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Climate Change Scenarios for the Mediterranean: A Basis for Regional Impact Assessment

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1. Introduction

1.1 General circulation models and climate change scenarios

General Circulation Models (GCMs) are considered to provide the best basis for estimating future climates that might result from anthropogenic modification of the atmospheric composition. Thus they provide the basis for the construction of climate change scenarios, which should be viewed as "internally-consistent pictures of a plausible future climate" rather than as predictions of future climate (Wigley *et al*., 1986). GCM output cannot, however, be widely or directly used in many impact assessments because of their relatively coarse spatial scale (typically 300 km for the current generation of models). Impact studies have also created a growing demand for climate scenarios with a high temporal resolution, i.e. for information at the daily, or shorter, time scale. Moving from the global to the regional scale, and from the annual to the monthly and ultimately the daily scale, confidence in the reliability of GCM output tends to diminish (von Storch *et al*., 1993). While a particular GCM may be able to successfully reproduce observed mean monthly or seasonal temperature, for example, it is likely to be less successful in reproducing daily temperature variability, particularly the higher-order statistics such as standard deviations and extreme values (Palutikof *et al*., 1997).

This is illustrated in Figure 1 which shows observed daily mean temperature data for Nova Siri Scalo in southern Italy plotted against 1970-79 model data for the nearest grid point (representing a sea box), the nearest land grid point, and values interpolated from the 16 surrounding grid points. In comparison to observations, the sea box values (and the interpolated values) have a very small seasonal cycle, and the day-to-day temperature variability is too low. Maximum temperature values are too low and minimum temperature values are too high. At the nearest land grid box, both maximum and minimum temperature are too low compared to observations. None of these series would provide an adequate basis for impacts analysis.

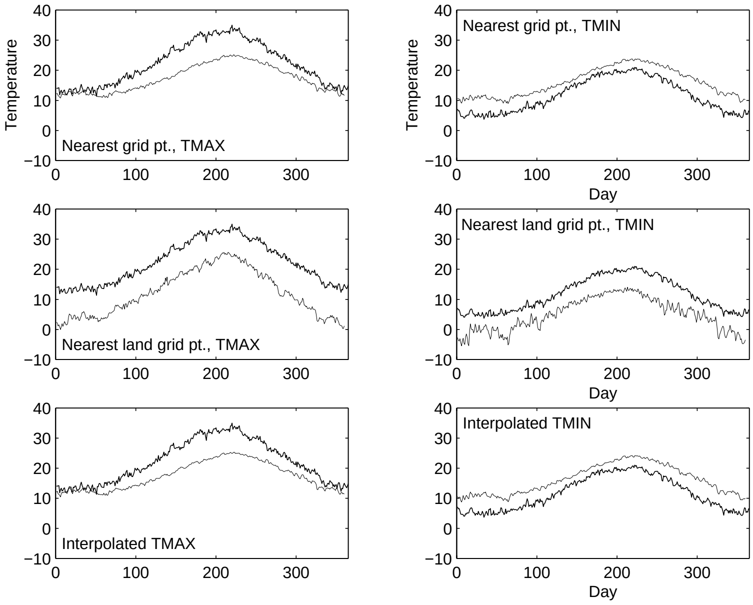


Figure 1: Nova Siri Scalo daily mean temperature observations (thick line) for 1970-79 plotted against 1970-79 HadCM2SUL GCM data (thin line) for the nearest grid point (a sea box), the nearest land grid point, and values interpolated from the 16 surrounding grid points.

In order to overcome these problems of mismatch in scale and of reliability, techniques for downscaling GCM output have been developed. Downscaling can be defined as “sensibly projecting the large-scale information on the regional scale” (von Storch *et al.*, 1993). A number of different downscaling methods have been proposed and can be divided into two general categories; model-based and empirical (Hewitson and Crane, 1996). The first approach, dynamical downscaling, involves nesting a finer-scale Regional Climate Model (RCM) within a GCM (Christensen *et al.*, 1997; Jones *et al.*, 1997; Giorgi and Mearns, 1999). The second approach, statistical downscaling, requires the identification of relationships between the observed large-scale and regional climate, which are then applied to large-scale GCM output. It encompasses methods based on multiple regression, canonical correlation and studies in which circulation classifications are used to describe the large-scale climate (Hewitson and Crane, 1996; Wilby *et al.*, 1998).

1.2 The MEDALUS regional and target area scenarios

Statistical downscaling methods have the advantage of requiring fewer data inputs and computing resources than dynamical methods. They have, therefore, been used by the Climatic Research Unit (CRU) to develop climate scenarios as part of the EU-funded Mediterranean Desertification and Land Use (MEDALUS) projects (see the MEDALUS III Final Report, Project 3 – Regional Indicators, Modules 3.10.2 and 3.11.2; available on-line at http://www.medalus.leeds.ac.uk/endreports/index.html). Two types of scenarios have been developed. First, regional scenarios for the Mediterranean region as a whole (see Section 2) and, second, scenarios at the river-basin scale for two of the MEDALUS target areas, the Guadalentin in southeast Spain and the Agri in southern Italy (see Section 3). All the scenarios are based on the HadCM2SUL experiment performed with the UK Hadley Centre GCM (Johns *et al.*, 1997). This transient response model has a spatial resolution of 2.5° latitude by 3.75° longitude. In the HadCM2SUL experiment atmospheric concentrations of CO_2 are based on historical data up to the present, and then increased in line with the Intergovernmental Panel on Climate Change scenario IS92a. Thus results can be related to a calendar date. The direct negative forcing effects of sulphate aerosols are also represented (Mitchell and Johns, 1997).

2. Regional Scenarios

2.1 Introduction

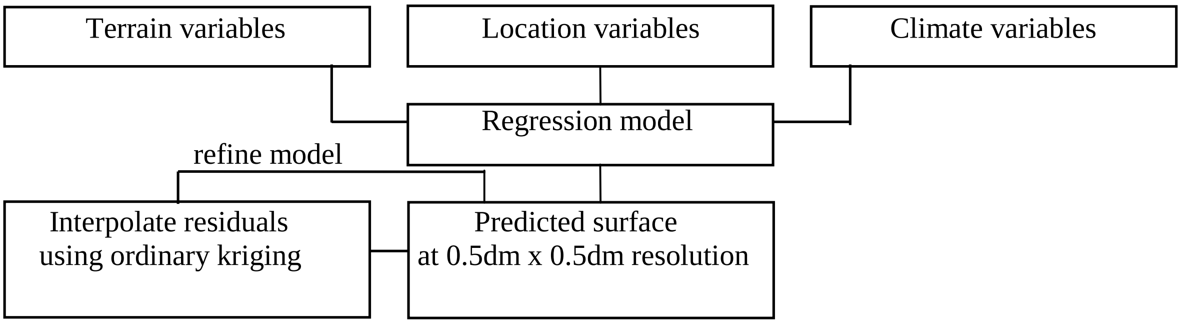
Scenarios of the change in mean seasonal temperature and precipitation over the whole Mediterranean have been constructed (see MEDALUS III Final Report, Module 3.11.2) using the method described by Palutikof and Wigley (1996) which harnesses the natural variability in station data. Results from several GCMs are combined, on the assumption that no one model can be considered superior to the others. The resolution of these scenarios is limited by the availability of observed station data. An alternative method, based on a Geographical Information System (GIS), which permits the construction of regional scenarios at a higher spatial resolution has been developed as part of the MEDALUS work and is described below.

2.2 GIS-based scenarios

The possibilities of using a GIS to spatially interpolate climate data from point sources (either station observations or GCM grid points) in the Mediterranean Basin, using information such as height above sea level, distance to the sea, and latitude/longitude as predictors have been explored (Agnew and Palutikof, 2000; MEDALUS III Final Report, Module 3.11.2). This approach has been successfully used to map observed seasonal means of temperature and precipitation and possible changes in the ‘observation’ surface for the periods 2030-39 and 2090-99, at a resolution of about 1 km, i.e. to produce high-resolution seasonal scenarios.

A two stage methodology was devised for this downscaling and is summarised in Figure 2. In the first stage, observed temperature and rainfall data (for 248 temperature sites and 289 precipitation sites averaged over the period 1952-89) were interpolated from the station locations to a resolution of 0.5 dm (decimal minutes) using stepwise multiple regression and terrain and location predictors. Latitude and elevation were found to be the most powerful predictors of local climate, while a measure of coastality also improved the fit. Finally, kriging was used to interpolate the residuals from the regression models. This increased the variance explained and reduced the root mean square error. Even with this refinement, validation reveals the temperature surfaces to be more accurate than the precipitation surfaces. The coefficients of determination (R^2) for temperature range from 0.87 in summer to 0.97 in winter. The poorer results for precipitation (with R^2 ranging from around 0.46 in autumn to 0.94 in summer) are not surprising given the strong spatial variability inherent in precipitation data and a bias in the distribution of precipitation sites towards lowland locations.

Stage I: Mapping observed climate variables at a resolution of 0.5dm



Stage II: Mapping GCM output at a resolution of 0.5dm

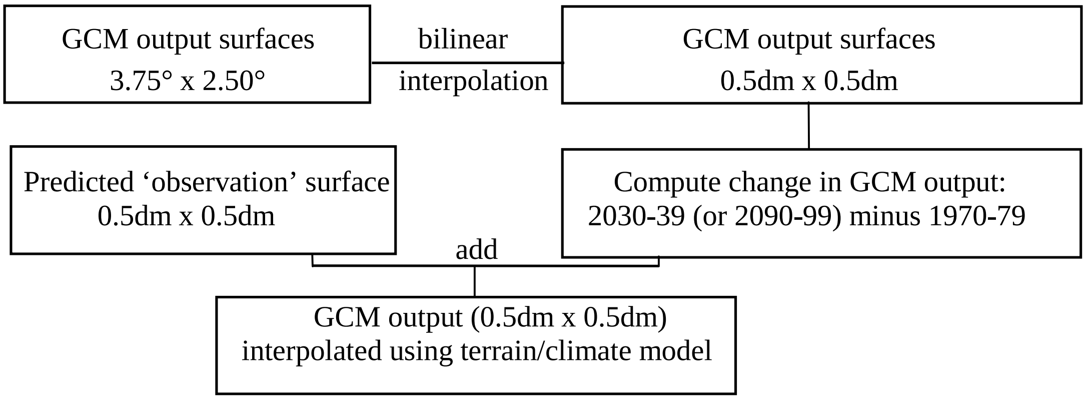
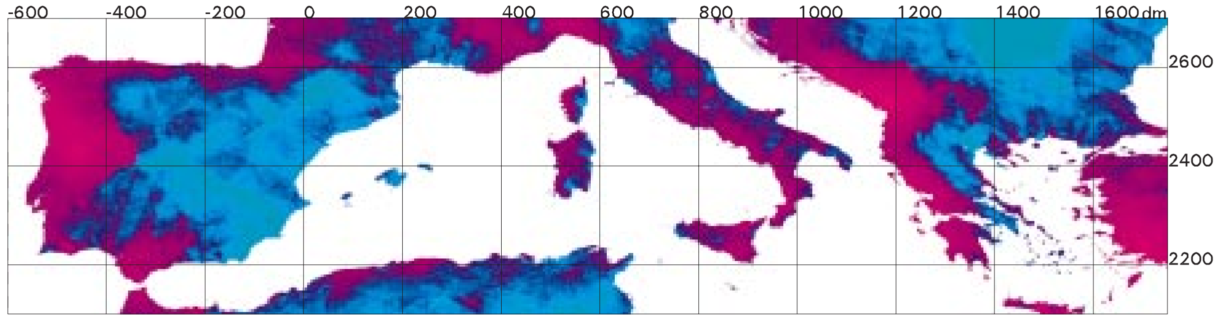
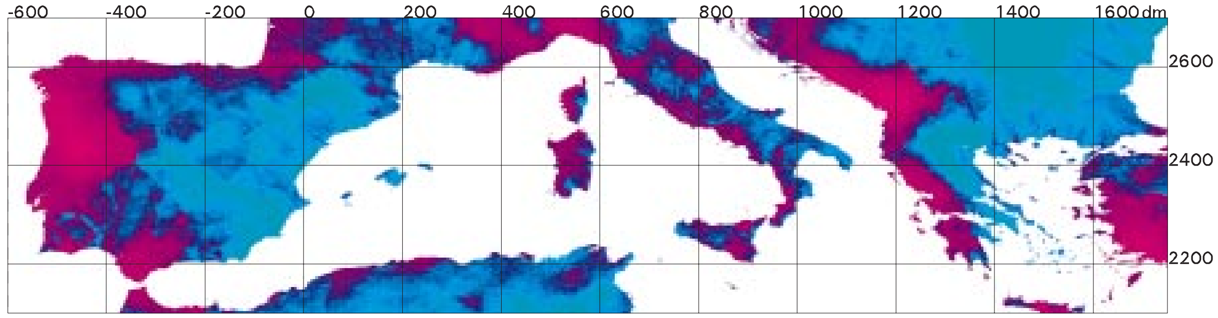


Figure 2: Two-stage methodology for constructing high-resolution (~1 km) climate change scenarios in a GIS.

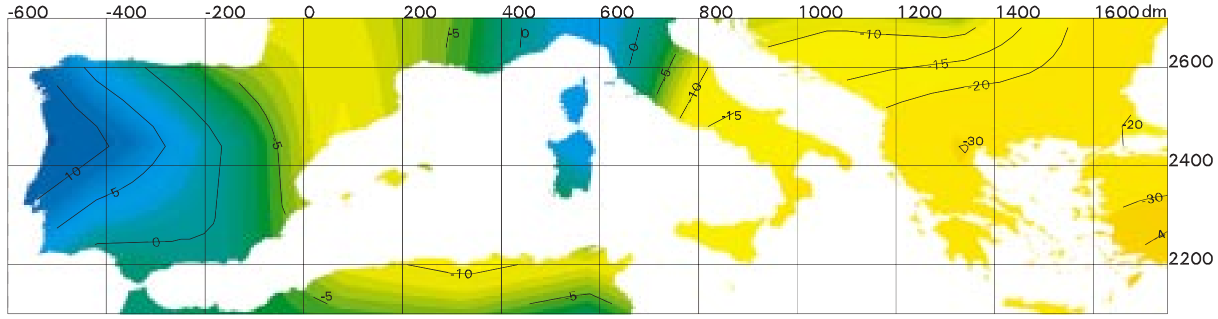
In the second stage, climate scenarios for the HadCM2SUL run were generated by adding the GCM-predicted perturbation to the 0.5 dm-resolution spatial variation in temperature and precipitation obtained in the first stage. Comparison of the GCM-derived surface for 1970-79 and the 'observation' surface for 1952-89 indicates that the latter is consistently cooler and drier than the GCM surface. The differences vary with season (from 0.4° C in summer to 2° C in winter in the case of mean regional temperature) and as a function of the terrain variables (cooler areas in the 'observation' surface generally correspond to mountainous areas which are not adequately represented in the GCM, for example).



(a) 1952-89 (mean: 74.5 mm)



(b) 2030-39 (mean: 64.9 mm)



(c) Precipitation change by 2030-39

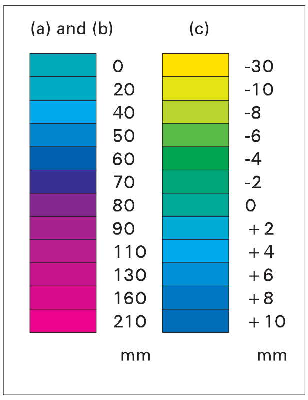


Figure 3: Gridded winter (DJF) precipitation (1 km x 1 km resolution) for (a) the 'observation' surface for 1952-89, (b) the GCM-derived surface for 2030-39, and (c) the difference between the GCM-derived surfaces for 1970-79 and 2030-39 (2030-39 minus 1970-79).

The temperature changes for the future scenarios (2030-39 and 2090-99) are spatially heterogeneous, but vary with season, particularly in the earlier decade (when they are greater in winter and autumn and lower in spring and summer). Annual changes in precipitation are very small (a mean decrease across the Mediterranean of 0.3 mm per day by 2030-39 and 1.6 mm per day by 2090-99) but mask considerable seasonal and spatial variations. In winter, for example, there is a division between western regions, particularly Portugal, which become wetter and eastern regions, especially Greece and Turkey, which become drier (Figure 3). Summer precipitation shows a general increase by the 2030s, although there are decreases in the western parts of the Mediterranean, especially in central Spain, Morocco and Algeria. However, this pattern changes in the 2090s, which show a general drying out which is most severe in eastern Spain, the eastern Adriatic coast and the heel of Italy.

As with all statistical downscaling methods, this GIS-based approach assumes that the relationships observed today (in this case, the relationships between climate and terrain variables) will remain the same in a future altered climate. Nonetheless, a GIS-based approach has considerable potential, especially given the complex configuration of seas and peninsulas, and the range of topography, in the Mediterranean. The approach described here has the particular advantage of providing seasonal scenarios for the entire Mediterranean region at a high spatial (~ 1 km) resolution. For scenarios with a high temporal (i.e. daily) resolution, however, different statistical techniques are required, such as the circulation-type approach and the transfer function approach described in the next section.

3. Target Area (River-basin Scale) Scenarios

3.1 Introduction

Multi-site scenarios of daily temperature and precipitation for the Agri and Guadalentin basins have been developed by the CRU as part of the MEDALUS III project (see MEDALUS III Final Report, Module 3.10.2). These scenarios were generated by statistical downscaling from HadCM2SUL output, and are in the form of daily time series for three time periods: 1970-79, 2030-39 and 2090-99. Because these time series are intended for input to hydrological models it is important, first, that the temperature and rainfall scenarios at a single site are consistent on a day-by-day basis and, second, that the rainfall (and temperature) scenarios are consistent between sites. The three-stage method of scenario construction developed to achieve these objectives is described below.

3.2 Reference rainfall scenarios

First, and for each of the three scenario decades, the rainfall scenario was constructed for a key site (the reference station), which for the Agri is Missanello and for the Guadalentin is Alcantarilla. On the basis of sea level pressure patterns in the GCM, the circulation type for each day over the key site was determined (Goodess and Palutikof, 1998; 1999). The classification scheme comprises fourteen types: six cyclonic/anticyclonic flow types and eight directional types (with a resolution of 45°). A conditional weather generator was then run in which the probability of rainfall on a day of that circulation type (calculated from the observed station series for 1958-87) is used in conjunction with a random number generator to assign the scenario day to either ‘wet’ or ‘dry’. This is the information which ties the temperature and rainfall scenarios together so that the temperature on any scenario day is consistent with the occurrence of rainfall. Rainfall occurrence depends on both the circulation type and on whether the previous day is wet or dry. On each ‘wet day’, the rainfall amount is determined by sampling from the observed rainfall distribution function.

For each of the three scenario decades, and for the observed circulation-type series for 1970-79, the conditional weather generator was run 1000 times. Output can be presented in the form of frequency distributions (Figure 4). Validation analyses indicate that the weather generator consistently underestimates the number of rain days and the amount of rain for Missanello and Alcantarilla. These errors are due, in part, to the underestimation by the GCM of the frequency of the cyclonic circulation types (which are associated with high rainfall) and overestimation of the anticyclonic types (which are associated with low rainfall).

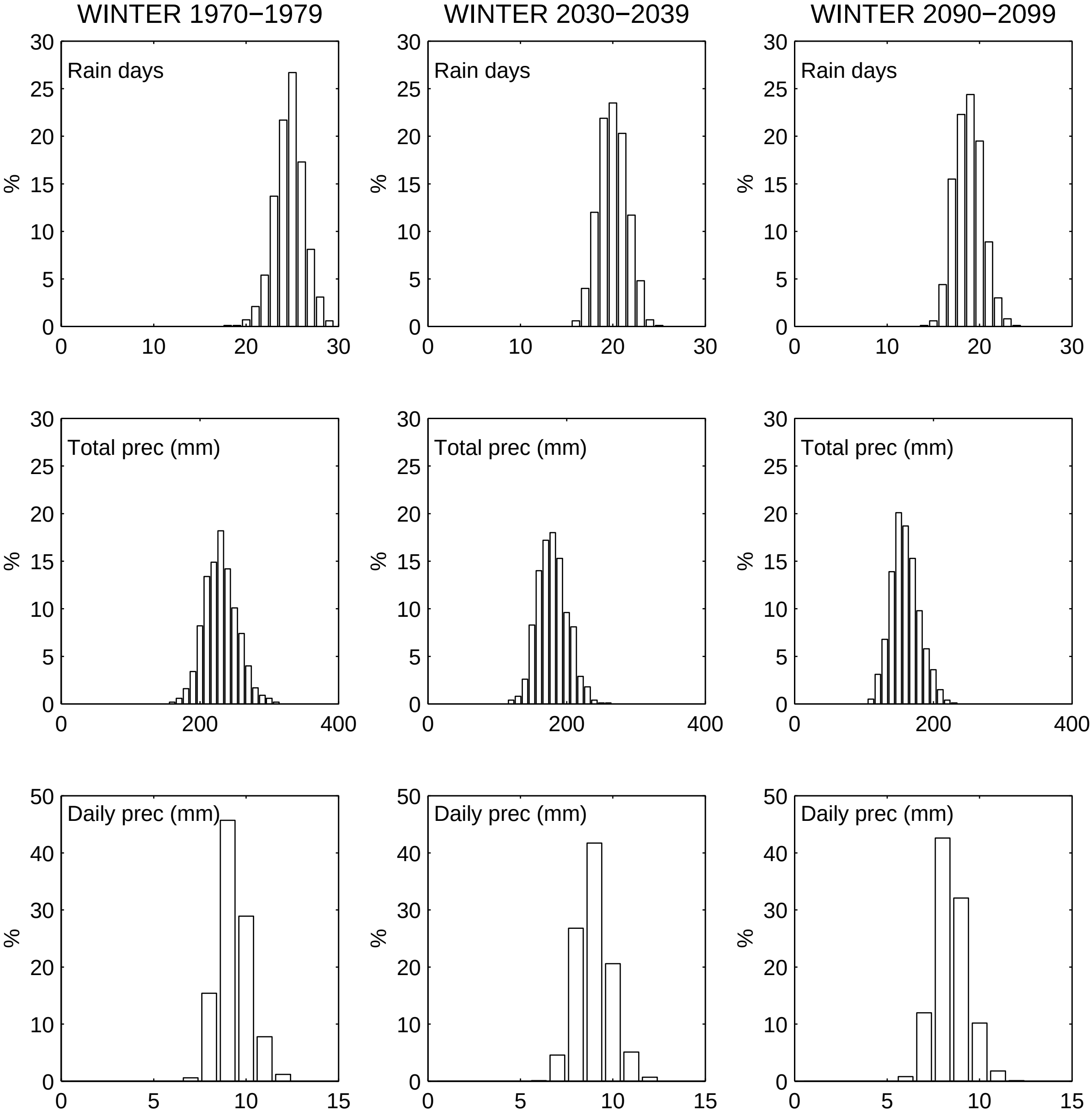


Figure 4: Output from 1000 simulations completed using the rainfall weather generator for Missanello in the Agri, presented as frequency distributions for winter.

The range of future climate change indicated by the simulation sets was calculated by ranking the 1000 runs on the basis of their mean annual number of rain days and then taking the difference between each ranked pair. For each set of differences, quantile values were calculated. Results for Missanello are shown in Table 1. The largest changes are indicated in winter when the number of rain days and total rainfall decrease. A smaller decrease is indicated in autumn. Little change or a relatively small increase in rainfall is indicated in spring and summer. The direction of change indicated for Alcantarilla in winter and autumn (increased rainfall) is opposite to that for Missanello. The quantile changes indicate the wide range of uncertainty associated with the scenarios. In the case of Alcantarilla, for example, the .10 and .90 quantile values have the same sign (+) in winter only.

Table 1 Quantile changes in rain days and rainfall amount for Missanello (Italy).

		.10	.25	.50	.75	.90
2030-1970						
Rain days (days)	Winter	-7.0	-6.0	-4.7	-3.4	-2.3
	Spring	-1.1	0.1	1.5	2.7	3.8
	Summer	-2.0	-0.9	0.2	1.3	2.4
	Autumn	-3.3	-2.3	-0.9	0.2	1.3
Total rain (mm)	Winter	-88	-72	-51	-30	-10
	Spring	-18	-2	14	31	47
	Summer	-24	-12	3	17	29
	Autumn	-49	-30	-12	8	27
2090-1970						
Rain days (days)	Winter	-8.2	-7.2	-5.9	-4.6	-3.4
	Spring	-1.6	-0.4	0.9	2.1	3.3
	Summer	-1.4	-0.5	0.5	1.6	2.6
	Autumn	-5.3	-4.2	-3.0	-1.9	-0.9
Total rain (mm)	Winter	-110	-91	-71	-52	-33
	Spring	-23	-8	10	27	42
	Summer	-21	-10	4	20	33
	Autumn	-75	-58	-40	-20	-2

A single reference scenario was selected for decade 1970-79 by sampling from all the simulations for this decade for which the mean number of rain days and the total rainfall for each season fall within the observed decadal range. The rank number (from 1-1000) of this randomly-selected scenario was determined on the basis of mean annual rain days. Scenarios with the same rank number were then selected for 2030-39 and 2090-99. These three key-site scenarios were used to construct the multi-site rainfall scenarios described below.

3.3 Multi-site rainfall scenarios

The rainfall observations at the sites for which scenarios were required (eleven sites in the Agri and six in the Guadalentin) were formed into a single file of multi-site daily observations. Each day was classified according to the season (because circulation type-rainfall relationships have been shown to vary by season), circulation type and whether the day at the key site was wet or dry. Then, taking the reference scenarios described above, each scenario day was assigned to a class, on the basis of its circulation type and the rainfall state at the key site. A random number generator was used (with replacement) to select one multi-site rainfall day from the observations in that class. By repeating the process, multi-site scenarios for all three scenario decades were built up. A corollary of this approach is that the variable in the future scenarios is the frequency of occurrence of circulation types. The method assumes that the relationships between circulation types and rainfall remain constant.

3.4 Daily temperature scenarios

The temperature scenarios were based on the transfer function method described by Palutikof *et al*. (1997) and Winkler *et al*. (1997). The principle of consistency (see Section 3.1) is maintained by constructing transfer functions separately for wet days and dry days. This latter information was available from the rainfall multi-site scenarios since the sites for which the temperature scenarios were constructed (three sites each in the Agri and Guadalentin) were members of the multi-site rainfall set.

The transfer functions were constructed using stepwise multiple regression. The independent variables were daily values of free atmosphere variables (sea level pressure, 500hPa geopotential height, 1000-500hPa geopotential thickness, and gradient and backward and forward tendency values of these variables). The dependent variables were minimum (TMIN) and maximum (TMAX) daily temperature. Both seasonal and annual equations were constructed. In order to link the rainfall and temperature scenarios, separate equations were constructed for wet days and dry days, on the assumption that temperatures are depressed when conditions are wet. Analysis of the results shows that there is some ‘added value’ in the use of separate wet-day and dry-day equations, although the improvement is less marked for the Agri than for the Guadalentin.

The regression equations were developed using ten years of observed data (1965-74) and tested on an independent validation period (1979-88). Both the annual and seasonal equations perform satisfactorily for the Agri and the Guadalentin stations in the validation period. In the Agri, root mean square errors tend to be lower, and the correlations between the observed and predicted temperatures tend to be higher, in the seasonal equations. However, the means and standard deviations are generally better predicted by the annual equations.

Following successful validation, the transfer functions were used to develop scenarios of future temperature, by initializing them with HadCM2SUL output. Table 2 shows the present-day (1970-79) TMAX and TMIN scenarios for Nova Siri Scalo in the Agri, based on HadCM2SUL data for the free atmosphere variables, wet/dry day occurrence taken from the multi-site rainfall scenarios, and the seasonal regression equations. These results are compared with observations for the period 1965-74 (the occurrence of missing data at the site made it impossible to make the comparison with observations for exactly the same period) and with temperatures interpolated to the site from GCM grid-point data. There is a clear improvement in the prediction of present-day temperatures when the transfer function method is employed. (The inadequacy of the interpolated values is also demonstrated in Figure 1.) Substantial improvements also occur for the Guadalentin stations.

Table 2 TMAX and TMIN (^{o}C) predicted by the wet/dry seasonal regression equations initialized with GCM data for 1970-79, compared with observations for 1965-74 at Nova Siri Scalo and with GCM interpolated values.

		Observed		GCM (interpolated)		Regression-derived	
		Mean	SD	Mean	SD	Mean	SD
Annual	TMAX	22.16	7.79	17.39	4.97	20.95	6.90
	TMIN	11.58	6.25	16.22	5.17	10.92	5.76
Winter	TMAX	13.72	3.63	12.33	2.53	13.40	3.11
	TMIN	5.34	3.16	10.89	2.92	4.75	2.72
Spring	TMAX	20.03	4.91	14.86	2.49	19.46	3.80
	TMIN	9.67	4.08	13.78	2.68	9.38	3.16
Summer	TMAX	31.26	3.88	23.02	2.36	29.80	2.93
	TMIN	18.79	3.17	22.01	2.34	18.33	2.14
Autumn	TMAX	23.47	5.52	19.33	3.60	21.41	4.49
	TMIN	12.43	4.93	18.19	3.75	11.21	3.92

Using identical procedures, scenarios for 2030-39 and 2090-99 were constructed, using the regression equations initialized with free atmosphere variables taken from HadCM2SUL. Examination of the results for the Agri stations revealed an immediate problem: the scenario temperatures for 2030-39 are sometimes colder than the observations for 1965-75, even though they are always warmer than the GCM-based scenario temperatures for 1970-79. A method was devised to remove this cold bias in the underlying GCM. A polynomial curve was fitted to the 'error' in the GCM-based scenario (defined as the difference between the seasonal means of the 1965-74 observations and the 1970-79 scenario). The polynomial value for each particular day in the year was added to the scenario temperature on that day. The effect of this correction is to reduce the differences between the observed and GCM-derived seasonal means so that no statistically different differences occur. This cold bias is not evident in the Guadalentin so no correction was necessary for these stations.

3.5 The MEDALUS daily scenarios

The daily temperature and rainfall scenarios developed for the two MEDALUS study areas demonstrate that statistical downscaling can be used to develop scenarios which represent an improvement over the grid-point GCM data, i.e. they have 'added value'. Furthermore, they are designed to be linked in a consistent manner, such that the inter-relationships of temperature and rainfall are properly modelled. This makes them suitable for input to hydrological models (such as those used by other MEDALUS participants) to study the impacts of climate and land use changes on runoff, erosion and desertification processes.

The resulting daily time series have been analysed with respect to the implications of climate change for the occurrence of extreme events. The Agri Basin scenarios, for example, indicate that the rainfall regime should become 'better behaved' as a result of global warming, with fewer long runs of dry days, but also more infrequent heavy rainfall days. As might be expected, all scenarios show an increase in the occurrence of heat waves and a reduced frequency of cold weather. One interesting result from all the scenarios, irrespective of the downscaling method used, is that even though the results validate successfully with respect to the means and standard deviations, they can still fail in their simulation of extremes. None of the downscaled scenarios for the 1970-79 GCM decade reproduced extreme temperature and rainfall behaviour well when compared to the observations (Figure 5).

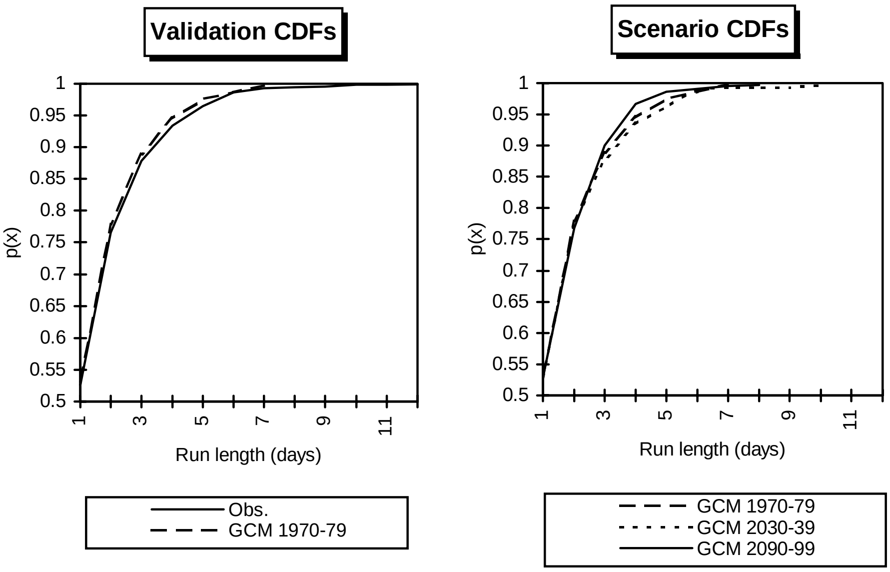


Figure 5: Empirical cumulative distribution functions of wet-day spell lengths for Missanello.

The validation graph in Figure 5, for example, shows that the 1970-79 precipitation scenario for Missanello in the Agri fails to capture the long tail of wet spells: whereas the longest observed spell is 12 days, the longest in the scenario is only seven. In consequence, the shorter-run lengths have a higher probability of not being exceeded in the scenario than they do in the observations. However, it is important to note that 20 years of observations are being compared with 10 years of scenario data – more long-duration spells might be expected with 20 years of scenario data, thus improving the comparison. The scenario graph shows that the longest tail occurs in 2030-39 (with two runs of 10 days). Although there is a higher probability of long runs in 2039-39 compared to 1970-79, by 2090-99 the situation has reversed, with runs between three and seven days having the highest probability of not being exceeded. The maximum wet-day run length in this decade is eight days.

4. Ongoing Studies and Future Developments

The methods of climate scenario construction described in Sections 3 and 4 provide examples of statistical downscaling at two different spatial and temporal scales. The GIS-based scenarios have a high spatial resolution (~ 1 km) and cover the whole Mediterranean region, but only provide information at the mean seasonal level. In contrast, the scenarios described in Section 3 are in the form of self-consistent daily time series of temperature and rainfall, but for only a limited number of sites within each study area. Both sets of scenarios are based on the assumption, common to all statistical downscaling methods, that the relationships between the large-scale and more local climate will be unchanged in a future altered climate. This assumption cannot be fully tested. Thus there is an argument for using dynamical downscaling methods, i.e. a RCM nested within a GCM (Giorgi and Mearns, 1999).

The current generation of RCMs have a typical spatial resolution of about 50 km (though ultimately a resolution of ~10 km may be possible). The Hadley Centre Regional Model, for example, has a latitude/longitude resolution of 0.44° which means that topography and land-sea distributions over the Mediterranean are considerably more realistic than in HadCM2. The ability of RCMs to reproduce present-day regional climate over Europe is the subject of ongoing inter-model comparative studies (Christensen *et al*., 1997). The nested-model approach is considered to offer the greatest long-term potential (Hewitson and Crane, 1996) but is very computer-intensive and is currently subject to a number of technical problems related, in particular, to model boundary conditions. There is also a need for detailed comparative studies of statistical and dynamical downscaling methods (Mearns *et al.,* 1999).

The boundary conditions for RCMs are obtained from GCMs. Hence, the reliability of both statistical and dynamical downscaling methods is limited by the reliability of the underlying GCM. There are major ongoing research efforts to improve the performance of GCMs. The Hadley Centre, for example, is now running simulations with HADCM3 (Gordon *et al.*, 2000). This is the first of a new generation of coupled atmospheric GCMs that do not require flux corrections to be applied to prevent the simulated climate from drifting as a result of an imbalance between the implied and actual ocean heat transports.

At the current time, no one GCM can be considered more reliable than any other and inter-model agreement, particularly for future precipitation patterns, is sometimes low. Methods of incorporating such uncertainties into climate change scenarios are being developed. For example, a set of climate change scenarios for Europe has recently been constructed for the ACACIA impact assessment by combining output from five different GCMs and for four different greenhouse gas emissions scenarios (Hulme and Carter, 1999).

Acknowledgements

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Relevant web sites

MEDALUS at CRU: http://www.cru.uea.ac.uk/cru/projects/medalus/
MEDALUS (including MEDALUS III final reports): http://www.medalus.leeds.ac.uk/
Climate Impacts LINK project: http://www.cru.uea.ac.uk/link/
IPCC Data Distribution Centre: http://ipcc-ddc.cru.uea.ac.uk/
ECLAT-2 Concerted Action: http://www.cru.uea.ac.uk/eclat/