Statistical downscaling for climate change projections in the Mediterranean region: methods and results

Jucundus Jacobeit · Elke Hertig · Stefanie Seubert · Karin Lutz

Abstract Besides dynamical downscaling by regional climate models, statistical downscaling (SD) is a major tool to derive climate change projections on regional or even local scales. For the Mediterranean area, an increasing number of downscaling studies based on different statistical techniques have been published in the last two decades with a broad range of sometimes differing results relating to different variables and regional domains. This paper gives a short review of these Mediterranean downscaling studies mainly considering the following two aspects: (1) what kind of progress has been realized in this field since the early 1990s? The review addresses the inclusion of extremes in downscaling assessments, the development of probabilistic approaches, the extension of predictor sets, the use of ensembles for both dynamical model simulations and statistical model assessments, the consideration of non-stationarities in the predictor–predictand relationships, and some advances related to synoptic downscaling. (2) What are the main regional climate change signals in the Mediterranean area, considering agreed and controversial points also with respect to dynamical models? Best accordance among future projections can be found in seasonal temperatures with lower rates of warming in winter and spring, and, in most cases, higher ones in summer and autumn. Different results are obtained for the intra-annual range of extreme temperatures, but high-temperature conditions are generally expected to increase. Regarding seasonal precipitation, predominant reductions are indicated for spring, summer, and autumn. For winter, however, projections are distinctly different (GCMs: rainfall decrease; RCMs: increase only in the northernmost parts of the Mediterranean region; SD: widespread increases in the northern and western parts in several studies). Different results are obtained for rainfall extremes, but the entire precipitation distribution tends to shift towards higher *and* lower values. Apart from some sub-regional deviations, there is a predominant increase in future dry period durations. For near-surface winds, only a few studies are available, and they project some decline mainly for the winter season.

Keywords Statistical downscaling · Regional climate change · Mediterranean area

Introduction

Despite a considerable advance in computing capacities, global climate model simulations are still characterized by horizontal spatial resolutions (mostly around 100 km) which are too coarse for obtaining useful and reliable information about future climate change on regional or local scales. Particular downscaling techniques are therefore required for this kind of information, which is most relevant for natural ecosystems and human societies. In general, two main types of downscaling approaches can be distinguished: a first one known as dynamical downscaling is based on high-resolution regional climate models driven by boundary conditions from a global climate model; thus, simulations of regional climate change with spatial resolutions down to a few kilometres can be obtained. In this paper, we focus on the second general approach known as

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statistical downscaling, which is characterized by computing demands distinctly lower when compared to dynamical modelling. A particular advantage consists in its capability of even providing local climate change assessments, which are required for many aspects of climate impact research, for example.

Statistical downscaling is defined as an estimation of regional or local climate variables derived from larger-scale predictor variables. Deterministic and stochastic approaches may be distinguished depending on whether or not an additional noise term for random variability is explicitly included (Maraun et al. 2010). In the context of climate change assessments, this kind of downscaling, which is based on relationships derived between observed predictors and predictands, is applied to predictors from dynamical model simulations representing climate change projections. This can be done subject to the following conditions: the large-scale predictors capture major effects of climate change, these effects are realistically simulated by the dynamical model, and some stationarity in the observed relationships between larger and smaller scales can be assumed (see below for further aspects on this topic). Different techniques for statistical downscaling are described in several textbooks and review publications (e.g. Hewitson and Crane 1996; Wilby and Wigley 1997; Benestad et al. 2008; Maraun et al. 2010; Wilks 2011). A general overview with examples from Mediterranean studies is given in the electronic supplementary material.

Referring to the Mediterranean region, there are special conditions requiring a state-of-the-art downscaling of future climate change projections: this region is considered as one of the hot spots of climate change (Giorgi 2006), characterized by highly varying attributes of the earth's surface due to land–sea distribution and orographic features, and affected by strong impacts of climate change, e.g. concerning water budget, vegetation and land use, geomorphological processes, and ecosystem stability. In fact, an increasing number of downscaling studies related to the Mediterranean area or some of its sub-regions have been published during the last two decades, including different statistical approaches.

The primary aim of this paper is to give a short review of Mediterranean downscaling studies focusing on those that are based on statistical techniques. We do not include studies on model output statistics, which may be a further step following dynamical climate modelling. Firstly, a general outline of the particular progress in statistical downscaling since the early 1990s, when first studies relating to the Mediterranean region became available (von Storch et al. 1991), will be given in section two. Subsequently, we will focus on main results of climate change projections for the whole Mediterranean area, as well as for various sub-regions. In this context, the applied techniques, the predictor variables, and the dynamical models providing the predictor projections will be specified as a general background for the statistical assessments. No detailed evaluation, however, will be performed with respect to dependencies of results on particular configurations of the entire downscaling procedure (this would require a separate, more comprehensive, and methodically elaborated paper). Main results of climate change projections will be summarized for precipitation (section three), dry periods (section four), temperature (section five), and near-surface wind (section six), before several conclusions will be given in the last section.

Progress in statistical downscaling

Initial studies had focused on mean temperature or precipitation totals based on observed relationships with some large-scale predictors. After validating these relationships within another sub-period independent from the calibration period, future projections for mean temperature or precipitation totals have been derived from these relationships by using predictor output from one or a few global climate model simulations. In later studies, statistical downscaling has also been applied to extremes of a broader range of predictand variables and to estimates of probability density functions (PDFs) for mean as well as extreme values, based on extended sets of predictors and particular ensembles for both dynamical model simulations and statistical model assessments.

Extreme conditions, which are of particular importance in the climate change context, are defined by various percentile thresholds in most cases and may be analysed in different ways. A basic approach uses particular extremes indices defined for individual stations or grid boxes on monthly or seasonal scales. To give an example for extreme precipitation, these indices describe the frequency of daily events above a prescribed percentile threshold (e.g. the 95th percentile of an appropriate reference period), the total amount, the mean intensity, and the percentage of total precipitation due to such events (see Moberg et al. 2006). Statistical downscaling from large-scale predictors is then performed for these indices on monthly or seasonal scales (e.g. Hertig et al. 2012a, 2013). A further approach is related to particular PDFs fitted to predictand time series downscaled by one of the techniques mentioned in the electronic supplementary material. Generalized Pareto distributions are often used to model extreme values (e.g. Paeth and Hense 2005; Seubert et al. 2013). An even better representation of local variability and extremes may, however, be achieved by randomizing downscaling results with respect to complete distributions (Maraun et al. 2010). In this context, Vrac and Naveau (2007) have designed mixed models with different functions for both normal and extreme values (for instance Gamma and generalized Pareto distributions, respectively, in the case of precipitation). Conditional mixture models built on neural networks (Carreau and Vrac 2011) are a further extension with model parameters as functions of predictor variables. They include a discrete component for the occurrence process, and a mixture of continuous densities for the intensity process.

Concerning predictor variables, more recent studies (e.g. Xoplaki et al. 2003, 2004; Busuioc et al. 2008; Hertig et al. 2013) have begun to include not only those 'classical' ones mostly related to the large-scale atmospheric circulation (SLP, geopotential heights, horizontal wind components), but also others describing thermodynamic conditions being likewise relevant to the predictand's variability (e.g. thickness of atmospheric layers, humidity, SST, convective indices). This also allows the derivation of separate downscaling models for predictor variables linked to circulation dynamics on the one hand and to thermodynamic conditions on the other hand, thus indicating their specific contributions to the total effect on the predictand (see Hertig et al. 2013 and some examples in "Precipitation" and "Dry periods" sections).

A particular downscaling approach linking the same variable between different scales (thus not linking local predictands to other large-scale predictor variables) has been further developed by means of transfer functions linking its cumulative distribution functions (CDF) on different spatial scales (Michelangeli et al. 2009; Vrac et al. 2012). Thus, local-scale values are not directly assessed (as in 'classical' downscaling techniques), but result from downscaled CDFs. This probabilistic approach, which can also be applied to the analyses of extremes (e.g. Kallache et al. 2011), may be primarily considered as a bias-correction method. However, since corrected large-scale distributions are used to model local-scale ones, a change of spatial scales is involved (Vrac et al. 2012), thus characterizing this novel approach as a particular technique of statistical downscaling.

Since global climate model simulations have been extended to ensemble simulations with individual members representing slightly different initial conditions, statistical downscaling results can now be specified in terms of predictand ranges due to the internal variability of the global climate model from which predictors are extracted. To give an example, the projected rising temperature trend towards the end of the twenty-first century for an eastern Mediterranean sub-region was different (exponential, linear, logarithmic) for predictors from different ensemble members (Hertig and Jacobeit 2008b). This underlines the importance of assessing uncertainties in climate change projections.

Uncertainties further arise from the statistical downscaling estimates themselves. They can be quantified in several ways. Concerning the CDF approach mentioned above, particular scores (e.g. Kolmogorov–Smirnov score or Cramer-von-Mises score) are used to measure the distance between simulated and observed CDFs. This is primarily a goodness-of-fit test, which, however, can also be used as a "proxy of uncertainty" (Lavaysse et al. 2012). Vrac et al. (2012), referring to the probability of rejecting or accepting the null hypothesis, when comparing simulated and observed CDFs, speak about an "assessment of the degree of confidence into the downscaling method" being associated with the assessment of uncertainty. Thus, particular measures of the quality of downscaling approaches are used as indicators for the corresponding uncertainty. Direct assessments of uncertainty can be obtained in the context of transfer-function downscaling, most easily by confidence intervals for the climate change signal, e.g. in terms of the lower and upper interval limits for spatial predictand fields. This may be based on pre-assumed normal distributions (e.g. Hertig and Jacobeit 2008a) or, on a more sophisticated level, on bootstrapping techniques for deriving confidence intervals (e.g. Hertig et al. 2012b, 2013). As for uncertainty quantifications of downscaled climatic time series, Vasiliades et al. (2009) have followed the approach of stochastic time series modelling for residuals from a regression-based downscaling of GCM predictors. This modelling is repeated 100 times and provides uncertainty ranges for the predictand time series. Finally, uncertainties associated with statistical model configurations have been addressed by García-Bustamante et al. (2012): they consider variations in the large-scale domain size, in the predictors or predictor combinations, in the number of EOFs and coupled CCA patterns, as well as in the cross-validation subset size, and derive a particular metric of related uncertainties (temporally averaged differences between maximum and minimum predictand values for each time step). Thus, they indicate the range of downscaling estimates depending on different model configurations.

A major improvement in statistical downscaling was made by not only using a single validated statistical model for future assessments, but a whole model ensemble derived from multiple calibration and validation periods. The general background for this extension is the fact that many relationships between large-scale predictors and small-scale predictands are affected by non-stationarities (Wilby 1998), thus compromising the implicit condition of stationarity for transferring statistical relationships from one period (e.g. a recent reference period) to a different one (e.g. a future projection period). If multiple calibration (and validation) periods are used, different variants in the relationships may be recorded and thus be considered in a range of future projections. Figure 1 presents an example

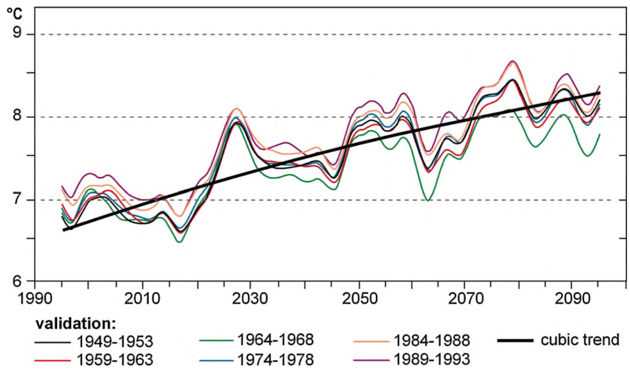

Fig. 1 Smoothed time series (Gaussian low-pass filter period 11 years) and cubic trend of statistically modelled January/February temperatures of the western part of the Mediterranean region based on six different calibration periods within the second half of the twentieth century (the corresponding validation periods are specified below). CCA downscaling models were applied with predictor values of 1000 and 500 hPa geopotential heights from an ECHAM4/OPYC3 model run under SRES B2 scenario assumptions (modified after Hertig and Jacobeit 2008b)

referring to the development of winter temperatures up to the end of the twenty-first century in the western part of the Mediterranean region (Hertig and Jacobeit 2008b): ten different calibration periods have been used, each of them leaving out another 5-year period for validation, thus providing multiple variants for the future projection (in this case only 6 different ones, since no valid models could be derived for the remaining periods). There is obviously a considerable range in the temperature assessments as a result of the ensemble approach. The fact that all variants in Fig. 1 reproduce similar decadal-scale variability superimposed onto the long-term trend is probably due to the large overlaps of the different calibration periods. However, reducing these overlaps would imply both a shortening of the calibration periods and a reduction in the number of ensemble members. Therefore, a systematic evaluation of non-stationarities and a strategy for defining statistical ensembles focused on particular periods with significantly differing relationships are urgently required. Some approaches have been initiated and will be developed further within the framework of the recent COST Action VALUE (Validating and Integrating Downscaling Methods for Climate Change Research, see www.value-cost.eu). The method developed by Hertig and Jacobeit (2013) based on running calibration periods, for instance, identifies non-stationarities by non-overlaps of the bootstrap confidence interval of the mean model performance (derived by averaging the performances of all calibration/validation periods) and the bootstrap confidence intervals of the individual model performance (so far applied to bias and correlation coefficient between modelled and observed daily precipitation). Remarkably, the uncertainty range in future projections arising from different statistical models, which can be derived in the case of non-stationarities, may be up to twice as large as the range resulting from the application of predictors from different GCM ensemble members. This kind of non-stationarity analysis, of course, has to be further extended to GCM data in order to achieve a substantiated selection of statistical models for future assessments.

In terms of synoptic downscaling, major progress has come from the improvements in classification techniques and from systematic evaluations of circulation type classifications with respect to regional or local predictand variables, as recently performed in the context of the COST Action "Harmonisation and Applications of Weather Type Classifications for European Regions" (e.g. Philipp et al. 2010; Beck and Philipp 2010). This, for example, allows selecting particular classifications of increased performance in explaining the predictand's variance, which depends on target variables and study domains. However, relating large-scale circulation types to at least daily resolved predictands still includes serious drawbacks (e.g. unrealistic distribution functions of these predictands in a downscaling context, see Maraun et al. 2010). More simple techniques, such as the analogue method (Zorita and von Storch 1999), are therefore still preferred in climate projections (Frías et al. 2006; Seubert et al. 2013).

Some improvement in downscaling models based on circulation-type classifications can be made by including the predictand as a covariate into the classification of the predictors, i.e. the latter will be conditioned on the former. An example referring to Jerusalem January precipitation is given in Fig. 2 (Lutz et al. 2012): it is based on a particular cluster classification of mean SLP fields comprising simulated annealing and diversified randomization techniques (for details see Philipp et al. 2007). This is extended to a conditioned cluster analysis by including the precipitation time series multiplied by a percentage weight reflecting the relative influence of precipitation within the SLP classification. This procedure has been done for different weights and in each case for statistical model ensembles (for details see Lutz et al. 2012). According to Fig. 2, model performance in terms of correlation coefficients between observed and modelled precipitation is increasing up to a weight of 5 %. No significant change in performance is achieved for further increasing weights. Beyond 20 %, the difference in correlation coefficients between calibration and validation periods even increases. Additionally, the variability between the ensemble members (blue line in Fig. 2) is lowest for weights between 5 and 20 %, thus confirming this range as being optimal for an improvement of the synoptic downscaling technique. This, of course, has to be proved by further studies, especially concerning the Mediterranean region. Another approach has been

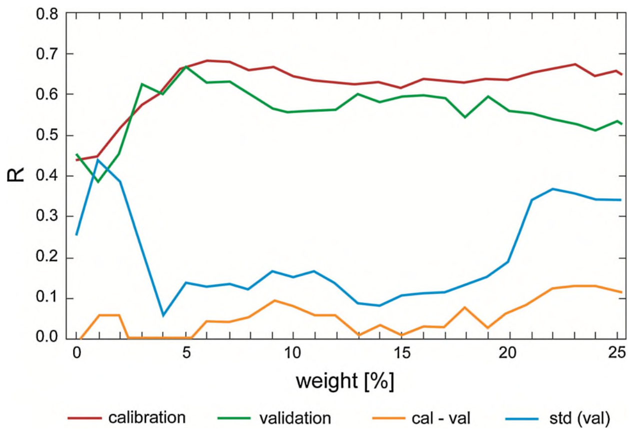

Fig. 2 Ensemble mean correlation coefficients (*R*) between observed and synoptically modelled Jerusalem January precipitation for different precipitation weights (*x*-axis). The *orange line* depicts the differences between correlation coefficients for calibration and validation periods. Std (val) denotes the standard deviation of the statistical ensembles with respect to the different validation periods (modified after Lutz et al. 2012)

developed by Vrac and Yiou (2010) with respect to weather regimes maximizing their correlation with local climate variables.

Following this outline on the progress related to principal methods and particular techniques, the next sections will focus on main results obtained from statistical downscaling studies for regional climate change projections in the Mediterranean area. Most results are based on SRES scenarios (Nakicenovic and Swart 2000) unless otherwise indicated.

Precipitation

Annual and seasonal precipitation

A first statistical downscaling study became available in 1991 (von Storch et al. 1991) and was published in an international journal 2 years later (von Storch et al. 1993). It referred to Iberian winter (DJF) precipitation, which was linked to the large-scale North Atlantic sea-level pressure by canonical correlation techniques. Future projections were made for two GCM experiments with an early version of the ECHAM model, an instantaneous CO_2 doubling and a transient simulation according to the former IPCC scenario A ("business as usual"). Iberian winter rainfall insignificantly increased in the first experiment, but decreased in the second (area-averaged by 7 mm/month for a 100-year model period). Corte-Real et al. (1995) get −12, 7 mm/month for a 54-year model period (confined to Portugal), based on SLP output from a transient UK Met Office simulation and a multivariate regression approach.

Likewise based on an early version of the ECHAM model and on the business-as-usual scenario, assessments of seasonal precipitation changes were made for the whole Mediterranean area (as far as station data were available) by Jacobeit (1994a, b, 1996, 2000). The applied technique of multiple regression analyses used PCA-derived centres of variation for the large-scale predictor variables (500 hPa geopotential heights, SLP, horizontal wind components, and relative vorticity at the 500 hPa level). The projected rainfall changes for the last decade of the twenty-first century, summarized for the whole rainy period from autumn to spring, indicate dominating rainfall decrease in the southern and eastern Mediterranean area, but also some rainfall increase in the northern and north-western regions (Jacobeit 2000), largely caused by corresponding changes during the winter season (Jacobeit 1994a). This pattern is largely reproduced by directly downscaling GCM-simulated rainfall changes (Palutikof and Wigley 1996). Some years later, this pattern has generally been confirmed and further specified by Hertig and Jacobeit (2008a) in an extended study using gridded rainfall data (0.5° × 0.5° resolution), CCA as statistical downscaling technique, further predictors (specific humidity besides geopotential heights), statistical model ensembles (see "Progress in statistical downscaling" section), and multi-model ensembles from more recent versions of coupled GCMs (ECHAM4/OPYC3 and HadCM3). For winter, there are once again rainfall increases in the northern and western regions, whereas in other regions and, generally, in the other seasons, decreases are dominant (SRES B2 scenario in this case for the last three decades of the twenty-first century).

A renewed analysis of future precipitation changes in the Mediterranean area has been carried out by Hertig et al. (2012b) using gridded rainfall data of a higher resolution (0.25° × 0.25°), generalized linear models (GLM) as a statistical downscaling technique, extended predictor sets including thermodynamic variables (see below), and ECHAM5/MPI-OM ensemble simulations for SRES A1B scenario assumptions. In addition to the seasonal results of this study, separate assessments are added in Fig. 3 for atmospheric circulation predictors (700 and 500 hPa geopotential heights, 850 hPa horizontal wind components), and for thermodynamic predictors (850 and 700 hPa specific humidity, convective inhibition (Myoung and Nielsen-Gammon 2010) and an index following Showalter (1953) as measures for convective activity). The inclusion of both predictor groups takes into account that Mediterranean precipitation is generally due to large-scale advection brought about by the atmospheric circulation or to smaller-scale convective activity. The separate assessments for these predictor groups have not been published so far concerning seasonal precipitation (with respect to indices of extreme precipitation see Hertig et al. 2013). Therefore,

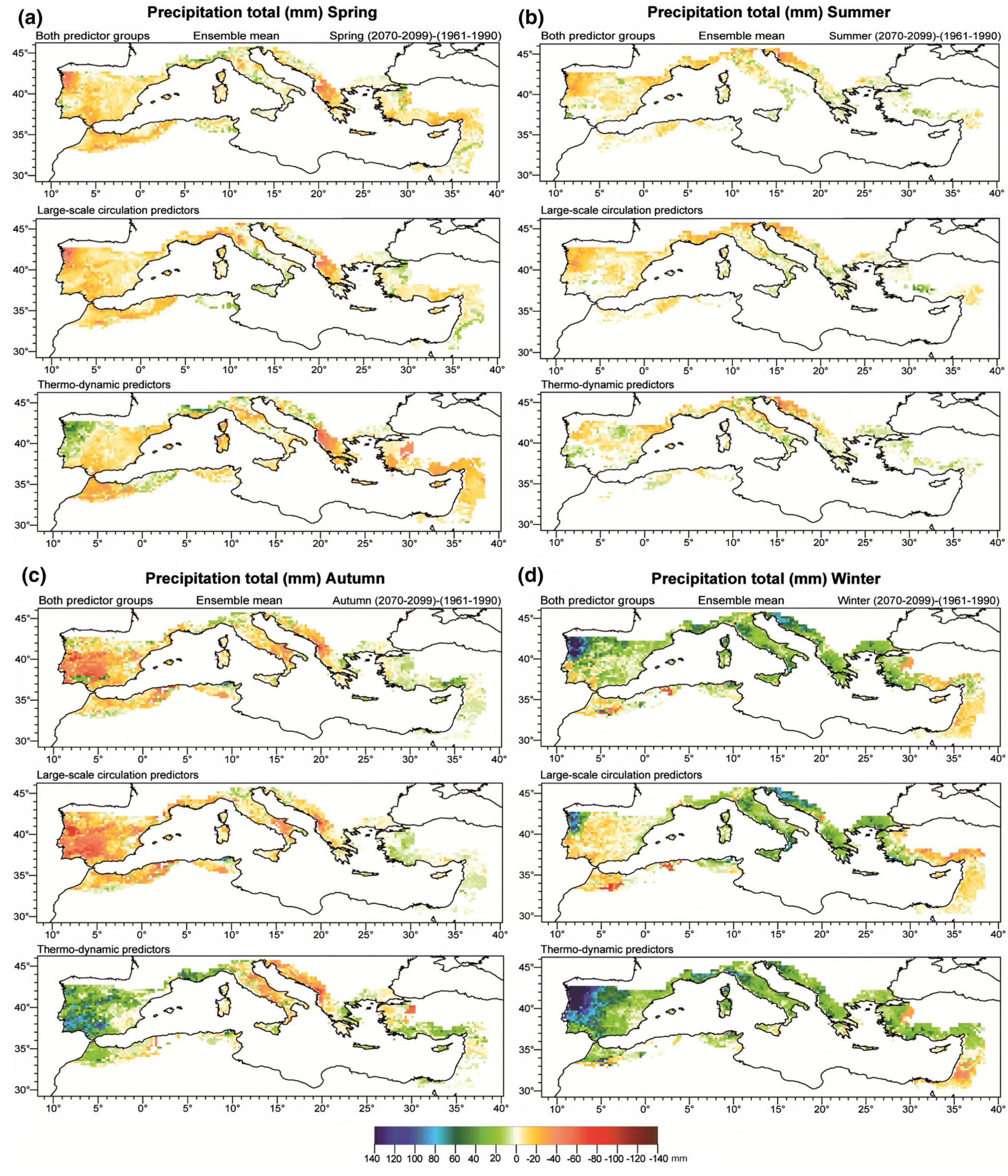

Fig. 3 Changes in seasonal precipitation totals (2070–2099 in relation to 1961–1990) according to generalized linear downscaling models using predictors from ECHAM5/MPI-OM simulations (SRES A1B scenario). Predictors include variables describing the large-scale atmospheric circulation (700 and 500 hPa geopotential heights, 850 hPa zonal and meridional wind components) as well as thermo-dynamic conditions (850 and 700 hPa specific humidity, convective inhibition, Showalter Index). Assessments are made separately for the two predictor groups and also for both of them. **a** Spring, **b** summer, **c** autumn, **d** winter

a more detailed description seems necessary including methods *and* results. It can be found in the electronic supplementary material.

Summarizing the results for the Mediterranean area as a whole, the statistical assessments point to predominating rainfall reductions in spring, summer, and autumn, whereas in winter, some differences occur compared to the well-known IPCC projections by global climate models indicating a general rainfall decrease in the Mediterranean area for this season, too (Solomon et al. 2007). Statistical downscaling results, however, also include widespread increases in rainfall up to the end of the twenty-first century for the Mediterranean winter season. Regional climate models, on the other hand, indicate higher winter rainfall only for the northernmost parts of the Mediterranean area (Gao et al. 2006; Giorgi and Lionello 2008; Giorgi and Coppola 2009), probably due to an increased cyclone activity in this region (Lionello and Giorgi 2007). The eastern Mediterranean area reveals another seasonal pattern in statistical downscaling assessments by showing precipitation increases in summer and autumn in contrast to rainfall decreases in winter (Fig. 3). Comparing these results with recent model simulations based on a 6-member ensemble (Planton et al. 2012) yields both agreements as well as some differences: in the dynamical approach, all seasons are dominated by rainfall reductions with maxima in spring, in summer, and—concerning the southern regions—in winter. Some precipitation increases are indicated for summer and autumn in the south-eastern part of the Mediterranean area and for winter in north-east Spain, in the northern parts of Italy and the Tyrrhenian Sea, and in the Adriatic region. Compared to Fig. 3, there is some agreement with respect to the seasonal character of rainfall increases, the spatial extensions, however, are different (in the dynamical approach less widespread in winter, and more confined to the south-eastern part in summer and autumn). Remarkably, a study by Murphy (2000), including both dynamical and statistical downscaling (regression techniques with SLP flow patterns and regional wind, temperature, humidity, and vorticity values as predictors), also points to wetter conditions for January 2080–2100 (based on HadCM2 predictor output) in the north-western part of the Mediterranean area. Dynamical CCLM projections for Portugal additionally indicate an increase in winter precipitation over the north-eastern part of this region as the most important exception with regard to an overall drying trend (Costa et al. 2012).

Further projections of rainfall changes based on statistical downscaling techniques have been performed with respect to particular sub-regions of the Mediterranean area. Palatella et al. (2010), for instance, refer to four sub-domains in Spain, Italy, and Turkey using CCA models with the large-scale SLP as predictor, three GCMs (Csiro-Mk2, HadCM3, CGCM2), and two scenarios (SRES A2 and B2). They achieve spatially varying results: spring and autumn rainfall in the Po Valley are reduced, as is summer precipitation in the Ebro Valley. There is, however, an increase in summer over Apulia and the Antalya region (including autumn for the latter). Increased summer rainfall is also indicated in the South Italian Agri catchment by Palutikof et al. (2002), who applied a conditional weather generator and a particular circulation weather typing (based on SLP data, model predictors from HadCM2); autumn and winter, however, are projected to get drier.

Several studies have focused on the Iberian Peninsula following the initial approach of von Storch et al. (1991, 1993) as mentioned earlier. Sumner et al. (2003) used an Analogue approach for downscaling precipitation in Spain: 19 characteristic regional atmospheric patterns were derived from 925 and 500 hPa geopotential heights and compared between the periods 1971–1990 and 2080–2099 (according to the earlier business-as-usual scenario, predictors from ECHAM4-OPYC3). They identified decreases for all westerly and two northerly patterns, but increases for most of the easterly near-surface flow types. Consequently, a reduction in annual precipitation results for Andalusia and the upland parts of Catalonia, whereas an increase is indicated for the northern part of the Mediterranean coast. In terms of winter precipitation, González-Rouco et al. (2000) obtained an increase for most of the Iberian Peninsula (except for the northern coast) based on a CCA model with large-scale SLP as predictor (projections from HadCM2 following the earlier business-as-usual scenario). The opposite trend concerning Iberian winter precipitation (a decrease by the end of the twenty-first century to around 60 % of that of the twentieth century) is obtained by Frías et al. (2006). They also use SLP as predictor and CCA modelling, however, based on the stronger SRES A2 scenario and output from ECHAM4/HOPE-G. These differences in future rainfall trends are probably related to diverging model projections of the NAO, which is negatively correlated with Iberian winter precipitation.

Again based on HadCM2 SLP output, and using artificial neural networks, Trigo and Palutikof (2001) compared half-century periods (2041–2090 vs. 1941–1990) of Iberian precipitation: in winter, most regions experience an increase, once again, being more intense towards the west; spring reveals positive changes in the western part and negative ones in the eastern part; autumn depicts a decrease throughout most of the Iberian regions. Focusing on south-east Spain, Goodess and Palutikof (1998), who used a circulation-type approach (SLP classification according to an automated version of the Lamb weather type classification scheme), a conditional weather generator and the last 10 years of a transient UK Met Office simulation (corresponding to an equivalent CO_2 doubling), had already obtained fewer rain days in spring, but an increase in summer.

Referring to the French Mediterranean region, Lavaysse et al. (2012) follow a transform approach of CDF (see "Progress in statistical downscaling" section) with respect to various meteorological parameters. Concerning precipitation, they project a decrease in rainfall occurrence between 20 and 40 % for the 2081–2100 period compared to 1981–2000 (SRES A2 scenario), based on large-scale output from three different GCMs (ECHAM5, IPSL, CNRM).

Finally, Tolika et al. (2007) referring to winter and spring precipitation in Greece, use an artificial neural network to assess changes in these variables from projections of 500 hPa geopotential heights, surface specific humidity, and raw precipitation data taken from the atmospheric model HadAM3P for 2070–2100 (SRES A2 scenario). They calculate decreases in the predictands for spring, but different results for winter: it is increased precipitation, when only using 500 hPa geopotential heights as predictors, but some opposite changes, when using all the predictors mentioned above. Again, this underlines the crucial impact of predictor variables, which have to be selected carefully.

Precipitation extremes

Particular attention in downscaling studies is paid to *precipitation extremes,* which might change differently to seasonal or annual means. This is mostly indicated by regional climate modelling for the Mediterranean basin, e.g. by Goubanova and Li (2007) with reduced mean precipitation in winter, spring, and summer, but increased rainfall extremes in all seasons except summer. Inverse changes of mean and extreme precipitation are also reported by Planton et al. (2012) for the French Mediterranean region, where the most heavy rainfalls (beyond the 96–99.9th percentiles) in most cases increase by 5–10 % outside the winter season, concurrently with a general decrease in total precipitation (comparing the last three decades of the twentieth and twenty-first centuries). This is not generally confirmed by statistical downscaling studies: Hertig et al. (2012b), for instance, referring to the whole Mediterranean area based on ECHAM5/MPI-OM or HadCM3 predictor output and on generalised linear models for seasonal mean precipitation as well as rainfall totals from events beyond the 95th percentile, get all combinations of total and extreme precipitation changes (both increasing or decreasing, or both inversely changing) until the end of the twenty-first century with the above-mentioned case (decrease in total and increase in extreme precipitation) not being the predominant one. It should be emphasized that these results have been obtained by statistical models not only considering large-scale circulation predictors, but also thermodynamic predictors influencing smaller-scale convection (as discussed in context of Fig. 3). The main results of this study point to seasonal and regional differences in the assessed rainfall changes: thus, opposite signs prevail in the western and central northern Mediterranean areas compared to parts of the eastern Mediterranean region during summer and autumn (decreases/increases in total and extreme precipitation in the former/latter area), as well as during winter (inverse distribution in changes). Only in spring, there are mostly similar changes over the entire Mediterranean area (decreases in total and extreme precipitation).

Another study by Hertig et al. (2012a) tries to compare performances of statistical (in this case based on canonical correlation analyses) and dynamical downscaling approaches (in this case based on the REMO model): concerning the frequency of extreme precipitation events, the statistical approach seems to provide a better representation than the dynamical one. But as for extreme rainfall intensity, the opposite seems to be true. However, note that the statistical models used by Hertig et al. (2012a) did not yet include predictors describing smaller-scale convection (as for instance in Hertig et al. (2012b, 2013), see also Fig. 3).

Beaulant et al. (2011) combine statistical and dynamical components of downscaling. The former is based on 500 hPa geopotential height clustering and the inclusion of low-level moisture transport in order to regionally characterize heavy precipitation (Nuissier et al. 2011). They detect a significant increase for the 2070–2100 period (SRES A2 scenario, ARPEGE Climate/OPAMED8 predictors) in the number of days with large-scale circulation patterns favourable for heavy precipitation in the French Mediterranean area, along with a slight increase in rainfall maxima and an increase in the spatial variability of high-precipitation events. Quintana-Segui et al. (2011) performing a weather typing approach (besides MOS techniques) with SLP and surface temperature discriminating for precipitation, estimate rainfall amounts beyond the 95th percentile for the Mediterranean basins of France—based on the SRES A2 scenario and output from a coupled regional climate model including the Mediterranean Sea. For the mid-twenty-first century, there are predominantly increases (except the Alps) with French Mediterranean maxima towards the borders with Spain and Italy. In a similar region, Lavaysse et al. (2012) obtain slight increases in the 95 % quantile for precipitation in winter, but mostly smaller values in summer for the 2081–2100 period (SRES A2 scenario, 3 different GCMs, transform approach of CDF). Another study by Tramblay et al. (2012) focuses on southern France in autumn (ENSEMBLES multi-model output, SRES A1B scenario 2070–2099) and shows an increase in the number of heavy rainfall events based on extreme value modelling, including the humidity flux from the Mediterranean Sea (which is projected to increase) as a model covariate. Seubert et al. (2013), however, obtain other signals for neighbouring regions at least in autumn: based on ECHAM5/MPI-OM SLP data and a synoptic downscaling approach using an Analogue method with subsequent extreme-value fitting by generalised Pareto distributions, they obtain a strong reduction in 30-year rainfall return-values for north-west Iberia and the northern central Mediterranean area; these assessments, however, have been made for SRES B1 scenario assumptions. They are confirmed by indications of a reduction in southerly displaced deep North Atlantic cyclones in autumn according to changes of circulation types associated with precipitation extremes (Seubert et al. 2013).

Despite considerable differences in the assessments of precipitation extremes, an overall tendency might become apparent for a general shift of the whole precipitation distribution towards higher *and* lower values, in accordance with the results from regional climate modelling (e.g. Gao et al. 2006). This might further be confirmed when looking at dry period characteristics (see next section).

Dry periods

As an opposite extreme to heavy precipitation, the length of dry periods is similar important in the climate change context. This is especially true in the Mediterranean area, which is generally characterized by a dry summer season and high rainfall variability on both inter-annual and intra-seasonal time scales. Vasiliades et al. (2009) refer to dry conditions as described by the Standardized Precipitation Index (SPI between −1.5 and −1.99 for severely dry and below −2 for extremely dry conditions). Based on multiple large-scale predictors (SLP, 2 m wind speed, precipitation, surface temperature, 500 hPa geopotential height, 500/1000 hPa thickness), they apply a multiple regression approach for monthly local precipitation and an additional stochastic time series modelling for rainfall residuals. Based on 9-month SPI time series and SRES A2 scenario assumptions (output from the Canadian model CGCMa2), they arrive, for example, at a median increase in the number of severely (extremely) dry months of 44 % (55 %) in the Lake Karla watershed (Thessaly, Greece) for the period 2070–2100.

A commonly used index for describing changes in dry period durations is the maximum number of consecutive dry days (CDD, see Moberg et al. 2006) within a base period (seasonally defined, for instance). A recent study on the whole Mediterranean area, applying GLMs for downscaling local variables from large-scale predictors (Hertig et al. 2012b), also includes assessments of CDD changes between the periods 2070–2099 and 1961–1990 according to SRES A1B scenario assumptions and ECHAM5/MPI-OM predictors. Beyond the seasonal results from this study, separate assessments are added in Fig. 4 for atmospheric circulation predictors and thermodynamic predictors (as already done for seasonal precipitation in Fig. 3, see "Precipitation" section). The separate assessments for these predictor groups have not been published so far concerning CDD. This is why a more detailed description seems necessary (see electronic supplementary material).

Another study including CDD analyses (Quintana-Segui et al. (2011), see "Precipitation" section) is related to the Mediterranean basins of France and displays mainly noisy anomalies for the mid-twenty-first century (even for the strong SRES A2 scenario), with some increase indicated for the Mediterranean coast. Further results on consecutive dry days are based on regional climate modelling and will only be mentioned for comparison. Costa et al. (2012) get strong increases in the dry spell lengths for autumn and spring in the period 2071–2100 in Portugal indicating an extension of the dry season from summer into the transitional seasons. Changes in a similar direction are obtained for Cyprus by Hadjinicolaou et al. (2011), although the increase in consecutive dry days refers to their annual number and to the earlier period of 2026–2050. Results from Fig. 4 for the last three decades of the twenty-first century mostly indicate an increase in consecutive dry days for Cyprus, too, but for Portugal, this is only valid mainly for autumn and, in the southern part, for summer. Especially during spring time, results are different for statistical and dynamical downscaling approaches.

For the River Jordan region, regional climate modelling indicates a prolongation of droughts for 2031–2060 (SRES A1B scenario) of between 22 and 46 days (compared to 1961–1990). The frequency of droughts is projected to decrease for moderate ones, but to increase for severe and extreme ones by a factor of 2 for the latter (Törnros 2010). Figure 4 (without appropriate models for summer in this region) addresses a later period (2070–2099), but points to a similar direction for winter and spring; for autumn, however, results from statistical and dynamical downscaling disagree.

Temperature

Annual and seasonal temperatures

Concerning seasonal temperatures, the entire Mediterranean area is affected by increases in projected downscaling assessments. The study of Hertig and Jacobeit (2008b)

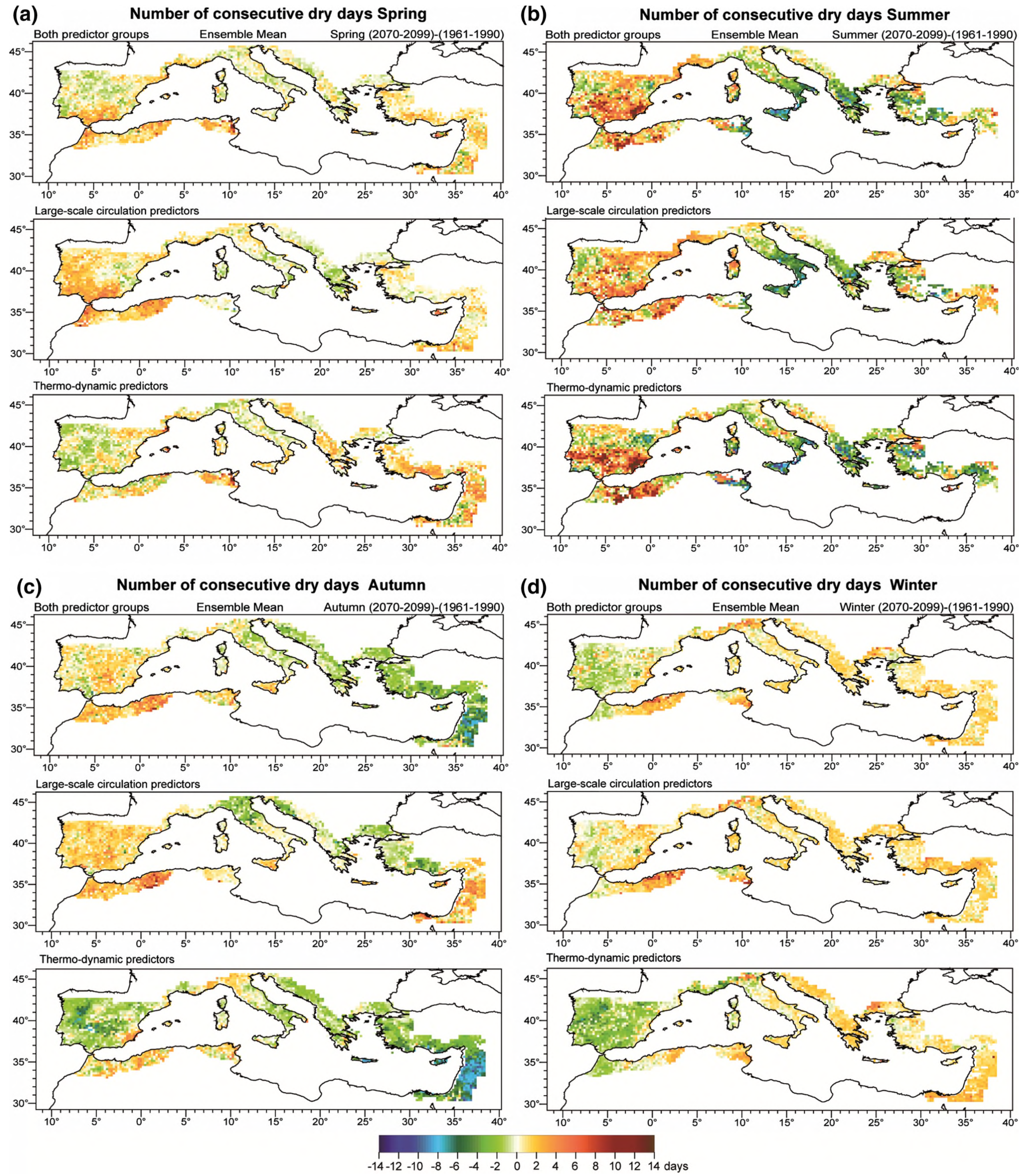

Fig. 4 Changes in the seasonal maximum number of consecutive dry days (2070–2099 in relation to 1961–1990) according to generalized linear downscaling models using predictors from ECHAM5/MPI-OM simulations (SRES A1B scenario). Predictors include variables describing the large-scale atmospheric circulation (700 and 500 hPa geopotential heights, 850 hPa zonal and meridional wind components) as well as thermodynamic conditions (850 and 700 hPa specific humidity, convective inhibition, Showalter Index). Assessments are made separately for the two predictor groups and also for both of them. **a** Spring, **b** summer, **c** autumn, **d** winter

based on canonical correlation analyses and linking 1000 and 500 hPa geopotential heights with gridded Mediterranean temperatures, indicates temperature increases mostly between 2 and 4 °C for the 2071–2100 period (SRES B2 scenario assumptions), compared to the 1990–2019 period, with some differences in mountainous areas of the north-eastern region between ECHAM4/OPYC3 and HadCM3 predictors. In winter, the lowest temperature rise of 1–1,5 °C occurs in the western part of North Africa, whereas the largest values of up to 3–4 °C are found in the eastern half of the Mediterranean area. Temperature rise is more uniform in the transitional seasons with values around 3 °C in spring and 4 °C in autumn. In summer, temperature increase remains at small values around 1 °C only in the eastern half of Mediterranean North Africa, whereas stronger increases (some in excess of 4 °C) are indicated in early summer for the western Mediterranean area, and in late summer also for the northern and eastern Mediterranean regions (Hertig and Jacobeit 2008b). The statistical downscaling results are in general agreement with regional climate modelling (e.g. Giorgi and Lionello 2008; Planton et al. 2012), especially concerning the seasonal differences with lower values in winter and spring and higher values in summer and autumn. Absolute amounts of temperature change may vary according to different scenarios and reference periods (thus, modelling results in Planton et al. (2012) are for SRES A1B in relation to 1961–1990).

Further results have been published for particular subregions of the Mediterranean area. For example, Palutikof et al. (2002) refer to the Guadalentin Basin in south-east Spain, developing linear transfer functions based on multiple regression analyses for daily maximum and minimum temperatures, separately for dry and wet days, with SLP, 500 hPa geopotential heights, and 500/1000 hPa geopotential thicknesses as predictors. Assuming a 1 % per year increase in equivalent CO_2 concentrations from 1990 onward (HadCM2 GCM), they get temperature increases for the last decade of the twenty-first century (compared to the 1970s) peaking during autumn (5.9–6.8 °C), with the other seasons lower at between 2.9 and 3.9 °C. In summer and autumn, T_{max} rises stronger than T_{min} in contrast to the opposite conditions for winter. The study of Lavaysse et al. (2012) on the French Mediterranean region (already mentioned in the "Precipitation" section) indicates stronger quantile increases for higher daily temperatures (SRES scenario A2, 2081–2100 vs. 1981–2000), rising from 2 °C for the 5 % quantile to 4 °C for the 50 % quantile, and to 6 °C for the 95 % quantile (no major seasonal differences).

Tomozeiu et al. (2007) refer to the Emilia-Romagna region in Italy, deriving statistical models based on canonical correlation analyses. With SLP, 500 hPa geopotential heights, and temperatures at the 850 hPa level as predictors, they get temperature increases for the 2070–2100 period (SRES A2 scenario, HadAM3P predictors) ranging between 2 and 2.5 °C for T_{min}, with less intense changes in spring than in the other seasons. T_{max} is projected to increase by 5 °C in summer, 3 °C in spring, and around 2 °C in winter and autumn. Thus, the latter season does not reveal such an outstanding extent of change as indicated for SE Spain.

Statistical relationships between large-scale predictors and regional temperatures have also been derived for Greece. However, CCA models by Xoplaki et al. (2003)—used to study recent inter-annual variability—as well as regression, CCA, and neural network models by Kostopoulou et al. (2007) focusing on methodical aspects, do not include future projections.

Temperature extremes

Some statistical downscaling studies have a special focus on extreme temperatures, mainly in terms of percentile-based indices or heat wave parameters. Hertig et al. (2010) have derived multiple regression models for the 5th percentile of minimum temperatures in winter, and for the 95th percentile of maximum temperatures in summer. These are based on daily station time series from the Mediterranean area, using 500 hPa geopotential heights (representing the atmospheric circulation) as well as 500/1000 hPa thickness fields (representing tropospheric temperatures) as large-scale predictors. In the book chapter of Planton et al. (2012), this approach has been added to by the use of CCA models based on gridded temperature data from the E-OBS data set (same predictors). Comparing the 2071–2100 period under SRES A1B scenario conditions (ECHAM5/MPI-OM predictors) to the reference period 1961–1990 points to a decrease in the intra-annual extreme temperature range in the eastern Mediterranean region, because extreme minimum temperatures in winter will increase more strongly (up to 1 °C) than extreme maximum temperatures in summer (up to 0.5 °C). This is in accordance with the general trends from global climate models, but disagrees with dynamical findings for the Mediterranean area with a simulated increase in this extreme temperature range (Tebaldi et al. 2006). Outside the eastern part of the Mediterranean area, however, the statistical assessments do not entirely agree (e.g. some increase in this range for CCA models and gridded surface data, but some decrease for regression models and station data in the central part of the Mediterranean area). For parts of the western Mediterranean region, even slight decreases in the temperature percentiles for both seasons (winter and summer) are indicated. Regional climate modelling, on the other hand, provides an overall increase in temperature extremes across the Mediterranean area (e.g. Giorgi and

Lionello 2008) with extreme daily maximum temperatures rising stronger than mean T_{max}, and extreme daily minimum temperatures rising weaker than mean T_{min}, thus implying a higher dispersion of extreme temperatures by the end of the twenty-first century (Sánchez et al. 2004).

The study of Seubert et al. (2013) based on daily maximum temperatures projected for 2070–2099 (SRES B1 scenario, ECHAM5/MPI-OM SLP data) by an Analogue approach and on corresponding extremes fitted by generalized Pareto distributions identifies the most distinctive changes for the autumn season with a pronounced increase of T_{max} extremes in south-west Iberia, central and south-eastern Mediterranean regions. Further, sub-regional results from statistical downscaling studies mentioned above should be added: according to Lavaysse et al. (2012), analysing the French Mediterranean region, the 95 % quantile of the 1981–2000 period roughly corresponds to the 80 % quantile of the 2081–2100 period. The future projections for Emilia-Romagna (Tomozeiu et al. 2007) provide general increases in the 10th percentile of minimum temperatures, highest in winter (around 4.5 °C) and lowest in autumn (around 1 °C). The 90th percentile of maximum temperatures is also increasing, between 4 °C in summer and less than 1 °C in winter. The heat wave duration index indicates the largest increase in spring (up to 10 days). Enhanced high-temperature conditions are also projected for SE Spain: Palutikof et al. (2002) get a fivefold increase in the number of hot days ($T_{max} > 35$ °C) comparing 2090–2099 to the 1970s.

Near-surface wind

Few statistical downscaling studies deal with regional or local wind conditions near the earth's surface. García-Bustamante et al. (2012), referring to the north-eastern Iberian Peninsula, link the regional wind field to the large-scale atmospheric circulation by Canonical Correlation Analysis (850 hPa geopotential height and 500/850 hPa thickness as predictors). However, they do not perform future projections, but instead reconstruct back in time by several centuries. In a subsequent paper (Garcia-Bustamante et al. 2013), downscaling refers to wind power production, directly linked to the large-scale atmospheric circulation or, by transfer functions, to downscaled wind values. The study of Martín et al. (2011) also refrains from future projections and focuses on coupled modes (derived by singular value decomposition) between monthly mean wind conditions at Iberian stations and large-scale circulation patterns of the 1000 hPa level. Thereby, the importance of the well-known Scandinavian, NAO, and East Atlantic patterns for regional wind conditions in the Iberian Peninsula has been confirmed.

With respect to southern France, Salameh et al. (2009) do not find discriminating power of North Atlantic weather regimes for downscaling surface winds, but they are able to relate not only station wind speed, but also horizontal wind components to explanatory variables (such as surface pressure gradients, large-scale winds, geopotential heights, and relative vorticity at various levels) by means of generalized additive models. Future assessments are again included in two further studies: the paper by Lavaysse et al. (2012) (already mentioned in "Precipitation" and "Temperature" sections) indicates a decrease in mean and extreme wind speeds by 1–2 m/s (mainly caused by changes during winter) for the French Mediterranean region in the 2081–2100 period (compared to 1981–2000) according to SRES A1B scenario assumptions (GCM data from ECHAM5, IPSL, and CNRM). Najac et al. (2011) use a combined approach defining wind classes based on zonal and meridional wind components of the 850 hPa level, and subsequently simulating randomly selected individual days from each wind class by a meso-scale atmospheric model down to 3 km horizontal resolution over the Mediterranean area of France. 10-m wind distributions at particular stations for the projection period 2046–2065 (SRES A1B scenario, output from 14 CMIP3 models) are obtained from frequency changes of the wind classes and indicate a significant decrease by nearly 6 % of the mean daily 10 m wind speed in the French part of the Mediterranean area for the extended winter season from October to March. This is associated with a decrease in westerly, north-westerly, and northerly winds in this region in accordance with less frequent negative phases of the NAO.

As for the Adriatic Sea area, regional surface wind fields (0.25° resolution) have been downscaled from ECHAM-4 SLP fields (T106 resolution) by CCA techniques with PCA pre-filtering (Lionello et al. 2003). This has been done for two 30-year time-slice experiments representing present and doubled CO_2 conditions. The downscaled wind fields have also been used to force a storm-surge and a wave height model for the Adriatic Sea leading to remarkable improvements compared to larger-scale forcings. No substantial change in the extreme surge level and a decrease in the extreme wave height have been identified for the future scenario. However, systematic underestimations for both variables have to be taken into account (Lionello et al. 2003).

Conclusions

The short reviews of "Precipitation", "Dry periods", "Temperature", and "Near-surface wind" sections have shown that there are considerable differences among future climate change projections in the Mediterranean area, concerning both the amount of projected changes in regional climate as well as the spatial distribution patterns of climate change. Here, we summarize the main climate change signals, highlight consensus, and discuss controversial points, also considering general results from dynamical modelling studies.

The best agreement in future projections can be found for seasonal temperatures, which will increase with enhanced greenhouse gas forcing. There is also a general consensus between statistical downscaling and regional climate modelling for the seasonal differences with lower rates of warming in winter and spring, and higher ones in summer and autumn (except the latter season according to a statistical study for the smaller Emilia-Romagna region). Absolute amounts of temperature change, however, may vary depending on different scenarios and reference periods. Different results are obtained for the intra-annual extreme temperature range: global climate models provide an increase for the Mediterranean area, regional climate modelling indicates a higher dispersion of extreme temperatures, whereas statistical downscaling points to a decreased range at least in the eastern Mediterranean area (varying changes in other sub-regions). But high-temperature conditions are generally expected to increase.

Future projections are more complex for precipitation, including differences between dynamical and statistical modelling. For the Mediterranean area as a whole, both assessments point to a predominance of rainfall reductions in spring, summer, and autumn, whereas in winter, some important differences occur: global climate models indicate a general rainfall decrease for this season, whereas several statistical downscaling results include widespread increases in rainfall for the northern and western parts. In contrast, the eastern Mediterranean area, where rainfall decreases in winter, shows some precipitation increases in summer and autumn. Regional climate models also indicate some seasonal rainfall increase, the spatial extent, however, being different: the area with wintertime increase is confined to the northernmost parts of the Mediterranean region, and the rainfall increase during summer and autumn is rather concentrated on the south-eastern part. Sub-regional studies also point to predominant rainfall reductions, but again include some cases with seasonal increase (in western Iberia during spring, in south-eastern Spain, parts of Italy and Turkey during summer, in parts of Iberia during winter). A synthesis is even more difficult for rainfall extremes: the combination of decreased total and increased extreme precipitation, in most cases indicated by dynamical studies, is not the predominant signal, according to statistical assessments, among all the combinations occurring (total vs. extreme rainfall change). Nevertheless, a general shift of the whole precipitation distribution towards higher *and* lower values may be seen as a corresponding signal of change.

Concerning future dry period durations in the Mediterranean region, the predominant climate change signals point to an increase. However, there are also indications for sub-regional decreases in the maximum number of consecutive dry days, e.g. in parts of the northern and western area in spring, in the Ionian and Aegean Sea in summer, in the north-central and eastern area in autumn, and in the western part in winter. These statistically derived assessments do not always agree with dynamical downscaling results, e.g. for Portugal in spring, or for the River Jordan region in autumn, where regional climate modelling points to a prolongation of dry periods.

Finally, only a few studies are available concerning near-surface winds. For the French Mediterranean region, a decrease in mean and extreme wind speeds is projected for the future, especially for the winter season. For the Adriatic Sea, no substantial change in the extreme wind surge level and a decrease in the extreme wave height are projected depending on downscaled regional wind fields. These sub-regional examples might indicate some reduction in the Mediterranean atmospheric circulation strength.

In summary, there are agreements as well as some considerable differences in regional climate change projections. This is why we have to deal with the aspect of reliability concerning statistical downscaling assessments. This is directly linked to the broad field of uncertainties connected with these techniques. They arise from GCM deficiencies transferred via the predictor input, from scenario assumptions and from constraints inherent to the statistical models themselves, due to, for example, the predictor selection, restricted model performance, or non-stationarities in the predictor–predictand relationships. So far, these uncertainties have not yet been analysed sufficiently (see below for further requirements), thus leaving substantial doubts in the reliability of some of the available downscaling assessments. As far as different predictands and the degree of correspondence between different assessments are concerned, one might conclude (from the Mediterranean studies discussed in this paper) that temperature-related estimates are more reliable than those related to rainfall, and estimates of mean conditions are more reliable than those of extremes. Furthermore, the degree of correspondence between different assessments seems to be lower for the highest possible resolution (individual grid boxes or stations) than for (sub-) regional aggregations (benefit of spatial smoothing).

Statistical downscaling assessments will obtain an improved reliability, if uncertainties (especially those inherent to the statistical models) are adequately quantified and if appropriate strategies are developed to reduce them. In this context, the following proceedings are particularly relevant:

1. Inclusion of an appropriate set of predictors: with regard to the Mediterranean region, this should not only imply large-scale atmospheric circulation predictors, but also regional oceanic and land-surface data (e.g. soil moisture) as well as thermodynamic variables describing, for instance, smaller-scale convection (in the case of rainfall predictands).
2. When using distribution functions in downscaling, the application of mixed models with different functions for normal and extreme values should be preferred.
3. Multi-GCM ensembles should be used not only for determining a particular uncertainty range of climate change projections, but also for developing specific weights for the downscaling results according to the different performance of the GCMs (e.g. with regard to regionally important dynamical conditions, whatever appropriate criteria for this might be). This would help to reduce uncertainties arising from the GCM scale, thereby enhancing the reliability of downscaling assessments.
4. Statistical model ensembles should be used not only for determining another range of uncertainty, but especially for considering different predictor–predictand relationships due to corresponding non-stationarities. This requires a sound identification of such non-stationarities in both observation and model data sets, subsequently allowing the derivation of specific downscaling assessments of enhanced reliability.

Considering the above-mentioned aspects, future assessments of regional climate change would be much more reliable including well-founded quantifications of remaining uncertainties. Such a level of performance would imply that statistical downscaling will take and maintain an important position besides dynamical downscaling in future projections of regional climate change.

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References

Anagnostopoulou CHR, Tolika K, Maheras P, Kutiel H, Flocas HA (2008) Performance of the general circulation HadAM3P model in simulating circulation types over the Mediterranean region. Int J Climatol 28:185–203

Bardossy A, Bogardi I, Matyasovszky I (2005) Fuzzy rule-based downscaling of precipitation. Theor Appl Climatol 82:119–129

Beaulant AL, Joly B, Nuissier O, Somot S, Ducrocq V, Joly A, Sevault F, Deque M, Ricard D (2011) Statistico-dynamical downscaling for Mediterranean heavy precipitation. Q J R Meteorol Soc 137:736–748

Beck C, Philipp A (2010) Evaluation and comparison of circulation type classifications for the European domain. Phys Chem Earth 35:374–387

Benestad RE, Hanssen-Bauer I, Chen D (2008) Empirical-statistical downscaling. World Scientific Publication, Singapore, p 215

Biau G, Zorita E, von Storch H, Wackernagel H (1999) Estimation of precipitation by kriging in the EOF space of the sea level pressure field. J Clim 12:1070–1085

Busuioc A, Tomozeiu R, Cacciamani C (2008) Statistical downscaling model based on canonical correlation analysis for winter extreme precipitation events in the Emilia-Romagna region. Int J Climatol 28:449–464

Carreau J, Vrac M (2011) Stochastic downscaling of precipitation with neural network conditional mixture models. Water Resour Res 47:W10502

Corte-Real J, Zhang X, Wang X (1995) Downscaling GCM information to regional scales: a non-parametric multivariate regression approach. Clim Dyn 11:413–424

Corte-Real J, Xu H, Qian B (1999) A weather generator for obtaining daily precipitation scenarios based on circulation patterns. Clim Res 13:61–75

Costa A, Santos J, Pinto J (2012) Climate change scenarios for precipitation extremes in Portugal. Theor Appl Climatol 108:217–234

Frías MD, Zorita E, Fernández J, Rodriguez-Puebla C (2006) Testing statistical downscaling methods in simulated climates. Geophys Res Lett 33:L19807

Gao X, Pal JS, Giorgi F (2006) Projected changes in mean and extreme precipitation over the Mediterranean region from high resolution double nested RCM simulations. Geophys Res Lett. doi:10.1029/2005GL024954

Garcia-Bustamante E, Gonzalez-Rouco JF, Navarro J, Xoplaki E, Luterbacher J, Jimenez PA, Montavez JP, Hidalgo A, Lucio-Eceiza EE (2013) Relationship between wind power production and North Atlantic atmospheric circulation over the northeastern Iberian Peninsula. Clim Dyn 40:935–949

García-Bustamante E, González-Rouco JF, Navarro J, Xoplaki E, Jiménez PA, Montávez JP (2012) North Atlantic atmospheric circulation and surface wind in the northeast of the Iberian Peninsula: uncertainty and long term downscaled variability. Clim Dyn 38:141–160

Giorgi F (2006) Climate change hot-spots. Geophys Res Lett. doi:10.1029/2006GL025734

Giorgi F, Coppola E (2009) Projections of 21st century climate over Europe. Eur Phys J 1:29–46

Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean area. Glob Planet Change 63:90–104

González-Rouco JF, Heyen H, Zorita E, Valero F (2000) Agreement between observed rainfall trends and climate change simulations in the southwest of Europe. J Clim 13:3057–3065

Goodess CM, Palutikof JP (1998) Development of daily rainfall scenarios for southeast Spain using a circulation-type approach to downscaling. Int J Climatol 10:1051–1083

Goubanova K, Li L (2007) Extremes in temperature and precipitation around the Mediterranean basin in an ensemble of future climate scenario simulations. Glob Planet Change 57:27–42

Hadjinicolaou P, Giannakopoulos C, Zerefos C, Lange M, Pashiardis S, Lelieveld J (2011) Mid-21st century climate and weather extremes in Cyprus as projected by six regional climate models. Reg Environ Change 11:441–457

Haylock MR, Hofstra N, Klein Tank AMG, Klok EJ, Jones PD, New M (2008) A European daily high-resolution gridded dataset of surface temperature and precipitation for 1950–2006. J Geophys Res Atmos 113. doi:10.1029/2008JD010201

Hertig E, Jacobeit J (2008a) Assessments of Mediterranean precipitation changes for the 21st century using statistical downscaling techniques. Int J Climatol 28:1025–1045

Hertig E, Jacobeit J (2008b) Downscaling future climate change: temperature scenarios for the Mediterranean area. Glob Planet Change 63:127–131

Hertig E, Jacobeit J (2013) A novel approach to statistical downscaling considering non-stationarities: application to daily precipitation in the Mediterranean area. J Geophy Res Atmos 118:520–533

Hertig E, Seubert S, Jacobeit J (2010) Temperature extremes in the Mediterranean area: trends in the past and assessments for the future. Nat Hazards Earth Syst Sci 10:2039–2050

Hertig E, Seubert S, Paxian A, Vogt G, Paeth H, Jacobeit J (2012a) Statistical and dynamical downscaling assessments of precipitation extremes in the Mediterranean area. Meteorol Z 21:61–77

Hertig E, Seubert S, Paxian A, Vogt G, Paeth H, Jacobeit J (2012b) Changes of total versus extreme precipitation and dry periods until the end of the twenty-first century: statistical assessments for the Mediterranean area. Theor Appl Climatol 111:1–20

Hertig E, Seubert S, Paxian A, Vogt G, Paeth H, Jacobeit J (2013) Statistical modelling of extreme precipitation indices for the Mediterranean area under future climate change. Int J Climatol. doi:10.1002/joc.3751

Hewitson B, Crane R (1996) Climate downscaling: techniques and application. Clim Res 7:85–95

Huth R, Beck C, Philipp A, Demuzere M, Ustrnul Z, Cahynová M, Kyselý J, Tveito OE (2008) Classifications of atmospheric circulation patterns: recent advances and applications. Ann NY Acad Sci 1146:105–152

Jacobeit J (1994a) Empirische Abschätzungen zur Änderung des Winterniederschlags im Mittelmeerraum bei anthropogen verstärktem Treibhauseffekt. PIK Reports (Potsdam-Institut für Klimafolgenforschung) 1: 117–121

Jacobeit J (1994b) Empirical estimations of Mediterranean rainfall changes in the transitional seasons due to enhanced greenhouse warming. In: Brazdil R, Kolar M (eds) (1994) Contemporary Climatology. Brno, 266-271

Jacobeit J (1996) Atmospheric circulation changes due to increased greenhouse warming and its impact on seasonal rainfall in the Mediterranean area. In: Nemesova I (ed) (1996) Climate variability and climate change vulnerability and adaptation. Proceedings of the Regional Workshop Praha 1995, pp 71–80

Jacobeit J (2000) Rezente Klimaentwicklung im Mittelmeerraum. Petermanns Geogr Mitt 144:22–33

Jacobeit J (2010) Classifications in climate research. Phys Chem Earth 35:411–421

Kallache M, Vrac M, Naveau P, Michelangeli PA (2011) Nonstationary probabilistic downscaling of extreme precipitation. J Geophys Res Atmos 116:D05113

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77:437–471

Kistler R, Kalnay E, Collins W, Saha S, White G, Woollen J, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V, van den Dool H, Jenne R, Fiorino M (2001) The NCEP/NCAR 50-year reanalysis. Bull Am Meteorol Soc 82:247–268

Kostopoulou E, Giannakopoulos C, Anagnostopoulou C, Tolika K, Maheras P, Vafiadis M, Founda D (2007) Simulating maximum and minimum temperature over Greece: a comparison of three downscaling techniques. Theor Appl Climatol 90:65–82

Lavaysse P, Vrac M, Drobinski P, Lengaigne M, Vischel T (2012) Statistical downscaling of the French Mediterranean climate: assessment for present and projection in an anthropogenic scenario. Nat Hazards Earth Syst Sci 12:651–670

Lionello P, Giorgi F (2007) Winter precipitation and cyclones in the Mediterranean region: future climate scenarios in a regional simulation. Adv Geosci 12:153–158

Lionello P, Nizzero A, Elvini E (2003) A procedure for estimating wind waves and storm-surge climate scenarios in a regional basin: the Adriatic Sea case. Clim Res 23:217–231

Lutz K, Jacobeit J, Philipp A, Seubert S, Kunstmann H, Laux P (2012) Comparison and evaluation of statistical downscaling techniques for station-based precipitation in the Middle East. Int J Climatol 32:1579–1595

Maraun D, Wetterhall F, Ireson AM, Chandler RE, Kendon EJ, Widmann M, Brienen S, Rust HW, Sauter T, Themeßl M, Venema VKC, Chun KP, Goodess CM, Jones RG, Onof C, Vrac M, Thiele-Eich I (2010) Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user. Rev Geophys 48:1–34

Martín ML, Valero F, Morata A, Luna MY, Pascual A, Santos-Muñoz D (2011) Springtime coupled modes of regional wind in the Iberian Peninsula and large-scale variability patterns. Int J Climatol 31:880–895

Michelangeli PA, Vrac M, Loukos H (2009) Probabilistic downscaling approaches: application to wind cumulative distribution functions. Geophys Res Lett 36:L11708

Moberg A, Jones PD, Lister D, Walther A, Brunet M, Jacobeit J, Alexander LV, Della-Marta P, Luterbacher J, Yiou P, Chen D, Klein Tank A, Saladié O, Sigró J, Aguilar E, Alexandersson H, Almarza C, Auer I, Barriendos M, Begert M, Bergström H, Böhm R, Butler CJ, Caesar J, Drebs A, Founda D, Gerstengarbe FW, Micela G, Maugeri M, Österle H, Pandzic K, Petrakis M, Srnec L, Tolasz R, Tuomenvirta H, Werner PC, Linderholm H, Philipp A, Wanner H, Xoplaki E (2006) Indices for daily temperature and precipitation extremes in Europe analysed for the period 1901-2000. J Geophys Res Atmos 111. doi:10.1029/2006JD007103

Murphy J (2000) Predictions of climate change over Europe using statistical and dynamical downscaling techniques. Int J Climatol 20:489–501

Myoung B, Nielsen-Gammon JW (2010) Sensitivity of monthly convective precipitation to environmental conditions. J Clim 23:166–188

Najac J, Lac C, Terray L (2011) Impact of climate change on surface winds in France using a statistical-dynamical downscaling method with mesoscale modeling. Int J Climatol 31:415–430

Nakicenovic N, Swart R (eds) (2000) Emissions scenarios 2000. Special report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 570

Nuissier O, Joly B, Joly A, Ducrocq V, Arbogast P (2011) A statistical downscaling to identify the large-scale circulation patterns associated with heavy precipitation events over southern France. Q J R Meteorol Soc 137:1812–1827

Paeth H, Hense A (2005) Mean versus extreme climate in the Mediterranean region and its sensitivity to future global warming conditions. Meteorol Z 14:329–347

Palatella L, Miglietta MM, Paradisi P, Lionello P (2010) Climate change assessment for Mediterranean agricultural areas by statistical downscaling. Nat Hazards Earth Syst Sci 10:1647–1661

Palutikof JP, Wigley TML (1996) Developing climate change scenarios for the Mediterranean region. In: Jeftic L, Keckes S, Pernetta JC (eds) Climatic change and the Mediterranean, vol 2. Arnold, London, pp 27–56

Palutikof JP, Goodess CM, Watkins SJ, Holt T (2002) Generating rainfall and temperature scenarios at multiple sites: examples from the Mediterranean. J Clim 15:3529–3548

Philipp A, Della Marta P, Jacobeit J, Fereday D, Jones PD, Moberg A, Wanner H (2007) Long-term variability of daily North-Atlantic–

European Pressure patterns since 1850 classified by simulated annealing clustering. J Clim 20:4065–4095
Philipp A, Bartholy J, Beck C, Erpicum M, Esteban P, Fettweis X, Huth R, James P, Jourdain S, Kreienkamp F, Krennert T, Lykoudis S, Michalides S, Pianko K, Post P, Rasilla Álvarez D, Schiemann R, Spekat A, Tymvios FS (2010) COST733CAT—a database of weather and circulation type classifications. Phys Chem Earth 35:360–373
Planton S, Lionello P, Artale V, Aznar R, Carillo A, Colin J, Congedi L, Dubois C, Elizalde A, Gualdi S, Hertig E, Jacobeit J, Jordà Sanchez G, Li L, Mariotti A, Piani C, Ruti P, Sanchez-Gomez E, Sannino G, Sevault F, Somot S (2012) The climate of the Mediterranean region in future climate projections. In: Lionello P et al. (eds) The climate of the Mediterranean region: from the past to the future. Elsevier, NY, pp 449–502
Quintana-Segui P, Habets F, Martin E (2011) Comparison of past and future Mediterranean high and low extremes of precipitation and river flow projected using different statistical downscaling methods. Nat Hazards Earth Syst Sci 11:1411–1432
Roeckner E, Bäuml G, Bonaventura L, Brokopf R, Esch M, Giorgetta M, Hagemann S, Kirchner I, Kornblueh L, Manzani E, Rhodin A, Schlese U, Schulzweida U, Tompkins A (2003) The atmospheric general circulation model ECHAM5. Part I: model description. Max Planck Institute for Meteorology Report 349, Hamburg, p 140
Roeckner E, Brasseur GP, Giorgetta M, Jacob D, Jungclaus J, Reick C, Sillmann J (2006) Climate projections for the 21st century. Max Planck Institute for Meteorology, Hamburg, p 32
Salameh T, Drobinski P, Vrac M, Naveau P (2009) Statistical downscaling of near-surface wind over complex terrain in southern France. Meteorol Atmos Phys 103:253–265
Sánchez E, Gallardo C, Gaertner MA, Arribas A, Castro M (2004) Future climate extreme events in the Mediterranean simulated by a regional climate model: a first approach. Glob Planet Change 44:163–180
Seubert S, Fernandez-Montes S, Philipp A, Hertig E, Jacobeit J, Paxian A, Vogt G, Paeth H (2013) Mediterranean climate extremes in synoptic downscaling assessments. Theor Appl Climatol. doi:10.1007/s00704-013-0993-y
Showalter AK (1953) A convective index as an indicator of cumulonimbus development. J Appl Meteorol 5:839–846
Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) (2007) Climate change: the physical science basis. Contribution of working group 1 to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, New York
Sumner GN, Romero R, Homar V, Ramis C, Alonso S, Zorita E (2003) An estimate of the effects of climate change on the rainfall of Mediterranean Spain by the late twenty first century. Clim Dyn 20:789–805
Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA (2006) Going to the extremes. An intercomparison of model-simulated historical and future changes in extreme events. Clim Change 79:185–211
Tolika K, Maheras P, Vafiadis M, Flocas HA, Arseni-Papadimitriou A (2007) Simulation of seasonal precipitation and raindays over Greece: a statistical downscaling technique based on artificial neural networks (ANNs). Int J Climatol 27:861–881
Tomozeiu R, Cacciamani C, Pavan V, Morgillo A, Busuioc A (2007) Climate change scenarios for surface temperature in Emilia-Romagna (Italy) obtained using statistical downscaling models. Theor Appl Climatol 90:25–47
Törnros T (2010) Precipitation trends and suitable drought index in the arid/semi-arid south-eastern Mediterranean region. In: Servat E, Demuth S, Dezetter A, Daniell T (eds) Global Change: Facing Risks and Threats to Water Resources (Proc. of the Sixth World FRIEND Conference, Fez, Morocco, 2010), vol 340. IAHS Publication, p 157–163
Tramblay Y, Neppel L, Carreau J, Sanchez-Gomez E (2012) Extreme value modeling of daily areal rainfall over Mediterranean catchments in a changing climate. Hydrol Process 26:3934–3944
Trigo RM, Palutikof JP (1999) Simulation of daily temperatures for climate change scenarios over Portugal: a neural network model approach. Clim Res 13:45–59
Trigo RM, Palutikof JP (2001) Precipitation scenarios over Iberia: a comparison between direct GCM output and different downscaling techniques. J Clim 14:4422–4446
Vasiliades L, Loukas A, Patsonas G (2009) Evaluation of a statistical downscaling procedure for the estimation of climate change impacts on droughts. Nat Hazards Earth Syst Sci 9:879–894
Von Storch H, Zorita E, Cubasch U (1991) Downscaling of global climate change estimates to regional scales: an application to Iberian rainfall in wintertime. Max-Planck-Institute for Meteorology Hamburg, report no. 64
Von Storch H, Zorita E, Cubasch U (1993) Downscaling of global climate change estimates to regional scales: an application to Iberian rainfall in wintertime. J Clim 6:1161–1171
Vrac M, Naveau P (2007) Stochastic downscaling of precipitation: from dry events to heavy rainfall. Water Resour Res 43 doi:10.1029/2006WR005308
Vrac M, Yiou P (2010) Weather regimes designed for local precipitation modelling: application to the Mediterranean basin. J Geophys Res 115. doi:10.1029/2009JD012871
Vrac M, Drobinski P, Merlo A, Herrmann M, Lavaysse C, Li L, Somot S (2012) Dynamical and statistical downscaling of the French Mediterranean climate: uncertainty assessment. Nat Hazards Earth Syst Sci 12:2769–2784
Wilby RL (1998) Statistical downscaling of daily precipitation using daily airflow and seasonal teleconnection indices. Clim Res 10:163–178
Wilby RL, Wigley TML (1997) Downscaling general circulation model output: a review of methods and limitations. Prog Phys Geogr 21:530–548
Wilks DS (2011) Statistical methods in the atmospheric sciences, 3rd edn. Academic Press/Elsevier, Amsterdam, p 704
Xoplaki E, Gonzalez-Rouco J, Gyalistras D, Luterbacher J, Rickli R, Wanner H (2003) Interannual summer air temperature variability over Greece and its connection to the large-scale atmospheric circulation and Mediterranean SSTs 1950–1999. Clim Dyn 20:537–554
Xoplaki E, Gonzalez-Rouco J, Luterbacher J, Wanner H (2004) Wet season Mediterranean precipitation variability: influence of large-scale dynamics. Clim Dyn 23:63–78
Zorita E, von Storch H (1999) The analog method as a simple statistical downscaling technique: comparison with more complicated methods. J Clim 12:2474–2489