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Multiscale Characterization of French Polynesia Climate for Dynamic Simulation of Buildings

Franck Lucas, Marania Hopuare, Charlotte Besnard and Pascal Ortega

Laboratoire GePaSud, Université de la Polynésie française, FAA'A Tahiti (French Polynesia)

Abstract

Performance assessment of buildings in tropical climates requires annual meteorological data files for an “energy approach” of air-conditioned buildings. It also requires localized climatic sequences allowing a real estimation of the natural ventilation potential of the sites for a "comfort" approach of non-air-conditioned buildings. The absence of this type of weather data in Polynesia considerably limits designer analysis means. This article presents two methods to establish meteorological sequences for both energy and comfort approaches. The first aims developing annual typical weather files from a reduced number of ground measurements. The missing meteorological variables are completed using a global to diffuse decomposition model of the solar irradiance. The second is based on a mesoscale climate model and a downscaling to obtain a characterization of localized natural ventilation potential and climatic data on a fine mesh. The weather sequences generated are used to perform energy calculation for air conditioned classrooms and wind potential and comfort assessment for cross ventilated classrooms of a primary school located in French Polynesia.

Keywords: *Weather data, tropical climate, dynamic simulations, natural ventilation.*

1. Introduction

The design of very low energy buildings or net zero energy buildings requires sophisticated analysis and forecasting tools. For assessing energy performance of buildings during the design phase, dynamic thermal simulation codes are now the most commonly used tools. These codes simulate building behavior using a physical description and weather data. Design methods have evolved in the last decades. At the beginning, the buildings performance analysis supposed steady states outside conditions, for example: the method of "outside based conditions" or the “Degree Days method". The more recent dynamics simulation tools propose building energy calculation on hourly or even lower time step. They account for a large number of input variables and parameters. Nevertheless, there are significant differences between energy performance of buildings estimated by dynamic simulation codes during the design phase and the real performance of the operating building. In his thesis, C Spitz (2012) evaluates all sources of uncertainty between the design and operating phase. Of course, "Design" phase calculations generate errors due to the assumptions on the building and its components description. But Spitz noted that the quality of meteorological data used in numerical simulations is also an important source of error that can cause deviations of up to 30% of the estimated consumption of an air conditioning system. To be representative of the building external loads meteorological data used by designers must meet specific standards. Several types of data can be used:

- "multi-year" data sets: they bring together all the meteorological data required for the simulation of buildings and over several years. They are complicated to use because of the large number of values they have. Example: SAMSON database 1961-1990 (NCDC 1993).

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- Typical weather annual files: the most commonly used data to estimate the average performance of a building. Example: Typical Meteorological Year (TMY), Weather Year for Energy Calculation (WYEC), Test Reference Year (TRY)...
- Short representative weather sequences: They can be used to study extreme weather conditions (very hot or cold, very sunny or very wet ...), localized weather (considering the influence of the relief on meteorology), the design of specific technical solutions (studying the potential for natural ventilation of a building) or the design of building components ("design day" sequences for the sizing of air conditioning systems).

The type of weather data to use and therefore generate, depends on the objectives for the design process. The French Polynesia like all island territories is facing a difficult situation because of energy supply difficulties and operating constraints of a non-interconnected electricity grid. The ambitious political commitment is to achieve a 50% renewable energy for electricity supply in 2020. Thus, an energy regulation is being drafted. This thermal regulation will target energy ratio for air-conditioned buildings but will also state minimum comfort performance for naturally ventilated buildings. In both cases, specific weather data are needed. For energy approach, annual weather sequences will assess the energy consumption of buildings. Short sequences are dedicated to the comfort evaluation. This paper presents the study to provide both types of meteorological data for French Polynesia. The first part addresses the creation of typical meteorological year for the energy approach. The chosen method uses a reduced meteorological database obtained from ground measurements. For the "comfort" approach, it is necessary to consider the high spatial variability of the meteorological inputs. In the second part, we use a climatic model to generate climate data on a fine mesh (around 1.3 km) compatible with the needs of dynamic simulations of buildings operating in natural ventilation. These weather sequences will then be applied to energy calculation and comfort evaluation for air conditioned classrooms and cross ventilated classrooms in French Polynesia.

2. Energy calculation with typical annual weather file

2.1 File Constitution

In preparation for the implementation of a thermal regulation in French Polynesia, the climatic sequences that seem most important and most urgent are the annual weather files. These sequences are very often used by building designers. They bring together all hourly climate variables needed for dynamic simulation of buildings for a period of one year. There are several possibilities to obtain these annual typical sequences. The first is based on the selection of the most representative month made in a database developed with ground measurements over long periods (between 10 and 30 years). The ground measurements are usually obtained from forecast utilities. For all the French territories, the first 200,000 digital values are provided free of charge for the public institutions by the French forecast utility Meteo France. Beyond, the data are charged. The second method is based on the use of stochastic models that generate time series climate data by extrapolation of measured data by ground stations. These tools are often called "weather generators." Developed by research laboratories since the 1980s (Van Passen, 1979) (Knight, 1990) (Adelard, 2000), (David, 2010), these methods were taken over by private providers for commercial services. Among them, for example Meteonorm (Remund, 2004) and Type 54 from TRNSYS (TRNSYS 2000) are commonly used by designers.

The annual typical weather data sets generated from ground measurements are the most widespread. It has been developed in several formats. The main ones are:

- TRY (Test Reference Year): One of the first weather data sets, developed in 1976.
- TMY (Typical Meteorological Year) developed from TRY format by especially adding global horizontal irradiance data. The TMY dataset includes measurements selected over the periods from 1945 to 1973. It evolved in 1995 in the TMY2 format by adding new weather variables such as direct solar irradiation and using more recent weather data (1961 to 1990). Then, the TMY3 format is built up with even more recent years, up to 2005.
- WYEC (Weather Year for Energy Calculation) were developed by ASHRAE. As for the TMY format, WYEC2 version was made from the WYEC files by adding additional variables, including the characterization of natural lighting.

Drury's study for US climates (Drury 1998) analyzes the estimation of the energy performances of a building according to the type of the weather files used. The performances are compared to the results of simulations with real weather data collected over 30 years. It notes that the climate data used in dynamic simulation of buildings can have a significant influence on the energy performance assessment and concluded by recommending the use of TMY2 formats (or TMY3) and the WYEC2. These two types of data sets are developed by selecting twelve typical meteorological months (TMM) from a multi-year weather database. The difference between the TMY and WYEC files comes with the TMM selection process. For TMY files, Hall (Hall 1978) presents a method for selecting the representative month by analyzing four climatic variables (global solar radiation, air dry temperature, dew-point air temperature, wind velocity) supplemented by daily maximum, daily minimum, daily mean air dry temperature and dew point temperature, daily maximum and daily mean wind speed, and daily global solar radiation. A total of 9 variables are required for the selection process. Each of these variables is weighted according to its importance on the behavior of buildings. The selection of each typical meteorological month in the database is operated following the Finkelstein-Shaffer statistical method. The weighting of each leads to several variants of the method (Hall 1978) (Yang 2007) (Yang, 2011). The drawback of this method is that the weighting process may seem subjective, but above all, it requires a large number of values in the selection database (over 1 million, just for the process selection). Crow (Crow 1984) proposes a method to generate annual typical weather files kinds requiring a smaller database for the selection of the TMM. It is based solely on the study of the dry air temperature. The selected representative month is the one whose monthly average dry bulb temperature is within a range of ± 0.3 ° C of the monthly average dry bulb temperature over the entire database. The choice of the TMM is done according to:

$$dx = \left| \overline{T}_x^i - \overline{T}^i \right| \qquad \text{(eq. 1)}$$

$\overline{T}_x^i$: Monthly average temperatures for the month i in year x.

$\overline{T}^i$: Monthly average temperatures for every month i on the entire database.

The selection process is carried out using only the values of the monthly average temperature over a period of 10 to 30 years. Once the TMM selection made, the values bought from the forecast utility to form the typical annual weather file are limited to the climatic hourly meteorological variables of the selected months. The total number of values required for the selection process is 360 and the file includes less than 44,000 values. On the available database for French Polynesia from 1997 to 2007, the weather typical year was formed by the months given in the table below:

Table 1: Selection of the TMM for the typical annual weather file for French Polynesia.

	J	F	M	A	M	J	J	A	S	O	N	D
Selected year	2006	2002	2001	1998	1997	1998	1999	1998	2001	1998	2004	1999

The meteorological data requested for each TMM are the hourly values of the following variables: dry air temperature, relative humidity, wind speed, wind direction, horizontal global irradiation. From these TMM a "Polynesian typical meteorological year" (PTMY) is then generated using the Matlab conversion tool "Weather xls to TMY2". However, the horizontal diffuse radiation has not been continuously measured by Meteo France in Polynesia and is no longer measured since 2006. It is, therefore, necessary to estimate the diffuse and direct irradiation form the other variables available.

a. Post processing of data: Decomposition of global irradiance

The creation of the typical annual weather file requires determining the diffuse and direct solar irradiance using the global horizontal irradiance. A decomposition model adapted to the climate of Polynesia is then necessary. A number of models are available in the literature. They are generally based on the use of the index clearness index K_t and diffuse fraction K_d given by: $K_t = \frac{G_h}{G_o}$ and $K_d = \frac{G_{d,h}}{G_h}$

Where, G_h is the global horizontal solar irradiance, G_o is the extraterrestrial solar irradiance, and $G_{d,h}$ is the diffuse solar irradiance on a horizontal plane. Among the available models, a pre-selection of four mathematical models was made: Orgill & Hollands (Orgill 1977), Li Lam (Lam 1996), Erbs (Erbs 1982) and Reindl (Reindl 1990). This series model is complemented by the DIRINT model established by Perez (Perez 1992) which is available through a Matlab toolbox or in Python. An additional model was established in this study. It is derived from a correlation established by Meteo France. This latter model, designated "PF model" whose interest is to be simple and valid throughout the interval 0<kt<1 is given by:

$$K_d = \frac{1}{1 + \exp(c_0 K_t + c_1)} \qquad \text{(eq. 2)}$$

c_0 and c_1 are coefficients determined from the diffuse radiation measurements available in Polynesia. The global and diffuse radiation measurements of 1993, 199, 1998 and 1999 were previously screened by the method of BSRN (Long 2002) and c_0 and c_1 are determined by the least squares method. The values obtained are: c_0 =7.122 and c_1 = - 3.511.

The comparison between the measurements for the years when diffuse radiation is available (1993, 1997, 1998, and 1999) and the different models is given in the table below by the value of the relative root mean square error (rRMSE).

Table 2: relative root mean square error between measurements and the different models.

rRMSE (%)	Erbs	Lam & Li	Reindl	Orgill & Hollands	Perez	PF Model
1993	43,0	37,7	43,6	44,3	42,6	32,0
1997	38,0	35,0	39,4	39,8	37,9	27,6
1998	37,3	32,0	38,7	38,8	37,2	25,7
1999	46,4	39,7	48,0	48,2	46,1	30,9
Average	41,175	36,1	42,425	42,775	40,95	29,05

3. Downscaling of climate models

Climate models are a numerical representation of the climate system based on the physical, chemical and biological properties of its components and their interaction processes. It calculates all climatic parameters with a very fine spatial resolution. Weather and Research Forecasting (WRF) climate model (Skamarock 2008) used in this study is a non-hydrostatic limited area model to zoom in on a particular region. WRF is known to have high bias and isn't the best method and model for solar resource assessments. WRF is parameterized with localized convective scheme and thus, can show some discrepancies when assessing solar radiation. Anyway, it is a useful tool for estimating coherent coupled climatic variables (temperature humidity, wind and also radiation). It is, therefore, adapted to provide climatic weather sequences. A realistic parameterization of the subgrid processes has been assessed for French Polynesia by Heinrich. (2009). An experimental comparison is also provided by Hopurare. (2016) which compare small scale prediction with ground measurements.

The method used consists in increasing the resolution within an area of interest by embedding other smaller domains. We get what is called a "downscaling cascade" with increasing resolution nested domains until the desired spatial resolution is obtained in the inner domain (Fig. 1). The spatial resolution is the dimension in km of a grid. The calculations have been carried out on three interacting grids, with horizontal resolutions of 20, 4, and 1.33 km, respectively. The use of a mesoscale model provides short weather sequences to address specific building design issues. This study presents a specific analysis on wind regimes in Tahiti with the objective of a fine-scale characterization of the natural ventilation potential for low energy buildings.

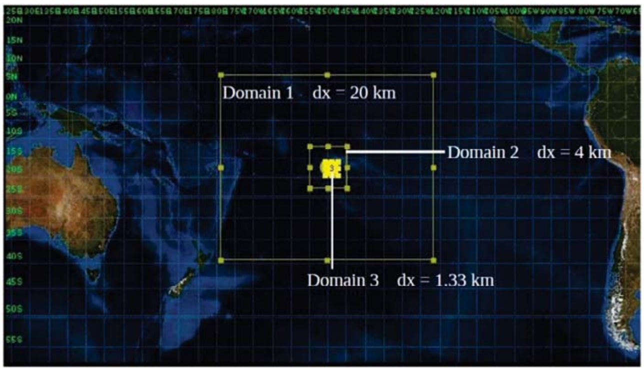


Fig. 1: Diagram of the downscaling with WRF positioned on a large central Pacific area, 20 km resolution and boundary conditions as the Interim reanalysis Era. A second domain is implemented with 4 km resolution centered on French Polynesia. A final domain (domain 3) is implemented in the domain 2 with a resolution of 1.3 km and centered on Tahiti.

3.1 Synoptic wind regimes in Tahiti and Moorea

ERA Interim dataset (http://apps.ecmwf.int/datasets) is a reanalysis product provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). In this study, Era Interim reanalysis data were processed to identify the regimes of most frequent winds in Tahiti. A statistical method on a time series of 31 years (1979 to 2009) has highlighted six main synoptic wind regimes (fig. 2).

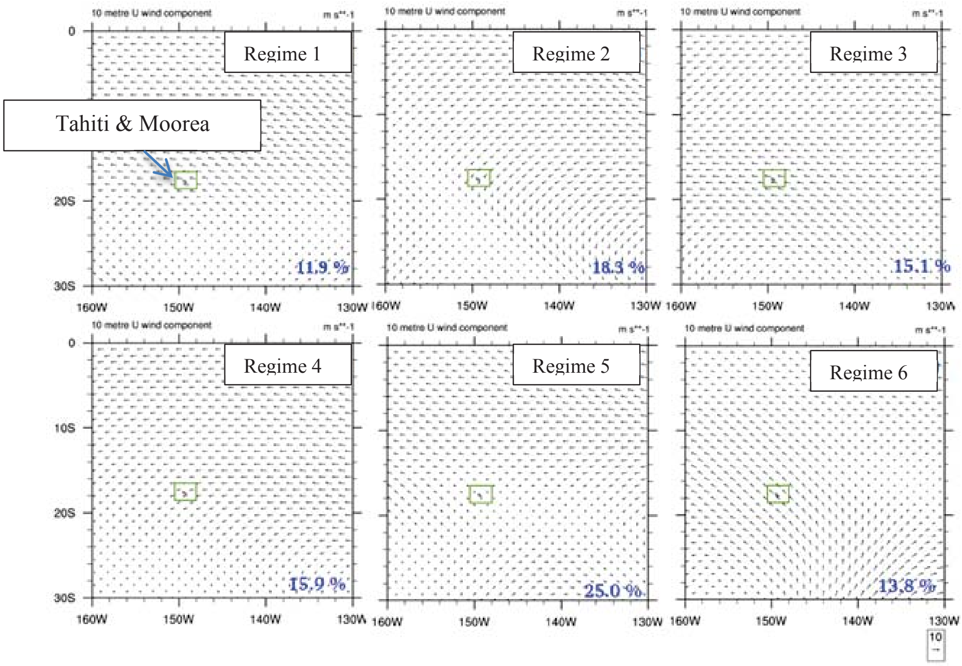


Fig. 2: Synoptic wind regime over French Polynesia obtained with 10m Era Interim reanalysis. The green square locates Tahiti.

The wind regime can be observed both on Tahiti and Moorea Islands with the following frequency of occurrence : Regime 1 (11,9%); Regime 2 (18,3%); Regime 3 (15,1%); Regime 4 (15,9%) ; Regime 5 (25,0%); Regime 6 (13,8%). It appears that at least 25% of a year, for the days of wind regime 5, the potential of natural ventilation is weak. The downscaling technique focused on a restricted area with a higher resolution gives a better estimate of the natural ventilation potential.

3.2 Downscaling

The Era Interim Reanalyzes data for five days for each of the six wind regimes were recovered and applied as boundary conditions of the WRF model domains. This provides five daily weather sequences simulated for each wind regime. The wind cartography for each regime at 1.3 km resolution is obtained by averaging the five days. The consideration of the relief is essential for small scales. Figure 3 shows the orographic description considered by the model for Tahiti and Moorea Islands. The relief description level remains coarse as the maximum altitude considered is 1200m while the highest point of Tahiti is actually 2240 m. However, greater finesse requires very long calculation times.

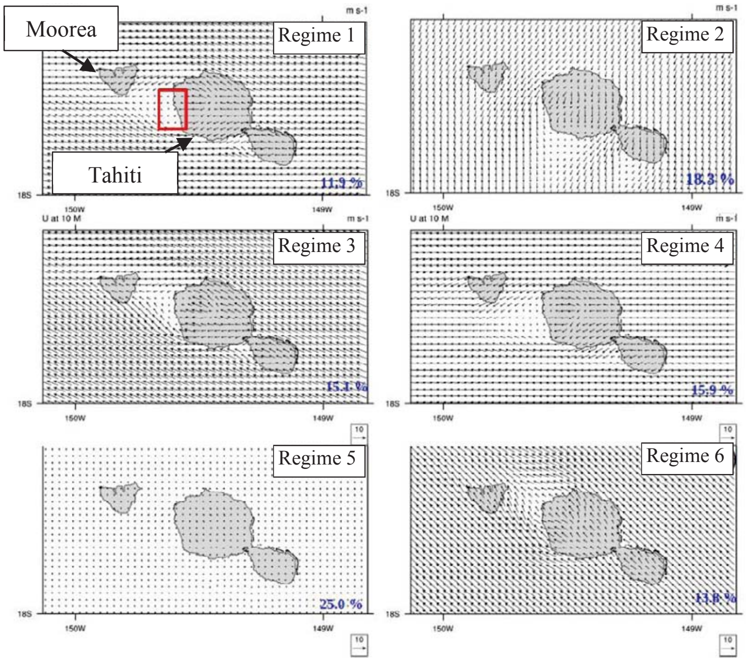


Fig. 3: Wind cartography at fine resolution (1.3 km) focused on Tahiti and Moorea islands and simulated with WRF model for the six wind regimes.

The downscaling with WRF has resulted in a more accurate and reliable wind cartography, showing the windward and leeward contrast for northeast, east and southeast wind regimes and is north. This study has highlighted the potential of natural ventilation throughout the islands of Tahiti and Moorea. It confirms that the main wind direction is South East with a frequency of 40% (regime 1, 3 and 6) and that for synoptic wind regime 5, natural ventilation of building might not be ensured as wind is very low. Moreover, for each coastal area, it evaluates the time percentages with light wind (<2.5 m/s) moderate wind (2.5 <wind <11 m/s) and strong wind (> 11 m/s). The results are as follows:

- North and East Coasts: low wind 25%, moderate wind 34.2%; strong wind 40.8%
- South Coasts: low wind 43.3%, moderate wind 15.9%; strong wind 40.8%
- West Coasts: low wind 67.9%, moderate wind 13.8%; strong wind 19.3%

The downscaling approach provides also fine scale short weather sequences (typically one day) for each wind regime as the example shown on fig 4. These hourly sequences include all meteorological data needed for dynamic simulations of naturally ventilated building.

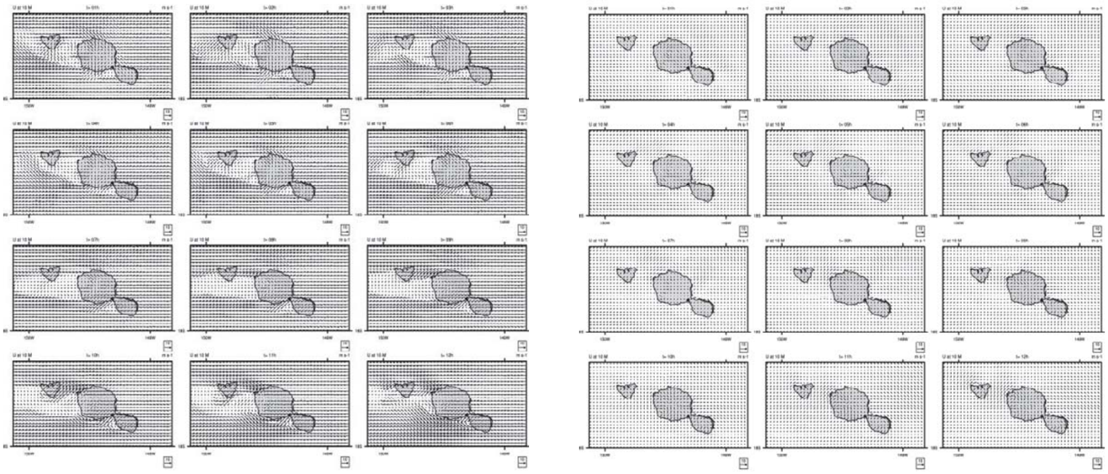


Fig. 4 : Example of hourly fine scale weather sequences. Hour by hour wind cartography for one day (from 0am to 12am) for a windy day (regime 1, on the left) and for day with low wind (regime 5, on the right)

4. Case study : building performance assessment using weather files

To compare the result of the weather sequences presented in this article, dynamic simulations using Energyplus software (Drury 2001) were carried out on a building located at Papetoai on the northwest coast of Moorea Island. (Fig 5). This building is a primary school building including 11 identical classrooms. Some classrooms are air conditioned whereas some are cross ventilated. Two different kinds of simulations where performed. The first simulations aim to compare the energy consumption of the air conditioned classrooms estimated with the PTMY weather file presented above and an annual weather file produced by Meteonorm. The second set of simulation includes simulations for each wind regime in order to estimate the comfort condition for the naturally ventilated classrooms. The one-day weather sequences used are generated hour by hour by the mesoscale model which perform a downscaling over Papetoai. All the simulations assess the classrooms are occupied with 20 people and their design is adapted to the tropical climate (solar shading, roof insulation, large openings equipped with louvers on opposite walls…) and to the operating mode. For the simulations of ventilated classroom the openings are supposed open all the time. For air conditioned rooms, these openings are closed and, according to sanitary regulations, mechanical ventilation provides $15m^3/h$ per person of outside air. The air conditioning system has a rated COP of 2.6 and the set point temperature is 26°C.

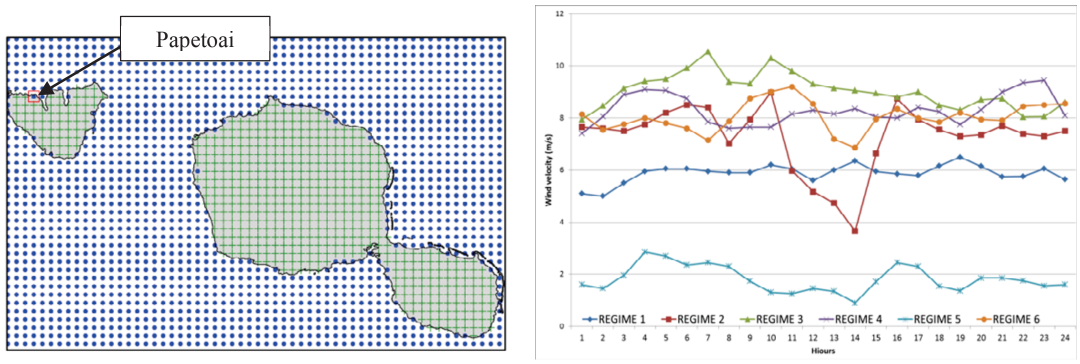


Fig. 5 : Location of the building under study on the north coast of Moorea plotted on the resolution grid of 1.33 km (left) and wind velocities for the short hourly sequences of the 6 wind regimes (right).

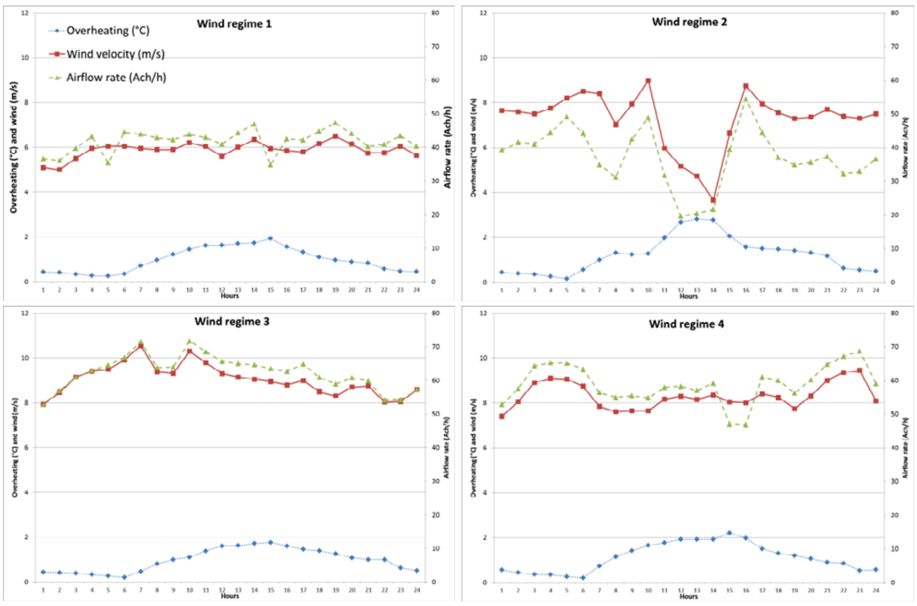
According to the Spitz's study mentioned in the introduction, the comparison of annual weather file will focus on the energy consumption and the cooling demand of the air conditioned classrooms. The output variables studied are the Air Conditioning sizing cooling load (kW), the annual cooling energy (kWh/year) and the annual electricity consumption of the AC system (kWh/year). The results are presented in table 3. The deviations observed are in the range of 10% for annual energies but rise to 18% for the cooling power required in the zone to reach the set point temperature. Consequently, the choice of the input weather file can lead to overestimate the air conditioning system size.

Table 3: Cooling rate, cooling energy and electricity consumption for the two weather files

Weather file	System sizing cooling load (kW)	Annual cooling energy (MJ/year)	Annual electricity consumption of AC system (MJ/year)
Meteonorm	10.5	28 519	12 711
PTMY	8.6	25 603	11 397
Deviation (%)	18.0%	10.2%	10.3%

To ensure comfort in buildings, natural ventilation has two objectives: one is to evacuate thermal loads from the building and the second is to generate air velocity on occupants. The simulations performed for non-air conditioned classrooms aim to verify if natural ventilation can be an effective solution for building design in French Polynesia especially when the potential of ventilation is weak. As mentioned above, synoptic wind is low everywhere on Tahiti and Moorea the days of wind regime 5. It is also low on leeward coasts for all other wind regimes. Then, natural ventilation may not be sufficient to ensure comfort. The building studied being located on the North West coast; one can suppose that it is not exposed to the main synoptic South-East trade winds. However, the specific weather sequences generated for this location show that the wind velocity is most of the time moderate (Fig. 5). For these simulations, the effect of cross ventilation in the classrooms is estimated by the temperature difference between interior and exterior (overheating) and by the airflow rates through the zone. The target values for airflow rates depend on many parameters and among them the main one would be the population habits and their expectation in terms of comfort. Few targets values can be found in the literature for the populations in the islands of the Pacific Ocean. Le Bars (2010) mentions that an average airflow rate of 15 ach/h limits the overheating at only 4 to 5°C for an office building. To reduce the overheating to 2°C the airflow rate must be at least 20 to 30 ach/h. For classrooms, the same airflows and overheating values can be targeted if building design is adapted.

The simulation results (Fig.6) confirm that the natural ventilation potential is weak for wind regime 5, as the wind velocity is always less than 3m/s (the average during the day is 1.8 m/s) and the overheating goes up to 3°C (average is 1.5°C and the maximum is 3.26°C at 2pm). The airflow rate is always less than 25 ach/h (the average is 13 ach/h). The other wind regimes lead to moderate wind velocities with averages during the day ranging from 5.8 to 8.3 m/s. The average airflow rates range between 37 to 58 ach/h. The average overheating is less than 1°C, but its maximum values stay high (from 1.7°C to 2.8°C).



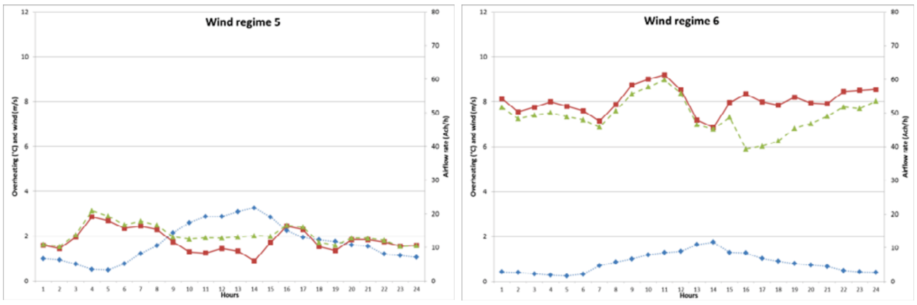


Fig. 6 : Simulation results with overheating, wind velocity and airflow rate for the 6 synoptic wind regimes

The use of localized short weather sequences shows that although the building is not located on the windward coast of Moorea, the local wind is most of the time moderate (between 2.5 and 11 m/s) and can be usable for effective natural ventilation. Thus, the airflows generated through the building are significant and overheating can be limited under 3°C all the days except for days of wind regime 5. Most of the time, comfort might be acceptable in ventilated classrooms, providing that the building design is suitable. From 1pm to 3pm during days of wind regime 5, the inside conditions are hot. In this case, ensuring an air velocity on occupants could be a solution to improve thermal comfort. The thermal simulation with Energyplus doesn't give access to air velocity in the thermal zone. Therefore a coupling with a CFD model should be investigated. At the last resort, ceiling fans could be added in the zone to generate the required air velocity.

5. Conclusion

Appropriate meteorological data is the first decision making tool that should be provided to building designers. This article presents the methods used to obtain climate data for addressing the building design in French Polynesia by following two approaches: an energetic approach for air conditioned buildings and a qualitative approach of comfort for naturally ventilated buildings. For the energy approach, the presented method proposes to establish a "Polynesian typical meteorological year" from a reduced ground measurement database. To complete the meteorological measurements on the ground, a global to diffuse decomposition model for solar irradiance was developed. This model presents interesting performances because it is easy to use by designers and has satisfactory accuracy. To carry out a qualitative analyzes of comfort in naturally ventilated buildings a climate model was used. This has highlighted six main synoptic wind regimes on Tahiti and Moorea Islands. The downscaling of this model has helped develop the wind cartography over a 1.33 km mesh and generate short weather sequences for each wind regime and for each point of the mesh. The weather sequences provided in this study have been used for energy calculation and wind potential assessment of a primary school building located in Moorea. For energy calculation, the "Polynesian typical meteorological year" is compared to an annual weather file from Meteornorm. The simulations of natural ventilation show that the fine mesh short weather sequences give a better evaluation of localized wind potential. To go further in this study, two directions must be investigated. The first is to carry on the downscaling toward a finer resolution (typically 100m) to better consider the orography and very localized climatic phenomenons. The second is to estimate the air velocities inside the building with CFD calculations using localized wind velocities as input. Considering the air velocities on the occupant will significantly improve the comfort assessment in the zone.

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