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Abstract

Green façades are living technologies applied to buildings. They are passive solutions able to produce many advantages for human wellbeing, buildings' functioning and cities environment, especially in Mediterranean areas. The knowledge of the energy behaviour of green façade systems is essential to define their energy performances, to produce the best design and application and to obtain the maximum benefits. The heat and mass exchanges occurring between the system and the surrounding environment must be determined. Among the heat transfer mechanisms involved, the radiative, the convective and the evapotranspirative ones are the most relevant. This paper focuses on convective heat transfers interesting the plant layer of a green façade system and the external air. Concerning the buildings energy balance, convection is one of the most difficult term to define. In presence of plant layers, the definition of convective heat transfer coefficients is even more complex and case-specific. In this research, experimental data collected at the University of Bari and regarding a green façade were used. The main convective type resulting from the measured data was the forced one. Some literature approaches to estimate convective transfers were considered and applied to empirical data. The different calculated convective fluxes were compared. Finally, the goodness-of-fit of the considered convective models was assessed by means of several statistical methods and indicators. The best fitting convective formulas were found. In perspective, an increase of measurements and observations about temperature and wind speed and directions and the implementation of CFD analysis could help to refine the results.

Keywords	green infrastructures; vertical greenings; modelling; convective coefficients; green layer; goodness-of-fit.
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To the Editor of
Biosystems Engineering

Subject: Paper "Convective heat transfers in green façade systems"
Authors Fabiana Convertino, Giuliano Vox, Evelia Schettini

Dear Editor,

I would like to submit the research paper entitled "Convective heat transfers in green façade systems", authors F. Convertino, G. Vox, E. Schettini for publication in Biosystems Engineering.

Best regards,

Evelia Schettini

Bari, 12/06/2019

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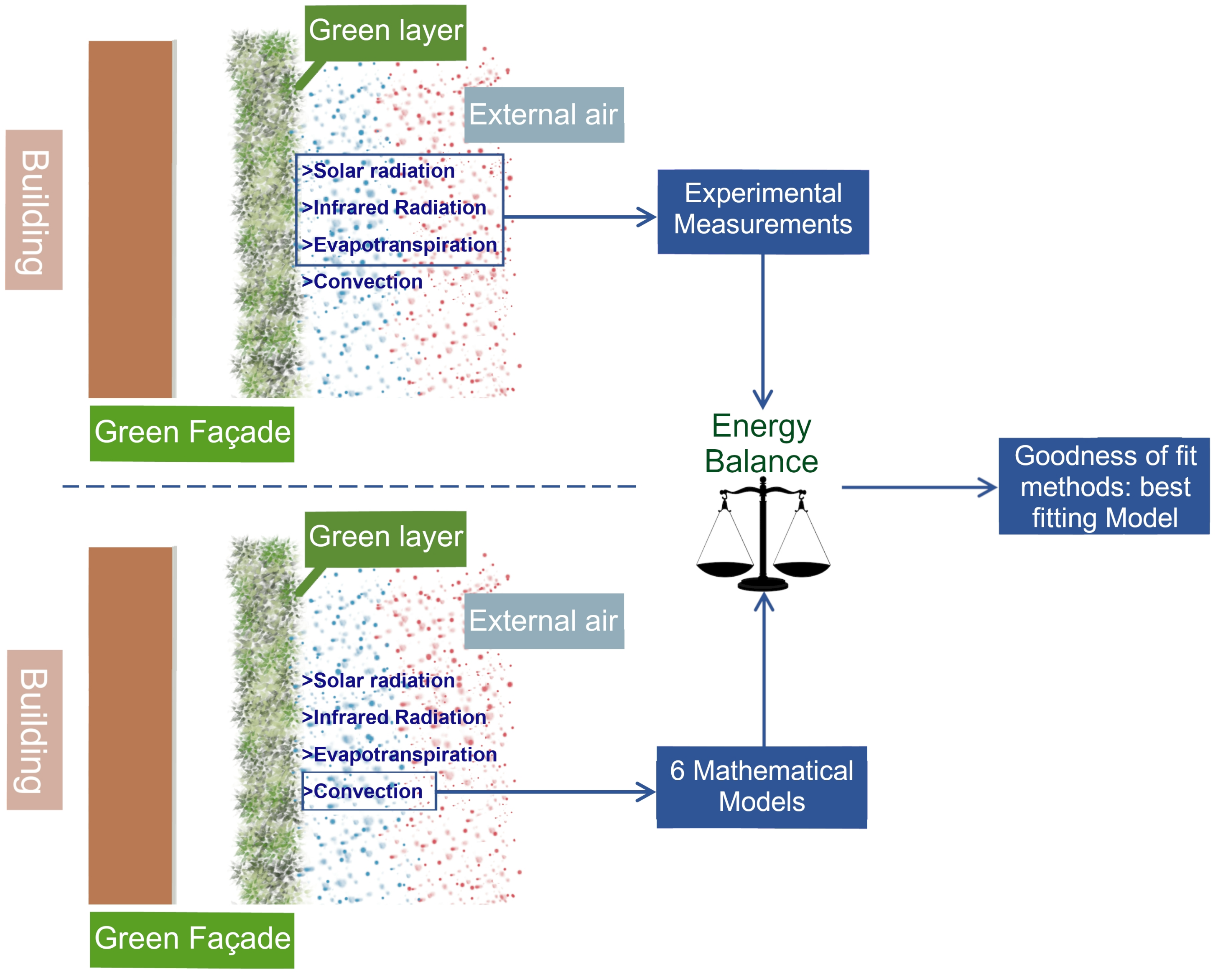
Highlights

- Green façade system is schematized through different layers.
- Heat transfer mechanisms in vegetation layer are studied.
- Convective fluxes are estimated by following several approaches.
- The goodness-of-fit of the convective formulas is carried out.


Building
Green layer
External air
>Solar radiation
>Infrared Radiation
>Evapotranspiration
>Convection
Green Façade
Experimental Measurements
Energy Balance
Goodness of fit methods: best fitting Model
Building
Green layer
External air
>Solar radiation
>Infrared Radiation
>Evapotranspiration
>Convection
Green Façade
6 Mathematical Models

Convective heat transfers in green façade systems

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Abstract

Green façades are living technologies applied to buildings. They are passive solutions able to produce many advantages for human wellbeing, buildings' functioning and cities environment, especially in Mediterranean areas. The knowledge of the energy behaviour of green façade systems is essential to define their energy performances, to produce the best design and application and to obtain the maximum benefits. The heat and mass exchanges occurring between the system and the surrounding environment must be determined. Among the heat transfer mechanisms involved, the radiative, the convective and the evapotranspirative ones are the most relevant. This paper focuses on convective heat transfers interesting the plant layer of a green façade system and the external air. Concerning the buildings energy balance, convection is one of the most difficult term to define. In presence of plant layers, the definition of convective heat transfer coefficients is even more complex and case-specific. In this research, experimental data collected at the University of Bari and regarding a green façade were used. The main convective type resulting from the measured data was the forced one. Some literature approaches to estimate convective transfers were considered and applied to empirical data. The different calculated convective fluxes were compared. Finally, the goodness-of-fit of the considered convective models was assessed by means of several statistical methods and indicators. The best fitting convective formulas were found. In perspective, an increase of measurements and observations about temperature and wind speed and directions and the implementation of CFD analysis could help to refine the results.

Keywords: green infrastructures, vertical greenings, modelling, convective coefficients, green layer, goodness-of-fit.

Nomenclature

C	coefficient for forced convection calculation	Nu	Nusselt number
c_f	both sides leaf coefficient	O	observed value [W m^{-2}]
CFD	Computational Fluid Dynamic	$\bar{O}$	mean of observed values [W m^{-2}]
C_{pa}	specific heat of air at constant pressure [J kg^{-1} K^{-1}]	P	predicted value [W m^{-2}]
CRM	Coefficient of Residual Mass	Pr	Prandtl number
CV	heat transfer by convection [W m^{-2}]	R	heat transfer by infrared radiation [W m^{-2}]
C_1, C_2	constants	Re	Reynolds number
d	characteristic dimension of the leaf [m]	Ri	Richardson number
E	solar radiation [W m^{-2}]	RMSE	Root Mean Square Error [W m^{-2}]
EF	Modelling Efficiency	S	heat storage [W m^{-2}]
g	gravitational constant [m s^{-2}]	T	temperature [K]
g_{Ha}	boundary layer conductance [kg m^{-2} s^{-1}]	ΔT	temperature difference [K]
Gr	Grashof number	u	wind speed [m s^{-1}]
h	convective coefficient [W m^{-2} K^{-1}]	UGI	Urban Green Infrastructure
IA	Index of Agreement	β	fluid volumetric coefficient of expansion [K^{-1}]
LAI	Leaf Area Index	λ	thermal conductivity [W m^{-1} K^{-1}]
MAE	Mean Absolute Error [W m^{-2}]	v	fluid kinematic viscosity [m^{-2} s^{-1}]
ME	Maximum Error [W m^{-2}]	ρ	density [kg m^{-3}]
n	Reynolds' exponent for forced convection calculation; number of samples for statistical indices evaluation	Φ	evapotranspiration [W m^{-2}]

Subscripts

a	air	i	i-th value
agl	air in the canopy	l	leaves
ea	external air	5	less than 5 m s^{-1}
gl	green layer		

1 Introduction

Urban Green Infrastructures (UGIs) can be defined as integrated network areas which bring vegetation elements inside cities to satisfy the need for more environmental sustainability. In fact, they contribute to mitigate urbanization's dangerous consequences and to improve the quality of urban contexts (Mekala & Hatton MacDonald, 2018).

The expression UGIs include several kinds of planned and unplanned green systems and, among these, green applications to buildings deserve particular attention (Norton et al., 2015; Raji, Tenpierik, & van den Dobbelsteen, 2015). Green façades and green walls, in particular, allow vegetation to grow on vertical surfaces of buildings, creating an additional layer attached or detached from the building's envelope. The advantages due to vertical greening systems are numerous, remarkable, under many points of view and at different scales. Especially in Mediterranean areas, the benefits deriving from the application of such green technologies are significative (Blanco et al., 2017; Schettini, Vox, Blanco, Campiotti, & Scarascia Mugnozza, 2018; Urrestarazu et al., 2014). Vertical greenings represent a new winning strategy to complement the traditional Mediterranean buildings (Convertino, Di Turi, & Stefanizzi, 2017). Vertical green systems allow to reduce energy consumption for air conditioning in warm periods and to improve thermal insulation in cold ones (Bianco, Serra, Larcher, & Perino, 2017; Blanco, Schettini, & Vox, 2018; Cameron, Taylor, & Emmett, 2014; Manso & Castro-Gomes, 2015; Santamouris, 2014; Vox, Blanco, & Schettini, 2018). Vertical greenings can be classified as passive technologies able to enhance the energy efficiency of buildings and to mitigate the heat events linked to Urban Heat Island. Vertical greenery systems improve microclimatic conditions, by reducing ambient temperature in hot periods and favouring human thermal comfort (Cameron et al., 2014; Norton et al., 2015; Pérez, Coma, Martorell, & Cabeza, 2014). The vegetation layer applied to building acts as a solar shading barrier during daytime, decreasing external surfaces' temperatures, and as a thermal barrier at night (Jim & He, 2011; Schettini et al., 2018). Additional benefits are given by the cooling effect linked to the evapotranspiration process of the plants (Bianco et al., 2017; Bowler, Buyung-Ali, Knight, & Pullin, 2010), and to the interaction of vegetation with air flows (Perini, Ottelé, Fraaij, Haas, & Raiteri, 2011).

When referring to vertical greenings, and green façades in particular, a critical aspect is the poor availability of detailed and realistic energy models, and consequently, of simulation tools, designed to describe and forecast their energy performances. One the most difficult parameters to define is the convective heat flow of the system, especially that involving the green layer.

The energy behaviour of a vertical green system can be studied by schematizing the system through the different layers that compose it (Convertino, Vox, & Schettini, 2019). In the energy balance study of a green façade, the definition of the convective term is essential to evaluate the quantity of sensible heat exchanged by the different layers. Generally, this kind of convective fluxes are defined through a convective coefficient, that exemplifies the heat transfer mechanisms between the considered layer and the fluid surrounding it. The definition of the heat transfer coefficient is the main criticality of the available equations for calculation of the convective heat exchanges. When referring to buildings and their elements, many factors influence the convective heat transfer coefficient determination: the building geometry and its surroundings, the building envelope, the roughness and orientation of surfaces, the fluid characteristics, the wind speed and direction, the terrain types and temperature differences. Besides, in urban areas, there is also a strong influence given by the buildings' arrangement and geometry.

There are different methods to derive values of convective coefficients: analytical, numerical and simplified empirical. The choice of the best fitting expression of the convective coefficient is particularly significant when evaluating the thermal balance of the system or the layers' surface temperatures. The analytical methods aim to find mathematical solutions of the continuity, momentum and energy equations, but can be applied only in specific flow and geometric conditions. The governing equations of convection are nonlinear and coupled and, thus, it is very difficult to obtain analytical solutions (Cai & Zhang, 2003). The numerical methods are mainly based on the Computational Fluid Dynamics (CFD) analysis, a very powerful and increasingly popular tool; however, they should still be improved (Defraeye, Blocken, & Carmeliet, 2011). As for the numerical methods, the models implemented in Building Energy Simulation programs derive from the huge number of the proposed empirical models and the range of application of these is not clear as well as the results are uncertain (Mirsadeghi, Cóstola, Blocken, & Hensen, 2013). To date, the experimental methods represent the main source for convective coefficients data (Clarke, 2001; Mirsadeghi et al., 2013; Palyvos, 2008;Vox et al., 2016). Each experimental method for determining the heat transfer coefficients has its pros and cons. Flat-plate experiments generally lack physical similarity related to the flow pattern but give important information regarding the surface texture influence. Full-scale measurements are the most realistic, but very case-specific and provide heat transfer coefficient for a limited number of points. Wind-tunnel experiments are generally performed not in the field of building engineering, but they give a better estimation of the energy losses through a surface-averaged coefficient and not a single point value. In literature, the number of heat transfer coefficient formulations is significative, but the critical aspect is that no relation and no model manage to take into account all the influencing factors. Wind speed is the factor commonly considered.

The complexity of the convective heat transfer definition and of the convective coefficient calculation is evident for common buildings' envelope solutions and it is even more in case of green vertical envelopes. In the presence of vegetation, the convective heat transfers interesting the greenery must be considered. Many scientists recognized early the significant role played by convection, in heat transfers between plant leaves and air. It is a great challenge to understand the sensible heat fluxes at surfaces covered with plants, because the surface is rough and porous. Their measurements are complex and difficult to obtain and their calculation can be made from the energy balance equation, if all other terms are known (Ayata, Tabares-Velasco, & Srebric, 2011; Tabares-Velasco & Srebric, 2011). When studying the convective phenomena, a significative aspect to consider is also the relationship existing between the heat transport, associated with convection, and vapour transport, due to evapotranspiration (Tabares-Velasco & Srebric, 2011). In the case of vegetated layer, studies regarding biophysical fields and greenhouses can be helpful (Bartzanas, Boulard, & Kittas, 2004; Campbell & Norman, 1956; Garzoli & Blackwell, 1981; Gates, 1980; Kimball, 1973; Kindelan, 1980; Nobel, 2009; Papadakis, Frangoudakis, & Kyritsis, 1992; Parkhurst, Duncan, Gates, & Kreith, 1968; Schuepp, 1993; Stanghellini, 1987). The leaves are considered the most important heat, mass and momentum sources in the plant canopy, by which they influence the local plant/canopy microclimate. Leaves are very various physical and biological entities and, thus, results coming from observations are not easy to generalize. When transfer processes to and from leaves in a natural environment take place, there are usually simultaneous variations in wind, humidity, radiation, physiological and microbiological factors. It is difficult to isolate an effect and to generalize observations. Thus, studies on abstract systems are, generally, accepted (Schuepp, 1993).

Energy is transferred to or from plant by convection if the plant's surface temperature is different from the air temperature. If the air is cooler than the surface of the plant, energy from the plant will be lost to the air by convection. If the air is warmer than the surface of the plant, energy will be delivered to the plant by convection. The wind produces forced convection of heat to or from the plants, if there is a temperature difference between the leaves and the air (Gates, 1980). Thus, it needs to be understood how plants are coupled to the climate around them (Gates, 1980; Nobel, 2009). When referring to a leaf surface, it is significative the concept of boundary layer. It is the region adherent to the surface, characterized by strong gradients in air velocity, temperature and gas concentrations. The convective heat transfer can be defined as a conductive transfer, with the introduction of the boundary resistance/conductance. The convective heat transfer coefficients are commonly used. Even in energy flows by convection involving plants, there is a proportionality constant, represented by the convective coefficient. It depends on various factors, such as size, shape, roughness and orientation of the plant's leaves, and on the properties of air. A small object has a high convection coefficient and its temperature is coupled to that of the air, while it is decoupled in case of a big object, because it has a thick boundary layer of fluid and, in consequence, a slower rate of heat transfer. The rate of heat transfer is inversely proportional to the characteristic dimension in the direction of the air flow, i.e. the width of the leaf. Convective heat transfer coefficients are defined as the ratio between the convective flux normal to the leaves' surfaces and the difference between the surface's and the reference temperatures. Air flow is a *conditio sine qua non* for convection and, since leaves are not isolated but part of the plant canopy, the air flow in and around them results very complex and case-specific. Plant species and geometry, leaf area density, leaf inclination, interaction between leaves, air flow and thermal conditions are some of the parameters influencing the convective mechanisms (Defraeye, Verboven, Ho, & Nicolai, 2013). As for air flow, it is evident that the conditions of negligible wind (free and mixed convection) have been considerably less studied in literature with respect to those of forced convection. It is likely a consequence of the perception that conditions of very low wind, in a natural environment, are really rare (Schuepp, 1993). The definition of the plants' heat transfer coefficient is mainly based on engineering theories and the use of real, artificial or virtual leaf sensors. Even if the use of convective coefficients represent a rather simplified way to evaluate convective transfers, they are really useful to define and forecast the energy exchange between leaves and environment. (Defraeye et al., 2013). Nowadays, CFD analysis seem to be the most promising method to deepen and refine this field of study (Koch, Samson, & Denys, 2019).

To describe realistically the energy behaviour of a vertical green system, all the terms of the energy balance must be determined in the most effective way. The convective component is as complex as fundamental to define the energy balance of green façades and also to develop useful mathematical models for simulation software.

This paper aims to investigate the convective heat transfer between the plant layer and the external air in green façades. Different formulas were considered and applied to experimental data. Qualitative and quantitative statistical methods were carried out to assess the goodness-of-fit of the different formulas. The performances of the considered convective methods, in the case of the green façade system, were evaluated and the best fitting formulas for the convective heat transfer in the vegetated layer was found.

2 Materials and methods

The energy balance of the green façade system was described through a schematic representation by means of 6 layers (Fig. 1). The heat transfer mechanisms interesting each layer were defined (Convertino et al., 2019; Kimball, 1973; Kindelan, 1980). Both the sensible and the latent terms of the heat fluxes were identified. The sensible exchanges include the convective, radiative and conductive heat transfer. The latent heat exchange relies on the evapotranspiration process.

In this paper the attention was focused on the convective heat exchanges concerning the vegetation layer. Experimental data were collected on walls made as prototype of a commonly used vertical building closure in Mediterranean civil construction. Measured data were used to calculate heat transfer terms occurring in the vegetation layer. Different formulas describing the convective heat exchange were evaluated and the suitable mathematical formulas describing the convective mechanism were defined, thanks to the introduction of several qualitative and quantitative statistical methods.

2.1 The experimental green façade

The experimental data used in this research were collected in 2015 at the experimental centre of the University of Bari, located in Valenzano (Italy). The experimental set-up consists of two small blocks: a green façade system and a control wall. The external walls of the blocks were realized in perforated bricks joined with mortar and characterized by a white plaster external finishing. The walls simulate the typical external envelope of Mediterranean buildings. The distance between the vegetation and the wall was 0.15 m thus creating an air gap. The green layer was made up of *Pandorea Jasminoides variegated*, an evergreen climbing plant, and of an iron net as plant supporting structure.

The experimental instrumentation was composed of a meteorological station, including two data loggers (CR10X and CR1000, Campbell, Logan, USA) and several sensors for climatic parameters detection. The solar radiation normal to the wall was measured by means of a pyranometer (model 8-48, Eppley Laboratory, Newport, RI, USA); the wind speed and direction were measured using a Wind Sentry anemometer (model 03002, R. M. Young Company, USA). Temperature and relative humidity of the air were measured by Hygroclip-S3 sensors (Rotronic, Zurich, Switzerland). Surfaces temperatures of the walls were measured using thermistors (Tecno.el s.r.l. Formello, Rome, Italy). Canopy temperature was measured by Apogee SI 400 IR radiometers (Logan, UT, USA). The longwave infrared radiation incident on the wall was measured by means of a pyrgeometer (Eppley Laboratory, Newport, RI, USA). The evapotranspiration was measured with a load cell (Scaime, Juvigny, France). The measurements, taken every 60s, were averaged every 15 min and stored into the data logger.

2.2 Convective heat transfer calculation

The sensible convective heat flux in a green layer is calculated by means of Newton's law of cooling:

$$CV = h(T_{ea} - T_{gl}) \quad (1)$$

where: *CV* is the sensible convective heat flux [W m^{-2}], *h* is the convective coefficient [W m^{-2} K^{-1}] and T_{ea} and T_{gl} are the external air and the green layer temperature [K], respectively.

The evaluation of the h coefficient is the basis for the convective heat flux calculation. In the present paper different formulas for the h coefficient were used and compared, including both analytical and empirical ones.

Considering analytical methods, the equations describing the convective phenomena are often function of dimensionless numbers as Nusselt (Nu), Reynolds (Re), Prandtl (Pr) and Grashof (Gr) numbers.

As for the analytical relations, only those formulas related to forced and mixed convection were selected in the present research as suggested by several authors (Gates, 1980; Nobel, 2009; Schuepp, 1993). This hypothesis was assessed by evaluating the Richardson (Ri) number. The Ri number depends on the Gr and the Re numbers (Table 1).

Table 1. Relation between Richardson (Ri) number and convection type.

$Ri = Gr/Re^2$	Convection type
$\ll 1$	forced
$\gg 1$	free
≈ 1	mixed

Gr and Re numbers are function of the weather conditions and are calculated as follows:

$$Gr = g\,\beta d^3 \nu^{-2}(T_{ea} - T_{gl}) \quad (2)$$

$$Re = d\,u\,\nu^{-1} \quad (3)$$

where: g is the gravitational constant [m s^{-2}], β is the fluid volumetric coefficient of expansion [K^{-1}], d is the leaf characteristic dimension [m], u is the wind speed [m s^{-1}] and v is the fluid kinematic viscosity [m^2 s^{-1}].

The Ri number was calculated by using the data collected at the experimental centre of the University of Bari. A summer week, 25-31 July 2015, characterized by clear sky conditions was considered. The most significant climatic data measured in this period are summarized in Table 2 and Fig. 2.

Table 2. Main climatic data measured at the experimental centre of the University of Bari, in the period 25-31 July 2015.

Climatic parameter	Maximum Air Temperature [°C]	Mean Air Temperature [°C]	Max Vertical Solar Radiation [W m^{-2}]	Mean Wind Speed [m s^{-1}]	Mean External Air Humidity [%]
Measured value	38.05	30.65	453.70	2.24	48.78

The Ri number, in the considered period, ranged between $5.05 \cdot 10^{-6}$ and 0.91, with a medium value of 0.006, thus it was less than 1, revealing that the convection type is the forced one (Table 1).

Despite this, a formula for mixed convection was also used to evaluate the presence of a component of free convection.

The h coefficient can be calculated by the Nu number (Gates, 1980; Monteith & Unsworth, 2014; Papadakis, Frangoudakis, & Kyritsis, 1994; Schuepp, 1993):

$$h = Nu\ \lambda_a d^{-1} \quad (4)$$

where λ_a [W m^{-1} K^{-1}] is the air thermal conductivity.

In turn the Nu number for forced convection can be calculated by:

$$Nu = C\, Pr^{0.33} Re^{n} \quad (5)$$

where the coefficient *C* and the exponent *n* are empirically obtained. As suggested by Schuepp (1993), leaves shape and orientation have an influence more significative on the coefficient *C* than on the Reynolds' number exponent. An accepted value for *n* is 0.5 in case of laminar flow. This value is also accepted by most experimental studies in turbulent flow. Wind in canopy is almost always turbulent. The turbulent flow near the leaves is favoured by free stream turbulence, surface roughness and other instability factors (Schuepp, 1993). The coefficient *C* is usually empirically determined and presented. It accounts for the effect of leaves inclination and for the effect of turbulence on heat transfer of leaves (Schuepp, 1993).

The 1st relation for forced convective flow applied in the present research was that proposed by Morrison and Barfield (Morrison & Barfield, 1981; Papadakis et al., 1994) for the calculation of the Nu number and then of the *h* coefficient by Eq. (4):

$$Nu = 0.328\, Pr^{0.33} Re^{0.5} \quad (6)$$

The 2nd applied formula, concerning the mixed regime, was that proposed by Stanghellini (1987) for the evaluation of the Nu number and then of the *h* coefficient by Eq. (4):

$$Nu = 0.37\left(Gr + 6.92 Re^{0.5}\right) \quad (7)$$

Considering empirical relations suitable for forced convection and in case of leaf size relatively small, McAdams' equation form can be considered (McAdams, 1942):

$$h = C_1 + C_2 u \quad (8)$$

where C_1 and C_2 are coefficients depending on climatic factors and surfaces characteristics. The formula proposed by Ayata et al. (2011) in accordance with McAdams (1942) was used as 3rd equation in the present paper:

$$h = 5.9 + 4.1 u_5 \frac{511 + 294}{511 + T_{ea}} \quad (9)$$

where u_5 is the wind speed when it doesn't exceed 5 m s^{-1}.

In the 4th formula we used the simplified method proposed by ASHRAE correlating the convective heat transfer coefficient with the wind speed (Alexandri and Jones, 2007; ASHRAE, 2019):

$$h = 5.6 + 18.6 u_5 \quad (10)$$

Campbell and Norman's (1956) approach in case of plant layers was also considered. They suggested to estimate the convective flux based on the heat conductance:

$$g_{Ha} = 1.4 * 0.135 * \left(\frac{u}{0.72 * d}\right)^{0.5} \quad (11)$$

where g_{Ha} is the boundary layer conductance for heat [kg m^{-2} s^{-1}]. The convective coefficient h used in the 5th formula was equal to:

$$h = g_{Ha} \cdot C_{pa} \quad (12)$$

where C_{pa} [J kg^{-1} K^{-1}] is the specific heat of air at constant pressure.

In the 6th formula, the Deardorff's method was used (Deardorff, 1978). This was adopted in several studies regarding the green roof systems (Ayata et al., 2011; Frankenstein & Koenig, 2004; Sailor, 2008) and was implemented in the EnergyPlus model for green roof. Deardorff's equation was opportunely modified for the case of the green façade system. In this system, in fact, the LAI considered for the determination of the foliage fractional coverage (a parameter needed to obtain some of the terms in the final convective formula) was that normal to the wall and not from the top of the plant to the ground. Besides, the ground temperature considered in the original formula was substituted by the external wall surface's temperature. This was due to the sequence of the layers in the green façade, where, instead of the ground layer (considered in the green roof) behind that of vegetation, there is the air gap delimited by the external building wall. Therefore, the convective flux was calculated, by the 6th formula, as follows:

$$CV = 1.1\ LAI\ \rho_{agl} C_{pa} c_f u_{agl} (T_l - T_{agl}) \quad (13)$$

where: 1.1 is a factor which accounts for plant components, such as stalks, stems, twigs and limbs exchanging heat but not transpiring (Deardorff, 1978), *LAI* is the leaf area index, ρ_{agl} is the air density in the proximity of the foliage [kg m^3], c_f is a dimensionless coefficient which takes into account both sides of the leaf, u_{agl} is the mean wind speed that both ventilates the foliage and promotes heat and moisture fluxes [m s^{-1}], T_l and T_{agl} are the leaf representative temperature and the mean air temperature within the canopy [K], respectively.

In the present research the fitting of the different formulas with the measured data was carried out. The energy balance of the green layer was used to this end (Convertino et al., 2019):

$$E + R + CV + S - \Phi = 0 \quad (14)$$

where *E*, *R* and *CV* represent the energy exchanged in the solar wavelength range, in the infrared wavelength range and by convection [W m^{-2}], respectively; *S* is the heat storage into the foliage layer [W m^{-2}]; Φ is the latent heat flow related to the evapotranspiration of the plant [W m^{-2}]. The terms E, R, CV and S are different forms of sensible heat flow.

The term *S* was neglected since the heat capacity of the vegetated layer is small compared to the other existing fluxes. The terms *E*, *R* and Φ were measured and calculated as in Convertino, Vox, and Schettini (2019) using the data recorded in the field. The applied simulation model was one-dimensional and only the energy flux normal to the wall was considered, thus neglecting the horizontal fluxes of energy.

The term *CV* was evaluated by using the different aforementioned equations (Eqs. 6, 7, 9, 10, 12, 13). The *CV* term must be equal to the algebraic sum of all the other terms of Eq. (14); indeed, energy balance of the vegetation layer must be always verified. The correlation of the six formulas with the experimental data was carried out.

3 Results and discussion

The measured data showed that the external air temperature was always higher than the green layer temperature, thus the heat exchanged by means of convection goes from the air to the vegetation, representing a quantity of energy gained by the plant. In the balance of the sensible heat, the convective exchanges were not the dominant contribution, in fact they were quantitatively less than the solar radiative terms, in the considered summer period.

As reported in Eq. (14), for the energy balance condition, the convective heat flux must be equal to the algebraic sum of all other terms of the balance. Since the terms of the energy balance of the green layer were known from the experimental measurements, the only one to be defined was the convective flux. In this paper, it was calculated by using the aforementioned equations (Eqs. 6, 7, 9, 10, 12, 13). The objective was to assess the goodness-of-fit of the different convective formulas and to find the best fitting ones. The assessment of the accuracy and precision of the simulated values of the convective flux with respect to the measured values was carried out. It was done with reference to the whole days, to the daytime only and to the night-time only, for the period 25-31 July 2015. This distinction was made to consider the changing in the energy balance due to the radiative and latent heat during the whole day. Model performance is, generally, assessed by comparing the calculated and the corresponding measured data. The evaluation of models performance should include both quantitative and qualitative means, statistical criteria and graphical displays, to capture distinct aspects of the models (Biondi, Iacobellis, & Mascaro, 2012; Legates & McCabe, 1999; Loague & Green, 1991; Moriasi et al., 2007; Pushpalatha, Perrin, Moine, & Andréassian, 2012; Ritter & Muñoz-Carpena, 2013). Therefore, both methods were implemented. At first, evaluations were made starting from plotted data. Initial considerations could result from the comparison of summary statistics for both the measured dataset and the different calculated datasets. To this end, a commonly used graphical technique, the boxplots, was employed (Fig. 3). They summarized, through boxes, lines and points, the minimum value, the first quartile, the second quartile (median), the medium value, the third quartile, the maximum value and any outliers, for each data matrix. Boxplots allowed to see which datasets have comparable statistics. The Morrison-Barfield and the Deardorff models were the closer to the measured data, the other relationships suggested an overestimation of the values. This behaviour was common to the values concerning the whole days, the daytime and the night-time.

Other useful graphical instruments were identified in the scatterplots, plots of the values calculated by means of the different formulas against the measurements (Fig. 4). These graphs suggested the degree to which the points match the identity line (i.e. the 1:1 line). The higher the agreement between the measured and the calculated values, the more the scatters concentrate close to the identity line. Values above the identity line represent overestimations of the model, values below the line are underestimations. This kind of graph allowed also to see if the model has a homogeneous performance, the relationship existing between the measured and the calculated datasets and, together with the boxplots, if there are any outliers. Graphs in Fig. 4 showed a considerable dispersion, for some of the considered models and especially in correspondence with higher value of flux. The 1st formula showed a trend line closer to the identity line.

A useful representation is also the comparison of the measured and calculated profiles plotted as time series. The curves of measured and calculated convective fluxes are traced, for 28 July 2015, in Fig. 5. Given the importance of the difference between external air and green layer temperature in convective heat transfers, it was plotted too, in the graph. It is relevant, since it influences the direction and the entity of the convective fluxes. Figure 5 shows how the convective flow is affected by temperature difference trend and how it is linked to the day period (daytime or night-time). It is also immediately evident that the Morrison-Barfield model fits better the observed values. The differences between the different approaches seem to be amplified as the temperature difference increases. Convective heat transfer has a rather irregular trend since it is influenced by the changing in wind speed.

At the same time, the quantitative approach is necessary. This implies the definition of some goodness-of-fit indices and their application to data. One of the possible methods could be the use of the correlation-based indices, such as the coefficient of determination (R^2). However, as shown in literature (Legates & McCabe, 1999; Ritter & Muñoz-Carpena, 2013), this indicator is inadequate to quantify the model performance, since it only evaluates linear relationships between observed and predicted values, neglecting additive and proportional differences, and it has also an oversensitivity to outliers, thus, leading to a misinterpretation of the relationship between the modelled and the observed values. When evaluating the goodness-of-fit of simulated vs. measured values only one specific linear correlation should be considered, the identity line, as in the proposed scatterplots (Fig. 3). As many literature authors (Legates & McCabe, 1999; Loague & Green, 1991; Moriasi et al., 2007; Ritter & Muñoz-Carpena, 2013; Willmott, 1981) suggested, a model performance assessment should include at least one absolute error indicator (in the variable units) and a dimensionless index for quantifying the goodness-of-fit, in addition to graphical representations. Thus, following these recommendations three dimensional (Mean Absolute Error (*MAE*); Maximum Error (*ME*); Root Mean Square Error (*RMSE*)) and three dimensionless (Index of Agreement (*IA*); Modelling Efficiency (*EF*); Coefficient of Residual Mass (*CRM*)) indicators were considered and applied to the analysed data. The statistical indices used were:

$$MAE = Mean\,|P_i - O_i|_{i=1}^{n}, \qquad MAE \in [0; \infty[\,; \qquad [\mathrm{W\,m^{-2}}] \qquad (15)$$

$$ME = Maximum\,|P_i - O_i|_{i=1}^{n}, \qquad ME \in [0; \infty[\,; \qquad [\mathrm{W\,m^{-2}}] \qquad (16)$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{0.5}, \qquad RMSE \in [0; \infty[; \qquad [\mathrm{W\,m^{-2}}] \qquad (17)$$

$$IA = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(|P_i - \overline{O}| + |O_i - \overline{O}|\right)^2}, \qquad IA \in [0; 1] \qquad (18)$$

$$EF = \frac{\sum_{i=1}^{n}(O_i - \overline{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2}, \qquad EF \in \,]-\infty; 1] \qquad (19)$$

$$CRM = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i}, \qquad CRM \in \left]-\infty; +\infty\right[\tag{20}$$

where P_i are the predicted values (i.e. values calculated through the different mathematical relationships), O_i are the observed values (i.e. values deriving from measurement campaign), $\bar{O}$ is the mean of the observed data and n is the sample size.

Concerning the first three indicators (*MAE*, *ME*, *RMSE*), the closer the value is to zero, the better the model is. As for the index of agreement (*IA*), higher values indicate better performance of the model simulations. The last two indices (*EF* and *CRM*) can have negative values. An *EF*<0 means that the mean of the observations is a better predictor than the model; while an *EF*>0 suggests that predicted values are better than the mean of the measurements. Negative values of *CRM* suggest that the model tends to overestimate data, while positive values express an underestimation of the data.

The statistical indices for each comparison between the measured and the calculated values, for all day long, daytime and night-time, respectively, are summarized in Tables 3, 4, 5. The best goodness-of-fit, for each index and for all periods, was expressed by the Morrison-Barfield's formula (1st formula), a very good agreement was also obtained by the Deardorff's relation (6th formula), followed, in almost all cases, by Ayata's (3rd formula) and Stanghellini's (2nd formula) models, the worst performances were assessed for ASHRAE's (4th formula) and Campbell-Norman's (5th formula) relationships. Only the 1st and the 6th formulas allowed to obtain positive values of *EF*, with the exception of the daytime periods, when they are negative, but however close to zero. Even for *CRM*, only the 1st and the 6th relationships showed positive values, but close to zero, the optimum. These conditions agree with the evidence of the scatterplots. In fact, Fig. 4 showed a general overestimation of the all models with the two exceptions of the Morrison-Barfield's and Deardorff's relationships, which tends to a slight underestimation.

Table 3. Statistic indicators calculated in the period 25-31 July 2015.

Method	Statistic indicators [1, 2]					
	MAE [W m^{-2}]	ME [W m^{-2}]	RMSE [W m^{-2}]	IA -	EF -	CRM -
Morrison-Barfield	10.11	43.67	14.38	0.84	0.50	0.16
Stanghellini	26.46	90.18	32.16	0.68	-1.52	-0.74
Ayata	21.92	71.78	26.20	0.74	-0.68	-0.59
ASHRAE	44.10	171.68	54.55	0.55	-6.26	-1.38
Campbell-Norman	59.65	190.08	71.79	0.45	-11.58	-1.86
Deardorff	14.83	48.14	19.81	0.69	0.04	0.44

[1] If measured and calculated values were the same, then, the indicators would be: MAE= 0, ME= 0, RMSE= 0, IA= 1, EF= 1 and CRM= 0.

[2] n= 672.

Table 4. Statistic indicators calculated for the daytime period, 25-31 July 2015.

Method	Statistic indicators [1, 2]					
	MAE [W m^{-2}]	ME [W m^{-2}]	RMSE [W m^{-2}]	IA -	EF -	CRM -
Morrison-Barfield	15.46	43.67	19.04	0.66	-0.33	0.23
Stanghellini	32.15	89.26	38.52	0.52	-4.44	-0.59
Ayata	26.31	70.15	31.28	0.58	-2.59	-0.45
ASHRAE	56.54	171.68	66.83	0.39	-15.39	-1.22
Campbell-Norman	74.19	190.08	86.97	0.30	-26.75	-1.61
Deardorff	23.06	48.14	25.94	0.52	-1.47	0.49

[1] If measured and calculated values were the same, then, the indicators would be: MAE= 0, ME= 0, RMSE= 0, IA= 1, EF= 1 and CRM= 0.

[2] n= 361.

Table 5. Statistic indicators calculated for the night-time period, 25-31 July 2015.

Method	Statistic indicators [1, 2]					
	MAE [W m^{-2}]	ME [W m^{-2}]	RMSE [W m^{-2}]	IA -	EF -	CRM -
Morrison-Barfield	3.86	19.49	4.99	0.93	0.77	0.08
Stanghellini	19.63	84.43	22.10	0.62	-3.59	-1.23
Ayata	16.65	64.63	18.24	0.67	-2.13	-1.04
ASHRAE	29.35	134.16	34.63	0.49	-10.28	-1.85
Campbell-Norman	42.35	184.10	47.60	0.38	-20.32	-2.65
Deardorff	5.27	44.02	8.17	0.76	0.37	0.29

[1] If measured and calculated values were the same, then, the indicators would be: MAE= 0, ME= 0, RMSE= 0, IA= 1, EF= 1 and CRM= 0.

[2] n= 311.

Considering the results of the qualitative and quantitative analyses, the best agreements were found for the Morrison-Barfield's relationship (1st formula) and, soon after, in the case of the adapted Deardorff' equation (6th formula). The temporal distinction between day and night suggested that the convective flux has a reduced weight compared to the other terms of the energy balance, especially radiative and latent fluxes. During daytime, when radiation and evapotranspiration are greater, than during night-time, the agreement between measured and calculated values of convection was slightly smaller.

Overall, the results of the analysis suggested the correctness of the followed approach and the suitability of the Eq. (6) and Eq. (13). The convective heat transfer between the external air and the green layer could be evaluated through the determination of the dimensionless numbers and the most direct equation of Morrison and Barfield (1981). The adaptation to the case of vertical greenings of the Deardorff's equation (1978), already applied for green roofs, can be used too.

In the analysed context, the forced convection type seems to be confirmed as the one interesting the exchanges between the external air and the vegetation layer of a green façade system. This conclusion is not the same of other literature authors in concerning vertical greenings. Stec, van Paassen, and Maziarz (2005) suggested to use the Stanghellini's formula, thus, assuming a mixed convective heat flux between plants and surroundings air. Flores Larsen, Filippín, and Lesino (2015) affirmed that in vertical green walls the convection regimes are usually the mixed and the free ones and proposed to use the Stanghellini's relation in the first case, and a McAdams's relation for free convection. The approach proposed by Ayata, Tabares-Velasco, and Srebric (2011), based on the McAdams (1942) equation for forced convection, was chosen by Šuklje, Medved, and Arkar (2016) to study the exchanges between canopy and ambient air. Mazzali, Peron, Romagnoni, Pulselli, and Bastianoni (2013) and Widiastuti, Caesarendra, Prianto, and Budi (2018) calculated both the convective and radiant transfer coefficients by applying the simplified relations according to the standards of EN ISO 6946 (2008). Deardorff's model of convective heat transfer was taken into account by Dahanayake and Chow (2017).

4 Conclusions

The study has investigated the mechanisms of heat transfer regarding the plant layer, as typical component of the green façade systems. The convective heat transfer process between the vegetation and the external air was analysed. Notwithstanding the difficulty of describing in a realistic way this kind of mechanism, several literature approaches were taken into account. Experimental data collected in the case of a green façade was considered. Once verified that the forced regime was the dominant one, the mathematical formulations were applied to the empirical data. The concept of energy balance of the green layer was recalled and, based on this, correlations between the measured values of sensible and latent heat flux, and the calculated values of convection were proposed.

Concerning the green façade systems, the present research proposes not only the application of different convective flux mathematical models, but, as further contribution, it introduces the use of statistical methods and indicators to assess the goodness-of-fit of the considered approaches. To this end, several graphical displays and statistical criteria were carried out. These analyses suggested the least and the most suitable approaches for convective heat transfer evaluation.

The results achieved can be considered useful to the definition of such specific term of the energy balance in the green façade systems. This study can be extended in order to obtain convective transfer formulas specifically written for vertical greenings. A major number of observations of temperature and wind speed at different elevations, along the height of the façade, and at different distances from it, can allow the application of the logarithmic wind profile method. It could be useful to pass from a surface averaged calculation to a more detailed one. The influence of the façade orientation with respect to the wind directions, thus the distinction of windward and leeward surfaces, can be another refining tool. A deepening of the interconnection between convection and evapotranspiration could be also interesting. At last, numerical models, based on CFD analysis, could be used to study the convective mechanisms, in and around canopy, as term of the coupled heat and mass exchanges with the environment, and in a very close to reality way.

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FIGURE CAPTIONS

Figure 1. Schema of a green façade system: layers involved in heat transfer mechanisms.

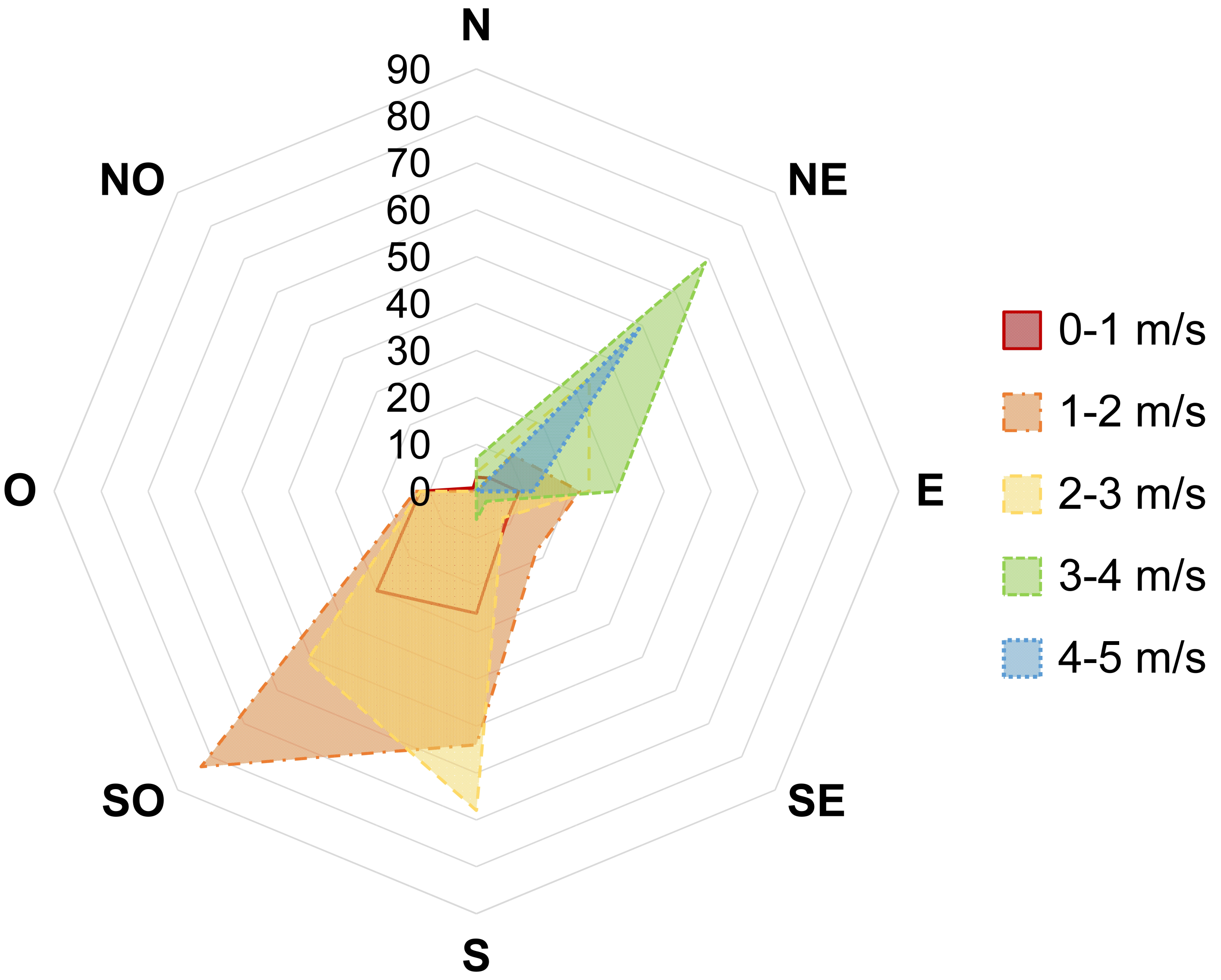
Figure 2. Distribution of the wind speed and direction at the experimental centre of the University of Bari, in the period 25-31 July 2015.

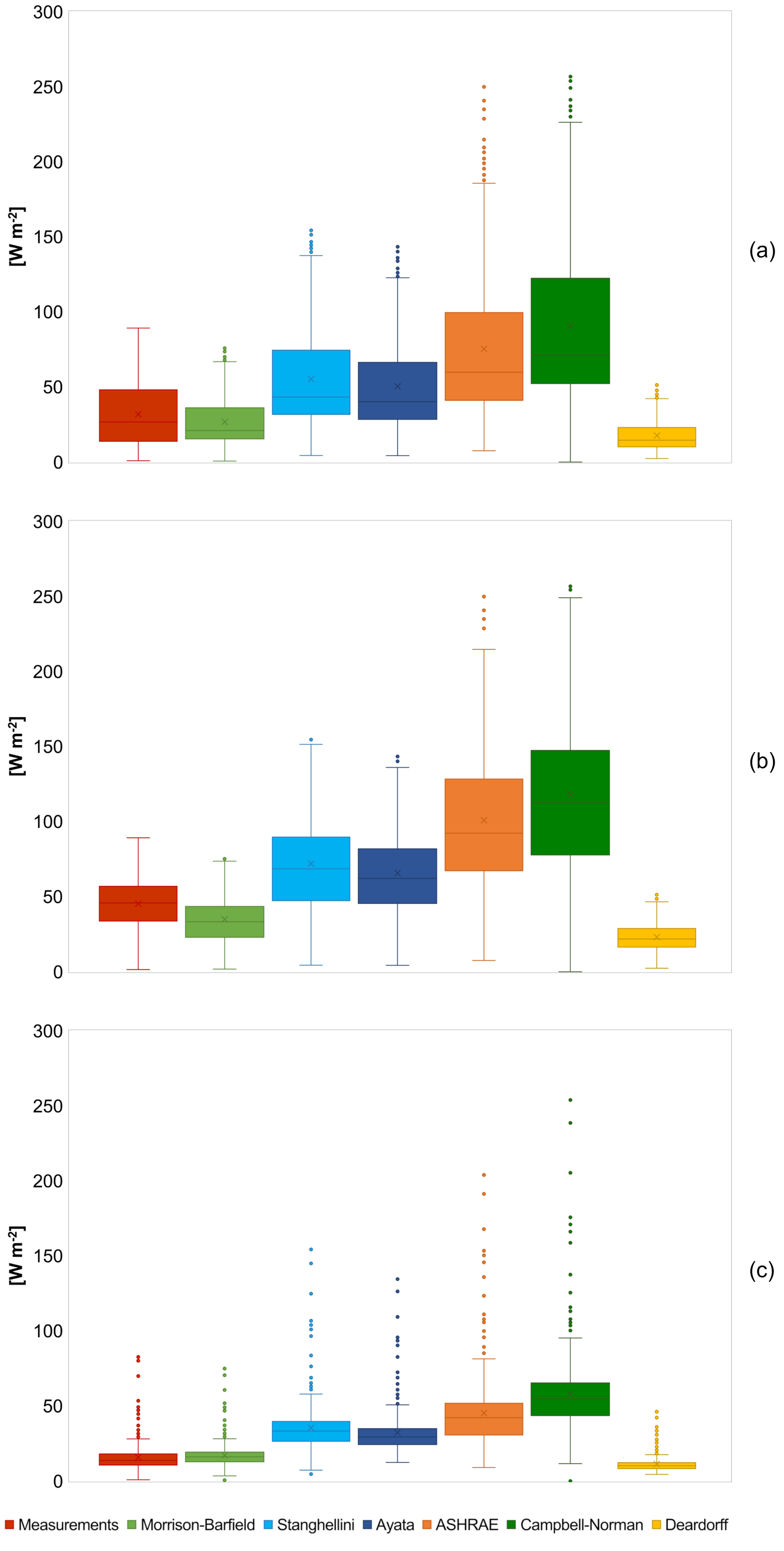
Figure 3. Boxplots for the measured dataset and the six calculated datasets: all day long (a), at daytime only (b) and at night-time only (c).

Figure 4. Scatterplots of the convective flux calculated through the six formulas against the measured flux, all day long, 25-31 July 2015.

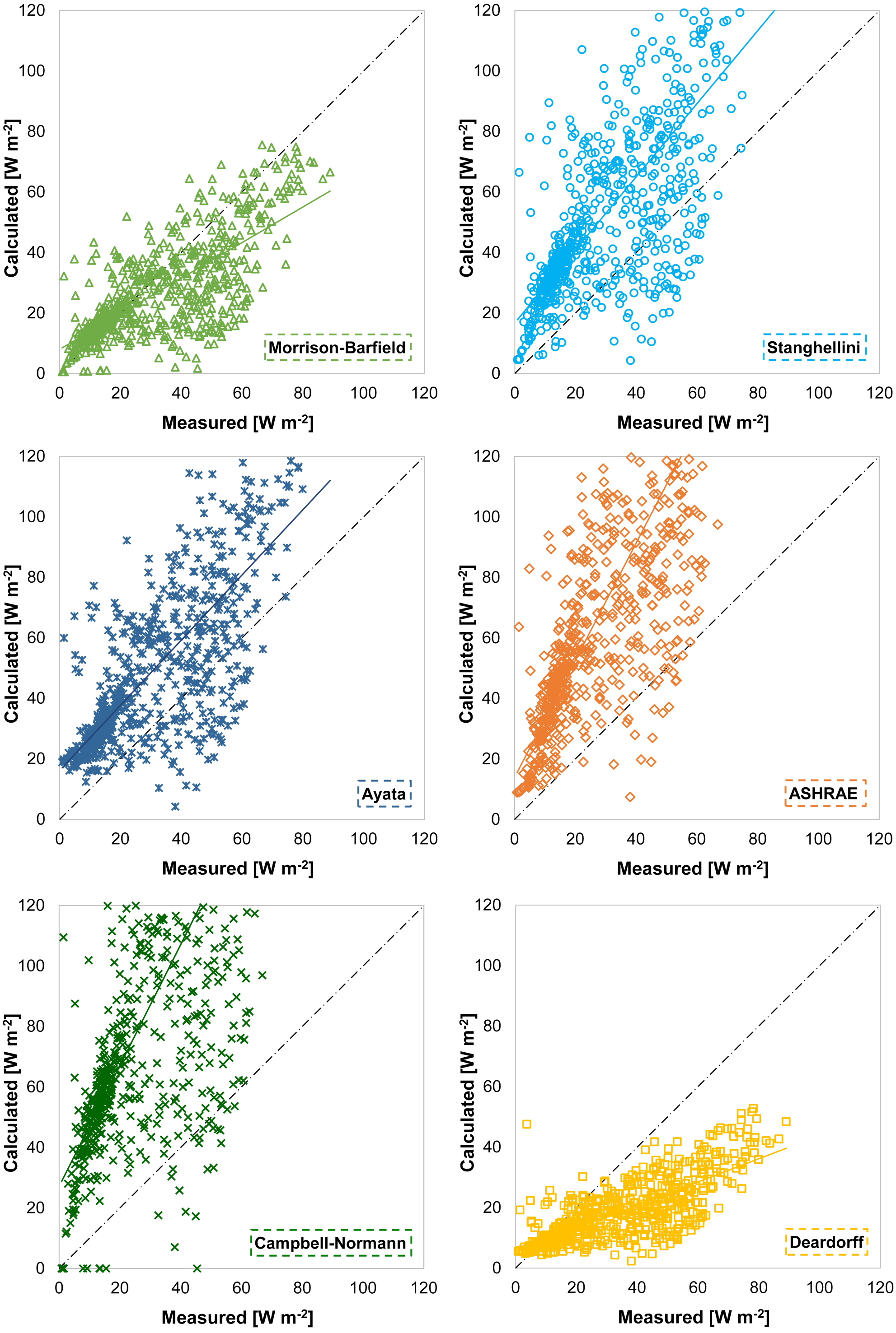
Figure 5. Convective heat flux measured and calculated according to the different approaches and temperature difference between external air and green layer (ΔT), at daytime (yellow section) and at night-time (blue sections), 28 July 2015.


Wall
Internal air
Wall
Air gap
Vegetation
External air

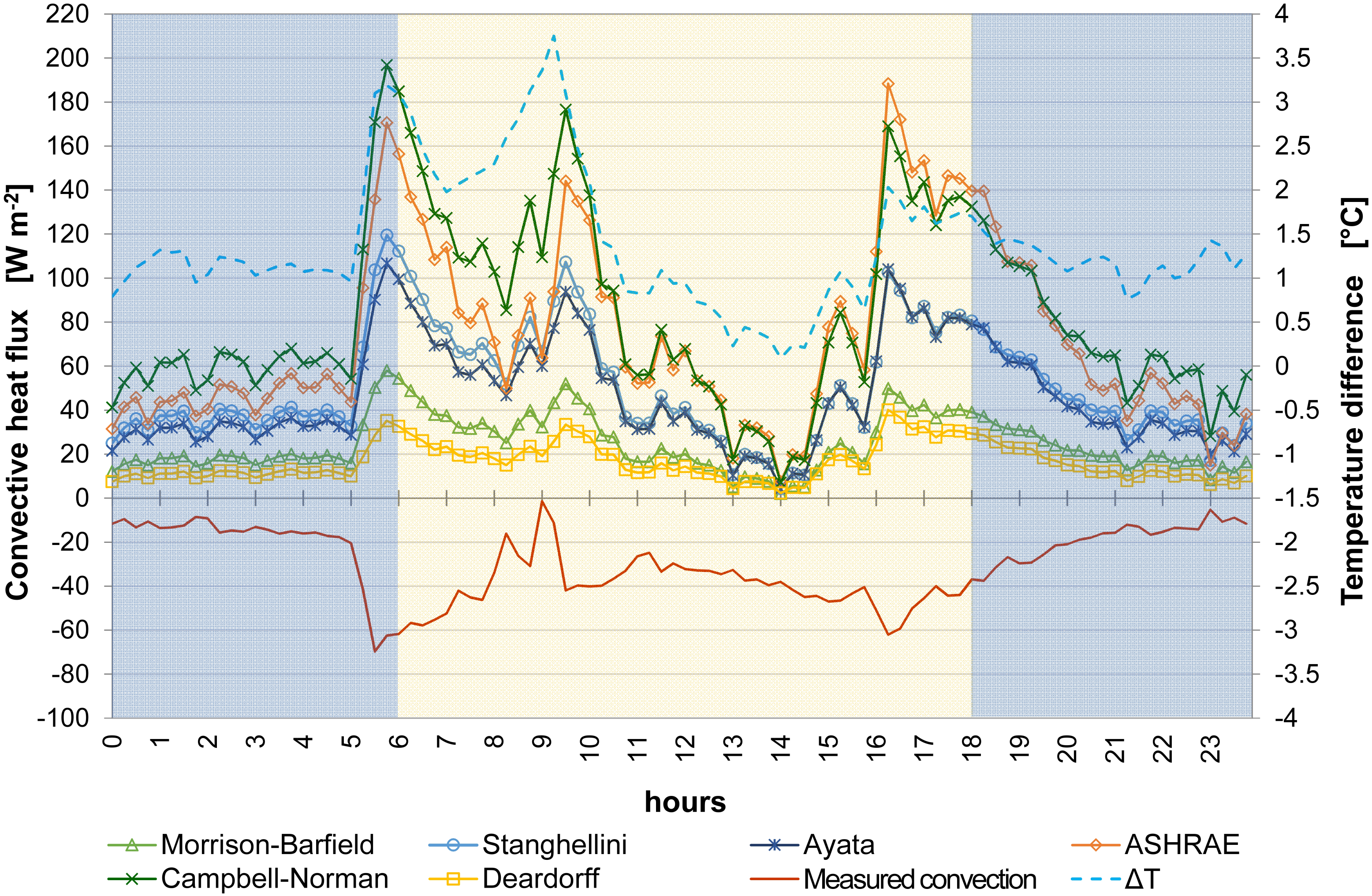

N
NE
E
SE
S
SO
O
NO
90
80
70
60
50
40
30
20
10
0
0-1 m/s
1-2 m/s
2-3 m/s
3-4 m/s
4-5 m/s



300
250
200
150
100
50
0
[W m-2]
(a)
(b)
(c)
Measurements
Morrison-Barfield
Stanghellini
Ayata
ASHRAE
Campbell-Norman
Deardorff



Morrison-Barfield
Stanghellini
Ayata
ASHRAE
Campbell-Normann
Deardorff
Calculated [W m-2]
Measured [W m-2]
0
20
40
60
80
100
120



Convective heat flux [W m-2]
Temperature difference [°C]
hours
Morrison-Barfield
Stanghellini
Ayata
ASHRAE
Campbell-Norman
Deardorff
Measured convection
ΔT