How uncertain are climate model projections of water availability indicators across the Middle East?

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The projection of robust regional climate changes over the next 50 years presents a considerable challenge for the current generation of climate models. Water cycle changes are particularly difficult to model in this area because major uncertainties exist in the representation of processes such as large-scale and convective rainfall and their feedback with surface conditions. We present climate model projections and uncertainties in water availability indicators (precipitation, run-off and drought index) for the 1961–1990 and 2021–2050 periods. Ensembles from two global climate models (GCMs) and one regional climate model (RCM) are used to examine different elements of uncertainty. Although all three ensembles capture the general distribution of observed annual precipitation across the Middle East, the RCM is consistently wetter than observations, especially over the mountainous areas. All future projections show decreasing precipitation (ensemble median between $-5$ and $-25\%$) in coastal Turkey and parts of Lebanon, Syria and Israel and consistent run-off and drought index changes. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) GCM ensemble exhibits drying across the north of the region, whereas the Met Office Hadley Centre work Quantifying Uncertainties in Model Projections—Atmospheric (QUMP-A) GCM and RCM ensembles show slight drying in the north and significant wetting in the south. RCM projections also show greater sensitivity (both wetter and drier) and a wider uncertainty range than QUMP-A. The nature of these uncertainties suggests that both large-scale circulation patterns, which influence region-wide drying/wetting patterns, and regional-scale processes, which affect localized water availability, are important sources of uncertainty in these projections. To reduce large uncertainties in water availability projections, it is suggested that efforts would be well placed to focus on the understanding and modelling of both large-scale processes and their teleconnections with Middle East climate and localized processes involved in orographic precipitation.

Keywords: climate; uncertainties; Middle East; projections; global climate model; regional climate model

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One contribution of 14 to a Discussion Meeting Issue ‘Water and society: past, present and future’.
1. Background

(a) Middle East climate

The region covering the eastern Mediterranean and the Middle East is characterized by contrasting land masses, mostly deserts and mountains and sea areas, including the Mediterranean, Black, Red and Caspian Seas. Although it is typified by a Mediterranean climate—cool, wet winters and hot, dry summers—these unique surface characteristics in combination with large-scale circulation processes exert a significant impact on the region’s weather and climate.

The region experiences typically high variability in the inter- and intra-annual distribution of precipitation, run-off and, correspondingly, drought indicators (Eshel et al. 2000; Cullen et al. 2002). The dominance of evaporation over precipitation means that most of the region lacks access to surface or groundwater resources (Cullen et al. 2002). Many areas across the region consistently experience less than 100 mm of precipitation per year (figure 1a).

During the winter, polar maritime and polar continental air masses control the weather systems. Mid-latitude troughs, which propagate from the North Atlantic across the northern Mediterranean coast, and cyclogenesis within the Mediterranean region caused by North Atlantic weather systems are responsible for the majority of the annual precipitation in eastern Mediterranean countries and many parts of the Middle East (Buzzi & Tibaldi 1978; Alpert et al. 1990; Cullen & deMenocal 2000; Trigo et al. 2004). Through this teleconnection, variations in climatic conditions in the North Atlantic, particularly the North Atlantic Oscillation (NAO), have been shown to exert a significant influence on Middle East winter precipitation variations (Hurrell 1995; Rodo et al. 1997; Rodwell et al. 1999; Xoplaki 2002; Trigo et al. 2004). In addition to this large-scale influence, orographic ascent of moisture-laden air is also an important cause of enhanced precipitation, particularly along the windward slopes of the northern Anatolian and Taurus Mountains in Turkey, the western mountain range of Lebanon, the Zagros Mountains in northern Iraq and through western Iran and the Yemeni Mountains in western Yemen. In summer, the Hadley cell moves northward, advection of moisture from the Atlantic is weakened and connections with Asian and African monsoons are stronger.

Although some of the broad features influencing weather and climate variability across the region are reasonably well understood and consistent across models (Mariotti et al. 2008), quantifying and understanding climate changes at the regional scale is currently one of the most important and uncertain issues (Lionello et al. 2006). In particular, interactions between large-scale processes and regional-scale characteristics are not well understood, yet this is vital to inform water resource planning in the region.

(b) Uncertainty in climate model projections

Despite the success of complex global climate models (GCMs) and regional climate models (RCMs) in simulating many features of present-day climate and climate variability, the projection of robust regional changes in climate
over the next 50 years presents a considerable challenge for the current generation of climate models. Limitations in computer resources and in our understanding of small-scale climate processes mean that there are often large disparities in future climate projections among models. There are several reasons for this.

Firstly, projections are dependent on future emissions of greenhouse gases and other radiative forcing agents, which, in turn, depend on the behaviour of humans, including the outcomes of international negotiations to limit such emissions. This is somewhat outside the realm of climate projection science, and hence it is common to present projections that are conditional on scenarios, such as those detailed in the Special Report on Emissions Scenarios (SRESs; Nakicenovic et al. 2000).

Phil. Trans. R. Soc. A (2010)
Secondly, climate varies naturally because of, for example, interactions between the ocean and the atmosphere, which are responsible for climate phenomena such as the El Niño Southern Oscillation (ENSO). It is not possible to predict the precise evolution of ENSO over anything more than a year or so, making long-term deterministic predictions for the coming century not possible. However, it is possible to characterize the envelope of the amplitude and phase of such oscillations. This type of uncertainty is often described as that due to natural variability.

Thirdly, and most importantly from the point of view of the projections discussed here, different GCMs and RCMs produce different responses at both global and regional scales. Work is continually underway to reduce ‘model errors’, i.e. imperfections in the model’s ability to reproduce the observed and future climate, but that represents a significant challenge, and hence modelling limitations remain. These imperfections are the principal causes of the ‘modelling uncertainties’, and they mean that, in any collection of different GCMs and RCMs, there is a range of different responses to the same radiative forcing.

Such uncertainties are particularly pertinent to water availability projections in the eastern Mediterranean and Middle East, because the representation of processes that influence large-scale and convective rainfall and their interactions with surface conditions is one of the major uncertainties in current climate modelling. Furthermore, the very steep north to south gradient across the region and the high spatio-temporal variability in precipitation are generally too localized to be fully reproduced in the relatively coarse resolution of climate models.

*(c) Study aims and objectives*

The aim of this study is to assess the magnitude of change and the degree of uncertainty in climate model projections of precipitation, run-off and drought index across the Middle East region for the 2021–2050 period (relative to the baseline 1961–1990 period). These three climate parameters and the future time period were chosen to provide an indication of the direction and degree of uncertainty in projections of renewable surface water availability across the region for a time period that is useful for water resource planning horizons. It is important to note that this study does not attempt to assess fresh water availability *per se*, because no consideration is taken here of fresh water available from groundwater reserves, man-made water stores or technological advances such as desalination.

Different elements of uncertainty are considered in this study by using two GCM ensembles and one RCM ensemble. Although we examine some of the currently known major sources of uncertainty, additional uncertainties are almost certain to emerge, and it is therefore possible that future climate changes may fall outside the ranges described here. Therefore, the results provide useful guidance on the locations where we currently have more or less confidence that climate change will have an impact on the direction and magnitude of renewable water availability indicators.

It is hoped that information will help direct future improvements in the modelling and also inform water resource planners concerned with managing future changes in water availability across the region.
2. Methodology

A range of climate models is used to explore uncertainties in the projections of water availability indicators across the region. For each ensemble, we consider differences between the 30 year ‘baseline’ period, 1961–1990, and the future 2021–2050 period. All model runs were forced with transient changes in emissions through time—during the baseline period, models are forced with observed emissions, and for the future period, model projections are forced with the A1B SRES.

(a) Indicators of water availability

Of the three climatological indicators of water availability studied, precipitation and run-off are direct outputs from the climate models. Precipitation is the sum of all forms of rain and snowfall, and run-off is the total of surface and subsurface run-off. Both are shown here as either millimetres per year or millimetres per season. The drought index is derived from the precipitation using the method detailed below.

There are many different indices of drought that have been preferentially used to highlight different aspects of hydro-meteorological and/or sociological drought (Alley 1984; Heim 2002). Here, we use the standardized precipitation index (SPI; Guttman 1999), which provides a comparison of the precipitation over the preceding 12-month period with the corresponding climatology. The SPI is purely related to climate, being dependent only on precipitation, and is derived from the monthly precipitation at each model grid cell; therefore, it is readily available and useful for planners and policy-makers. For each grid cell, the SPI is estimated by fitting a gamma probability distribution to the distribution of 12-month accumulations of precipitation. This fitted distribution is then transformed to a normal distribution (Guttman 1999). This was done for the period 1961–1990, for which the SPI has a mean of zero. The parameters of the fit for the period 1961–1990 were then used for the period 2021–2050 to transform the 12-month accumulations of precipitation to a normal distribution.

Threshold values for drought were defined for each grid cell as the 20th percentile of the distribution of monthly SPI. Therefore, by definition, for the baseline period, 1961–1990, a grid cell is in drought for 20 per cent of the time. The proportion of the time the grid cell is in drought during the period 2021–2050 is calculated by assuming that there is drought in grid cells where the drought index is less than the derived threshold. It is assumed that the SPIs were stationary during each 30 year period to enable a sufficient sample size for the drought analysis. Although 30 years is a relatively short time period over which to study drought based on a monthly index, Burke & Brown (2008) concluded that a limited sampling size will only slightly underestimate the change in drought.

(b) Exploring uncertainties

(i) Multi-model ensemble

The Coupled Model Inter-comparison Project (CMIP; Meehl et al. 2007; http://www.clivar.org/organization/wgcm/cmip.php) has been responsible for coordinating GCM experiments and for collecting the output so that it can be accessed by climate researchers. This ‘multi-model ensemble’ (MME) represents
a diverse set of GCMs, which have been examined in a large number of different studies and form much of the basis for assessing future climate change in, for example, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4).

The MME has the advantage that it is composed of many different GCMs and hence there is the potential for a large ‘gene pool’ of possible models and thus possible responses to climate change. However, it is common to share model components (e.g. ocean components or individual parameterization schemes), and hence it is by no means a comprehensive sample of the space of all possible GCMs. Despite the huge effort by the CMIP to coordinate and gather data, the size of the ensemble is limited by the capability of individual modelling centres to perform experiments and transfer the output.

Here, we use a 22-member ensemble of coupled atmosphere–ocean GCMs from phase 3 of CMIP—CMIP3 (called AO-MME by Collins et al. (submitted)), which were downloaded from the Program for Climate Model Diagnosis and Intercomparison database (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). These models are the same as those used in the IPCC AR4 and are listed in table 8.1 of IPCC (2007), excluding the BCC-CM1 model for which the data were unavailable from the database.

(ii) Perturbed physics ensemble

The perturbed physics ensemble (PPE) approach takes a single GCM structure and varies the controlling parameters within that structure to generate different ensemble members and different structures. The advantage is that it is possible to control the experimental design (i.e. the values of the parameters) and to generate many more ensemble members than in the case of the MME. The approach also allows the implementation of Bayesian probabilistic techniques, which rely on the variation of model input parameters to quantify uncertainty (Murphy et al. 2007, 2009).

The potential disadvantage of the PPE approach is that it cannot sample all the possible choices that one might have made when building a climate model. Nevertheless, there is evidence that, by adjusting the sampling strategy, it is possible to vary both the error and response characteristics of GCMs within the PPE framework, which are comparable with MMEs such as CMIP3. There are a number of issues in choosing types of ensemble and in the experimental design of PPEs that we cannot discuss in detail here. The reader is referred to a Special Issue of the Philosophical Transactions of the Royal Society A for further information (Collins & Knight 2007).

Here, we use the 17-member coupled atmosphere–ocean HadCM3 ensemble (called QUMP-A (Collins et al. submitted)), in which parameters in only the atmosphere version of the GCM are varied. This is sufficient to generate some significant spread in the global temperature response of different versions of HadCM3 and hence facilitates a useful comparison with the AO-MME (called AR4 in this study). Equivalent experiments in which the atmosphere parameters are fixed and the ocean parameters are varied show very little spread in terms of surface and atmospheric feedbacks (Collins et al. submitted) and hence would add little to this study so are not examined. However, this study could be extended by the addition of experiments in which perturbations are made to parameters controlling chemical and biological feedbacks (Murphy et al. 2009).
In addition to the sampling of parameter values, each member of the ensemble also starts from a random ocean initial condition so that there is some sampling of the spread in natural variations in climate as well as modelling uncertainty (e.g. Hawkins & Sutton 2009), although it should be stressed that these simulations are not initialized with real-world data as in the case of Smith et al. (2007).

(iii) RCM ensemble

The resolution of the current generation of GCMs is often too coarse to provide reliable estimates of localized changes or feed directly into local impact models. This is the case particularly for hydrological processes in which an accurate description of both orography and land use is essential to correctly capture elements of the water cycle, such as precipitation and run-off. To fill this resolution gap and to describe local processes that are not captured by the coarse GCM resolution, several downscaling techniques can be adopted. These range from a statistical post-processing of GCM data to dynamical downscaling. This latter technique uses a high-resolution RCM nested inside a GCM, where the RCM is a full, physically based climate model, representing most or all of the processes, interactions and feedbacks between the climate system components that are represented in the GCM.

GCMs can offer a description of climate processes at a scale comparable to the resolution of their spatial grid (200–300 km). Where terrain is flat for thousands of kilometres and away from coasts, the coarse resolution of a GCM may mean that RCM and GCM projections are similar. However, in most land areas, surface features such as mountains and coastlines are on scales of less than 100 km. The finer resolution of RCMs enables the influence of such features on climate in the region to be more realistically captured. This is particularly important over mountainous terrain, which can significantly affect climate indicators such as temperature and precipitation. For example, studies over the Alps (Frei et al. 2003, 2006) have shown that model resolution not only affects the rainfall mean but also the distribution and the intensity of the extreme events. RCMs are also able to represent smaller land areas such as islands and peninsulas and have been shown to provide more credible simulations of extremes of weather such as heavy rainfall or high temperatures and mesoscale weather features such as cyclones and hurricanes.

Although orography is the most common example, other features are important for differentiating between GCM and RCM simulations. Owing to their generally coarser resolution, GCMs tend to smooth out variations in land-use characteristics such as mechanical (roughness), thermodynamic (surface temperature) and radiative (emissivity) parameters.

The ensemble of RCM simulations presented in this paper was generated through an international project that aims to provide the Egyptian government with the most recent climate outlook projections for the area of Nile sources (Buontempo et al. 2010a). The five RCM runs were made with the Met Office Hadley Centre’s ‘HadRM3P’ model, covering the Middle East region. The horizontal resolution is 0.44° latitude by 0.44° longitude, which corresponds to approximately 50 km², and, at its lateral boundaries, the RCM was driven by five of the GCMs from the 17-member PPE ensemble, described in §2b(ii). These five
were chosen to sample the spread of model simulations in the present-day climate as evenly as possible. A description of the methodology followed can be found in Buontempo et al. (2010b).

(c) Visualizing uncertainties

As climate modelling has progressed towards ensemble-based approaches that explore uncertainties in projections, various techniques have been used to visualize these uncertainties. In the IPCC AR4, maps were included that illustrated both the ensemble-average climate change and the level of agreement in the direction of the change across an MME (e.g. IPCC AR4, fig. SPM.7). In this case, stippling (and whiteout) is used to highlight areas where there is high (more than 90%) and low (less than 66%) agreement in the direction of change among the ensemble members.

For this study, a technique was developed that provides greater flexibility for defining uncertainty levels than that used in the IPCC AR4. This technique adjusts the intensity of a small palette of colours to map both the average climate change and the strength of agreement between ensemble members. In practice, for each ensemble, this involves combining a colour map of the ensemble median climate change with a corresponding dataset that represented the percentage agreement in the direction of change among the ensemble members at each grid box. This percentage agreement dataset is used to scale the intensity of the colour associated with each climate change category. The higher the percentage agreement the more intense the colour. This technique is described in detail in Kaye (2010).

3. Results

(a) Observed versus modelled precipitation

To test that the climate models provide a reasonable representation of the current climatology across the region, the spatial variation in precipitation for the median member of each of the three model ensembles is compared with the Global Precipitation Climatology Centre (GPCC) gridded global precipitation observations over land (Rudolf et al. 2005; http://gpcc.dwd.de/) for the average 30 year baseline period, 1961–1990 (figure 1).

Spatial variations in the annual precipitation of each model ensemble median member are in broad-scale agreement with the GPCC dataset—from the areas of highest precipitation (between 250 and 1250 mm yr\(^{-1}\)) across Turkey, northern Iraq and Iran and along the Zagros Mountains in Iran to the areas with the lowest precipitation (less than 100 mm yr\(^{-1}\)) across central parts of the Arabian Peninsula.

Although the general spatial variations in precipitation are captured by the models, in certain locations, large differences exist between the models and GPCC observations (figure 2). Both the AR4 and QUMP-A ensemble medians are consistently drier than the GPCC observations across the central Arabian Peninsula, in northern Iraq, Syria and the Caucasus and wetter across central and eastern Turkey, the Zagros Mountains and in western Yemen. Similar spatial patterns of wet and dry bias are noted with the RCM ensemble median, although
Table 1. Country average precipitation (mm yr⁻¹) during the 1961–1990 period. Columns show data from the GPCC observations and the median of the AR4, QUMP-A and RCM model ensembles. The ensemble minima and maxima are shown as subscript and superscript, respectively.

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<th>Country</th>
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<th>max</th>
<th>QUMP-A min</th>
<th>median</th>
<th>max</th>
<th>RCM min</th>
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The wet bias is significantly wetter (over 100 mm yr⁻¹ wetter in many countries) than that noted for the GCMs. These wetter regions tend to coincide with areas of high orography, where the higher resolution of the RCM would be expected to lead to higher average precipitation.

In terms of country average precipitation, table 1 shows that the GPCC-observed values are captured within the maximum and minimum ranges of the AR4 model ensemble for 11 out of the 14 countries in the study region. However, for the QUMP-A ensemble, only six of the 14 country average precipitation values from the GPCC observations were within the ensemble ranges, with all of the remaining countries, except Yemen, showing drier values for all ensemble members than the GPCC dataset. In comparison, the RCM ensemble shows larger variability in country average precipitation across the region, with all ensemble members for six of the countries being drier than the GPCC, four of the countries being wetter and only four countries capturing the GPCC value within the ensemble range.

(b) Projected changes

Annual changes in precipitation (mm yr⁻¹ and %) for the median of all three model ensembles are shown in figure 3, and country averages for the range across ensemble members are shown in figure 4. Despite there being reasonably good agreement (typically more than 75% of the members agree) in the direction of changes across the region within each ensemble, there is little consistency in the magnitude of changes among the three ensembles. This is also the case for seasonal projected changes in precipitation (figure 5).
Figure 2. Differences in precipitation (mm yr\(^{-1}\)) between (a) the GPCC observation dataset, (b) the median IPCC AR4 ensemble member, (c) the median QUMP-A ensemble member, and (d) the median RCM ensemble member. Note that the key for (b) applies also to (c,d).

The AR4 ensemble shows a clear signal of decreasing annual precipitation (between \(-5\) and \(-25\%\)) across the north of the region, including Turkey, Lebanon, Syria, Iraq, Iran, Israel and Jordan, but less than 5 per cent changes and little agreement in the direction of changes elsewhere (figure 5). Seasonally, the projected decreases are generally distributed throughout the December to August period (depending on the location), with relatively little change projected across the whole region between September and November.

In contrast, the QUMP-A and RCM ensembles show large (more than 25\%) increases in annual precipitation, with strong agreement among ensemble members, across the south of the region, particularly Yemen, Oman and southern Saudi Arabia, but less than 5 per cent annual changes and little agreement in the direction of changes across most of the north of the region.
The RCM projections indicate a general increase in the average precipitation for most countries across the region, and these are consistently wetter than the QUMP-A projections. For some country averages, e.g. Qatar, Oman and Yemen, the median RCM precipitation projections are approximately 20 per cent wetter than the QUMP-A and at least 25 per cent wetter than the AR4 (table 2). Although the RCM variations show large variability between seasons, there is no clear consistency in the seasonal distribution of these changes for either RCM or QUMP-A ensemble.

One area of consistency in the direction and general magnitude of precipitation changes for all the ensembles is in coastal western areas of Turkey and in parts of Lebanon, Syria and Israel. In these areas, the median members of all three model ensembles show decreasing future precipitation projections of between $-5$ and
Figure 4. Country average annual precipitation change (mm yr$^{-1}$) from 1961–1990 to 2021–2050 for all ensemble members in (a) the AR4 ensemble, (b) the QUMP-A ensemble, and (c) the RCM ensemble. The ensemble median members are the larger dots, and the arrow and value show the highest ensemble value where off scale.

Figure 5. Country average seasonal precipitation change (mm per season) from 1961–1990 to 2021–2050 for all ensemble members in (a) the AR4 ensemble, (b) the QUMP-A ensemble and (c) the RCM ensemble. The ensemble median members are the larger dots, and the arrow and value show the highest ensemble value where off scale. Different shades of grey represent the four seasons: March–May (mam); June–August (jja); September–November (son) and December–February (djf).
Table 2. Country average precipitation (mm yr\(^{-1}\)) during the 1961–1990 period and precipitation changes (mm yr\(^{-1}\) and %) between the 1961–1990 and 2021–2050 periods. Columns show data from the median of the AR4, QUMP-A and RCM model ensembles. The ensemble minima and maxima are shown as subscript and superscript, respectively.

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<th>Country</th>
<th>AR4</th>
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<td>change (mm yr(^{-1}))</td>
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<tr>
<td>Lebanon</td>
<td>261</td>
<td>−55.1−26(^{1.6})</td>
<td>−21.3−9.9(^{2.1})</td>
</tr>
<tr>
<td>Oman</td>
<td>88</td>
<td>−36.6(^{3})−122.9</td>
<td>−41.60.6(^{37.6})</td>
</tr>
<tr>
<td>Qatar</td>
<td>102</td>
<td>−36.3−6.7(^{9.8})</td>
<td>−42.6−5(^{3.3})</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>58</td>
<td>−25.1−3.8(^{5.5})</td>
<td>−32−7(^{3})</td>
</tr>
<tr>
<td>Syria</td>
<td>232</td>
<td>−48−21.6(^{1.7})</td>
<td>−20.7−9.8(^{2.4})</td>
</tr>
<tr>
<td>Turkey</td>
<td>525</td>
<td>−106.3−32.2(^{5.6})</td>
<td>−13.9−6.1(^{9.8})</td>
</tr>
<tr>
<td>UAE</td>
<td>54</td>
<td>−25.5−4.7(^{1.9})</td>
<td>−40.7−2.8(^{6.3})</td>
</tr>
<tr>
<td>West Bank</td>
<td>62</td>
<td>−19.2−8(^{5.2})</td>
<td>−34.1−10.6(^{8.1})</td>
</tr>
<tr>
<td>Yemen</td>
<td>186</td>
<td>−93.46.9(^{13.4})</td>
<td>−223.8(^{34.3})</td>
</tr>
</tbody>
</table>
Figure 6. Median percentage change in annual run-off between the baseline (1961–1990) and future (2021–2050) periods for (a) the AR4 and (b) the QUMP-A ensembles. All models are forced by the A1B SRES. The colour transparency level indicates the percentage of members in each ensemble that agree in the direction of change.

−25 per cent. This is also consistent with projections of decreasing precipitation in these areas noted in CMIP3 multi-model simulations (Mariotti et al. 2008). However, when considering country average precipitation, only Lebanon, Syria and Israel show decreases in the median of all three ensembles, although this signal is not consistent for all ensemble members, with some also projecting increases in precipitation for these countries.

Projected annual changes in run-off (figure 6) and SPI (figure 7), available for the two GCM ensembles only, show patterns of change that are consistent with those of precipitation. This is also the case for seasonal changes in these variables (data not shown). As with precipitation, the AR4 ensemble shows strong agreement for decreasing run-off (−5 to −25%) and increasing SPI across the north of the region, but little agreement across the south. The QUMP-A ensemble shows strong agreement for increasing run-off and decreasing SPI across the south of the region and some patchy agreement for decreasing run-off and increasing drought index across the north. Run-off or SPI values were not available for the RCM ensemble.

4. Discussion

The results presented here highlight some of the major uncertainties involved in modelling the climate of this region, particularly those relating to climate-related water availability. All three model ensembles show reasonable agreement with broad spatial variations in observed precipitation across the region, which indicates that the large-scale processes influencing precipitation distribution are represented in the models. However, when considering the spatial variations in more detail, some large biases exist between the modelled precipitation
Climate model uncertainty: Middle East

Figure 7. Median percentage change in the 12-month standardized precipitation index (SPI) between the baseline (1961–1990) and future (2021–2050) periods for (a) the AR4 and (b) the QUMP-A ensembles. All models are forced by the A1B SRES. The colour transparency level indicates the percentage of members in each ensemble that agree on the direction of change.

distributions and the GPCC observations. It is curious to note that the location and sign of many of these biases are consistent across the three ensembles. Similar distributions could be expected for the QUMP-A and RCM ensembles, because the RCM is forced at its boundaries by QUMP-A ensemble members. However, only one of the QUMP-A ensemble members is included in the 22-member AR4 ensemble, and, given that the AR4 models vary in their structure, it would not necessarily be expected that the distribution of biases in the AR4 ensemble would be similar to the other ensembles.

This consistency in the bias distribution between the models and GPCC observations and the accentuated wet bias noted for the RCM ensemble could, at least in part, be the result of the relatively sparse spatial distribution of GPCC stations across the Arabian Peninsula and in some of the mountainous areas (see http://gpcc.dwd.de/), which may result in unrepresentative GPCC precipitation values in these areas. There is some evidence to suggest that observed annual precipitation is indeed higher over the mountainous regions of Turkey than indicated by the GPCC dataset (Cullen & deMenocal 2000). However, higher resolution observations over the whole region, not available for this study, would be required to examine this further.

Comparing climate change projections from the AR4 and QUMP-A GCM ensembles, it is clear that the AR4 models show a strong signal of decreasing precipitation and run-off and increasing drought index across the north of the Middle East region. However, the QUMP-A and RCM members show a relatively weak drying signal in the north and a strong wetting signal across the south of the region. Although it is beyond the scope of this study to explore the mechanisms for these different spatial signals, other studies (see §1a) have demonstrated strong teleconnections between large-scale circulation patterns, such as the NAO, and wetness across the northern part of the region. Differences in the modelling
of these circulation patterns between the AR4 and QUMP-A ensembles may well explain their projected difference wetness distributions. If this is the case, improving the understanding and modelling of such large-scale processes and their teleconnections to the Middle East region has the potential to significantly reduce the range of uncertainties in the current projections of water availability indicators across the region as a whole.

The influence of spatial resolution on modelled precipitation is explored by comparing the QUMP-A and RCM ensembles. Differences in annual and seasonal precipitation between these two ensembles indicate that spatial resolution does have an important influence on the magnitude and range of uncertainty in modelled precipitation across the region. The higher resolution provided by the RCM generally increases the 1961–1990 precipitation across most of the regions and by 100s of mm per year in some mountainous areas (i.e. the higher peaks in the Zagros Mountains). It also results in enhanced sensitivity in the future projected changes in precipitation across the region, with some countries experiencing considerably wetter (i.e. Yemen) and drier (i.e. Lebanon) projected changes than those for the GCM ensembles. Furthermore, the RCM ensemble members typically show larger ranges in uncertainty in these future projections than either of the GCM ensembles, supporting the indication that, as the model resolution is increased, the sensitivity of the modelled precipitation projections and their uncertainty ranges also tend to increase. This highlights large uncertainties that currently exist in the modelling of regional-scale precipitation processes, and it emphasizes the need to focus on improving the large-scale processes and key model parameters of importance for precipitation in order to provide more robust projections of regional precipitation changes across this region.

5. Summary

This study examines the magnitude of change and the degree of uncertainty in current and future projections of precipitation, run-off and drought index across the Middle East region. It uses the latest GCM and RCM ensembles (the AR4, QUMP-A and RCM) to assess the spatial distribution and the nature of current modelling uncertainties and to indicate areas for improvement.

Results show that the median member of each of the three ensembles captures the distribution of observed annual precipitation across the region. The magnitude of observed annual precipitation is also reasonably well modelled by the GCMs, but is consistently wetter for the RCM, especially over the mountainous areas. This is a well-known feature of increasing the model resolution, which improves the representation of orographic effects. However, in this area, it is not clear whether the RCM is overpredicting or the GPCC observation network is underpredicting precipitation owing to poor station coverage across the region. A denser observation network, especially in the mountainous areas, would be required to further assess the accuracy of the RCM results.

Large uncertainties exist in both the spatial distribution and the magnitude of precipitation, run-off and drought index within and between the three ensembles. One area of consistency in the direction and general magnitude of precipitation
changes for the median members of all the ensembles is for decreasing future precipitation (between $-5$ and $-25\%$) in coastal western areas of Turkey and parts of Lebanon, Syria and Israel. However, even in these locations, some of the ensemble members project increases in precipitation. Run-off and drought index changes generally show spatial distributions that are comparable to those for precipitation.

The AR4 ensemble exhibits a consistent drying signal across the northern regions, whereas the QUMP-A and RCM ensembles show slight drying in the north and significant wetting across the south. The RCM projections show an increased sensitivity (both wetter and drier) and a wider uncertainty range than the QUMP-A. These results suggest that both large-scale circulation patterns, which influence region-wide drying/wetting patterns, and regional-scale processes, which affect more localized water availability, are important sources of uncertainty in the projections in the eastern Mediterranean and Middle East. It is therefore suggested that large uncertainties in water availability projections across this region could be reduced by improving the understanding and modelling of large-scale processes and their teleconnections with regional climate and by improving the understanding and validation of more localized processes such as those involved in orographic precipitation.

D.H. acknowledges the support of the EU FP6 project ‘CIRCE—Climate Change Impact Research: the Mediterranean Environment’ for supporting part of the analyses of the GCM ensemble data. C.B. acknowledges the support of the UNEP/UNESCO-funded project ‘Regional Climate Modelling of the Nile Basin: Preparation of Climate Scenario Outputs for Assessment of Impact on Water Resources in the Nile Basin’ for providing the RCM outputs used in this study. The authors also acknowledge the support of the Joint DECC and Defra Integrated Climate Programme—DECC/Defra (GA01101). The authors would like to thank the reviewers for their helpful comments.

References


Phil. Trans. R. Soc. A (2010)


