Past, present and future precipitation in the Middle East: insights from models and observations

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Anthropogenic changes in precipitation pose a serious threat to society—particularly in regions such as the Middle East that already face serious water shortages. However, climate model projections of regional precipitation remain highly uncertain. Moreover, standard resolution climate models have particular difficulty representing precipitation in the Middle East, which is modulated by complex topography, inland water bodies and proximity to the Mediterranean Sea. Here we compare precipitation changes over the twenty-first century against both millennial variability during the Holocene and interannual variability in the present day. In order to assess the climate model and to make consistent comparisons, this study uses new regional climate model simulations of the past, present and future in conjunction with proxy and historical observations. We show that the pattern of precipitation change within Europe and the Middle East projected by the end of the twenty-first century has some similarities to that which occurred during the Holocene. In both cases, a poleward shift of the North Atlantic storm track and a weakening of the Mediterranean storm track appear to cause decreased winter rainfall in southern Europe and the Middle East and increased rainfall further north. In contrast, on an interannual time scale, anomalously dry seasons in the Middle East are associated with a strengthening and focusing of the storm track in the north Mediterranean and hence wet conditions throughout southern Europe.

Keywords: precipitation; Middle East; Levant; climate change; Holocene

1. Introduction

All of the IPCC models project that under a business-as-usual greenhouse gas (GHG) scenario, boreal winter precipitation in the Middle East will decrease and temperature will increase, with significant changes evident by the end of the twenty-first century (e.g. Kitoh et al. 2008; Evans 2009). The resultant reduction in available water is likely to have devastating consequences for the people of the Middle East—many of whom already live in conditions of water poverty. Understanding the mechanisms underlying these projected changes is essential for critically evaluating the veracity of the projections. Other papers in this issue describe various aspects of both the future and the past climate of the Middle

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East. This short contribution brings together these strands of research into a comparison between the evolution of climate through the Holocene, projected changes over the twenty-first century, and the interannual variability experienced today. The questions we aim to address are as follows.

— To what extent is the regional climate model (RCM)’s simulation of the differences between late and early Holocene precipitation consistent with the proxy evidence?
— To what extent can the aridification of the Middle East that occurred in the past be considered an analogue for the drying projected for the future?
— Are the mechanisms underlying interannual variability (i.e. the occurrence of particularly dry seasons) similar to those underlying the aridification during the Holocene, and the projected aridification over the twenty-first century?

The rest of this paper is organized as follows. Section 2 summarizes the observed data and modelling methodologies; §3 gives a brief overview of the present-day climate; §4 describes how climate in the Mediterranean region has evolved during the Holocene, with particular focus on the well-known aridification experienced by the Middle East since the early Holocene; §5 describes regional model projections for the end of the twenty-first century. Section 6 compares past, present and future climate change/variability and discusses the ramifications of these comparisons for the credibility of the future projections. Section 7 draws some preliminary conclusions.

2. Data and methodology

The sources of the published palaeoenvironmental data referred to in this paper are described in §4. The following section summarizes the historical climate data and modelling methodologies.

(a) Observed data

Global Precipitation Climate Centre (GPCC) data were used for the historical rainfall data analyses. The GPCC product referred to in this study is a 0.5 × 0.5° gridded product, which is based only on rain gauge measurements (Schneider et al. 2008). The wind data used for the calculation of 850 mb vorticity were taken from the ERA-40 re-analysis. The methods of calculating vorticity and deriving track densities are summarized in Brayshaw et al. (2010) and described in detail in Hodges (1994, 1995).

(b) Modelling methodology

The climate in the Mid-Holocene was investigated through a time-slice experiment at 8ka. This was one of a set of time-slice experiments for 12, 10, 8, 6, 4 and 2ka, the pre-industrial period and the present day, carried out as part of the study described in Brayshaw et al. (2010). For each time slice, the climate forcings were specified to correspond to those experienced at the time period in question. Specifically, the forcings included were changes in GHG
concentrations (CO$_2$ and CH$_4$ only), the Earth’s orbital parameters and, for periods at or before 8 ka, land ice sheets and sea level. These integrations cannot be considered a true snapshot of the climate at a particular time because of the internal variability of the atmosphere, uncertainties in the initial conditions of the atmosphere and ocean and omission of potentially important feedbacks and forcings, such as land surface change. However, comparison between time slices gives insight into how the climate has responded to changes in natural forcings during the Holocene.

Each integration lasted 20 years—a length chosen to give some idea of interannual variability without being prohibitively expensive. The global runs were carried out using the Hadley Centre HadSM3 global climate model. The HadRM3 RCM, forced by boundary conditions from the global model, was then used to dynamically downscale the output over the Mediterranean area. HadRM3 is based on the Hadley Centre atmosphere-only model HadAM3 (described fully in Pope et al. (2000)). The formulation of HadRM3 used both in this contribution and in Brayshaw et al. (2010) has a horizontal resolution of 0.44° and 19 levels in the vertical.

The future climate integrations followed a generally similar method, with a global climate model (in this case HadAM3 forced with sea surface temperature (SST) anomalies from HadCM3) providing lateral boundary forcing for HadRM3. The only forcing applied was changes in GHG concentrations. As with the past time slices, the impact of land surface change was not considered. In this contribution, two simulations are considered:

— a baseline scenario (1961–1990) driven with lateral boundary conditions derived from a run of HadAM3P forced with observed climatological SST and land surface at the lower boundary and
— an A2 emission scenario (2070–2100) driven with lateral boundary conditions derived from HadAM3P forced with HadCM3 A2 scenario SST changes added to the observed SST.

3. Present-day rainfall variability

Most rainfall in the Middle East falls in boreal winter, as a result of the eastward passage of Mediterranean cyclones over the region (see seasonal cycle shown in figure 1). The summer is almost completely dry, with occasional rainy events triggered by anomalous synoptic conditions (Ziv et al. 2004). Although Mediterranean cyclones are the dominant cause of rainfall, other factors also play an important role. In particular, the occurrence of Red Sea trough systems is the main cause of rainfall in October and May (Tsivieli & Zangvil 2005). Moreover, although uncommon during the boreal winter, when they occur, Red Sea troughs may cause intense rainfall and flooding (Krichak et al. 2000; Ziv et al. 2005).

The Middle East experiences large interannual variability in annual precipitation (see time series shown in figure 1). For example, in Jerusalem, the standard deviation in annual precipitation is approximately 30 per cent of the mean. The proximity of the Middle East to Europe raises the possibility that the modes of variability that affect rainfall in Europe also affect the Middle East,
and previously published work suggests that this is the case. Eshel & Farrell (2000, 2001) demonstrate links between Middle East rainfall and circulation over Europe and the Atlantic, whereas Krichak et al. (2002) found a link between east Mediterranean rainfall and the North Atlantic Oscillation (NAO)/East Atlantic West Russia (EAWR) pattern and argued that variability in the region is primarily affected by the EAWR, with secondary influence from the NAO (Krichak et al. 2002; Krichak & Alpert 2005a,b).

On a more local level, Enzel et al. (2003) argued that interannual variability in Israel rainfall is modulated by a shift in the path of cyclones over the Mediterranean, with rainy years associated with a southward diversion of the cyclones over Jordan and Israel and dry years associated with a northward diversion of the cyclones over Turkey. Enzel et al.’s conclusions are borne out by the composites of precipitation and cyclone track densities for the five wettest and five driest years shown in figure 2. The precipitation composites show that dry years in Israel are associated with higher than average rainfall in Europe (figure 2a). Consistent with this, the track density composite (figure 2b) shows that there tend to be more weather systems crossing the northern Mediterranean during dry years than during wet years. This suggests that during dry years, the Mediterranean storm track is generally stronger, but that its location and orientation lead to fewer cyclones entering Jordan and Israel.

Figure 1. (a) Seasonal cycle and (c) time series of annual total precipitation for Jerusalem (location shown in (b)). The error bars on the seasonal cycle in precipitation represent one standard deviation from the mean.
Figure 2. (a) Difference in precipitation between the five wettest and five driest years in a region defined by the longitudes and latitudes: 34/35/31.5/32.5 (October–March since 1948). (b) Track density difference between the five wettest and five driest years (December–February).

The composites in figure 2 indicate that variability in mid-latitude weather systems influences interannual variability in Israel precipitation. It is, nevertheless, likely that other factors are also relevant. Specifically, the frequency of Red Sea troughs may be important (Tsvieli & Zangvil 2005). The composite plots shown in figure 2 hint at this, with low rainfall in the Middle East associated with fewer than usual weather systems entering the region from the south. These results are, however, preliminary and inconclusive, and further studies are needed to clarify the relationship between Red Sea troughs, mid-latitude cyclones and interannual variability in Middle East rainfall.

4. Holocene climate in the Middle East and Europe: models and observations

Palaeoclimate proxies suggest that during the Early and mid-Holocene (i.e. approx. 12–8 ka), precipitation in Europe, the Mediterranean and the Middle East was markedly different than it is today, with southern Europe, the Mediterranean and the Middle East being wetter and northern Europe drier. In particular,
vegetation reconstructions for Europe over the Holocene suggest that between 9 and 6 ka colder winters, warmer summers and greater available moisture led to the replacement in much of northern Europe of the deciduous forests, which dominated prior to 9 ka, by mixed and boreal forests (Landmann et al. 2002). In contrast to the situation in northern Europe, geological and isotopic data from lakes in Israel, Turkey, Greece and Spain suggest more available moisture (greater precipitation) in the Early Holocene in southern Europe (Landmann et al. 1996; Giralt et al. 1999; Roberts et al. 2001). Moreover, changes in vegetation type and pollen assemblages for southern Europe are consistent with the hypothesis that, between 9 and 6 ka, Mediterranean type vegetation replaced the deciduous forests that dominated in the Early Holocene (Huntley & Prentice 1993).

Direct comparison between proxies taken from different localities supports the hypothesis that local variations in precipitation were part of a Europe-wide pattern. Comparison of $\delta^{18}O$ time series for three speleothems suggests that climate variability in southern Europe was in anti-phase with that in southwest Ireland throughout the Holocene (McDermott et al. 1999). Lacustrine records across Europe are also responsive to increased rainfall (Roberts et al. 2008) and show a significant shift in isotopic signals during the Holocene.

Consistent with the Europe-wide pattern of precipitation change during the Holocene, there is substantial evidence that the Middle East has become drier during the Holocene. In particular, a decrease in Pistacia and oak in the pollen records (Horowitz 1971, 1989; Rossignol-Strick 1995, 1999) and a northward migration of the Negev Desert boundary during the Holocene (Goodfriend 1999) point to aridification during the Holocene. Further west, the deposition of red palaeosols on the Israeli coastal plain during the early Holocene indicates a higher precipitation at this time (Gvirtzman & Wieder 2001). The increase in annual rainfall suggested by all these records is consistent with higher Dead Sea levels (e.g. Neev & Emery 1995; Klinger et al. 2003; Robinson et al. 2006). Conservative estimates of palaeo-rainfall from cave sequences at this time suggest values of 550 and 700 mm yr$^{-1}$ in comparison with 300 mm yr$^{-1}$ or less in that region now (Bar-Matthews et al. 2003). The differences between Late and Early Holocene climate for the Middle East and for Europe described in this section are sketched in figure 3.

Figure 3. Summary of rainfall signal from the proxy data for the Middle East and Europe described in the text. Pluses indicate an increase in rainfall during the Holocene (i.e. the Early and Mid-Holocene were drier than the present day) and minuses indicate a decrease in rainfall during the Holocene (i.e. the Early and Mid-Holocene were wetter than the present day).
The model time-slice experiments exhibit a broadly similar pattern of precipitation change during the Holocene to that suggested by the climate proxy observations (figure 4). In particular, the RCM suggests a decrease in boreal winter rainfall during the Mid-Holocene in southern Europe. Brayshaw et al. (2010) suggest that these precipitation changes result from global and regional scale changes in the storm tracks in response to gradual changes in GHG concentrations and insolation. The broad pattern of precipitation changes suggested by the proxy evidence is consistent with this hypothesis. In particular, a poleward shift of the North Atlantic storm track and a weakening of the Mediterranean storm track are consistent with the increase in precipitation in northern Europe and decrease in southern Europe suggested by the proxy evidence.

Although the spatial pattern in rainfall changes during the Holocene is captured reasonably well, the approximately 25 per cent increase in rainfall projected for Jerusalem would not be sufficient to cause the observed changes in Dead Sea level, which require a doubling in rainfall (Whitehead et al. in press). This suggests either that the changes in the storm track cannot, in themselves, explain the higher precipitation during the Early Holocene or that they are unable to represent the magnitude of the change. There is some evidence that feedbacks not included in the RCM time-slice integrations would generate extra rainfall. Sensitivity studies, in which a green Sahara was imposed on the model, indicate that changes in the African land surface may have contributed some extra rainfall (Brayshaw et al. in press). Nevertheless, the biases in precipitation revealed by comparison with historical data (described fully in Black 2009) suggest that much of the deficit in rainfall is attributable to model deficiencies.
5. Future climate projections

Figure 4 shows that under a business-as-usual scenario, precipitation in the whole of southern Europe and the Middle East is projected to decrease. These results are consistent with published studies (e.g. Lionello & Giorgi 2007; Kitoh et al. 2008; Mariotti et al. 2008; Black 2009; Evans 2009) and the fourth IPCC assessment (Christensen et al. 2007). The track density changes shown in figure 4 indicate that these changes in boreal winter precipitation are accompanied by a reduction in the number of low pressure systems crossing the Mediterranean, which would indicate a weakening of the Mediterranean storm track. A poleward shift of the Atlantic storm track and a weakening of the Mediterranean storm track in response to GHG-driven climate change are also suggested by several other studies using different models and scenarios (e.g. Bengtsson et al. 2006; Lionello & Giorgi 2007; Pinto et al. 2007).

A survey of changes in the daily rainfall statistics for the Jordan River region suggests that the projected decrease in the boreal winter rainfall results from a decrease in the number of storms entering the Middle East rather than a reduction in their intensity (Black 2009). Thus, the model projections presented here along with several published studies suggest that under some emissions scenarios, precipitation in the Middle East will decrease in a manner consistent with a weakening of the Mediterranean storm track.

6. Comparison between past, future and present variability: ramifications for future projections

For a given emissions scenario and a set of initial conditions, the credibility of our projections of precipitation change rests on how well climate models can represent underlying mechanisms. Black (2009) demonstrated that the general spatial patterns and seasonal cycles of precipitation and temperature are well represented by the model used in this study, although precipitation intensity is underestimated. Moreover, several published studies using a variety of regional and global models (e.g. Bengtsson et al. 2006; Lionello & Giorgi 2007) show that the Mediterranean storm track can be adequately simulated by climate models. As was discussed in §5, these same studies argue that the Mediterranean storm track will weaken in response to increasing GHG concentrations. The fact that the dominant cause of the reduction in rainfall is consistently projected by several climate models lends credence to the projection.

The RCM’s ability to represent some features of precipitation change over Europe during the Holocene suggests that it can capture the gross precipitation response to highly perturbed global forcings. Although this lends a degree of credence to its projections of future climate, the RCM’s representation of some aspects of precipitation remains poor, and significant uncertainty remains—particularly with regard to projections of rainfall intensity.

In a broad sense, the RCM’s ability to represent both the present-day patterns in precipitation and the regional precipitation response to a strongly perturbed climate forcing lends credibility to its projections for the future (with the caveats given above). More specifically, the possibility exists that some aspects of the
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aridification during the Holocene are analogous to the projected drying in future. In particular, although the ultimate forcings of the climate system are rather different, the changes in the boreal winter climate of the tropics simulated and observed in the past resemble those projected for the future (i.e. the tropics warm over time) with profound implications for the atmospheric circulation. The response of the Mediterranean climate, and specifically precipitation in the Middle East, to these large-scale changes in the climate in the past appears to be somewhat analogous to that projected for the future.

The similarity between the differences between precipitation in the Mid-Holocene and pre-industrial period (both observed and simulated by the climate model) and those projected over the next hundred years adds weight to this argument (figure 4). In particular, in both cases, a weakening of the Mediterranean storm track leads to reduced precipitation over the Mediterranean and its northern and eastern margins, along with increased precipitation further north and west.

It is interesting to compare the long-term changes in climate experienced during the Holocene and projected for the future with the present-day interannual variability. Comparison between figures 2 and 4 shows that although the magnitude of rainfall variability on interannual time scales is similar to the changes projected for the future and experienced during the Holocene, the underlying mechanisms are different: while long-term aridification results from a weakening of the Mediterranean storm track, unusually dry years result from a strengthening and focusing of the storm track in the north of the Mediterranean. Consistent with this, on interannual time scales, dry conditions tend to be restricted to eastern margin of the Mediterranean (including Jordan, Israel, Lebanon and some of Syria) with wet conditions prevailing further north and west.

Comparison between present-day interannual variability and future/past shifts in the European and Middle East climate is highly relevant to our understanding of the social and hydrological impacts of climate change. The differences in the spatial scales of interannual variability and longer term climate change may mean that the social and political methods currently used to cope with interannual variability are not applicable to the climate change situation. One of the reasons for this is that hydrological systems are affected by rainfall over a large area, and hence the scale over which rainfall anomalies occur is of crucial importance to their impact.

In summary, the comparisons presented here suggest that climate change over the next century may have more in common with the evolution of climate through the Holocene than with the variability experienced today. Improved understanding of the factors that drove past changes in the climate may thus provide valuable insight into the changes projected for the future. Moreover, comparison with proxy observations of the past is a tough but crucial test of a climate model’s ability to simulate the response of the Earth system to strongly perturbed global forcings. This study is a first attempt at comparing RCM output with proxy observations and relating Holocene climate change with future projections. Further work is needed to improve the realism of climate model simulations of the region, compare proxy data and climate model output more formally and investigate sources of Middle East climate variability and change other than the storm tracks.
7. Conclusions

— Both climate and proxy observations suggest that the Middle East and southern Europe have become drier during the Holocene and that northern Europe has become wetter.
— The pattern of precipitation changes since the Mid-Holocene simulated by the RCM has some similarity to those projected by the end of the twenty-first century under an A2 scenario.
— The RCM’s capacity to replicate the general pattern of precipitation changes observed in the proxy and observed record lends credence to the future projections. Moreover, the fact that increases in GHG concentrations and changes in the spatio-temporal distribution of insolation (driven by orbital variations) have caused a poleward shift in the storm track in the past adds credibility to the projection of such a change in the future.
— The underlying mechanism, and hence the spatial scale of interannual variability in precipitation, appears to be markedly different from that underlying future and past climate change.

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References


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