Designing a Global Weather Station Network based on H3 grid

Dr. Stavros Keppas, Dr. Haris Balis, Dr John Pagonis, 14/06/23 - WeatherXM AG

Designing a weather station network over an area is not an easy task and depends on the purposes served by this network. Most studies aim to redesign/redistribute an existing network to eventually use it for particular purposes. However, WeatherXM's objective is to develop a multi-purpose weather network from the ground up, with the aim of serving not only its clients, but also the scientific pursuits of meteorology and climatology. A great body of scientific literature review shows that a weather network should be dense over complex topography or complex urban structures (often 1-3km or even finer) to meet demanding hydrological requirements or urban micrometeorology research purposes. In fact, there are meteorological phenomena that require such densities in order to be well represented. These are convective precipitation and sea breeze that are mesoscale phenomena with a temporal resolution of a few minutes to hours. Furthermore, the persistence of temperature inversions at near-surface layers is significantly influenced by topography, leading to prolonged periods of inversion. In our study, according to previous work, but also a series of logical scientific arguments we propose three main criteria to describe the design of a global weather network, the density of which can be adjustable to the land use and/or topography of an area.

1 Introduction

The estimation of the maximum allowed distance (or the minimum number of weather stations per cell) seems to be a challenging task, as the scientific community has not agreed on a unified methodology for sensor network design [Chacon-Hurtado et al., 2017]. Designing a weather station network has often been driven by non-meteorological factors, such as budget and installation area availability [Loucks et al., 2005].

As a general rule, the design of a weather network should ensure that the collected data are representative and sufficient, and can be used to derive the analysis required from the measurements [US EPA, 2002]. In particular, at least three aspects should be considered, when designing networks of meteorological sensors, which eventually seems to be a multi-objective problem. Hence, the network should: *a. meet the needs of various purposes, which may conflict together, b. be robust in cases that one or more sensors fail to measure, c. take into account different needs, purposes and users with different temporal and spatial scales* [Singh et al., 1986, Loucks et al., 2005, Kotecha et al., 2008].

2 Network density, topography and land use

2.1 Generic thresholds and the need for denser networks

In general, it seems that topography and land use of the areas have a great contribution to the decision on designing a weather network [Moss and Taskert, 1991]. Although WMO suggests a minimum density of rain gauges depending on the topography or land use [**Table 1**; Liang and Wang et al., 2019], there is a significant body of literature review showing that different purposes and research areas lead to different decisions on designing a weather station network, often suggesting densities much higher than WMO recommends [e.g., Leung and Law, 2002; Mishra, 2013; Ochoa-Rodriguez et al., 2015; Schroeer et al., 2018; Sofiza et al., 2019]. Among a series of complex methodologies (e.g., interpolation variance, entropy etc) for redesigning an existing weather network, user survey may be a way of designing a network from scratch without requiring a pre-existing network. Although this method is a non-automated detection of station positions, it may cover research aspects not covered by an automated process [Chacon-Hurtado et al., 2017]. An additional factor for designing a network is the desired time window within which weather conditions should be monitored. As a matter of fact, the variability of parameters (e.g., precipitation, temperature etc) within a long period (after averaging through months/years for climate analysis) is lower than within a short-term period of a few hours or days. As a matter of fact, Jenne and Joseph [1985] analysed data from a rain gauge network in Texas and they showed that denser networks are needed when focusing on daily (instead of monthly) and summertime (instead of winter) precipitation. Thus, a denser weather station network may be needed for nowcasting/operational purposes, while keeping a climatic archive demands a sparser network [Dent, 2012]. As an illustration, short term variabilities in precipitation, wind or even temperature over a certain area may be larger than long term ones due to small scale phenomena (e.g., summertime thunderstorms). Thus, while maintaining a high density network is imperative, it may be cost-effective to identify representative points within an area. This is the reason that existing networks quite often need redistribution [e.g., Sofiza et al., 2019; Wadoux et al. [2020]].

Table 1. Minimum density of precipitation gauge networks suggested by WMO for areas with different topography [Liang and Wang et al., 2019].

Region type	Range of norms for minimum network (km^2/gauge)	Range of provisional norms in difficult situations (km^2/gauge)
I	600−900	900−3000
II_a	100−250	250−1000
II_b	25	
III	1500−10,000	

I, Flat regions in temperate, Mediterranean, and tropical zones; II_a, Mountainous regions in temperate, Mediterranean, and tropical zones; II_b, Small mountain/islands with irregular precipitation patterns, requiring dense hydrographic networks; *III*, Arid and polar zones.

Each meteorological parameter may change in time and space in different ways. Precipitation and wind seem to present a larger spatial variability against other meteorological parameters [Hubbard, 1994; Ghosh et al., 2021]. This means that a precipitation or wind oriented network should be denser, but still the strategic decision of station position is important. In other words, a network focused on hydrological/wind investigation of an area may be sufficient for examining other parameters such as temperature. A large amount of studies have been conducted on the optimisation of existing weather station networks over mountainous catchments with complex topography or urban areas focusing on the accurate precipitation representation for hydrological purposes (e.g., run-off estimation which may have impact on hydroelectric power production at a dam or cause floods downstream). Indeed, *a dense network of rain gauges can account for the mountainous effects, but can also be an important step for forecasting flash flood or calibrating of the radar rainfall* [Lee and Jun, 2014]. According to Sofiza et al. [2019], *a dense rain gauge network can assist in watershed management, water budget studies, reservoir operation, and flood control/forecasting*. Eventually, the precipitation data of a rain gauge network should adequately represent the precipitation distribution over an area through appropriate interpolation methods.

2.2 Network Density over Mountainous Areas

Here, we summarise the results of various studies that used weather station networks over mountainous areas and elevated basins mostly for hydrological purposes. Prior to proceeding with the presentation of the findings, it is essential to examine some general characteristics of precipitation over complex topography, such as mountainous regions. It seems that ~70-90% of the wintertime precipitation occurring over mid-latitude mountains falls as snow, and of this, there is a ~80% that is caused by orographic effects. The latter demonstrates the distinctive behaviour of precipitation over mountainous regions and underscores the significance of its measurement. Furthermore, it should be noted that the topographic slope, acting as a natural barrier, can exert a significant influence on the amount of precipitation by inducing greater funneling of air flow around these barriers. [WMO, 1985; Smith and Barstad, 2004; Roe, 2005]. However, the relationship between precipitation and elevation is not linear and larger amounts of precipitation are more likely to occur on the slopes rather than at the top of mountains [Moran-Tegeda et al., 2022].

For all the predescribed reasons, a great body of research has been conducted on optimising weather networks over mountainous areas. Shope and Maharjan [2015] showed that in a 64km^2 basin, ranging in elevation between 339-1321m, a network density of **4km^2** is fairly high to represent the precipitation over the area using kriging or (Inverse Distance Weighting) IDW interpolation methods. However, they suggest that an optimum density for this area would be 50-142 stations (1 rain gauge per **1.28-0.45km^2**). In the Vallon de Nant catchment of 13.4km^2 located in western Alps, where the elevation ranges between 1200-3051m, Micehelon et al. [2020] recommend that a density of ~1 rain gauge per **1km^2** is needed in order not to misestimate rainfall event by a factor of 2. In the complex basin of Thur in NE Switzerland ranging between elevations of 357-2437m, Wadoux et al. [2020] found that one rain gauge per **340km^2** may be enough to predict the total run-off at this basin. They highlight, though, that this density cannot easily be generalized, because it is likely case-dependent. The surprisingly low rain gauge density is also likely related to the 10-day time step used in the particular case study. In contrast, Schroeer et al., [2018] mention that rain gauges are usually >10 km apart in operational networks, and this spacing is not capable of observing extreme rain intensities from summer convective phenomena, which occur over small temporal and spatial scales. Comparing with a super-dense network of one rain gauge per **2km**^{2} (deployed over an area of 300km^2 with elevation of ~300m), they found that extreme rainfall at point scale seem to be underestimated by ~20%. This seems to agree with the fact that the area with the most extreme intensity in a convective storm cell can be smaller than 1km^2. Indeed, Nikolopoulos et al. [2015] investigating rainfall thresholds for debris flow occurrence, found that even a density of **10km**^{2} could lead to an error >9% on the way to estimate the debris flow occurrence in mountainous areas of northern Italy. Moran-Tegeda et al. [2022] also highlighted the significance of placing weather stations in mountainous areas, where the topography complexity has a great impact on precipitation. Deploying a weather station on one of the highest areas at the central Iberia, they found that regression models applied on 36 stations' precipitation (with a distance of **1.9-19.9km**) underestimated rainfall intensities by 60% on average (compared to the one station deployed). In addition, they showed that different atmospheric circulation patterns are associated with *different precipitation patterns related with different orientation of the slopes of the mountainous area*.

2.3 Network Density over Urban Areas

In this section, we discuss the results of studies focusing on weather station networks in urban environments. Muller et al. [2013] suggest that there are three different scales of developing a network and monitoring urban weather conditions, depending on the spatial scale of the phenomena to be observed. The two finest scales are *city scale* and *microscale* , which aim to monitor general weather conditions in the cities and research urban micrometeorology respectively. In terms of network density, current urban networks range between **4.5-36km^2** (for city scale) and tens to hundreds of m^2 (for microscale). The need for long-term, high-density urban weather/climate networks is also highlighted in order to improve the understanding of urban environments, where the majority of the population lives.

Discussing the urban microclimate, other, less variable, parameters may significantly vary within microscale level (a few thousands of metres). This occurs due to the fact that the structure of urban areas is complex, and various (artificial or not) surfaces store and diffuse heat in different ways (e.g., conduction, convection, radiation etc). As a result, a city compared to its suburbs (city scale) or an urban fabric neighbourhood compared to a park closeby (microscale) can present a significant difference in temperature (Urban Heat Island effect, e.g., Rizwan et al., 2008; Keppas et al., 2021) or wind. In cases, this temperature difference (between non-urban surrounding areas and dense urban fabric) may reach 1-7°C especially during the night

[Moreno-garcia, 1994]. In a warming Earth where more than 50% of the global population lives today in urban agglomerates [Zhang, 2016], significant research is conducted (on a global scale) on the impact of green interventions within dense urban areas in order to mitigate climate change's effects on large population aggregations [e.g., Bowler et al., 2010; Demuzere et al., 2014; Gunawardena et al., 2017; Shafizadeh-Moghadam et al., 2020; Khan et al., 2022] because UHI may significantly impact on health [e.g., Tan et al., 2010; Heaviside et al., 2017; Keppas et al., 2021; Parliari et al., 2022] and energy [e.g., Santamouris et al., 2015; Lowe et al., 2016] . However, this requires weather measurements around such areas [e.g., Heusinkveld et al., 2014; Lyu et al., 2022]. Additionally, buildings cause friction and, thus, wind may notably weaken over cities or even from a neighbourhood to another [Bornstein and Johnson, 1977; Emmanuel and Johansson [2006]; Millward-Hopkins et al., 2013]. This differential intensity of flow over cities has been found to be able to trigger even cloud and precipitation downwind the cities [Sanderson and Gorski, 1978; Han et al., 2014].

Larger artificial areas have a much more intense effect on the microclimate of an area. According to Oke [1973] an urban agglomeration in Canada with a population of 1,000 individuals may be characterised by an UHI of ~1°C, which may exceed 7°C in cases of cities with population >1,000,000. The population density in developed countries is in average 35 individuals per hectare or 1,000 individuals per 0.4km^2 [Angel et al., 2011]. However, as UHI may be problematic especially during summer in cities, green urban areas seem to be one of the solutions. Indeed, even a small green area of 0.015km^2 can have a cooling effect on a buffer of 25m to more than 100m, with larger green areas of 26km^2 may have a cooling impact on a few hundreds of metres to a few kilometres [Algretawee, 2022]. As a conclusion, the urban environment seems to be fairly complex and requires a sufficient representation.

As already mentioned, the establishment of dense urban weather station networks becomes increasingly important in order to comprehensively understand the microclimate and micrometeorology within cities. As a matter of fact, Maier et al. [2020] investigating the spatial variability in the urban area of Graz (Austria) during summertime concluded that a density of **6km^2** is not sufficient to fully represent and observe the precipitation from convective storms. Berne et al. [2004] analysed the relation between the minimum required spatial resolution of rainfall measurements and the catchment size involving precipitation data and runoff records from six urban catchments on the French Mediterranean coast. Their study suggests that a resolution of 3x3km, for urban catchments may be sufficient. Similar resolutions (**~1-3km**) arise from other studies as well [Emmanuel et al., 2012; Notaro et al., 2013], which point out the importance of such dense networks for hydrological applications in urban environments. Ochoa-Rodriguez et al. [2015] agreeing with previous studies, suggests that a sufficient spatial resolution of precipitation measurements for urban areas is **1-3km**, while the **temporal resolution should be 1-5min** in order to be able to observe short time scale phenomena. Similar densities are also recommended by Leung and Law [2002], for the hilly area of Hong Kong (**8km^2** per station or higher). It is stated that the network density should be even higher especially on the Hong Kong island for slope stability monitoring. In a slightly different approach, Mishra [2013] used rain gauge observations and satellite data to show that a homogeneous distribution of rain gauges (at a density one per **7x7km area**) may provide reasonable accuracy (**absolute error ~15%**) in the urban area of Bangalore in India.

3 Small scale phenomena

As seen in the previous sections, topography and land use often have a significant impact on the weather conditions observed by meteorological stations. However, there are small-scale physical phenomena (often affected by topography and land use) that should be observed by a typical weather station, and they could be detected only under the presence of a dense weather station network or a network with stations that have been carefully deployed at representative locations. These phenomena are: a. Convective precipitation, b. Temperature Inversion and c. Sea Breeze.

3.1 Convective Phenomena

Convective phenomena occur when warm, moist air rises in the atmosphere triggering usually small scale cloud turrets (**Figure 1**), which are often associated with small scale precipitation and occasional change in wind and temperature. With the exception of tornadoes, convective phenomena, such as showers and thunderstorms, represent the smallest-scale weather events that can be detected by a standard meteorological station. In particular, a thunderstorm can affect an area of diameter of ~1-20km (**Figure 2**), which means that within this area weather can significantly change compared to the surroundings [e.g, Tavakolifar et al., 2017]). Indeed, WMO

[1985] suggests a 10km spacing for cumulus scale phenomena stating that a weather station spacing of 1km could also be used for observing precipitation.

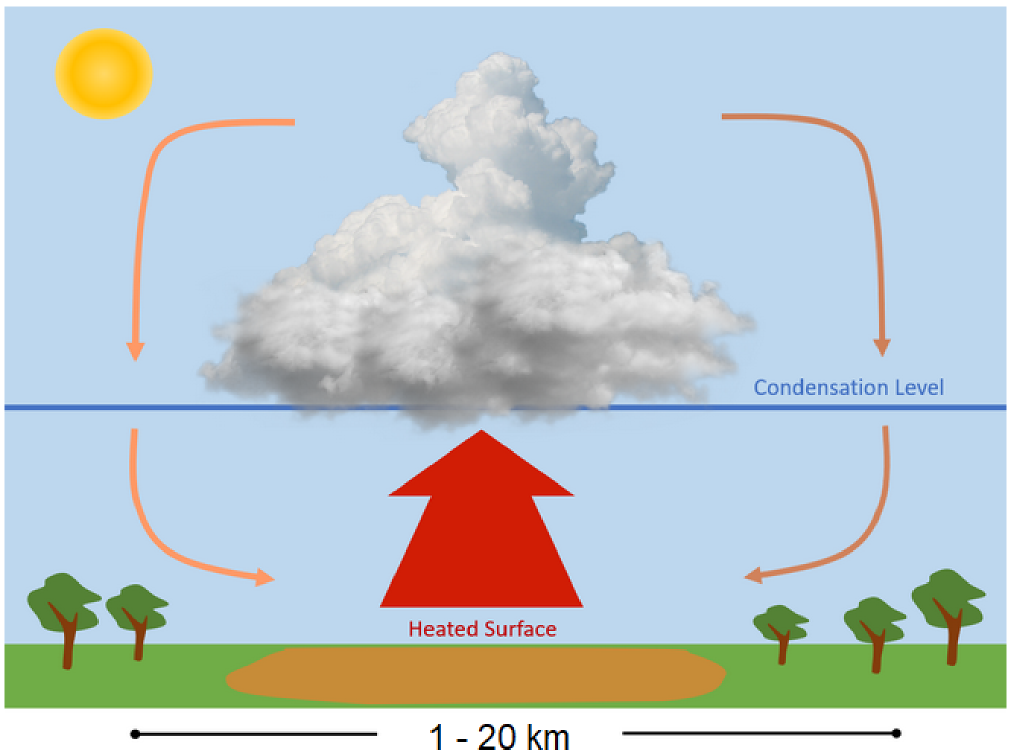

Figure 1. Production mechanism of a convective cloud turret.

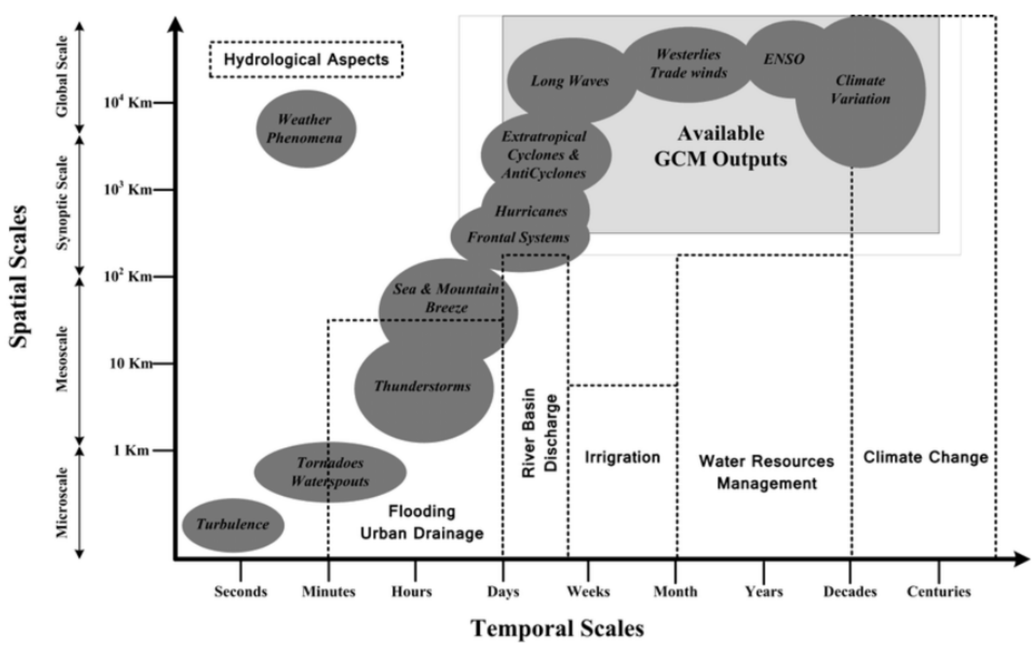

Figure 2. The spatiotemporal magnitude of meteorological events, the resultant outputs of General Circulation Models, and the evaluation of hydrological impacts [Tavakolifar et al., 2017].

The fact that a shower or thunderstorm can affect a small diameter area or a narrow-width zone (as it moves), means that a sparse network of weather stations is highly likely to miss such an event. Furthermore, if a small diameter shower occurs at the upper or downwind side of a mountain where a river originates, a hydroelectric dam situated downstream may be impacted. However, we can only make such predictions if we have recorded precipitation data at the mountain summit. Similarly, a flash flood may be detected only by a dense weather network. As climate change has been linked to the intensification of extreme midlatitude convective precipitation events (Barbero et al., 2017; Dai et al., 2017), it is becoming more important to accurately interpret and evaluate climate models and precipitation measurements at a resolution of kilometres using dense networks.

3.2 Sea Breeze Impact

Sea breeze forms due to the unequal heating rates of land and sea during a sunny day with no synoptic winds, as cooler maritime air replaces rising warm air above the land (**Figure 3**). The sea breeze is a mesoscale phenomenon (**Figure 1**) that impacts areas tens to hundreds of kilometers inland from the shoreline (Simpson et al., 1977; Miller et al., 2003), creating gradients in temperature, humidity, and wind speed as one moves further away from the coast. However, the structure of an urban area complicates the sea breeze impact. Emmanuel and Johansson [2006] demonstrated that urban areas located within approximately 5km of the shoreline are subject to varying impacts from the sea breeze phenomenon (~7°C and ~20% difference in temperature and relative humidity respectively). Even if a weather station is located near the waterfront, if a building obstructs the view between the station and the water, there can still be a notable temperature difference (~3°C) compared to another station situated closer to the shoreline. In addition, Potgieter et al. [2021] using 10 national and 492 NETatmo weather stations presented large temperature variations (up to 6°C) from zone to zone (coastal-central-inland), but also within zones of the city of Sidney during warm days. In general, sea breeze can be affected by the roughness of the land, and thus both topography and land use can spatially limit its effect [Bonnardot et al, 2001; Puygrenier, 2005].

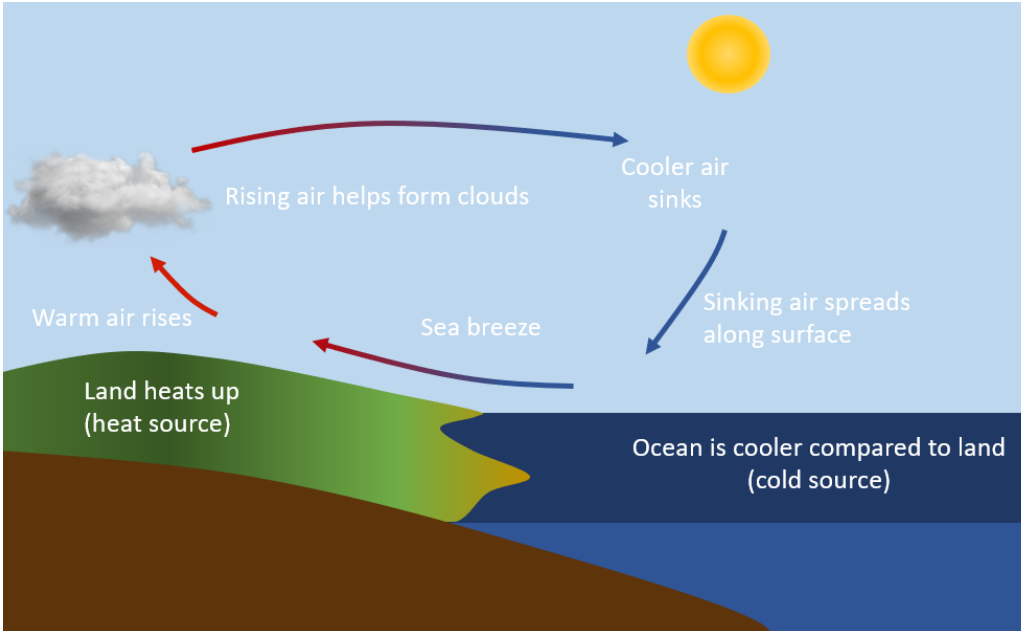

Figure 3. Sea breeze flows and mechanism.

3.3 Temperature Inversion

Temperature inversion is a meteorological phenomenon where the normal decrease in temperature with altitude is inverted, resulting in an increase in temperature with altitude in a layer of the atmosphere. A temperature inversion at lower layers of the troposphere can occur for various reasons (e.g., frontal passage, radiation cooling, topography etc). In case of radiation cooling of the ground (**Figure 4a**) or cold air over mountains move down a slope being trapped in a valley (**Figure 4b**), temperature inversion can develop and remain for long hours especially during the night under anticyclonic calm and clear sky conditions being occasionally harmful crops at lower ground areas [Evans, 1999; Sakai, A., & Larcher, 2012; Apostol and Ilie, 2015]. Temperature inversions (caused by topography or radiation cooling) usually occur at the bottom of a basin having a depth of 100-1000m and a vertical temperature gradient of <1°C/100m to >10°C/100m [Whiteman, 1982; Kahl, 1989; Whiteman et al., 1999; Li et al., 2019; Niedźwiedź et al., 2021].

Figure 4. Radiation cooling mechanism (a) and cold air trapping due to topography (b) during night time.

4 Building a Global Network - Recommended Specifications

Taking advice from the international literature review, we are able to recommend a series of criteria for the minimum density of weather stations required in order to build a global network of weather stations that will be capable of representing weather conditions across the globe in high accuracy. The process can be facilitated by the H3 hexagonal grid system, which provides a range of various grid cell sizes.

After conducting deep scientific literature research, we summarise and present our methodology for the optimal positioning of weather stations in the following section. Instead of providing only the exact location of stations, we provide flexibility by defining zones which could host a station so that cases where inaccessible areas can be avoided. Our methodology is devised in two parts, namely the topographic analysis and the land use analysis.

a. Topographic analysis

Topographic analysis refers to the introduction of weather stations responsible for capturing variation due to landscape and orography. The process begins with evaluating whether the maximum elevation difference within the cell exceeds the 100m threshold (**Figure 5**). Identifying cases where this threshold is exceeded is useful for capturing harmful frosts which may occur at the lower ground areas of a valley or for describing significant changes of various meteorological parameters (i.e., air flow) due to a complex topography. If this 100m-threshold is not exceeded then the cell is considered flat and only one weather station is required. In the opposite case, we proceed with the creation of two zones of points, one with all points above (*high-zone*) and another with all points below (*low-zone*) the critical altitude (z_{crit}). z_{crit} is defined as the maximum altitude in the cell (z_{max}) minus 100m ($z_{crit} = z_{max} - 100$). We locate one station in high-zone, ideally at the location with altitude z_{max}. For points in the low-zone, we proceed with the identification of continuous sub zones with the same aspect which we refer to as *aspect-zones* (**Figure 6**). If multiple aspect-zones with the same aspect (e.g. two aspect-zones with North aspect) are identified, then we keep the largest one. Finally, we place one station in each aspect-zone, ideally at the lowest point of each aspect zone, if the aspect zone's area is larger than ⅙ of the area of the cell (to exclude insignificant small areas). The high-zone is excluded from this criterion. In case that only the high-zone is present in a cell (because none of aspect-zones fulfils the area criterion), then the aspect zone with the lowest point elevation is selected as an additional zone for deploying a weather station.

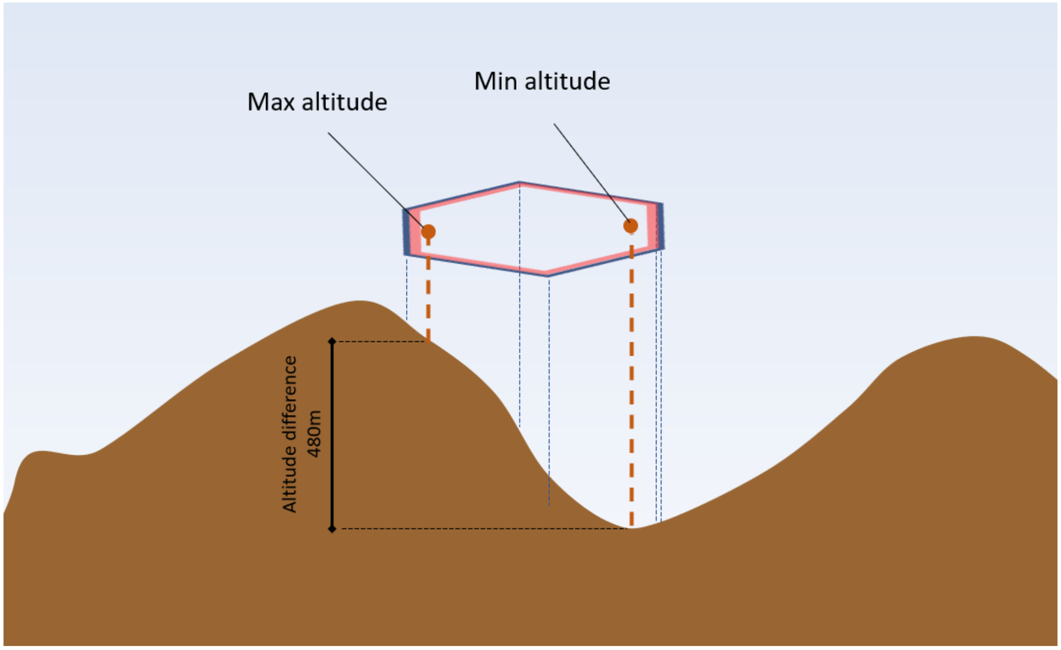

Figure 5. Positions of weather stations (orange bullets) over a complex topography. Red zones indicate the areas that should be avoided (only for determining the ideal locations of stations). For simplicity reasons points instead of zones are used in the scheme.

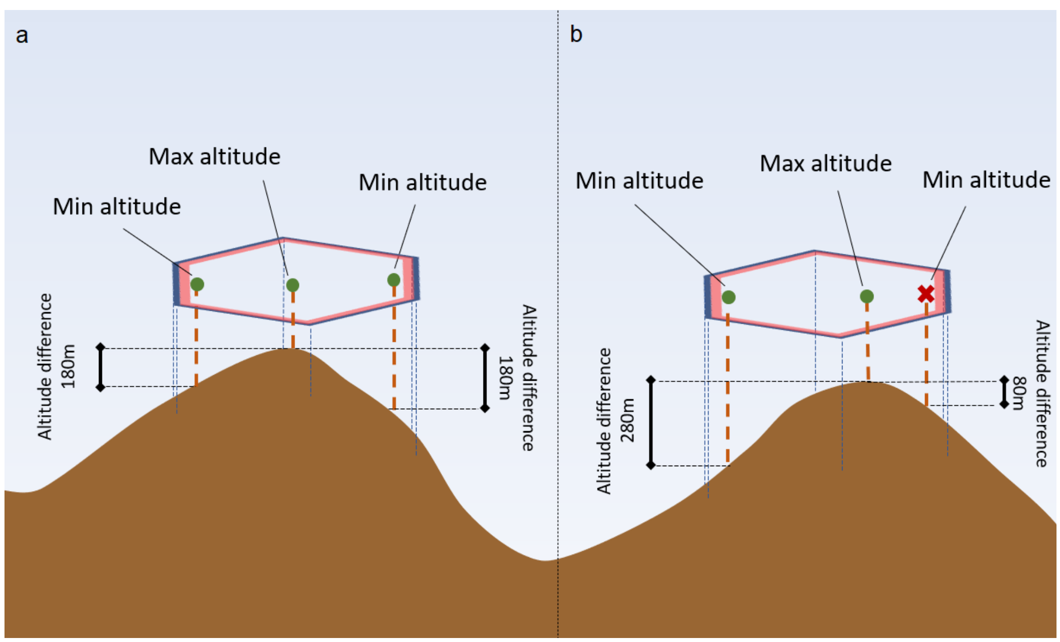

Figure 6. Positions of weather stations (green bullets) over a complex topography with differently oriented slopes. Red zones indicate the areas that should be avoided (only for determining the ideal locations of stations). The “x” symbol indicates an example of a non-recommended location. For simplicity reasons points instead of zones are used in the scheme.

As an additional example, in an extreme case that a mountain/hill with a "pyramidal" shape is included in a cell (assuming that its base points are at least 100m lower than the top), then 5 weather stations should be placed, the 4 of them at the lowest possible location of each differently oriented surface and one at the highest point (**Figure 7**). Similarly, an area with four differently aspected surfaces and a lowest point in the middle should also be represented by 5 weather stations.

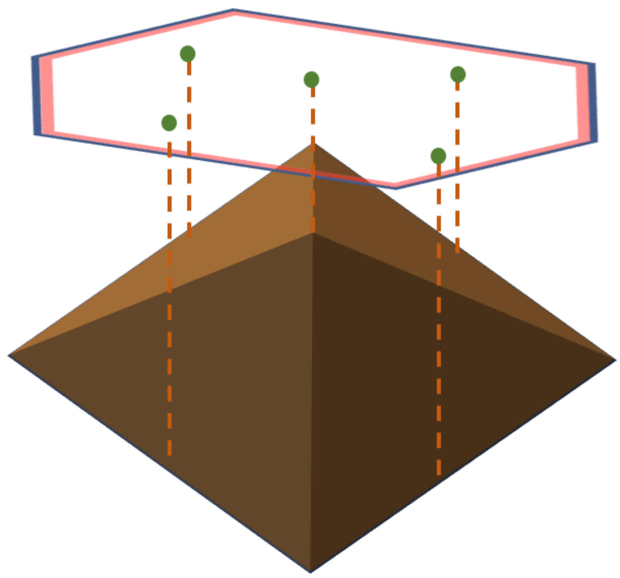

Figure 7. An extreme case of a "pyramidal" shaped mountain and the recommended locations of the stations. For simplicity reasons points instead of zones are used in the scheme.

b. Urban Land use analysis

Urban land use analysis is responsible for identifying the location of stations which capture variations of weather conditions due to the effect of urban areas. To simplify the analysis we consider three main land use categories as the most influential ones, namely urban (buildings, houses, offices, etc.), green (e.g. parks) and coastline. The procedure begins with the identification of urban and green areas, which are buffered by 100m, and then dissolved in order to combine nearby elements with the same land use type. Then, the process filters out urban zones with area less than 0.4km^2 and green areas smaller than 0.015km^2. In order to further reduce the number of required stations, for each cell we keep only the largest urban and green zone (within the largest urban zone), assuming that the effect of the land use is adequately captured by a single sensor per land use type. In addition, when the cell intersects with the coastline we place an additional station anywhere on a 50m buffered area along the coastline. For cases where multiple islands are present within the cell, the station is placed on the longer coastline. The previous section is visualised in **Figure 8**.

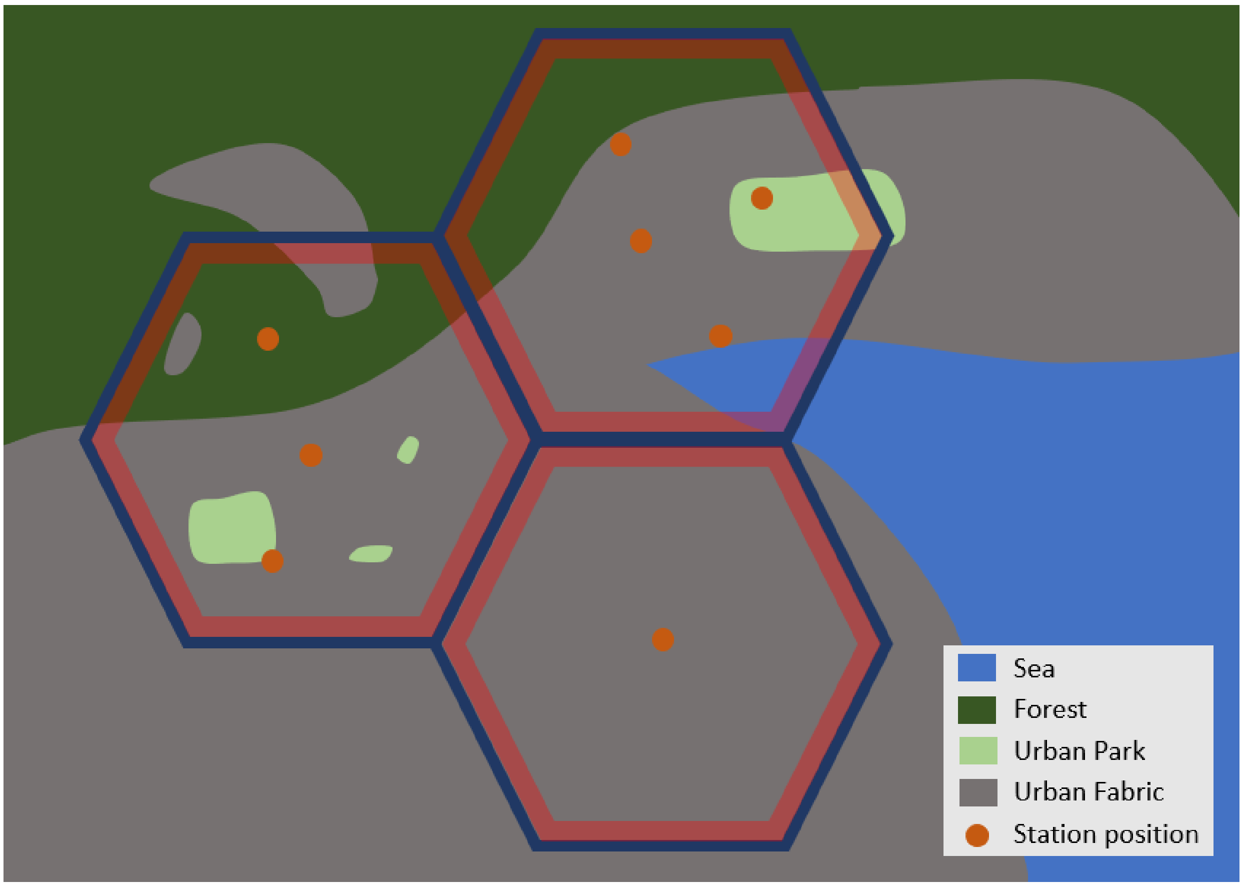

Figure 8. Minimum required stations (orange bullets) over an urban environment. Red zones indicate the areas that should be avoided (only for determining the ideal locations of stations). For simplicity reasons points instead of zones are used in the scheme.

c. The Grid System

In order to determine the appropriate number of weather stations required for meteorological representation, our methodology is applied to two different H3 grid cell sizes (5 and 7), allowing us to establish the minimum and maximum number of zones that necessitate a weather station.

WMO recommends a minimum density of ~1 station per 600km^2 in flat areas. Such an area is better represented by the cell size 5 hexagon (where a hexagon covers an area of 253km^2) rather than the other H3 sizes provided. Considering that 2,016,830 size 5 hexagons cover the entire planet and that 71% of the Earth is covered by oceans, the minimum number of required weather stations should be ~584,881 if all areas across the Earth were flat. However, based on the proposed methodology, **a total of 1,088,505 stations are necessary to adequately cover the Earth's surface, suggesting a global network density of 1 station per 136km^2.**

On the contrary, multiple studies advocate for the establishment of significantly denser weather station networks, recommending densities as high as one station per 1-9km^2 or even lower, especially in areas characterised by intricate topography and urban settings. This is particularly important especially when the focus is on hydrological applications. To investigate the areas requiring such dense networks we opt for the cell size 7 hexagon (where a hexagon covers an area of 5.2km^2). Again, considering that 71% of the Earth is covered by oceans, **t**he minimum number of required weather stations should be ~28,659,297 if all areas across the Earth were flat. By employing the suggested methodology, **the total number of required stations is 35,397,821 the density of the network varies from one station for every 4.2km^2**.

It is noted that (regardless of the H3 grid size) as a general principle and in order to reduce the number of stations within a small distance between adjacent cells, we define an internal buffer within each cell of 0.25km where stations cannot be placed.

Summary

Applying the above-described methodology, a cell may eventually require up to 8 weather stations (4 for differently oriented aspects, 1 for the highest area, 1 for the largest urban area, 1 for the largest urban green and 1 for the coastal area of a cell). Considering that convective phenomena can present an extent of **1-20km** (according to literature review) and WMO suggests a density of **one station per 1-10km for measuring convective activity**, the present methodology may achieve a density of 1 station per 5.6km, which agrees with the already recommended densities. Dividing the world into hexagon shaped cells (according to the UBER H3 model), we try to define the weather representativeness of weather stations within a cell and also to facilitate the WeatherXM rewarding mechanism. Finally, it is important to highlight that the present study defines the locations of well deployed weather stations. However, a number of additional weather stations around a well-deployed (reference) one should also exist, being able to confirm that the reference station works properly and preserve its condition.

5 References

Algretawee, H. (2022). The effect of graduated urban park size on park cooling island and distance relative to land surface temperature (LST). *Urban Climate*, *45*, 101255.

Angel, S., Parent, J., Civco, D. L., Blei, A., & Potere, D. (2011). The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050. *Progress in Planning*, *75*(2), 53-107.

Apostol, L., & Ilie, N. (2015). Thermal hazards in cold semester of the year in the mountain area of Moldova river (sector between Vama and the Springs of Moldova river). *Present Environment and Sustainable Development*, (1), 251-262.

Barbero, R., Fowler, H. J., Lenderink, G., & Blenkinsop, S. (2017). Is the intensification of precipitation extremes with global warming better detected at hourly than daily resolutions?. *Geophysical Research Letters*, *44*(2), 974-983.

Berne, A., Delrieu, G., Creutin, J. D., & Obled, C. (2004). Temporal and spatial resolution of rainfall measurements required for urban hydrology. Journal of Hydrology, 299(3-4), 166-179.

Bleasdale, A. (1965). Rain gauge networks development and design with special reference to the united kingdom. In *Proceedings of the WMO/IASH Symposium the Design of Hydrological Networks, IASH Pub* (No. 67, pp. 46-54).

Bonnardot, Valérie, et al. "Sea breeze mechanism and observations of its effects in the Stellenbosch wine producing area." *Wynboer* 147 (2001): 10-14.

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and urban planning*, *97*(3), 147-155.

Chacon-Hurtado, J. C., Alfonso, L., & Solomatine, D. P. (2017). Rainfall and streamflow sensor network design: a review of applications, classification, and a proposed framework. *Hydrology and Earth System Sciences*, *21*(6), 3071-3091.

Dai, A., Rasmussen, R. M., Liu, C., Ikeda, K., & Prein, A. F. (2020). A new mechanism for warm-season precipitation response to global warming based on convection-permitting simulations. *Climate Dynamics*, *55*, 343-368.

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., ... & Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of environmental management*, *146*, 107-115.

Dent, J. E. (2012). *Climate and meteorological information requirements for water management: A review of issues*. WMO.

Emmanuel, R., & Johansson, E. (2006). Influence of urban morphology and sea breeze on hot humid microclimate: the case of Colombo, Sri Lanka. *Climate research*, *30*(3), 189-200.

Emmanuel, I., Andrieu, H., Leblois, E., & Flahaut, B. (2012). Temporal and spatial variability of rainfall at the urban hydrological scale. *Journal of hydrology*, *430*, 162-172.

Evans, R. G. (1999). Frost protection in orchards and vineyards. *Washington State Univ. Coop. Ext. Pullman*.

Ghosh, M., Singh, J., Sekharan, S., Ghosh, S., Zope, P. E., & Karmakar, S. (2021). Rationalization of automatic weather stations network over a coastal urban catchment: A multivariate approach. *Atmospheric Research*, *254*, 105511.

Gunawardena, K. R., Wells, M. J., & Kershaw, T. (2017). Utilising green and bluespace to mitigate urban heat island intensity. *Science of the Total Environment*, *584*, 1040-1055.

Heaviside, C., Macintyre, H., & Vardoulakis, S. (2017). The urban heat island: implications for health in a changing environment. *Current environmental health reports*, *4*, 296-305.

Heusinkveld, B. G., Steeneveld, G. V., Van Hove, L. W. A., Jacobs, C. M. J., & Holtslag, A. A. M. (2014). Spatial variability of the Rotterdam urban heat island as influenced by urban land use. *Journal of Geophysical Research: Atmospheres*, *119*(2), 677-692.

Hubbard, K. G. (1994). Spatial variability of daily weather variables in the high plains of the USA. *Agricultural and Forest Meteorology*, *68*(1-2), 29-41.

Jenne, R., & Joseph, D. (1985). Sensitive Experiments with Different 1 to 500 km Scale Networks (NCAR). *WDO/TD*, (115).

Kahl, J. D. (1990). Characteristics of the low‐level temperature inversion along the Alaskan Arctic coast. *International Journal of Climatology*, *10*(5), 537-548.

Keppas, S. C., Papadogiannaki, S., Parliari, D., Kontos, S., Poupkou, A., Tzoumaka, P., ... & Melas, D. (2021). Future climate change impact on urban heat island in two mediterranean cities based on high-resolution regional climate simulations. *Atmosphere*, *12*(7), 884.

Khan, A., Papazoglou, E. G., Cartalis, C., Philippopoulos, K., Vasilakopoulou, K., & Santamouris, M. (2022). On the mitigation potential and urban climate impact of increased green infrastructures in a coastal Mediterranean city. *Building and Environment*, *221*, 109264.

Kotecha, P. R., Bhushan, M., Gudi, R. D., & Keshari, M. K. (2008). A duality based framework for integrating reliability and precision for sensor network design. *Journal of process control*, *18*(2), 189-201.

Lee, J. H., & Jun, H. D. (2014). A methodology for rain gauge network evaluation considering the altitude of rain gauge. *Journal of Wetlands Research*, *16*(1), 113-124.

Leung, J. K., & Law, T. C. (2002). Kriging analysis on Hong Kong rainfall data. *HKIE Transactions*, *9*(1), 26-31.

Liang, S., & Wang, J. (Eds.). (2019). *Advanced remote sensing: terrestrial information extraction and applications*. Academic Press.

Loucks, D. P., & Van Beek, E. (2017). *Water resource systems planning and management: An introduction to methods, models, and applications*. Springer.

Lowe, S. A. (2016). An energy and mortality impact assessment of the urban heat island in the US. *Environmental impact assessment review*, *56*, 139-144.

Lyu, F., Wang, S., Han, S. Y., Catlett, C., & Wang, S. (2022). An integrated cyberGIS and machine learning framework for fine-scale prediction of urban Heat Island using satellite remote sensing and urban sensor network data. *Urban Informatics*, *1*(1), 6.

Maier, R., Krebs, G., Pichler, M., Muschalla, D., & Gruber, G. (2020). Spatial rainfall variability in urban environments—High-density precipitation measurements on a city-scale. *Water*, *12*(4), 1157.

Miller, S. T. K., Keim, B. D., Talbot, R. W., & Mao, H. (2003). Sea breeze: Structure, forecasting, and impacts. *Reviews of geophysics*, *41*(3).

Mishra, A. K. (2013). Effect of rain gauge density over the accuracy of rainfall: a case study over Bangalore, India. *SpringerPlus*, *2*, 1-7.

Moss, M. E., & Tasker, G. D. (1991). An intercomparison of hydrological network-design technologies. *Hydrological Sciences Journal*, *36*(3), 209-221.

Muller, C. L., Chapman, L., Grimmond, C. S. B., Young, D. T., & Cai, X. (2013). Sensors and the city: a review of urban meteorological networks. *International Journal of Climatology*, *33*(7), 1585-1600.

Niedźwiedź, T., Łupikasza, E. B., Małarzewski, Ł., & Budzik, T. (2021). Surface-based nocturnal air temperature inversions in southern Poland and their influence on PM10 and PM2. 5 concentrations in Upper Silesia. *Theoretical and Applied Climatology*, *146*(3-4), 897-919.

Nikolopoulos, E. I., Borga, M., Creutin, J. D., & Marra, F. (2015). Estimation of debris flow triggering rainfall: Influence of rain gauge density and interpolation methods. *Geomorphology*, *243*, 40-50.

Notaro, V., Fontanazza, C. M., Freni, G., & Puleo, V. (2013). Impact of rainfall data resolution in time and space on the urban flooding evaluation. *Water science and technology*, *68*(9), 1984-1993.

Ochoa-Rodriguez, S., Wang, L. P., Gires, A., Pina, R. D., Reinoso-Rondinel, R., Bruni, G., ... & ten Veldhuis, M. C. (2015). Impact of spatial and temporal resolution of rainfall inputs on urban hydrodynamic modelling outputs: A multi-catchment investigation. *Journal of Hydrology*, *531*, 389-407.

Oke, T. R. (1973). City size and the urban heat island. *Atmospheric Environment (1967)*, *7*(8), 769-779.

Parliari, D., Cheristanidis, S., Giannaros, C., Keppas, S. C., Papadogiannaki, S., de'Donato, F., ... & Melas, D. (2022). Short-term effects of apparent temperature on cause-specific mortality in the Urban Area of Thessaloniki, Greece. *Atmosphere*, *13*(6), 852.

Potgieter, J., Nazarian, N., Lipson, M. J., Hart, M. A., Ulpiani, G., Morrison, W., & Benjamin, K. (2021). Combining high-resolution land use data with crowdsourced air temperature to investigate intra-urban microclimate. *Frontiers in Environmental Science*, 385.

Puygrenier, V., et al. "Investigation on the fine structure of sea-breeze during ESCOMPTE experiment." *Atmospheric Research* 74.1-4 (2005): 329-353.

Rizwan, A. M., Dennis, L. Y., & Chunho, L. I. U. (2008). A review on the generation, determination and mitigation of Urban Heat Island. *Journal of environmental sciences*, *20*(1), 120-128.

Roe, G. H. (2005). Orographic precipitation. *Annu. Rev. Earth Planet. Sci.*, *33*, 645-671.

Sakai, A., & Larcher, W. (2012). *Frost survival of plants: responses and adaptation to freezing stress* (Vol. 62). Springer Science & Business Media.

Santamouris, M., Cartalis, C., Synnefa, A., & Kolokotsa, D. (2015). On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review. *Energy and buildings*, *98*, 119-124.

Schroeer, K., Kirchengast, G., & O, S. (2018). Strong dependence of extreme convective precipitation intensities on gauge network density. *Geophysical Research Letters*, *45*(16), 8253-8263.

Shafizadeh-Moghadam, H., Weng, Q., Liu, H., & Valavi, R. (2020). Modeling the spatial variation of urban land surface temperature in relation to environmental and anthropogenic factors: a case study of Tehran, Iran. *GIScience & remote sensing*, *57*(4), 483-496.

Shope, C. L., & Maharjan, G. R. (2015). Modeling spatiotemporal precipitation: Effects of density, interpolation, and land use distribution. *Advances in Meteorology*, *2015*.

Simpson, J. E., Mansfield, D. A., & Milford, J. R. (1977). Inland penetration of sea‐breeze fronts. *Quarterly Journal of the Royal Meteorological Society*, *103*(435), 47-76.

Singh, K. P., Ramamurthy, G. S., & Terstriep, M. L. (1986). *Illinois streamgaging network program: Related studies and results* (Vol. 94). Illinois State Water Survey.

Smith, R. B., & Barstad, I. (2004). A linear theory of orographic precipitation. *Journal of the Atmospheric Sciences*, *61*(12), 1377-1391.

Sofiza Abu Salleh, N., Aziz, M. K. B. M., & Adzhar, N. (2019, November). Optimal Design of a Rain Gauge Network Models. In *Journal of Physics Conference Series* (Vol. 1366, No. 1, p. 012072).

Tan, J., Zheng, Y., Tang, X., Guo, C., Li, L., Song, G., ... & Chen, H. (2010). The urban heat island and its impact on heat waves and human health in Shanghai. *International journal of biometeorology*, *54*, 75-84.

Tavakolifar, H., Shahghasemi, E., & Nazif, S. (2017). Evaluation of climate change impacts on extreme rainfall events characteristics using a synoptic weather typing-based daily precipitation downscaling model. *Journal of Water and Climate Change*, *8*(3), 388-411.

US Environmental Protection Agency. (2002). Guidance on choosing a sampling design for environmental data collection.

Wadoux, A. M. C., Heuvelink, G. B., Uijlenhoet, R., & De Bruin, S. (2020). Optimization of rain gauge sampling density for river discharge prediction using Bayesian calibration. *PeerJ*, *8*, e9558.

Whiteman, C. D. (1982). Breakup of temperature inversions in deep mountain valleys: Part I. Observations. *Journal of Applied Meteorology and Climatology*, *21*(3), 270-289.

Whiteman, C. D., Bian, X., & Zhong, S. (1999). Wintertime evolution of the temperature inversion in the Colorado Plateau Basin. *Journal of Applied Meteorology and Climatology*, *38*(8), 1103-1117.

WMO. (1985). Review of requirements for area-average precipitation data, surface-based and space-based estimation techniques, space and time sampling, accuracy and error; data exchange.

Zhang, X. Q. (2016). The trends, promises and challenges of urbanisation in the world. *Habitat international*, *54*, 241-252.