22nd International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
10-14 June 2024, Pärnu, Estonia

EVALUATING A 3D ATMOSPHERIC MODEL FOR THE DEVELOPMENT OF NOCTURNAL KATABATIC COLD AIR DRAINAGE FLOWS

Patrick Hogan[1], Benedicht Brecht[1], Rowell Hagemann[1] and Helmut Lorentz[1]

[1]Lohmeyer GmbH, Germany

Abstract: Nocturnal katabatic cold air drainage flows can reduce the thermal and air pollutant loads in urban environments by transporting air from cooler rural surroundings into a warmer urban area. Given the need to reduce pollutant concentrations, while at the same time an increased densification of the urban environment is expected in the near future, identification of katabatic flow patterns near urban areas is of high importance to urban planners. As the cold air model must encompass the entire cold air catchment area in which katabatic flows develop, which may be at the regional scale in the case of large river valleys, development and transport of cold air and the resulting wind fields are generally simulated with 2-dimensional models based on the shallow-water equations. 2-dimensional models are however limited in their representation of complex geography or urban areas. In this context, the urban climate model PALM is used to carry out regional 3-dimensional simulations of the development and flow of katabatic winds in the complex terrain of the "Stuttgart Basin" according to the German Association of Engineers guidelines "VDI 3783 Part 7 test case 8". The depth of the cold air layer as well as the flow direction and size based on the 3d results are evaluated.

***Key words:** Cold air drainage flow, PALM-4U, urban pollution, urban heat island.*

INTRODUCTION

In areas of heterogenous topography katabatic cold air drainage flows may develop under calm, clear-sky conditions such as are typically found in anticyclonic, high pressure weather systems. As these weather conditions are also typically associated with increased temperatures during summer months as well as an increase in pollutant load due to reduced wind speeds and turbulence, nocturnal katabatic cold air drainage flows can play an important role in the dispersion of pollutants as well the reduction of thermal loads in urban environments. Cold air is generated over soil and green surfaces by radiative cooling on cloudless nights, and under the influence of gravity the cold air drains downslope (Gudiksen et al. 1992). With a sufficiently large catchment area the cold air flows can form locally and regionally significant flows which may be relevant for nearby urban areas, as the cold and fresh rural air flows into the city providing a cooling effect on urban surfaces as well as transporting and dispersing pollutants (Biggs et al. 2014).

Cold air flows and their effect on the urban environment have been investigated since the middle of the twentieth century, with early research focused on detecting and measuring these flows and with modern research focusing on the impact of these flows on thermal and pollutant loads (Largeron and Staquet 2016, Kossmann and Sturman 2004, Yang and Li, 2009). In recent years the development of 2-dimensional models for simulating the development and transport of cold air flows have enabled the quantification of the cooling effect (Döscher et al. 2023) as well as allowing for the investigation of the incorporation of the flows into climate mitigation strategies for cities (Grünwald et al. 2019). While 2-dimensional models are capable of describing the generation, direction and size of the cold air flows they are unable to provide explicit values of the 3-dimensional wind and temperature fields, which can limit their application in urban areas and in areas of complex topography where cold air flows of varying strengths and depths may mix and pool. Increasingly 3-dimensional atmospheric models are being applied to this area, however due to the more general nature of the models their suitability must be tested. To provide a suitable and standardised experiment for testing 3-dimensional mesoscale models the German Society of Engineers developed a set of guidelines for evaluating the results of models, VDI 3783 Part 7 (2017).

The 3-dimensional atmospheric simulation model PALM has recently been extended to include the PALM-4U components which allow for the simulation of urban environments, including the dispersion of pollutants, calculating the energy balance of urban surfaces as well as modelling 3-dimensional vegetation (Maronga et al. 2019, Maronga et al. 2020). PALM-4U has been validated for summer and wintertime conditions in an urban environment (Resler et al. 2021, Van der Linden et al., 2023). As PALM-4U can be run at both mesoscale and microscale spatial resolutions and allows for the direct coupling between 'nested' simulations with different resolutions, it has the capacity to simulate the development of cold air flows at a large spatial resolution in complex natural topography near an urban area during clear sky conditions which can then be directly used to provide the wind and temperature field for a high resolution dispersion simulation of the urban area where buildings and vegetation are explicitly resolved.

In this paper the 3-dimensional atmospheric model PALM-4U is used to simulate cold air flows in the area of the 'Stuttgart Cauldron' and the results are evaluated according to VDI 3783 Part 7 test case Stuttgart for cold air flows, to determine if the model is suitable for use in simulating the development of nocturnal cold air flows in complex topography and the resulting wind fields, which can be used to modelling the dispersion of pollutant and thermal loads.

METHODOLOGY

The study area is located in the region of Stuttgart in southwest Germany. The city of Stuttgart lies in a so-called 'cauldron' where the valley floor at approx. 200 m a.s.l. is surrounded by heights up to approx. 400 m high (Figure 1). To the south of the city lies the Nesenach Valley while to the northeast it joins the valley of the Neckar.

Meteorological Observations

As part of the Stuttgart 21 development project measurement campaigns were conducted between 01 April 1997 and 03 April 1997 whereby among other observations a tethered weather balloon was deployed to measure the cold air flow near the Stuttgart planetarium. The results of this measurement campaign form the basis of the test case E8 for the evaluation of dynamic and thermally generated prognostic wind field models from the German Society of Engineers. Meteorological observations from the Stuttgart radiosonde station (48.83° N 9.2° E) of the German Meteorological Service as well as surface level observations form the nearby SYNOP station on the 02 April provide the initial and boundary conditions for the simulation. The radiosonde and weather balloon measurements show an upper-level flow from the northeast at 2 ms^{-1} to 3 ms^{-1}. To evaluate the model the simulated vertical profiles of wind and temperature are compared to the observations from the tethered weather ballon at the Planetarium location direction between 22:00. and 23:00., i.e. two to three hours after sunset.

PALM-4U

The PALM model system is based on solving the incompressible, Boussinesq approximated Navier- Stokes equations for the three components of the wind field (u, y, z) as well as scalar quantities (temperature, humidity, passive scalars such as pollutants) on a staggered Cartesian grid. PALM can be run as a Large Eddy Simulation (LES) model, for this study however a RANS turbulence closure was used. Advection is calculated using the 5th order upwind scheme of Wicker and Skamarock and time discretization by the 3rd order Runge-Kutta timestep scheme. The PALM model includes several components which expand upon the PALM model core to create the PALM-4U system. In this study the land surface model, the offline nesting component, and the radiation model are used. As the aim of this study is to first validate the model at the mesoscale, areas of high vegetation and urban structures were taken into account here using parametrisations of their surface properties within the land surface model. Further information on the model as well as a detailed description of the model components can be found in Maronga (2015), Maronga (2020) and Gehrke et al. (2021).

A two step offline nesting method was used where the outer domain was defined to encompass the entire possible catchment area for cold air flows which might affect the evaluation area given by the guidelines. The coarser outer simulation domain covers approx. 40 km x 40 km with a horizontal grid width of 200 m. The nested inner domain, which includes the evaluation area (blue frame in Figure 1), has a horizontal extent of approx. 20 km x 20 km with a horizontal resolution of 100 m. The vertical resolution is 8 m in the lower layers for both simulations. The simulations start at 17:30, i.e. roughly two and a half hours before sunset. The topographical input data for the simulation is defined and provided by the evaluation guidelines while the land use data is taken from the CORINE Land Cover 2006 dataset.

RESULTS

Figure 1 shows the wind direction and wind speed at approx. 10 m above ground level from the lower model layers at 22:00. In the undeveloped areas of the study area, cold air forms near the ground due to the weather conditions, and then flows into the Stuttgart valley basin and the neighbouring side valleys as a downslope wind.

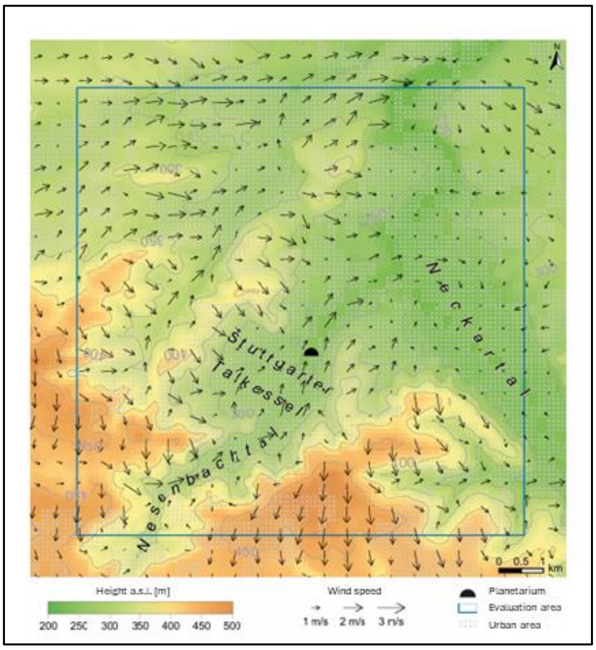

Figure 1. Simulated near surface wind speed and direction results overlaid on the topography and urban land cover. The evaluation area defined by the guidelines is outlined as a blue rectangle, with the location of the observation weather balloon installed at the planetarium marked by the black semicircle.

In the Nesenbach valley, the cold air from the valley slopes combines resulting a strong drainage flow of cold air, which carries cool and fresh air masses down the valley into the Stuttgart basin during the course of the night. The air masses reach the Planetarium from a south-south-westerly direction at around 1 ms^{-1} and then flow north-east towards the Neckar valley. Figure 2 shows the simulated vertical profiles of the wind speed and wind direction distribution at the Planetarium site at 10 pm and 11 pm. At both observation times, the maximum cold air flow velocities there are around 2.5 ms^{-1} at 20 m to 40 m above the ground with cold air flow directions from the south-southwest up to a height of around 108 m and 116 m respectively. Above this height, the wind turns to a north-easterly direction which corresponds to the higher-level wind measured by the ballon and radiosonde at around 2 ms^{-1}, i.e. the cold air flows are decoupled from the higher-level inflows. The cold air volume flow density is derived from the flow velocity and the thickness of the cold air. Table 1 shows the layer thicknesses, volume flow densities and directions of the cold air flow derived from the measurements and simulations as mean values for the two observation periods. All simulated values are within the permitted ranges, meaning that the PALM-4U model fulfils test case E8 with the selected setup.

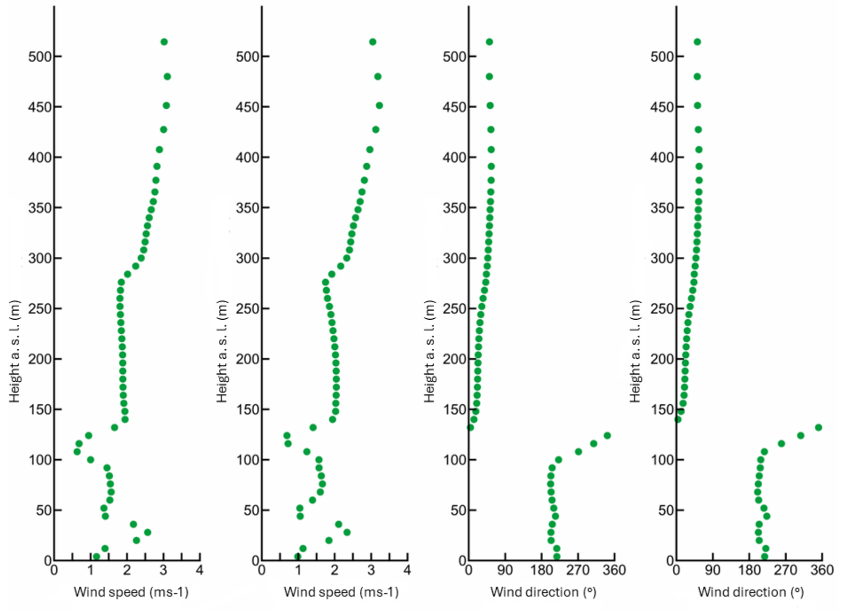

Figure 2. Simulated vertical profiles of the wind speed and direction at the location of the observation weather balloon installed at the planetarium at 22:00 and 23:00.

Table 1. Cold air layer thickness, cold air volume flow density and cold air flow direction at the Planetarium site.

	Measured value	**Permitted range**	**Simulated value**
Vertical thickness of the cold air layer (m)	95 – 110	85 – 160	112
Cold air flow density ($m^3m^{-1}s^{-1}$)	134 – 176	90 – 195	171
Direction of the cold air flow between 25 m und 65 m (°)		174 – 221	207

OUTLOOK

In this study PALM-4U was successfully evaluated for simulating cold air drainage flows from a large catchment area in areas of pronounced topography. For calculating pollutant dispersion or thermal loads, further high-resolution calculation grids can be included by means of nesting, with both urban structures and high vegetation explicitly modelled. As PALM-4U is also able to simulate aerosol dispersion with atmospheric chemistry and dispersion model components, PALM-4U is able to harmonise the complex simulation process for modelling air pollution in the urban environment under varying atmospheric conditions by providing a single model environment for the entire process. This enables evaluations and statements to be made for the daytime and nighttime wind field in complex urban areas.

In comparison to 2-dimensional models or 3-dimensional models where buildings must be parametrised, PALM-4U is able to model combined cold air flows from a number of sources and directions at different levels. In urban environments this is particularly advantageous as in urban areas air flows in street canyons, in the presence of tall vegetation and above roof level may have differing wind directions. With a high level of spatial resolution PALM-4U can also estimate the depth at which cold air drainage flows can penetrate and permeate into the urban area which allows for urban planners to identify ventilation lanes as well as obstacles which can lead to the removal or build-up of pollutants, further harmonising the urban planning process.

REFERENCES

Bigg G.R., S.M. Wise, E. Hanna, D. Mansell, R.G. Bryant and A. Howard, 2014: Synoptic climatology of cold air drainage in the Derwent Valley, Peak District, UK, Meteorol Appl 21:161–170.

Gehrke K.F., M. Sühring and B. Maronga, 2021: Modeling of land–surface interactions in the PALM model system 6.0: land surface model description, first evaluation, and sensitivity to model parameters, Geosci. Model Dev. 14(8):5307–29.

Grunwald L., M. Kossmann and S. Weber, 2019: Mapping urban cold-air paths in a Central European city using numerical modelling and geospatial analysis, Urban Clim 29:100503.

Gudiksen P.H., J.M. Leone, C.W. King, D. Ruffieux and W.D. Neff, 1992: Measurements and modeling of the effects of ambient meteorology on nocturnal drainage flows, Journal of Applied Meteorology,31, 1023–1032.

Ingenieure, V.D. Environmental meteorology-prognostic mesoscale windfield models- Evaluation for dynamically and thermally induced flows. In VDI Guideline 3783, Part 7; Dusseldorf, Germany; May 2017.

Largeron Y. and C. Staquet, 2016: Persistent inversion dynamics and wintertime PM10 air pollution in Alpine valleys, Atmos. Environ. 135:92–108.

Kossmann M. and A. Sturman, 2004: The surface wind field during winter smog nights in Christchurch and coastal Canterbury, New Zealand, Int. J. Climatol. 24:93–108.

Maronga B., M. Gryschka, R. Heinze, F. Hoffmann, F. Kanani-Sühring, M. Keck, et al. 2015: The Parallelized Large-Eddy Simulation Model (PALM) version 4.0 for atmospheric and oceanic flows: model formulation, recent developments, and future perspectives, Geosci. Model Dev. 8(8):2515–5

Maronga B., S. Banzhaf, C. Burmeister, T. Esch, R. Forkel, D. Fröhlich, et al. 2020: Overview of the PALM model system 6.0, Geosci. Model Dev.;13(3):1335–72.

Maronga B, G. Gross, S. Raasch, S. Banzhaf, R. Forkel, W. Heldens, et al. 2019: Development of a new urban climate model based on the model PALM – Project overview, planned work, and first achievements. metz;28(2):105–19.

Resler J, K. Eben, J. Geletič, P. Krč, M. Rosecký, M. Sühring, et al. 2021: Validation of the PALM model system 6.0 in a real urban environment: a case study in Dejvice, Prague, the Czech Republic. Geosci. Model Dev;14(8):4797–842.

Van der Linden, L., P. Hogan, B. Maronga, R. Hagemann, and B. Bechtel, 2023: Crowdsourcing air temperature data for the evaluation of the urban microscale model PALM—A case study in central Europe, PLOS Climate. 2. 10.1371/journal.pclm.0000197.

Yang, L., and Y. Li, 2009: City ventilation of Hong Kong at no-wind conditions, Atmos. Environ. 43, 3111–3121.

! IMPORTANT !

We ask you to name your files as follows, where H22-XXX is the code of your contribution (see the letter of acceptance online):

Extended abstract: H22-XXX_Name_Surname.pdf

Permission form: H22-XXX_Permission.pdf
(to be sent after the conference, instrucitons will be given in due time: take care of specifying what you want/do not want to be published online)