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Innovative Projects

Three-Dimensional Observation of Atmospheric Processes in Cities

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Abstract

To cope with weather and climate-induced impacts as well as with air pollution in cities, the German research programme "Urban Climate Under Change" ([UC]^2) aims at developing, testing and validating a new urban climate model, which is able to cover the full range of temporal and spatial scales of urban atmospheric processes. The project "Three-dimensional Observation of Atmospheric Processes in Cities" (3DO), which forms the module B of the [UC]^2 research programme, aims at acquisition of comprehensive, accurate three-dimensional observational data sets on weather, climate and air quality in the German cities of Berlin, Hamburg and Stuttgart. Data sets from long-term observations and intense observation periods allow for evaluation of the performance of a new urban climate model called PALM-4U that is developed by the project "Model-based city planning and application in climate change" (MOSAIK), which forms the module A of the [UC]^2 research programme. This article focuses on collaborative activities for compilation of existing and acquisition of new observational data within the 3DO project.

Keywords: urban weather, urban climate, air quality, observational data, long-term observations, intense observation periods, urban climate model, model validation, applicability tests

1 Introduction

More than half of mankind lives in urban regions, and the global trend for urbanisation is ongoing (United Nations, 2014). Urban weather and climate, as well as air quality are major environmental factors influencing living conditions in cities. Severe weather events like storms or intense rainfall, and climate events like long-lasting heat waves or droughts have proven to be costly and deadly natural hazards. Atmospheric processes control air quality by dispersion of air pollutants emitted from various natural and anthropogenic sources, the latter being highly concentrated in urban regions (World Health Organization, 2013). Thus, development of new city quarters, as well as transformation of existing cities towards more sustainable places according to the United Nations SDG No. 11 ('Make cities inclusive, safe, resilient and sustainable', United Nations, 2015) require observational data combined with scenario-based numerical simulations provided by urban climate models for environmental impact assessment. This holds true even if climate change would not be considered. However, future hazards due to regional consequences of global climate change form the background for the fact that mitigation of and adaptation to climate change have recently become important tasks for urban administrations (e.g. Solecki, 2012; UN-Habitat, 2016), in addition to ongoing, established tasks of considering atmospheric processes in urban planning or air-quality control, among others.

Urban regions, and thus their atmospheric environments, are characterised by large heterogeneity across a wide range of spatial and temporal scales. Cities are morphologically complex (Stewart and Oke, 2012), and are characterised by highly complex spatial patterns of emissions of heat, water vapour and air pollutants (see e.g. Barlow et al., 2017). Micro-scale atmospheric processes, taking place at buildings, trees and other forms of vegetation, in street canyons and at infrastructure components like bridges over distances of metres up to decametres, need to be considered, particularly with respect to ambient atmospheric conditions of humans. Local-scale (also called neighbourhood-scale) atmospheric processes that spatially extend over hundreds of metres up to several kilometres are fundamental when investigating atmospheric conditions in city quarters or districts. Large cities are further influenced by mesoscale atmospheric processes, which extend over kilome-

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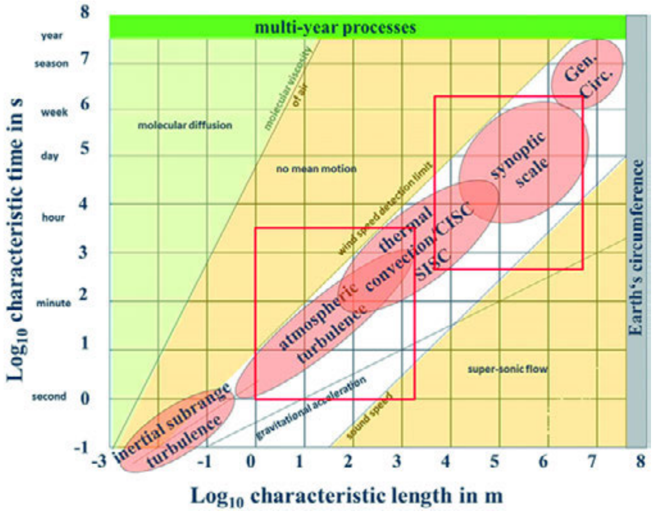

Figure 1: Characteristic scales of atmospheric flow phenomena based on Orlanski (1975) and Schlünzen et al. (2011). Various limiting thresholds and forbidden zones are depicted by straight lines and coloured areas. The two red frames indicate phenomena modelled by micro-scale models (left frame) and meso-scale models (right frame). CISC: Convective-Induced Secondary Circulation, SISC: Surface-Induced Secondary Circulation. From Emeis (2015).

tres up to hundreds of kilometres. Regional- to synoptic-scale weather situations and climate conditions, as well as long-distance transport of air pollutants are likewise crucial to be considered in urban atmospheric studies. Finally, global atmospheric circulation, climate variability and change influence atmospheric environments in cities. Fig. 1 displays the broad range of atmospheric processes acting on temporal scales from seconds to decades, all of them relevant for present and future living conditions in cities.

Despite the huge number of studies of urban weather, climate and air quality, data from long-term observation (LTO) of atmospheric processes in cities are generally sparse (see e.g. Grimmond, 2006; Grimmond et al., 2010; Muller et al., 2013). Only a few climate stations provide multi-decadal or even centennial climate data for urban regions. In Germany, cities like Frankfurt, Freiburg, Stuttgart, Berlin or Aachen conducted long-term meteorological measurements at single urban weather stations that resulted in multi-decadal or even centennial climate data (e.g. Mollwo, 1958; DWD, 2017a). Such data have to be homogenized due to urban growth, changing locations and therefore changing site conditions, or new instrumentation and observation methods over the years. Nevertheless, they are a valuable source for investigating general characteristics of and trends in climates of the respective cities.

Muller et al. (2013) stated that single weather stations do not allow for investigations of urban atmospheric processes, and therefore reviewed the state of urban sensor networks. They found that such networks at city scales have mainly started after 2000. The authors did not include routine networks used for monitoring of near-surface concentrations of major air pollutants in their review, although a limited number of meteorological variables are also measured by these networks. The need for integrated studies linking urban weather and climate with air-quality aspects has been stressed by Barlow et al. (2017).

Data from weather stations are mainly used in support of weather forecasting, thus comparable micro- to local-scale site conditions are required to reveal meso- to synoptic-scale gradients in atmospheric variables. Therefore, the WMO has set up and updated a guide to meteorological instruments and methods of observation (World Meteorological Organization, 2017). Site requirements for synoptic weather stations are, however, not representative for built-up areas. With respect to monitoring of climate change, synoptic weather stations within cities are problematic since regional-scale climate change and urbanisation may induce long-term trends in atmospheric variables, making attribution of observed trends a difficult if not impossible task. For these reasons, a guideline for weather observations at urban sites was introduced (World Meteorological Organization, 2006).

Three-dimensional processes in the entire planetary boundary layer (PBL) strongly control urban climates as perceived by humans and recorded by weather stations. In this respect, the height of the PBL is of utmost importance for air quality in cities, since it strongly influences dispersion of air pollutants (Stull, 1988; Angevine et al., 1998). The PBL is strongly modified over urban regions, such that the urban boundary layer (UBL) and the urban canopy layer (UCL) develop through altered exchange of momentum, sensible and latent heat due to intensification of mechanically and thermally induced turbulence. These modifications interact with urban energy and water balance, formation of UHIs, BLUHIs, and SUHIs (Arnfield, 2003; U.S. Environmental Protection Agency, 2008). Unfortunately, PBL dynamics over cities and related atmospheric processes are not yet sufficiently studied since data from LTOs of PBL heights are sparsely available. In most urban studies, atmospheric probing addressing the entire PBL have been carried out during dedicated, short-term IOPs. One of the most important experiments in this respect was the "*Basel UrBan Boundary Layer Experiment*" (BUBBLE) (Rotach et al., 2005) that took place over one year, with additional measurements during a special IOP.

New observational technologies, in particular for ground-based remote sensing of atmospheric variables throughout the entire PBL and beyond, have been recently developed (e.g. Emeis, 2015). The still high costs for purchasing and operating these instruments are a main reason for the fact that three-dimensional observational atmospheric data are generally sparse and hardly cover longer periods. In conclusion, observations of atmospheric processes within cities will remain difficult despite new emerging technologies (Chen et al., 2012).

Since 2016 a new research programme entitled "*Urban Climate Under Change*" ([UC]^2) (www.uc2-program.org) is funded by the BMBF for a first period of three years to address the above-mentioned challenges. The $[UC]^2$ research programme is in line with research activities in other countries, e.g., in the United Kingdom (Barlow et al., 2017). It is structured in three different modules (A, B, and C). This article presents an overview on compilation and acquisition of observational data for model evaluation and application examples processed by module B "*Three-dimensional Observation of Atmospheric Processes in Cities*" (3DO) (www.uc2-3do.org). Three further articles present an overview on the entire $[UC]^2$ research programme (Scherer et al., 2019), and discuss the specific research and development tasks for development of a new urban climate model called PALM-4U (read: PALM for you) by the project "*Model-based city planning and application in climate change*" (MOSAIK) (module A; Maronga et al., 2019), and the evaluation of the practicability and user serviceability of the PALM-4U model by the projects "*Climate Models for Practice*" (KliMoPrax) and "*Review of practical and user serviceability of an urban climate model to foster climate-proof urban development*" (UseUClim) (module C; Halbig et al., 2019).

2 Aims and objectives

As described by Scherer et al. (2019), the $[UC]^2$ research programme aims at development, validation and application of an innovative building-resolving urban climate model (spatial resolution 10 m or finer) for entire cities in size of up to 2000 km^2, embedded in different regional climates and topographic situations. Thus, comprehensive observational data sets on weather, climate and air quality in large cities are required to assess the performance of the PALM-4U model, which is based on the Large Eddy Simulation Model PALM (Raasch and Schröter, 2001; Maronga et al., 2015), and is extended for urban applications (see Maronga et al., 2019).

A major aim of the 3DO project is to explore the impact of the third, vertical dimension on flow features, energy exchange and air quality processes in the urban atmosphere. Many processes in the UBL can only be understood if their vertical structure is known, e.g., the impact of air-temperature inversions a few hundreds of metres above ground on near-surface air-pollutant concentrations. Mobile remote sensing devices (e.g. SODARs, wind-LIDAR systems) and UASs have been developed recently. They offer the opportunity to acquire data on the vertical structure of the atmosphere at different intra-urban locations. Among others, air pollutants like ultra-fine particulates (UFPs) and black carbon (BC) are within the focus of the project. Since a few years, mobile measurement platforms (e.g. mobile measurement cars, bicycles, tethered balloons) are available to measure concentrations of UFPs and BC. Thus, the 3DO project is one of the first projects deploying and using the above-mentioned instruments in a larger, co-ordinated framework. Furthermore, the philosophy of the 3DO project is to obtain scale-consistent data of a broad spectrum of atmospheric variables to validate the numerical model PALM-4U, which, as large-eddy resolving model with grid spacing down to 1 m or less, is able to simulate very small-scale features of urban climates. Concurrent high-resolution observations, both in time and space, are therefore required at many sites and for different vertical levels. The 3DO project is thus not a repetition of earlier experiments but designed to obtain improved knowledge on three-dimensional processes in the urban atmosphere, and specifically, how they influence atmospheric environments of urban inhabitants. The main hypothesis is thus that three-dimensional atmospheric data sets provide relevant information for various applications in urban planning and air quality control, as well as for design and implementation of actions for mitigation of and adaptation to climate change.

The 3DO consortium partners (Table 1; acronyms of the institutions are used hereinafter) process existing atmospheric data sets and acquire new observational data sets by new LTO instruments and measurements during dedicated IOPs in three large German cities (Berlin, Hamburg, Stuttgart). Measurements are carried out at very high temporal and spatial resolution over sufficiently long periods to improve the data inventories available for the three cities and their surrounding regions. Data from wind tunnel experiments carried out by the UHHmeteo complement the observational data sets since they allow for characterizing spatial and temporal representativeness of near-ground flow and dispersion measurements, and offer an additional opportunity for model validation.

Reference data sets of known accuracy are derived from LTO and IOP data using rigorous quality control procedures ensuring their applicability for model tests and validation. For this purpose, new measurement concepts and analysis tools for effective and efficient data acquisition, analysis and management, for model validation, as well as for distribution of data and results to end users in diverse scopes of applications are developed and tested in the 3DO project. Reference data sets do not only cover the atmosphere near ground in the three cities and their surroundings, but also vertically extend over the PBL, and partly beyond.

Module A will use observational data provided by module B for testing individual model components of PALM-4U as well as the entire model. Modules A and B will jointly evaluate the PALM-4U model using quality-controlled reference data (see Maronga et al., 2019; Scherer et al., 2019). Finally, modules B and C will jointly test the applicability of observational methods for practical applications using real-case examples (see also Halbig et al., 2019; Scherer et al., 2019).

All partners except those of subproject 13 (GEONET) have performed or continue to perform measurements or process space-borne RS data, while GEONET has developed and is operating a data management system (DMS) for the $[UC]^2$ research programme.

Table 1: Overview on subprojects (SP), principal investigators (PI) and institutions part of the 3DO consortium.

SP	PI	Institution	Acronym
1	Dieter Scherer	Technische Universität Berlin (TUB), Fachgebiet Klimatologie	TUBklima
1	Andreas Philipp	Universität Augsburg (UA), Institut für Geographie	UAgeo
1	Jörn Welsch	Senatsverwaltung für Stadtentwicklung und Wohnen Berlin	SenSWB
1	Andreas Kerschbaumer	Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin	SenUVKB
2	Christoph Schneider	Humboldt-Universität zu Berlin (HUB), Geographisches Institut	HUBgeo
3	Sahar Sodoudi	Freie Universität Berlin (FUB), Institut für Meteorologie	FUBmeteo
4	Stephan Weber	Technische Universität Braunschweig (TUBS), Institut für Geoökologie	TUBSgeo
5	Erika von Schneidemesser	Institute of Advanced Sustainability Studies Potsdam	IASS
6	Dieter Klemp	Forschungszentrum Jülich (FZJ), Institut für Energie- und Klimaforschung	FZJiek8
7	Stefan Emeis	Karlsruher Institut für Technologie (KIT), Institut für Meteorologie und Klimaforschung, Atmosphärische Umweltforschung	KITimkifu
7	Norbert Kalthoff	Karlsruher Institut für Technologie (KIT), Institut für Meteorologie und Klimaforschung, Troposphärenforschung	KITimktro
8	Ulrich Vogt	Universität Stuttgart (US), Institut für Feuerungs- und Kraftwerkstechnik	USifk
8	Ulrich Reuter	Amt für Umweltschutz Stuttgart, Abteilung Stadtklimatologie	AfUSklima
9	Valeri Goldberg	Technische Universität Dresden (TUDD), Professur für Meteorologie	TUDDmeteo
10	Bernd Leitl	Universität Hamburg (UHH), Meteorologisches Institut	UHHmeteo
10	Felix Ament	Universität Hamburg (UHH), Meteorologisches Institut	UHHmeteo
11	Meinolf Koßmann	Deutscher Wetterdienst (DWD), Geschäftsbereich Klima und Umwelt	DWDku1
12	Günter Groß	Leibniz Universität Hannover (LUH), Institut für Meteorologie und Klimatologie	LUHimuk
13	Peter Trute	GEO-NET Umweltconsulting GmbH	GEONET
14	Thilo Erbertseder	Deutsches Zentrum für Luft- und Raumfahrt (DLR), Deutsches Fernerkundungsdatenzentrum	DLRdfd
14	Anke Roiger	Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre	DLRpa

3 Overview on atmospheric observations

Observational atmospheric data sets from existing and new LTOs, as well as data acquired during four IOPs are provided by the 3DO partners for the cities of Berlin, Hamburg and Stuttgart including their surrounding regions (Fig. 2). The winter IOPs took place in 2017 and 2018 during the months January and February, while the summer IOPs lasted from July to August both in 2017 and 2018. A few IOP measurements took place slightly before or after the main IOP periods due to logistical reasons. The exact timing of the measurements is stored together with the data in the respective data files.

Data sets comprise weather and climate data, data on wind and turbulence, energy and water balance components, momentum and mass fluxes, as well as data on air pollution by gas-phase air constituents and particulate matter including UFPs. Atmospheric data near the surface are mainly acquired through AWSs, ECSs, and AQSs. The 3DO partners developed a sophisticated experimental research set-up to acquire complementary three-dimensional data sets on atmospheric processes over cities at very high temporal and spatial resolution over sufficiently long periods. In addition, data sets acquired by space-borne RS systems are comprehensively available for the three city regions (and beyond).

Berlin, the capital and largest German city (890 km^2, 3,520,000 cap (December 2015), 3,900 cap/km^2) was chosen since it provides an ideal test bed for validation of urban climate models. Atmospheric pro-

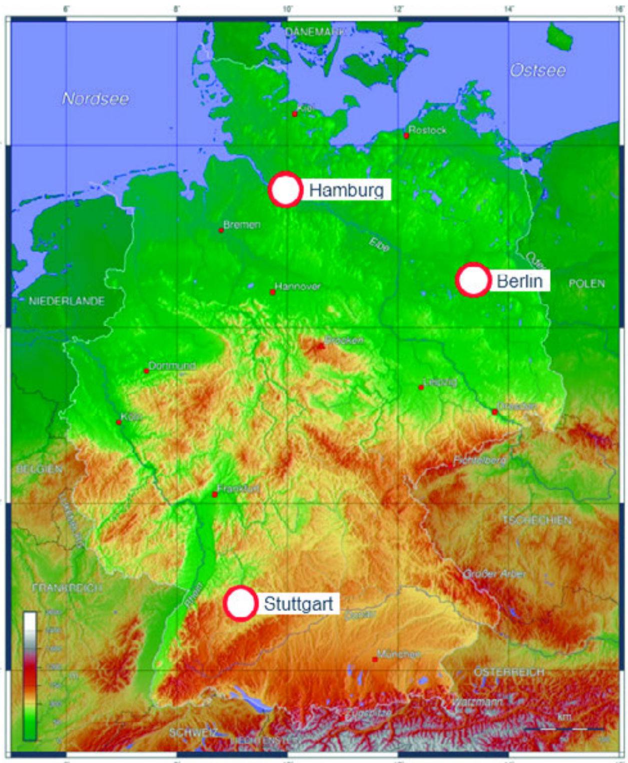

Figure 2: The German cities of Berlin (B), Hamburg (HH), and Stuttgart (S), for which experimental studies are carried out in the 3DO project (module B) of the [UC]^2 research programme. Map source: Wikipedia.

cesses, and thus urban climate and air quality conditions in Berlin are neither masked by topographically induced atmospheric processes nor by land-sea breezes or other coastal influences. In contrast, maritime influences are present in Hamburg (760 km^2, 1,860,000 cap (December 2016), 2,300 cap/km^2), and their effects on urban atmospheric processes need to be better understood. Stuttgart (210 km^2, 624,000 cap (December 2015), 3,000 cap/km^2) is one of the German cities with largest problems in air quality, mainly caused by its geographic situation in topographically complex terrain. However, topographically induced processes like cold-air flows can also positively influence urban air quality year-round and mitigate urban heat island effects during summer nights.

Tables 2 and 3 illustrate the broad spectrum of observational methods that the 3DO partners apply. Existing data sets comprise basic geo-data (e.g. digital terrain elevation, building and vegetation heights) and structural data (e.g. administrative borders) available from GISs and RS systems. Time series data on atmospheric variables are available from various sources for decades or longer back in time, for instance from weather stations provided by the DWD in and nearby Berlin, Hamburg and Stuttgart, from official AQS networks, or from observations as operated in Berlin by the TUBklima with the UCON Berlin and the FUBmeteo with the Berlin City Measurement Network. In addition, the 3DO partners compiled multi-annual observational data on specific atmospheric variables, e.g. from ECS, vertical profilers, and from air- and space-borne RS systems, which are continuously updated.

The existing data sets, although comprehensive in nature, are not sufficient for reaching the overall goals of the [UC]^2 research programme. Incomplete spatial coverage, both in horizontal and vertical dimensions, as well as missing variables require additional observations. Thus, some of the 3DO partners extended the measurements at existing LTO sites by new sensors and instruments that are also able to acquire 3D data, and installed new LTO stations at sites in urban areas that were not sufficiently represented, so far. Mobile LTOs using a variety of sensors and platforms complement the LTO sites. Some of the existing and new LTOs (e.g. by the RADAR systems) are intended to be utilised after completion of the first phase of the 3DO project, but measurements are taking or will take place already during the first phase to ensure data availability for additional investigations (e.g. on strong precipitation events).

During the four IOPs, 3DO partners carried out station-based observations and mobile measurements by pedestrians, bicycles, cars and public transport infrastructures. Three-dimensional data were acquired by utilizing high masts, SODAR and LIDAR systems, passive microwave radiometers, tethered balloons, radiosondes, manned and unmanned aircrafts and copters, and by space-borne RS systems. Vertical profile measurements are available for different LTO and IOP sites, and some of the instruments acquired spatially distributed data along flight routes, horizontal paths (transects), or as gridded data. The DLRdfd processes and provides space-borne RS data sets for the three cities, both as LTO and IOP data. Selection and calibration of instrumentation, execution of measurements, as well as data processing and quality control were and are carried out following general guidelines and state-of-the art methods to ensure high data quality. Dedicated wind tunnel experiments carried out by the UHHmeteo allow to comprehensively characterize selected urban areas in which intense observations take place both by LTOs and during the IOPs in dedicated areas called IOLs within the three cities. The IOLs are studied at a very high level of spatial detail to enable comprehensive evaluation of the PALM-4U model. Together with the LTO and IOP measurements at areas outside the IOLs, the resulting data sets will enable concurrent analyses of city-wide processes (meso- to local-scale) and processes in neighbourhoods, street canyons, and around individual buildings (local- to micro-scale). The wind tunnel simulations, which are partly completed, aim at provision of additional reference data sets at a slightly reduced level of complexity, still resolving the spatio-temporal variability of flow and transport phenomena dominated by near-ground, shear- and obstacle-induced turbulence.

Data provided by 3DO partners are rigorously quality controlled before being shared within the [UC]^2 research programme, with the scientific community, or the general public. Data are stored using open standard data formats like NetCDF (www.unidata.ucar.edu/software/netcdf). Data sets comprise metadata that follow general scientific conventions like the NetCDF CF version 1.7 (www.cfconventions.org). The [UC]^2 data standard is fully documented, and is publicly available (see Scherer et al., 2019). The 3DO website (www.uc2-3do.org) provides overview maps of LTO and IOP measurements in Berlin, Hamburg and Stuttgart, including further information on the stations.

3.1 Berlin

The concept behind the measurements in Berlin is twofold. Data from LTO sites representing different urban structures spread over the whole city are used to characterize intra-urban variations of atmospheric conditions both near the ground and in the PBL. Thus, these data allow for analysis and evaluation of meso-scale patterns in near-surface atmospheric variables like air temperature, humidity or concentrations of air pollutants, as well as of vertical profiles of wind, turbulence or aerosol concentrations as derived from both observations and numerical simulations. IOP measurements were mainly carried out within the two IOLs in Berlin, for which PALM-4U simulations are scheduled using model domains of 1 m grid spacing. Since many of the LTO sites are also located within the two IOLs, the resulting data sets cover a broad spectrum of atmospheric variables

Table 2: Instrumentation of long-term observations (LTOs) used by the subprojects (SP) of the 3DO consortium (see Table 1 for acronyms). Type of observation is either stationary (s) or mobile (m); City: Berlin (B), Hamburg (HH), Stuttgart (S). Observed variables refer to Appendix – List of symbols.

SP	Instrumentation	#	Type	Platform	Owner	City	Observed variables	Height (a.g.)
1	Ceilometer (Lufft CHM 15k)	2	s	roof/ground	TUBklima	B	β, N_{al}, h_{al}, h_{cl}, c_{cl}	0.015 to 15 km
1	Temperature and humidity sensor (Campbell CS215), barometer (Motorola MPXA4100A), tipping bucket rain gauge (Young 52203)	12	s	AWS	TUBklima	B	T, U, p, P	2 m
1	Temperature and humidity sensor (Vaisala HMP155), barometer (Vaisala), four-component radiometer (Kipp & Zonen CNR4), open-path gas analyser and 3D ultra-sonic anemometer (Campbell IRGASON), disdrometer (Thies laser precipitation monitor), sunshine pyranometer (Delta-T SPN1)	1	s	EBS (roof)	TUBklima	B	T, U, p, u, v, w, $E_{sw,d}$, $E_{sw,u}$, $E_{lw,d}$, $E_{lw,u}$, E_{dif}, T_{va}, P_l, P_s, CO_2, H_2O	47 to 57 m
1	Temperature and humidity sensor (Vaisala HMP155), barometer (Vaisala), four-component radiometer (Kipp & Zonen CNR4), open-path gas analyser and 3D ultra-sonic anemometer (Campbell IRGASON), disdrometer (Thies laser precipitation monitor, sunshine pyranometer (Delta-T SPN1), soil temperature profile probe (UMS TH3), soil humidity profile probe (Delta-T PR6), heat flux plate (Hukseflux HFP01)	1	s	EBS	TUBklima	B	T, U, p, u, v, w, $E_{sw,d}$, $E_{sw,u}$, $E_{lw,d}$, $E_{lw,u}$, E_{dif}, T_{va}, P_l, P_s, T_{soil}, θ_{soil}, H_{soil}, CO_2, H_2O	−1 to 40 m
2	Heat flux plate (Hukseflux), temperature and humidity sensor (Vaisala HMP 155A), wind monitor (Young 05103–5), four-component radiometer (Kipp & Zonen CNR1), soil thermistor probe (Campbell 107), soil water content reflectometer (Campbell CS616), tipping bucket rain gauge (UMS), NO_2 diffusive sampler (Passam AG), aerosol spectrometer (Grimm 107)	1	s	AWS	HUBgeo	B	q, T, U, p, u, v, $E_{sw,d}$, $E_{sw,u}$, $E_{lw,d}$, $E_{lw,u}$, T_{soil}, θ_{soil}, H_{soil}, P, NO_2, PM_{10}, $PM_{2.5}$, $PM_{1.0}$	−2 to 3 m
2	Temperature and humidity sensor (HMP 155A), wind monitor (RM-YOUNG-05103–5), net-radiometer (Hukseflux RA01–05), tipping bucket rain sensor (UMS), condensation particle counter (Grimm EDM 465 UFPC), temperature, humidity, air pressure, precipitation, and wind sensor (Lufft WS600), global radiation sensor (Minikin RTHi)	1	s	AWS (roof)	HUBgeo	B	T, U, p, u, v, $E_{sw,d}$, $E_{lw,d}$, P, $N_{0,007-2}$	14 to 20 m
2	Aerosol spectrometer (Grimm 1.109)	1	s	ground	HUBgeo	B	PM_{10}, $PM_{2.5}$, $PM_{1.0}$, $N_{0.25-32}$	1.5 m
3	Ceilometer (Lufft CHM 15k)	1	s	roof	FUBmeteo	B	β, N_{al}, h_{al}, h_{cl}, c_{cl}	0.015 to 15 km
3	Temperature and humidity sensor (Rotronic LOG HC2-S3)	21	s	mast	FUBmeteo	B	T, U	2 m
3	Water thermometer (Thies)	4	s	water	FUBmeteo	B	T_w	−0.8 to −0.5 m
3	2D ultra-sonic anemometer (Gill WindSonic)	4	s	mast	FUBmeteo	B	u, v	2 to 130 m
3	Wind vane and anemometer (Thies 3–1042 Hz)	3	s	mast	FUBmeteo	B	u, v	3 to 8 m
3	Temperature and humidity sensor (Thies)	9	s	mast	FUBmeteo	B	T, U	2 to 130 m
3	Hygro-thermosensor (Lambrecht)	2	s	mast	FUBmeteo	B	T, U	2 m
3	Bowen-Ratio System (Kipp & Zonen)	1	s	mast	FUBmeteo	B	T, U, u, v, $E_{sw,d}$, $E_{sw,u}$, $E_{lw,d}$, $E_{lw,u}$, T_{soil}, θ_{soil}	0.95 to 1.9 m
4	3D ultra-sonic anemometer (METEK USA1), engine exhaust particle sizer (TSI 3090)	1	s	mast (roof)	TUBSgeo	B	u, v, w, T_{va}, $N_{0.0056-0.56}$	57 m
8	Tapered element oscillating microbalance (Thermo Fisher Scientific TEOM1400a), opticle particle counter (Grimm EDM180), NO/NO_x sensor (MLU 200A), CO sensor (Horiba APMA 360), O_3 sensor (Horiba APOA 360), aethalometer (Magee AE33), wind monitor (Lufft WS200-UMB), meteorological instrument (Lufft WS301-UMB), tipping bucket rain gauge (Lambrecht 8353.12H)	1	s	car	USifk	S	PM_{10}, PM_{25-32}, $N_{0.25-32}$, NO, NO_x, NO_2, CO, O_3, BC, u, v, T, U, p, $E_{sw,d}$, P	3 m, 10 m
8	Optical particle counter (Alphasense N2), NO sensor (Alphasense B4), NO_2 sensor (Alphasense B43F), CO sensor (Alphasense B4), O_3 sensor (Alphasense B431), temperature, humidity, and pressure sensor, GPS	1	m	rack rail	USifk	S	PM_{10}, $PM_{2.5}$, $PM_{1.0}$, NO, NO_2, CO, O_3, T, U, p, x, y	variable
10	X-band RADAR (self-built GEM scanner SU70–25E)	1	s	roof	UHHmeteo	HH	Z	0 to 20 km
10	Temperature sensor (PT100), humidity sensor (Humicap HMP45/155), 3D ultra-sonic anemometer (METEK uSonic-3), open-path gas analyser (LI-COR 7500), pyranometer (Kipp & Zonen CMP21), pyrgeometer (Kipp & Zonen CGR4), infra-red remote temperature sensor (Heitronics KT19), barometer (Vaisala PTB200), water content reflectometer (Campbell CS616), temperature probe (Campbell 107)	1	s	radio mast	UHHmeteo	HH	T, U, p, u, v, $E_{sw,d}$, $E_{lw,d}$, P, T_{soil}, θ_{soil}, T_{va}, CO_2, H_2O	−1.2 to 280 m
10	3D ultra-sonic anemometer (METEK uSonic-3)	1	s	top of church	UHHmeteo	HH	u, v, w, T_{va}	147 m
10	Temperature sensor (Campbell 107), humidity sensor (Vaisala HMP155)	3	s	spire of church	UHHmeteo	HH	T, U	96 to 123 m
10	Temperature and humidity sensor (Vaisala HMP155), barometer (Campbell CS106), weather transmitter (Vaisala WXT530), 2D ultra-sonic anemometer (Gill WindSonic), pyranometer (Campbell CS300), infra-red remote temperature sensor (Campbell IR120), tipping bucket rain gauge (Young 52202), soil heat flux plate (Campbell HFP01)	10	s	tripod	UHHmeteo	HH	T, U, p, u, v, $E_{sw,d}$, $E_{lw,u}$, P, H_{soil}	1 to 3 m
10	Water content reflectometer (Campbell CS616), temperature probe (Campbell 107), soil matric potential monitor (ecoTech pF-meter)	9	s	soil	UHHmeteo	HH	T_{soil}, θ_{soil}, pF_{soil}	−1.6 to −0.05 m
10	3D ultra-sonic anemometer (Campbell CSAT3), open-path gas analyser (LI-COR 7500), temperature and humidity sensor (Vaisala HMP155), pyranometer (Campbell CS300)	1	s	cell tower	UHHmeteo	HH	T, U, u, v, w, T_{va}, $E_{sw,d}$, CO_2, H_2O	30 m
11	Temperature and humidity sensor (Vaisala HMP45d), four-component radiometer (Kipp & Zonen CNR4), weighing precipitation bucket (Ott Pluvio), wind speed sensor (Thies 4.3303.22.000), wind vane (Thies 4.3120.22.002)	1	s	AWS	DWDku1	B	T, U, u, v, $E_{sw,d}$, $E_{sw,u}$, $E_{lw,d}$, $E_{lw,u}$, P	1 m, 2 m
11	Temperature and humidity sensor (Vaisala HMP45d), wind speed sensor (Thies 4.33.3.22.000), wind vane (Thies 4.3120.22.002)	4	s	AWS	DWDku1	S	T, U, u, v	2 m
11	Temperature and humidity sensor (Vaisala HMP45d), four-component radiometer (Kipp & Zonen CNR4), weighing precipitation bucket (Ott Pluvio), wind speed sensor (Thies 4.3303.22.000), wind vane (Thies 4.3120.22.002)	1	s	AWS	DWDku1	S	T, U, u, v, $E_{sw,d}$, $E_{sw,u}$, $E_{lw,d}$, $E_{lw,u}$, P	1 to 10 m
14	Landsat-8	1	m	satellite	DLRdfd	B, S, HH	T_b	surface
14	ENVISAT/SCIAMACHY	1	m	satellite	DLRdfd	B, S, HH	NO_2	0 to 12 km
14	AURA/OMI	1	m	satellite	DLRdfd	B, S, HH	NO_2	0 to 12 km
14	MetOp/GOME-2	2	m	satellite	DLRdfd	B, S, HH	NO_2	0 to 12 km
14	Sentinel-5P/TROPOMI	1	m	satellite	DLRdfd	B, S, HH	CO, CH_2O, CH_4, NO_2, O_3, SO_2	0 to 12 km
14	Sentinel-3/OLCI, SLSTR	2	m	satellite	DLRdfd	B, S, HH	AOD, $PM_{2.5}$	0 to 100 km
14	AQUA/MODIS	1	m	satellite	DLRdfd	B, S, HH	AOD, $PM_{2.5}$	0 to 100 km
14	CALIPSO/CALIOP	1	m	satellite	DLRdfd	B, S, HH	h_{pbl}	0 to 10 km

Table 3: Instrumentation of intense observation periods (IOPs) used by the subprojects (SP) of the 3DO consortium (see Table 1 for acronyms). Type of observation is either stationary (s) or mobile (m) ; City: Berlin (B), Hamburg (HH), Stuttgart (S). Observed variables refer to Appendix – List of symbols.

SP	Instrumentation	#	Type	Platform	Owner	City	Observed variables	Height (a.g.)
1	Temperature and humidity sensor (Campbell CS215), 3D ultra-sonic anemometer (Thies 3D), tipping bucket rain gauge (Young 52203), net-radiometer (Kipp & Zonen CNR4), soil temperature profile probe (UMS TH3), soil humidity profile probe (Delta- PR6)	1	s	AWS	TUBklima	B	T, U, u, v, w, $E_{\mathrm{sw,d}}$, $E_{\mathrm{sw,u}}$, $E_{\mathrm{lw,d}}$, $E_{\mathrm{lw,u}}$, T_{va}, P, T_{soil}, θ_{soil}	−1 to 10 m
1	Temperature and humidity sensor (Campbell CS215), 3D ultra-sonic anemometer (Gill WindMaster), net-radiometer (Kipp & Zonen NR Lite), pyrgeometer (Apogee IRTS), pyranometer (Apogee CS300)	4	s	AWS	TUBklima	B	T, U, u, v, w, T_{va}, $E_{\mathrm{sw,d}}$, $E_{\mathrm{sw,u}}$, R_n, T_b	2 to 5 m
1	Temperature and humidity sensor (Driesen+Kern HumiLog), pyranometer (Apogee CS300), surface temperature thermocouple (Driesen+Kern EU-325)	14	s	balcony, room	TUBklima	B	T, U, $E_{\mathrm{sw,d}}$, T_s	2 to 40 m
1	Thermal IR camera (InfraTec VarioCam)	1	s	tripod	TUBklima	B	T_b	
1	Temperature and humidity sensor (Campbell CS215), 3D ultra-sonic anemometer (Gill WindMaster), net-radiometers in six directions (Kipp & Zonen CNR4), globe thermometer (Omega thermocouple type T inside a ping-pong ball)	1	s	human-biomet. station	TUBklima	B	T, U, u, v, w, T_{va}, $E_{\mathrm{sw,6d}}$, $E_{\mathrm{lw,6d}}$, T_{globe}	1 to 1.5 m
1	Thermal IR camera with integrated terrestrial 3D laser scanner (Zoller+Fröhlich)							
1	Temperature and humidity sensor (SHT75, Temod Pt1000/P14), GPS	3	m	UAS	UAgeo	B, S	T, U, u, v, x, y	0 to 250 m
2	Condensation particle counter (Grimm EDM 465 UFPC), temperature, humidity, air pressure, precipitation, and wind sensor (Lufft WS600)	1	m	bus, roof	HUBgeo	B	$N_{0.007-2.0}$, T, U, p, u, v, P	1.35 to 6 m
2	Condensation particle counter (TSI 3007), electric mobility spectrometer (TSI 3910), temperature, humidity, and wind speed sensor (Kestrel 5000), temperature, humidity, and global radiation sensor (Minikin RTHi)	1	m	bicycle	HUBgeo	B	T, U, ws, $N_{0.01-0.4}$, N, $E_{\mathrm{sw,d}}$	1.3 m
2	Temperature and humidity sensor (Campbell HMP155A), wind monitor (Campbell 05103–45), net-radiometer (Hukseflux NR01)	1	m	human-biomet. station	HUBgeo	B	T, U, u, v, $E_{\mathrm{sw,d}}$, $E_{\mathrm{sw,u}}$, $E_{\mathrm{lw,d}}$, $E_{\mathrm{lw,u}}$	1.1 to 2 m
3	Aerosol spectrometer (Grimm 1.109)	1	m	bus, bicycle	HUBgeo	B	PM_{10}, $PM_{2.5}$, $PM_{1.0}$, $N_{0.25-32}$	1.5 m
3	Aerosol spectrometer (Grimm 1.108)	1	s	bus, bicycle	HUBgeo	B	PM_{10}, $PM_{2.5}$, $PM_{1.0}$, $N_{0.3-20}$	variable
3	Optical particle counter (Alphasense N2)	3	m	bicycle	HUBgeo	B	PM_{10}, $PM_{2.5}$, $PM_{1.0}$	variable
3	Meteorology and air chemistry instrument (URBMOBI 3.0)	5	m	vehicle	HUBgeo	B, S	T, U, $E_{\mathrm{sw,d}}$, PM_{10}, $PM_{2.5}$, $PM_{1.0}$, NO_2, NO, O_3	variable
3	Temperature and humidity sensor (Rotronic LOG HC2-S3)	10	s	mast	FUBmeteo	B	T, U	1.1 m, 2 m
3	Temperature, humidity, and wind speed sensor (Testo 410–2)	4	m	hand-held	FUBmeteo	B	T, U, u	1.1 m, 2 m
3	Thermal IR camera (Flir E30)	1	m	hand-held	FUBmeteo	B	T_b	surface
3	IR thermometer (Testo 830-T1)	8	m	hand-held	FUBmeteo	B	T_b	surface
3	Globe thermometer (PCE-WB 20 SD)	6	m	hand-held	FUBmeteo	B	T, U, T_{globe}	1.1 m
3	Anemometer/wind vane for Vantage Pro2 (Davis Instr. 6410)	2	s	mast	FUBmeteo	B	u, v	variable
3	Temperature and humidity sensor (Type 3031, Theodor Friedrichs), 2D ultra-sonic anemometer (Gill WindSonic), net-radiometer (Kipp & Zonen CNR1)	1	s	mast	FUBmeteo	B	T, U, u, v, $E_{\mathrm{sw,d}}$, $E_{\mathrm{sw,u}}$, $E_{\mathrm{lw,d}}$, $E_{\mathrm{lw,u}}$	1.1 m
3	Water thermometer (Lambrecht)	1	m	hand-held	FUBmeteo	B	T_w	−0.5 m
3	Wind speed sensor (Windmaster 2)	5	m	hand-held	FUBmeteo	B	ws	variable
4	Thermal IR camera (FLIR T425)	1	s		TUBSgeo	B	T_b	surface
4	IR remote temperature sensor (Campbell IR100)	1	s	bicycle	TUBSgeo	B	T_b	surface
4	IR gas analyser (IRGA, LI-COR 840A), condensation particle counter (TSI 3787)	1	s	container	TUBSgeo	B	CO_2, H_2O, N	4 m
4	Thermocouple (Campbell Scientific FW3), IR gas analyser (IRGA, LI-COR 840A), condensation particle counter (TSI 3007)	1	m	bicycle	TUBSgeo	B	T, CO_2, H_2O, N	1.3 m
4	2D ultra-sonic anemometer (Gill WindSonic), condensation particle counter (TSI 3007), electric mobility spectrometer (TSI 3910), aethalometer (AethLabs AE51)	1	m	bicycle	TUBSgeo	B	u, v, N, $N_{0.01-0.42}$, BC	1.3 m
5	Zephyr small sensor (Earthsense)	10	s, m	bicycle, car, balcony	IASS	B	O_3, NO_2, PM	0.5 to 40 m
5	NO_x/NO_2/NO sensor (Teledyne API T-200); O_3 sensor (2B Technologies 205); cavity attenuated phase shift NO_2 (Aerodyne), aethalometer (Magee AE 33)	1	s	balcony	IASS	B	NO_x, NO_2, NO, O_3, BC	20 m
5	O_3 sensor (Teledyne API 430)	1	s	roof	IASS	B	O_3	40 m
5	Aethalometer (Magee AE33)	2	s	van	IASS	B	BC	2.5 m
5	Aethalometer (MicroAeth AE51)	1	s, m	bicycle	IASS	B	BC	1.1 m
5	Laser aerosol spectrometer (Grimm Mini-LAS 11-E)	1	s, m	bicycle, balcony	IASS	B	PM_{10}, $PM_{2.5}$, $PM_{1.0}$, PSD	1.1 m, 20 m
5	Laser particle counter (Purple Air PA-II: Dual Laser Air Sensor)	3	s	mast	IASS	B, H	PM_{10}, $PM_{2.5}$, $PM_{1.0}$, $N_{0.3-10}$	0.5 to 2 m
5	Ceilometer (Vaisala CL31)	1	s	roof	IASS	B	β, N_{al}, h_{al}, h_{cl}, c_{cl}	0 to 7.6 km
6	Chemiluminescence of generated NO_2 (Eco-Physics), NO_2 photolytic converter + chemiluminescence of NO_2 (Eco-Physics), O_3 titration with excess NO + chemiluminescence of NO_2 (Eco-Physics modified)	1	m	car	FZJiek8	B, S	NO, NO_2, O_3	2 m
6	CO resonance fluorescence (Aero laser), cavity attenuated phase shift (Aerodyne)	1	m	car	FZJiek8	B, S	CO, NO_2	2 m
6	IR cavity ringdown (Picarro), IR-ICOS laser absorption (LosGatos)	1	m	car	FZJiek8	B, S	CO, CO_2, CH_4, H_2O, N_2O, NH_3	2 m
6	VOC canister sampling (Restec), GC-MS (Agilent)	1	m	car	FZJiek8	B, S	C_2-C_{12} HC, $OVOC$	2 m
6	Meteorology instrument (Vaisala HMT 330), GPS (Wintec WBT202)	1	m	car	FZJiek8	B, S	T, U, u, v, x, y	2 m
6	Electrical low pressure impactor (Dekati), CPC-3788 (TSI)	1	m	car	FZJiek8	B, S	$N_{0.006-10}$	2 m
6	O_3 sensor (Ansyco 41M), SO_2 sensor (Thermo Fisher TE 43i)	1	m	car	FZJiek8	B, S	O_3, SO_2	2 m
7	Ceilometer (Vaisala CL51)	1	s	roof	KITimkifu	S	β, N_{al}, h_{al}, h_{cl}, c_{cl}	40 to 2000 m
7	Wind LIDAR (Halo Photonics Streamline XP)	3	s	roof	KITimkifu	S	u, v	40 to 600 m
7	Thermal IR camera (Optris PI)	1	s	roof	KITimkifu	S	T_b	surface
7	Wind LIDAR (Leosphere Windcube WLS 8)	1	s	roof	KITimktro	S	u, v, w	40 to 600 m
7	Wind LIDAR (Lockheed Martin WindTracer HYB and WTX)	2	s	ground	KITimktro	S	u, v	0.4 to 8 km
7	Microwave radiometer (Radiometer Physics HATPRO G4)	1	s	roof	KITimktro	S	T, U, h_{lw}, h_{wv}, T_b	0 to 10 km
7	X-band RADAR (Gematronik)	1	s	ground	KITimktro	S	Z, Z_{dr}, θ_{dp}, LDR, v_r	0 to 100 km

SP	Instrumentation	#	Type	Platform	Owner	City	Observed variables	Height (a.g.)
8	Condensation particle counter (TSI 3007), optical particle counter (Grimm 1.108, Palas Fidas Frog), NO_2/NO/NO_x sensor (2B Technologies 405 nm), O_3 sensor (2B Technologies OM202), aethalometer (AethLabs AE51), meteorological instrument (Gill Maximet GMX501), GPS (Garmin), camera (GoPro)	1	s	bicycle	USifk	S	N, $PM_{0.3\text{–}20}$, $N_{0.3\text{–}20}$, $PM_{0.18\text{–}100}$, $N_{0.18\text{–}100}$, NO_2, NO, NO_x, O_3, BC, T, U, p, u, v, $E_{sw,d}$, x, y	variable
8	Condensation particle counter (TSI 3007), optical particle counter (Grimm 1.108), optical particle counter (Palas Fidas Frog), NO_2/NO/NO_x sensor (2B Technologies 405 nm), O_3 sensor (2B Technologies OM202), aethalometer (AethLabs AE51), meteorological instrument (Kroneis)	1	s	tethered balloon	USifk	S	N, $PM_{0.3\text{–}20}$, $N_{0.3\text{–}-20}$, $PM_{0.18\text{–}100}$, $N_{0.18\text{–}100}$, NO_2, NO, NO_x, O_3, BC, T, U, p, u, v	up to 470 m
8	NO_2/NO_x diffusive sampler (Passam)	14	s	ground	USifk	S	NO_2, NO_x	3 m
9	Thermocouple (Campbell FW3), weather transmitter (Vaisala WXT520), IR sensors in four directions (Campbell IR120), IR sensor (Impac In15 plus), pyranometer (Skye SKS1110), quantum sensors in four directions (Licor LI-190SZ), GPS (Garmin 16-HVS), GPS (Garmin GPSmap60cs), camera (Gopro Hero 3)	1	m	backpack	TUDDmeteo	B	T, U, p, u, v, $E_{sw,6d}$, $E_{lw,6d}$, P, x, y	1 m, 2 m
9	Thermocouple (Campbell FW3), temperature and humidity sensor (Vaisala HMP45), IR sensor (Voltkraft IR 1000), pyranometer (Apogee CS300), quantum sensors in two directions (Skye SKP215), cup anemometer (Anemometerbau Rostock Präz.-Schalenkreuz A.), GPS (Garmin 16-HVS), GPS (Garmin GPSmap64s), camera (GoPro Hero 5)	1	m	bicycle	TUDDmeteo	B	T, U, u, v, $E_{sw,4d}$, $E_{lw,4d}$, x, y	1 m, 2 m
9	Thermal IR camera (InfraTec VarioCAM HR)	1	s	roof	TUDDmeteo	B	T_b	surface
9	3D ultra-sonic anemometer (Young 81000)	1	s	mast	TUDDmeteo	HH	u, v, w, T_{va}	2.5 to 31 m
9	Tripod (Campbell CM106BE), 3D ultra-sonic anemometer (Young 81000)	1	m	mast	TUDDmeteo	HH	u, v, w, T_{va}	0.4 to 4 m
9	Tethered sounding system (Vaisala DigiCORA)	1	m	tethered balloon	TUDDmeteo	HH	T, U, p, u, v	40 to 500 m
9	Weather transmitter (Vaisala WXT520)	1	m	roof	TUDDmeteo	HH	T, U, u, v, P	40 m
10	Weather transmitter (Vaisala WXT520)	1	s	mast (roof)	UHHmeteo	HH	T, U, u, v, P	5 m
10	Wind LIDAR (METEK Doppler LIDAR Stream Line)	1	s	roof	UHHmeteo	HH	u, v	50 to 500 m
10	3D ultra-sonic anemometer (METEK uSonic-3)	12	s	mast	UHHmeteo	HH	u, v, w, T_{va}	3.25 m, 6.75 m
10	Laser particle counter (Purple Air PA-II: Dual Laser Air Sensor)	3	s	mast	IASS	HH	PM_{10}, $PM_{2.5}$, $PM_{1.0}$	0.5 to 2 m
11	SODAR (METEK)	1	s	trailer	DWDku1	S	u, v, w	30 to 300 m
11	Frankenberger psychrometer (Friedrichs T3010), temperature sensor (Hettstedt MWT PT100), humidity sensor (E+E Elektronik EE33), air pressure sensor (Druck Limited DPI261)	1	m	car	DWDku1	B, S	T, U, p	2 m
11	Radiosonde (Vaisala RS92)	1	s	balloon	DWDku1	B, S	T, U, p, u, v	0 to 15 km
11	Tethered balloon sondes (Vaisala DigiCORA system), pyranometer (Kipp & Zonen CM21), pyrgeometer (Kipp & Zonen CG4)	1	s	tethered balloon	DWDku1	B, S	T, U, p, u, v, $E_{sw,d}$, $E_{sw,u}$, $E_{lw,d}$, $E_{lw,u}$	0 to 300 m
11	Wind monitor (Gill Solent)	2	s	ground	DWDku1	S	u, v	1 m
12	Hexacopter (DJI Flamewheel550), radiosonde (GRAW DFM-06), GPS	3	m	UAS	LUHimuk	B, S	T, U, p, u, v, x, y	0 to 300 m
12	Hexacopter (DJI Flamewheel550), camera (GoPro Hero 4 silver), thermal IR camera (FLIR Tau 2 640/09 mm fully radiometric + TeAx ThermalCapture 2.0), PM sonde (self-built, sensor technology: NOVA SDS011, DHT22, BMP180)	1	m	UAS	LUHimuk	B, S	T_b, PM_{10}, $PM_{2.5}$	0 to 300 m
14	Open-wire PT100 (custom-made), absolute/differential pressure transducer (PMP 4100), capacitive humidity sensor (Vaisala Humicap HMP230), dewpoint mirror (Meteolabor TP3-S modified by DLR), Ly-alpha absorption hygrometer (Buck research L5)	1	m	aircraft	DLRpa	B, S	T, U, p, u, v, w, x, y, z	0.15 to 6 km
14	Dual quantencascade laser (Aerodyne), cavity attenuated phase shift NO_2 (Aerodyne), UV absorption (2B Technologies)	1	m	aircraft	DLRpa	B, S	CO, CO_2, C_2H_6, O_3, CH_4, NO_2, N_2O	0.15 to 6 km

concurrently measured at a multitude of locations and vertical levels with state-of-the art instrumentation.

Atmospheric data from LTO in Berlin are comprehensively available from a variety of sources (Fig. 3), and allow for detailed studies of urban atmospheric processes. Some of the time series cover periods of more than 20 years. The longest time series in Berlin has been and is acquired at the DWD weather station 'Tempelhofer Feld' starting from 1948. The time series from the nearby DWD weather station in Potsdam, although not being an urban station, is even longer and fully covers the 20th century. A large amount of additional LTO data in the surroundings of Berlin is available, mainly from weather stations of the DWD and from the Lindenberg Meteorological Observatory – Richard Assmann Observatory, which routinely operates a large number of vertical profilers, as well as comprehensive short- and long-wave radiation and energy balance measurements that characterize the surrounding rural atmosphere (DWD, 2017b). The DWDku1 has installed an additional AWS in Berlin for measurements over at least two years.

The city-scale UCON Berlin operated by the TUBklima since 1990 (a few measurements even started already in 1986) provides one of the longest time-series data sets on urban climates in the world. This is justified by the fact that the earliest city-scale network listed in the review by Muller et al. (2013) is the Berlin City Measurement Network operated by the FUBmeteo since 2000. The BLUME AQS network operated by the SenUVKB provides multi-decadal time series data on concentrations of air pollutants. In addition, the 3DO project started new LTOs that shall continue in larger parts beyond the project's duration. The TUBklima and FUBmeteo partners increased the number of instruments and sites of their urban measurement networks in Berlin, and installed a network of three ceilometers within the city.

In 2018, the TUBklima installed a new 40 m tall measurement mast in an urban neighbourhood of Berlin (Rothenburgstraße, Berlin-Steglitz). The mast is instrumented to perform vertical profile LTO measurements of air temperature and humidity, up- and down-welling short- and long-wave radiation (four component radiometers), 3D wind components, sensible and latent heat fluxes (3D sonic anemometers and open-path gas analysers) at five levels in the UCL and above the roof level up to the inertial sublayer. In addition, the TUBklima deployed two wind LIDAR systems and a

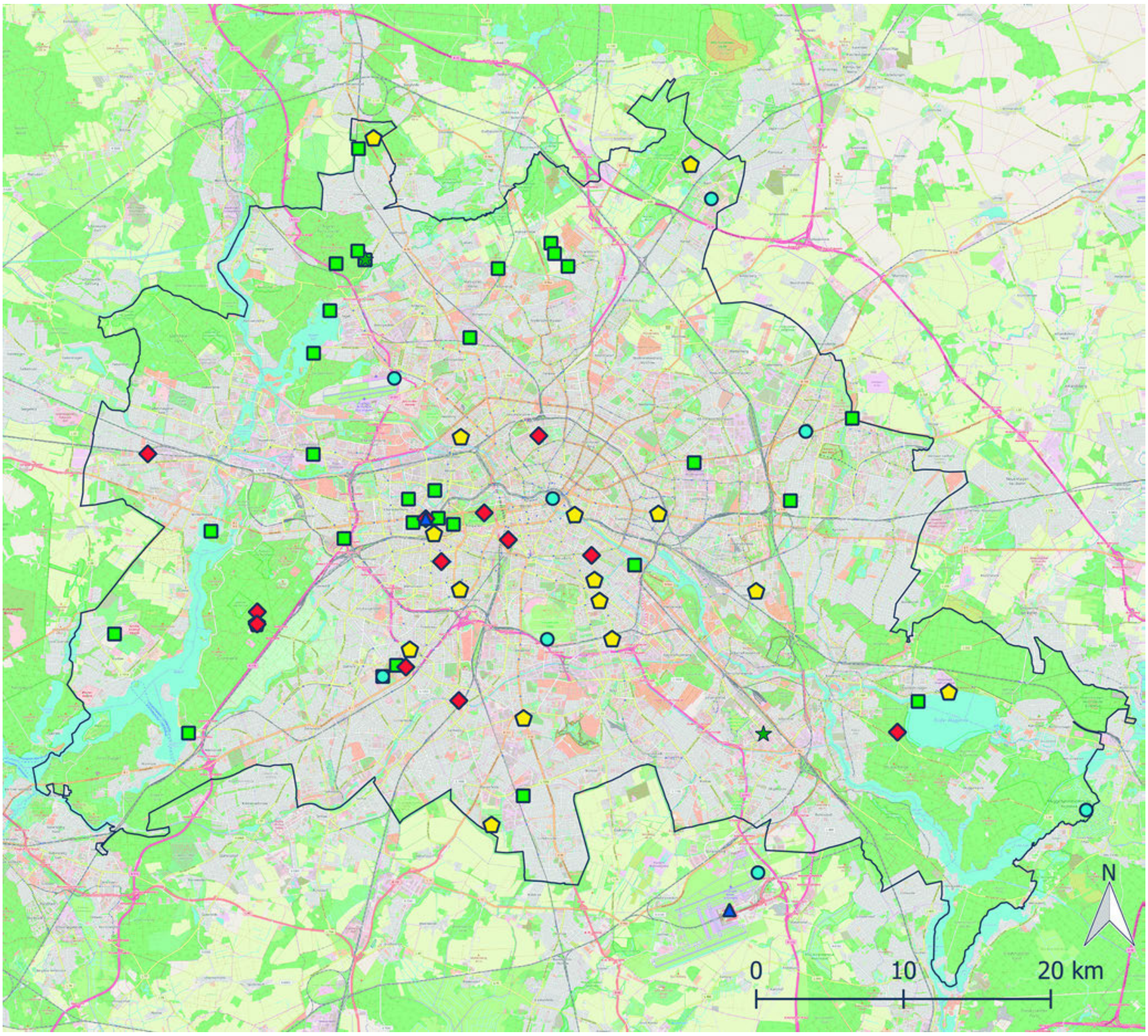

Figure 3: Long-term observations (LTOs) in Berlin (black line: city border) as part of 3DO research. Data from LTOs are provided by the following institutions (see Table 1 for abbreviations): SenUVKB, Berliner Luftgüte Messnetz (BLUME) (yellow pentagons); DWD (cyan circles); FUBmeteo (light green squares); HUBgeo (dark green stars); TUBklima (red diamonds); TUBSgeo (dark blue triangles). Map source: OpenStreetMap – published under ODbL 1.0.

passive micro-wave air temperature/humidity profiler deployed within the two IOLs (Fig. 4) as LTOs. A dual-polarimetric X-band Doppler weather RADAR system will complement the LTO instrumentation in the beginning of 2019. A TIR camera system with an integrated terrestrial 3D laser scanner was used for mobile measurements of urban structures with complex geometries during the IOPs (and beyond). The entire instrumentation of the TUBklima for 3D observation of atmospheric processes in Berlin and its surroundings forms the UCO Berlin, which will officially start after completion of instrument deployment for unlimited time. The UCO Berlin will provide an experimental platform for researchers in urban atmospheric and environmental sciences.

The HUBgeo operates a LTO site at Berlin-Adlershof in the Southeast of Berlin combining meteorological and air quality variables including UFPs counters. The HUBgeo will further install semi-permanent LTO of major air pollutants at selected sites using cost-effective custom-made micro-electronic small-scale sensor systems. The HUBgeo will also deploy additional mobile LTO by installing a new generation of URBMOBI sensors (Seidel et al., 2016) at buses, trams, taxis, garbage trucks or similar vehicles on a semi-permanent basis through agreements with vehicle operators.

The TUBSgeo installed additional 3D ultrasonic anemometers, a fast electric mobility spectrometer to measure size-resolved particle concentrations including UFPs, fast optical sensors (IR absorption) to measure

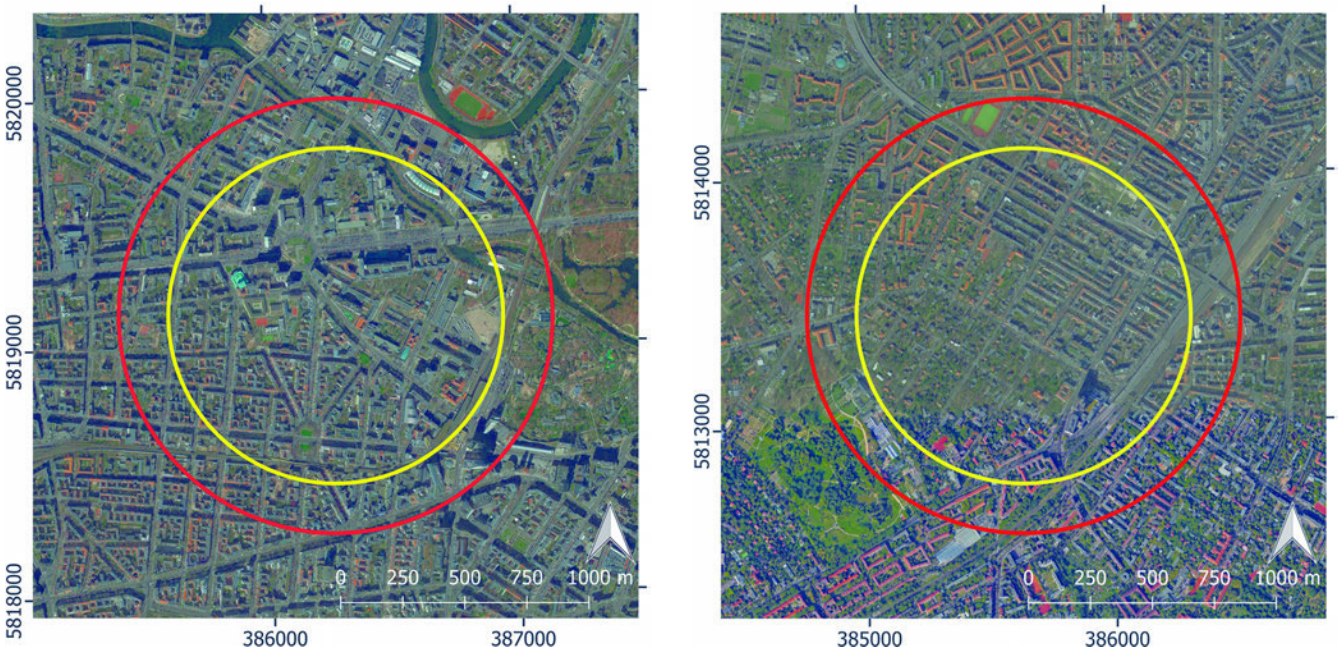

Figure 4: Intense observation locations (IOLs) in Berlin (see Table 1 for acronyms). Left: TUB Campus Charlottenburg; right: Rothenburgstraße, Steglitz. Red circles: scale models (radius 875 m) to be used for wind tunnel experiments by the UHHmeteo; yellow circles: areas to be analysed (radius 675 m). Images are in WGS84/Pseudo-Mercator projection. Coordinates on image borders are in UTM33. Map source: © 2017 GeoBasis-DE/BKG (© 2009), Google.

fluctuations of carbon dioxide and water vapour concentrations, as well as condensation particle counters (Weber et al., 2013).

The IASS equipped a number of LTO sites with a prototype of a micro-sensor instrument (Zephyr) for measuring a variety of variables at high spatial density and temporal resolution relevant for city-scale numerical modelling, including air pollution components, such as ozone, nitrogen dioxide, and particulate matter, as well as air temperature and relative humidity.

During the four IOPs, mobile and airborne in-situ measurements were performed by the TUBklima, HUBgeo, FUBmeteo, TUBSgeo, IASS, FZJiek8, TUDDmeteo, DWDku1, LUHimuk, and the DLRpa. The IOP measurements focused on the two IOLs, but also covered other areas in and around Berlin. Comprehensive stationary and mobile instrumentation both for meteorological variables and concentrations of carbon dioxide and air pollutants were used for short-term measurements at selected sites, as well as for repetitive measurements along transects, using temporary stations and various mobile platforms. Ultrasonic anemometers allowed for detection of weak cold-air flows, while radiometers (four components) enabled acquisition of data on up- and down-welling short- and long-wave radiation, surface temperatures of different surface types including walls and roofs of buildings, and on mean radiant temperature, which is a key variable to characterise human-biometeorological conditions. Vertical profiles of atmospheric variables were acquired by UASs by the UAgeo and the LUHimuk, and by a tethered balloon system by the TUDDmeteo over several days, the latter during the two summer IOPs. In addition, the DLRpa carried out a flight campaign using the DLR Cessna aircraft during the summer IOP in 2018.

3.2 Hamburg

A two-tier LTO strategy is implemented in Hamburg to monitor both regional-scale and local weather conditions within the city to assess atmospheric modifications by the urban environment. Basic information about overall near-surface weather conditions, i.e., screen-level air temperature and humidity, as well as wind at 10 m height, is provided by a network of weather stations operated by the DWD featuring eight stations in the vicinity of Hamburg (Fig. 5). Unfortunately, almost all weather stations operated by the DWD inside the city of Hamburg stopped operation close to the end of the last century rendering any extensions of long-term urban climate analyses like those presented by Schlünzen et al. (2010) impossible. Inside the city only the observational record of the station Fuhlsbüttel ranging back to 1891 is continuously updated.

This set-up was extended by the UHHmeteo through two profiling sites east and northwest of the city, respectively, and at the tall tower facility "Hamburg Wettermast" (Brümmer et al., 2012; Brümmer and Schultze, 2015) located at the eastern outskirts of Hamburg providing digitalized observations since 1995. Observations comprise in-situ profiles of air temperature, humidity and wind speed acquired with analysers measuring turbulent fluctuations of wind, air temperature, humidity and carbon dioxide to derive corresponding turbulent fluxes. The Hamburg Wettermast site is

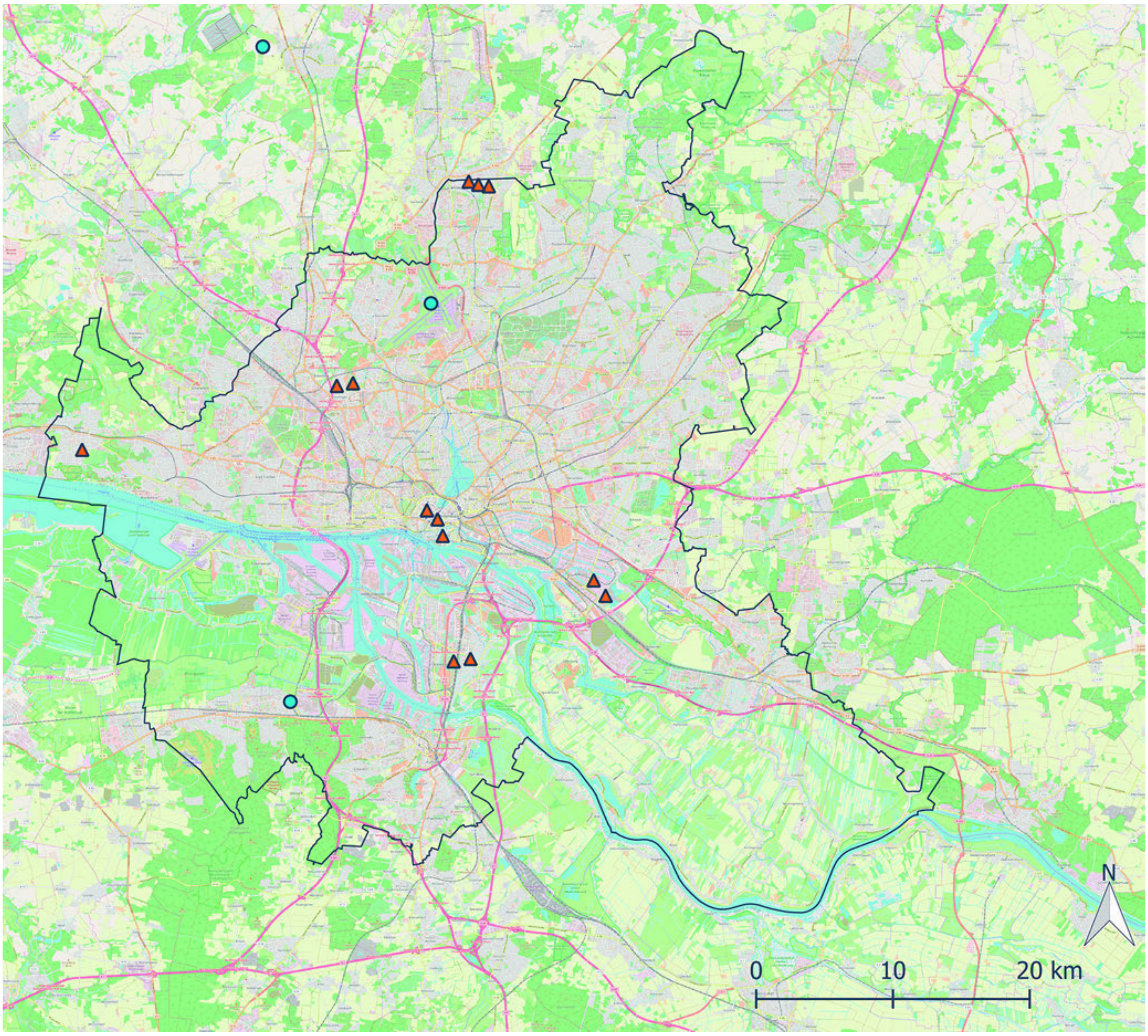

Figure 5: Long-term observations (LTOs) in Hamburg (black line: city border) as part of 3DO research. Data from LTOs are provided by the following institutions (see Table 1 for acronyms): DWD (cyan circles); UHHmeteo (orange triangles). Map source: OpenStreetMap – published under ODbL 1.0.

complemented as energy balance station by soil temperature, radiation, precipitation (rain gauge and micro rain radar) and cloud measurements (ceilometer, cloud temperature and optical cloud camera). A similar energy-balance station set-up, using a 10 m-mast instead of a tall tower, was deployed at the airfield Hungriger Wolf located 50 km northwest of Hamburg close to the city of Itzehoe. Vertical profile data of air temperature and wind are acquired by a micro-wave radiometer and a wind SODAR, respectively. While these two profiling sites outside the city, in combination with the DWD network, monitor regional-scale weather conditions, a network of ten autonomous weather stations (HUSCONET); Wiesner et al., 2014) observes locally modified urban weather and climate conditions since September 2010. Each station measures standard near-surface meteorological variables (air temperature and humidity, wind at 3 m height, solar irradiance, pressure, precipitation, surface temperature, soil heat flux). In addition, all seven stations at unsealed locations are equipped with five-layer soil temperature and soil moisture sensors.

The IOPs at Hamburg were the small-scale counterparts of the LTOs offering reference data for model validation, particularly for wind and turbulence. The surrounding of the HCU, located at the river Elbe directly in the city centre, was selected as target area as it features comparably simple incident flow conditions from the river (Fig. 6). Following again a two-tier approach, measuring both the forcing and the local response, allows to set up a well-defined test case for models simulating flows over and around the HCU building. The UHHmeteo and the TUDDmeteo measured undisturbed

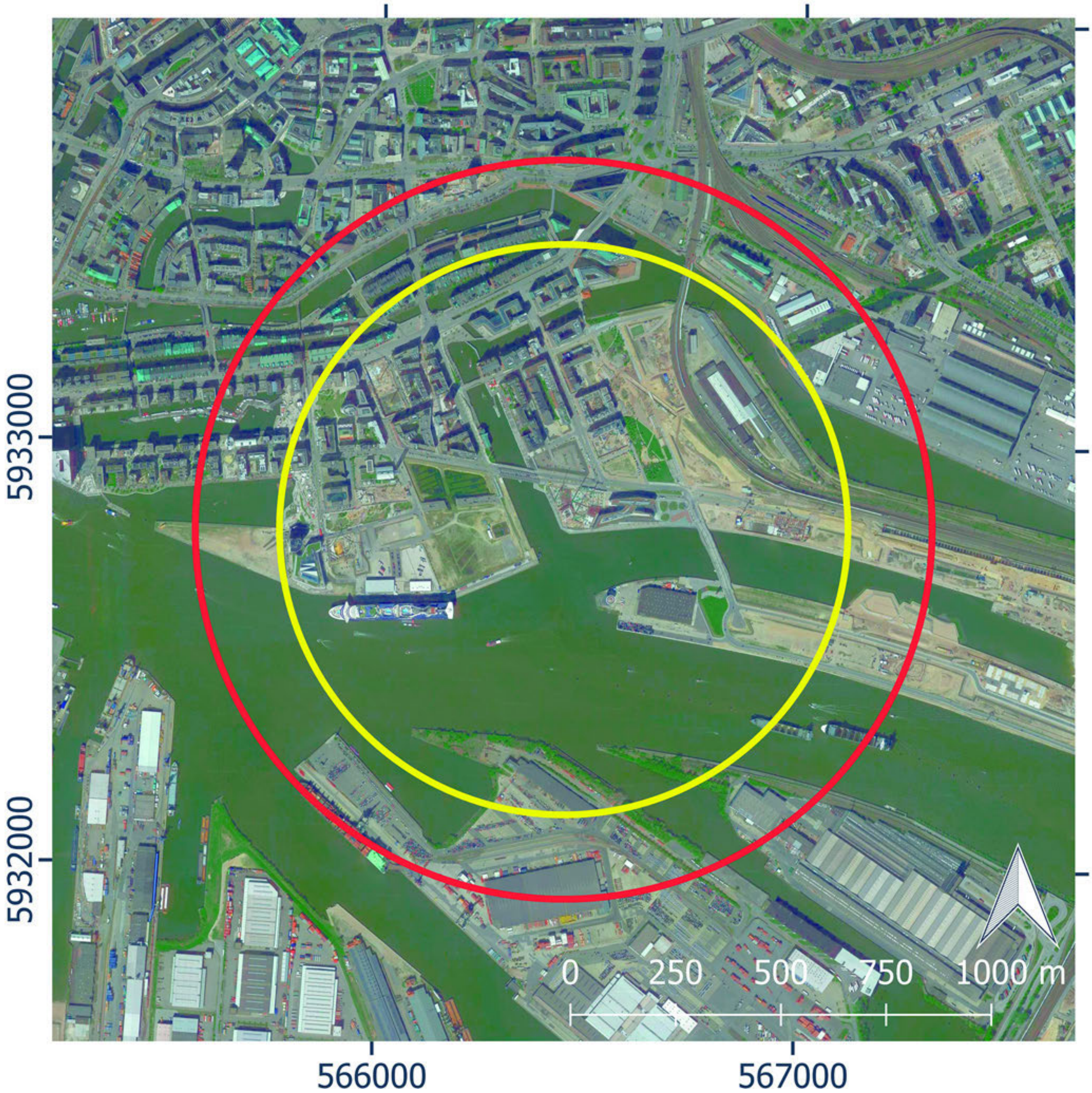

Figure 6: Intense observation location (IOL) in Hamburg HafenCity (see Table 1 for acronyms). Red circle: scale model (1:500; radius 875 m) to be used for wind tunnel experiments by the UHHmeteo; yellow circle: area to be analysed (radius 675 m). Images are in WGS84/Pseudo-Mercator projection. Coordinates on image borders are in UTM32. Map source: © 2017 GeoBasis-DE/BKG (© 2009), Google.

wind conditions with two wind masts, a tethered balloon and a wind LIDAR. Detailed flow structures on the north side of the building were detected by an array of twelve 3D ultrasonic anemometers mounted at six wind masts at 3 and 6 m height. Data from this array were recorded at 20 Hz to provide detailed insight into spatial and temporal structures of turbulent flows. The IOPs are accompanied by corresponding experiments by the UHHmeteo in a large boundary-layer wind tunnel, where simulations for several flow directions allow for an analysis of fully 3D flow structures, and thus provide reliable information on representativeness of local measurements. In addition, wind-tunnel simulations of the Hamburg IOL for a future stage of the HafenCity district were performed by the UHHmeteo. Such data will be used to test the ability of the PALM-4U model to capture effects caused by changing building structures, among others.

3.3 Stuttgart

Acquisition of data on topographically induced winds and their modifications by the urban fabric are one of the major objectives of the measurements carried out in Stuttgart. In particular, the role of atmospheric flows

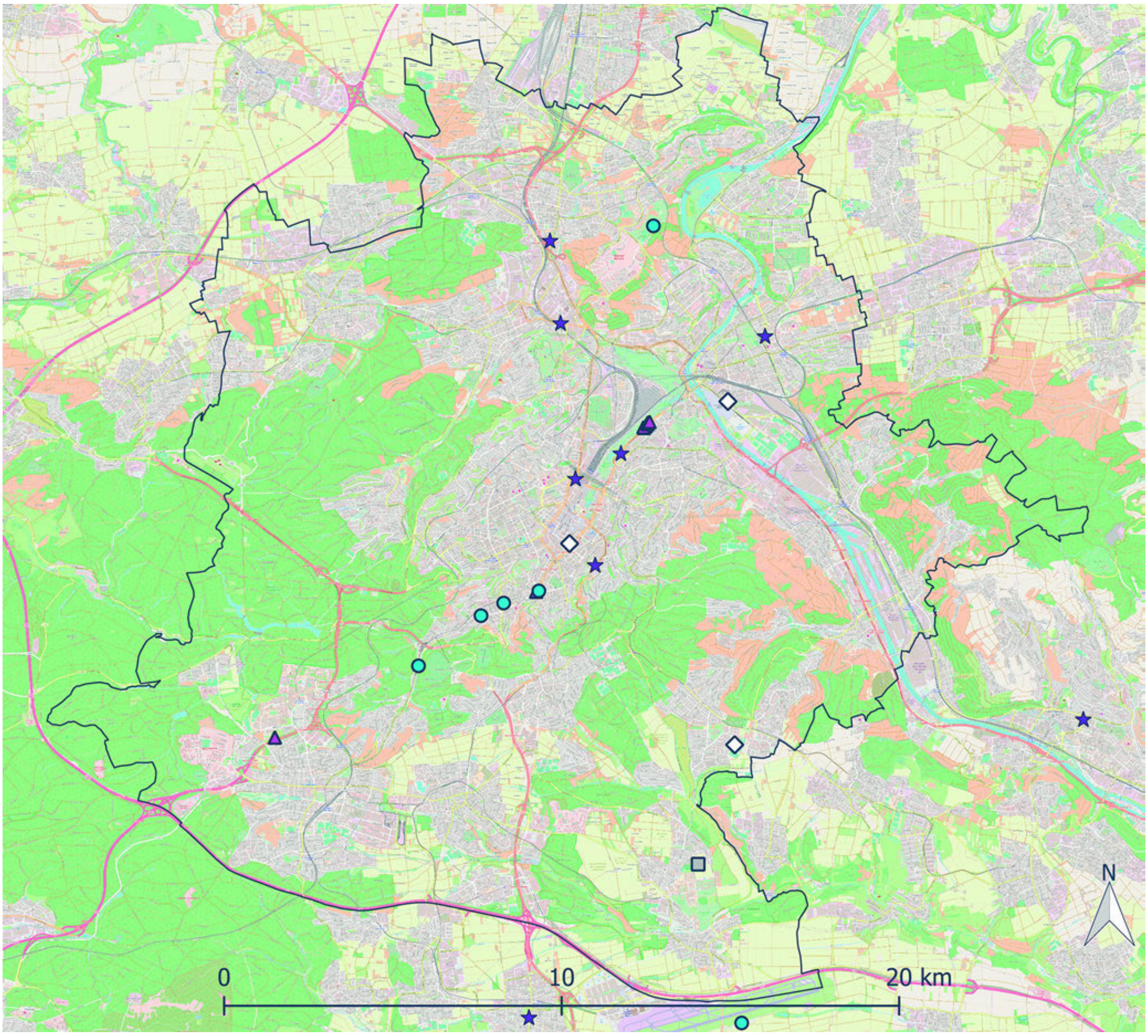

Figure 7: Long-term observations (LTOs) in Stuttgart (black line: city border) as part of 3DO research. Data from LTOs are provided by the following institutions (see Table 1 for acronyms): Landesanstalt für Umwelt Baden-Württemberg (LUBW) (purple stars); AFUSklima (white diamonds); DWD (cyan circles), Universität Hohenheim (UH) (grey square), USifk (pink triangles). Map source: OpenStreetMap – published under ODbL 1.0.

for dispersion of air pollutants is of utmost importance since Stuttgart is one of the German cities with highest concentrations of air pollutants.

Atmospheric data from LTOs in Stuttgart are available from different sources (Fig. 7). The longest time series is available since the late 19th century (1878) from the Universität Hohenheim. Meteorological variables like air and soil temperature, humidity, wind speed and direction, solar radiation, and precipitation are continuously measured since then. Additionally, new LTO sites were installed to fill gaps in 3DO data sets.

The DWDku1 installed five additional weather stations equipped with instruments to measure different meteorological variables, and the USifk installed a measurement car on the central Marienplatz to measure meteorological variables and concentrations of air pollutants.

During the IOPs, 3DO partners performed numerous measurements of meteorological variables and air pollutants including in-situ measurements at different sites on street level, RS measurements, mobile measurements on street level, as well as vertical soundings. IOP measurements focus on two IOLs in Stuttgart, one of them also foreseen for wind-tunnel experiments by the UHHmeteo (Fig. 8).

In-situ measurements of air pollutants and measurements of meteorological variables are performed by the USifk with a measurement car. During the IOPs, passive samplers (Passam) were applied for measuring nitrogen dioxide and nitrogen oxide concentrations at ap-

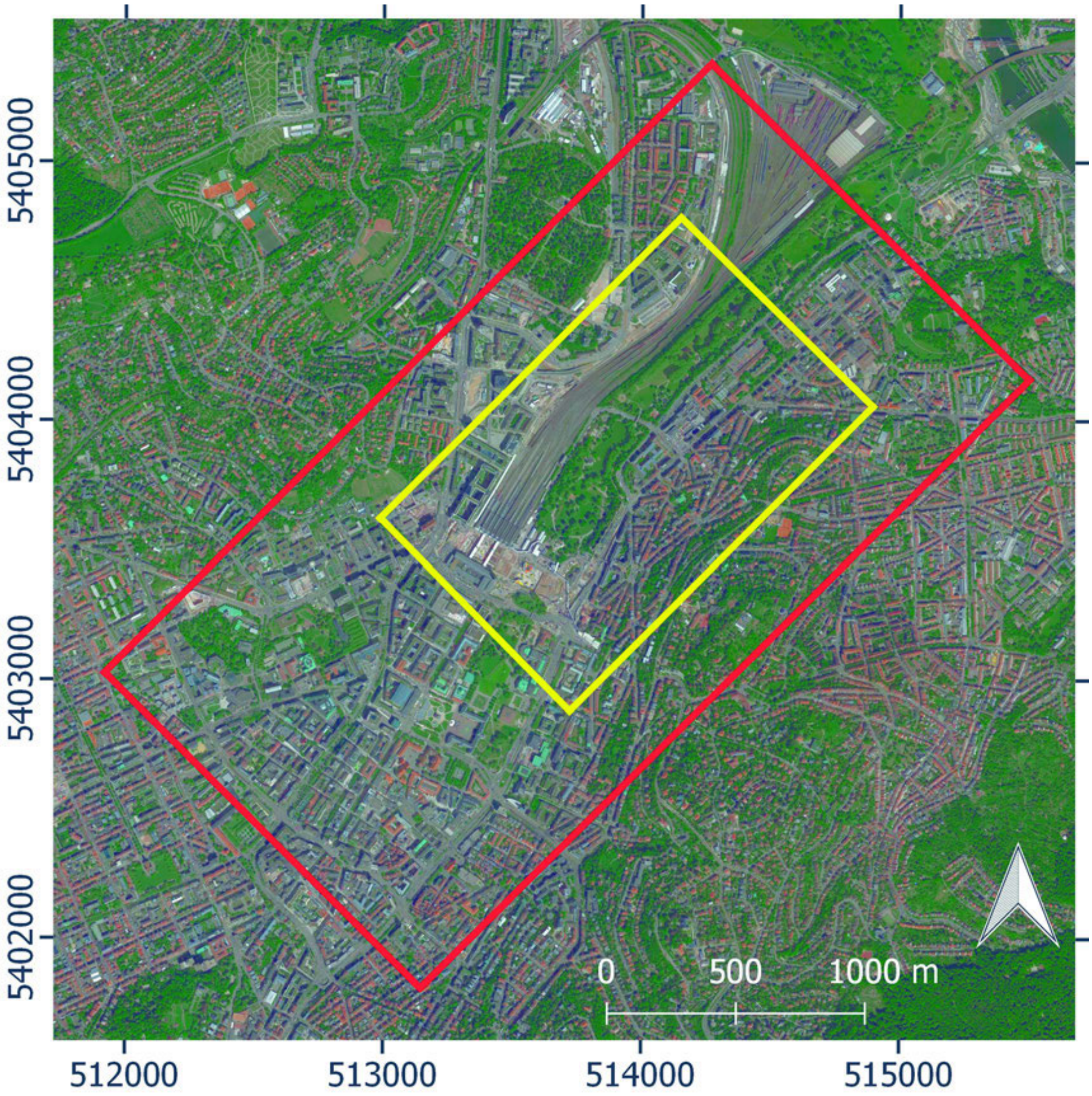

Figure 8: Intense observation location (IOL) in Stuttgart (see Table 1 for acronyms). Red rectangle: scale model (1:500; extent 875 m) to be used for wind tunnel experiments by the UHHmeteo; yellow rectangle: area to be analysed (extent 675 m). Images are in WGS84/Pseudo-Mercator projection. Coordinates on image borders are in UTM32. Map source: © 2017 GeoBasis-DE/BKG (© 2009), Google.

prox. 15 sites in the city to supplement the mobile measurements. The KIT Institut für Meteorologie und Klimaforschung, Atmosphärische Aerosolforschung, supported the 3DO partners with a fully equipped monitoring station for the determination of air pollutants with focus on particulate matter identification by an aerosol mass spectrometer (AMS) and a laser ablation aerosol time of flight (LAAPTOF) instrument, among others.

TheKITimktro and KITimkifu used different RS devices to determine horizontal and vertical distributions of meteorological variables. Instruments in operation were a ceilometer (mixing height), six Doppler wind LiDAR (horizontal and vertical wind speed and wind direction), an X-band Doppler RADAR (precipitation), a TIR camera (surface temperature), and a micro-wave radiometer (temperature, humidity, water vapour content). The DWDku1 operated a SODAR system for determination of vertical wind profiles. Some of the instruments delivered data up to 12 km above ground.

The FZJiek8 performed mobile measurements with a measurement van also used in Berlin. At high temporal and spatial resolution, different air pollutants were determined for transects along streets within the city of Stuttgart but also in windward and leeward directions. For air temperature, humidity and pressure, similar measurements were performed by the DWDku1. The USifk used a bicycle to perform transect measurements of meteorological variables and air pollutants. Compared to the mobile measurements by car, the bicycles could easily be used aside the roads, e.g. in parks and pedestrian zones. As generally applied for mobile measurements, the bike measurements were performed such that artefacts stemming from the moving platform or the release of heat, particulates, etc. were avoided or, at least, reduced to a minimum. Therefore, additional measurements (e.g. by a GPS that provides both location and speed of the bike) were included for post-processing the bike data.

The USifk and the DWDku1 performed tethered balloon measurements for meteorological variables up to a height of 470 m above ground (limitation of height due to flight security). The USifk additionally measured concentrations of different air pollutants with the help of the tethered balloon. Tethered balloon soundings were supported by radio-sounding measurements of meteorological variables performed by the DWDku1. The USifk applied particulate-matter and gas sensors for mobile measurements on a rack railway for profile measurements from the city centre of Stuttgart to the outskirts. The LUHimuk performed vertical profile measurements with a multicopter, and the UAgeo measured vertical profiles of atmospheric variables by UAS during the summer IOP in 2017. A flight campaign using a Cessna aircraft was carried out by the DLRpa during the summer IOP in 2018.

4 Conclusions and perspectives

The 3DO project was able to implement a highly ambitious observational research concept combining existing, comprehensive LTO data sets from three German cities with state-of-the-art instrumentation for acquisition of new, three-dimensional atmospheric data at a level of detail that has not yet been realised in Germany. The 3DO approach is integrative, i.e., it combines investigations on weather, climate and air quality phenomena, following the requirements formulated by Barlow et al. (2017). The goals of the 3DO project are only achievable by a large consortium, since the multitude of measurements requires versatile and expensive instrumentation, as well as many highly skilled people installing and operating them. Finally, data analysis is highly complex. Thus, scientific and logistic co-ordination of the 3DO project and its embedding into the entire [UC]^2 research programme is essential for reaching the goals.

Although evaluation of the PALM-4U model is not yet completed, the 3DO partners are, based on the results already obtained by LTOs and during four IOPs, confident that they will be able to provide a broad portfolio of suitable, accurate reference data sets including data on turbulence essential for validating LES models like PALM-4U, which could also be used for evaluating other numerical atmospheric models. 3DO data sets are expected to provide the basis for design and implementation of an urban climate model intercomparison project that is planned for the future.

The [UC]^2 data standard ensures that fully documented 3DO data sets from both LTO and IOP measurements will not only be available for studies within the [UC]^2 research programme but also for further research and applications. The 3DO data sets that are already available are promising in this respect, thus, the 3DO partners expect that their data sets will be of high scientific and practical value for long time, not only for model evaluation but also for stand-alone studies and applications.

The 3DO partners will also work on further enhancing the measurement strategies and methods. Crowdsourcing and citizen science are two examples of emerging methodologies in urban climatology (Chapman et al., 2015, 2017; Meier et al., 2017) that will develop in the upcoming years and need to be integrated into future research.

Appendix –Abbreviations

AMS	Aerosol mass spectrometer
AWS	Automatic weather station
AQS	Air quality station
BC	Black carbon
BLUHI	Boundary-layer urban heat island
BLUME	Berliner Luftgütemessnetz
BMBF	German Federal Ministry of Education and Research
CF	Climate and Forecast Metadata Conventions
ECS	Eddy-covariance station
GIS	Geographic information system
GPS	Global positioning system
HCU	HafenCity University
HUSCONET	Hamburg Urban Soil Climate Observatory Network
IOL	Intense observation location
IOP	Intense observation period
IR	Infra-red
LAAPTOF	Laser ablation aerosol time of flight
LIDAR	Light detecting and ranging
LTO	Long-term observation
NetCDF	Network Common Data Format
PALM	Parallelized Large Eddy Simulation Model for Atmospheric and Oceanic Flows
PBL	Planetary boundary layer
RADAR	Radio detecting and ranging
RS	Remote-sensing
SDG	Sustainable development goal
SODAR	Sound detecting and ranging
SUHI	Surface urban heat island
TIR	Thermal infra-red
UAS	Unmanned aerial system
UBL	Urban boundary layer
UCL	Urban canopy layer

UCO	Urban Climate Observatory
UCON	Urban Climate Observation Network
UFPs	Ultra-fine particulates
UHI	Urban heat island
URBMOBI	Urban Mobile Measurement System
WMO	World Meteorological Organization
3D	Three-dimensional

Appendix – List of symbols

Symbol	Description
AOD	aerosol optical depth
BC	mass concentration of black carbon
β	backscatter coefficient
c_{cl}	cloud coverage
CH_4	mass concentration of methane
CO	mass concentration of carbon monoxide
CO_4	mass concentration of carbon dioxide
C_2H_6	mass concentration of ethane
$E_{\mathrm{sw,d}}$	down-welling short-wave irradiance
$E_{\mathrm{sw,u}}$	up-welling short-wave irradiance
$E_{\mathrm{sw,4d}}$	short-wave irradiance from four cardinal directions
$E_{\mathrm{sw,6d}}$	short-wave irradiance from six cardinal directions
$E_{\mathrm{lw,d}}$	down-welling long-wave irradiance
$E_{\mathrm{lw,u}}$	up-welling long-wave irradiance
E_{lw}	long-wave irradiance
E_{dif}	diffuse solar irradiance
h_{al}	height of aerosol layers
HC	mass concentration of hydrocarbons
h_{cl}	cloud height
h_{lw}	liquid water path
h_{pbl}	height of the planetary boundary layer
h_{wv}	water vapor path
H_{soil}	soil heat flux
LDR	linear depolarization ratio
N	number concentration of particulate matter
N_{al}	number of aerosol layers
NO	mass concentration of nitrogen monoxide
NO_2	mass concentration of nitrogen dioxide
NO_2	mass concentration of nitrogen oxides
v_{r}	radial Doppler velocity
O_3	mass concentration of ozone
$OVOC$	mass concentration of oxygenated volatile organic compounds
p	air pressure
P	total precipitation
pF_{soil}	soil water potential
P_{l}	liquid precipitation
PM	mass concentration of particulate matter
P_{s}	solid precipitation
PSD	particle size distribution; diameters for PM and N are specified as subscripts inμ m.
T	air temperature
T_{b}	brightness temperature
T_{globe}	globe temperature
T_{soil}	soil temperature
T_{w}	water temperature
T_{va}	virtual acoustic temperature
θ_{dp}	differential phase
θ_{soil}	volumetric water content
U	relative humidity
u	wind component in x-direction
v	wind component in y-direction
VOC	mass concentration of volatile organic compounds
w	wind component in z-direction
ws	wind speed
x	eastward location in cartesian coordinates
y	northward location in cartesian coordinates
z	vertical location in cartesian coordinates
Z	reflectivity
Z_{dr}	differential reflectivity

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