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THE POTENTIAL USE OF WEATHER GENERATORS IN PALÆOCLIMATIC AND PALÆOECOLOGICAL RESEARCH: THE SWELTER *(SYNTHETIC WEATHER ESTIMATOR FOR LAND USE AND TERRESTRIAL ECOSYSTEM RESEARCH)* MODEL*

S. P. Evans
Climate Change Unit, Soil Survey and Land Research Centre, Cranfield University, Silsoe, United Kindgom
E-mail: S.Evans@Cranfield.ac.uk

RIASSUNTO - *Il possibile impiego di generatori climatici nella ricerca paleoclimatica e paleoecologica: il modello SWELTER (*Synthetic Weather Estimator For Land Use And Terrestrial Ecosystem Research*)* - Il Quaternario *Italian Journal of Quaternary Sciences*, **9**(2), 1996, 643-648 - Viene descritta la struttura del modello SWELTER per introdurre una panoramica sul possibile impiego di generatori climatici nella ricerca paleoclimatica e paleoecologica. Con l'ausilio di un esempio, viene illustrata la versatilità di questi modelli per sviluppare dati di ingresso a modelli biologici e biofisici a carattere meccanicistico in grado di descrivere cambiamenti paesaggistici durante il Quaternario. In particolare viene evideziato il possibile impiego di modelli integrati e meccanicistici a livello di biosfera per ottenere simulazioni statisticamente indipendenti dai dati paleoecologici. Viene discussa la possibilità che l'approccio modellistico integrato possa fornire nuove ipotesi sulla potenziale dinamica degli ecosistemi terrestri che subiscono rapidi mutamenti ambientali nel complesso paesaggio del Quaternario.

ABSTRACT - *The potential use of weather generators in palæoclimatic and palæoecological research: the SWELTER (Synthetic Weather Estimator For Land Use And Terrestrial Ecosystem Research) model* - Il Quaternario *Italian Journal of Quaternary Sciences*, **9**(2), 1996, 643-648 - The structure of the SWELTER model is outlined and used to introduce an overview of the potential use of weather generator models in palæoecological and palæoclimatic research. The suitability of such models to develop climate inputs for process-based biological and biophysical models addressing issues of landscape change during the Quaternary is outlined and illustrated. In particular, the possible use of integrated biospheric process models to develop simulations which are statistically independent of the palæoecological record is highlighted. It is suggested that the integrated modelling approach could provide new insights into the potential dynamics of terrestrial ecosystems undergoing rapid environmental change in complex landscapes during the Quaternary.

Keywords: Weather generator, palæoecology, palæoclimatology, model, climate dynamics
Parole chiave: Generatore climatico; paleoecologia; paleoclimatologia; modello; dinamica climatica

1. INTRODUCTION

Process-based modelling of past biotic assemblages and landscape dynamics is increasingly used as a means of improving our understanding of mechanisms underlying spatial and temporal patterns observed in the palæoecological record. Such data have also provided a major source of background information for assessing the expected environmental impacts of climate change (IPCC, 1996). All models, whether empirical or process-based, require weather data as input, since the physical expressions of climate, primarily solar radiation, temperature and precipitation, are the driving forces which ultimately determine the nature of natural systems and processes. Currently, climate data used as input to process-based models and run to simulate Quaternary scenarios are obtained by perturbing present-day climatologies using (Δ-values, or 'differences compared to the present', the size of which is suggested by multi-proxy indicators (for instance COHMAP Members, 1988; Prentice *et al.*, 1992a; 1992b; 1993; Smith *et al.*, 1992; Huntley, 1993; Evans & Trevisan, 1995a). More recently spatially and temporally discrete indications on the size of this interval have been derived by statistically equilibrating the pollen record with modern pollen-plant-climate relationships.

However, such methods require large databases holding georeferenced instrumental data of 'average' current weather (*e.g.* Leemans & Cramer, 1991) which, for a variety of reasons (costs, data availability, computing power, issues of spatial and temporal scaling) can curtail their effective application (*e.g.* Hulme *et al.*, 1994) in process-based models. An alternative, and potentially complementary, approach to the use of such datasets is represented by weather generators. This option has so far received little attention from the palæoecological and palæoclimatic communities but is of growing interest amongst other researchers dealing with space-time dynamics of biotic and abiotic systems (Wilks, 1992; Woo, 1992; BAHC, 1994; IGBP, 1994).

Weather generators belong to the family of *stochastic-deterministic* models: synthetic time series are obtained by constraining the distribution of random numbers, hence stochastic, to the distribution of observed instrumental weather data inputted into the model, and which refers to a particular location. The constraint on the distribution of random numbers is obtained by inputting, together with the mean monthly value, the standard deviation as a measure of the variability around this mean, to which the first-order monthly auto-correlation, an indication of the 'historical memory' of the given

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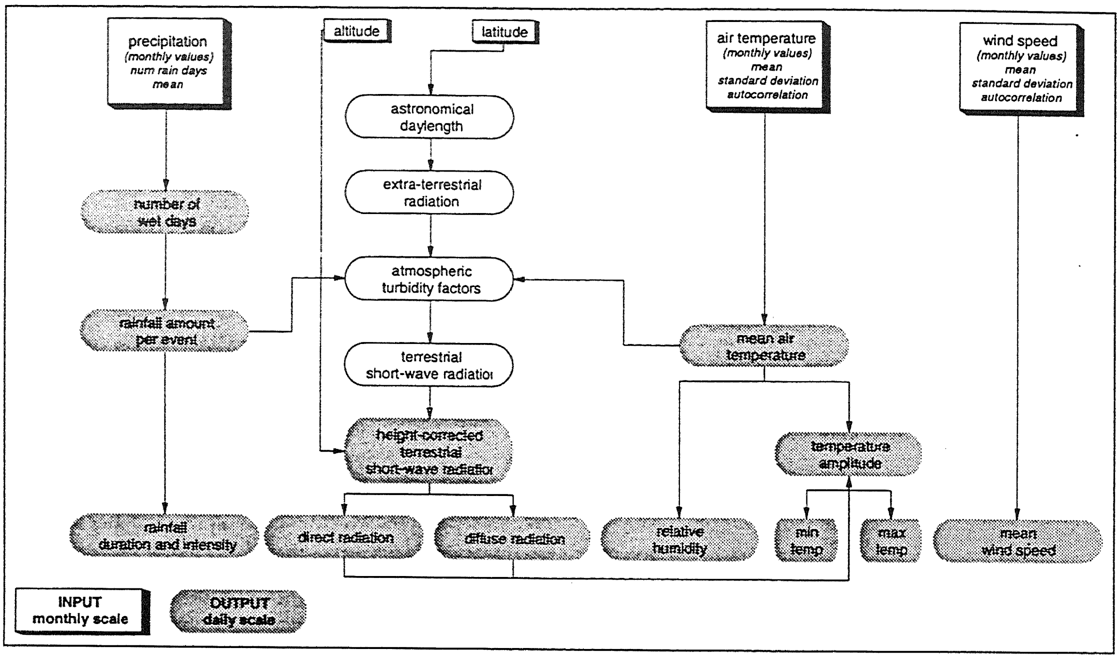

Fig. 1 - Structure of the SWELTER model. The figure provides the flow-diagram of the model and identifies inputs (❑) of instrumental data at the monthly scale and model outputs (shaded symbol) at the daily scale, together with intermediate values (open symbol) required to calculate successive steps.

Stuttura del modello SWELTER. La figura fornisce un diagramma di flusso del modello ed indica i dati di ingresso (❑) di dati strumentali a scala mensile e le uscite del modello (area retinata) a scala giornaliera, unitamente ai valori intermedi (area in bianco) necessari per il calcolo dei passaggi successivi.

variable, is also added. The purpose of constraining the random number distribution around the mean±standard deviation is to produce time series with means±standard deviations not significantly different from the input data, hence *deterministic.* Within this framework, empirically-based physical and biophysical relationships are used to develop synthetic time series of weather parameters which approximate the observed instrumental values. In the SWELTER model described below, monthly scale georeferenced instrumental weather data are used as the distribution within which the model generates synthetic time series of physically interpretable weather phenomena at different spatial and temporal scales.

The purpose of this paper is to outline the basic structure of the SWELTER (Synthetic Weather Estimator for Land use and Terrestrial Ecosystem Research) weather generator (Evans, 1996a and b, submitted) in the context of a broader discussion on the implications deriving from the use of weather generators inputting synthetic weather to process-based models applied to palæoecological research objectives. An illustration on the potential use of the model in ecological research is also outlined.

2. THE MODEL

2.1 Model structure

SWELTER is a three-dimensional model for generating daily or hourly synthetic weather time series, annual or pluri-centennial in length, within differently-scaled georeferenced spatial cells of known elevation. The model, extensively described elsewhere (Evans, 1996a, submitted), has been developed as a VisualBasic™ programme running on a PC platform. Model structure is shown in Figure 1: inputs identify a georeferenced spatial unit (latitude, longitude, elevation, slope and aspect) characterised by an 'average' weather pattern (precipitation, temperature and wind speed) for each month over a number of years. The model outputs up to 18 georeferenced weather variables, which are downloaded into ASCII-format files; version 2 (Evans, in prep.) will also include sub-modules for auto-calibration, statistical assessment of goodness-of-fit for validation purposes and graphics display.

Within the model synthetic weather time series can be coupled to an 'average plant cover' of known composition (tree height, leaf area index) and physiological characteristics (stomatal water conductance) which together with the average atmospheric CO_2 concentration, is used to generate estimates of reference evapotranspiration. In its current version a suite of evapotrans-piration formulæ are available, most notably the complete Penman-Monteith equation. This equation closely approximates plant water demand by taking into account a range of physical (notably long- and short-wave solar radiation, reflectance, air and soil temperature, relative humidity, saturated/unsaturated water vapour and air pressure, wind speed, atmospheric CO_2 concentration) and biophysical (notably stomatal and leaf boundary layer resistance to water diffusion) parameters to calculate water evaporation from the soil surface, canopy transpiration and evaporation from a saturated plant canopy.

2.2 Model validation and sensitivity analysis

Extensive validation of the SWELTER model under current climates has been carried out using instrumental meteorological data from sites in the UK and Europe (Evans, 1996a, submitted). The predictive ability of the model has been assessed using a suite of statistical goodness-of-fit tests; results indicate that estimated values are very close to the instrumental inputs, suggesting an overall high predictive ability of the model. Sensitivity analysis (Evans, 1996b, submitted) has also been carried out for the 3 input weather variables (precipitation, mean air temperature and wind speed), by varying values at predefined intervals within a constant scenario. Results indicate that the model responds correctly even at extreme value ranges; beyond the prescribed value range the model ceases to function.

2.3 Model application

As an illustration of the model's potential to generate high-resolution (10 km) synthetic weather scenarios and ecologically relevant parameters based on these scenarios at large spatial scales, Figure 2 illustrates the Potential Soil Moisture Deficit (PSMD) in G.B. under the current climate (1961-1990 baseline) at a resolution of 10 km, predicted by the model. PSMD is defined as the difference between reference evapotranspiration and rainfall, where reference evapotranspiration is calculated using the Penman-Monteith equation assuming a uniform land cover and an atmospheric CO_2 concentration of 360 ppm.

3. WEATHER GENERATOR MODELS IN PALÆOCLIMATIC AND PALÆOECOLOGICAL RESEARCH: APPLICATIONS AND IMPLICATIONS

The application of weather generator models such as SWELTER is perceived as having both potential applications and implications for palæoclimatic and palæoecological research.

A major application in palæoecology stems from the model's ability to downscale instrumental weather databases at coarse spatial and temporal resolutions to finer resolutions, by developing elevationally sensitive and georeferenced synthetic weather series. Bearing in mind that for palæoecological applications the quality and the chronological resolution of the proxy data underpinning Δ-values will ultimately determine the quality of the achievable results, downscaling may be undertaken in two ways:

- *linear* downscaling, obtained by integrating Δ-values with current climates to generate palæo-data sets of synthetic weather. This approach could lead to the development of georeferenced, spatially- and elevationally-averaged synthetic palæoclimatic data-sets at regional scales, which incorporate the regional variability inherent in the proxies (*e.g.* Huntley, 1993). Such data-sets would represent an important contribution towards enhancing the role of process-based models of plant dynamics at plot and landscape scales (*e.g.* Prentice *et al.*, 1991; Sykes *et al.*, 1992; Evans, 1996) or biophysical models (for instance Prentice *et al.*, 1993; Evans & Trevisan, 1995b; Huntley *et al.*, 1995, 1996a) in paleoecological research;
- *mechanistic* downscaling, obtained by modifying one or more of the physical and biophysical assumptions embedded in the model. For instance, spherical geometry is employed to quantify incoming solar radiation as a function of planetary eccentricity and obliquity (Berger, 1978), thus allowing daily estimates of terrestrial solar radiation through time to be approximated for sites worldwide; changes in cloudiness may also be introduced to assess impacts on biomass production via photosynthesis. A key feature is the model's ability to approximate the effects of changes in atmospheric CO_2 concentration on the theoretical water requirements of plants, as approximated by the evapotranspiration equations. The experimental literature indicates that increasing CO_2 results in higher Water Use Efficiency (WUE), defined as the ratio of weight of dry matter gain (Marks & Strain, 1989) to the amount of water transpired, or the rate of assimilation to the rate of transpiration (Eamus, 1991). Furthermore, under different CO_2 concentrations this ratio varies, with a resulting change in the amount of water required to produce biomass, and which will in turn alter the plant's demand on soil water and its overall sensitivity to dry or wet soil conditions. It has also been shown that in the medium term parallel physiological mechanisms of adaptation concur to mitigate this sensitivity to variations in CO_2, for instance by increasing/decreasing stomatal

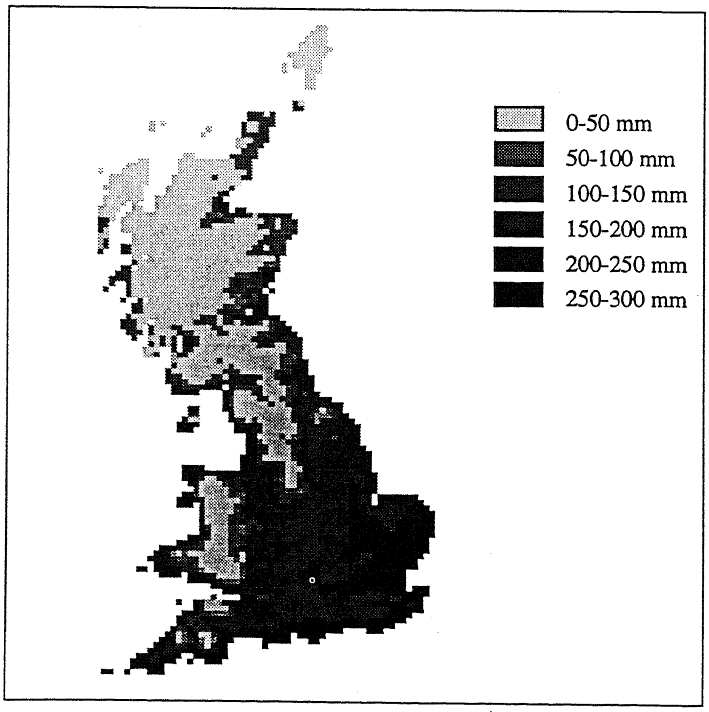

Fig. 2 - Application of SWELTER in G.B. under current climate (1961-1990 baseline) to calculate the Potential Soil Moisture Deficit (PSMD) at a resolution of 10 km: PSMD is defined as the difference between reference evapotranspiration and rainfall.

Esempio applicativo del modello SWELTER in Gran Bretagna con il clima attuale (intervallo 1961-1990) utilizzato per calcolare il Potenziale Deficit Idrico del Suolo (PSMD) ad una risoluzione spaziale di 10 km; PSMD viene definito come la differenza tra il fabbisogno idrico teorico delle piante (EPT) e le precipitazioni.

density per leaf unit area (Beerling & Woodward, 1995; Woodward & Kelly, 1995). The SWELTER model incorporates a suite of evapotranspiration equations which are sensitive to the level of atmospheric CO_2 and to changes in leaf morphology. Synthetic time series of reference evapotranspiration can therefore be produced to explore the effects on of CO_2 variations on the theoretical water demand of plants. Furthermore inputs mimicking leaf morphology adaptation to new conditions can be progressively introduced in a model run spanning long time periods. Such applications may be of interest to plant palæoecologists who, for instance, use variations in potential evapotranspiration of reconstructed Quaternary vegetation to indicate fluctuations in local climate conditions (*e.g.* Huntley *et al.*, 1996b).

The proposed distinction between linear and mechanistic perturbations rests on a broader consideration of the nature and quality of information on palæoclimate which can be derived from multi-proxy indicators. The majority of proxies provide quantitative indications primarily for 2 weather parameters, namely temperature and, to a lesser extent, precipitation, as well as indications on atmospheric CO_2. Such data refer to average climate differences spanning perhaps decade and in most cases at least a century; only for limited spatial areas where the chronological framework allows such precision (for instance laminated sediments and tree rings), can the resolution be improved to encompass annual or seasonal differences. In general however, little or no quantitative data are forthcoming on intra-annual variations. Current observational evidence and, to a less reliable extent, simulations from process-based models run under current climates, indicate that even minor differences in the intra-annual distribution of weather, repeated over a period of time, can result in significant differences in stand growth, which in turn can lead to modified stand composition and structure, substantially influencing landscape processes. Given the structure of weather generators such as the SWELTER model, which allows both linear and mechanistic perturbations to be introduced, suitable synthetic scenarios may be developed which allow the impact on terrestrial ecosystem dynamics of different scenarios of intra-annual variability to be investigated. This would be achieved by introducing such scenarios into appropriate process-based biological or biophysical models of landscape processes; under such an approach the effects of different weather scenarios on simulated stand dynamics could then be compared with the palæoecological record to investigate the degree of climate variability which the observational evidence may be encompassing. One major advantage of an integrated, process-based approach is that statistical independence between the simulated and the observed datasets is maintained, given that no model input is directly derived from the observed data. Consequently appropriate and robust statistical techniques may be introduced to verify the degree of acceptability of individual simulations against palæoecological data. This has not traditionally been the case, and the lack of an appropriately robust validation methodology has frequently been considered to undermine the efficacy of the palæoecological record as a means of assessing environmental change impacts (*e.g.* IPCC, 1996).

4. CONCLUSIONS

Weather generators such as the SWELTER model can be used to develop elevationally sensitive synthetic weather time series, at different scales of spatial and temporal resolution, for use in research investigating past, current and future climate impacts on environmental changes. In palæoecological research, synthetic weather time series can be used as input to process-based models to investigate landscape processes during the Quaternary. It is anticipated that such models have potentially major implication for palæoclimatic and palæoenvironmental research and could foreseeably lead to the development of standard synthetic palæoclimatic weather datasets at different spatial and temporal resolutions. Furthermore integrated models, combining weather generators with appropriate biological and biophysical process-based models may be used as investigative tools in their own right, for example to address topical issues such as the variability of the climate system underpinning terrestrial ecosystem dynamics during the Quaternary at high space-time resolutions. It is suggested that integration between weather generators and process-based models of ecosystem dynamics operating at different levels of complexity would further strengthen the role of the Quaternary as a suitable backdrop against which to assess the impacts of ongoing climate change phenomena.

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