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Downscaling future climate change: Temperature scenarios for the Mediterranean area

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ABSTRACT

For the assessment of Mediterranean temperature under anthropogenically forced climate conditions canonical correlation models are established for the 1948–98 period between highly resolved Mediterranean temperatures and large-scale North-Atlantic–European 1000 hPa-/500 hPa-geopotential height fields. Predictor output from two different global general circulation model runs (ECHAM4/OPYC3 and HadCM3), both forced with B2 scenario assumptions according to the Special Report on Emission Scenarios (SRES), is used to assess Mediterranean temperature changes in the 21st century. The results show a temperature increase for the whole Mediterranean area for all months of the year in the period 2071–2100 compared to 1990–2019. The assessed temperature rise varies depending on region and season, but overall substantial temperature changes of partly more than 4 °C by the end of this century have to be anticipated under enhanced greenhouse warming conditions.

1. Introduction

In view of expected global changes in climate for the near future due to anthropogenic greenhouse forcing it is crucial to know about the thermal and hydrological changes on a regional scale. For a region like the Mediterranean area in the transitional zone between the tropical and extra-tropical climate systems, additionally characterized by a complex topography and high climatic variability, downscaling of general circulation model (GCM) output is particularly important for assessing regional climate change. In recent years, different downscaling techniques have been developed to obtain information on regional and even local scales from global GCMs (see for example Wilby and Wigley, 1997; Murphy, 1999). In this study Mediterranean temperatures are assessed for the 21st century under enhanced greenhouse warming conditions by means of statistical downscaling techniques using simulated large-scale predictor fields of 1000 hPa- and 500 hPa-geopotential heights. The downscaling procedure is based upon statistical relationships linking a set of large-scale atmospheric variables (predictors) to regional climate variables (predictands) in an observational calibration period. After a particular verification within independent subperiods the established statistical relationships are used to predict the response of future regional climate from simulated climate model changes of the large-scale variables.

2. Data and methods

2363 grid boxes are selected from the CRU05 temperature dataset (Climatic Research Unit (CRU) in Norwich, see New et al. (1999, 2000)) for the Mediterranean land areas. The original station data were mainly obtained from the World Meteorological Organization, the National Weather Services as well as from CRU archives. After applying thin plate splines interpolation techniques the global data set comprises monthly values of temperature on a 0.5°×0.5° grid for terrestrial areas. Recently there are updates of this dataset available (Oesterle et al., 2003, Mitchell et al., 2004, Mitchell and Jones, 2005), but a comparison between the different versions of this dataset revealed that there are no significant modifications for the area and time of interest justifying the use of the original dataset in this study. As large-scale predictors mean sea level pressure (MSLP) and geopotential heights of the 1000 hPa- and 500 hPa levels in a 2.5°×2.5° grid for the area 20°N–70°N and 70°W–70°E are selected from the NCEP/NCAR-reanalysis project (National Centers for Environmental Prediction/ National Center for Atmospheric Research, Kalnay et al., 1996; Kistler et al., 2001). The limits of this area incorporate the major dynamic influences on the Mediterranean region, especially the mid-latitude westerlies in the upstream area. The wide extension to 70°W allows to include possible teleconnection couplings, for example related to the upper-level troughs over eastern North America being an important part of the upper long-wave patterns. Potentially important pressure anomalies in the North and in the East of the Mediterranean area (e.g. the Russian high pressure system) are also considered. Both MSLP and 1000 hPa-geopotential

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heights are extracted from this dataset, because of different climate model data availability. In the assessment using output of the climate model ECHAM4, 1000 hPa- and 500 hPa-geopotential heights act as predictors, whereas in the HadCM3-based assessments MSLP and 500 hPa-geopotential heights have to be employed (see below for climate model descriptions).

S-mode Principal Component Analysis (e.g. von Storch and Zwiers, 1999) is applied to the Mediterranean temperature fields and to the large-scale predictor fields in order to condense information. Depending on the analysed months, temperature fields are reduced to 2–6 PCs with overall explained variances (EVs) between 74 and 96%. Regarding geopotential height data, the 1000 hPa and 500 hPa levels are processed together in one combined analysis, yielding 15–18 PCs with EVs around 80%. For Mediterranean temperature the spatial centres of variation (regions) are defined by groups of gridboxes with PC loadings greater than 0.5 on a particular PC. This threshold was used because it leads to non-overlapping temperature regions covering the Mediterranean area almost entirely.

In a next step temperature time series of the resulting regional centers of variation for bi-monthly combinations of the years 1948 to 1998 are linked to the large-scale atmospheric circulation in the same period. Canonical Correlation Analysis (CCA, e.g. von Storch and Zwiers, 1999) is used to establish predictor–predictand-relationships. The number of significant canonical correlation patterns is determined by Rao's *F*-test (Rao, 1973) with a significance level of 0.05.

The study period from 1948 to 1998 is divided into ten different calibration periods, each leaving out another 5-year period from the whole 51-year period. In each case the resulting 46 calibration years are used to derive a statistical model which is verified within the corresponding five independent years by comparing observed and statistically assessed temperature values. Those of the statistical models yielding correlation coefficients above 0.3 with corresponding observations in the verification period are subsequently used for further processing. The number of cases for calculating these correlation coefficients corresponds to the number of 0.5°×0.5° grid boxes per region (ranging between 20 and 1300), implying that coefficients greater than 0.3 are statistically significant at least at the 10% level for every region. Depending on the particular verification years correlation coefficients range between 0.2 and 0.9, with an average correlation over all periods of about 0.7 for most of the regions (for detailed statistics on the correlation coefficients in the calibration and verification periods see tables in Hertig, 2004, p. 246–258). By removing the low-skill models from future assessments it is possible to consider non-stationarities in the circulation–temperature-relationships. The remaining models are combined to a statistical model ensemble which is applied to predict the response of regional temperatures in the Mediterranean area to large-scale changes represented by climate model simulations of the North-Atlantic–European circulation.

Temperature changes are initially calculated for the regional temperature indices, represented by the s-mode PC time coefficients. Subsequently, a spatial back-transformation of the assessment results to the original 0.5°×0.5° grid is done via multiplying the index-related assessments (time coefficients) by the original PC loadings.

The presented results are based on output of two different Atmosphere–Ocean General Circulation Models (AOGCMs), both with T42 horizontal resolution which corresponds to a longitudinal and latitudinal resolution of approximately 2.8°. On the one hand model-simulated values from an ECHAM4/OPYC3-run are used (Oberhuber, 1993; Roeckner et al., 1996), on the other hand output from a HadCM3-model run (Gordon et al., 2000; Pope et al., 2000), both covering the period 1990–2100, and both forced with SRESB2-scenario assumptions (SRES: Special Report on Emissions Scenarios, Nakicenovic and Swart, 2000). The SRESB2 scenario focuses on local and regional solutions to economic, social, and environmental sustainability. It describes a world with continuously increasing global population, intermediate levels of economic development, a relatively diverse technological change, and an orientation towards environmental protection. It lies at a medium level of greenhouse gas emissions compared to the other SRES scenarios.

3. Results and discussion

For consecutive bi-monthly combinations the temperature changes in the period 2071–2100 are shown in comparison to the period 1990–2019, resulting from statistical downscaling of ECHAM4/OPYC3-model output in Fig. 1, of HadCM3-model output in Fig. 2. In addition, the significance of the change resulting from the comparison

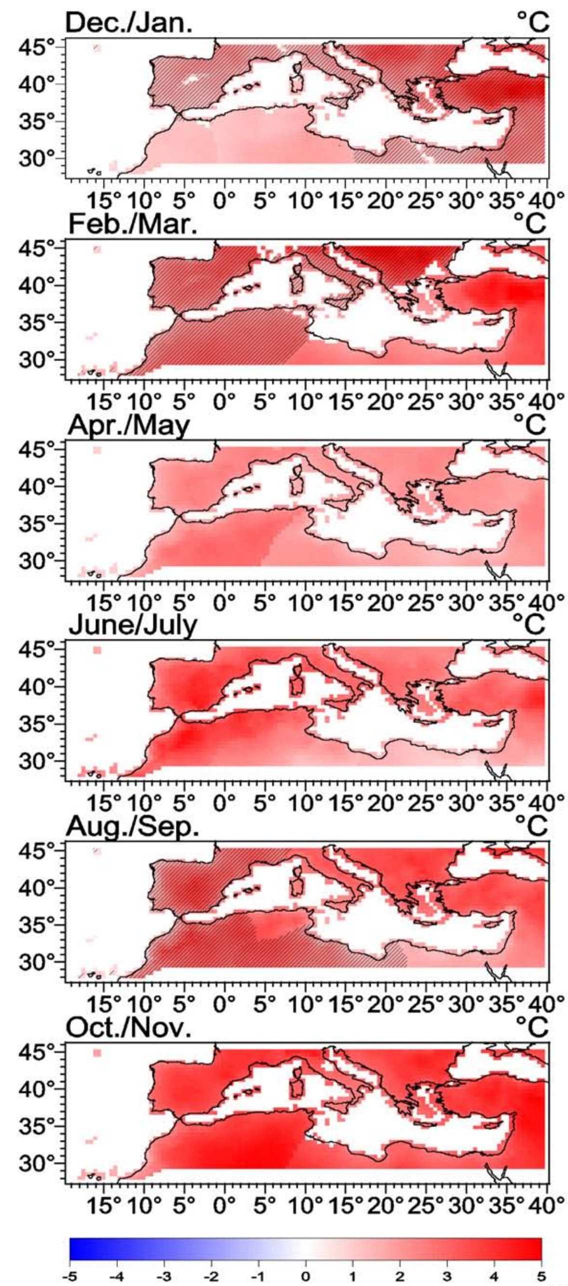

Fig. 1. Temperature assessments for the Mediterranean area using ECHAM4/OPYC3-model values of 1000 hPa-/500 hPa-geopotential heights as predictors for statistical downscaling models. Difference of statistically modelled mean temperatures for the 30-year periods at the end (2071–2100) and at the beginning (1990–2019) of the entire model period 1990–2100. Statistical downscaling method: CCA. Scenario: SRESB2. Transverse hatching: signal/noise ratio > 1.960 (confidence level = 95%).

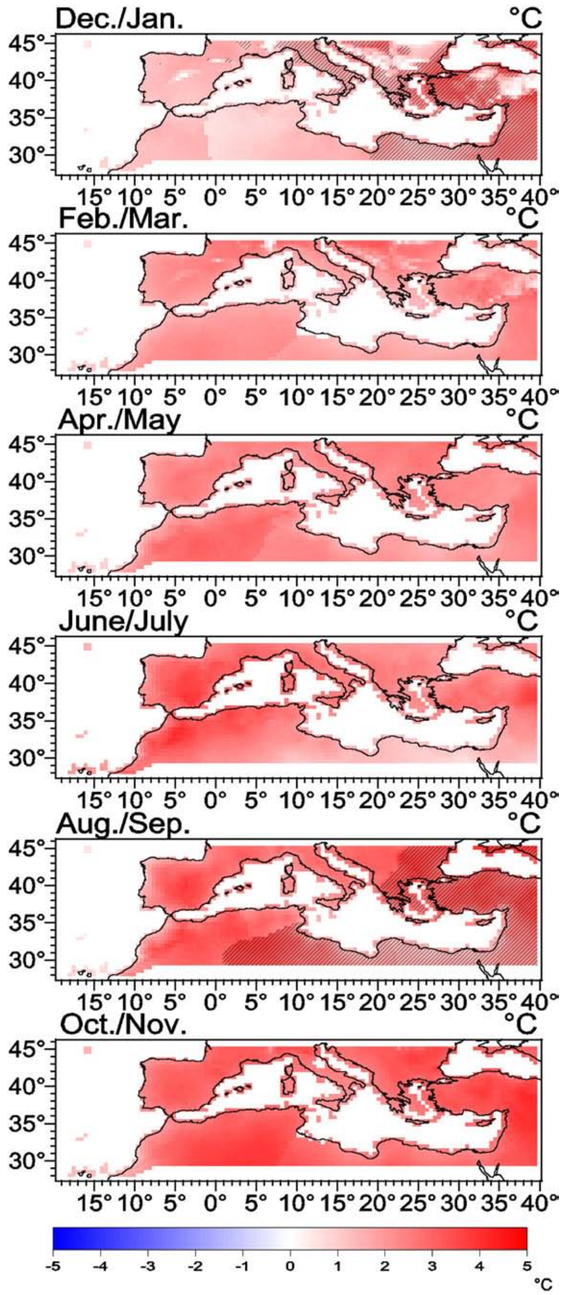

Fig. 2. Temperature assessments using HadCM3-model values of MSLP and 500 hPa-geopotential heights as predictors for statistical downscaling models. Difference of statistically modelled mean temperatures for the 30-year periods at the end (2071–2100) and at the beginning (1990–2019) of the entire model period 1990–2100. Statistical downscaling method: CCA. Scenario: SRESB2. Transverse hatching: signal/noise ratio > 1.960 (confidence level = 95%).

of the two intervals is evaluated by the “signal to noise ratio” (see for example Rapp and Schönwiese, 1995). Regions with a signal to noise ratio being significant at the confidence level of 95% (S/N greater 1.960) are marked with transverse hatching in Figs. 1 and 2.

Overall temperatures show an increase for the whole Mediterranean area for all months of the year in the period 2071–2100 compared to 1990–2019 under SRESB2-scenario conditions. In detail, both assessments indicate a relatively small temperature rise in the western part of Northern Africa and significant increases in the eastern half of the Mediterranean area for December/January. But a remarkable exception appears for the mountainous areas in the northeastern Mediterranean region. While the assessment with ECHAM4 predictors leads to a pronounced temperature rise, almost no increase is evident in the assessment with HadCM3 data for these areas. This feature continues to appear in February/March. There is generally a much stronger temperature rise in winter indicated in the ECHAM4-based assessments. Composite maps of the canonical loading patterns for these areas show that positive temperature anomalies are connected with a zonal cyclonic flow, whereas negative temperature anomalies result from a northerly flow at the front side of a ridge ranging from the western Mediterranean area to Central Europe. The tendency towards the positive mode is more pronounced in the ECHAM4 run compared to the HadCM3 run resulting in an increased advection of mild air masses. The warming could additionally be amplified by the positive snow albedo feedback, whereas the relatively moderate increases in the HadCM3-based assessments might be due to a preserved closed snow cover. In spring and autumn both downscaling assessments show a relatively uniform spatial distribution of temperature increases with a total of approximately 3 °C temperature rise in spring and more than 4 °C in autumn. In the summer months June/July stronger increases of partially more than 4 °C are indicated in the western Mediterranean area, and in August/September also in the northern and eastern Mediterranean regions, whereas mostly only small increases occur around the Gulf of Sidra and further eastwards.

To indicate how winter temperatures progress during the course of the 21st century, two examples are presented in Fig. 3 including the time series ensembles of December/January-temperatures of the eastern Mediterranean region and of January/February-temperatures of the western Mediterranean region. In each case the cubic trend is taken from that statistical model with the highest correlation between statistically estimated and observed temperatures. For the eastern Mediterranean region (left side of Fig. 3) a temperature increase from about 5 °C at the beginning of the study period to about 8 °C at the end of the 21st century appears. In contrast to that, there is a smaller rise of approximately 1.5 °C for the western Mediterranean region (see right hand of Fig. 3). In-between, most notably, we see a relatively strong temperature rise between the years 2020 and 2030 in both graphs. There is a general agreement that further increases in the atmospheric concentrations of greenhouse gases result in a temperature rise in the Mediterranean area. According to the Intergovernmental Panel on Climate Change, an annual warming rate of between 0.1 and 0.4 °C per decade is estimated for southern Europe from different GCMs for the SRES scenarios (McCarthy et al., 2001). Direct HadCM3 climate model output points to an annual temperature increase of between 2 °C and 4 °C for most of the Mediterranean area in the period 2070–2099 under SRESB2-scenario conditions compared to a control simulation. In the area of the Atlas Mountains increases even reach values of between 4 °C and 6 °C (Johns et al., 2003). Simulations with a variable resolution model under SRESB2 scenario assumptions by Gibelin and Déqué (2003) show (for the period 2070–2099 compared to 1960–1989) a temperature increase in winter of about 1 °C over parts of the Iberian Peninsula up to approximately 3 °C over Eastern Europe and over high mountains. The seasonally largest warming occurs during summer with values up to 4 °C. In comparison to other European regions the future annual warming rate is greatest in southern Europe (Spain, Italy, Greece) and also in northeast Europe (Finland, western Russia). The lowest values appear along the Atlantic coastline. The strongest temperature rise in winter occurs in the continental interior of eastern Europe and western Russia, whereas in summer there is a strong south-to-north gradient, with southern Europe warming at a rate between 0.2° and 0.6 °C per decade and northern Europe warming at a rate of 0.08° to 0.3 °C (McCarthy et al., 2001).

Generally, various uncertainties arise in the context of obtaining climate change information for the 21st century. They result from future emission scenarios and from the particular GCM response to a given forcing scenario. The latter is taken into account by the present downscaling approach considering predictor output from two

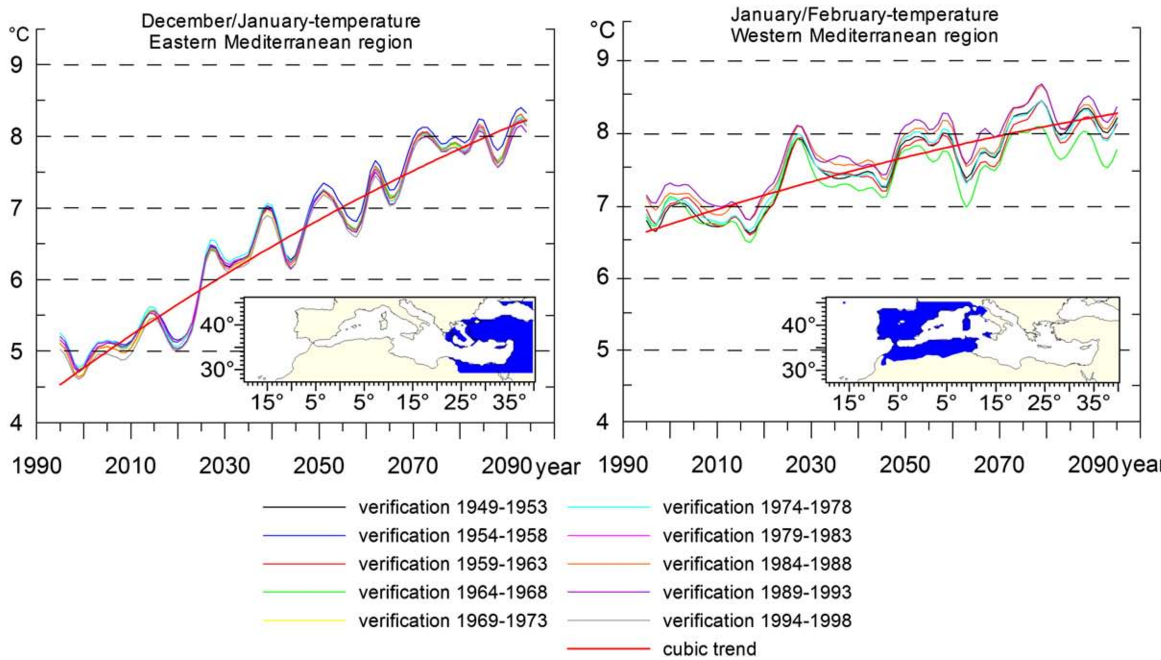

Fig. 3. Smoothed time series (Gaussian low-pass filter period 11 years) and cubic trend of future temperatures 1990–2100 of the Eastern Mediterranean region (left side) and of the Western Mediterranean region (right side) using predictor values of 1000 hPa-/500 hPa-geopotential heights from an ECHAM4/OPYC3 model run under SRESB2 scenario assumptions and CCA as statistical downscaling method. The cubic trend is derived from that statistical model with the highest correlation of statistically modelled temperatures and observed temperatures. Inside maps: blue areas indicate the location of the particular temperature regions (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

different AOGCMs. In general, these models simulate average climate features well on planetary and continental scales (Houghton et al., 2001). To obtain climate change information on a regional scale, however, different kinds of downscaling techniques are usually applied. This leads to further uncertainties, for example arising from the basic assumption that relationships found for present climate conditions will also be valid for future climates with different forcings and boundary conditions. This assumption, however, may be acceptable if future mean changes do not largely exceed the present level of interannual variability. Another shortcoming might be associated with the non-incorporation of other important predictor types into the statistical downscaling equations, like for example sea surface temperatures. For Mediterranean temperature variations, geopotential height anomalies have to be regarded as primary factors (von Storch, 1999, Lionello et al., 2006), becoming evident in this study by the high values of explained temperature variance of about 80 to 90% in the CCA equations. However, there is still a need to explore further the suitability of other large-scale predictors for statistical downscaling models of Mediterranean temperatures.

4. Conclusions

Mediterranean temperature changes for the 21st century were assessed using the simulated model output of MSLP (HadCM3), 1000 hPa (ECHAM4)- and 500 hPa-geopotential heights (both models). Canonical correlation analyses were used to establish predictor–predictand-relationships in ten different calibration periods each leaving out a different 5-year period from the whole study period 1948–1998. These remaining periods were used to verify the performance of the statistical models, respectively. The entire procedure allowed to constitute ensembles of statistical models for the assessment of future Mediterranean temperature changes.

Temperatures show an increase for the whole Mediterranean area for all months of the year in the period 2071–2100 compared to 1990–2019 under SRESB2-scenario conditions, ranging mostly between 2° and 4 °C, depending on region and season.

Even though there is still a high degree of uncertainty regarding the regional distribution of climate change in the Mediterranean area, substantial temperature changes of partly more than 4 °C by the end of this century have to be anticipated under enhanced greenhouse warming conditions. This has also an important impact on evaporation rates and thus on water budget and availability in the semi-arid Mediterranean region. Within the scope of providing high quality climate change information on a regional scale, further efforts are necessary to reduce uncertainties in the assessments to distinctly lower levels than nowadays.

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