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Microclimatic measurements in tropical cities: Systematic review and proposed guidelines

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ABSTRACT

To tackle urban overheating induced by the combined effect of global warming and intensive urbanization, researchers have recommended assimilating microclimate-related strategies into urban design practices. Field measurements, playing a central role in urban climatology, have been widely applied worldwide. Reviewing the last five years' field measurement studies and existing guidelines and standards from WMO (World Meteorological Organization) and ISO (International Organization for Standardization), this study identified a gap between available guidelines and researchers' practical needs to ascertain the collection of high caliber data. Therefore, dedicated guidelines are required to explain the crucial conceptual and application issues and refine systematic field measurement methods. This demand is particularly acute for microscale and urban environments. This study proposed and explained integrated and comprehensive guidelines for systematic microclimate field measurements. The suggested workflow included four main steps: formulating field measurement plan, preparing for field measurements, sustaining measurement quality, and curating data. The complex and heterogeneous environment in urban areas was carefully evaluated to hone the data acquisition campaign and ascertain data quality. Relevant concepts and practices learned from existing guidelines and standards, experiences from actual field studies, and professional recommendations were distilled and incorporated into the guidelines. The significance of a complete report with full metadata was emphasized. Detailed hints, precautions, recommendations, examples, and a metadata checklist were provided as a helpful and actionable package of research procedures.

1. Introduction

Due to the combined effect of global warming and intensive urbanization, many cities suffer from the urban heat island (UHI) effect with severe heat stress for residents [1]. The menace of accumulated heat may bring multiple negative impacts such as compromised human thermal comfort [2], excess heat-related morbidity and mortality [3], additional cooling energy consumption [4], etc. Research on urban microclimate has been widely conducted to deal with urban overheating and thus integrated climate-sensitive design strategies into urban design practices (e.g., Hong Kong Green Building Council: Guidebook on Urban Microclimate Study; City of London: Wind Microclimate Guidelines, Thermal Comfort Guidelines for developments in the City of London, etc.). Regarding urban climatology research approaches, Oke et al. [5] classified them into four main categories: field observation, physical modeling, empirical generalization and synthesis, and numerical modeling. Field observation, relying on measurements of surface and atmospheric properties using sensors, has been widely applied in previous decades and plays a central role in evaluating urban climate effects [5,6].

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Field measurements are fundamental to urban microclimate studies. They help researchers obtain perceptual knowledge. The advantages include acquiring the most direct evidence of the 'real-world' microclimate conditions [5,7], portraying reliable results [8,9] with a high temporal resolution [10] as the first-hand information, etc. Numerous microclimate studies are mainly based on field measurements, including assessing the thermal or human-biometeorological effects of the urban environment [11–13]. Although numerical modeling is another widely-used research approach, field measurement data are indispensable in model validation and calibration [14]. Due to using "approximations" in numerical models and variations of simulation conditions, model performance must be validated by field measurement data as the evaluation reference [15,16].

Some guidelines, standards, and handbooks on meteorological measurements have been published to clarify and standardize the measurement process. The Guide to Instruments and Methods of Observation (WMO No. 8 guideline) [17], first published in 1950, served to standardize meteorological measurements. It suggested a systematic way to establish stationary stations with standard instruments. Unwin [18] summarized in 1978 some fundamental techniques for microclimate measurements and explained their meaning. Ozawa et al. [19] published a book in 1965 focusing on local climate measurements, introducing their experiences in instrument use, data collection, related field methods such as observing plant phenology, etc. Oke [20] developed guidance in 2006 for meteorological observations in urban areas. They considered the complexity and heterogeneousness of the urban environment. His guidelines on site selection and instrument exposure for urban stations have been included in WMO No. 8 guideline since the 2008 edition [21]. Standards from the International Organization for Standardization (ISO) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) were frequently adopted in human biometeorological studies. They include ISO 7726-1998 Ergonomics of the thermal environment —Instruments for measuring physical quantities [22], ISO 7730-2005 Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria [23], and ASHRAE handbook-fundamentals [24]. For metadata, WIGOS (WMO Integrated Global Observing System) metadata standard [25] was published in 2019. It classified the meteorological metadata into ten categories, providing a set of tables detailing all the elements, including definition, notes and examples, obligations and implementation phase.

Despite existing guidelines and standards about meteorological observations, when it comes to microclimate field measurements in the urban environment, three issues of practical significance have remained inadequately understood:

(1) Application scale

Currently, the seminal meteorological observation guidelines [17,20,25] refer to standard climate stations designed to monitor the climate conditions at local scales and avoid microclimate effects. Some standards in microclimate studies are initially developed for indoor or working thermal environments [22–24]. The lack of complete guidance for outdoor microclimate measurement means that researchers tend to use selected parts of different standards. Therefore, there is a need for guidance focusing on the special needs of outdoor microscale measurement.

(2) Application location

The urban microclimate is a complex and heterogeneous consequence of diverse parameters involving a wide range of natural and urban processes [20,26]. The microclimate of high-density cities is strongly affected by some key factors: high-rise buildings, narrow street canyons, inhomogeneous urban fabric, changeable anthropogenic heat/cooling/moisture, diverse vertical and horizontal exchanges of momentum, complex human activities, etc. [20]. The urban conditions generate thermal environments entirely different from rural or airport locations. In urban areas, it is impossible to conform to the existing guidelines for site selection and instrument exposure [20]. The research design should consider specific principles and concepts unique to urban areas to ensure meaningful observations. Due to considerable spatio-temporal variations, the guidance cannot be rigid rules. It needs to guide researchers to intelligent and flexible applications to match the complex and often unique realities of the specific environment.

(3) Systematic workflow

Systematic guidance on the complete experimental workflow is needed. Some existing guidance mainly focuses on equipment instructions, but few mention the experimental workflow, including the pre- and post-processing. Oke et al. [5] reported that the researcher's ability to measure and the record had significantly advanced in recent decades. However, the practical question of the best way to observe in a complex and heterogeneous setting like a city has remained largely unanswered. Therefore, it is essential to provide researchers with a systematic and comprehensive field measurement workflow, providing a clear path to consider every detail in urban microclimate field measurements.

To solve these pending issues, this study aims to review critically recent literature and propose a systematic approach to conduct microclimate field measurements appropriately at the pedestrian level in tropical cities. The approach to formulating the guideline is shown in Fig. 1. The proposed guideline aims to ensure the systematization and reliability of observations by standardization, preparations, and precautions. Our work is based on research experiences in the tropics, applicable parts from existing guidelines/standards, and professional recommendations. Four steps in microclimate field measurements will be elaborated: formulating field measurement plan, preparing for field measurements, sustaining measurement quality, and curating data. Where appropriate, examples and checklists are provided for illustration and reference.

2. Review of microclimate field measurement studies

To understand to what extent the available guidelines of field measurements could fulfill the researchers' real needs, we attempted a condensed literature survey for the last five years in the tropics. We developed a four-step workflow (i.e., formulating field measurement plan, preparing for field measurements, sustaining measurement quality, and curating data) that served as the analytical framework. The eligibility criterion "tropics" was defined by both location (cities located in tropical (23.5°S–23.5°N) and subtropical (between 23.5–35°S and 23.5–35°N) latitudes [27]) and climate zone (cities with a hot and humid summer, classified as type *A*- and *Cfa* in the Köppen-Geiger climate classification [28]). Thirty-five papers were reviewed (review records listed in Appendix A).

Some basic statistics were extracted from the papers, focusing on essential information that needs to be reported (Fig. 2). All reviewed studies reported the most basic information of field measurements such as date, time, country name, city name, number of stations, locations of stations, measurement type, and measured variables. However, detailed information on measurement environments is not comprehensive. In the local environment, about half of the studies mentioned the latitude and longitude of the measuring city (20, 57%), but only a small number of the reviewed studies mentioned city elevation (4,11%) and geomorphology (2, 6%). In order to describe the local climate condition, only one-third of the studies (11, 34%) applied the Köppen–Geiger climate classification. Regarding site environment, most studies described the measuring site literally (24, 69%), but only a few applied urban morphology parameters. Regarding data quality reporting, few

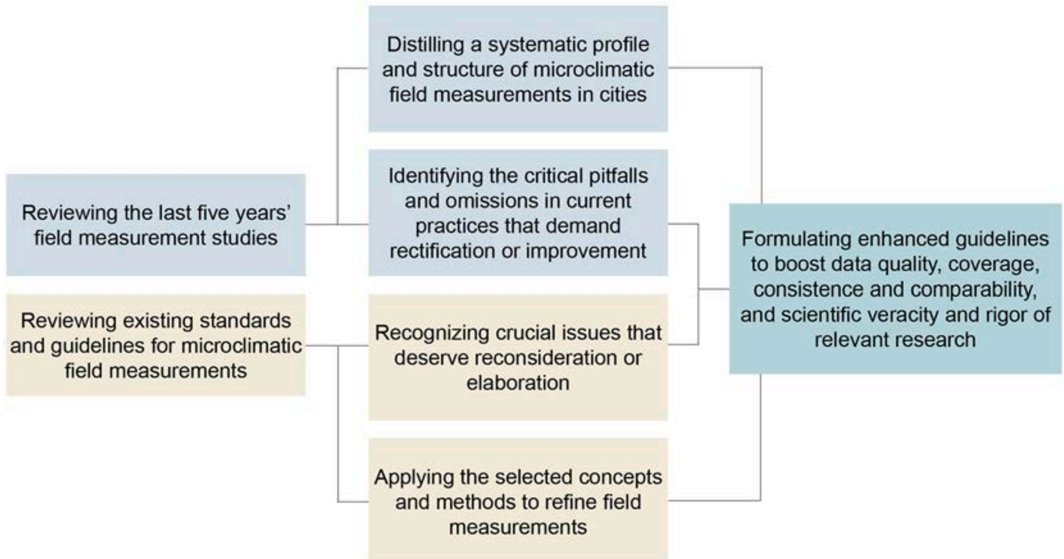

Fig. 1. The approach to formulating the guidelines.

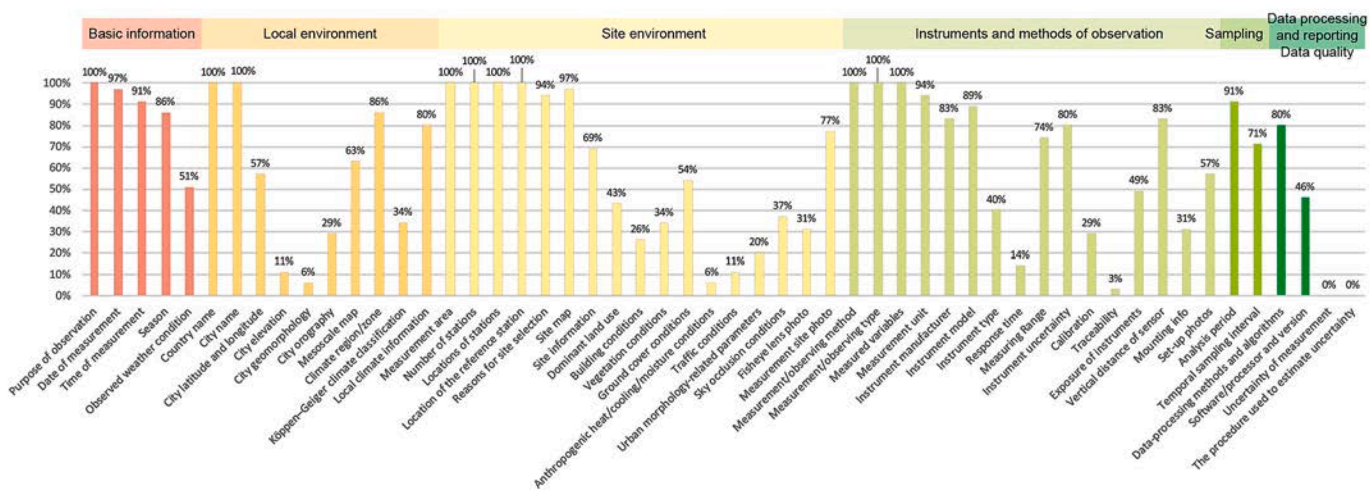

Fig. 2. The percentage of 35 reviewed papers that reported essential information on microclimatic measurements in tropical cities.

studies reported significant information such as traceability, the uncertainty of measurement, and the procedure used to estimate uncertainty. In reviewing the field measurement studies, four somewhat inadequate aspects deserve more attention:

(1) Improving measurement designs

A well-conceived measurement plan is a prerequisite for a successful field measurement campaign. The pertinent details, including field site representativeness, instrumental techniques, field day weather selection, etc., must be considered carefully and thoroughly in the planning stage. For instance, the selected measurement sites could not represent the microclimate conditions demanded by the study objectives in some reviewed studies. Regarding instrument selection, the lack of fundamental understanding of the instruments' underlying concepts, limitations and measurement techniques may cause incorrect choice or usage.

(2) Enhancing field measurement quality

Calibration is a critical step in minimizing measurement uncertainty by ensuring equipment accuracy. However, only 29% of the reviewed studies included self or manufacturer calibration. This omission is scientifically unacceptable because it would not be possible to quantify and control errors or uncertainties to an acceptable level. Moreover, the consistency of the equipment's readings cannot be ascertained.

(3) Refining operations

Human and measurement errors may occur if the operation or equipment placement is not properly implemented. Instruments may obstruct and interfere with each other, such as the conflicts between too closely-spaced radiation and wind-related sensors. The operation issues such as lacking enough stable time ahead, regular checks, and data saving may compromise data accuracy and the final results. These essential issues are often overlooked or neglected.

(4) Establishing comprehensive metadata

According to WMO (World Meteorological Organization), all the information or data about the measurement data, e.g., how, where, when and by whom the data were recorded, gathered, transmitted and managed, is called metadata [29]. It is essential to keep a thorough metadata record because any absent or missing parts could incur difficulties attributing variations over time to changes in climate per se [5]. The Global Climate Observing System (GCOS) Climate Monitoring Principle describes the significance of metadata as " (Metadata) should be documented and treated with the same care as the data themselves" [25]. However, almost none of the reviewed articles have reported comprehensive metadata.

3. Suggested field measurement workflow

The suggested field measurement workflow and proposed steps are depicted in Fig. 3.

3.1. Formulating field measurement plan

3.1.1. Establishing clear measurement objectives

The clarity in expressing the objectives for conducting a field measurement study is essential to its success. Two of the most common research objectives are: (1) to evaluate the outdoor thermal environment and its driving factors [12,30–53]; (2) to assess the outdoor human thermal comfort condition and thermal perception, from both subjective and objective perspectives [54–63]. Sometimes, both research purposes may appear in the same study. A clear understanding of the research objective can facilitate the plan's realization, such as site selection, microclimate variable selection, required spatial (horizontal and vertical) and temporal resolution, etc. It also allows selecting appropriate

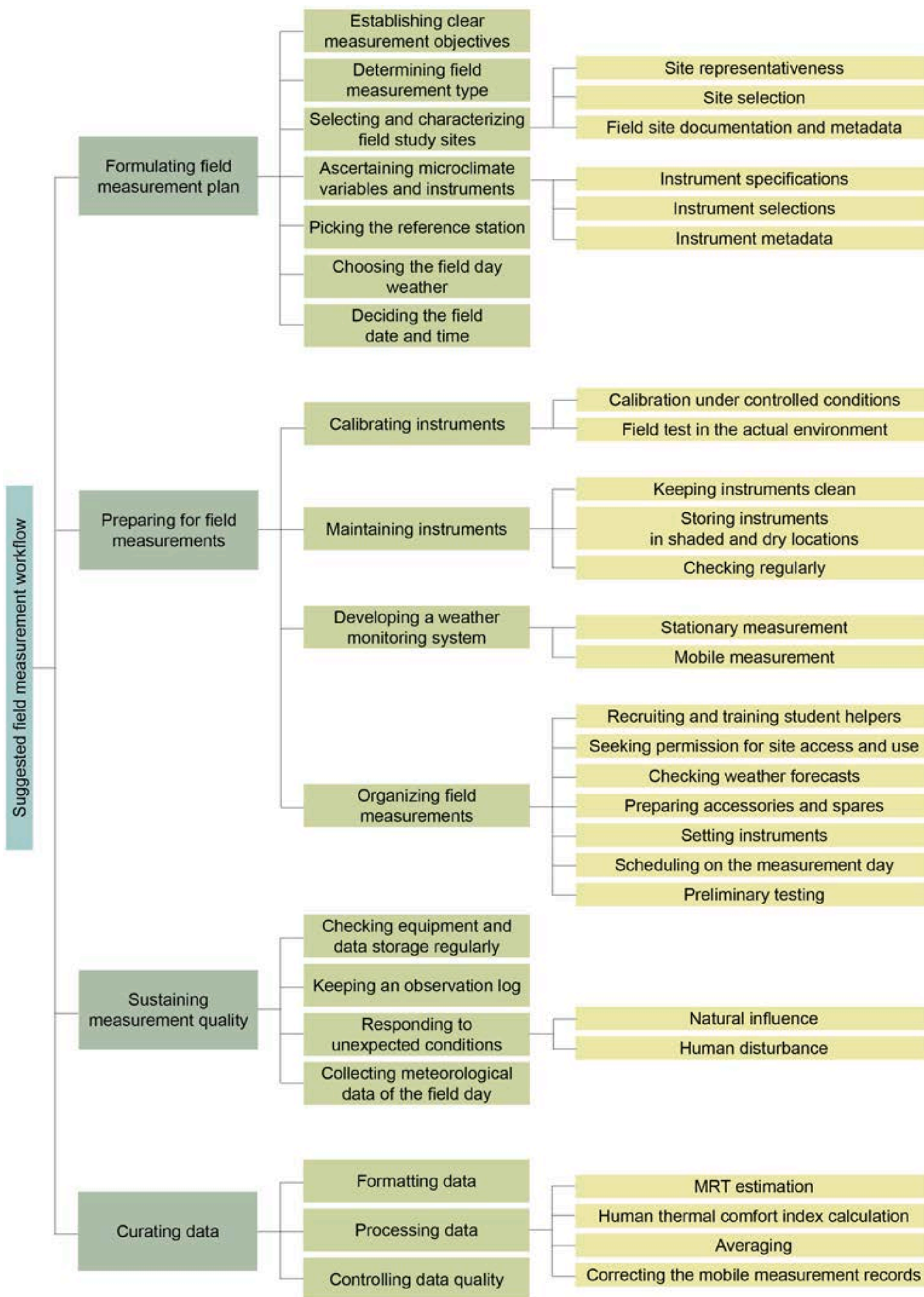

Fig. 3. The suggested field measurement workflow and proposed steps.

instruments and deploying them correctly and efficiently [5].

3.1.2. Determining field measurement type

The microclimate field measurement types are threefold: stationary (fixed), mobile, and flow-following measurements [5] and the choice of measurement type depends on the research aim. The stationary approach, generally the most commonly used, observes urban microclimate at regular time intervals as the atmosphere passes by a fixed point in space. The temporal characteristics of different weather elements in the designated urban environments can be assessed. However, it has limitations like poor mobility and high demand for instruments and personnel [64]. The mobile approach permits sampling urban microclimate over space by moving the sensors through the urban atmosphere. Mobile traverses can overview microclimatic diversity in urban environments. A "stop-and-go" strategy is a variant of the mobile approach. It includes stops at specific transect points to take measurements [5]. This strategy is particularly suitable in cities with heterogeneous urban covers within a small area, such as Hong Kong, Singapore, etc. The mobile measurement data can supplement stationary station networks [5]. The flow-following method is a special form of mobile measurement to visualize the flow by tracking the selected air parcel(s) movement using balloons, bubbles, and colored gas or smoke [5]. This guideline will not discuss the flow-following measurements due to their low use frequency in microclimate field measurements.

3.1.3. Selecting and characterizing field study sites

3.1.3.1. Site representativeness. The results of the field observations can represent the range of urban areas, called site representativeness. Every surface and object at the measurement site results in the microclimate of the site and its immediate vicinity. The typical scales of urban microclimates extend from less than one meter to hundreds of meters, related to the dimensions of individual buildings, trees, roads, streets, courtyards, gardens, etc. [20]. An urban station has relatively homogeneous urban covers, not influenced by relatively large occluded patches of anomalous covers [20]. It may represent the general climate condition of a relatively large domain. For example, in a street canyon zone in a densely built-up part of a city, its site dimensions (height, width and length) can represent the surrounding neighborhood on a large scale because of the homogeneous urban form. Therefore, there is no need to set many measurement sites in this case, and a limited number of stations can record the microclimate 'typical' of that zone. In contrast, a site in a hilly or coastal location is unlikely to represent the zone's climate. Instead, a network of measurement sites is required to assess the spatial microclimate characteristics [5,21]. As site representativeness varies by location, measurement sites should represent the urban characters in question [65].

3.1.3.2. Site selection. The control variable method is the most common way to investigate the thermal effect of urban elements. It can compare site thermal conditions with different characteristics and distributions of urban morphologies, ground covers, shading conditions, surrounding landscape elements, etc. [32–35,40,47]. Oke [20] summarized the four most important basic features to select potential sites, i.e., the urban structure, urban cover, urban fabric, and urban metabolism. Potential sites should have the highest probability of finding maximum effects.

LCZ (Local Climate Zone) [30,39,41] is commonly used as a reference for selecting a specific urban form. Land-use categories are also used [62], but they mainly depict the function rather than the physical form of the urban area [20]. Moreover, the research design should include the heat releases from air conditioners and vehicles in urban areas.

For some specific studies, additional criteria need to be considered. Two examples are used to illustrate this idea. For studies including a questionnaire survey, the following participant-related criteria can be considered in selecting measuring sites:

- Visible and accessible to most participants [57];
- Diverse outdoor activity facilities and spaces for varying crowd activities (e.g., outdoor seating like bench and planter ledge) [42,48,53,57].

For studies focusing on the thermal effect of an individual tree, the candidate sites can follow some criteria to avoid surrounding thermal influence:

- Sites with sample trees with diverse tree crown characteristics [51,53,63];
- the sample tree stands independently with little space sharing with neighbor trees or other features [51,60,63];
- No overlapping shade between the sample tree and any neighbor features [12,51,60,63];
- Sites with a high sky view factor allow almost unobstructed solar access and energy dissipation by outgoing terrestrial radiation [66].

The route should be designed to cover most of the typical and representative urban conditions for mobile measurements. The selection principles for fixed sites described earlier also apply to the design of mobile measurement routes. An effective measurement route should not take too much time to traverse. Otherwise, the background meteorological conditions may have changed too much between the start and finish time to compromise the accuracy of mobile data correction [55]. Besides, for a more robust temporal correction, it is highly recommended that the mobile route be designed to pass locations where fixed long-term weather monitoring stations are located [67]. If not feasible, the fixed reference point must be selected for synchronized background weather measurements (more details are provided in section 3.1.5).

Field studies should consider the availability of permitted spaces [54] and electrical power (if needed). Oke [5] suggested that "it is helpful to identify potential 'friendly' site owners", such as institutional, public or business concerns such as schools, universities, utility facilities and transport arteries because "they often possess security from vandalism and may allow connection to electrical power". Also, advance field trips cannot be omitted since it is impossible to fully understand site conditions in detail from digital maps or satellite images. The planned route should be traversed at least once before launching the field measurement, particularly for mobile measurements. Through advanced field surveys, problems that could occur during the traverse, such as inaccessibility of specific locations, could be identified at an early planning stage. Appropriate and timely amendments can be made. At the planning stage, site selection criteria and considerations should be documented in detail and implemented accordingly.

3.1.3.3. Field site documentation and metadata. Field sites must be accompanied by metadata to fully document the geographical and meteorological conditions of the local environment and site characteristics. This guideline suggests a metadata checklist (Table 1) for a comprehensive microclimate field observation concerning the WIGOS Metadata Standard [25] and reviewed studies.

(1) Geographical and Meteorological Background

In a microclimate study, the city's basic geographical and urban climate information must be collected (details are shown in the checklist, Table 1). It would be good to provide more quantitative information about the urban climate, such as the annual/monthly mean/maximum/minimum air temperature and relative humidity, as well as the annual/monthly wind rose, selecting depending on the research purpose (an example is shown in Fig. 4).

Table 1
The comprehensive metadata checklist for microclimate field measurements.

Metadata category	No.	Item	Definition	Example
1. Purpose of observation	1	Purpose of observation	The intended application(s) for which the observation is primarily made [20]	To investigate the thermal environment of some green areas
2. Basic information	2	Date of measurement	The measurement date	21.06.2022 (Summer solstice)
	3	Time of measurement	The period over which a measurement is taken	08:30–19:00
	4	Season	The season when the measurement is taken	Summer
	5	Observed weather condition	The weather condition on the measurement day	Fair clear sky day
3. Local environment	6	Country name	The country where the measurement is taken	China
	7	City name	The city where the measurement is taken	Hong Kong SAR
	8	City latitude and longitude	The latitude and longitude of the city of measurement	22.32° N, 114.17° E
	9	City elevation	The elevation of the city of measurement	The territory's highest point is 957 m above sea level
	10	City geomorphology	Description of the landforms of the city of measurement	Hong Kong has a compact urban built form consisting of high-rise and high-density dwellings, and mixed land uses.
	11	City orography	Description of the terrain of the city of measurement	Hong Kong's terrain is hilly and mountainous, with steep slopes. Lowlands are found mainly in the northern part of Hong Kong.
	12	Mesoscale map	The city unit map [5]	(See Fig. 5)
	13	Climate region/zone	The climate region of the measured city, e.g., tropical, subtropical, etc.	Subtropical
	14	Köppen–Geiger climate classification	The Köppen climate classification of the region where the observing facility is located. The Köppen-Geiger climate classification scheme divides climates into five main groups (A, B, C, D, E), each with types and subtypes [20]	Cfa
	15	Local climate information	Description of the city's climate conditions	(See Fig. 4)
4. Site environment	16	Measurement area	The location where the measurement is taken	The Chinese University of Hong Kong
	17	Number of stations	The number of weather stations or monitoring systems used in the measurement	2
	18	Locations of stations	Description of the measurement sites	Site 1: under a tree, near the Lake Ad Excellentiam
	19	Location of the reference station	Description of the reference station	The reference station is located in an open area near the Lake Ad Excellentiam
	20	Reasons for site selection	Description of the measurement site selection criteria	Site 1 is for measuring the thermal environment under a tree
	21	Site map	The map to show all locations of measurement sites	(see Fig. 5)
	22	Mobile route	The map to show the route of the mobile measurement	(should show in a site map, if any)
	23	Site information	Non-formalized information about the location and surroundings at which an observation is made that may influence it [20]	Site 1 is located under a median size *Taxodium distichum* on the north bank of Lake Ad Excellentiam
	24	Dominant land use	Description of the dominant land utilization type of the measurement sites	Institutional
	25	Building conditions	Description of the surrounding buildings (e.g., building characteristics, surface material, building height, etc.)	A low-rise burned brick building is located north at 20 m from Site 1. A 13-story double glass curtain building is located in the northeast at about 100 m from Site 1.
	26	Vegetation conditions	Description of the surrounding vegetation (e.g., the species, growth form, and characteristics of trees, shrubs, herbs, etc.)	Site 1 was under a *Taxodium distichum* tree with a 10 m height, 6.2 m crown width, 3 m bole height, and 4.86 LAI. A row of *Hibiscus schizopetalus* with a height of 1 m is situated to the south of Site 1.
	27	Ground cover conditions	Description of the ground cover materials in the vicinity of the observation	3 cm height grass under Site 1
	28	Anthropogenic heat/ cooling/moisture conditions	Description of human-made heat/cooling/moisture at the facility or in the vicinity that may influence the observation	A row of air conditioners hanging on the first floor of the low-rise building, 20 m north from Site1
	29	Traffic conditions	Description of traffic conditions in the vicinity that may influence the observation	Low traffic condition
	30	Buffer size (if any)	The radius used in urban morphology parameter calculation	250 m (typical local size [5])
	31	Urban morphology-related parameters	(The frequently-used urban morphology-related parameters and their definitions can be found in Appendix B)	Site 1: Building coverage ratio = 0.13 Building volume density = 3.6 Frontal area index = 0.12 Green and blue coverage ratio = 0.67
	32	Sky occlusion conditions	The extent to which the sky is obscured is generally described as SVF (Sky View Factor)	Site1: SVF = 0.21
	33	Fisheye lens photo	Photo taken by a fisheye lens	(See Fig. 5)
	34	Measurement site photo	Photos of measurement sites at the pedestrian level	(See Fig. 5)
5. Instruments and methods of observation	35	Measurement/ observing method	The method of measurement/observation used (e.g., field measurement, questionnaire survey, etc.)	Field measurement + questionnaire survey
	36	Measurement/ observing type	The type of field measurement, e.g., stationary or mobile measurement	Stationary measurement
	37	Measured variables	Measured microclimate variables (e.g., air temperature, relative humidity, solar radiation, etc.)	Solar radiation
	38	Measurement unit	Real scalar quantity, defined and adopted by the convention, with which any other quantity of the same kind	W/m^2

(*continued on next page*)

Table 1 (*continued*)

Metadata category	No.	Item	Definition	Example
			can be compared to express the ratio of the two quantities as a number [20]	
	39	Type of sensors	The type of sensors, e.g., a split sensor, all-in-one sensor, etc.	A split sensor
	40	Instrument manufacturer	Details of instrument manufacturer	Apogee
	41	Instrument model	Details of instrument model	SN-500-SS
	42	Instrument type	Details of instrument type	Net radiometer
	43	Response time	Details of instrument response time	0.5 s
	44	Measuring Range	Details of the instrument measuring range	0–2000 W/m^2 (net shortwave irradiance)
	45	Instrument uncertainty	Details of instrument uncertainty, the numerical expression of the instrument accuracy [21]	5%
	46	Calibration	Descriptions of calibration process and results	Calibration conducted by the manufacturer Calibration uncertainty: 5%
	47	Traceability	A statement defining traceability to a standard, including a sequence of measurement standards and calibrations used to relate a measurement result to a reference [20]	Calibration can be traced to World Radiometric Reference (WRR)
	48	Instrument routine maintenance	Description of maintenance routinely performed on an instrument [20]	Clean radiometer domes before starting measurement
	49	Exposure of instruments	Description of any shielding or configuration/setup of the instrumentation or auxiliary equipment needed to make the observation or to reduce the impact of extraneous influences on the observation [20]	Radiation shield used for temperature-humidity probe
	50	Vertical distance of sensor	The vertical distance of the sensor from a (specified) reference level, such as the ground [20]	1.5 m above the ground for pedestrian level study
	51	Mounting info	Descriptions of how the instruments are mounted	Instrument box mounted on a tripod. Staggered mounting of instruments to avoid blocking incoming radiation and wind
	52	Set-up photos	Photos showing how the instruments are mounted	(See Fig. 6)
6. Sampling	53	Analysis period	The period that the measured data is used for analysis	9:00–19:00
	54	Temporal sampling interval	The period between the beginning of consecutive sampling periods [20]	1 min
	55	Problems encountered	Descriptions of aberrant natural/human issues encountered in field measurement	A pedestrian touched the shortwave radiation sensor at 2:00 p.m.
7. Data processing and reporting	56	Data-processing methods and algorithms	The methods and algorithms used to process data	Averaged every 30 min
	57	Software/processor and version	The details of software/processor applied in the data processing	Microsoft Excel 2013
	58	Level of data processing	The level of data processing (e.g., pre- or post-processing)	Pre-processing
8. Data quality	59	Uncertainty of measurement	The non-negative parameter associated with the result of a measurement that characterizes the dispersion of values that could reasonably be attributed to the observation/measurement [20]	An outlier appeared at 2:00 p.m., maybe because the pedestrian blocked the incoming solar radiation
	60	The procedure used to estimate uncertainty	A reference or link pointing to a document describing the procedures/algorithms used to derive the uncertainty statement [20]	Origin8.5

(2) Site characteristics

Two kinds of information are necessary to describe the measurement sites: (1) site map and photos; (2) qualitative and quantitative descriptions. Examples of site aerial photographs and ground images are shown in Fig. 5. Oke [20] suggested using an aerial photograph as the local scale map because it furnishes details of buildings and trees. Site photos, including panoramic ones, can provide a perspective view, supplementing details at the pedestrian level. For research on specific objects such as trees, it would be better to show an overview of the sample trees [12,60,63]. To give a view of the sky occlusion conditions, fisheye photos are commonly applied [30,36,39,44,47,49,54,55,57,59,61].

Qualitative site descriptions include dominant land use, building types and materials, plant types and species, ground cover materials, anthropogenic heat/cooling conditions, traffic conditions, etc. LCZ classification, a worldwide standard in UHI studies to classify urban morphologies and natural landscapes, is commonly used for the basic description of the local urban form [30,36,39,41].

Quantitative site descriptions are important because the urban morphology parameters can be objectively compared and analyzed in assessing the thermal effect of different sites. Frequently used urban morphology parameters and their definitions are listed in Appendix B. The sky view factor (SVF) is the most popular one to represent the shading level in spaces containing buildings, trees, and landscapes. Its strong correlation with outdoor thermal comfort has been demonstrated [68]. Regarding the buffer size in urban morphology parameter calculation, 10 m [49], 20 m [46], 150 m [61], 250 m [62], 300 m [69], 500 m [62], 750 m [62] were used in previous studies. Sensitivity tests should be conducted because the suitable buffer size varies from research areas and selected parameters [61].

3.1.4. *Ascertaining microclimate variables and instruments*

3.1.4.1. Instrument specifications. Air temperature, relative humidity, wind speed and direction, radiation, and surface temperature are the five common microclimate variable types included in existing guidelines and standards [5,22,70].

Regarding instrument selection, many studies referred to the ISO standards [22,23,70] for measuring range and uncertainty. ISO 7726 listed two instrument specification requirements according to the extent of the thermal annoyance to be assessed, i.e., the comfort standard and the heat stress standard [22]. The former is for the moderate environment (approaching comfort conditions) and may not meet the requirement to measure the summertime outdoor urban microclimate. For environments subject to great or even extreme thermal stress, the heat stress standard is summarized in Table 2. Despite ISO 7726's original

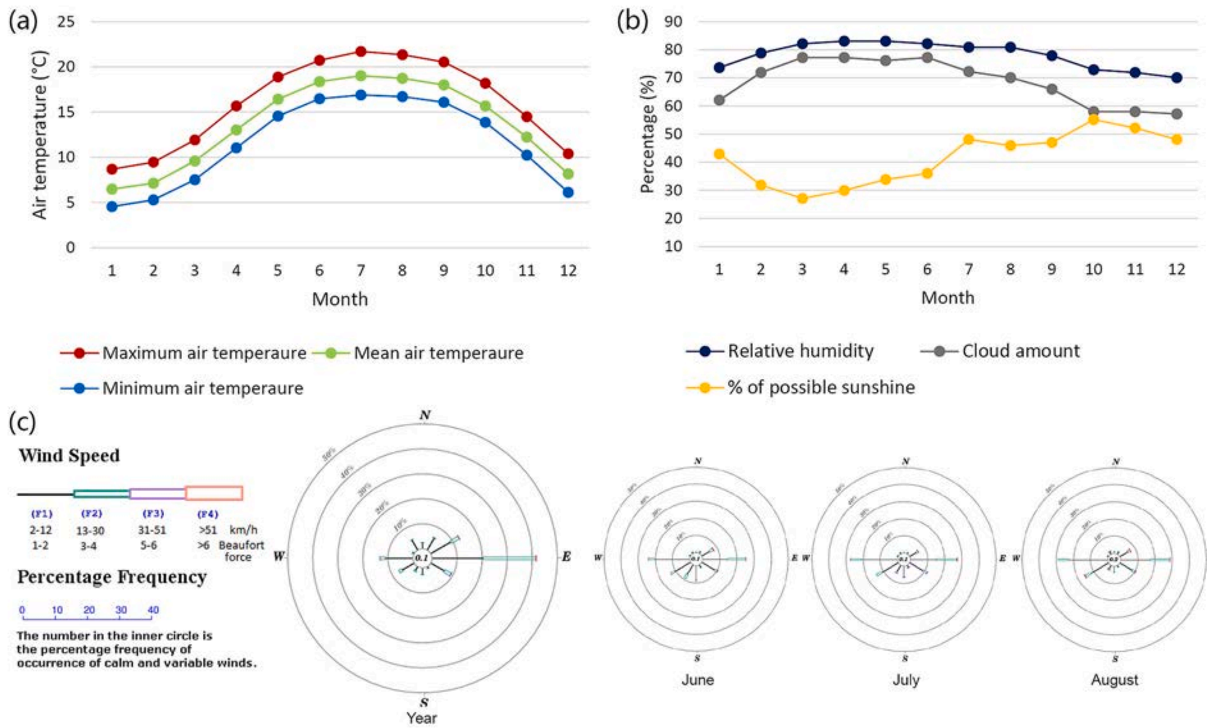

Fig. 4. Monthly means of daily maximum, mean, and minimum in 1991–2020: (a) air temperature, (b) relative humidity, cloud amount, percentage of possible sunshine, (c) wind roses (data from Hong Kong Observatory, see: https://www.hko.gov.hk/en/cis/climahk.htm).

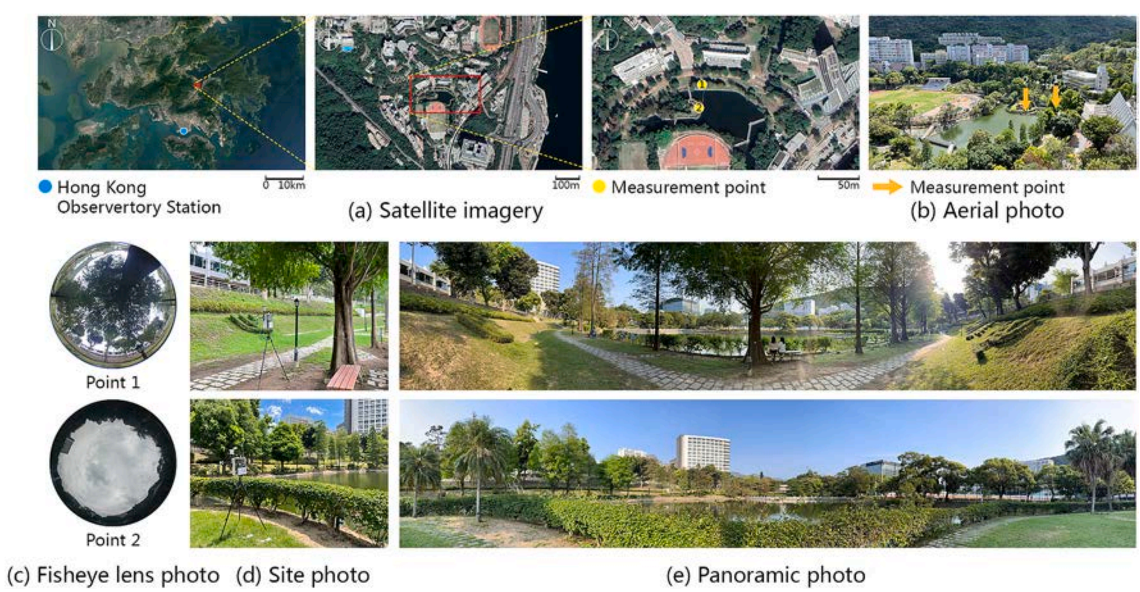

Fig. 5. Examples of site aerial photographs and ground images.

intent for indoor environments, its heat stress standard has a wide measuring range that may suit outdoor measurements. Its appropriateness should be carefully assessed before use. WMO listed the operational measurement uncertainty and instrument performance requirements in its Annex 1A. It presents general requirements that have been used in urban climatology and synoptic, aviation, and marine meteorology [17].

Regarding response time, WMO applied the term "time constant", referring to the time taken for the sensor to indicate 63.2% of a step-change in measurement [17]. It is recommended to have a 20 s time constant for thermometers, hygrometers, and radiometers, 1 s for wind direction measurements, and a 2–5 m distance constant (usually expressed as response length) for wind speed measurements [17].

If the response time of the instrument is much faster, it is necessary to take samples and filter or average them [21]. The sampling interval is the time between successive observations, which should not exceed the largest time constants of all the devices and circuitry preceding the acquisition system [21]. In general, radiation studies need a very short sampling interval (such as 10 s [54,56]) as the short- and long-wave radiation changes rapidly in urban environments. WMO mentioned that the output averaging time is 1 min for most weather-station instruments and 2 and 10 min for wind speed and direction [17]. It is also worth noting that instruments with fast response times is a must in

Table 2
Requirements on measuring range and uncertainty (the ISO standard for accuracy) of instruments for stressful thermal environments according to ISO 7726 [26].

Measured parameter	Measuring range	Accuracy	
		Required	Desirable
Air temperature	−40 °C to +120 °C	±0.5 °C (0 °C–50 °C)	±0.25 °C (0 °C–50 °C) (Required accuracy/2)
Mean radiant temperature	−40 °C to +150 °C	±5 °C (0 °C–50 °C) ± [5 + 0.08 (MRT-50)] °C (50 °C–150 °C)	±5 °C (0 °C–50 °C) ± [0.5 + 0.04 (MRT-50)] °C (50 °C–150 °C)
Air velocity	0.2 m/s to 20 m/s	± (0.1 + 0.05Va) m/s	± (0.05 + 0.05Va) m/s
Absolute humidity expressed as the partial pressure of water vapor	0.5 kPa–6.0 kPa	±0.15 kPa	/
Surface temperature	−40 °C to +120 °C	±1 °C (−10 °C–50 °C) >50 °C: ±[1 + 0.05 (Ts-50)]	Required accuracy/2
Radiation directional	−300 W/m^2 to 2500 W/m^2	±5 W/m^2 (−300 W/m^2 to 100 W/m^2) ±10 W/m^2 (100 W/m^2 to 1000 W/m^2) ±15 W/m^2 (1000 W/m^2 to 2500 W/m^2)	/

mobile measurements, especially in vehicle-based platform-based mobile measurement and transient outdoor pedestrian thermal comfort measurements [71].

Instrument selections should consider traceability to ensure valid measurement results. Since various instruments have been deployed in different measurement approaches worldwide, only items with assured traceability can generate reliable and comparable measurement data. The Commission for Instruments and Methods of Observation (CIMO) in WMO highlighted that the absence of measurement-result traceability would lead to questionable effectiveness of WIGOS. Therefore, CIMO emphasized the importance of a "calibration strategy for traceability assurance" [17]. With assured traceability in measurement results, SI (The International System of Units), one of the international well-accepted standards, can be connected with high confidence. To achieve traceability, the calibration is conducted by accredited laboratories with national accreditation bodies certifying their executed quality management system by ISO/IEC (the International Electrotechnical Commission) 17025 or by CIPM MRA (International Committee of Weights and Measures, the Mutual Recognition Arrangement) [17]. It is recommended to select sensors calibrated in accredited laboratories with ISO/IEC17025.

3.1.4.2. Instrument selections.

(1) Air temperature and humidity

The sensors used in general meteorological stations to measure air temperature and humidity are appropriate in urban areas, including their accuracy and response characteristics [20]. For humidity sensor selection, the suitable operational environment listed in the instrument specification should be followed. In some cities located in tropical or subtropical climate zones where the relative humidity may exceed 90% in wet season. Many humidity sensors or loggers are not designed for such a humid environment.

The temperature and humidity sensors may be heated by radiation sources such as the sun and surrounding warm urban surfaces (such as a sunlit wall, road, or a vehicle with a hot engine, or it may receive reflected heat from glass building envelopes [20]). Under extremely unfavorable conditions, the air temperature could be overestimated by up to 25 K [17]. Therefore, a radiation shield or screen with proper ventilation should be applied to minimize radiative exchange between the instrument and its surroundings [20,22]. The following hints can be considered in selecting the thermometer and radiation shield:

- WMO recommended electrical thermometers for temperature measurements [17].
- Three means can reduce the radiation effect on the probe: (1) lower the emission factor of the sensor; (2) reduce the temperature difference between the sensor and the adjacent walls; (3) increase the coefficient of heat transfer by convection by raising the air velocity around the sensors (forced ventilation) and reduce the sensor size [72].
- Use an aspirated shield to maximize convection and avoid warm air formation around the probe [21].
- The varied devices and shielding methods for microclimatic temperature measurements have been summarized in [73].
- Additionally, for the vehicle-based mobile measurement, the thermometer needs to be at a sufficient distance from the vehicle body surface, and a larger radiation shield should be used to block the heat radiated from the surface [67].

(2) Wind speed and direction

For wind speed and direction, various anemometers based on different techniques have been summarized in ISO 7726. Their selection mainly depends on wind characteristics in the urban study areas. In tropical high-density cities, the pedestrian-level wind behaviors can be highly irregular due to mechanical effects induced by a densely built environment and thermal effects induced by unstable atmospheric stratification [74]. The changeable wind behaviors can be further complicated by variations of prevailing wind induced by monsoon seasons and local sea-land circulations induced by heterogeneous terrain and complex coastline [75]. Thus, accurate measurements of urban wind conditions require proper anemometers. The following guidelines can be considered in selecting anemometers:

- Variations of wind direction: To capture the turbulent flow in tropical urban areas, measurements should preferably select omnidirectional or three-directional anemometers (e.g., omnidirectional hot-wire, hot-sphere and pulsed wire anemometers, as well as more advanced ultrasonic and laser-doppler anemometers) [22]. Alternatively, unidirectional or bi-directional anemometers (e.g., unidirectional hot-wire and cup and vane) can be applied for the unidirectional-flow situation (e.g., street-canyon-channeling flow or unaffected upwind flow), or the vertical component of wind speed is not of interest.
- Magnitude of wind speed: As tropical urban areas usually suffer from weak wind conditions [76], instruments with limited measurement ranges and accuracies in calm conditions should be avoided. For example, hot-wire anemometers are insensitive to angular changes in the velocity vector normal to the wire axis [77] and thus can be inaccurate at low speed with strong turbulence intensities. Another example is cup and vane anemometers which can record wind speed below a threshold value erroneously as zero [78].
- Intensity of wind turbulence: The selected instruments are expected to have sufficient measurement frequencies to provide information on wind turbulent intensities. This information provides valuable supplements to understanding flow behaviors, given that turbulent diffusion plays a crucial role in transporting air and heat in urban areas [79]. This information also serves Air Ventilation Assessment (AVA) in Hong Kong [76] and other cities [80–83].

- Tolerance to adverse conditions: Some anemometers (e.g., hot-wire and laser-doppler) are easily affected by adverse weather or surrounding conditions and should not be used during rain, typhoon and high-temperature drift [84,85].

Other pioneering guidelines on selecting anemometers focusing on specific spatial scales and boundary layer climates are available [20–22, 78].

(3) Radiation-related variables

Regarding radiation, the mean radiant temperature (MRT) is a key variable for investigating the radiative exchange between the human body and the surrounding environment [22]. ISO 7726 assessed several measuring and calculation methods for MRT estimation [22,78,86]. The following guidelines provide hints for selecting the MRT estimation method and globe thermometer:

- The six-directional technology is deemed the most accurate method for MRT estimation [87], even though the globe method is more frequently-used due to simple instrumentation and easy access. If the budget allows, using three pairs of pyrgeometer and pyranometer facing six directions at each site can measure twelve separate components of net radiation.
- Globe size: The Ø150 mm black-painted copper globe thermometer mentioned in ISO 7726 [72] is unsuitable for the urban environment with rapidly varying outdoor radiative fluxes and air velocity because of its long response time (20–30 min) [22]. Ø38 mm or Ø40 mm is recommended due to their faster response, portable size, and small heat capacity [38,78]. A globe thermometer can be custom-built by placing a thermocouple wire in the center of a table tennis ball that is painted black [71].
- Globe color: Medium grey color is recommended by both ISO 7726 (1998) [72] and ASHRAE Handbook-Fundamentals [24], due to its similar absorptivity with the outer surface of clothed persons when exposed to solar radiation [22,78].
- Globe shape: An ellipsoid-shaped sensor can give a closer approximation of the shape of the human body for both standing and seated situations. Still, the spherical shape has proven to work rather well, at least in mid-to high-latitude climates [78,86].

It would be more direct to measure radiation fluxes by meteorological radiation instruments. WMO classified the meteorological radiation instruments into several categories: pyrheliometer, sunphotometer, pyranometer, pyrgeometer, and pyrradiometer [21]. The net radiometer, consisting of a pyranometer pair and a pyrgeometer pair, is commonly used in microclimatic radiation studies [40,54,56,57] due to its high accuracy and recording of four variables. One net radiometer can be used for MRT estimation [78,88], while three net radiometers can be assembled to measure six-directional short- and long-wave radiation.

(4) Surface temperature

Contact and non-contact measurements are the two main approaches for measuring surface temperature. Their advantages and limitations are summarized in Table 3. For the contact approach, it is recommended to use an ultrafine-wire thermocouple in sunny environments because it can provide temperature estimates with adequate accuracy for most purposes, at a substantially higher accuracy than the majority of common devices [73]. For non-contact (infrared) sensors, an accurate measurement of surface temperature requires knowledge of the long-wave emissivity of the object and the radiant field surrounding the object. An internal or external reference temperature is required to make absolute surface temperature measurements [72].

Table 3
The advantages and limitations of contact and non-contact temperature measurements.

Temperature measurement category	Instrument type	Advantage	Limitation
Non-contact (infrared sensors)	Scanning radiometer (also known as a thermal imaging camera)	● can give temperature readings for each pixel of the entire thermal image from larger distances (hand-held or drone-mounted) ● allow researchers to visualize an entire scene in a thermal unit	● influenced by the emissivity of the surface
	Point radiometer (also known as a spot pyrometer or a temp gun)	● remote measurement of temperature ● store the detected temperature directly ● easy to carry and use	● single spot measurements ● influenced by the emissivity of the surface
Contact	Contact thermometers (resistance, thermocouples)	● simple working principles ● short response time ● wide temperature ranges ● small size ● low price ● easy installation	● single spot measurements ● using a contact thermometer may change the heat exchange between surface and environment, especially on a surface with low thermal conductivity, thereby resulting in false measurements [26]

3.1.4.3. Instrument metadata. Once the measuring microclimate variables and their corresponding instruments are determined, the instrument-related metadata should be documented in detail. The recommended metadata items and their definitions are listed in the metadata checklist (Table 1). The WMO No. 8 guideline mentioned that the wording "an accuracy of ±x" is common but less precise, and it should be replaced by "an uncertainty of x" [17]. The instrument specification should be noted.

3.1.5. Picking the reference station

A reference station is indispensable in both stationary and mobile measurements to ensure that the source of the thermal effect is indeed from the urban elements in question. In mobile measurements, the data from the reference station can be used to conduct the elevation correction or temporal data correction [55] to adjust that data in accordance with the diurnal change of the weather elements.

However, the distance between field sites and the local weather station should be considered to judge its suitability as a reference. Otherwise, the researchers should set up a dedicated urban weather station in a nearby open area. This urban reference station aims at monitoring the local climate. It should avoid extraneous microclimate influences or other local or mesoscale climatic phenomena that may complicate the urban record. Oke [20] recommended centering the urban station in an open space where the surrounding aspect ratio is approximately representative of the locality, i.e., the areas of reasonably homogeneous urban areas without large patches of anomalous structure, cover or materials. The detailed standards for urban station installation and site selection can be found in Refs. [20,21].

3.1.6. Choosing the field day weather

The field day weather selection depends on the research objectives. In summer, field measurements were usually planned to be in "sunny days [12,38,48,57,62,63]" or "fair clear sky days [39,40,54,59]". The selection should ensure hot climate conditions and avoid interferences from other factors such as cloud cover and participation [47,49,57]. Partly cloudy days were also selected because in some cities (e.g., Guangzhou, Hong Kong, Taipei, and Naha), cloudy days are more usual than clear sky days in summer [56]. Since questionnaire surveys and micrometeorological measurements may be conducted at different urban sites and repeated several times, a common weather type should be chosen to minimize the variations among observation days [39].

"Typical summer days" or "representative days" are commonly used concepts to assess the specific effects of the main weather conditions [43,89]. The typical weather scenarios are based on climatic normal data in the past decades computed by the local weather bureau [90]. For the definition of "typical/representative days", a threshold criterion can be applied based on local weather data for the typical-day selection [89]. For example, Jim et al. [89] selected the "typical summer sunny day" in Hong Kong as the day with 700 W/m^2 of average daytime solar radiation and no or little rainfall.

3.1.7. Deciding the field date and time

In general, the extreme conditions, i.e., the hottest part of the day (around 15:00) [36–38,71] or the strongest incoming solar radiation of the day (12:00–13:00) [91], should be considered in most microclimate research, guided by study objectives. For human thermal comfort studies, research objects' outdoor activity time should also be considered [36,48,49,54,57]. In cities of subtropical South China, residents tend to start outdoor activities from about 15:00 in summer, regardless of weekends or weekdays [54,92].

Regarding mobile measurements in urban areas, Oke [20] suggested the best time to be a few hours after sunset or before sunrise on nights with relatively calm airflow and cloudless skies. The selected period should maximize the differentiation of urban micro- and local climate differences. It should also avoid the period of rapid changes in weather variables which can make meaningful spatial comparisons difficult. In "stop-and-go" measurements, Qi et al. [64] recommended a 10–15 min moving and measuring time from one stop point to the next to optimize data collection quantity and meteorological data simultaneity. A 10 min interval can be adopted for large-scale measurements and 15 min for small-scale ones.

Outdoor field measurements should meet contingencies by repeating the experiment more than once to determine if the data were a fluke or represented the normal case. Particularly for wind speed measurements, measurements at a designated spot should have sufficient durations and preferably be repeated several times as the urban flow can be highly unstable.

3.2. Preparing for field measurements

3.2.1. Calibrating instruments

3.2.1.1. Calibration under controlled conditions. The recommended method to calibrate instruments is using the service provided by accredited laboratories with ISO/IEC 17025 or with CIPM MRA. This approach can yield the most accurate measurement results. However, it is a costly method if many instruments have to be deployed. Instead, as inspired by CIMO, an alternate approach can be adopted. Portable calibration devices that have been regularly calibrated at accredited laboratories can be utilized to conduct calibration.

Take electrical resistance thermometers as an example. Referring to the WMO No. 8 guide [17], comparison calibration can be conducted. By exposing the instrument in a stable and controlled condition, which usually can be established by a climatic chamber or well-mixed liquid bath, a comparison against reference standard thermometers at the designated temperature can be made. However, one limitation is that it is time-consuming if the planned testing range is wide, thereby hardly obtaining a continuous calibration result at every desired temperature point. Nevertheless, the air temperature range common in the field should be tested to ensure precise and accurate results. The uncertainty of each instrument at specific temperatures should be documented to permit data adjustment (if any) in the post-processing stage.

The following subsections provide a condensed overview of calibration approaches to raise awareness of the importance of calibration. Specific detailed calibration procedures of instrument types can be found in the WMO No. 8 guidelines [17].

3.2.1.2. Field test in the actual environment. Besides calibrating instruments in controlled conditions, field testing of instruments has been commonly adopted to conduct calibration [56]. Nevertheless, the data quality may not be as high as the calibration techniques mentioned in Section 3.2.1.1. In other words, the actual uncertainty of individual instruments may be larger.

If data comparison with official operational weather stations is adopted, it is recommended to calibrate beside the operational instruments. As most operational weather stations are not accessible to the public, the tested instruments can be placed proximal to the operational weather station with a similar urban environment for several hours under fine and cloudy weather conditions. This setup ensures that the data obtained by the instruments to be deployed are not biased under different weather conditions. The tested instruments should be placed at the same elevation from the ground as the benchmark sensors in the weather stations since some microclimate variables (e.g., wind speed) are sensitive to heights within the urban canopy [79].

Another common approach compares instruments. All instruments are placed close to an open field with homogeneous cover, with the same exposure to sunlight and wind for hours. Such site conditions can avoid urban structures such as buildings or trees that only cast influences on individual instruments. In other words, the instruments to be tested should be measuring the same environmental conditions. It is also suggested to have field testing under different weather conditions to understand the performance of the instruments thoroughly. Then, the difference in measurements of individual instruments can be recorded. This method can confirm the bias range of each instrument.

As calibration methods and field testing may affect data quality, it is recommended to state and describe the methods in future research publications.

3.2.2. Maintaining instruments

Frequent and proper maintenance is necessary to ensure high quality of data across different instruments [17]. Both preventative and corrective maintenance should receive adequate attention. The former includes regular checking and inspection of instruments, and the latter refers to repairing or replacing broken instruments. Regular preventative maintenance can reduce the frequency of corrective maintenance [17,93]. The following subsections describe general reminders for instrument maintenance; the details can be found in the WMO No. 8 guideline [17].

3.2.2.1. Keeping instruments clean. In urban areas, air pollution is a severe problem. In particular, particulate matters deposition may reduce sensor sensitivity and measurement accuracy. Air pollution may exert more impact on the following instruments:

- The accumulated deposition may intensify radiation errors [17], thereby reducing the shield's effectiveness, increasing the temperature inside and hence possibly overestimating the ambient temperature.
- Mechanical anemometers (e.g., cup and vane) consist of moving parts; their performance can be degraded by physical damage and bearing friction and corrosion due to accumulated dust [17] and sand particles.
- The sensitivity and accuracy of the transducers or scanning head of ultrasonic and laser-doppler anemometers may be reduced by accumulated dust or trapped substances.
- Dust and aerosol depositions can lower the transmissivity of the radiometer's glass dome. WMO suggested cleaning the glass dome while avoiding abrasions by blowing off loose depositions on the glass dome before wiping it very gently [17].

3.2.2.2. Storing instruments in shaded and dry locations. According to the manufacturers' instructions, instruments should be stored in safe temperature and humidity levels. To prevent moist air ingress, sensitive items should be stored in shaded and dry locations and waterproof cases with desiccators. This protective measure is essential in hot-humid locations, where the relative humidity can often exceed 90% or even reach 100% continuously for several days at ground level.

The direct contact of the electronic components with water droplets from condensation or rainwater should be avoided, even if some instruments are stated as waterproof. In the worst condition, the sensors can malfunction with direct contact with water. In addition, condensation, triggered by temperature differences, should be avoided. Water droplets will change radiation transmission. For a radiometer, this will introduce errors to the radiation flux readings. For many hot places, air conditioning is commonly used to alleviate indoor thermal comfort in summer. If the pyranometer is cooled indoors before deploying in the field under hot conditions, condensation of water droplets on the radiometer's glass dome will reduce measurement accuracy.

3.2.2.3. Checking regularly. Regular checking is needed for all instruments. For electrical resistance thermometers, WMO suggested identifying any changes in the electrical characteristics by a specialist [17]. Regarding the artificially ventilated radiation shields, WMO highlighted the crucial need to check regularly [17]. As the fan's efficiency can affect the effectiveness of minimizing the shield microclimate, maintenance of the fan can assure the realization of its full potential. For mechanical anemometers used for an extended period, corrective maintenance may be required to replace the critical wind-sensing components (e.g., transducers or scanning head).

3.2.3. Developing a weather monitoring system

3.2.3.1. Stationary measurement. For commercial all-in-one weather stations, it is relatively easy to deploy by mounting the weather stations according to the manufacturers' instructions. Some could be mounted without difficulty on a tripod.

If sensors from different manufacturers are chosen, the research team can assemble a weather station, as illustrated in Fig. 6. It includes a TESTO 480 Digital Meter (Testo SE, Titisee-Neustadt, Germany) placed inside a waterproof polymer box fixed on a tripod. The probes for air temperature, relative humidity, wind speed and globe temperature extend outside the box through waterproof cable connectors. A naturally ventilated white radiation shield covers the temperature and humidity probe to guard against direct insolation and precipitation. For wind measurements, a non-directional probe for turbulence measurement is adopted. It is more sensitive to the slight wind changes, making it suitable for urban measurement where the air flow at the pedestrian level is very weak. Besides, a black globe is a temperature probe installed in the center of a table tennis ball of 38 mm diameter painted black. Three sets of radiometers (Apogee Instruments, Logan, UT) are mounted outside the waterproof polymer box to measure the net radiation from six directions. This setup is suitable for measuring the essential weather elements. Additionally, according to study objectives, thermocouples for measuring wall surface temperature, leaf surface temperature and ground surface temperature can be added. It should be noted that the instruments must not obstruct or interfere with each other, especially

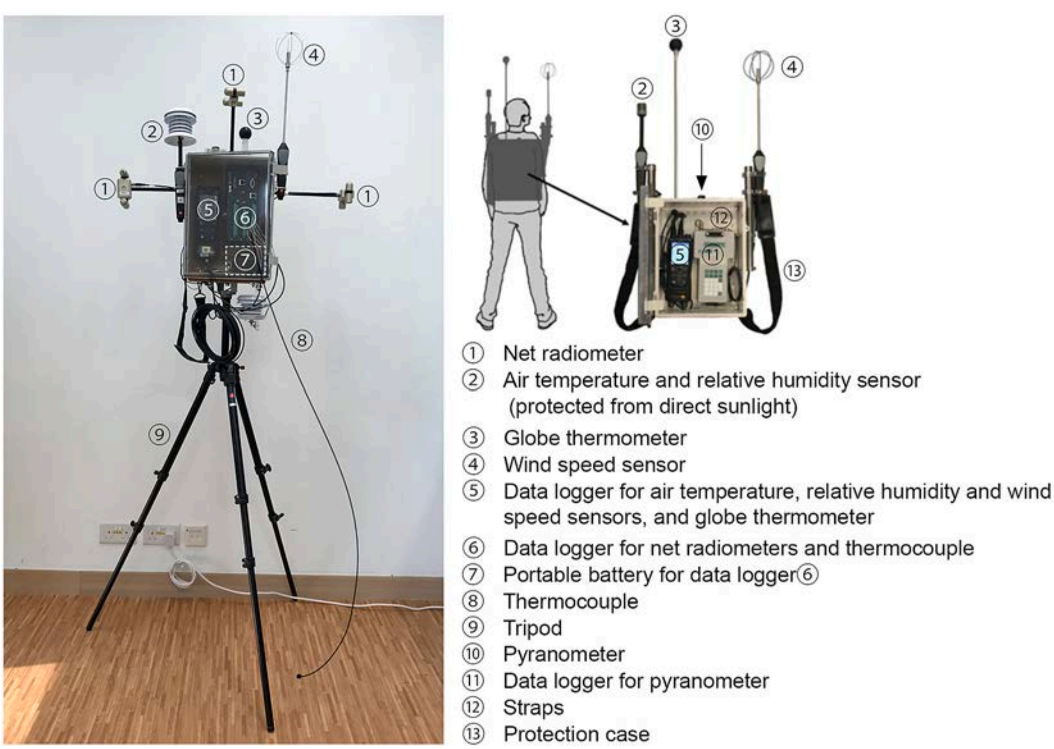

Fig. 6. An example of the self-developed weather monitoring systems: (a) the stationary station type; (b) the type for mobile measurement.

wind sensors and radiometers. The detailed instrument specifications are listed in Appendix C.

Regardless of the type of weather station, it is usually mounted at the height of 1.1 m [22,30–36,41,43,45] to 2 m (WMO [17]) above ground on a flat surface. This height aims to measure the ambient conditions exposed to standing or walking pedestrians. In some human-biometeorology-related studies, a height of 0.6 m is applied to represent a sitting person [22,32,78]. Suppose the anemometers are directional in response, such as one with a unidirectional propeller. Wind sensors should be oriented to the wind direction of interest [22] and maintained at the same horizontal level at different sites.

3.2.3.2. Mobile measurement. As mentioned in Section 3.1.5, a benchmark station is required for elevation, spatial and temporal data correction. Commercial all-in-one and self-assembled weather stations can be used in traverse observations like the stationary station. The mobile measurement systems can be mounted on various platforms, such as a vehicle, bicycle, cargo bike, cart, portable tripod, and backpack [5,94] (Fig. 7). Vehicle platforms can collect roadside data in traverse observations. However, in the "stop-and-go" strategy, the idling of vehicles for minutes may not be allowed at the roadside in some busy urban districts. Using a bicycle or walking is more flexible. They can overcome the limitation of the road network, vehicle access and idling in urban environments. The measurement systems should keep enough distance between the operator and sensors to avoid obstructing solar and terrestrial radiation and wind. Complementary structures may be used to separate the instruments. However, it may make the measurement system heavier and more visible, particularly for backpack platforms. The simultaneous location and time data should be marked by a Global Positioning System (GPS) unit to monitor the traverse observations. Fig. 6(b) provides a backpack set-up used in previous research, which can be found in Ref. [71].

3.2.4. Organizing field measurements

3.2.4.1. Recruiting and training student helpers. For multiple field measurements established simultaneously, it is not easy to monitor every station at the same time. It is essential to recruit helpers, preferably university students, who should receive systematic training:

- The basic operation of instruments to ensure their normal and uninterrupted operation.
- Actions to take to handle urgent situations such as unexpected precipitation.
- Writing the observation log.
- Conducting questionnaire surveys, if needed.

3.2.4.2. Seeking permission for site access and use. Permission for site access and use should be secured at the planning stage. The available date and time for measurement at sites should be double-checked. It is essential for measurements involving multiple sites to coordinate the team members according to the site's available timeslots to achieve a smooth implementation.

It is essential to check the availability of external power sources at the sites. If a power supply is unavailable, sufficient charged batteries should be prepared in advance.

3.2.4.3. Checking weather forecasts. Checking weather forecasts is an important step in confirming field measurements' timing under the target weather conditions. Jim et al. [90] suggested that for a given weather scenario, two days before, it should have a similar weather scenario to minimize the effect of antecedent weather. Thus, the monitored sunny day should be preceded by two sunny days, and the same is true for cloudy and rainy days.

The weather forecast allows planning the field measurement schedules as it provides hints to identify preferred weather scenarios. However, as weather forecasts are based on global and regional scale numerical models involving data assimilation, there could be changes in forecast results when time passes. Hence, the forecast should be checked daily to confirm the suitable measurement days.

3.2.4.4. Preparing accessories and spares. Unexpected incidents could happen in the field. To ensure smooth measurement, some accessories or spares should be prepared:

- A spare set of monitoring systems (if possible) with tripods. If the resource is limited, the systems should be meticulously checked to confirm normal functioning before field launching.
- Cable ties, scissors and tapes. For self-assembled systems, faults may appear in the mounting materials after long transportation and usage. These accessories are needed for urgent and temporary fixation.
- Batteries or power banks with corresponding cables and connectors. The type to be prepared depends on the instruments used. Details of the power supply of the parts should follow the manufacturers' instructions.
- Cordon tape and "do not touch" signs. They are needed to remind pedestrians not to disturb the measurement, especially in urban locations with pedestrian traffic.
- Contact information of the person in charge. In the form of a weather-proof placard, this information can be attached to the cordon tape to allow helpers or pedestrians to establish phone or email contact.
- Waterproof cloth for the system. This can provide essential protection to the system against sudden showers before relocation.
- Stationery to be used in the thermal comfort questionnaire survey.

3.2.4.5. Setting instruments. Some instrument setting procedures can be completed before field launching to minimize the workload in the field:

- Synchronize the clocks of all instruments. To ensure simultaneous data acquisition by different instruments and data comparison, it is important to keep the instrument synchronized to the official standard time. If the thermal comfort survey is also conducted, the time kept by interviewers should also be synchronized with the instrument one.
- Set the unit to the designated SI units. For example, degrees Celsius should be used for temperatures and m/s for wind speed. Keeping common units for data analysis saves time and work for conversion at

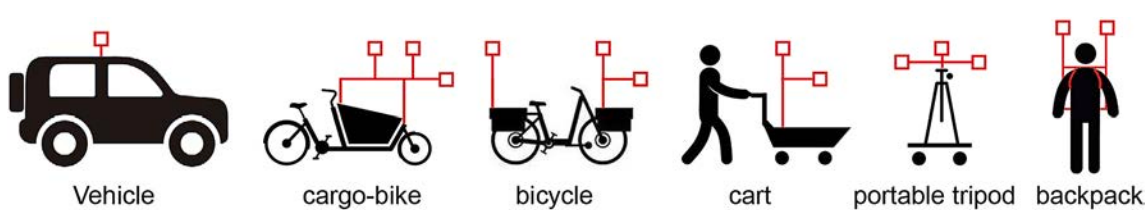

Fig. 7. Various mobile measurement systems.

a later stage. Moreover, the units should be consistent throughout the field measurement period.

- Check the power remaining in the instrument. The instruments should be fully charged before being deployed in the field, as battery replacement could disrupt the measurements.

3.2.4.6. Scheduling on the measurement day. Sometimes, unexpected early morning showers may develop at field locations, even on a day predicted to be fine weather. In this case, decisions to postpone the field measurement should be considered, especially for thermal comfort surveys. Even though no showers may fall later on the same day, the land surface's evaporative flux will be altered compared with a day without early morning showers. As a result, the perceived relative humidity of interviewees may be affected to induce a bias in the responses to the outdoor thermal comfort survey.

Since each instrument has its own response time, it is better to turn on the instruments before the formal starting time to allow for "spin-up time". Due to the sensors' thermal inertia, a thermometer requires a certain period to reach equilibrium. ISO 7726 suggested leaving at least 1.5 times the probe's response time (90%) [22]. Regarding globe thermometers, the commonly used Ø38mm grey globe can reach thermodynamic equilibrium within 5 min based on indoor tests [86].

Another merit of starting earlier is to spot any suspected faults in the instruments and their setups. Issues such as insecure mounting, power shortage and mistakes in instrument settings can be detected and corrected in the opportunity time window.

3.2.4.7. Preliminary testing. Preliminary testing could be regarded as the rehearsal for the live measurement. By conducting preliminary testing of the whole range of procedures, from planning to data analysis, helpers can learn the operations in the on-the-job mode. Moreover, potential issues in any part of the measurement campaign could be discovered to allow timely modifications or improvements. Therefore, live measurements can be conducted smoothly.

3.3. Sustaining measurement quality

3.3.1. Checking equipment and data storage regularly

After starting the measurements, all equipment should be checked at least once every 2 h, ascertaining their proper working order and operational status, such as remaining battery power, instrument orientation, and sensor mutual interference condition. For instruments without built-in automatic data saving, the saved data should be checked hourly or more frequently.

3.3.2. Keeping an observation log

Few studies have mentioned keeping an observation log during field measurements. Although the data loggers can track weather variations, there is still a need to record the field conditions during field measurements. Through the log, details of field conditions can be recalled. Although a standardized format is rarely found, keeping a consistent format is an essential point:

A comprehensive log can include the following information.

- List the date and time of the field measurement. The date-time format should be standardized to prevent confusion. Markov [95] suggested using the names of the month instead of numbers.
- State the location of field measurements, especially if measurements are established in various locations on the same day.
- Keep the serial numbers of instruments at each site, particularly for a study using many sites. This can help distinguish the data files from many dataloggers.
- Describe the site weather. This record is vital for areas where the local weather conditions may differ from the general weather forecasts. In summer, the local cloud coverage and showers triggered by high temperatures in the afternoon are common. A clear sky at one site does not represent the same at other sites. Therefore, detailed local sky conditions should be logged to assist in data interpretation.
- The cloud cover conditions affect the measurement results significantly, particularly for the radiation-related variables such as MRT and incoming solar radiation. In urban areas, the cloud cover conditions can quickly vary in spatial and temporal dimensions. Using the daily average cloud amount reported by the weather station is not enough for urban microclimate analysis. In conducting field measurements, the cloud cover should be recorded by photographs every one or two hours and reported in oktas in the observation log.
- Take notes regarding special field conditions, including but not limited to the time and duration of unpredicted precipitation, the time of large vehicles idling beside roadside stations, and suspected sudden malfunctioning of instruments. Any conditions suspected to affect weather measurements should be recorded in detail.
- Attach photographs of the field environment. The measurement environment may vary continually in urban areas, influenced by the vagaries of weather, human activities, and other unexpected events and circumstances. A camera can monitor the field measurement process, particularly in mobile measurements. The photographs should be taken from different directions during the field measurement, as some minute details may not be adequately described in words in the logbook.

3.3.3. Responding to unexpected conditions

3.3.3.1. Natural influence. Unexpected precipitation may frequently occur in field measurements. Afternoon showers are common in tropical and subtropical summer. Large-scale numerical models used in weather forecasts have limitations, so local-scale sudden showers may not be reliably predicted. Besides, the varied urban landscapes and terrains may generate their atmospheric feedback to bring specific weather to different sites. For example, in summer, thunderstorms may occur in the rural areas while the weather could remain fine in the city center. Therefore, nowcast for precipitation at different field locations and radar images should be enlisted to prepare for unforeseen precipitation, especially in summer.

The instruments' International Protection Marking (IP code) can tell whether they can satisfy the waterproofing needs for outdoor deployment. If the rain is about to fall, the save buttons should be pressed immediately (if any). The microclimate monitoring system should forthwith be moved to the nearest rain shelter, or at least covered by a rainproof cloth. Rainwater on the thermometer sensor can bring evaporative cooling dependent on the local airflow [17]. Whether the field measurements should continue after the rainfall or whether the measured data on that day can be included in the data analysis depends on the research aim.

3.3.3.2. Human disturbance. Keeping pedestrians from the instruments is necessary to avoid blocking the incoming solar radiation and wind and causing measurement uncertainty. Usually, 0.5 m is sufficient. A temporary warning cordon line can be installed in stationary measurements to keep pedestrians at bay. At least one student helper should stay at the site to ensure the safety of instruments and guard against disturbances. Any unexpected happenings should be recorded in detail on the logbook.

3.3.4. Collecting meteorological data of the field day

After completing field measurements, the local meteorological data of the field day should be collected in time for data analysis. In general, the data of the field day can be downloaded from the local weather station website shortly after the target date. It is recommended to collect the meteorological data from the nearest urban station.

Moreover, the actual weather on the field day may differ from the forecast. It is necessary to use quantitative criteria to check whether the expected weather condition has been satisfied within an acceptable margin.

3.4. Curating data

3.4.1. Formatting data

Data formatting involves two main steps: digitization and database-building. The first step converts observations archived on paper or other media to the digital form as Excel spreadsheets or a similar machine-readable format. Generating output files with a consistent format and designated units from the dataloggers can save time on cumbersome manual manipulation of file formatting. The database-building step converts the digitalized observations into the format and schema of the database and adds the observations to it [96].

3.4.2. Processing data

3.4.2.1. MRT estimation. In estimating MRT by the globe method, the diameter of the globe in the equation provided by ISO 7726 [72] should be recorded in meters, not in millimeters. Standard and localized recalibrated MRT estimation methods were summarized in Ref. [97].

3.4.2.2. Human thermal comfort index calculation. In analyzing the thermal environment and outdoor human thermal comfort, human thermal comfort indices such as PET (Physiological Equivalent Temperature) [98], SET (Standard Effective Temperature) [99], UTCI (Universal Thermal Climate Index) (see: http://www.utci.org/), COMFA (COMfort FormulA) [100] (see: https://research.arch.tamu.edu/microclimatic-design/COMFA/index.html) are commonly used. The justifications for choosing an index should be elaborated on in the report. Details on the essential characteristics of the indices are summarized in Ref. [101].

3.4.2.3. Averaging. Averaging is common in the data analysis step to manage the raw data. The averaging duration depends on research aims. The 5 min period is frequently used in reviewed studies [42,44,54,57]. For MRT estimated by the globe method, some researchers recommended the 10-min average values [35,86,102] because this approach can render the results more consistent with those acquired by the more accurate six-dimensional technique (cf. Section 3.1.4.2). The effect of rapid changes in the radiation fluxes can be smoothed, and the sensor could follow them rather consistently. The WMO suggested a typical example of sampling every minute and averaging by 10-min brackets.

3.4.2.4. Correcting the mobile measurement records. If the benchmark station has a continuous measurement record, it is necessary to “calibrate” the mobile traverse data against the stationary benchmark station [5]. Regarding the “stop-and-go” measurements, the first 5 min of data should be eliminated to improve the measurement accuracy [64]. Qi et al. [64] reported that to eliminate the first 5 min of air and globe temperature data can improve accuracy by about 20% and 30% respectively.

3.4.3. Controlling data quality

Processed data quality control deals with comprehensive checking of temporal and internal consistency, evaluation of biases and long-term drifts of sensors and modules, malfunction of sensors, etc. [103]. Five quality control flags are used to classify the measured data: *good* (accurate; data with errors less than or equal to a specified value); *inconsistent* (one or more parameters are inconsistent); *doubtful* (suspect); *erroneous* (wrong; data with errors exceeding a specified value); *missing data* [103].

The erroneous data can often be identified in detailed data analysis. For example, the measured data are erroneous if dew point temperature > air temperature; wind direction = 00 but wind speed ≠ 00; or wind direction ≠ 00 but wind speed = 00, etc. [103].

When erratic value occurs, the primary causes should be ascertained. The field videos, field photos, and observation logs can be evaluated for human or other measurement errors. The apparent aberrations may be valid data, demanding detailed explanation and analysis. The data treatment approach for errors and outliers should be reported with explanations, regardless of the omission or retention decision.

Deletion and imputation are two common techniques to treat the missing values. The reasons for choosing the treatment techniques should be reported clearly.

4. Conclusion and future work

This guideline provides a systematic and actionable workflow of microclimate field measurement procedures in urban areas under tropical climates. The standardization of the multiple steps is based on literature reviews and long-term tropical microclimate research experience. A four-step scheme in microclimate field measurements was presented and discussed in detail, i.e., formulating field measurement plan, preparing for field measurements, sustaining measurement quality, and curating data. Applicable concepts and techniques were tapped from guidelines and standards, relevant studies’ experiences and professionals’ recommendations were incorporated into appropriate parts of our synoptic guidelines. Experience, hints, recommendations, precautions, examples, and a metadata checklist were provided for researchers’ reference. Despite the proposed guideline based on research experiences in the tropics, pieces can also be applied in other climate zones but need careful consideration.

By reviewing the last five years’ field measurement studies and the existing guidelines and standards, Knowledge gaps between existing practices and researchers’ practical needs were found. Regarding existing guidelines and standards, the inappropriate application scale and location and the lack of a systematic workflow have limited their applications to outdoor microclimate field measurement. The continued shortage of comprehensive and appropriate guidelines could bring ill-conceived measurement design, insufficient preparation, improper operations, and incomplete report of field measurement studies.

In conducting field measurements in urban areas, it is necessary to apply guiding principles rather than rules and adopt a flexible approach. Experiment design, data quality control, and complete report are the three main domains of field measurements. Choosing field sites that conform to research purposes is fundamental and critical for a successful experiment in an urban area. Instrument selection should consider the application scenarios, instrument specifications, and traceability. Data quality control can include measurement operations and data processing. A detailed experiment and contingency plan are critical because some errors creeping into the measuring process cannot be eliminated later. The significance of a complete report, i.e., incorporating the full metadata, has seldom been prescribed or stressed in previous field measurement studies. This pitfall has been duly emphasized in our guidelines. Comprehensive metadata ensures comparability among studies, enabling further meta-analysis.

An important component of refined guidelines is standardizing the questionnaire design in human thermal comfort research. They include upgrading and standardizing crucial issues such as question-wording, question order, subjective judgment scales for outdoor environment, consideration for special populations (e.g., children, the elderly, the disabled, etc.), survey data post-processing, and questionnaire metadata report.

More accumulated experiences in urban microclimatology under diverse conditions and circumstances cannot be more emphatically stressed for a successful data acquisition campaign. Learning from current guidelines and standards and field measurement studies is important. However, the precious extensive experience of researchers and professionals can be recorded and shared for continual honing of the measurement methods and precautions.

CRediT authorship contribution statement

Zhixin Liu: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Ka Yuen Cheng:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Yueyang He:** Writing – review & editing, Writing – original draft. **C.Y. Jim:** Writing – review & editing, Funding acquisition. **RobertD. Brown:** Writing – review & editing. **Yuan Shi:** Writing – review & editing. **Kevin Lau:** Writing – review & editing. **Edward Ng:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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