ΠΡΑΚΤΙΚΑ 6ου ΔΙΕΘΝΟΥΣ ΣΥΝΕΔΡΙΟΥ ΠΕΡΙΒΑΛΛΟΝΤΙΚΗΣ ΕΠΙΣΤΗΜΗΣ ΚΑΙ ΤΕΧΝΟΛΟΓΙΑΣ

PROCEEDINGS OF THE 6th INTERNATIONAL CONFERENCE ON ENVIRONMENTAL SCIENCE AND TECHNOLOGY

ΤΟΜΟΣ Β΄
VOLUME B΄

ΕΚΔΟΣΗ: Θ. ΛΕΚΚΑΣ
EDITOR: T. LEKKAS

ΤΜΗΜΑ ΠΕΡΙΒΑΛΛΟΝΤΟΣ

ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΙΓΑΙΟΥ

GLOBAL NEST

ΠΥΘΑΓΟΡΕΙΟΝ ΣΑΜΟΥ
30 ΑΥΓΟΥΣΤΟΥ
2 ΣΕΠΤΕΜΒΡΙΟΥ 1999

DEPT. OF ENVIRONMENTAL STUDIES
UNIVERSITY OF THE AEGEAN

GLOBAL NEST

PYTHAGORION, SAMOS, GREECE
30 AUGUST-2 SEPTEMBER 1999

ISSN 1106-5516

THE USE OF CIRCULATION PATTERNS TO ESTIMATE LOCAL PRECIPITATION UNDER CLIMATE CHANGE

Dionysia Panagoulia[1] and George Dimou[2]
[1] National Technical University of Athens, Department of Civil Engineering,
Division of Water Resources – Hydraulic and Maritime Engineering,
5 Iroon Polytechniou, 15780 Zographou, Athens, Greece
e-mail: dpanag@central.ntua.gr
[2] Dr civil engineer, 7 Voutyra, 16673 Voula, Athens, Greece

ABSTRACT

A stochastic approach is developed to estimate at three locations (catchment elevation zones) the effect of climate change on daily precipitation. The approach is based on the use of daily atmospheric circulation patterns (CPs) and the linkage between types of CPs and daily precipitation. Historical data and 10-year outputs of the Max Planck Institute general circulation model for the $1\times CO_2$ and $2\times CO_2$ cases are used. Nine CP types for the winter and summer half years are obtained to characterize large-scale climatic forcing in Mesochora catchment in Central Greece. Under the continental climate of Mesochora catchment the effect of the $2\times CO_2$ case on elevation zone precipitation is variable and significant: the probability of daily precipitation slightly increases, whereas the mean and variance decrease considerably during the summer season.

Η ΧΡΗΣΗ ΤΩΝ ΤΥΠΩΝ ΚΑΙΡΟΥ ΣΤΗΝ ΕΚΤΙΜΗΣΗ ΚΑΤΑΚΡΗΜΝΙΣΜΑΤΟΣ ΤΟΠΙΚΗΣ ΚΛΙΜΑΚΑΣ ΓΙΑ ΚΛΙΜΑΤΙΚΗ ΑΛΛΑΓΗ

Διονυσία Παναγούλια[1] και Γιώργος Δήμου[2]
[1] Εθνικό Μετσόβιο Πολυτεχνείο, Τμήμα Πολιτικών Μηχανικών,
Τομέας Υδατικών Πόρων – Υδραυλικών & Θαλάσσιων Έργων,
Ηρώων Πολυτεχνείου 5, Ζωγράφου 15780, Αθήνα
e-mail: dpanag@central.ntua.gr
[2] Δρ πολιτικός μηχανικός, Βουτυρά 7, Βούλα 16673.

ΠΕΡΙΛΗΨΗ

Αναπτύσσεται ένα στοχαστικό προσομοίωμα για να εκτιμήσει σε τρεις επιφάνειες (υψομετρικές ζώνες λεκάνης) τις επιπτώσεις της κλιματικής αλλαγής στο ημερήσιο κατακρήμνισμα. Το προσομοίωμα αναλύει τους τύπους της ατμοσφαιρικής κυκλοφορίας και τους συνδέει με το ημερήσιο κατακρήμνισμα. Χρησιμοποιούνται δεδομένα ιστορικά και 10-ετους περιόδου που προέκυψαν από το προσομοίωμα γενικής κυκλοφορίας του Max Planck Institute για τις σειρές $1\times CO_2$ και $2\times CO_2$. Εξετάζονται εννέα τύποι ατμοσφαιρικής κυκλοφορίας για τη θερινή και χειμερινή περίοδο στη λεκάνη της Μεσοχώρας. Για το ηπειρωτικό κλίμα της λεκάνης, το σενάριο $2\times CO_2$ αλλάζει σημαντικά το ημερήσιο κατακρήμνισμα; η πιθανότητα εμφάνισης αυξάνεται ενώ η μέση τιμή και η σκέδαση μειώνονται σημαντικά στη θερινή περίοδο.

1. INTRODUCTION

Atmospheric general circulation models (GCMs) are currently the only global models which can be used to estimate the effects of increasing greenhouse gases on climate. Results from GCMs suggest a globally averaged temperature increase of 1 to 4 degrees Celsius (°C) in the next 40-60 years, but do not agree with the spatial distribution of increases in temperature and changes in precipitation [5].

For water resource management purposes, predicted changes in precipitation from GCMs cannot be reliably translated into specific changes in precipitation over a watershed. Computational requirements limit the spatial resolution of GCMs to nodal spacing of several degrees latitude by longitude. A resolution increase of a factor 10 or more would be needed in the present GCMs to give realistic regional projections of future climate. This increase in resolution may not be available for another 20 years, emphasizing the need the GCM outputs to be downscaled (disaggregated to a small spatial extent) for use in predictions of regional climate change.

This study examines the time series of daily GCM-produced atmospheric circulation patterns (CPs), to estimate local precipitation under climate change. The daily precipitation assessed for three elevation zones (upper, middle, lower) of the Mesochora catchment over the period 1972-1986 is considered [7]. The climate change is analyzed through GCM outputs for $1\times CO_2$ and $2\times CO_2$ evaluated in a regional scale with a downscaling technique. The semi-empirical downscaling approach is used. This is based on the stochastic modeling of daily atmospheric Circulation Patterns (CPs) and the linkage between CP types and local precipitation. The outputs of atmospheric component (ECHAM T21) of the coupled ocean-atmosphere GCM of the Max Planck Institute for Meteorology (MPI), Hamburg, Germany [3] are used.

The classification and statistical modelling of daily circulation patterns are described in the next section. Then, daily CPs are classified and analysed for historical and GCM produced data for $1\times CO_2$ and $2\times CO_2$ scenarios. The space-time precipitation model is presented. The methodology section is followed by the analysis of results. A discussion and conclusions section integrates the paper.

2. CLASSIFICATION AND STATISTICAL MODELING OF DAILY CIRCULATION PATTERNS

Three types of daily CP data are used [6].

(a) Historical data are represented by the Meteorological Center (NMC) grid point analyses of the height of 500 hPa pressure fields available from the National Center for Atmospheric Research (NCAR). The analysis is based on daily values (12 ^{00} UT) at 35 points on a grid covering the sector 30° -70° N, 20° W-40° E for the period January 1948 - June 1989.

(b) A 10-year long data series for the same pressure level was obtained from the output of the MPI GCM corresponding to the $1\times CO_2$ scemario,

(c) An equivalent series was obtained from the $2\times CO_2$ scenario.

Classification schemes of spatial meteorological variables are often based on macrocirculation patterns characterized by the spatial distribution of either sea level air pressure field or low or middle tropospheric pressure heights. One frequent classification approach is the so-called objective classification method [4]. Objectivity means here that a given algorithm automates the data processing although the choice and application of a given algorithm is subjective.

The periods from April to September (summer half year) and from October to March (winter half year) were examined separately and pressure height values at each grid point were standardized to exclude the annual cycle. Nine CP types in both half years were defined using principal component analysis coupled with k means clustering technique. Motivation of these techniques and the choice of the number of CP types are described in Matyasovszky *et al.* [6]. The nine CP types for winter and summer seasons are presented in the Appendix (Figures 1-2).

A statistical model of daily CP types should reproduce the relative frequencies and the persistence properties of the various types. These properties are described by a Markov chain model. Such a model is characterized by a transition probability matrix, that is, in the present case, the matrix of transition probabilities from one CP type to another. Let a random variable A_t at time t taken on states a_1, a_2, ..., a_I, where I is the number of circulation pattern types. The transition probability from pattern a_j to a_i is written as:

$$q_{ij} = P(A_t = a_i \,/\, A_{t-1} = a_j) \quad i, j = 1, \cdots, I$$

If the duration of CP types is exponential, as it appears to be the case here, then a Markov chain is obtained. Otherwise, a more complicated semi-Markov chain must be used as in Bardossy and Plate [1].

3. SPACE-TIME PRECIPITATION MODEL

To reproduce the space-time statistical structure of local precipitation, a suitable model should be chosen. Autoregressive processes represent a well-developed and commonly used tool to model time series. They have been developed principally for Gaussian processes, but precipitation does not usually follow a Gaussian distribution. Therefore, it is desirable to construct a transformation establishing a relationship between the distribution of a local precipitation and a normal distribution. Let the vector $Z(t) = (Z(t,u_1), Z(t,u_1), \cdots, Z(t,u_K))$ represent a daily precipitation at locations u_1, u_2,... u_K and time t and let $W(t)$ be a K-dimensional normal random vector at time t. The time dependency of $W(t)$ is described using first-order autoregressive (AR(1)) processes. The transformation of a precipitation series into normal vector $W(t)$ is described and discussed in detail in Matyasovszky *et al.* [6].

The Markov chain model for CP type sequences, the AR(1) process and the inverse of transforming of the precipitation element into $W(t)$ were used to simulate the time series of precipitation amounts. Statistical properties of the precipitation data series were compared to the properties of historical data sets and a good reproduction was found [2].

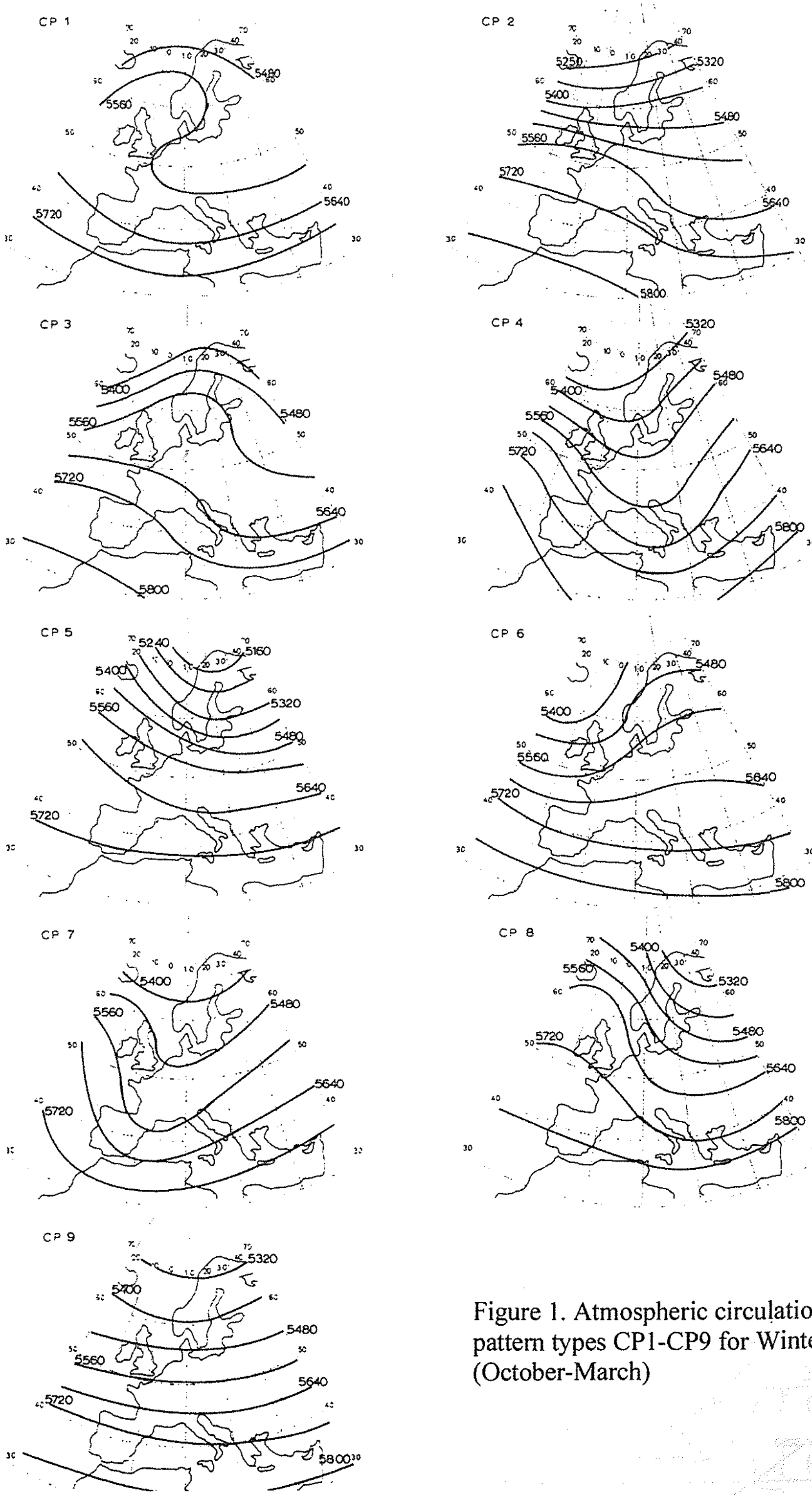

Figure 1. Atmospheric circulation pattern types CP1-CP9 for Winter (October-March)

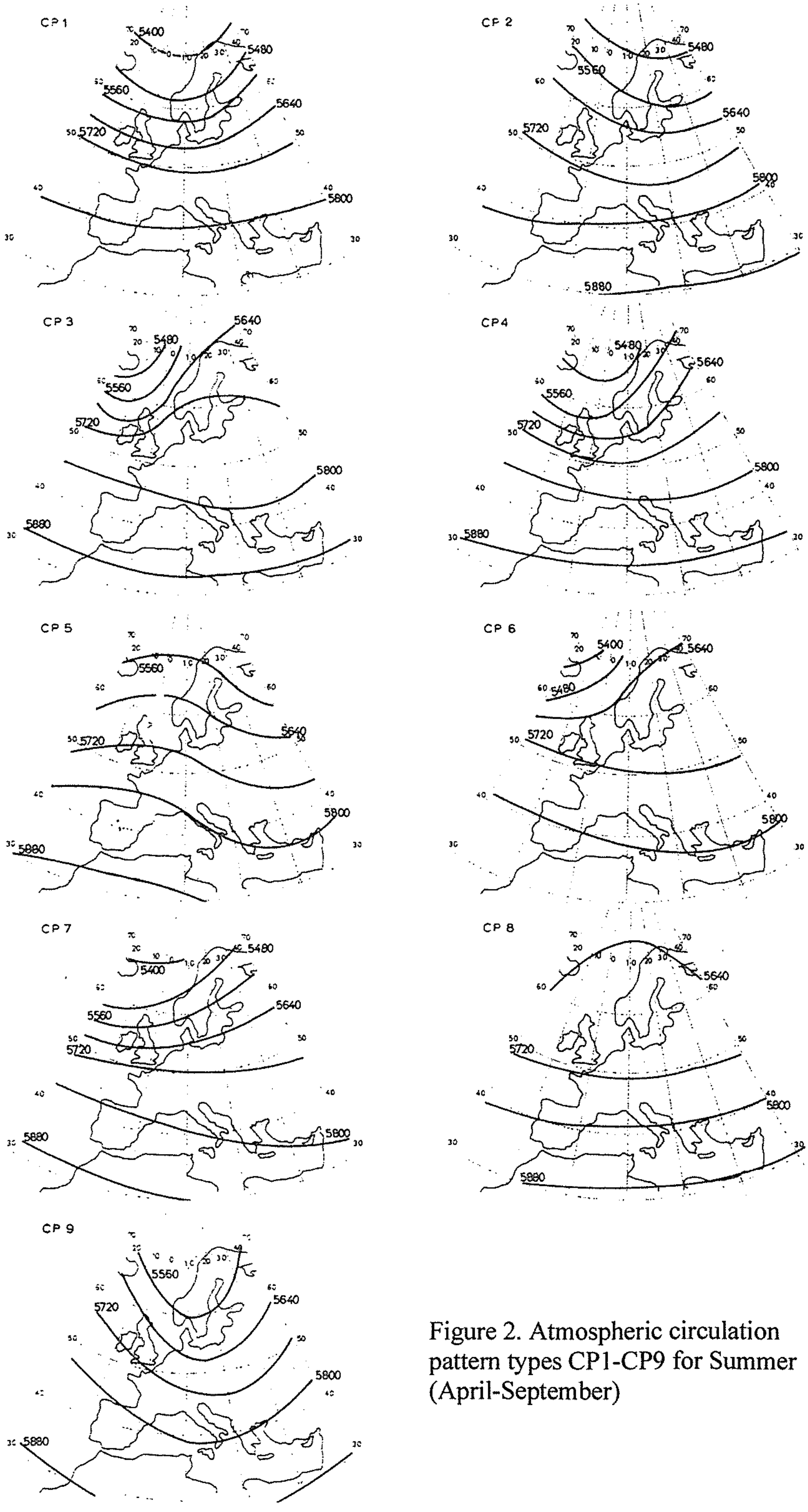

Figure 2. Atmospheric circulation pattern types CP1-CP9 for Summer (April-September)

4. CONSIDERATIONS OF THE PRESSURE FIELD HEIGHT

Within each CP type, daily precipitation depends on the actual spatial average height z of the 500 hPa pressure field. This relationship can be used to estimate the effect of climate change on local precipitation. Thus, the spatially averaged pressure height is included in the analysis and the annual cycle of the pressure height is considered as an analogy of the difference between present and $2\times CO_2$ climates. The relationship between the probability distribution of daily precipitation and spatial average height is described using historical data.

Because the average heights of (a) the $1\times CO_2$ and $2\times CO_2$ cases for every type and (b) the historical and $1\times CO_2$ CPs for several CP types, may change, the local precipitation statistics reflecting the $2\times CO_2$ scenario were estimated in two steps. First, the differences of the Fourier coefficients between $1\times CO_2$ and $2\times CO_2$ cases were calculated and secondly the Fourier coefficients obtained from the historical data were corrected using the above differences to arrive at the probability distribution reflecting the $2\times CO_2$ scenario [6].

5. RESULTS

Four data series are compared in order to evaluate the local effect of climate change on precipitation over three elevation zones (upper, middle, lower) of the Mesochora catchment. The first is the historical data set, the second is a simulated data set based on the precipitation model, and the third and fourth are simulated data sets corresponding to $1\times CO_2$ and $2\times CO_2$ cases respectively.

The results for the probability of daily precipitation occurrence are summarized in Table 1. The simulation based on historical data very slightly over- or under-estimated the probability, but these differences are not considerable. This discrepancy may be attributed to the use of different data sets for the parameter estimation and simulation. Simulated probabilities corresponding to the $1\times CO_2$ and $2\times CO_2$ cases were almost statistically unchanged, except for the probability estimated for the upper zone $1\times CO_2$ case in summer season.

Table 2 shows the simulation of historical data resulted in a systematic small under-estimation of the daily mean rainfall. The $1\times CO_2$ simulation produced a considerable decrease in both seasons, while the $2\times CO_2$ simulation generated a significant decrease for three elevation zones only in summer season.

Table 1 Probability of daily precipitation occurrence estimated for historical data and simulated data corresponding to historical, $1\times CO_2$ and $2\times CO_2$ cases.

Precipit	Winter (October-March)				Summer (April-September)			
Zone	precipitat	Simulated historical	Simulated $1\times CO_2$	Simulated $2\times CO_2$	Historical	Simulated historical	Simulated $1\times CO_2$	Simulated $2\times CO_2$
Upper	0.541	0.539	0.530	0.538	0.386	0.397	0.282	0.446
Middle	0.598	0.624	0.600	0.654	0.449	0.485	0.371	0.441
Lower	0.695	0.670	0.692	0.684	0.496	0.470	0.374	0.477

TABLE 2. Mean of daily positive precipitation (mm) estimated for the historical data and simulated data corresponding to historical, 1×CO_2 and 2×CO_2 cases.

Precipitat	Winter (October-March)				Summer (April-September)			
Zone	Historical	Simulated historical	Simulated 1×CO_2	Simulated 2×CO_2	Historical	Simulated historical	Simulated 1×CO_2	Simulated 2×CO_2
Upper	13.1	12.3	10.7	13.0	7.7	7.0	5.4	6.8
Middle	12.3	11.4	10.0	11.0	7.1	6.3	4.9	6.3
Lower	11.1	11.0	8.9	10.3	5.2	5.5	3.2	4.8

Table 3 shows that the historical simulation and 1×CO_2 case resulted in reduced dispersions of daily rainfall amount. The 2×CO_2 case decreased the dispersions, except for the Upper zone in the winter.

Tables 4 and 5 summarize the results of the correlation matrices of daily mean precipitation in two seasons (winter and summer).The stochastic model appears to simulate well the spatial dependency of the precipitation.

6. DISCUSSION AND CONCLUSIONS

A space-time precipitation model was coupled with the stochastic simulation of daily CPs to generate time series of daily precipitation occurrence with and without climate change at three elevation zones (subareas of the Mesochora catchment). To this end, in addition to historical data, daily large-scale atmospheric pressure outputs of the GCM of the Max Planck Institute in Hamburg, Germany, for the 1×CO_2 and 2×CO_2 cases were used. The approach is based on the statistical relationship between daily CP types and daily precipitation. The application results indicate a spatial variable and a considerable

TABLE 3. Dispersions of daily precipitation (mm) estimated for the historical data and simulated data corresponding to historical, 1×CO_2 and 2×CO_2 cases.

Precipitat	Winter (October-March)				Summer (April-September)			
Zone	Historical	Simulated historical	Simulated 1×CO_2	Simulated 2×CO_2	Historical	Simulated historical	Simulated 1×CO_2	Simulated 2×CO_2
Upper	17.0	15.8	14.7	17.3	10.9	9.4	7.2	8.3
Middle	16.5	15.2	13.7	15.9	10.4	9.4	8.5	8.6
Lower	16.6	15.9	13.9	15.2	9.2	12.6	5.6	7.5

TABLE 4. Correlation matrix of daily mean precipitation in winter. (The (i,j)-th element of the diagonal matrix shows the correlation between i-th and j-th precipitation zones)

Historical			Simulated historical			Simulated 1×CO_2			Simulated 2×CO_2		
1.0	0.680	0.718	1.00	0.628	0.475	1.0	0.608	0.447	1.0	0.592	0.439
0.680	1.0	0.922	0.628	1.0	0.773	0.608	1.0	0.736	0.592	1.0	0.746
0.718	0.922	1.0	0.475	0.773	1.0	0.447	0.736	1.0	0.439	0.746	1.0

TABLE 5. Correlation matrix of daily mean precipitation in summer. (The *(i,j)*-th element of the diagonal matrix shows the correlation between *i*-th and *j*-th precipitation zones)

Historical			Simulated historical			Simulated $1\times CO_2$			Simulated $2\times CO_2$		
1.0	0.716	0.678	1.00	0.500	0.386	1.0	0.387	0.324	1.0	0.406	0.280
0.716	1.0	0.913	0.500	1.0	0.649	0.387	1.0	0.680	0.406	1.0	0.630
0.678	0.913	1.0	0.386	0.649	1.0	0.324	0.680	1.0	0.280	0.630	1.0

effect of climate change on the distribution of daily precipitation in the Mesochora elevation zones.

The following conclusions can be derived:

- A Markov model can describe the occurrence of daily CP; the difference between the relative frequencies and Markov properties of CPs corresponding to $1\times CO_2$ and $2\times CO_2$ cases are not greater than the differences between estimates from historical data and the $1\times CO_2$ case.
- The stochastic climatological model reproduces local precipitation conditions.
- The local response to climate change varies in the three elevation zones.
- Time series of local precipitation under climate change can also be generated. The summer season precipitation is characterized by a significant decrease of mean and variance.
- A slight increase can be observed in the probability of precipitation occurrence.
- For the Mesochora catchment a more variable precipitation climate is detected for the $2\times CO_2$ scenario.

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