ELSEVIER Agricultural Water Management 40 (1999) 393–403

Agricultural water management

Modelling the local climate in island environments: water balance applications

Eduardo Brito de Azevedo[a,*], Luís Santos Pereira[b], Bernard Itier[c]

[a]*Department of Agriculture, University of Azores, Azores, Portugal*
[b]*Department of Agricultural Engineering, Technical University of Lisbon, Lisbon, Portugal*
[c]*Department of Environment and Agronomy, INRA, Grignon, Paris, France*

Abstract

In small volcanic islands the local scale climate is influenced by the regional scale climate and by the orography and orientation of air masses movement over the islands. A model was developed in a GIS environment to generate local scale climate variables from those observed at the synoptic scale, from coastal weather stations. An advective submodel, based on the Foehn effect and assuming the conservation of mass and energy, computes local scale air temperature, relative humidity, clouds occurrence and precipitation. A radiative submodel, using information generated by the advective submodel, computes local scale global radiation. A rotational terrain model allows that computations be performed according to the direction of wind. Because the model works within a GIS, results concern the spatial distribution of all climatic variables on the island territory. Results of the validation of temperature, relative humidity, global radiation and rainfall are presented. For agro-meteorological purposes, an application of generated data to perform the sequential water balance is also analysed by comparing results from computations using simulated and observed data at a control weather station located at medium altitude. Results support assumptions utilised in the model and the further use of generated local climate fields for water management and environmental studies in small island environments. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Advective process; Radiative process; Climatic variables; Small volcanic islands; Spatial variability; Foehn

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* Corresponding author.

PII: S0378-3774(99)00012-8

1. Introduction

The knowledge of the spatial variation of climatic conditions in small volcanic islands is a matter of special importance for local agriculture and water management purposes. In these environments, the surface meteorological information available is scarce and confined to coastal locations, considered to be representative at a regional or synoptic scale. Therefore, this information cannot reflect the spatial variation of the climate as influenced by elevation, relief and advective processes.

One approach to solve the problem of spatial variation of meteorological and climatic parameters could be the increase in density of the data observation locations with further application of geostatistical methods. Although very useful in short term climate characterisation and required for models validation, this option is of difficult application as a routine method given the obvious economic and technical restrictions. Also, the empiricism inherent to this approach makes difficult the full interpretation of the mechanism or factors that determine the spatial variation of the climatic variables and creates serious limitations when performing simulations of the climatic variation in time and space, namely when applications are intended for different but similar environments.

Adopting numerical mechanistic modelling could help to bridge the gap between local scale processes, which are at the origin of the local scale meteorology (and, of course, by time integration the local climate), and regional scale processes corresponding to the atmospheric synoptic conditions. This mathematical modelling approach requires observations at the regional scale to compute local scale climatic variables. These mainly include the advective and radiative processes governing temperature, relative humidity, cloudiness and solar radiation variation when air masses move over a mountainous small island.

Numerical models can be coupled or built in a geographical information system (GIS) environment, which allows easy and appropriate analysis of the spatial variation for water resources and environmental studies (Goodchild et al., 1993). This approach is used in model CIELO (Azevedo, 1996). Main results from the application of this model to produce the variables required to perform a local scale water balance for the Terceira Island, Azores, are presented.

2. The model CIELO

2.1. General aspects

A main goal of the CIELO model (acronym for ‘clima insular à escala local’) is to constitute a functional predictive tool for water and environment management. In that perspective, the model was constructed in order to conciliate the knowledge about the processes governing the spatial variation of climatic variables at the local scale, using the smallest number of parameters, with the limited available data from synoptic coastal meteorological stations. The model was built as an alternative to the more sophisticated three-dimensional approaches based on an atmospheric multiple layer parameterisation which, although very consistent concerning the conservation of mass and energy, are less

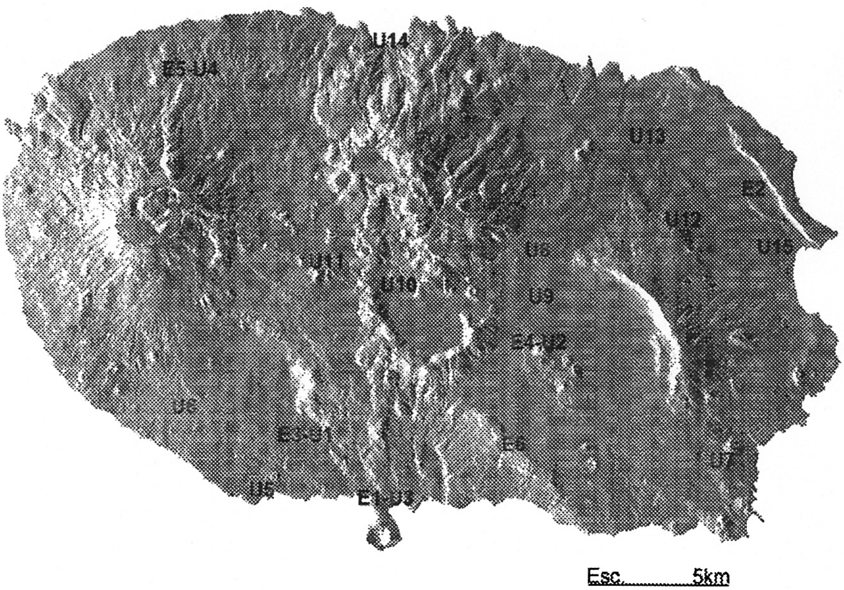

Fig. 1. Terceira Island Orography, Azores (Azevedo, 1996).

realistic functional tools when applied to small islands like the Azores. The model has been calibrated and validated for the Terceira Island Azores (Fig. 1).

The model has been developed in a raster GIS environment and can be applied in order to get an appropriate spatial distribution of any specific climatic variable over the island, and to apply other distributed climatic dependent models using the previously generated variables. Using the capabilities of the GIS, namely integrating other different spatially distributed parameters, the model CIELO can combine several climatic variables and produce highly elaborated spatially distributed outputs.

The domain of computation of the CIELO model is a two-dimensional finite fixed matrix (Fig. 2) that is parameterised with a digital elevation model (DEM) which is virtually oriented according to the direction of the air mass circulation. For this purpose, a specific algorithm named rotacional Terrain model (RTM) is applied.

Due to the geographical characteristics of the small islands, the CIELO model assumes the synoptic meteorology (or the regional climate) as the governing regime at the external boundaries of the model domain. The numerical model of the Terrain provides the surface boundary parameters. A set of differential equations is used to reproduce the advective regime and the evolution of air characteristics across the territory (virtual domain).

The model CIELO consists of two main submodels. The advective submodel reproduces the thermodynamic processes governing the variations of air temperature and humidity, cloudiness of local orographic origin, and precipitation, the so-called Foehn effect (Brinkmann, 1971; Yoshino, 1975; Barry, 1992). The second, the radiative submodel, taking into consideration the orographic clouds produced by the advective submodel and the shadow produced by the relief, generates the radiative variables adjusted to the topography.

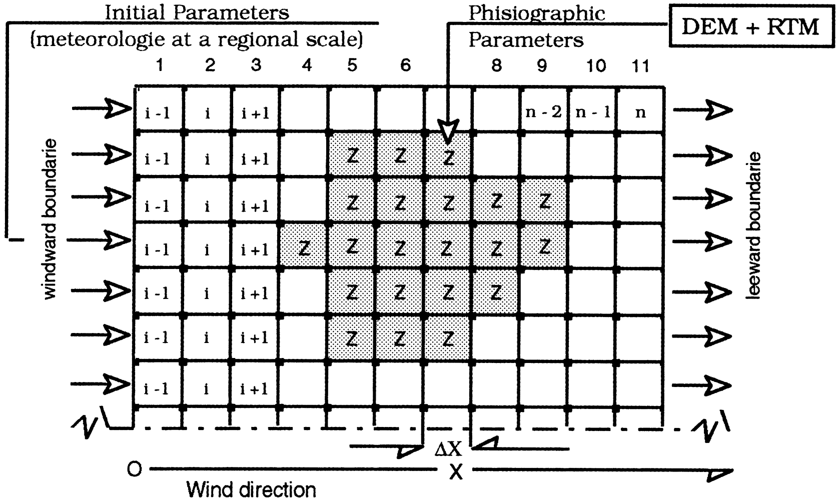

Fig. 2. Computational domain of CIELO model. Two-dimensional finite fixed matrix structure.

2.2. The advective submodel

The local climate at one location over a small island results from the regional climate affected by orography. This comes from adiabatic processes occurring when air crosses over the mountain producing changes in air temperatures (T), air humidity (R_h), cloudiness, rainfall (R) and radiation (R_s) (e.g. Triplet and Roche, 1986 and Peixoto and Oort, 1992).

The basic idea in the advective component of the CIELO model is that it is possible to simulate the effects of these processes by forecasting the changes which affect a small volume of air moving from close to the sea level to over the mountain. The regional meteorological conditions of the air at sea level are provided by the data from a typical reference synoptic weather station.

When air masses progress over the island (Fig. 3) it is possible to estimate the level of water condensation from the dry adiabatic lapse rate γ_d, which is close to 0.01°C m^{-1}. Then, from the saturated adiabatic lapse rate γ_s, which is always smaller, it is possible to compute the amount of liquid water content (q_l) in the unit volume of air. One fraction (α) of that liquid water content falls as precipitation. To estimate both T and R_h fields and to forecast the orographic rain field, it is necessary to know this fraction α. The fraction α is obtained by searching the value of α which optimises the relationship between computed liquid water content and the rainfall observed at different locations in the island (stations U in Fig. 1). During the corresponding calibration procedure, it was observed that α is constant all over the year and is equal to 1.2×10^{-4} m^{-1} of air displacement along the transect. Using the calibrated α and taking into account the decrease in q_l due to rain, it is then possible to compute the variations of T and R_h all along the transect, which is often called ‘Foehn effect’ downwind.

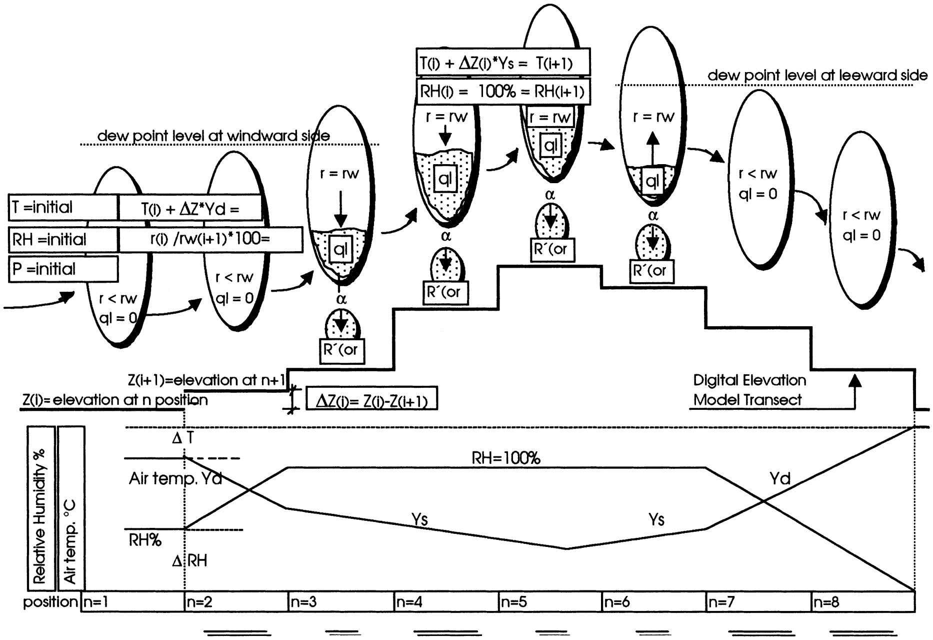

Fig. 3. Conceptual approach for the unidirectional evolution of temperature (T) and relative humidity (R_h) across an island transect. Other symbols are: P – air pressure; Z – elevation; Y_d – dry adiabatic lapse rate; Y_s – saturated adiabatic lapse rate; q_l – liquid water content per unit volume; x – fraction of q_l which falls as rain; $R'_{or} = \alpha q_l$; r – actual mixing ratio; rw – mixing ratio at saturation; D – difference leeward–windward.

To predict the precipitation of orographic origin, R_{or}, it is not enough to know the portion of liquid water in the unit volume of air which falls as rain ($\alpha q_l = R'_{or}$), but also estimate the size or the vertical development of clouds associated with the air mass movement. This implies the use of a scaling factor D. This scaling factor was obtained form comparing the rainfall observed at different locations and altitudes (Fig. 1) with the αq_l values computed for the same locations. It was then observed that D is a linear function of the precipitation at sea level, representing the regional precipitation, R_r in Fig. 4, taken as reference precipitation. The value retained for D is $D = 0.415R_r$ which was obtained with $r^2 = 0.941$. Obviously, for periods of more than one wind direction, each direction is taken into account weighted by the respective wind velocity.

The absolute field of the total precipitation results from the sum of the regional precipitation, observed at the reference station and considered the same over all the territory, and the orographic precipitation, which varies spatially over the island. More detailed information is given in Azevedo et al. (1998).

2.3. The radiative submodel

The daily regional radiative climate is inferred from the extra-terrestrial radiation calculated for the average regional latitude converted to the surface (regional scale)

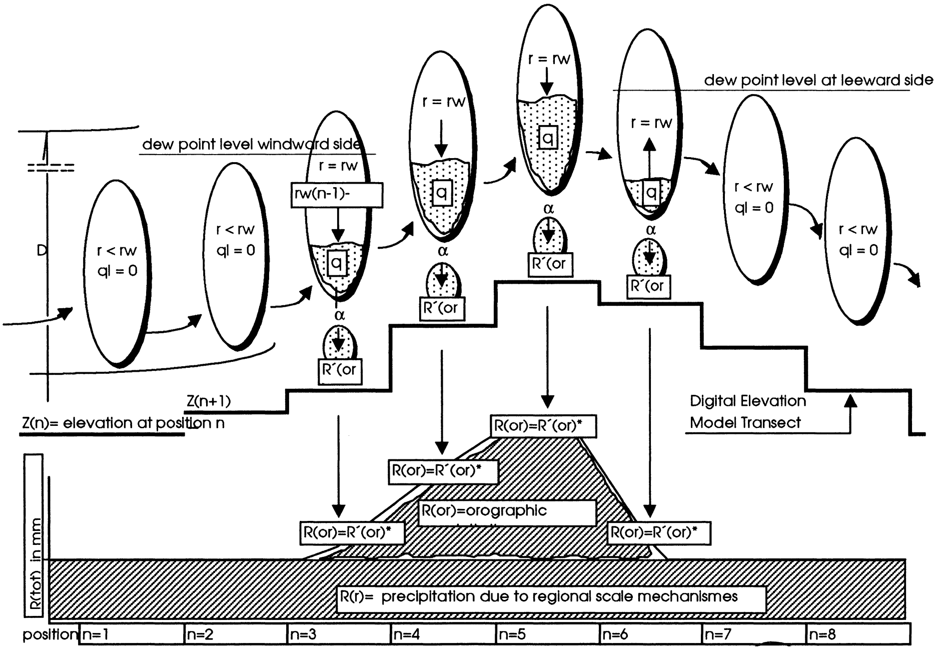

Fig. 4. Conceptual approach for the unidirectional evolution of precipitation across an island transect. Symbols as in Fig. 3 and: V – wind velocity; D – scaling factor (see text); R_{or} – orographic precipitation; R_{r} – regional precipitation and R_{tot} – total precipitation.

global radiation (R_{s}) assuming the Angstrom approach and using the sunshine duration observed at the reference station. The methodology proposed by Allen et al. (1994) is adopted. The short-wave global radiation at the local scale is computed from the sunshine duration modelled for the local scale as illustrated in Fig. 5. Sunshine duration is calculated using an extinction coefficient related with the occurrence and the thickness of the orographic cloud cover produced by the advective model. The spatial expression of the orographic clouds cover is assumed at the locations (cells) where the air layer, in adiabatic progression over the territory, have conditions to contain liquid water in suspension (q_{l} in Figs. 3 and 4).

The component of the global radiation controlled by the sunshine duration and assumed as direct radiation, is later adjusted to the orography by taking into consideration the shadow effect of the relief, mainly early morning and late afternoon. Details on the respective computational aspects are given in Azevedo (1996).

3. Validation of the CIELO model

The CIELO model was validated against rainfall data observed in the existing pluviometric network and using data from automatic weather stations specially installed for that purpose. The respective locations are indicated in Fig. 1. The model has been

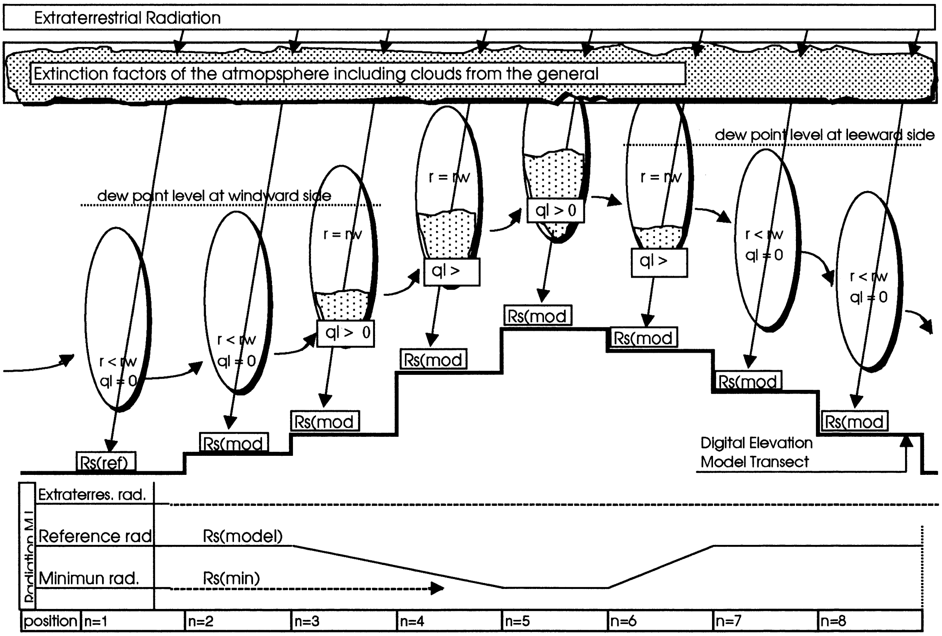

Fig. 5. Conceptual approach for the daily solar radiation (R_s) computation. Symbols as in Fig. 3 and Fig. 4.

rune at different time resolutions (hourly, daily and several days). The validation was performed in order to prove the capability of the model to produce a continuous field of the local scale climatic variables for the Terceira Island territory. The set of cell values from the numeric grid outputs coincident with the observation points (control weather stations) have been statistically compared with the observed data.

Results of the model validation relative to the estimation of the mean daily temperature (T) are presented in Fig. 6. A linear regression compares T estimates for the control stations E4 (elevation 380 m), E5 (100 m, North coast) and E6 (400 m) with those observed at the same locations. Computations use data from the reference station E1 (100 m, South coast) relative to 30 days during the period January–July 1995. The regression equation is $y = 1.001x$, with a determination coefficient $r^2 = 0.911$ and a standard error of estimates SE = 0.66°C. A similar regression performed without using the model produced $y = 0.485x + 8.5$, with $r^2 = 0.457$.

The results obtained for the mean daily relative humidity (R_h) are shown in Fig. 7. Using the same locations and dates, the regression equation is $y = 0.993x$, with $r^2 = 0.812$ and SE = 3.78%. These results are less good than for the temperature but still show the value of the model. Without the model $y = 0.294x + 57.24$, with $r^2 = 0.1$. To be noted that several data in Fig. 7 are represented on only one point for R_h =100%.

The validation of the rainfall component has been performed with data for the full year 1992, using the same reference station E1 and the control station E4 (380 m). Because the scaling factor D has been calibrated for periods of several days and not for daily observations, the model produces daily rainfall with a relatively large dispersion. Thus,

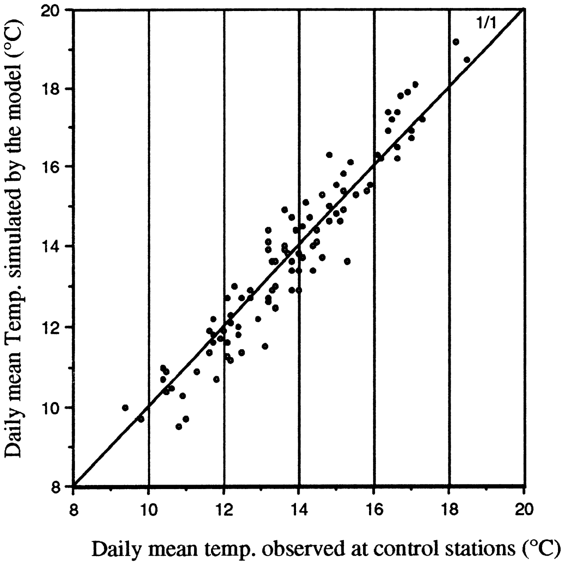

Fig. 6. Validation of mean daily air temperature simulation comparing temperature observed at control station E4, E5 and E6 with temperature simulated for the same locations (January–July 1995).

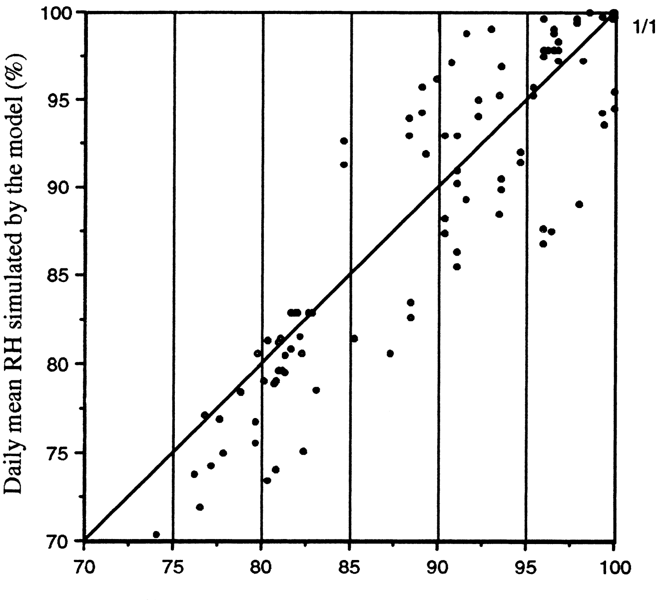

Fig. 7. Validation of mean daily relative humidity simulation comparing data observed at control stations E4, E5 and E6, with values simulated for the same location (January–July 1995).

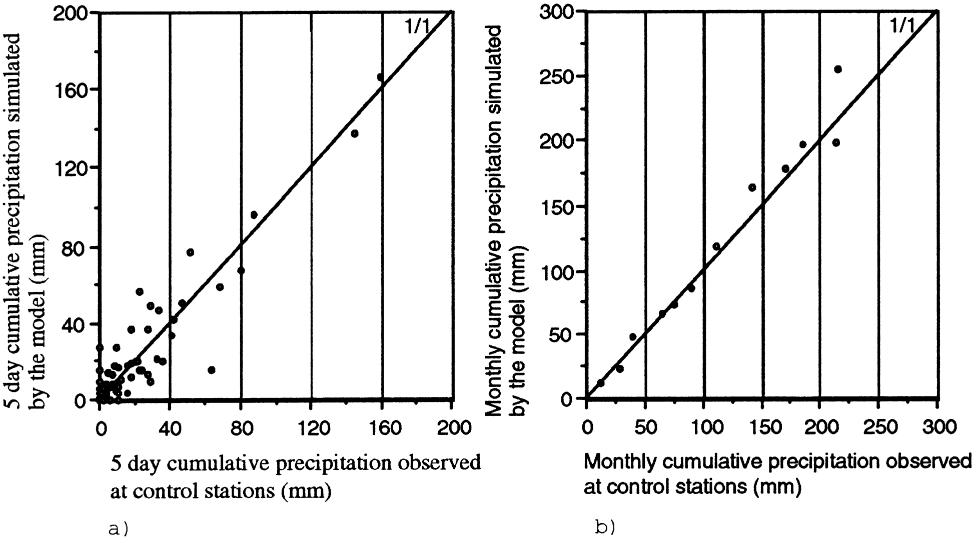

Fig. 8. Validation of precipitation simulation comparing: (a) five-day precipitation observed at the control station E4 with values simulated for the same location; (b) monthly precipitation observed at the same station with that simulated (1992).

the model has been validated for five-day and monthly precipitation. Results for five-day rainfall (Fig. 8(a)) produce the regression $y = 0.96x$ with $r^2 = 0.85$ and SE = 11.6 mm or 2.3 mm per day. When monthly rainfall is simulated (Fig. 8(b)), it results $y = 1.06x$, with $r^2 = 0.95$ and SE = 18.1 mm, thus only 0.6 mm per day.

The validation for global radiation R_s was performed with the same data sets for T and R_h. Results can be summarised through the regression equation between modelled and observed R_s: $y = 0.97x$, with $r^2 = 0.80$ and SE = 1.8 MJ m^{-2} per day. These results are very similar to those produced without the model: $y = 1.033x$, with $r^2 = 0.78$.

4. Water balance application

Results of model validation as analysed before show that the model is able to produce the fields of temperature, relative humidity, solar radiation and precipitation spatially distributed over the island. Hence, it is possible to produce a water balance using the local climate variables generated by the model. In particular the reference evapotranspiration ET_O can be computed using the Penman–Monteith approach as proposed by Allen et al. (1994). For that purpose, wind velocity was that observed at the reference station.

Computations are performed on a five-day time step in agreement with model capabilities to predict rainfall. The application has been performed for the period 1st January to 30th April, 1996. The evaluation of model capabilities to produce the Rain–ET_O balance was performed for the control station Granja (E4 in Fig. 1).

Results comparing the (Rain – ET_O) values computed from the modelled climatic variables with those obtained from observed climatic variables are presented in Fig. 9.

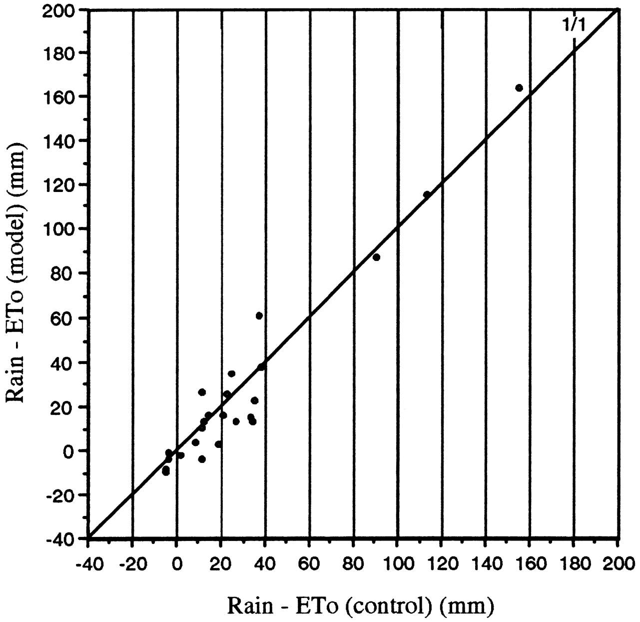

Fig. 9. Comparison of computed values for the water balance (Rain–ET_O) at control station E4, January–April 1996, using modelled and computed climatic data.

The regression is $y = 0.99x$, with $r^2 = 0.93$ and SE = 10.7 mm. SE for (Rain – ET_O) is close to the SE for rainfall (SE = 11.6 mm) which is explained by the dominance of rainfall over ET_O during this period (cumulative rainfall is 870 mm and cumulative ET_O is 170 mm).

5. Conclusions

Due to the spatial limitations of small island territories, the climate at regional scale can be considered as the uniform forcing regime that provides the external boundaries for the parameterisation of local scale climatic mechanistic simulation. This is confirmed by results of the application of a model to generate the fields of local climatic variables.

The evolution of the air state parameters during its progression over the islands can be well explained by the adiabatic mechanisms. The Foehn effect provides the simulation of the well-known climatic asymmetries, at the same altitude, from the windward to the leeward side. This is of particular importance for the simulation of air temperature and humidity fields, cloud cover, precipitation of orographic origin and, then, for the simulation of global radiation at local scale. However, the simulation capabilities of the model need to be improved regarding the prediction of daily global radiation. Improvements of rainfall simulation could also be considered if the application requires daily estimates.

The GIS environment has proved to be an excellent tool to combine spatially distributed parameters and the mathematics involved in the simulation of climatic mechanisms. To provide the orientation of the relief according to the direction of air masses circulation, the use of a RTM has proved to be essential. Using the capabilities of the GIS, namely integrating several spatially distributed variables, as it was tested for the simplified water balance application, shows that the model CIELO can combine all the variables and produce appropriate spatially distributed outputs. This may be particularly relevant for soil water balance computations when soil and vegetation parameters would be included in GIS format.

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