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Development of a Low-Cost Weather Station to Measure *in Situ* Essential Climate Variables

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Abstract: A weather station is proposed especially designed for developing countries, and to meet the standards of the international scientific community making research on the earth system. The station would measure *in situ* several ECV (essential climate variables). These data may enable an agricultural breakthrough in countries lacking meteorological infrastructure, help in climate change monitoring, and facilitate diffusion of wind energy. A pre-feasibility analysis is presented. It appears interesting that the station is supplied by a social enterprise. A research to establish the best shelter design using computational fluid dynamics is also reported. The criterion is the accuracy with which the surface air temperature is reproduced inside the shelter. A design following recommendations by the WMO (World Meteorological Organization), a smaller design with identical geometry, and two alternative small designs are analyzed. All four designs are simulated in PVC, natural rubber and wood, with and without white paint coating. The smaller shelters perform better. The influence of the material, dimensions and design is smaller than that of the white paint. Shelters made of PVC or rubber, and/or in alternative designs, may be more interesting if other criteria are considered, like whether logistics, manufacturing, etc. are more sustainable, easier and/or cheaper.

Key words: Meteorological station, essential climate variable, CFD (computational fluid dynamics), thermal analysis, temperature.

1. Introduction

Many regions of the earth are lacking basic infrastructure necessary to measure atmospheric parameters like surface air temperature, rainfall, or wind speed and direction. For developing countries, the high cost of commercial weather stations is one of the main causes impeding implementation of proper meteorological networks. The ultimate goal of this research is to develop a small-size, low-cost, robust weather station especially designed for developing countries, and to meet the requirements and standards of the international scientific community and international organizations involved on research on the earth system and climate change. The station would measure *in situ* some ECV (essential climate variables)[1], valuable for many industries and services worldwide, namely:

1. First benefit: A breakthrough in agricultural production in countries lacking proper meteorological infrastructure [1], since it would be possible to estimate the evapotranspiration ET_0 [2] and the dew temperature, enabling an optimization of irrigation systems and water input into crops.

2. Second benefit: Availability of time series of satellite, airborne and *in situ* observation data, covering at least several decades, is essential for the monitoring, characterization and prediction of changes in the earth system (e.g., to validate climate models, which provide essential information for

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[1] GCOS (The Global Climate Observing System) ECV are based on a priority list of variables to be observed systematically, in order to properly monitor the climate change. There are 45 ECV organized in atmospheric, oceanic and terrestrial categories [11, 12].

decision-making processes related to climate change). Continuity of consistent and calibrated observations is the major requirement, and calibration and inter-calibration of the time series of observation data and validation of derived products are a pre-requisite for the consistency and efficient use of these data [3]. In this sense, the station would:

(1) Bridge some of the existing gaps *in situ* ECV observation, e.g., land surface wind speed/direction (Fig. 1). This problem affects all countries, but is particularly important in developing countries[2];

(2) Allow for calibration and validation of satellite data and derived products. While *in situ* observations are essential (e.g., to obtain data that cannot be measured from space), earth observation satellites are the only realistic means to obtain the necessary global coverage. With well-calibrated space-based measurements, space-based sensors would become a key tool for climate monitoring.

3. Third benefit: Availability of time series of *in situ* observations of wind speed and direction on the land surface, covering at least several years, is essential for installation and optimization of wind turbines, and also for establishing appropriate runway orientations for an aerodrome in a given location. Energy systems and services are essential to social and economic development [4], but the current structure of the global energy system is not compatible with sustainable development [5]. Much wider and greater energy inputs and access to modern energy services are critical in achieving Millennium Development Goals, because this contributes effectively to the improvement of well-being [4]. The station would enable widespread wind data acquisition, facilitating the diffusion of wind energy.

This work presents a brief pre-feasibility analysis of the proposed meteorological station and reports a preliminary research to determine the best shelter design, as a first step in the overall design of the station. Following this introduction, Section 2 presents the pre-feasibility analysis. Section 3 presents the methodology used in this research. In Section 4, the results are presented and discussed, while Section 5 reviews briefly some considerations on data storage and transmission. Finally, the conclusions are exposed in Section 6.

2. Pre-feasibility Analysis

The needs for climate data have been manifested by parties of the UNFCCC (United Nations Framework Convention on Climate Change). These parties have addressed the needs and priorities in relation to observations, especially in developing countries 2. There is agreement in the following [3]:

1. Data should be accessible to all: Data should be fully and openly accessible at the minimum cost and available with the minimum time delay.

2. Data should be useful: Data should be standardized, robust and ready-to-use.

3. Data should be transparent: Transparency should be granted through data access policies in agreement with the GEOSS (Global Earth Observation System of Systems) Data Sharing Principles.

4. Traceability indicators describing the information and its origin should be defined, and benchmarking approaches should be applied, for decision-makers to have high confidence in the integrity of the information and in its origin.

The GEOSS Ten-Year Implementation Plan acknowledges the importance of data sharing in achieving the GEOSS vision and anticipated societal benefits. The plan establishes the GEOSS Data Sharing Principles [6]: (1) there will be full and open exchange of data, metadata and products shared within GEOSS, recognizing relevant international instruments

[2] Limited progress has been achieved on *in situ* ECV data acquisition systems in developing countries and even a decline has been detected in some regions [13]. UNFCCC (The United Nations Framework Convention on Climate Change) also noted limited progress in filling *in situ* observation gaps in developing countries. According to the IPCC (Intergovernmental Panel on Climate Change) there is a significant “lack of geographic balance in data and literature on observed changes, with marked scarcity in developing countries” [14].

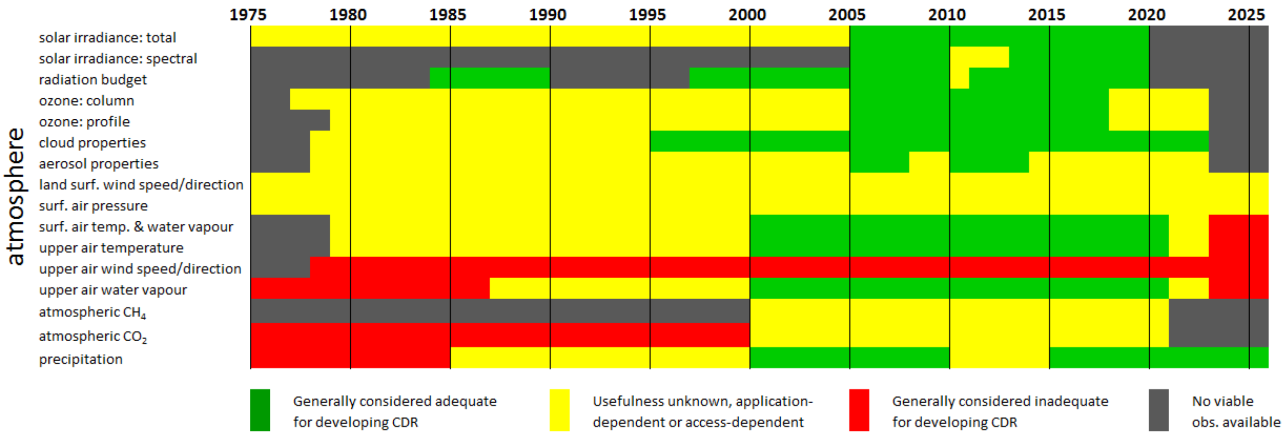

Fig. 1 Gap analysis for ECV (essential climate variables) data records from 1975 to 2025, where CDR stands for climate data records [3].

and national policies and legislation; and (2) all shared data, metadata and products will be made available with minimum time delay and minimum cost, and being free of charge or no more than cost of reproduction will be encouraged for research and education.

2.1 Sectors to Which the Proposed Station is Aimed and Potential Clients

The proposed station may enable implementation of extensive meteorological networks, especially in developing countries. The data recorded by the stations would be valuable for many sectors of human activity, enabling new economic sectors, activities and services to flourish and growth, and fostering a more sustainable development. The potential users of the station would be governments, public administrations and institutions, public and private companies, NGO (non-governmental organization), farmers, and transnational or intergovernmental organizations like the GCOS (Global Climate Observing System), the FAO (Food and Agriculture Organization), the WCRP (World Climate Research Program), the WMO (World Meteorological Organization), etc..

2.2 Situation of the Market in Relation to the Proposed Station

There is a wide variety of small meteorological stations in the market. These stations, supplied by large companies, are typically high-technology and high-performance products specially designed for the domestic and agricultural markets mainly in developed countries. These products are not generally thought for satisfying the needs of developing countries, and their relatively high costs do not match limited budgets. On top, many developing countries, facing at present day critical problems like famine, violence, diseases and degradation of the environment, aggravated by a persistent lack of resources, do not consider meteorology a priority. Therefore, the niche in these markets exists due to the high cost of commercial products equivalent to the proposed station.

2.3 Guidelines and Milestones to Obtain Profitability

The proposed station could be supplied by a social enterprise, giving rise to an inclusive business, an economically profitable initiative, featuring social and environmental responsibility, which will make use of capitalistic strategies and market mechanisms to fight poverty, and improve human well-being, the society and/or environmental standards. Unlike a conventional enterprise, profitability in a social enterprise is critical only so as to ensure the long-term survivability for the company to accomplish its philanthropic goals. To be considered a social enterprise, and thus to have access to or to be eligible for some of the associated advantages, the company would have to meet particular requirements specified by target public administrations. Some examples of such requirements are as follows:

1. The unit price of the station should be incremental respect to customer income: While for developed countries, the price would be adjusted to market prices, for developing countries, the price would be significantly lower than market prices, or even lower than the manufacturing cost. The losses must then be counterbalanced with fiscal advantages and financial incentives and support that social enterprises may be granted by public institutions and administrations, private foundations and donors, social banks, etc. Also, social enterprises may raise funds from grants for cooperation and development projects, or for projects involving climate change fight, renewable energies, etc.

2. The local community (e.g., local cooperation institutions, administrations, families, NGO) should participate in the value chain:

(1) As suppliers of prime materials, preferably local materials;

(2) As manufacturers and/or agents that add value to the station; and

(3) As sellers/distributors of the station, maintenance/customer service providers, etc., making easier and/or cheaper aspects like logistics, shipping and manufacturing, and making the business more sustainable, user-friendly, etc.

3. The station should enable access of developing countries to new business opportunities and ways to improve well-being.

The UNFCCC calls for supporting programmes, networks, and organizations in defining, conducting, assessing, and financing research, systematic observations and strengthening of systematic observation and research capacity (in particular in developing countries). The GEOSS supports the development of observational capabilities for ECV identified by the international scientific community which is necessary to understand the climate change [3]. Thus, either the UNFCC, the GEOSS or both organizations may support the development and implementation of the station.

3. Methodology

The procedure followed in this research emulated the typical steps in CFD (computational fluid dynamics) analysis: (1) creation of the 3D shelter geometries and the simulation domain; (2) meshing (discretization) of the domain; (3) definition of the physics of the problem and the boundary conditions; (4) solution of the fluid dynamics and thermal problem; (5) post-processing and analysis of the results obtained for each shelter design.

3.1 Studied Shelter Configurations

As a first step in the development of the proposed station, four different shelter designs have been studied using and SolidWorks[3]: first, a design based on recommendations by the WMO (shelter #1, the Stevenson’s screen) [7], followed by a smaller design with identical geometry (shelter #2, shown in Fig. 2). The objective was to assess whether smaller dimensions (more convenient for reducing manufacturing costs) result in better performance. Namely, the dimensions of shelter #1 and #2 were (909 × 580 × 560) mm^3 and (685 × 200 × 200) mm^3, respectively. Two alternative shelter designs were also analysed: shelters #3 and #4, shown in Figs. 3 and 4, respectively. These geometries follow some general features of the Stevenson’s screen (i.e., double-layer floor, roof, and lateral walls), but present a different configuration of the lateral walls and, particularly, the ventilation orifices. The objective was to assess the effect on performance of these simpler configurations of lateral walls. Since shelter #2 was proved to perform better than shelter #1, as shown in Section 4, shelter #3 and shelter #4 have similar dimensions to shelter #2. All four designs were simulated in three

[3] Commercial multiphysics software from Dassault Systèmes SolidWorks Corp., Waltham, MA (USA).

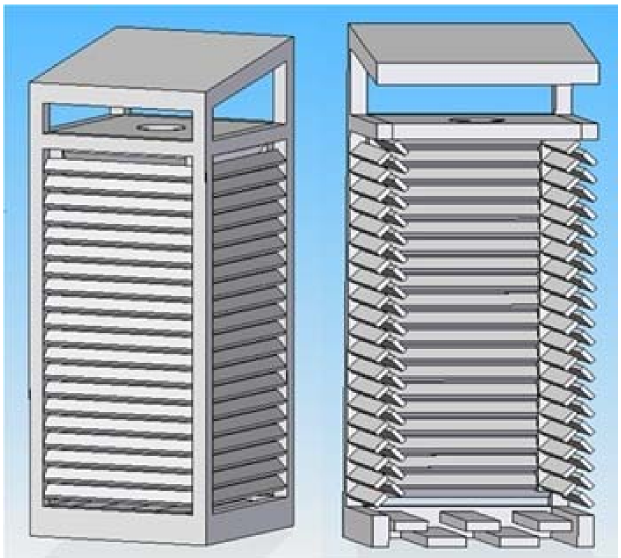

Fig. 2 3D view and cross-section of shelter #2.

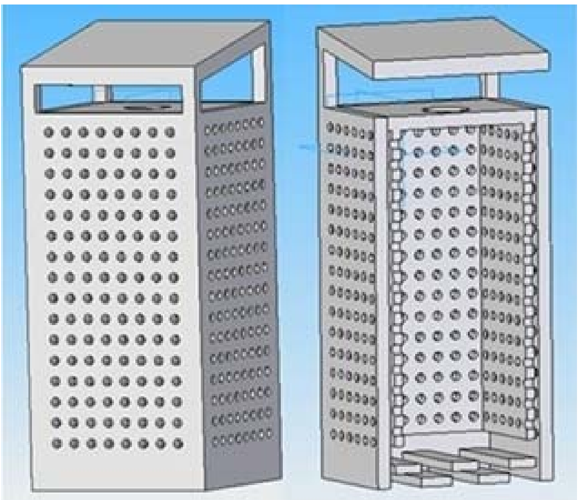

Fig. 3 3D view and cross-section of shelter #3.

different materials (PVC (polyvinyl chloride), natural rubber and wood), with and without white paint coating. The objective was to assess the effect of the material and paint on performance. PVC was considered due to its low weight and cost (a number of commercial shelters are nowadays made of PVC). Natural rubber was considered because old used tires pose a challenge for waste management. If rubber was proved to be a good material for mass production of shelters, this would be an interesting option for recycling tires. Finally, wood was considered because many shelters are made of this material, which is a good thermal insulator. Iroko wood from Africa, was

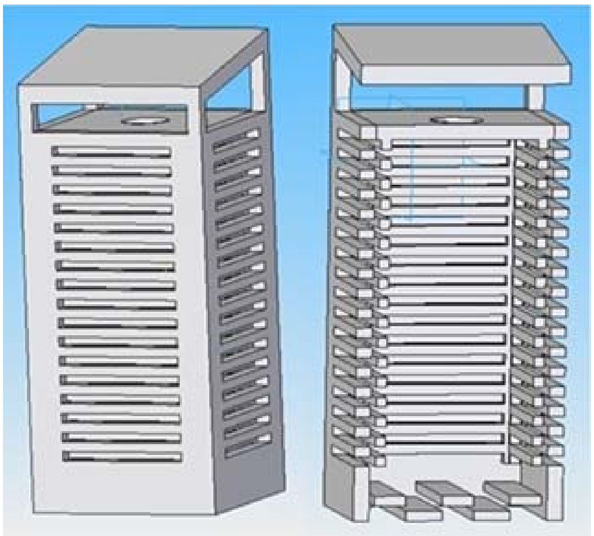

Fig. 4 3D view and cross-section of shelter #4.

chosen for proximity to potential customers. Not having to import material from distant locations reduces shipping costs.

3.2 Definition of the Physics of the Problem and Boundary Conditions

In this work, focus is placed on surface air temperature. Accordingly, the criterion to measure the performance of each shelter design was the accuracy with which this ECV is reproduced in a hypothetical reference position of the sensor inside the weather station. The input parameters for the SolidWorks simulations were defined with the purpose of simulating shelter performance in the most demanding scenario. For measuring accurately surface air temperature in target developing countries, since the critical issue is heat evacuation to prevent overheating of the air mass within the shelter (leading to wrong temperature and humidity readings), extreme temperature and solar radiation were simulated in this research:

1. Incident solar radiation: defined by:

a. Geographical location: Sabha, Libya (27°02′ North, 14°26′ East).

b. Date and time: July 15 at noon (12 LT).

2. Properties of shelter materials and white paint: PVC and rubber were already available in the materials database of SolidWorks, while the properties

of wood were introduced manually. For PVC, we used the optical properties of white Tedlar® plastic [8]. For wood, we used optical properties averaged from those of dark wood and oak. For the white paint, we used optical properties averaged from those of commercial paints (Table 1) [9].

3. Temperature: The surface air temperature was set to 45 °C, and the initial temperature in the shelter was 20 °C, with 20% of moisture.

4. Boundary conditions: Two of the control volume faces (all far from the shelter) were defined as velocity inlet and pressure outlet[4], and the remaining faces as walls.

5. Wind speed: To assess the effect of this parameter on performance, an almost no-wind condition and a moderately strong wind condition were simulated (wind speed 2 m/s and 10 m/s, with no vertical component, respectively).

4. Results and Discussion

In this section, the results obtained from the simulations are presented and discussed, and the performances of the shelters are compared to establish the best shelter design. Table 2 shows the temperature in the reference position for the studied shelters, in PVC, natural rubber and wood, for wind speed of 2 m/s and 10 m/s, respectively. In view of the results shown in Table 2, it is evident that, if the shelter is painted in white, the temperature in the reference position is significantly lower (around 4 °C to 5.5 °C), and thus closer to the surface air temperature (45 °C), compared to the analogue cases with no white-paint coating. In general, the performance is better for lower wind speed: the temperature in the reference point is 0.45 °C lower in average, compared to higher wind speed. This is due to the high temperature of the ambient air, such that higher wind speed (causing a larger mass flow of warm air to enter the shelter) leads to increased internal overheating. Regarding the studied materials, wood performs the best in all the studied conditions, but is followed very closely by PVC. The shelters made of rubber are by far the worst performing, but the differences become very small when the materials are painted in white.. Thus, the effect of the paint is dominant, and the material is not so critical when it is coated with white paint.

In all the studied conditions, shelter #2 performs better than shelter #1 (the shelter based on recommendations by WMO). Namely, for shelter #2, the temperature in the reference position is 1.17 °C (3.03 °C) lower in average with (without) white paint coating, compared to shelter #1. In view of these results, shelter #3 and shelter #4 were simulated with dimensions similar to shelter #2. No significant differences in performance are observed between these small shelters, but again shelter #2 performs better. Nonetheless, shelters made of PVC or rubber instead of wood, and/or with alternative designs like shelters #3 and #4, may be more interesting if we also consider other criteria.

A priori, shelter #1 was expected to perform the best because a larger shelter volume implies a larger mass of air within the shelter and thus, for a same energy input from solar radiation, the air temperature would increase less compared with that within smaller shelters. However, the results show the opposite. A plausible explanation is that the increased surface exposed to solar radiation by shelter #1 is dominant and causes a comparatively increased warming. Figs. 5 and 6 show, respectively, the temperature contours for the less performing case (highest observed temperature in the reference position, 56.87 °C) and the most performing case (closest value to the surface air temperature in the reference position, 46.37 °C)[5].

[4] In CFD simulations, using the boundary condition settings termed “velocity inlet” and “pressure outlet” is recommended when working with incompressible flows, e.g., very low subsonic flows like in this problem.

[5] Actually, the temperature in the reference position closest to 45 °C occurs for a rubber-made shelter. This is clearly out of the observed trends and the expected results. Thus, this particular result is disregarded in this analysis since probably the error in the simulation is significantly large.

Table 1 Properties of shelter materials used in this research.

Properties	Units	PVC	Rubber	Wood
Density	kg/m^3	1,379	1,200	700
Thermal conductivity	W/m·K	0.16	0.15	0.10
Specific heat	J/kg·K	1,004	1,000	1,081
Optical properties	Paint	Tedlar®	Rubber	Wood
Emittance	0.90	0.90	0.95	0.90
Absorptance	0.20	0.40	0.95	0.60

Table 2 Temperature in the reference position for the studied shelters, in PVC, natural rubber and wood, at a wind speed of 2 m/s and 10 m/s.

Material	Paint	Wind speed (m/s)	Shelter #1 (ºC)	Shelter #2 (ºC)	Shelter #3 (ºC)	Shelter #4 (ºC)
PVC	No	2	52.58	49.65	50.38	50.10
	No	10	53.15	50.42	50.51	51.01
	Yes	2	47.32	47.25	46.96	46.92
	Yes	10	48.10	46.71	47.15	47.26
Rubber	No	2	56.14	52.28	52.81	52.54
	No	10	56.87	53.08	53.13	53.76
	Yes	2	47.45	45.93	47.35	46.87
	Yes	10	48.49	46.63	47.06	47.21
Wood	No	2	52.27	50.43	50.29	49.84
	No	10	52.76	50.12	50.32	50.64
	Yes	2	47.36	46.37	46.84	46.71
	Yes	10	47.73	46.38	46.92	47.04

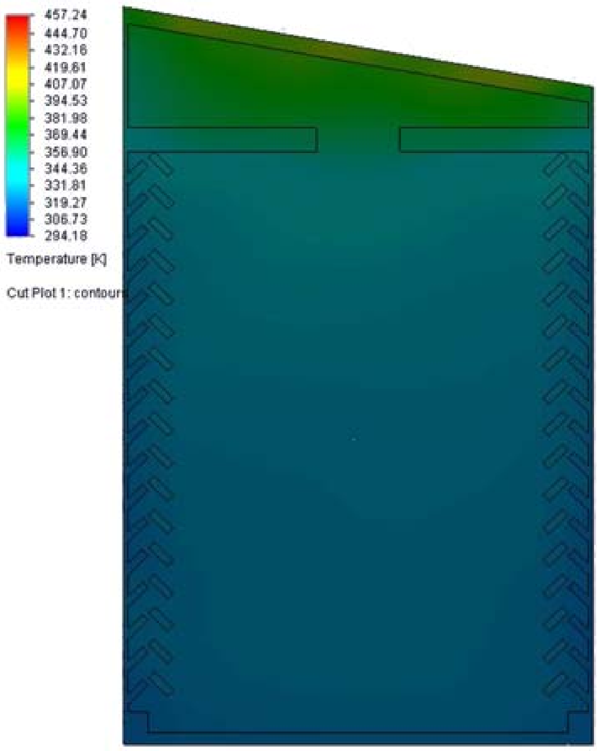

Fig. 5 Temperature contours for the worst performing case: shelter #1, in natural rubber without white paint coating, for wind speed 10 m/s.

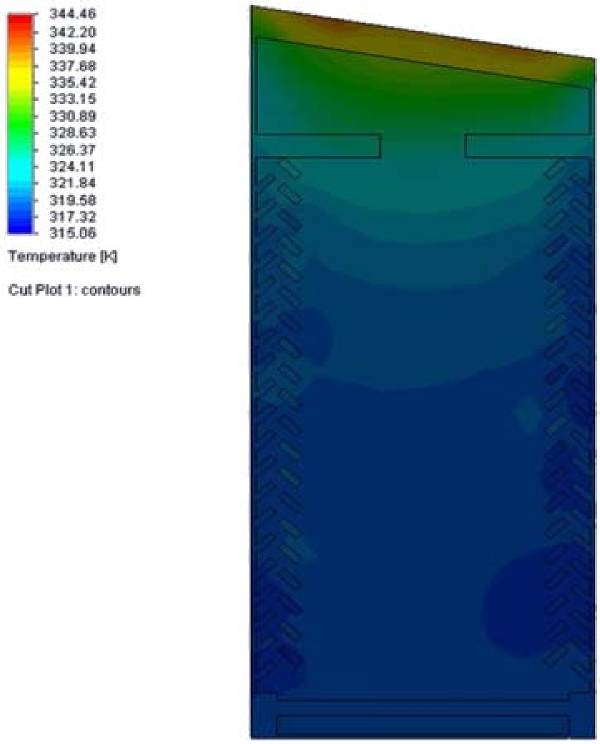

Fig. 6 Temperature contours for the best performing case: shelter #2, in wood with white paint coating, for wind speed 2 m/s.

5. Data Storage and Transmission

As mentioned in Section 2, acquired data should not only be useful, of course, but also transparent and accessible to all at the minimum cost, and should be uploaded to the internet in real time or with high frequency. Several methods for storage and transmission of the ECV data acquired by the proposed station are under consideration:

1. Data transmission to laptop/PC by Wi-Fi: Advantages: advanced data management technologies and wireless data transmission technologies between devices or networks of devices are available. Disadvantages: need for data storage capabilities (data loggers); need for short station-to-laptop/PC distance and energy supply (e.g., for a 100 m range, need for 220 V electric supply); and an operator should visit the station frequently (e.g., on a monthly basis, depending on sampling frequency and storage capacity of the data logger), resulting in low frequency of data uploading on the internet.

2. Data transmission to laptop/PC by Ethernet cable: Advantages: very simple, widely used technology. Disadvantages: need for data storage capabilities (data loggers); need for direct station-to-laptop/PC cable connection and energy supply; and an operator should visit the station frequently, resulting in low frequency of data uploading on the internet.

3. Data transmission directly to the web by means of conventional mobile phones: Advantages: acquired data may be uploaded to the internet in real time or almost; and second hand mobile phones may be recycled for this purpose. Disadvantages: need for energy supply; and need for proximity of the station to a repeater.

4. Data transmission directly to the web by means of satellite-based systems: Advantages: acquired data may be uploaded to the internet in real time or almost, and free of cost, by means of systems like Argos[6] [10]. Disadvantages: need for increased energy supply.

6. Conclusions

The proposed weather station features competitive advantages respect to equivalent commercial stations in large markets (e.g., developing countries) and in particular applications (e.g., networks to monitor climate change). An idea to explore is that the station is supplied by a social enterprise. A research was conducted to establish the best shelter to operate in extreme temperature and solar radiation conditions. Four designs were simulated in PVC, natural rubber and wood, with and without white paint coating. The conclusions are:

1. The smaller shelters (#2, #3 and #4) perform better than that based on recommendations by the WMO (shelter #1), possibly because the increased surface exposed to solar radiation by the latter causes higher internal warming.

2. The design based on recommendations by the WMO but in smaller dimensions (shelter #2) is the best performing.

3. Shelters made of wood perform better than those made of PVC or rubber.

4. Due to the high temperature of the ambient air, the performance is better for lower wind speed, as higher wind speed leads to increased internal overheating.

5. The shelter material, dimensions and design have a significantly smaller effect on performance than the white paint, and thus are not so critical in achieving the best performance compared to an adequate coating.

6. Shelters made of PVC or rubber instead of wood, and/or in alternative designs like shelters #3 and #4, may be more interesting if other criteria are taken into account, like whether they make more sustainable, easier and/or cheaper logistics, manufacturing, etc..

[6] Argos is a satellite-based system which collects, processes and disseminates climate data from fixed and mobile platforms worldwide. This system was implemented by the CNES (Centre National d'Etudes Spatiales), the US NOAA (National Oceanic and Atmospheric Administration), and the US NASA (National Aeronautics and Space Administration). At present day, many remote automatic weather stations report acquired data via Argos.

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