. The duration of a foehn was defined as the number of consecutive hours when these criteria were fulfilled; long episodes were defined as lasting $>24 \text{ h}$ and short episodes as $\leq 24 \text{ h}$. Baumann *and others* (1997) concerned anabatic flows in the USA and defined 'upslope flows' as thermally driven (daytime only), near-surface flows. Wind direction data was classified in 20 (18°) wind sectors, and 'upslope flows' ranged from 0-

216° (north to southwest), and occurred for 26% of the time at higher altitudes and 30% at lower altitudes.

Air flow events associated with Urban Heat Islands (UHIs) were not well defined. Urban heat island (UHI) intensity (UHII), although not a thermal flow itself but may influence timings and intensities of thermal flows, was defined in some studies. For example, Wang *and others* (2022a) defined UHII as observed differences in average 2 m air temperature between all urban and all rural stations. Varentsov *and others* (2021) defined UHII as the air temperature deviation from the mean background air temperature.

How thermal flows are generated will be subject to the local conditions (e.g. topography, meteorology, etc.), and therefore it is important to note that multiple criteria may be required to characterise all situations.

3.2 Tools used for simulating thermally generated air flows

Mesoscale atmospheric flow modelling is a mature field, with many decades of published work including thermal flows and some clear trends emerging. Over half of the papers identified (n=87, 58%) include an element of flow modelling, generally supported by and compared with field measurements of meteorological parameters. Some focus on the air movements while others take modelled wind fields and use them to model transport of pollutants. The most sophisticated incorporate atmospheric chemistry schemes that incorporate formation, conversion and losses of air pollutants, for example through photochemical reactions.

The modelling process can be described as a series of stages (Figure 3). Models were used to determine impacts of the different thermal wind categories in isolation. UHIs and sea-land flows were the most frequently represented, with limited numbers of slope- and valley-winds being modelled. In a greater number of cases modelling included interactions between thermal wind features, either of the same kind (for example, UHIs from different urban areas in a landscape) or of different types (interactions of UHI effects with land-sea breezes and in some cases UHI, land-sea breezes and mountain winds all considered).

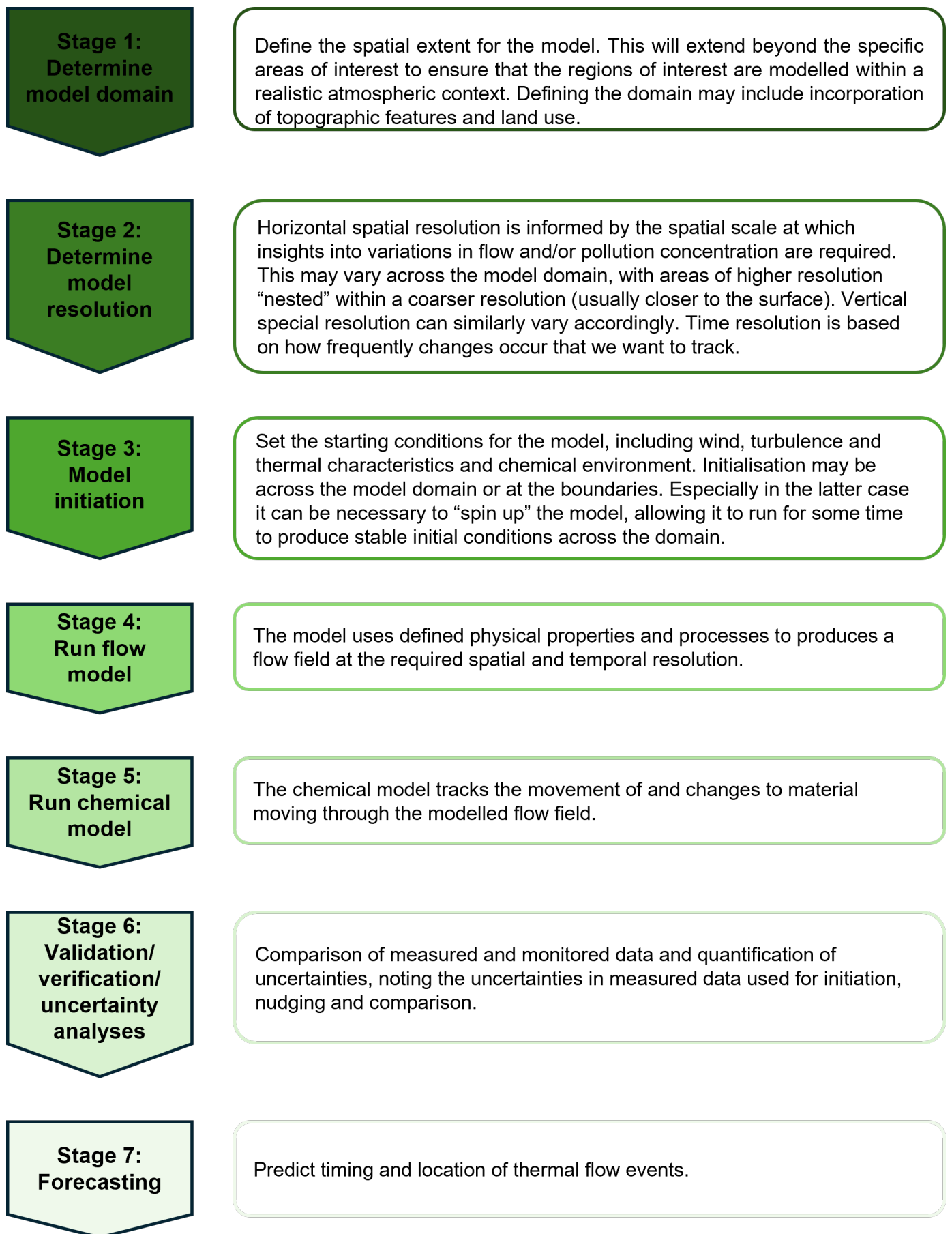


Figure 4. Stages in modelling impacts of thermal flows

The evidence from the reviewed literature is summarised according to each stage outline in Figure 3 in the following sections.

3.2.1 Model domain

Modelled domains are typically in the 10s to low 100s of km horizontal dimension. Most of the studies consider one or more city areas and adjacent features such as coastline and mountains inland, for example the Po Valley, Italy (Diémoz *and others*, 2019) Gulf of Guinea (Flamant *and others*, 2018) Shanghai and surrounding area (Hu *and others*, 2022). Ohashi and Kida (2004) represented a 160 x 80 km area of coast including two urban areas and mountains and mountains.

Resolution of topography within the domain can be high. For example, Brandsma and Wolters (2012) used 0.5 by 0.5 m surface elevation model and land use at 25 m x 25 m.

3.2.2 Model resolution

Horizontally, nested grids were generally used with the highest spatial resolution focused on the key areas of interest. For studies utilising the Weather Research and Forecasting Model (WRF), examples include Campbell *and others* (2016) with nested grids for WRF model coupled with chemistry (WRF-Chem) of 81 km, 27 km and 9 km, Hai *and others* (2018) used grids of 25 km, 5 km, and 1 km, Hu *and others* (2022) with grids of 9 km, 3 km and 1 km and Kang *and others* (2022b) with 9 km, 3 km and 1 km. Vertical resolution typically involved dividing the height from surface to several km altitude into a few 10s of layers, with lower layers spaced more closely than those above. For studies utilising WRF, varying numbers of vertical levels were used, for example; Campbell *and others* (2016) used 49 vertical levels, 25 of which were within the first 4km above ground. Hai *and others* (2018) used 30 vertical layers and Kang *and others* (2022b) used 37 vertical layers, with 20 within the first 2 km above ground, and the lowest five were 10 m within the defined urban canopy.

Similar applications were seen for other Eulerian flow models. Dry Atmospheric Regional Demonstrations (DryARD) was used in Ohashi and Kida (2004) with a 2 km horizontal grid and 30 vertical layers from 3 m, 10 m, 30 m, 70 m, 100 m then widening to 200 m, 400 m and up to 5 km. The non-hydrostatic mesoscale atmospheric model (meso-NH), frequently used in France, was applied with horizontal grids of 9 and 3 km, with 50 vertical layers, finer near the surface. Coupled Ocean-Atmospheric Mesoscale Prediction System (COAMPS) (Jiang *and others*, 2011) was applied at 40.5 km, 13.5 km, 4.5 km, 1.5 km and 0.5 km, with 30 vertical levels, 20 in the lowest 3 km. High-Resolution Rapid Refresh (HRRR) used a 3 km horizontal grid. Biggart *and others* (2021) focuses on an UHI and variations across it, looking at 100 m variations.

For very fine scale features finer resolution could be used. For example, Mott *and others* (2019) used Advanced Regional Prediction System (ARPS) to calculate flow field at a 20 m horizontal grid over an Alpine massif with 60 terrain-following vertical layers, with the lowest between 1.4 and 2.6 m. For more generalisable and adaptive models such as Computational Fluid Dynamics (CFD) and Urban Canopy models resolution can be down to metres,

depending on objectives, computational resources available and timescale in which information is needed.

Thermally driven flows are largely driven by diurnal cycles of heating and cooling. Accordingly, time resolution is set to capture variation within the course of a day (over one or multiple days). For example, in Cholakian *and others* (2023) 3-hourly steps were used and in Pace *and others* (2015) hourly. ARPS ran at a much shorter time step but for less than 12 hours.

3.2.3 Model initiation

These might be determined by interpolation of measurements, such as satellite observations and ground measurements, or by coarser models such as those used for large-scale weather forecasting. For example, a number of studies make use of boundary meteorology from the European Centre for Medium-range Weather Forecasting or their US or Japanese equivalents.

3.2.4 Flow models

Models of mesoscale thermal flows in the environment use known physical behaviours of the atmosphere to simulate its behaviour. Several classes and sub-classes of model appear in the literature:

3.2.4.1 Analytical or semi-analytical

These models assume a change in atmospheric properties with height above the surface, the more sophisticated taking into account properties affecting buoyancy. They were referred to only in early papers (e.g. (Kimura and Takeuchi, 1978)) and appear to have been superseded, certainly in the research environment, by numerical flow models. They have played a useful role in exploring the conditions under which idealised thermal flows might occur.

3.2.4.2 Eulerian

By far the most frequently used in the literature, these models represent the atmosphere as a series of volumes defined by a horizontal grid in the order of a km to many kms mesh size, which might extend over a large domain, and a few tens of vertical layers, typically varying in depth with the narrowest close to the surface where rates of change are typically most rapid. The coordinate system may be set to follow the underlying terrain or adopt a sigma

(σ) coordinate system¹ which results in a lower layer following a smoothed version of the actual terrain. Flows through the modelled domain are solved numerically over a series of time steps.

Examples in the literature include simulations of UHIs, sea-land circulations, valley and other katabatic flows and interactions between one or more of these. UHIs, sea-land circulations and their interactions are by far the most frequently investigated, with fewer studies looking at slope flows. Inputs to these models include initial boundary conditions, surface topography and land use. They are frequently coupled with other models describing, for example, detailed properties of the surface and the effects these have on atmospheric flow, such as their effect on warming/cooling. Comparison with measured meteorological data show that these models are capable of good performance if correctly configured.

This class of model can be divided into two categories:

Hydrostatic

These make a simplifying assumption (the hydrostatic approximation) that the atmosphere is in hydrostatic balance i.e. that the vertical pressure gradient in the atmosphere is balanced by the weight of the air above so that vertical acceleration is negligible. This is a reasonable assumption for larger scales and relatively simple terrain but causes inaccuracy when horizontal grid resolution falls below 3 km, below which scale the atmosphere is often non-hydrostatic (Jacobson, 1998). While they have the advantage of greater stability and need less computational power, they are not suitable for simulating small scale phenomena and are less accurate in complex terrain.

Examples in the literature include DryARD (e.g. (Ohashi and Kida, 2004)) and High Resolution Limited Area Model (HLAM) (e.g. (Leslie and Speer, 1998)).

Non-hydrostatic

These make no assumptions about hydrostatic balance and so are suitable for use at smaller scales (down to tens of metres) and in more complex terrain. They are therefore better suited to simulate convective and other localised atmospheric dynamics.

Examples used the literature include ARPS (e.g. (Mott *and others*, 2019)), Meso-NH (e.g. (Saïd *and others*, 2007)), and, by far most frequently, WRF (and its predecessors such as Fifth-Generation Penn State/ National Center for Atmospheric Research Mesoscale Model (MM5) and Regional Atmospheric Modelling System (RAMS)). WRF (developed by the US National Science Foundation's National Centre for Atmospheric Research) was used in 40

¹ A sigma (σ) coordinate defined by p/p_s where p is pressure at a forecast level within the model, and p_s is the pressure at earth's surface (not necessarily mean sea level) lowest coordinate surface (usually labelled 1) and follows a smoothed version of the actual terrain.

of the papers reviewed, including many of the most recent and for all types of thermal wind and their interactions.

Both classes of Eulerian model must include a representation of the surface underlying them and read in terrain and land use data.

Urban surfaces are generally more complex than rural ones and can be represented with various degrees of Urban Canopy Models that can be coupled to mesoscale atmospheric models are reviewed in some detail in Qian *and others* (2022). The authors identify four types:

- Slab models, in which the urban area is treated as a two-dimensional surface with simplified bulk parameterisations for roughness, albedo and heat capacity, energy balance and a surface treatment such as a Monin-Obukhov scheme to estimate surface fluxes. These have the advantage of computational efficiency but do not include specific urban features such as building structures.
- Single Layer Urban Canopy Models (SLUCM). These include a simplified three-dimensional street canyon component and solar radiation model that take into account diurnal change in solar zenith angle and shadowing effects. They also include consideration of energy balance for roof, wall and ground and account for more impacts on atmosphere above the urban surface.
- Multi-layer Urban Canopy Models, which resolve building effects vertically. In addition to the spatial effects on solar irradiation impacts given by SLUCMs, therefore, these can account for the vertical distribution within the canopy of sinks and sources of momentum, heat and moisture fluxes, and hence impacts on momentum, potential temperature and turbulent kinetic energy.
- Small-scale building-resolved models use “microscale” urban transport models or CFD methods (see 3.2.4.3) to resolve urban airflows at local or city scales. The CFD models can explicitly resolve building structures and different urban features, including street-level flow, channelling, local turbulent mixing and downwash.

3.2.4.3 CFD

These models are in essence a subset of Eulerian models in that they also divide the study domain into finite volumes and solve the fundamental equations of fluid dynamics, such as the Navier-Stokes equations. We include them as a distinct category here since the term is generally used to describe generalised models with no native assumptions or parameterisations specific to atmospheric flows. This allows great flexibility but brings with it the responsibility of defining appropriate parameter values. They can make use of unstructured grids (not restricted to cuboids) and adaptive meshing that allows resolution to vary throughout the model domain, allowing the highest resolution to focus on those areas with the greatest rate of change in flow. They are computationally intensive but appear to be more commonly used now that desktop computers are sufficiently powerful to run them. They rely on use of accurate boundary conditions, and in particular appropriate

representation of the boundary layer structure as it enters the model domain. They also rely on representation of topography and surface features; in the past this has been a factor limiting practical application of CFD modelling but high-resolution data is increasingly available, as are means of creating surface elevation models from those data.

A particular challenge in application CFD models is ensuring that they represent turbulence (short-term and small-scale fluctuations in flow velocity at a given point) in the flow correctly, since this is responsible for transfer of momentum in the flow and hence its overall behaviour and the fate of scalars such as temperature and pollution concentration. Much of this turbulence occurs at a scale below the grid size(s) within the model domain, and various schemes are used to represent this sub-grid turbulence. The structure of turbulence in a flow is strongly dependent on circumstances, and the choice of turbulence model should be well-validated as being appropriate for a given type of application; “CFD calculations of “new” turbulent flows should never be accepted without any validation against high quality experimentation” (Versteeg and Malalasekera, 1995).

Three examples of the use of CFD models were found in the literature search:

Di Sabatino *and others* (2020) used CFD CD-Adapco STAR-CCM+ 19.2, a Reynolds Averaged Navier Stokes (RANS) model using a $k-\epsilon$ turbulence scheme, to compare an UHI with and without vegetation cover. Modelling was down to urban street canyon scale. Model predictions were compared to measurements from an air quality monitoring network and meteorological stations within and outside of the urban area and the model was found to replicate the UHI characteristics they had observed.

In Hrebtov and Hanjalić (2019) the authors used a CFD solver (BuoyFlow, TU Delft, Netherlands) to model interactions between an UHI and a river in different seasons. The model was a RANS model using a $k-\epsilon-\theta_2$ turbulence scheme and buoyancy-accounting functions. They were able to include realistic orography and building heights, with averaged temperatures from local observations. Pollutant emissions were similar in summer and winter but resulting patterns of air pollution concentration. The modelling was able to explain the observations as being brought about by the relative temperature of the river: in winter, when it was warmer than its surroundings the resulting updraft drew pollutants into the city centre. In summer the relatively cold river blocked air motion from one area of the city to another, creating two separate convective flows.

Belda *and others* (2021) used Parallelised Large-Eddy Simulation Model (PALM) 6.0 to model an UHI. PALM is a Large Eddy Simulation (LES) model, an approach that is considered to better represent complex, unsteady and turbulent flows and with less reliance on empirical turbulence models. Initial and boundary conditions were obtained using WRF, in turn initialised from the global forecast system operational analyses and forecasts. They carried out sensitivity analyses, and found that information at the very local scales at which this system was capable of operating relied on availability of detailed, precise and accurate local parameterisation, including those required for solving the local flow and energy balance equations such as albedo, emissivity roughness length, thermal conductivity and thermal capacity.

3.2.5 Chemical models

Fifty-one studies (34%) included chemical models to simulate the movement of air pollution within thermal air flows. O₃ was the most modelled pollutant, followed by nitrogen oxides (NO_x), including nitrogen dioxide (NO₂), and PM (PM₁₀ and PM_{2.5}). Data sources included meteorological stations, satellite observations, emission databases and inventories, and field measurements. Some studies incorporated more advanced features like chemical mechanisms to simulate pollutant transformations or considered factors like building geometry and vegetation. Most studies (n=37, 73%) used Eulerian models, or hybrid models integrating a Eulerian component with Lagrangian air packet tracking. Twenty-three studies coupled a model to WRF; 19 were Eulerian models, 3 Lagrangian and one CFD model. WRF-Chem (n=11) and WRF-Community Multiscale Air Quality (CMAQ) (n=5) combinations were most common.

WRF-Chem allows pollutant emissions, transport, mixing, chemical transformations to be simulated alongside meteorology (US NSF, 2025). Several studies (Campbell *and others*, 2016; Darby *and others*, 2007; Han *and others*, 2020; Li *and others*, 2017; Lin *and others*, 2021; Niwano *and others*, 2007; Wang *and others*, 2022a; Werner *and others*, 2006; Xie *and others*, 2016a; Xie *and others*, 2016b; Zhong *and others*, 2018) used WRF-Chem; most studies used WRF-Chem to simulate UHI related thermal flows, although two studies (Darby *and others*, 2007; Niwano *and others*, 2007) used WRF-chem to simulate sea breeze related thermal air flows, one (Werner *and others*, 2006) to simulate CAD and sea breeze related thermal air flows, and one (Lin *and others*, 2021) simulated several linked thermal flows (land-sea breeze, katabatic winds and anabatic winds), in relation to a typhoon event. Niwano *and others* (2007) compared modelled simulations with LIDAR-observed O₃ data in Japan and found that the model accurately captured high O₃ concentrations on specific days, and day-to-day variations 1.5 km above sea level (ASL). However, O₃ concentrations tended to be overestimated below 1.5 km ASL, and underestimated above this, which were attributed to underestimation of vertical mixing in the boundary layer. O₃ concentrations were simulated in the Rhone Valley region of France where mistral katabatic winds interact with sea breezes (Werner *and others*, 2006). It was found that the mistral wind modified the sea breeze, delaying onset, limiting vertical and horizontal extents and redirecting flow resulting in high pollution levels in densely populated areas such as Marseille; the model was found to accurately reproduce O₃ concentrations when compared to measured data. Li *and others* (2017) modelled O₃ and NO₂ in the Yangtze river delta region in China, focusing on UHI, but also considered sea-land breeze circulations. They used the Carbon Bond Mechanism version Z gas-phase chemistry scheme and the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) aerosol scheme. When incorporating Moderate Resolution Imaging Spectroradiometer (MODIS) satellite-derived surface parameters, instead of using standard WRF values (which US Geological survey (USGS) data), meteorological simulations were improved which in turn improved the accuracy of NO₂ and nocturnal O₃ concentrations, particularly in urban areas.

CMAQ is an air quality model developed by the US Environment protection Agency (US EPA), which can be used alone, or coupled with other models, such as WRF. Several studies (Kang *and others*, 2022b; Loughner *and others*, 2014; Ryu *and others*, 2013; Torres-

Vazquez *and others*, 2022; Zhu *and others*, 2015) used WRF coupled with CMAQ; Three studies (Kang *and others*, 2022b; Ryu *and others*, 2013; Zhu *and others*, 2015) used WRF-CMAQ to simulate pollutants in UHI related thermal flows. Kang *and others* (2022b) investigated UHI impacts on vertical distribution of aerosol in Hangzhou, China, and simulated PM_{2.5}. CMAQ was used the same grid as WRF (horizontal grid with 9 km, 3 km and 1 km spacings, and 37 vertical levels, with the lowest 20 layers below 2 km, 5 of which were within 10 m) with outer domain concentrations derived from the Model for O₃ and Related Chemical Tracers (MOZART)-4, emission inventories were used for anthropogenic emissions (using the multi-resolution emission inventory for China), biogenic emissions were modelled using Model of Emissions of Gases and Aerosols from Nature (MEGAN) 2.1, and CMAQ model AERO6 was used for aerosol dynamics. Good agreements between modelled outputs and observations were observed. Ryu *and others* (2013) and Zhu *and others* (2015) simulated O₃ and NO₂ in Seoul, South Korea, and Shanghai, China, respectively; both found that the UHI effect modified O₃ concentrations; Ryu *and others* (2013) found increased concentrations night and day, but did not comment on model performance. Zhu *and others* (2015) found increased O₃ production in the upper boundary layer but decreased in the lower boundary layer due to UHI circulation and found that CMAQ accurately simulated O₃ and NO_x concentrations. Loughner *and others* (2014) and Torres-Vazquez *and others* (2022) used WRF-CMAQ to simulate sea breeze related thermal flows, both in the USA. Both studies simulated O₃, with Torres-Vazquez *and others* (2022) also simulating NO_x, PM and sulphates. Loughner *and others* (2014) found that NO_x was overestimated and positive bias in O₃ concentrations, although vertical transport and boundary layer dynamics were captured well.

WRF was also coupled with Lagrangian models such Stochastic Time-Inverted Lagrangian Transport (STILT) (Lopez-Coto *and others*, 2020), Flexible Particle dispersion model (FLEXPART) (Kang *and others*, 2022a) and HYSPLIT (Ou *and others*, 2023). Ou *and others* (2023) predicted PM_{2.5} and NO₂ concentrations in the Yangtze River delta region in China, an area affected by sea breeze flows. When comparing modelled outputs to monitored concentrations, a good model performance was found, with correlation coefficients exceeding 0.76.

3.2.6 Model uncertainty and performance analysis

3.2.6.1 Statistical treatment

Examination of measured data and its comparison with modelled data was carried out some of the papers reviewed. At its simplest such examination was descriptive, reporting wind roses of measured wind speed and direction, and analysing time spent in various sectors and how winds varied diurnally (e.g. (Li *and others*, 2013; Mallet *and others*, 2005; McHugh and Ellis, 2001)).

Around 20 papers described intercomparison of modelled and monitored data to evaluate model performance. This generally involved calculation of a Pearson correlation coefficient and reporting an R² value. Sekula *and others* (2021) and Torres-Vazquez *and others* (2022) describe how comparison was made between paired data temporally and spatially. Another

statistic commonly calculated (13 papers) was mean bias, in some cases more specifically mentioning mean fractional bias (Biggart *and others*, 2021; Wang *and others*, 2022c) normalised mean bias (Loughner *and others*, 2014; Ryu *and others*, 2013; Zhu *and others*, 2015).

Various techniques were used to explore and quantify the relationship between parameters. Linear regression was used to examine pairs of parameters, but it was generally recognised that interactions between multiple parameters mean that multiple regressions are required. Some references (e.g. (Agathangelidis *and others*, 2020; Varentsov *and others*, 2021; Yang *and others*, 2024; Yu and Sun, 2024)) refer to use of multiple linear regression, while others recognise that interrelationships between parameters can be non-linear and so use non-linear tools, including multiple non-linear regression (Brandsma and Wolters, 2012) and Generalised Additive Models (Di Virgilio *and others*, 2018). These allow the impacts of multiple factors to be considered in concert and the relative contributions of each to the chosen end point assessed.

Combinations of factors can be grouped together in terms of their impacts on air movement and air quality. Principal Component Analysis (PCA) can group variables into uncorrelated groups, simplifying analysis while retaining the information on variability in the dataset. It was used in several papers (Refs 48,145). Dong *and others* (2023) refers to use of the Empirical Orthogonal Function to derive Principal Components. Lee *and others* (2013) uses positive matrix factorisation, a similar but more sophisticated approach that tends to yield more readily interpretable components.

Cluster analysis can be used to group data into sets. For example, a set of meteorological circumstances might be associated with a particular air quality outcome. In Darby (2005) hourly wind data were clustered, while Hu *and others* (2019) carried out cluster analysis – Potential Source Contribution Function analysis - to identify conditions and particular air masses associated with high O₃ levels. Qiu *and others* (2019) categorised data into four typical wind patterns, including three prevailing synoptic directions and local circulation, and discuss their impacts on the sources influencing the receptor and the accumulation or otherwise of local pollutants. In Nodzu *and others* (2011) composite analysis aimed to understand the specific meteorological factors that led to production of stable atmospheric layers. For each occurrence of stable air in the data series, it was possible to identify the dominant thermal factors contributing to stability.

An issue in detecting and in modelling mesoscale and local thermal winds is their variability over time as non-steady state systems, which can preclude some analytical and modelling methods. Karttunen *and others* (2022) conduct Wavelet Analysis (able to carry out frequency analysis for non-steady state systems where a standard Fourier analysis would not be applicable) to analyse fluctuations in temperature during specific events such as the passage of a front.

A small number of studies carry out detailed analysis of model performance and optimisation. Belda *and others* (2021) carries out a systematic sensitivity analysis of the LES-based PALM 6.0 model system, while Jiang (2012) describes in sensitivity to controlling parameters over time. Igel *and others* (2018) describe construction of a statistical emulator.

This uses the outputs of 121 model simulations, and the resulting model is validated against a further 22 simulations. The reported percentage of variance contributed by each factor was determined.

Moreira and Albuquerque (2016) raises the issue of artifacts and arising from the use of numerical (as opposed to analytical) models. They explore the number of terms and steps required to achieve convergence of the model onto a solution (for example, inappropriately selected time steps can result in the model failing to converge on a stable solution).

Treatment of input data to minimise uncertainty are discussed below.

3.2.6.2 Findings on statistical relationships and uncertainty

Using these statistical techniques, it was possible to identify and quantify relationships between parameters. For example, use of PCA in Yu and Sun (2024) revealed that PM_{2.5} was negatively correlated with UHI, whereas population density and enhanced vegetation index were positively correlated with UHI intensity. In Muzaky and Jaelani (2019) land surface temperature (LST) was found to correlation positively with increasing building cover, while Agathangelidis *and others* (2020) showed a similar relationship between LST and the “impervious urban fraction” of an area. Muzaky and Jaelani (2019) and Tian *and others* (2024) showed a negative correlation with vegetation cover. Hereher *and others* (2022) found that at the seasonal level, the highest NO₂ concentrations were correlated with the surface UHI (SUHI) that occurs during spring ($R^2 = 0.59$), while the CO reached a maximum during winter ($R^2 = 0.51$). Seasonal Sulphur dioxide (SO₂) distribution was poorly related to the SUHI and this was put down to SO₂ being significantly associated with the industrial land use. Changes in correlation can be informative; Cheung *and others* (2022) found a moderate correlation ($r = 0.60$) between particle number concentrations at both urban and suburban sites, which implied that PM pollution was a regional pollution issue for the area, especially under the influence of monsoon conditions which gave a significantly higher correlation coefficient ($r = 0.70$) compared to that during land-sea breeze period ($r = 0.30$).

3.2.6.3 Model performance

The statistical analyses of model performance showed a range of levels of performance depending on model used, data being input, assumptions made, the parameters being modelled, the range of climates and meteorological conditions.

In Brandsma and Wolters (2012) a fitted statistical model (parametric, non-linear) accounted for more than 75% of the variance in temperature profile of the UHI over Utrecht, while Kang *and others* (2022b) found that modelled impact of UHI impacts on circulation and atmospheric chemistry with WRF-CMAQ produced results that matched well with surface measurements. Jin and Raman (1996) compared numerical and modified Gaussian models and found that they gave concentration estimates in the same order of magnitude and had similar patterns, with thermal internal boundary layer and local sea-land circulation both playing a role. They noted that the Gaussian approach did not provide detailed structure of the plume, while a shortcoming of the numerical model is that concentrations were grid averaged. Sensitivity experiments with the numerical model showed that coastal dispersion is sensitive to magnitude of ambient wind, upwind stability, source release time, grid resolution and coastal topography.

Arthur *and others* (2022) made a comparison of model bias against measured temperature and windspeed profiles. As noted by (Wilczak *and others*, 2019) overestimates of near-surface wind speed are a common model bias during cold air pooling (CAP) events. Of particular note is that numerical mixing in the model can also lead to apparent early erosion of the CAP, accentuating this bias and leading to poor predictions. Campbell *and others* (2016) found that their model depiction was reasonable overall, and that the core thermodynamic effects, including land/sea breeze structure, were well resolved. However, the model did not resolve the convective mixing of aerosol particles into the lower free troposphere or the enhancement of near-surface concentrations arising from nighttime cooling and hygroscopic effects. Geddes *and others* (2021) reported that the fine scale of the sea breeze in Boston was not reliably represented by meteorological reanalyses products commonly used in chemical transport models as required to provide inputs for retrievals of concentration data from satellite observations. This implied a higher systematic error in the retrievals on sea breeze days compared to other days.

Borys *and others* (2006) further explored parameterisation and the impact of scale on performance. Their baseline simulation used a horizontal resolution of 1 km, which is close to the resolution of operational regional mesoscale model forecasts; they found this neither matched the strength of the observed CAP nor retained the cold pool throughout the day. Varying the Planetary Boundary Layer (PBL) parameterisation, increasing the vertical resolution, and increasing the model spin-up time (the number of model time steps allowed for the initial boundary conditions to propagate throughout the model) did not significantly improve the results. However, the inclusion of snow cover, increased horizontal resolution, and an improved treatment of horizontal diffusion did all have a sizable effect on the forecast quality. In addition to improving the resolution of flow features in steep terrain, resulting in, for example, less drainage out of the valley being modelled, the increase in horizontal resolution led to a better forecast because of a reduced magnitude of horizontal diffusion calculated along the terrain-following model surfaces. Calculating horizontal diffusion along the constant height levels had a beneficial impact on the quality of the simulations, producing effects similar to those achieved by increasing the horizontal resolution, but at a fraction of the computational cost.

The representation of urban landscapes and their impacts on flow and dispersion were explored in several studies. Karlický *and others* (2018) found the impact of cities on wind speed to be significantly dependent on the complexity of the urban parameterisation employed. Simpler models were less effective in capturing the reduction in wind speed caused by urban environments, whereas more complex models provide better simulations. Nonetheless the study suggested that while more complex models tend to perform better, even simpler models can be effective if they include the most relevant processes. Lopez-Coto *and others* (2020) found that most model configurations captured the UHI, but differences in performance indicated the need for further research and intensive experimental campaigns to improve modelling accuracy in urban areas. They found that most PBL height modelling schemes significantly underestimated PBL height at night, with only one scheme reproducing PBL height consistently. They found using the most sophisticated urban canopy model did not improve the model performances in general and had an adverse impact on PBL height and sensible heat flux as compared to measurements.

For air quality modelling, Diémoz *and others* (2019) found modelled PM₁₀ concentrations to be 4–5 times lower than the those measured, and maxima were anticipated in time by 6–7 hours. They suggest that underestimated concentrations were likely due mainly to deficiencies in the emission inventory and to water uptake of the advected particles not fully reproduced, highlighting the importance of a robust emission inventory and an understanding of the composition of particulate pollutants and the influence of this on properties such as water uptake. In Travis *and others* (2022) models applied in East Asia were found generally to underestimate sulphate during haze events and overestimate nitric acid and the gas–particle partitioning of nitric acid to aerosol. Model underestimates in deposition could be explained by missing treatment of turbulence driven by the UHI effect and by the heterogeneity of the urban landscape, which would also increase the surface area available for deposition. Observations of O₃ and nighttime mixed layer height implied insufficient nighttime mixing and an overly rapid collapse of the afternoon mixed layer in the model. These were attributed these errors to the premature shutdown of afternoon eddies and missing treatment of the UHI effect that typically generates a positive nighttime heat flux. They suggest that future studies require models that can simulate a large domain to calculate long-range transport but include the detailed parameterizations of the urban environment such as the UHI effect are required to successfully simulate nitrate.

3.2.7 Forecasting

Only a small proportion of studies (n=24, 16%) made mention of forecasting thermal flows. Of these, several studies only made mention of forecasting to comment on its difficulty, need and usefulness or as an area for future consideration and did not attempt to forecast thermal flows as part of their study.

Studies concerning CAD provided the most insight into the challenges and opportunities when forecasting thermal air flow forecasting. Sabatier *and others* (2020) highlighted that fine-resolution models and orography particularly improved initialisation of snow cover at high resolution which is required for the accurate forecasting of thermal air flow effects in mountainous areas. Borys *and others* (2006) also found snow cover to be an important factor when investigating which factors most influence accuracy of real-time numerical simulations of a CAP in a mountain valley in Colorado, USA. They also found that the simulations conducted at a resolution close to that used for operational regional mesoscale forecasting are unsuccessful at reproducing the CAP effects, and that the resolution required to simulate the cool air pool effects more successfully are not likely feasible for operational use in the near future. Likewise, Whiteman *and others* (2001) highlighted the challenges of the forecasting CAPs due to the large number of processes and multiplicity of scales required to simulate their build up and breakdown. The timing of CAP breakup is particularly challenging to forecast as passing low pressure systems can prevent breakup. Forecasting other meteorological phenomena (e.g. precipitation type and timing, temperature maxima and minima) depend on the CAP forecast. Sekuła *and others* (2021) used the Application of Research to Operations at Mesoscale (AROME) model to forecast meteorological conditions over 24-hour intervals during foehn wind episodes in Krakow, Poland, and compared the results against data collected from four meteorological stations. Generally, parameters could only be predicted within relatively wide margins; wind speed could be forecasted within $\pm 2 \text{ m s}^{-1}$, air humidity within $\pm 20\%$, and air temperature within $\pm 5 \text{ }^\circ\text{C}$ margin.

Only two studies that looked at sea-breeze wind effects made any substantive commentary on forecasting. Igel *and others* (2018) stated that large-scale winds are well simulated when forecasting sea-breeze effects, although better representation of sea surface temperatures may lead to improved forecasts. Zhang *and others* (2020) used CMAQ to forecast hourly O₃ in New York, USA. Sharp spatial gradients of O₃ were observed via on-road measurements the Long Island coastline but failed to be replicated in the model forecasts. However, it is worth noting that the CMAQ model was run at a relatively coarse resolution of 15 km.

One study (Li *and others*, 2017), made mention of forecasting in relation to urban health island effects. They found that incorporating MODIS land surface parameters into the WRF-Chem model improved the accuracy of meteorological forecasts.

3.3 Parameters used when assessing thermally generated air flows

A key objective of this study is to identify features within an area that indicate potential for local thermally driven movement of air to arise, which may impact upon the movements of air pollution and subsequent exposure risk.

In this section we consider what those features might be and when they might be of sufficient magnitude, either in isolation or in combination, to warrant inclusion in an air quality assessment.

3.3.1 Meteorological

The quality and uncertainty associated with input data has a direct influence on uncertainty in conclusions drawn from it and contributes to the variance associated with model outputs. Several references describe their approach to quality control of data, with seemingly anomalous data being checked (Wang *and others*, 2022a) and the presence of biases in data, such as might arise from meteorological stations not being optimally located (Borys *and others*, 2006).

Temporal gaps in time series data could prove a source of uncertainty and invalidate certain statistical approaches. Various methods of gap-filling may be appropriate. For example, in Darby (2005) if an occasional one–four consecutive hours were missing from a station and the data could be easily interpolated over the missing hours (i.e., no significant change in wind direction or speed was indicated by the measured data bracketing the missing data), then a linear interpolation was performed to fill in the gaps. Otherwise, the station had to be dropped from the cluster analysis being undertaken, because for the cluster analysis to work, continuous data are required.

Spatial paucity of data can to some extent be compensated for statistically by extrapolating from values measurement locations. In Kim *and others* (2020) an inverse distance interpolation is used, with due consideration of kinematic effects of the terrain, slope flows, blocking effects and convergence or divergence of flows. Mallet *and others* (2005) also make use of spatial interpolation, in this case to interpolate between air quality measurements to produce an estimate of the concentration field. In this case they make use

of kriging, which differs from a simple inverse distance approach in that it makes use of specific functions (these can be derived experimentally) that describe the progressive decoupling of values with increased separation, and hence the reliability of estimates away from measurement points.

Ultimately, however, the quality of an estimate of a parameter depends on the use of an appropriately designed monitoring network (which may be informed by modelling).

3.3.1.1 Wind speed and direction

Given that wind speed and direction are key properties that change in response to thermal gradients it is unsurprising that all studies reviewed here consider these parameters, and that around half of them describe taking field measurements. These range in complexity from single ground location measurements, through wider networks to remote measurements.

Numbers of ground sites reported per study vary from 1 to over 100; for example, Brandsma and Wolters (2012) used one site, Aman *and others* (2023) used 5 sites, Fung *and others* (2005) had 14 sites, Di Virgilio *and others* (2018) had 30 sites, Keeler and Kristovich (2012) had 66 while Torres-Vazquez *and others* (2022) and Wang *and others* (2022b) had 131 and 135 sites respectively. Some studies installed bespoke networks, others made use of measurements from existing monitoring stations such as those run by environmental or meteorological services while some used both; for example, Kitada *and others* (1986) made use of surface wind data from 41 permanent and an additional 20 temporary locations plus information from two regional stations. The more bespoke approach allowed placing of sites to explore particular questions; for example, Barr and Orgill (1989) refers to measurements taken at the crest of a ridge, while Borys *and others* (2006) looked at points on the east side of a valley.

Frequency of measurement generally reflected the rapid timescales of change in thermally driven local flows, with hourly averaged data being common, up to 10 Hz where higher speed sonic anemometers were deployed to provide turbulence as well as average wind speed and direction data (see below).

Most ground measurements were taken at the standard heights of 2 and 10 metres, the former being the more common for reasons of ease of access. For example, Lopez-Coto *and others* (2020) used 85 ground-based monitors measuring at both heights. Some studies made use of masts and towers to gain more comprehensive vertical wind profiles that could be used to understand changes in speed and direction of wind with height and vertical fluxes of momentum and scalars such as heat or pollution. For example, Karttunen *and others* (2022) uses a 31 m mast, while McRae *and others* (1981) made use of a ship to record at 4.2, 7 and 22.5 m. Studies focusing on urban effects included measurements at various heights and locations to reflect influence of the “urban canopy”, with Barbano *and others* (2020), for example, deploying sonic anemometers at ground level, mid street canyon and rooftop.

More extensive measurements of vertical wind profile can be achieved using balloons – either tethered (Naemura *and others*, 1997) or released as pilot balloons (McRae *and others*, 1981). A number of studies (Han *and others*, 2020; Karlický *and others*, 2018; Keeler and Kristovich, 2012; Kitada *and others*, 1986; Li *and others*, 2018; Li *and others*, 2014; Malakooti and Bidokhti, 2014; Orgill, 1989; Rife *and others*, 2002) use radiosondes, with the advantage that these can be tracked remotely and carry additional instrumentation for other meteorological parameters. Other *in situ* measurements are made using aircraft, either manned or unmanned (Finardi *and others*, 2018; Geddes *and others*, 2021; Loughner *and others*, 2014; Mallet *and others*, 2005; Orgill, 1989; Pace *and others*, 2015; Reid *and others*, 2008; Saïd *and others*, 2007; Wang *and others*, 2022b). Commercial aircraft record and share meteorological data reports and Geddes *and others* (2021) used these to gain 20 m vertical resolution data. Orgill (1989) used radiosondes and aircraft to explore transitions from nocturnal drainage to up slope and up valley winds.

Several remote sensing technologies have been used to measure atmospheric structure and motions. Doppler LIDAR was referred to several times (Campbell *and others*, 2016; Carter *and others*, 2012; Li *and others*, 2018; Werner *and others*, 2006), with Li *and others* (2018) describing its use to derive winds at 15 levels from 8 to 325 m at 1 min time resolution. Pace *and others* (2015) described the use of acoustic sonic detection and ranging (SODAR), a technique that can be used to probe atmospheric stratification. Others carry out wind profiling by radar (Darby *and others*, 2007; Kang *and others*, 2022a; Keeler and Kristovich, 2012; Lappin *and others*, 2024; Li *and others*, 2015; Saïd *and others*, 2007; Werner *and others*, 2006; Whiteman *and others*, 2001; Zhang *and others*, 1998).

3.3.1.2 Temperature and humidity

Fine-scale differences in temperature are fundamental to studies of thermally-generated local and mesoscale winds, and so it is unsurprising that half of the papers reviewed explicitly describe temperature measurements made during or obtained for their studies.

As with wind velocity information many of these involved ground stations and numbers of sites ranged from 1 to 82 sites. The majority of these refer to air temperature (for example Aman *and others* (2023), Darby *and others* (2007), Di Virgilio *and others* (2018), Hai *and others* (2018), Li *and others* (2014), Saïd *and others* (2007), Sekuła *and others* (2021), Yang *and others* (2024)). Where a measurement height is given, this is generally 2 m (for example Hai *and others* (2018), Li *and others* (2014), Torres-Vazquez *and others* (2022), Xie *and others* (2016a)), with some sites adding 10 m measurements (Loughner *and others*, 2014). An exception was Podstawczyńska and Chambers (2018), where vertical temperature gradient was measured between 0.2 and 2 m above ground level in a study on radon flux from the ground. Brandsma and Wolters (2012) describe supplementary coverage achieved by bicycles equipped for temperature measurements, Loughner *and others* (2014) mention measurements from a ship, while Varentsov *and others* (2021) refer to use of crowd sourced data to supplement an already dense urban and surrounding network. Sekuła *and others* (2021) used 4 met stations to compare air temperature on a hilltop and valley floor, while Sharma *and others* (2016) measured at rooftop height. Li *and others* (2013) also considered anthropogenic heat contributions, of potential importance for urban canopy modelling.

In situ measurement of temperature profiles over greater heights were obtained using tethered balloons (Fritz *and others*, 2021; Naemura *and others*, 1997) and radiosondes (Karlický *and others*, 2018; Li *and others*, 2018; McRae *and others*, 1981; Orgill, 1989). The latter are more restricted than the former in that frequency of measurement is limited by the number of sondes that can be released over a period of interest, with 2-hourly being the shortest interval mentioned (Rife *and others*, 2002). Aircraft measurements were also used (Loughner *and others*, 2014; Lu *and others*, 2003; Orgill, 1989; Pace *and others*, 2015; Wang *and others*, 2022b; Zhang *and others*, 1998).

Remote sensing of air temperature could be carried out using an infra-red camera (Mott *and others*, 2019). Reference was also made to thermal data being extracted or inferred from wind profiling measurements made by radar (Pace *and others*, 2015; Zhang *and others*, 1998) and acoustic soundings (Zhang *and others*, 1998).

Surface temperatures, including those of land, sea and inland water, are a key parameter for measuring, modelling and interpreting local and regional thermal flow evolution. Some references allude to direct measurements made at the surface (e.g., Trigo *and others* (2008)) but many more make use of remote sensing information, particularly from satellites (Aman *and others*, 2023; Hereher *and others*, 2022; Lopez-Coto *and others*, 2020; Mutani and Todeschi, 2020; Muzaky and Jaelani, 2019; Tian *and others*, 2024). Aman *and others* (2023) and Hereher *and others* (2022) specifically mention use of MODIS satellite data, while Muzaky and Jaelani (2019) refers to Landsat 8's Band 10 data.

Humidity is a significant parameter in that atmospheric water vapour has a high specific heat capacity and so can absorb energy as latent heat which would otherwise manifest as a measurable increase in temperature (sensible heat). It is measured at many of the sites recording temperature, including fixed sites, balloons and sondes, and aircraft. It is generally reported as Relative Humidity (RH, the fraction present of the total moisture the air can hold at a given temperature) but in some cases dew point is given (temperature at which RH reaches 100%, and hence an absolute measure of moisture in the atmosphere). Torres-Vazquez *and others* (2022) gives water vapour mixing ratio, another absolute (i.e. not temperature dependent) measure defined as the ratio of mass of water vapour to the mass of dry air present.

3.3.1.3 Radiation balance

The difference between incoming and outgoing energy determines rises and falls in temperature and so are important for measuring, modelling and interpreting local and mesoscale thermal winds. Twenty-two papers mention collecting radiation data explicitly. At the most basic level Ohashi and Kida (2002b) records duration of sunshine. Mutani and Todeschi (2020) discusses two methods of inferring solar irradiation from sunlight duration – the Angström-Prescott formula and use of a sky view factor, being the percentage of visible sky at specific locations. Others (Aman *and others*, 2023; Reid *and others*, 2008; Ryu *and others*, 2013) record solar radiation directly, giving a better quantitative account of incoming energy over time. Some studies record net radiation, and consider both the incoming and outgoing energy, at both short- and long wavelengths. For example, Grimmond *and others* (2004) uses a net radiometer measuring incoming and outgoing short- and long-wave

radiation, while Karttunen *and others* (2022) uses a four-component net radiometer on a 31m mast at 1 minute resolution.

Cloud cover has a significant impact on radiation balance; Mott *and others* (2019) used data from clear days only since cloud led to high spatial variability in temperature, and 10 references mention measurement of it. Diémoz *and others* (2019) uses data from continuous LIDAR ceilometers, while Geddes *and others* (2021) relies on satellite remote sensing of cloud fraction.

3.3.1.4 Atmospheric structure

While the mean wind direction and speed give a general direction of advection of air pollutants their dispersion vertically and laterally, and their fluxes to and from the surface, are driven by turbulence in the atmosphere. This is determined in part by the underlying surface roughness, but it's exacerbation or damping is strongly impacted by vertical temperature profile. Cooling with increasing height at less than the adiabatic lapse rate leads to a more stable atmosphere which suppresses turbulence and vice versa. Where an inversion occurs, with temperature increasing with height, then this damping is sufficient to act as a barrier to the vertical spread of pollution. A raise in inversion height effectively dilutes pollution concentration in the area below, while a low inversion can lead to high concentrations of pollutants emitted below the inversion. Atmospheric stability is referred to in 9 of the papers reviewed. It can be determined from temperature profile measurements such as those using radiosondes (McRae *and others*, 1981). Inversion height can also be determined using LIDAR (Pace *and others*, 2015), since there is a disjoint in aerosol concentration at the inversion boundary that leads to enhanced backscatter, and by SODAR (Fung *and others*, 2005) since the refractivity of the air changes with temperature. Li *and others* (2017) and Li *and others* (2013) mention boundary layer height only. Karlický *and others* (2018) and Qian *and others* (2022) refer to stability indices. Of these a common system is Pasquill stability category; the six discrete categories range from very unstable to very stable and are defined in terms of solar radiation, wind speed and cloud cover. A more continuous and quantitative measure, used in Pace *and others* (2015) and Ren *and others* (2023), is Richardson number, a dimensionless number relating change in temperature and windspeed to height above the surface shear. Another dimensionless number used (Baik and Han, 2008; Barr and Orgill, 1989; Karlický *and others*, 2018) is the Froude number, which looks at the ratio of gravity and inertial forces on a flow and hence the likelihood of a flow moving over or being deflected around a physical obstacle. This number is affected by air temperature; for example, cooler air gives a lower Froude number indicating that the flow is more likely to be blocked by an obstacle. A widely used parameter indicating degree of atmospheric stability in the Monin-Obukov length; it is commonly used in boundary layer and pollution dispersion modelling, but was rarely mentioned in any of the papers reviewed (Li *and others*, 2013; McHugh and Ellis, 2001).

Measurement of turbulence can provide information on the flux of momentum and scalars such as heat and air pollutants to and from a surface, and on their rate of dispersion. A number of papers describe measurement of turbulence in situ, using sonic anemometers which can sample air velocity at a high enough rate (10 Hz) to capture most of the spectrum of atmospheric turbulence. Finardi *and others* (2018) describes use of a network of 42 of

these, while Li *and others* (2018) describes 10 Hz measurements at 15 heights from 8 to 325 m.

3.3.1.5 Other meteorological parameters

Precipitation is considered as a parameter in 12 papers (including (Campbell *and others*, 2016; Cheng and McColl, 2023; Cholakian *and others*, 2023; Fares *and others*, 2009; Han *and others*, 2020; Lee *and others*, 2013; Lin *and others*, 2021; Økland, 1990; Wang *and others*, 2022b). It may have a number of impacts on atmospheric structure, such as cooling the land surface and raising humidity. In the form of snow, it can affect albedo. Darby (2005) describes using 24-hour averages from the nearest weather station to their study. Karttunen *and others* (2022) relies on a rain gauge while Klein *and others* (2016) makes use of satellite data.

Atmospheric pressure is mentioned in Baumann *and others* (1997), Diémoz *and others* (2019), Fares *and others* (2009) and Lu *and others* (2009), with Mallet *and others* (2005) recording vertical profiles measured by aircraft.

Some papers make reference to Ventilation Coefficient, the product of wind speed and the height through which pollution can be mixed (generally capped by an inversion), as an indicator of how well pollution will be dispersed.

3.3.1.6 Meteorological observations and their significance

The meteorological observations above play an important role in identifying thermal winds, the conditions they occur under and the physical factors which influence them. Various thermal wind types were detected, including sea breeze (Aman *and others*, 2023; Atlas *and others*, 1983; Augustin *and others*, 2020; Igel *and others*, 2018; Jiang, 2012; Miller *and others*, 2003), UHI air movement (Baik and Han, 2008; Barbano *and others*, 2020; Han *and others*, 2020; Huang *and others*, 2020; Karl *and others*, 2020; Kimura and Takeuchi, 1978; Liu *and others*, 2018; Yang *and others*, 2024; Yu and Sun, 2024), valley winds (Barr and Orgill, 1989), up-slope flows (Baumann *and others*, 1997) and CAP and dispersion (Whiteman *and others*, 2001).

Several papers consider the evidence for occurrence of, or conditions likely to be associated with, local and mesoscale thermal winds. These include appropriate synoptic conditions such as low winds and clear skies (Aman *and others*, 2023; Fung *and others*, 2005; Igel *and others*, 2018; Pace *and others*, 2015), detection of simultaneous rapid changes in surface wind vector, temperature and relative humidity (Augustin *and others*, 2020; Miller *and others*, 2003), soil moisture (Igel *and others*, 2018), anthropogenic heat contribution (Xie *and others*, 2016a), and factors affecting radiation flux (Yang *and others*, 2024) such as cloud cover (Di Virgilio *and others*, 2018). The interactions of these parameters are explored statistically by regression analyses by Yang *and others* (2024) while Varentsov *and others* (2021) highlights the potential for using machine learning techniques to study UHI patterns.

Turbulence and atmospheric stability were found to be important interlinked parameters in terms of both formation and impact of local thermal winds. Turbulence enhances the rate of mixing of air, breaking down temperature gradients and impacting on rate of surface

radiative cooling (Barr and Orgill, 1989). Karttunen *and others* (2022) observes that temperature fluctuations are generally produced by thermal turbulence in unstable conditions, and mechanically induced turbulence in stable conditions. Cheng and McColl (2023) notes that increased turbulent mixing at the surface, caused in this case by anomalous surface roughness, decreases land surface temperature and outgoing longwave radiation. As mentioned previously, stable atmospheres tend to dampen turbulent mixing and so help maintain the temperature gradients that drive local thermal winds. This aligns with the observations that thermal winds occur most readily under stable conditions. Note, however, that the elevated temperatures of UHIs can enhance vertical mixing by thermally generated turbulence, raising the height of the atmospheric boundary layer while mixing pollutants throughout it, leading to lower concentrations of pollution at ground level (Xie *and others*, 2016a).

Humidity is an important parameter since flux of heat energy may involve sensible (directly measurable) heat and/or latent heat that used in change of state (evaporation/condensation) of water. Karttunen *and others* (2022) expresses this in terms of the Bowen ratio (ratio of sensible to latent heat flux), They found high Bowen ratios in low vegetation city centres, implying that most energy is used in heating the air. Several papers discuss the role of vegetation in reducing the UHI effect, with Liu *and others* (2018) describing how an increase in vegetation cover of 10% can reduce temperature by 2°C. Evapotranspiration is implicated.

Radiation balance impacts local temperature and consequently plays a significant role in creation of the temperature gradients that give rise to thermal winds. Radiation measurements may therefore provide insights into their occurrence and provide appropriate parameterisations for models. Fung *and others* (2005) found net solar radiation of around 30 mW cm⁻² were associated with high pollution days. Radiation measurements in Karl *and others* (2020) showed the influence of shading within street canyons, resulting in greater turbulent fluxes when the street level receives direct solar radiation.

Concentrations of some pollutants can interact to influence thermal characteristics of the atmosphere. Aerosols can influence radiation flux and once deposited, albedo. For example, Wang *and others* (2022a) concludes that black carbon aerosol plays a key role in aggravating an UHI, particularly at night. Han *and others* (2020) discusses seasonal variations in UHIs; in summer the presence of aerosols lowers surface temperatures more in urban than rural areas due to their higher concentrations and offsetting urban heating, weakening the UHI, while in winter the presence of aerosol weakens near-surface heat transport over urban areas. Another feedback mechanism is given in Lappin *and others* (2024), which describes the significance of aerosol for cloud formation, which in turn impacts on thermal breeze formation. Aerosols also proved a useful diagnostic for identifying air mass origins; Lee *and others* (2013) found less aging in aerosols in air of oceanic influence and more aged aerosol in coastal and continental air masses.

The Interaction between mechanical and thermal effects in non-flat topography can be hard to tease apart since effects are closely interlinked; differential heating due to different angles of insolation and orientation of slopes generates temperature gradients, while slopes provide the means for colder air to create drainage flows culminating in CAP. Topography may channel or be a barrier to thermal flows, blocking or deflecting them according to the Froude

number of the flow (Karlický *and others*, 2018). The shape of the coastline can influence sea breeze behaviour inland (Atlas *and others*, 1983). Jiang (2012) describes how deviation from a straight coastline can lead to differences in the progression of the local wind over time with, for example, horizontal convergence and divergence of winds on a sinusoidal coastline leading to different rates of the vertical subsidence that completes the sea breeze circulation. Pace *and others* (2015) used a combination of ground-based, aircraft and remote sensing measurements to analyse a domain affected by topography, sea breezes and synoptic scale air movements; they found a reasonable comparison to their modelled predictions. Changes in surface roughness can increase turbulent mixing.

Interactions can occur between different thermal winds, such as sea breezes impinging on UHIs. Carter *and others* (2012) were able to demonstrate this.

Precipitation can both influence and be influenced by local and mesoscale thermal flows. Baik and Han (2008) describes how the advection of rising air from an UHI could initiate moist convection resulting in downwind precipitation. Xie *and others* (2016a) explore the impact of including anthropogenic heat emissions in their UHI model show temperature increases of 0.5 to 1°C, leading in turn to altered moisture distribution and a 15-30% increase in precipitation in cities.

3.3.2 Land use

Seventy studies (47%) consider or make mention of land use in the study area. The majority of these studies concern thermal flows around UHIs, of these, most use freely available datasets, derived from satellite data. For example, Hussein and Assaf (2023), Kang *and others* (2022b), Wang *and others* (2022a), Xie *and others* (2016a), Xie *and others* (2016b) and Zhu *and others* (2015) used MODIS land cover data. MODIS is an instrument aboard two satellites; Terra and Aqua, which view the entirety of the Earth's surface every 1-2 days (MODIS, 2025). Xie *and others* (2016a), Xie *and others* (2016b) and Zhu *and others* (2015) used the MODIS 20 category land data at a 30 arcsecond resolution (equivalent to approximately 1 km).

Other satellite-derived datasets were also used, including the European commission Coordination of Information on the Environment (CORINE) land cover (CLC) inventory; Huszar *and others* (2020), the latest version of CLC which uses data from dual date satellites; Tian *and others* (2024) used China's land use and land cover datasets derived from Landsat satellite images on Google Earth. Local climate zone data were used by several studies (Alghamdi *and others*, 2021; Biggart *and others*, 2021; Varentsov *and others*, 2021; Zhang *and others*, 2021), which is a universal classification scheme comprising of 17 zones based on surface cover and structure properties (Huang *and others*, 2023) and often derived from using satellite imagery. Three studies used models to classify land-use; Cosgrove and Berkelhammer (2018) used the Noah land surface model, Karlický *and others* (2018) used WRF land-use inputs, and Malakooti and Bidokhti (2014) used urban land use information defined by WRF preprocessing systems and terrain modules of the MM5 model, alongside land use data from Geographical Information System (GIS) databases. Some studies did not explicitly define land use but did consider other surface

properties which affect air flows, such as vegetation cover (e.g. Huang *and others* (2020) used MODIS vegetation data), and/or building height (e.g. Hrebtov and Hanjalić (2019) used building maps to weight buildings by height), whilst others simply provided land use maps (Podstawczyńska and Chambers, 2018; Sharma *and others*, 2016; Zhong *and others*, 2018).

Of the studies concerning thermal flows during land/sea breeze events, most studies opted to use models to classify land use, often in hybrid with satellite data or other databases. Igel *and others* (2018) used the Land Ecosystem-Atmosphere Feedback (LEAF-3) surface model, which is a sub-model of RAMS; Fung *and others* (2005) used a meteorological model, which was formed of the MM5 model with a detailed database of land use entries at a resolution of 0.5 km. Ohashi and Kida (2002b) used the DryARD model and LPDM, which incorporated land-use data with a horizontal resolution of 100 square meters, divided into 11 categories to include buildings, rice paddies, and forests. Karttunen *and others* (2022) used a LIDAR-derived digital surface model, provided by the University of Helsinki.

Only one study concerned CAD flows and land use data; Rife *and others* (2002) used the US geological survey earth resources observing system and stated the soil type database at a 1 km resolution to feed into a surface model.

3.3.3 Topographical

Sixty-two studies (42%) consider or make mention of topography in the study area the majority of which simply describe and/or provide a map of the topography in the study area (e.g. Anabatic and katabatic flows: (Barr and Orgill, 1989; Baumann *and others*, 1997; Borys *and others*, 2006; Glojek *and others*, 2020; Jiang *and others*, 2011; Whiteman *and others*, 2001); Sea breezes: (Geddes *and others*, 2021; Jin and Raman, 1996; McRae *and others*, 1981; Miller *and others*, 2003); UHIs (Han *and others*, 2020); other/combinations of thermal flows (Hai *and others*, 2018; Hu *and others*, 2022; Matola de Miranda Cardoso *and others*, 2024; Ren *and others*, 2023; Saïd *and others*, 2007; Werner *and others*, 2006; Zhang *and others*, 1998)).

Some studies accounted for topographical effects within modelling. Studies using the WRF model accounted for topography by either using the standard model setup (e.g. (Karlický *and others*, 2018; Li *and others*, 2017; Malakooti and Bidokhti, 2014; Niwano *and others*, 2007; Sharma *and others*, 2016)), and/or using more advanced setups. For example, Torres-Vazquez *and others* (2022) coupled the Pleim-Xu land surface model to WRF to account for topography. Karlický *and others* (2018) used both the WRF model and the Regional Climate Model version 4 (RegCM4) to assess how different types of urban parameterisations affect the simulation of urban climate phenomena including the UHI effect in Central Europe; USGS-based data are used to represent topography in a standard RegCM4 setup. A provision setup of the HRRR model, which is based on an advanced research version of WRF, was used during a wind forecast improvement project to better predict CAD flows conducted in the Western US (Arthur *and others*, 2022).

Other models noted in the studies include the MM5 model, used by Malakooti and Bidokhti (2014) who utilised the terrain model (and considered other factors to compliment topography, such as vegetation height, vegetation density and building height) when modelling UHI effects in Tehran, Iran. Sekuła *and others* (2021) used the AROME model, to study the role of foehn winds on PM₁₀ concentrations in Krakow, Poland. Mott *and others* (2019) used the ARPS model to simulate katabatic and other atmospheric flows in the German Alps, accounting for topographical differences due to snow cover, which were measured using high-resolution surface measurements conducted with a terrestrial laser scanner.

Digital elevation data were also used in several studies. Yu and Sun (2024) used a digital elevation model (DEM) to designate urban and non-urban topography when quantifying the spatiotemporal distribution of UHI intensity in China. Agathangelidis *and others* (2020) used a digital surface model at 0.8 m resolution and a digital terrain model at 5 m resolution to characterise topographical features when assessing thermal flows in Athens, Greece. Seo *and others* (2014) considered topography based on USGS data and a DEM in South Korea, although they do not state the resolution at which these were used. Kim *and others* (2020) accounted for surface elevation by using the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global digital elevation model version 2 (ASTGTM2) when simulation pollution dispersion in a coastal megacity, Ulsan, in South Korea.

Other methods of defining and incorporating topography include use of satellite data (Li *and others*, 2013), lab-scale modelling (Reuten *and others*, 2007), GIS data (Hrebtov and Hanjalić, 2019) and idealised orientated valleys (Rendón *and others*, 2015). Li *and others* (2013) investigated the intensity and spatial patterns of UHI and sea breezes in Singapore; although the authors state that there is no pronounced topography in Singapore (with the highest natural point 164 m above sea level), nonetheless high-resolution Shuttle Radar Topography Mission data were used to represent the terrain. Reuten *and others* (2007) investigated air flows over sloped terrain in Canada using a combination of numerical models, field observations and water tank experiments; in the latter topographical features were mimicked. Hrebtov and Hanjalić (2019) generated terrain orography information from GIS data when investigating air quality effects of UHIs in Russia. Rendón *and others* (2015) investigated how the orientation of an urban valley influences local atmospheric dynamics and pollutant concentrations in an idealised simulation; topography was considered by using idealised north to south and east to west orientated valleys in the simulation.

3.4 Frequency

Of the 14 references that explicitly mention frequency of thermal wind occurrences, 9 refer to sea-land breezes. Of these some make only generic observations about the circumstances when sea breezes occur; Ohashi and Kida (2002b) concludes that the frequency of sea breezes in Japan is influenced by the presence of urban areas and surrounding mountains; Lu *and others* (2009) discusses the seasonal variation of land-sea breezes during different seasons, with winter more likely to produce the synoptic conditions

necessary to allow the thermal wind to develop. In a global review of sea breezes Miller *and others* (2003) finds that sea breezes are a common phenomenon in coastal regions and can occur almost daily during certain times of the year, especially in areas with consistent thermal contrasts between land and sea; Reid *and others* (2008) notes that sea breeze phenomena can be observed on most days of the year over the Arabian Gulf coastline.

Several studies quantify occurrence of sea breezes over various periods of recording. McRae *and others* (1981) monitored in Southern California for 8 days, of which 2 showed evidence of a sea breeze. McLaren *and others* (2010) reports monitoring in the Lower Fraser Valley near Vancouver, where sea breezes occurred on 9 out of the 13 nights recorded. Augustin *and others* (2020) looked at 2 months in summer in the vicinity of Dunkerque, over which they observed 27 sea breeze episodes; these tended to begin around 9:00 and last until around 20:00. Geddes *and others* (2021) looked at the months from June to August from 2010 to 2019; they identified sea breezes on an average of 28 sea breeze days, albeit with considerable interannual variability. Hu *and others* (2019) provide detailed data over a 12-month period in Southeast China; each month was identified as having at least 1 day of sea breeze, with 4 days being the mode and 8 days the maximum.

Rife *and others* (2002) describe a similar phenomenon, the “salt breeze”, associated with lake breezes from the Great Salt Lake and Utah Lake, USA. These frequently penetrate far inland and interact with local circulations. These include early evening drainage flows from nearby terrain which occur commonly, typically initiating around sunset.

Nocturnal drainage winds are found to be a consistent night-time phenomenon in Colorado, USA (Orgill, 1989). Upslope anabatic winds reliably develop each morning as the valley sidewalls heat up after sunrise. The transition from nocturnal drainage winds to upslope winds occurs around 7am. However, Baumann *and others* (1997) describe upslope thermal winds near Denver, Colorado, USA as “occasional”.

While not necessarily evidence of drainage winds the occurrence of CAP events could be considered an indicator of conditions under which such winds might develop. Westburg *and others* (1977) and Whiteman *and others* (2001) describe CAP events in the Columbia Basin, USA; on average the area experiences 11.6 CAP events per winter.

3.5 Impacts and significance

3.5.1 Meteorological impacts and their general significance for air quality

Many (around 30) of the papers reviewed presented observations of the impacts of local surface temperature differences on local and mesoscale meteorology. Many of these involved climatic conditions with greater extremes than those found in England, but while little work was found on England specifically some studies were carried out in conditions that might be considered applicable to the situation in England, either now or in the foreseeable future.

3.5.1.1 Slope flows

While anabatic and katabatic flows and their consequences, such as CAD, cold pooling and containment within channels, are described in standard textbooks few papers were identified in this search which focused exclusively on them, perhaps reflecting that the formative work in that knowledge area was largely carried out some time (decades) ago. Their consideration in more recent literature is generally in the context of their interaction with other types of thermal flow (see below).

The papers that did consider them in isolation focused on thermal extremes. Three considered hot climatic conditions; Orgill (1989) and Baumann *and others* (1997) describe an experimental campaign carried out in Colorado, USA. Studying a valley they found that nocturnal drainage winds occurred, driven by cooling of the valley floor and side walls, resulting in wind speeds of 4-8 ms⁻¹ around 100 m above the valley floor. After sunrise they observed an early morning transition to up-valley winds and flows up the valley sides as these became heated. The up-valley winds effectively ventilated the valley of a tracer simulating pollution released in the valley. Occasionally they found that the effect of synoptic wind was overridden by the thermally driven upslope flow which showed its influence over a considerable distance, drawing in polluted air masses from a nearby urban region. Jiang *and others* (2011) looked at dust transport in Owen's valley, Sierra Nevada, USA, using modelling and a two-month monitoring campaign. They successfully simulated qualitative features of the flow and dust movement in this complex valley area, including thermal and topographic (mountain wave) influences and coupling and decoupling with regional winds. The study confirmed the importance of up-valley winds in dust lofting and along-valley transport.

Mott *and others* (2019) compared numerical flow modelling with measurements over an alpine ice field. A shallow katabatic flow was predicted and measured. They discuss two competing effects; turbulence generated by the induced flow enhancing the flux of sensible heat to the surface and a strong inversion which may suppress this effect by decoupling the katabatic flow from the air above, inhibiting heat transfer to the surface.

Both cases represent extremes but demonstrate the processes that generate thermal winds in conditions that might occasionally be approached in England during winter freezes or summer heatwaves.

3.5.1.2 Coastal, lake and riverine impacts

Miller *and others* (2003) describe a comprehensive review of sea breeze systems globally, noting that they are a common phenomenon in coastal regions and can occur almost daily in some regions at certain times of year, especially where there is consistent thermal contrast between land and sea. They conclude that sea breezes significantly influence local weather patterns and air quality and call for continued research to improve forecasting and better understand their effects on air quality.

Westburg *and others* (1977) gives an example of the influence of a sea breeze on air quality. In Connecticut, US, a well-developed sea breeze pattern led to a reduction in pollution

concentrations in coastal areas as sea air arrived and helped to disperse pollutants. However, it was also associated with elevated pollution concentrations further inland where pollutants were trapped and transported inland by the breeze. The authors note that the interaction of the sea breeze with wider conditions, such as a synoptic offshore breeze complicate the prediction of air quality impacts; a need for better understanding of such interactions is indicated.

Several studies look at the importance of considering the complete circulation of the sea breeze, including the counterflow from land to sea that occurs and the fronts where the flow penetrates inland and where subsidence of the return flow over the water. Fung *and others* (2005) describe a severe pollution episode that occurred in Hong Kong, during which pollutants became trapped within the local sea breeze circulation. Kitada *and others* (1984) describe a numerical experiment in which transport of a suite of chemicals was modelled with constant sea temperature and land temperature fluctuating with an amplitude of 5 °C. Under some circumstances, notably at nighttime when turbulent mixing was low, two distinct peaks were apparent in the vertical pollutant concentration profile, associated with the ground level flow and the counterflow aloft.

The role of turbulent mixing in thermal flows is also mentioned. Karttunen *and others* (2022) describe a study of a coastal urban atmospheric surface layer structure, made using a distributed temperature monitoring network and meteorology from a 31 m tower. Fluctuations in temperature across the network were associated with different levels of turbulence, associated with differing atmospheric stability, and the network was able to track the movement of a front, such as might be associated with penetration inland of a sea breeze circulation.

Water-land temperature differences involving smaller bodies of water have also been found to be significant. Hrebtov and Hanjalić (2019) describes how a river bisecting the city of Krasnoyarsk, Russia, influences concentrations of traffic pollution seasonally despite emissions remaining similar. In winter the river is warm compared to the land; rising air draws cooler air in horizontally from both sides drawing pollutants into the city centre. In summer the river is colder than its surroundings; cool air above it blocks air motion resulting in separate convective flows either side of the river. Jin and Raman (1996) describes Eulerian and modified Gaussian modelling of local circulations seen around the Kennedy Space Centre, USA, an area with sea-land and land-river interfaces in close proximity. These flows increased low-level wind by around 30% over land and decreased it by 30% over the river. The plume of a putative pollutant released from an elevated source (60 m high, 0.5 km inland) was modelled: estimates of ground level concentrations were much lower using the Gaussian than the Eulerian model; the former simulated internal boundary layer growth and consequent shoreline fumigation but was inherently unable to simulate the effects of flow circulation. The Eulerian model captured circulation, which led to greater vertical growth of the plume and lower surface concentrations. Cosgrove and Berkelhammer (2018) considered the influence of Lake Michigan, US, on the fate of heat from the city of Chicago on its shore. The lake acted as a heat-sink, cooling the warm air plume and reducing its extent to around 40 km

3.5.1.3 UHI impacts

Only 5 papers were found which examined thermal winds driven only or primarily by UHI, and quantitative information is sparse. Many more examples were found in combination with other thermal winds, as described below.

UHIs are frequently described in terms of the effect they have on boundary layer height, with thermal mixing during the day leading to greater height and hence a reduction in surface pollution concentration. However, this is a static rather than a thermal flow effect and is out of scope of this review unless linked with advection. Qian *and others* (2022) concluded that the net effect of urbanisation on air quality appears to be dilution of pollution through increased mixing and dispersion within and above the urban canopy, but in low regional wind conditions a dome-like UHI flow can develop, with internal circulation of pollutants but also some drawing in of pollutants from the surrounding area and their ejection into the flow above the UHI “dome”.

Moreira and Albuquerque (2016) describe a semi-analytical solution to the flow produced by an UHI. This demonstrates the theoretical possibility that UHI-induced vertical transport can draw in polluted air to urban areas. Malakooti and Bidokhti (2014) describe a measurement campaign and Eulerian modelling study of Tehran, Iran. This concluded that certain parts of the city were more affected by UHI flows, especially at night, while suburban regions were more influenced by topographically driven flows. A study of the Yangtze River delta (Zhong *and others*, 2018) found that the UHI increased instability and vertical velocity component of overlying air, increasing boundary layer height and ventilation over the urban area and favouring dispersion of pollutants from urbanised areas to their immediate vicinities. Li *and others* (2013) describe the contribution of anthropogenic heat to the overall UHI in Singapore, which they estimate as up to 1.6 °C at the maximum UHI intensity. They also note that boundary layer height has a strong diurnal cycle but that sea breezes reduce the height in coastal areas.

3.5.1.4 Combined Impacts

Seventeen papers considered combined effect of different thermal flows, thermal flows interacting with flows affected by topography through means other than differential heating, and thermal flows interacting with regional winds.

The most complex examples demonstrate how multiple thermal flows amidst complex topographies can lead to flow regimes that can be difficult to predict. For example, Fritz *and others* (2021) considers a mountainous region of Germany, where heterogenous land use and mountainous topography cause complex interactions between valley-scale and local airflows leading to thermal signatures characterized by strong, small-scale variability. Li *and others* (2015) add a further degree of complexity, referring how in a city on the leeward side of a mountain range features interactions between flowing air and pockets of stationary but thermally stratified air. To make predictions in specific, rather than general, terms under such circumstances would require the most sophisticated modelling, together with a detailed understanding of initial conditions and of sensitivity to perturbations in those initial conditions. Nonetheless some inferences can be drawn about potential impacts of thermal

flows in a complex landscape. Matola de Miranda Cardoso *and others* (2024) uses consideration of sea breeze, valley wind and UHI effects and their interaction with topographical features that block or channel flow to describe qualitatively meteorological observations in the region of Rio de Janeiro, Brazil.

The most frequently studied combination (8 papers) is that of water-land breezes with UHIs. Qian *and others* (2022) present a review of the impact of urbanisation on regional climate and extreme weather, which includes consideration of urban, urban/sea breeze and urban/slope flow interactions. Going on from their consideration of UHI behaviour at low prevailing windspeeds they report that in higher winds the higher parts of the “dome” and the pollutants ejected from it may be pushed downwind, with potential for ground level fumigation events to occur.

Other papers give specific examples of these UHI-wind interactions. Simulations around Shanghai, China, in August show a UHI circulation tending to drift downwind, where the driving wind is a combination of prevailing wind and a sea breeze penetrating around 20 km inland. Li *and others* (2014) and Lu *and others* (2009) show that in the Pearl River Delta, China, extra heating in urbanised areas enhances the sea breeze. The urbanisation is spatially heterogeneous so the effect can vary but can impact upon the trapping or dispersal of pollutants. Hai *and others* (2018) describe a sea breeze front approaching Qingdao, China, part of a circulation with a return flow reaching 600m aloft, enhancing the updraft of air within a UHI. Keeler and Kristovich (2012) report on the lake breeze impinging on Chicago, USA, where the breeze front moves inland at average speed of 1.4 ms^{-1} . The daytime UHI did not significantly impact the movement of the lake breeze front through Chicago. However, a strong relationship was identified between the maximum magnitude of the nighttime UHI before the development of the lake breeze and a reduction in the speed of the lake breeze front as it moved through the southwest of the city, indicating that nighttime UHI effects might play a role in slowing down movement of the lake breeze. Sharma *and others* (2016) describe how the interaction between the UHI and lake breeze was affected by green and cool roofs, affecting boundary layer structure and potentially increasing pollution retention near the surface.

Ohashi and Kida (2002a) and Ohashi and Kida (2002b) also describe sea breeze-UHI interactions. In this case the sea breeze was found to distort the UHI dome of a coastal city to a degree where it connected with a second UHI further inland. This enhances movement of coastal pollutants inshore beyond that if only sea breeze advection was taking place.

The chain flow efficiently transported pollutants emitted from the coastal urban area into the lower layer over the suburban area between the two urban sites, prior to the arrival of the sea-breeze front. Because pollutants emitted from the inland urban area were also transported by the heat island circulation into the upper layer over the suburban area, the suburban area could receive high concentrations of pollutants at both levels. The chain flow transported coastal urban pollutants into the inland urban area earlier in time and at much higher concentrations than would have been expected from the sea breeze alone. Complex topography inland adds to the complexity of air movements. The presence of mountains weakened the heat-island circulation, preventing the stagnation of the sea-breeze front and enhancing its inland penetration. This resulted in increased surface temperatures and drier

conditions in suburban areas until the sea-breeze front arrived. A valley circulation played a crucial role in transporting pollutants from suburban areas to mountainous regions.

Qian *and others* (2022) note the significant observation that the influence of the UHI can lead to greater precipitation above and downwind of cities, with consequential impacts on pollution deposition through wet deposition processes as well as more direct air flow-driven dry deposition. Matola de Miranda Cardoso *and others* (2024) also describes how thermal flows can trigger thunderstorms.

3.5.2 Specific Air Quality impacts

3.5.2.1 Particles

Advection of particulate pollution by sea and land breeze circulations is described a number of papers. Chen *and others* (2023), Pandolfi *and others* (2011) and Reid *and others* (2008) describe how particles emitted in coastal locations can be transported out to sea or further inland. Kitada *and others* (1986) describe a flow model incorporating wind observations around Mikawa Bay, Japan; a stable particle tracer inserted into the flow field showed transport far out to sea followed by return inland on a diurnal cycle. In this case the sea breeze was augmented by a mountain valley wind. Sea breezes can combine with synoptic winds resulting in effects which can be unexpected. Perth, Australia, experienced a severe and unexpected episode of poor air quality caused by smoke from wildfires to the west of the city (Leslie and Speer, 1998). These had been forecast to follow a trajectory out over the sea, but a sea breeze contributed to its being returned to shore. Consequently, routine three-dimensional modelling which takes this into account was planned. Flamant *and others* (2018) describe how the sea breeze circulation on the coast of Ghana and Togo can be skewed by interaction with synoptic winds so that its point of return to shore is different from its point of departure.

Thermally driven slope flows are also reported as contributing to transport of PM. Glojek *and others* (2020) and Sekuła *and others* (2021) describe respectively katabatic flows in locations in Slovenia and Krakow, Poland; these carry particle laden air downhill and can lead to a build-up of pollution where pooling of cold air occurs. A modelling study in the Arve valley, France, predicted daytime anabatic winds which led to greater vertical than horizontal transport, raising near-surface pollution to higher altitudes and contributing to the heterogeneity of the pollution field in the area (Sabatier *and others*, 2020). At night a down-valley katabatic flow could transport pollution released in the area to lower levels in the river basin, where they could accumulate because of CAP. However, pollutants released from higher land could be prevented from reaching the surface by the strong capping inversion above this cold pooling. The authors comment on the need for fine resolution understanding of flows in complex terrain areas.

Interactions of thermal flows can add complexity to pollutant behaviours. A complex diurnal pattern of PM_{2.5} concentrations in Beijing, China, could be explained by the combined effect of UHI circulations and mountain katabatic winds (Li *and others*, 2018). During the daytime, increased turbulent mixing and greater boundary layer height resulted in dilution and hence a reduction in near-surface PM_{2.5} concentrations. In the evening reduced turbulence and a reduction in boundary layer height led to increased concentrations, exacerbated by a mountain wind which carried polluted air from the intervening plain to the city. As cleaner mountain air reached the city PM_{2.5} levels fell, and the peak concentration moved downwind

of the city. The stable nighttime boundary layer over the city could eventually decouple the mountain wind from the surface. The following day increasing turbulence could result in polluted air above the city being mixed downwards.

Thermally driven local circulations can impact upon the average composition of atmospheric aerosol. In Shenzhen, China, mixing between sea salt and other aerosols reduced overall aerosol acidity, particularly under sea breeze conditions (Wang *and others*, 2022b). A UHI circulation in Hangzhou, China developed sufficiently to inject pollutants into the free troposphere. Resulting impacts on temperature and Relative Humidity influenced the equilibrium between ammonium nitrate aerosol and its gaseous precursors. In the coastal Mediterranean (Mallet *and others*, 2005; Pace *and others*, 2015) sea breeze-driven recirculation carried aerosol inland; the composition of the aerosol changed over the day with indications of new particle formation and changes in optical properties suggesting an increase in the secondary aerosol component.

3.5.2.2 O₃

O₃ is secondary air pollutant, not emitted directly but formed through photochemical reactions in the atmosphere and impacted by the presence or absence of anthropogenic pollutants that promote its creation (volatile organic compounds) and destruction (NO_x). The relationship between its concentration in the atmosphere and thermally driven mesoscale air flows can therefore be complex and non-linear.

O₃ accumulates in the marine boundary layer due to lower levels of destruction in the relatively clean air over the ocean. It can be brought ashore by sea breezes, leading to elevated levels in coastal areas that are depleted as the air mass encounters higher levels of NO_x inland (Darby *and others*, 2007; Loughner *and others*, 2014; Naemura *and others*, 1997; Seo *and others*, 2014). However, Finardi *and others* (2018) describe how primary pollutants emitted on the coast and transported inland can also result in new O₃ production between the coast and the mountains inland. Griggs *and others* (2024) and Grimmond *and others* (2004) describe how diurnal variation in the sea to land and land to sea breezes influence the timing of peak O₃ concentrations; in Houston, US, elevated nighttime concentrations are most likely with a sea breeze from the Gulf of Mexico, while peak O₃ was routinely preceded within the previous six hours by a period of stagnation during the transition from offshore to onshore breeze.

The sea breeze circulation also plays a part in determining surface O₃ concentration. O₃ concentration increases with height above the surface, and the sea breeze circulation can result in these higher concentrations being brought to the surface (Lin *and others*, 2021; Lin *and others*, 2007). O₃ created during the passage of air inland can be injected into the upper boundary layer at the sea breeze front, transported out to sea in the return leg of the circulation, descend and then be brought back to land, adding to the O₃ produced within the marine circulation (Finardi *and others*, 2018; Niwano *and others*, 2007). This can be enhanced when the sea breeze interacts with valley winds inland (Douglas and Kessler, 1991).

UHIs and associated circulating flows also influence O₃ concentrations. The increase in height of, and turbulence in, the urban boundary layer effectively dilute primary pollutant emissions, leading to reduced destruction and hence increasing concentration of urban O₃ (Huszar *and others*, 2020; Li *and others*, 2017; Ryu *and others*, 2013). Karl *and others* (2020) and Ryu *and others* (2013) describe situations in Innsbruck, Austria, and Seoul,

Korea, where the UHI circulations carry pollutants away from the urban area into surrounding countryside. Here they can react with biogenic O₃ precursors in a lower NO_x atmosphere to create more O₃, which can be drawn into the urban area by the returning UHI recirculation resulting in an accumulation of O₃. In both cases there is interaction of the UHI circulation with valley flows and, in the Korean case, with sea breeze. Ryu *and others* (2013) describe how the valley flows are influenced by the orientation of the valleys involved, which impacts on whether they remain symmetrical or become skewed by the addition of cross-valley circulations arising from differential heating of the valley sides.

3.6 Mitigation

Only 20 (13%) studies made some commentary on mitigating thermal effects, many of the studies made general commentary on mitigation to state that mitigation was required, that different mitigation strategies are needed in different conditions, or that the findings of the study could help design mitigation strategies by means of future work.

Most of these studies that made commentary on mitigating thermal effects concerned UHI effects (n=12). The majority concerned 'greening' interventions (e.g. increasing the number of trees, park areas, green roofs etc.). For example, Knight *and others* (2021) conducted a systematic review of 308 studies to consider the evidence of the effectiveness of such interventions in reducing urban temperature, ultraviolet and ground-level O₃ concentrations. They found that green spaces density and spacing is important for UHI mitigation, and that urban greening generally provides cooling effects and lower NO_x levels but impacts with O₃ is more complex and varied. Di Sabatino *and others* (2020) investigated the nature of UHI with thermal flow and pollution dispersion, comparing urban street canyons in tree lined street versus those without in Bologna, Italy. They found that UHI intensity was mitigated by approximately 40% and reduced mean temperatures (by ~2°C) and wind speeds (by ~0.5 ms⁻¹) when trees were present. Mutani and Todeschi (2020) considered use of green spaces and green roofs as ways to mitigate UHI in Turin, Italy, and generally found that land surface temperature and air temperature decreased as the green areas increased. Sharma *and others* (2016) also explored green roofs as well as cool roofs as a mitigation strategy for UHI and also found reductions in surface temperatures. They also found that interactions between UHI and lake breeze effects were altered by green and cool roofs by affecting regional circulation, boundary layer structure, and potentially increasing pollution retention at ground-level. Huszar *and others* (2020) also highlighted the importance of ensuring mitigation strategies are balanced and do not cause any unintended consequences elsewhere as UHI mitigation effects may cause a reduction in PBL height and vertical turbulent transport, which may decrease ground-level O₃, but increase primary pollutants. Belda *and others* (2021) modelled the impacts of common UHI mitigation measures, including greening, but also changes to surface materials. They found that surface parameters, which influence radiation balance equations, were most sensitive, followed by volumetric heat capacity and thermal conductivity of building walls, whereas other parameters had a limited effect. They also noted competing effects; e.g. improved thermal comfort resulted in deteriorated PM_{2.5} concentrations.

Combined thermal flow effects may mitigate each other. For example, Geddes *and others* (2021) highlighted that cooler temperatures during sea breeze effects can mitigate or eliminate UHI effects, but not always. Hu *and others* (2019) looked at O₃ concentration in

Pingtang, China, and found that as a typhoon approached and wind speed increased and the high-pressure system moved southwards, O₃ was mitigated.

4. Discussion

4.1 Current state of knowledge

4.1.1 An issue for the UK?

This scoping review found a considerable body of work on thermal flow topics, indicating that it is an ongoing source of concern and active research. These concerns include impacts on air quality and on thermal regulation of urban areas, and more direct meteorological outcomes such as rainfall patterns and mechanical effects of variation in wind speed and direction.

References spanned several decades, and track developments over those years. Good progress appears to have been made, but the occurrence of recent work and the number of groups working on the topic indicate that there is more to do. Nonetheless, work to date has resulted in findings that are of immediate relevance to the aims of this project.

There was little information addressing thermal flows in the UK specifically. What there was indicated that thermal flows do occur and can be considered as a potential issue here. While non-UK work covered conditions ranging from hot deserts to alpine snowfields, some took place in more temperate regions with maritime climates that could be likened to UK conditions. Anecdotal accounts of the presence of thermal flows under UK conditions are therefore endorsed by the peer reviewed literature.

4.1.2 Sea breezes

Of the three types of thermal flow that this work considers, those driven by difference in temperature between adjacent land and water were the most represented in the literature. In most cases the water in question was the sea or a large lake, but there were also examples that demonstrated the impact on air movement of smaller bodies of water such as rivers. The latter can give rise to complex movements of air in three dimensions, and it may well be more difficult to assess their potential impacts on airflow patterns.

There were many examples of how these winds impacted on air pollution levels, both positively and negatively; for example, pollutants could be carried out to sea or considerable distances inland. The diurnal nature of sea breezes means that pollutants carried to sea at night might subsequently return on the reversed daytime flow. The recirculating nature of these flows adds another degree of complexity, with the possibility of air pollutants accumulating in the circulation culminating in episodes of high air pollution. A further complexity still is their potential for impact on atmospheric composition, and especially on secondary pollutant formation. O₃ was mentioned several times in this context.

Sea breezes were found to occur frequently, including under northern European conditions. Considering this and their potential impact on the fate of air pollutants there is a robust case

for recommending that the potential for impact of bodies of water be considered when assessing sources of pollution within a few kilometres of them.

4.1.3 Slope flows

Surprisingly few papers were found looking in isolation at thermal flows associated with topography. Those that were found focused on thermal extremes; while those looking at desert conditions are of limited relevance to the UK, those looking at flows over snow and ice are more so since such conditions do occur here.

The paucity of papers published within the timeframe searched perhaps reflects that much foundational work in this area was done in the last century and is embedded in textbooks. More recent work has concerned slope flows in the wider context of their interactions with other types of thermal flow, and this will be discussed below. Quantitative work looking specifically at CAD flows in situations beyond idealised slopes appears to be a relatively recent development, with studies not yet having reached the peer review literature.

Nonetheless some significant features could be identified:

Downslope flows of clean upland air can purge areas of air pollution, while flows of polluted air were seen to transport pollutants downstream. Upslope flows were weaker and by their convective nature not capped in the way a downslope flow is, but they were still observed to transport pollutants into mountainous areas. As with sea breezes, transport of pollutants such as nitrogen oxides and volatile organic compounds into cleaner regions could give rise to formation of secondary pollutants such as O₃.

The stable or inverted temperature profile necessary for CAD means that turbulent exchange of air between the flow and the free air above is suppressed, and can ultimately become decoupled, so that near surface pollution concentrations remain high. Downward flux of heat is similarly suppressed so that the cold surface layer endures. Unlike a static CAP situation, however, the movement of air over the ground generates turbulence mechanically and so a degree of mixing can be restored.

While static CAP is not in itself a thermal flow it can be a consequence of and the ultimate destination for air draining down a finite slope. This will need to be borne in mind when considering the fate of pollutants in channelled flows draining into hollows or onto open plains. It might be tempting to consider dispersion in terms of a dense gas dispersion model, but a more accurate physical description might be that of a pollutant-bearing dense gas flowing into a cleaner, slower-moving or static gas of equal density. Continuity requires that air flowing down the slope must be replaced, and so a circulation may be established with a counterflow aloft.

4.1.4 UHIs

It seems inevitable that urban areas, with their thermal properties and anthropogenic heat sources, would be warmer than surrounding areas, but that the consequences of this would depend on the magnitude of that difference.

Few studies looked at UHI-generated flows in isolation (cases involving interaction with other flows are described below). Those that did found that a key impact was a more unstable lapse rate, leading to an increase in boundary layer height and greater mixing within it. Consequently, during daytime pollution was mixed through a greater depth and concentration at ground level decreased accordingly. Like CAP this initially seems to be a static, or at least contained, situation. However, under low wind speed conditions the rise of air above the urban area can result in an inflow of cooler air from the surrounding area and a circulation may be established, with consequences that include pollution from peri-urban areas being drawn into the city and adding to urban pollutants already accumulating in the circulation. This circulation can acquire sufficient momentum to inject polluted air into the free troposphere above the capping inversion, with consequences for longer range transport.

What was not clear from the literature was how significant UHI-induced flows might be under UK conditions, and under what conditions. Further work is required to determine this and should include consideration of the consequences of rising temperatures and any increase in peri-urban pollution sources.

4.1.5 In combination

Atmospheric flow above a landscape is rarely, if ever, likely to be dominated by a single controlling influence at any but the shortest spatial or temporal scales. Synoptic weather conditions play an important role in determining whether the requisite conditions are present for mesoscale or local thermal flows to develop to a degree sufficient to impact on pollution advection and dispersion. Similarly, topography and land cover exert mechanical, as well as thermal influences. Consideration of the significance and interplay of these factors should have a place in assessing air pollution movements within a specific landscape. Nor are the different types of thermal wind found in isolation. Studies of their effects in combination dominate the literature reviewed, indicating that this is an active field of research.

The range of possible combinations and the complexity of interactions make generalisation challenging, but some themes do emerge that make clear the significant impact these interactions can have on pollution movement. Sea breezes can distort UHI circulations, leading to movement of urban pollution further inshore than might otherwise be expected, while the sea breeze front (the region of the circulation where the vertical component of flow is most significant and feeding into the returning flow aloft) can accelerate the upwelling of air above urban areas. Further inshore (and it appears that penetration can extend into the tens of kilometres under some conditions) sea breezes can encounter complex topography, which can impact on air movement both through directly through mechanical interactions and indirectly through the influence of slope winds.

As for the thermal flows in isolation it is not clear from the literature how significant these flow couplings might be in the UK and further work is required to explore this. In the meantime, it would seem appropriate to take a holistic view of landscapes in which air pollution movement is to be considered in order that potential interactions might be anticipated.

4.1.6 Implications for assessment

A significant message from the literature is that thermal flows occur and hence are likely to impact on air pollution movements, under conditions that are found in the UK. This is supported by work elsewhere in this project, in which we have collected and reported anecdotal evidence of pollution observations and anomalies in monitoring data in the UK that might plausibly be explained by thermal flows.

Details of the occurrence and magnitude of these impacts are sparse, however, so it is difficult to draw conclusions about their significance and any benefits that might accrue from formally including consideration of thermal flows in assessment processes. We are fortunate in the data that is available to us for the UK, including detailed surface and topological data, and a considerable number of site-specific studies which record local meteorology and pollution concentrations. We are carrying out analyses of existing flow data to search for thermal flow signals and the conditions under which they have occurred.

In the meantime, this review has found or inferred a hierarchy of assessment methods that *could* be drawn upon as appropriate should the need arise.

These begin with simple observation of landscapes for indicators of potential for thermal flows – slopes, water bodies, abrupt changes in land use, urban to rural transitions – and the locations of pollution sources and sensitive receptors relative to them. Such observations might be of use in design of monitoring campaigns, in pointing to possible explanations for anomalies and in flagging pathways that might lead to enhanced exposure at sensitive receptors. For example, do the “fall lines” down which cold, polluted air may flow under gravity, perhaps culminating in polluted air accumulating in CAPs, intersect with sensitive receptors?

Routine modelling for permit assessment purposes relies on Gaussian plume models, which are unsuited for recirculating, non-steady state situations. Gaussian puff models represent a more suitable, but still routinely used and not computationally overdemanding approach. It would be necessary to ensure that the meteorological data used to drive the model captured the thermal wind effects and was of a sufficiently high time resolution to account for diurnal variation.

The bulk of the studies reviewed made use of Eulerian models, mostly WRF. These models are capable of simulating complex flow fields, considering both thermal and topographical effects. Their capabilities can be further extended by coupling to other models to add capabilities such as chemical modelling and the impact of urban design. However, they are computationally demanding, require greater specialist experience to operate and have heavier input demands.

More detailed and specific assessment, especially in complex-built environments, required the flexibility of generalised CFD models. Three papers described using CFD tools; these were from the last 5 years, perhaps reflecting their growing use in environmental flow modelling more generally. Once again, though, they represent an increment in operator specialism and are exquisitely sensitive to input parameters.

Different spatial scales of model operation can be “nested” to provide the appropriate resolution for each part of the model domain. Indeed, there are examples of different model types being nested according to their suitability for different parts of the flow and dispersion simulation.

It was apparent that the more detailed the flow analysis, the greater the cost, complexity, timescale for delivery and dependency on detailed knowledge of controlling parameters. Given this trade-off it would seem beneficial to have access to a range of tools, allowing selection of one with sufficient capability to deliver at the resolution and level of confidence required for a given situation and purpose without excessive demand for input detail and monitoring data for validation. For example, a high-risk decision may justify the additional resource required to improve confidence in model outputs.

Regardless of complexity, it should be borne in mind that the uncertainty associated with any model output is associated not only with the resolution and underlying physics embodied in the model but with uncertainties in input information. These uncertainties are in part associated with limits to the measured data available, which even for the more intensive studies reviewed here was relatively sparse, but also reflect the natural variation in the basket of parameters that drive atmospheric flows. For example, the precise radiation flux will vary as insolation changes during the day, and cloud cover comes and goes, temperature difference between land and sea, and synoptic wind strength and direction will vary over time. One approach that might be used is probabilistic modelling, in which a model is run repeatedly with parameter values selected each time from plausible probability distributions. However, this can become computationally very intensive.

A more pragmatic option might be to consider what would be realistic worst-case scenarios for a given thermal flow in a particular situation, and how likely it is to occur. This might be explored by considering the controlling parameters, beginning with the ones to which the flow might be most sensitive. However, there is a risk of being over-conservative, as the probability of “worst cases” occurring together for two parameters is lower than either of them in isolation unless the parameters are closely coupled.

Identifying a potential or actual thermal flow impact raises the question of how we might mitigate that impact. A key benefit of understanding thermal flows is the opportunity to take them into account when planning the location of a new emission source or a new receptor. Other than this there were few suggestions for mitigation in the literature. An exception was the increased greening of urban areas to reduce their UHI intensity. The intermittent occurrence of thermal flows and their diurnal cycles when they do occur suggests that where a polluting process can be controlled it might be reduced or halted under conditions and at times of day where impacts might exceed acceptable levels. There was some evidence that the depth of down-slope cold air flows is in the order of a few metres, suggesting that in some circumstances it may be feasible to divert the flow mechanically.

4.2 Strengths, limitations and areas for future work

This is a scoping review. As such it is neither comprehensive nor includes any formal quality assessment process, relying on the peer review process and our professional judgement to

gauge the value of the information contained in the papers included. Nonetheless it has given a broad picture of an extensive topic in sufficient detail to indicate the current state of the science, to identify options for assessment of risks from thermal flows and to highlight evidence gaps that limit such assessments

Probably the greatest gap identified is in our understanding of the significance of thermal flows relative to other factors that influence air pollution dispersion. This is a prerequisite to designing practical guidance on where and how to consider thermal wind effects in the UK, and for choosing proportionate tools to do so. Research elsewhere in this project has begun to address this question and findings will be presented in other outputs. The literature indicates two approaches that might be of use. One is observational, making new measurements but also mining the extensive archives of air quality and meteorological data available for the UK. The other is modelling; Sensitivity analyses across realistic ranges of parameter value in a well-validated model will help identify features indicative of thermal flow risks. They will also provide an opportunity to build our understanding of the the relative effort and costs versus incremental benefits of using different models (similar exercises have been carried out, for example, to optimise choice of model category for use in assessing dispersion of a toxic gas in an urban environment).

5. Conclusions

Do thermally driven processes influence air pollution dispersion? If so where, how often, and under what conditions?

We believe the review supports the hypothesis that thermal flows can have an influence on air pollution under UK conditions, but there is insufficient information to define the frequency and specific conditions under which such flows occur.

Some general conclusions can be drawn indicating that low synoptic wind speeds and clear skies are required for thermal flows to become significant relative to synoptically driven flows, but additional work is required to be more specific and to gauge the magnitude of flows involved.

What tools are best for simulating thermally generated local air flows?

Choice of tool depends on objectives and the level of risk involved. The preferred option across the research reviewed here is Eulerian modelling with tools such as WRF. These seem to offer the flexibility to model complex scenarios, and many of the data inputs required are readily available in the UK. However, for regulatory screening Gaussian puff models may be sufficient. An initial screening for thermal flow risk factors might be made from map data.

What types of thermal wind effects can significantly impact air pollution dispersion?

All three categories of thermal flow considered here can impact on air pollution dispersion, but it is unclear the extent to which they would do so under UK conditions (this is being explored elsewhere in this project).

What parameters (e.g. meteorology, topography and land use) determine how and when they arise?

Key parameters are topography, land use, proximity of water, and synoptic meteorology. Thermal flows arise where temperature differentials are sufficient to drive convective and subsidence processes leading to circulation; or where net radiative flux allows cooling near the ground, leading to a stable or inverted lapse rate and a body of dense air that can flow down slopes. Synoptic winds near the surface must be of a similar or lower magnitude to the thermal flow if the impact of a thermal flow is to be detectable.

How frequently do those sets of parameters arise?

There is insufficient evidence in the literature to determine this for the UK. Non-UK data from similar temperate, maritime climates suggests that sea breezes can occur at least several times each month, and even more regularly in some seasons.

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Appendix 1.

Quick scoping review search terms

Table A 1. The search terms used in Scopus to identify peer-reviewed literature in the quick scoping review.

Search No.	Research Question	Concept	Search terms	Search string used in Scopus	No. of hits (search conducted: 10/07/2024)
1	How do thermally driven processes influence air pollution dispersion?	A. Thermally driven processes	"thermally driven process*" OR "Temperature driven process*" OR "Heat induced process*" OR "Thermal process*" OR "heat driven mechanism*" OR "Thermal dynamic*" OR "Heat related process*" OR "thermal* gen*" OR "thermal flow*" OR "Differential heat*"	A AND B AND C AND D	381
		B. Air	atmospher* OR air OR airborn*		
		C. Pollution	pollut* OR contam* OR quality		
		D. Dispersion	dispers* OR diffus* OR transport OR distribut*		

Search No.	Research Question	Concept	Search terms	Search string used in Scopus	No. of hits (search conducted: 10/07/2024)
2.	What dispersion models are best for simulating thermally generated local air flows?	A. Thermally driven processes	"thermally driven process*" OR "Temperature driven process*" OR "Heat induced process*" OR "Thermal process*" OR "heat driven mechanism*" OR "Thermal dynamic*" OR "Heat related process*" OR "thermal* gen*" OR "thermal flow*" OR "Differential heat*"	A AND D AND E AND F AND NOT G	524
		D. Dispersion	dispers* OR diffus* OR transport OR distribut*		
		E. Models	model* OR "simulat*" OR "Computational fluid dynamics" OR "CFD" OR "Lagrangian" OR "eulerian" OR "Gaussian" OR "Hybrid" OR "integrated" OR "Large-Eddy" OR "Large eddy" OR "large eddy simulation" OR "LES" OR "Reynolds averaged navier stokes" OR "reynolds-averaged navier stokes" OR "reynolds averaged navier-stokes" OR "reynolds-averaged navier-stokes" OR "RANS" OR "numerical weather prediction" OR "statistical"		
		F. Scale (Include)	"local" OR "Regional" OR "mesoscale" OR "microscale" OR "misoscale" OR "boundary layer"		

Search No.	Research Question	Concept	Search terms	Search string used in Scopus	No. of hits (search conducted: 10/07/2024)
		G. Scale (Exclude)	"global" OR "synoptic" OR "worldwide" OR "international" OR "large scale" OR "cyclonic scale"		
3.	What types of thermal wind effects significantly impact air pollution dispersion?	B. Air	atmosph* OR air OR airborn*	H AND B AND C AND D AND F AND NOT G	612
		C. Pollution	pollut* OR contam* OR quality		
		D. Dispersion	dispers* OR diffus* OR transport OR distribut*		
		F. Scale (Include)	"local" OR "Regional" OR "mesoscale" OR "microscale" OR "miso-scale" OR "boundary layer"		
		G. Scale (Exclude)	"global" OR "synoptic" OR "worldwide" OR "international" OR "large scale" OR "cyclonic scale"		
		H. Thermal Wind effects	"Urban heat island" OR "urban heat island effect" OR "sea breeze" OR "onshore breeze" OR "offshore breeze" OR "katabatic flow" OR "catabatic flow" OR "katabatic wind" OR "catabatic wind" OR "drainage wind" OR "fall wind" OR "cold air drainage" OR "anabatic flow" OR "up valley wind" OR "upslope flow" OR "down valley wind" OR "downslope flow" OR "rain shadow wind" OR "foehn wind" OR "fohn"		

Search No.	Research Question	Concept	Search terms	Search string used in Scopus	No. of hits (search conducted: 10/07/2024)
			wind" OR "chinooks" OR "chinook winds" OR "bora" OR "bora wind" OR "pitera" OR "valley exit jet" OR "wind driven" OR "oasis effect" OR "country breezes" OR "cold air pool" OR "Dunkelflaute"		
4.	What meteorological, topographical, and land use aspects determine thermal flows and how they arise?	A. Thermally driven processes	"thermally driven process*" OR "Temperature driven process*" OR "Heat induced process*" OR "Thermal process*" OR "heat driven mechanism*" OR "Thermal dynamic*" OR "Heat related process*" OR "thermal* gen*" OR "thermal flow*" OR "Differential heat*"	A AND I OR J OR K AND F AND NOT G	1,345
		F. Scale (Include)	"local" OR "Regional" OR "mesoscale" OR "microscale" OR "misoscale" OR "boundary layer"		
		G. Scale (Exclude)	"global" OR "synoptic" OR "worldwide" OR "international" OR "large scale" OR "cyclonic scale"		
		I. Meteorology	temperature OR "ambient temperature" OR "temperature gradient*" OR "Wind speed" OR "wind direction" OR "stability" OR "atmospheric stability" OR "atmospheric instability" OR "unstable equilibrium" OR "stable equilibrium" OR "boundary layer depth" OR "boundary layer height" OR "planetary boundary layer" OR "PBL" OR		

Search No.	Research Question	Concept	Search terms	Search string used in Scopus	No. of hits (search conducted: 10/07/2024)
			"atmospheric boundary layer" OR "ABL" OR "peplosphere" OR "solar radiation" OR "bowen ratio" OR "advection"		
		J. Land use	"land use" OR "land-use" OR "Land cover" OR "land-cover" OR "urban" OR "urbanisation" OR "urbanization" OR "periurban" OR "peri-urban" OR "rural" OR "vegetation cover" OR "albedo" OR "surface albedo" OR "coastal" OR "coast" OR "anthropogenic heat emission" OR "wetlands"		
		K. Topography	"surface roughness" OR " terrain slope" OR "complex topograph*" OR "topograph* effects" OR "terrain topograph*" OR "complex terrain" OR "Hill*" OR "altitude" OR "coast*"		
5.	How frequently do thermal flows arise?	A. Thermally driven processes	"thermally driven process*" OR "Temperature driven process*" OR "Heat induced process*" OR "Thermal process*" OR "heat driven mechanism*" OR "Thermal dynamic*" OR "Heat related process*" OR "thermal* gen*" OR "thermal flow*" OR "Differential heat*"	A AND L AND F AND NOT G	216
		F. Scale (Include)	"local" OR "Regional" OR "mesoscale" OR "microscale" OR "misoscale" OR "boundary layer"		

Search No.	Research Question	Concept	Search terms	Search string used in Scopus	No. of hits (search conducted: 10/07/2024)
		G. Scale (Exclude)	"global" OR "synoptic" OR "worldwide" OR "international" OR "large scale" OR "cyclonic scale"		
		L. Frequency	"analysis of meterol* data" OR "statistical analysis of meterol* data" OR "meteorol* assessment" OR "analysis of weather data" OR "statistical analysis of weather data" OR "weather assess*" OR "long-term monitor*" OR "climat* stud*" OR "case stud*" OR "frequency" OR "how often" OR "number of times" OR "occurrence" OR "circumstance"		

Table A 2 The key word(s) by category

Category	Key word(s)
Thermal flow types	Thermal processes Heat transfer Urban heat island Sea breeze (Katabatic flow) (Anabatic flow)
Simulation and analysis	Dispersion Modelling Numerical simulation Numerical analysis Numerical investigation
Media	Air quality

Anabatic and katabatic flows were added as these were considered to be important types of thermal flows to include. The key words in Table A 2 were combined to produce the follow search terms:

1. Thermal process and air quality
2. Heat transfer and air quality
3. Urban heat island and air quality
4. Sea breeze and air quality
5. Katabatic flow and air quality
6. Anabatic flow and air quality
7. Air quality dispersion and thermal processes
8. Air quality dispersion and heat transfer
9. Air quality dispersion and urban heat island
10. Air quality dispersion and sea breeze
11. Air quality dispersion and katabatic flow
12. Air quality dispersion and anabatic flow
13. Modelling and air quality and thermal processes
14. Modelling and air quality and heat transfer
15. Modelling and air quality and urban heat island

16. Modelling and air quality and sea breeze
17. Modelling and air quality and katabatic flow
18. Modelling and air quality and anabatic flow
19. Numerical and air quality and thermal processes
20. Numerical and air quality and heat transfer
21. Numerical and air quality and urban heat island
22. Numerical and air quality and sea breeze
23. Numerical and air quality and katabatic flow
24. Numerical and air quality and anabatic flow

Databases and sites searched

The following databases were searched:

- OpenAire, a non-profit partnership of 50 organisations to ensure a permanent open scholarly communication (OpenAIRE, 2025).
- The OpenGrey, a database of open access grey literature in Europe (OPENGREY, 2025).
- World Cat, a library of book, ebooks, audio books, videos, databases, research materials, data, maps, records, archives, digitized documents, scans of rare works, photos of local historical significance, musical scores, genealogical records, and more from across the world (WorldCat, 2025).

The following websites were searched:

- Gov.uk, the website for UK government services and information (GOV.UK, 2025).
- The European Environment agency website (European Environment Agency, 2025).
- The US Environmental Protection Agency website (US EPA, 2025).

The following databases and websites were considered but not searched:

- Theses databases (as this was a quick scoping review, it was assumed that key outputs from any theses would have been written up as peer-reviewed reports and identified in the peer-reviewed search):
 - EThOS (Electronic Theses Online Service), an e-thesis online service hosted by the British Library (please note that this library is currently unavailable due to a cyber-attack) (University of Leicester, 2024).
 - Open Access Theses and Dissertations (OATD, 2025).
 - DART-Europe, an e-theses portal (DART-Europe, 2025) (please note this portal was permanently closed down on 03/02/2025, after the search was conducted).
- The European centre for Medium-Range Weather Forecasts (ECMWF, 2025). This database was initially considered, but it was found that the search resulted in short news article-type webpages summarising ongoing, or already published work, and no original data.
- Google new archive (Google News, 2025). Although newspaper articles can sometimes contain useful information, they are not scientific and unlikely to contain

useful information or data beyond that of the peer-reviewed search, or the rest of the grey literature search.

Grey literature was also sought from previous experiences and knowledge of the project team.

Inclusion and exclusion criteria

Results were sorted by relevance, and the top 10 were screened on title and, where available, abstract. If available, a search filter was used to limit the search to non-peer reviewed articles. Only non-peer reviewed articles were screened, with the assumption that key peer-reviewed articles were picked up in the main search. Dissertations and theses were excluded, on the assumption that any key findings from such work will have been written up and published in a peer-reviewed journal. Summaries and news articles were also excluded, as these did not contain enough detail, or provided links to peer-reviewed research (these links were not followed – it was assumed that key peer-reviewed articles were picked up in the main search).

Grey literature was also excluded if

- They did not concern thermal flows
- They did not concern air pollutants
- They concerned indoor air
- They were on topics outside of scope (e.g. sub-surface thermal flows)
- They concern other research fields (e.g. geology, materials science, manufacturing toxicology etc.)
- They were not available in English
- A full text was not readily available

Appendix 2. References

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