Changes in Water Vapor Transport and the Production of Precipitation in the Eastern Fertile Crescent as a Result of Global Warming

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(Manuscript received 27 November 2007, in final form 4 May 2008)

ABSTRACT

This study investigates changes in the types of storm events occurring in the Fertile Crescent as a result of global warming. Regional climate model [fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5)–Noah] simulations are run for the first and last five years of the twenty-first century following the Special Report on Emissions Scenarios (SRES) A2 experiment. Then the precipitation events are classified according to the water vapor fluxes that created them. At present most of the region’s precipitation is from westerly water vapor fluxes. Results indicate that the region will increasingly get its precipitation from large events that are dominated by southerly water vapor fluxes. The increase in these events will occur in the transition seasons, especially autumn.

1. Introduction

The Fertile Crescent is defined here as an area encompassing southeast Turkey, northeastern Syria, northern Iraq, and northwestern Iran and is shown in Fig. 1 (it is the eastern half of the full Fertile Crescent). The area of interest covers approximately 20,000 km². It is centered over a large precipitation maximum found in both data and model results, and includes most of the headwaters of the Tigris River; hence, precipitation here is an important source of freshwater for parts of Turkey, Syria, and Iraq. Being a dominantly arid area, relatively little evaporation occurs over the land compared to the surrounding water bodies: the Black Sea to the northwest, the Caspian Sea to the northeast, the Mediterranean Sea to the west, and the Persian Gulf to the south. Although it has been generally accepted that the area is dominated by storm systems moving in from the Mediterranean Sea, earlier modeling work (Evans et al. 2004; Evans and Smith 2006) indicated that water vapor contributing to some of these storm events is dominated by a southerly flux. In fact, Evans and Smith (2006) showed that though a relatively small number of events are dominated by southerly fluxes, these events are very large and, hence, any change in the number of these events can have a significant influence on the total of freshwater resources within the Euphrates–Tigris watershed.

Growing acceptance of the reality of global warming has recently led to an increase in the publication of studies related to the influence of global warming. Many global climate model (GCM) simulations were performed as part of the Intergovernmental Panel on Climate Change’s (IPCC) Fourth Assessment Report (AR4), and the resulting model output has been made available for use in impact studies as the World Climate Research Programme’s (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset. Some of these studies focus on global changes in various phenomena that are important for the Middle East such as changes in storm tracks (Bengtsson et al. 2006; Lambert and Fyfe 2006), temperature (Min and Hense 2006), and drought (Wang 2005). Evans (2008b) presents the changes in climate predicted for the Middle East during the twenty-first century by an ensemble of 18 GCMs using the Special Report on Emissions Scenarios (SRES) A2 case, which is the situation closest to a “business as usual” scenario in the SRES family (Nakicenovic and Swart 2000). That study found an increase in temperature for the region of almost 4 K by late century, along with significant changes in precipitation that include a decrease in an area stretching from Turkey and the eastern Mediterranean across to northeastern Iran and an increase across much of the Persian Gulf and Saudi Arabia. It is worth noting
that the high-resolution GCM simulations; Community Climate System Model, version 3 (CCSM3); and Hadley Centre Global Environmental Model, version 1 (HadGEM1)—which have horizontal resolutions of ~1.5°—predict much smaller decreases in precipitation over the Fertile Crescent, eastern Turkey, and the Caucasus Mountains (and even an increase over the southern Caspian coast) compared to the lower resolution GCMs. This suggests that resolving the topography better may have significant influence on the simulated climate for this region.

Evans (2008a, manuscript submitted to Theor. Appl. Climatol.; hereafter EVA) investigated changes, as a result of global warming, in precipitation-causing mechanisms for various regions within the Middle East using a regional climate model. Similar to the GCM ensemble (Evans 2008b) the regional simulations predict a precipitation decrease over western Turkey and the eastern Mediterranean. A small increase in precipitation is, however, predicted for the Fertile Crescent, with the dominant precipitation mechanism being less associated directly with storm tracks and more associated with the upslope flow of water vapor. Along with changes in the amount of and triggering mechanisms for precipitation in the Fertile Crescent, one may expect changes in the water vapor pathways and source regions leading to this precipitation. This study investigates these latter changes using a regional climate model (RCM) run under present day and future globally warmed conditions presented in section 4. The conclusions of the study are presented in section 5.

2. Climate model and simulation description

This study examines the changes in water vapor transport in the Middle East caused by global warming. To accomplish this, the output from a GCM simulation is downscaled using an RCM, and the output from these RCM simulations is used to investigate the connection between water vapor transport and the precipitation in the Fertile Crescent.

a. CCSM3

The Community Climate System Model, version 3, is a coupled climate model developed and maintained by the National Center for Atmospheric Research (NCAR) and described in Collins et al. (2006). The model couples components that model the atmosphere, ocean, sea ice, and land surface. The simulation used in this study came from a T85 version of CCSM3 and is described in detail in Meehl et al. (2006). In short, the model has atmospheric grid points roughly every 1.4° latitude and longitude, and 26 vertical levels. The ocean is modeled on a nominal 1° grid with 40 vertical levels. No flux adjustment is used. Atmospheric composition is in accordance with the SRES A2 emission scenario for the twenty-first century (Nakicenovic and Swart 2000). Various aspects of the performance of CCSM3, the GCM used to provide boundary conditions in this study, under different emission scenarios can be found in Meehl et al. (2006).

b. Regional climate model (MM5–Noah)

The fifth-generation Pennsylvania State University–NCAR (PSU–NCAR) Mesoscale Model (MM5) is described in Dudhia (1993) and Grell et al. (1994). The MM5 is a limited-area nonhydrostatic model that uses a terrain-following vertical coordinate system. It has two-way nesting capabilities and flexible physics options. In this study, the MM5 was implemented with the Reisner mixed-phase explicit moisture scheme (Reisner et al. 1998), the Medium-Range Forecast (MRF) planetary boundary layer scheme (Hong and Pan 1996), the Rapid Radiative Transfer Model (RRTM) radiation scheme (Mlawer et al. 1997), and the Grell scheme for convective precipitation (Grell et al. 1994).

The MM5 is operationally linked with the Noah land surface model (LSM). Noah is a direct descendent of the Oregon State University (OSU) LSM (Mahrt and Ek 1984; Mahrt and Pan 1984; Pan and Mahrt 1987), a sophisticated land surface model that has been extensively validated in both coupled and uncoupled studies.
(Chen and Mitchell 1999; Chen and Dudhia 2001). The Noah LSM simulates soil moisture, soil temperature, skin temperature, snowpack depth and water equivalent, canopy water content, and the energy flux and water flux terms of the surface energy and water balances. In its MM5-coupled form, Noah has a diurnally dependent Penman potential evaporation (Mahrt and Ek 1984), a four-layer soil model (Mahrt and Pan 1984), a primitive canopy model (Pan and Mahrt 1987), modestly complex canopy resistance (Jacquemin and Noilhan 1990), and a surface runoff scheme (Schaake et al. 1996).

The MM5 has been applied successfully at grid cell resolutions ranging from greater than 100 to less than 1 km and is used for weather forecasts, climate research (Zaitchik et al. 2005; Evans et al. 2005), and process studies (Zaitchik et al. 2007b, a). Here, we apply the model at 27-km horizontal resolution and 23 vertical levels over a domain that includes much of the Middle East and the surrounding water bodies. Figure 1 shows the model domain excluding the rows and columns that are directly influenced by the boundary conditions. Previously, RCM simulations over the same domain were performed using regional climate model version 2 (RegCM2; Evans et al. 2004) and the MM5 (Evans and Smith 2006) during the early 1990s. These simulations showed good agreement with observations, with the MM5 performing best.

In this study three MM5 simulations are discussed. Two of these MM5 simulations are for the period 2000–04: one of these runs uses initial and boundary conditions from the NCEP–NCAR reanalysis (NNRP; Kistler et al. 2001) and is denoted as MM5–NNRP; the other run is from the CCSM3 simulation performed for the IPCC AR4 using the SRES A2 emission scenario and is denoted as MM5–CCSM2000. The third simulation covers the period 2095–99, with initial and boundary conditions coming from the same CCSM3 SRES A2 simulation, and is denoted as MM5–CCSM2095. In each case the two months of the MM5 simulation is considered “spinup,” and the relevant statistics are calculated using the remaining time of the model run. For the SRES A2 simulations, the atmospheric CO2 concentration is set at the mean over the five years, as used in the CCSM3 simulation. That is, for the present day and late century simulations, the CO2 concentration is set at 376 and 809 ppm, respectively. The evaluation of the RCM model performance for the simulation used here can be found in EVA. Given unlimited computing resources, an ensemble of longer simulations would have been preferable. However, the resources available limited the length of simulation to five years. An examination of the annual precipitation from the CCSM3 simulation through the twenty-first century shows that the first and last five years do not represent anomalous periods being within 10% of the respective 20 yr means and even closer to the 10-yr means. An examination of the CCSM3 simulation derived winter North Atlantic Oscillation (NAO), using the sea level pressure at the relevant grid points, shows these last 5 yr to be representative of the last 20 yr of simulation in terms of the mean value, 0.44 and 0.34 respectively, and in distribution of years with some strong NAO positive years and some weak NAO negative years. Similarly, the first 5 yr are representative of the first 20 yr, with mean values of −0.78 and −0.70, respectively. Thus, the change in NAO simulated by the 5-yr RCM simulations is comparable to the change computed from longer periods of the CCSM simulation. It must be remembered that the boundary conditions for the RCM come from a single GCM realization and, thus, are indicative of possible changes rather than being a true prediction of future change.

3. Precipitation event classification

Using the method described in Evans and Smith (2006), the importance of this southerly water vapor flux to precipitation in the Fertile Crescent is quantified by clustering the precipitation events based on the fluxes through the sides of the box, shown in Fig. 1. Each event is represented by a data series consisting of a three hourly flux series from each direction (north, south, east, and west) and the precipitation series. These series extend from one day before to one day after the time of peak precipitation. The use of all the major fluxes guarantees that the complete data series has a mean close to zero regardless of the size of event and removes the potential for the clustering algorithm to cluster points based on differences in their means.

This clustering is performed using the Iterative Self Organizing Data Analysis Technique Algorithm (ISODATA; Ball and Hall 1967), applied to the above data series for the 200 largest precipitation events over the five-year period. In total they account for ~72% of all the precipitation falling within the box, shown in Fig. 1 over the five-year period for the MM5–NNRP simulation. The algorithm was run using the remote sensing analysis software ENVI4.0. The maximum class standard deviation was set to $5.51 \times 10^{11}$ kg H$_2$O, and the minimum class distance was set to $1.5 \times 10^{12}$ kg H$_2$O; these values gave stable convergence to the same set of classes regardless of the number of classes to which it was assigned. In all cases only six classes of events, with a minimum of five members, were produced by the algorithm. That is, the algorithm found it
necessary to merge classes because of their similarity until only six classes remained. This increases the confidence that this six-class clustering is a robust result. Once the classes are established using the ISODATA algorithm applied to the MM5–NNRP simulation results, a minimum Euclidean distance algorithm is used to assign events from the two CCSM-based simulations to these classes.

As a statistical measure of the uncertainty associated with the allocation of an event to a class, we introduce the measure \( U \):

\[
U_i = \frac{1}{d^*_i} = \frac{1}{\sum_{k=1}^{c} 1/d_{ki}},
\]

where \( d^*_i \) is the Euclidean distance from the \( i \)th event to its assigned class mean, \( d_{ki} \) is the Euclidean distance from the \( i \)th event to class \( k \), and \( c \) is the total number of classes. For this measure, with six classes, a value of 0.1667 (1/6) is achieved if an event lies exactly between all six classes and, hence, the event’s true class is very uncertain. Similarly, if the distance from an event to its nonassigned class means is 100% further than the distance from that event to its assigned class mean, a value of 0.286 is achieved; hence, this event certainly belongs to the class to which it was assigned. Higher values of \( U \) indicate more certainty that an event belongs to the class to which it has been assigned.

4. Results

a. Present day simulation

The evaluation of the MM5–NNRP simulation against observational datasets can be found in EVA. The MM5–NNRP was generally found to perform better than the NNRP alone, with lower root-mean-square errors and higher pattern correlations associated with both near-surface temperature and precipitation. The examination of precipitation time series for various zones within the Middle East also showed the MM5–NNRP performing better than just NNRP, including the Fertile Crescent zone.

The examination of the precipitation time series for the Fertile Crescent reveals significant interannual variability, with 2000 being the driest year (considered a drought in some parts of the region) and 2003 being the wettest with approximately twice as much total precipitation. There is a strong seasonal cycle, with almost no precipitation through the summer and a winter maximum. Although most precipitation falls during winter, the largest events occur during the transition seasons.

The percent of events, total precipitation, and mean uncertainty associated with each class produced by the

<table>
<thead>
<tr>
<th>Class</th>
<th>Dominant flux</th>
<th>Percent of events</th>
<th>Percent of total precipitation</th>
<th>( U )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>W + S</td>
<td>27</td>
<td>22.8</td>
<td>0.321</td>
</tr>
<tr>
<td>2</td>
<td>W</td>
<td>42.5</td>
<td>31.3</td>
<td>0.300</td>
</tr>
<tr>
<td>3</td>
<td>W + S</td>
<td>15.5</td>
<td>12.4</td>
<td>0.262</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>6</td>
<td>18.3</td>
<td>0.275</td>
</tr>
<tr>
<td>5</td>
<td>W</td>
<td>5.5</td>
<td>8.8</td>
<td>0.282</td>
</tr>
<tr>
<td>6</td>
<td>S</td>
<td>3.5</td>
<td>6.4</td>
<td>0.303</td>
</tr>
</tbody>
</table>

ISODATA algorithm applied to MM5–NNRP is given in Table 1. The uncertainty is the mean \( U \) [defined by Eq. (1)] for all events in that class. Class 1 is the most certain class. Class 1, class 2, and class 6 all have events that are on average more than twice as far from the other class means as from their own. Class 3 is the most uncertain class, but even these events tend to be \(~78%\) further from the other class means than their own class mean. Approximately 75% of all events produce \( U > 0.286\), implying that the storms look similar to the canonical storm for that class, which leaves approximately one quarter of the events with some uncertainty associated with their class assignments.

In previous work focused on the early 1990s, Evans and Smith (2006) found four classes rather than six classes as having been found here. A comparison between the classes found here and the classes found in the previous study show the current class 3 and class 5 are equivalent to the previous class 2 and class 3, respectively; while merging class 1 and class 2 recovers the previous class 1, and merging class 4 and class 6 recovers the previous class 4. Several factors may come into play in determining the number of classes produced by a clustering algorithm. It appears likely that the five-event minimum imposed on the classes previously caused class 6 (now just seven events) to be merged with class 4. Overall, the fact that the clustering algorithm applied on independent datasets produced (with appropriate merging) almost identical class signatures emphasizes the robustness of this approach. The six-class classification produces classes with lower uncertainty, in a relative sense, than the four-class classification and will be used throughout this paper.

The mean water vapor fluxes for each of the classes are presented in Fig. 2. In every case, fluxes from the west and south tend to be into the box, whereas fluxes from the east and north tend to be out of the box. The flux of water as a result of precipitation is considered to be out of the atmospheric box. Focusing on the incoming fluxes, the events are split according to the relative
importance of westerly and southerly fluxes, as shown in Table 1. Class 2 and class 5 are dominated by westerly fluxes, whereas class 4 and class 6 are dominated by southerly fluxes, and class 1 and class 3 have significant contributions from both fluxes. Class 1 has a dominant southerly flux just before reaching the precipitation peak, and then this flux rapidly decreases and the system is again dominated by the westerly flux. Class 3 has similar southerly and westerly fluxes before the precipitation peak, after which the southerly flux decreases more rapidly than the westerly flux. Events in classes 1–3 tend to produce relatively small amounts of precipitation overall. The magnitude of all the fluxes tends to increase with increasing class number; however, class 4 produces the most precipitation. For all events, the peak in total incoming water flux occurs about six hours before the peak in precipitation. This lag implies brief storage of water in the atmospheric box.

Several quantitative conclusions can be drawn from the number and size of events in each class, as shown in Table 1. In every case the percentages given below refer only to the tested events, that is, the 200 largest precipitation events. Westerly fluxes play a dominant role in 48% of events (class 2 and class 5), which account for only 40.1% of the precipitation. Fluxes from the west and south contribute similar amounts in 42.5% of events (class 1 and class 3), representing 35.2% of the total precipitation. Only 9.5% of the events are dominated by southerly fluxes; however, these events tend to be large and account for ~24.7% of the total precipitation. That is, although events dominated by westerly fluxes are more common, they produce less actual precipitation per event than events dominated by southerly fluxes.

The vertical cross section of fluxes into the box on the western and southern boundaries can be found in Fig. 3, whereas Fig. 4 shows the vertically integrated water vapor flux and 500-hPa geopotential height 3 h before the precipitation peak. Class 1 is characterized by weak cyclonic circulation centered over the Fertile Crescent at low levels that manifests itself as areas of inflow and outflow in the western and southern cross sections. Class 2 is dominated by westerlies, showing a broad influx of water vapor through the western cross section but little action through the southern cross section. Class 3 is dominated by westerlies at low levels, which turn southwest at mountain top height. This can be seen in the cross sections, with a broad westerly influx along with a broad southerly influx that is strongest just above the mountains. Class 4 is the first class

Fig. 2. The six water vapor flux–based precipitation event classes.
dominated by southerly fluxes and has the strongest influx of any class. The intense influx is concentrated above the Euphrates–Tigris valley and on the Zagros Mountains’ slopes, assisted in large part by the formation of a barrier jet there. It should be noted that this barrier jet assisted influx is relatively confined spatially and low-resolution models (GCMs) would find it difficult to resolve this feature. There is also influx through the southern portion of the western cross section, which is balanced in part by low-level outflow in the northern portion. Class 4 is characterized by strong cyclonic circulation centered over Turkey, west of the area of interest. Class 5 is dominated by westerly fluxes that are broad and deep in the atmosphere, with a maximum at $\sim 700$ hPa—much deeper than the maxima for any other class. Class 6 is also characterized by strong cyclonic circulation; however, it is centered over the northeastern Mediterranean rather than central Turkey, as it is in class 4. The result is a much larger and stronger zone of outflow through the western boundary, and the near southerly flow across the southern boundary causes a large area of inflow but only a weak barrier jet. Thus, class 6 events do not have the intense low-level inflow of water vapor that is seen in class 4.

The MM5–CCSM2000 simulation is not strictly comparable to the MM5–NNRP simulation because it represents a possible realization of the weather given the global boundary conditions, largely the solar insulation and atmospheric composition. Nevertheless, it should represent the mean climate for the period. The MM5/CCSM2000 simulation is compared to the NNRP-driven simulation as well as to observations in EVA and was found to perform quite well in reproducing surface temperature and precipitation over the region as a whole. The Fertile Crescent area shows the MM5–CCSM2000 simulation underestimates the winter precipitation. A comparison of the frequency of event classes reveals some substantial differences that reflect this winter precipitation underestimation, which can be seen in Table 2. There is a substantial increase in the number of events that fall into class 1, the smallest precipitation class. This increase is produced largely by decreases in class 2 and class 3 and is caused by generally lower fluxes from the west in the MM5–CCSM2000 simulation. This can also be seen in the movement of events from class 4 to class 6. Despite these differences, the MM5–CCSM2000 simulation–derived class frequency is closer to that given by the MM5–NNRP simulation than was found for the early 1990s in Evans and Smith (2006) and will be used to assess potential future changes as a result of global warming.

b. Global warming simulations

The impact of global warming for the Middle East has been investigated elsewhere (Evans 2008b). For the Fertile Crescent, the consensus of GCMs found an in-

Fig. 3. Vertical cross sections of the water vapor flux crossing the west and south sides of the Fertile Crescent box 3 h before the precipitation peak (topography is shown in white).
FIG. 4. Vertically integrated water vapor flux (vectors) and the 500-hPa geopotential height (gray contours) 3 h before the precipitation peak.
crease in mean annual temperature of \(\sim 4.6\) K and a
decrease in precipitation of \(\sim 60\) mm, which represents
\(\sim 17\%\) of the present day total. As stated previously,
the higher-resolution GCM simulations, including the
CCSM simulation used here, predicted much smaller
decreases in precipitation for the eastern Fertile Crescent
than the multimodel ensemble. The five-member
CCSM ensemble predicts no change in mean annual
precipitation over the eastern Fertile Crescent area of
interest, whereas the ensemble member that provides
the boundary conditions used here simulates an in-
crease of slightly more than 6%. In all CCSM members,
there is a decrease in winter but an increase in autumn
precipitation. The CCSM simulation that provided the
boundary conditions used here had an autumn increase
of almost 20 mm or \(\sim 27\%\). The global warming affect
simulated using the combination of MM5 and CCSM,
as used here, was investigated in EVA. For the Fertile
Crescent, it was found that the near-surface tempera-
ture changed little in winter but increased \(\sim 6\) K during
summer. Precipitation was found to increase in all
seasons, with the largest increases in autumn. In the MM5
simulation, this increase was 80 mm or almost 160%.
Spring provided the second largest increase of slightly
more than 40 mm. An examination of the changes in the
frequency of various precipitation event types given
below provides insight into the causes of these precipi-
tation increases.

In section 4a, it was shown that storm systems, which
produce large southerly fluxes of water vapor, although
less common, are very important in the cumulative pre-
cipitation total. The presence or absence of a few of
these events may be the difference between an average
and a poor precipitation year. Thus, if global warming
causes changes in the frequency of these events, which
may be small in terms of the number of events, it may
have a significant affect on the total precipitation falling
in the eastern Fertile Crescent and headwaters of the
Euphrates and Tigris Rivers.

The global warming–induced changes in event fre-
quency for each class are shown in Table 2. The largest
changes include a significant decrease in the frequency
of class 1 events; therefore, the contribution of class 1
events to the total precipitation drops from \(\sim 45\%\) to
less than 25%. Significant increases occur for class 3,
class 4, and class 6. The southerly flux–dominated
classes (4 and 6) substantially increase their contribu-
tion to the total precipitation, with class 4 increasing
from 10.7% to 27.4% and class 6 increasing from 8.6%
to 30.0%. Thus, the southerly flux–dominated events
increase their total contribution from 19.3% to 57.4%,
that is, these events dominate the precipitation in the
Fertile Crescent by the end of the twenty-first century,
contributing almost 60% of the total precipitation de-
spite only accounting for \(\sim 25\%\) of the events.

The distribution of events through the year in the
MM5–CCSM2000 simulation can be found in Fig. 5.
Class 1 dominates precipitation throughout the year in
terms of both the number of events and total precipi-
tation. Class 2 also occurs throughout the cold season,
although it has distinct peaks either side of winter (No-
vember and March). The November peak is produced
because these events are consistently among the largest
class 2 events, whereas the March peak is caused by a
significant increase in the number of events. The events
in class 3 are largely winter events, although they also
contribute precipitation in April and October. The first
southerly dominated class, class 4, plays a minor role
during winter but a larger role in the transition seasons,
with two distinct peaks in November and March when
the largest class 4 events occur. Class 5 events are
strictly springtime events, contributing almost no pre-
cipitation at other times of the year. Class 6, the other
southerly dominated class, contributes most during Oc-
tober when the majority of these events occur, although
it also contributes during winter.

Figure 6 shows the change in distribution of events by
the end of the century (MM5–CCSM2095—MM5–
CCSM2000). The largest change is an increase in pre-
cipitation because of class 6 events occurring in Sep-
tember. There is a movement of class 6 events to earlier
in autumn (the peak is in October early in the century),
and a substantial increase in both the number and the
mean size of these events; this is the single largest

<table>
<thead>
<tr>
<th>Class</th>
<th>Dominant flux</th>
<th>MM5–CCSM2000</th>
<th>MM5–CCSM2095</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>W + S</td>
<td>61.5</td>
<td>45.4</td>
</tr>
<tr>
<td>2</td>
<td>W</td>
<td>18.0</td>
<td>19.0</td>
</tr>
<tr>
<td>3</td>
<td>W + S</td>
<td>7.5</td>
<td>10.7</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>2.0</td>
<td>10.7</td>
</tr>
<tr>
<td>5</td>
<td>W</td>
<td>4.5</td>
<td>5.6</td>
</tr>
<tr>
<td>6</td>
<td>S</td>
<td>6.5</td>
<td>6.5</td>
</tr>
</tbody>
</table>

TABLE 2. Size of each class for the CCSM simulations. W indicates a westerly flux; S indicates a southerly flux.
change to the precipitation regime in the area. The second largest increase in monthly precipitation occurs in November and is a result of an increase in the number of class 4 events and not an increase in their size. The combination of these two large increases account for the more than doubling of precipitation simulated by the model. A similar story exists for spring, with class 6 events in March increasing in both number and size and class 4 events in April increasing in number. Again, the increases in these two classes account for the majority of the large increase in the simulated spring precipitation. It should be noted that the event types responsible for the majority of the precipitation increase (class 4 and class 6) are characterized by the formation of a mountain barrier jet west of the Zagros Mountains. Such a spatially confined feature, which relies on the size and slope of mountainsides to form, is poorly represented in low-resolution GCMs and, hence, these events may not be captured at all.

The other change of note is a decrease in the number

FIG. 5. (a) Mean monthly precipitation and (b) number of events by class for the MM5–CCSM2000 simulation.
of class 1 events in spring and autumn; these events increase in size during spring but remain relatively unchanged during autumn. The net result is relatively little change in the contribution of class 1 events during spring but a substantial decrease during autumn. Various other relatively minor changes also occur, such as a decrease in the total precipitation from class 2 events in March and November by approximately 40% and 60%, respectively. The March decrease is caused by a combination of a decrease in the number and mean size of these events, whereas the November decrease is caused by a larger decrease in the mean size of these events than is experienced in March.

The global warming affect on the water vapor fluxes causing precipitation in the Fertile Crescent is, therefore, a large increase in southerly flux-dominated events. This increase occurs almost entirely in the transition seasons, with a particularly large increase in autumn (and late summer). It is also worth noting that this precipitation increase is due to increases in the number
of large storms (classes 4–6), which increases from 13% of all storms to 29%. This increase in large storms may have important implications for urban storm water systems as well as levee and reservoir management.

c. Discussion

Currently, the southern portion of the domain in Fig. 1 is dominated by subsidence related to the downward arm of the Hadley cell during summer, reinforced by Rossby waves produced by the Indian monsoon (Rodwell and Hoskins 1996; Staubwasser and Weiss 2006), resulting in practically no precipitation during this time and a very dry land surface by autumn. The evaporation that does occur from the nearby water bodies (Red Sea, Persian Gulf, and Arabian Sea) is confined to the near-surface atmosphere as a result of the large-scale subsidence, limiting the total evaporation that can occur. A combination of the Hadley cell subsidence retreating to the south and the lack of any low-level moisture contribution from the land surface, as a result of the lack of evaporation, continues to suppress precipitation well into autumn.

By the end of the century, the examination of the simulated mean meridional cross section of the atmosphere in this region reveals that the ITCZ has moved northward. The strength of the Hadley cell–related subsidence has decreased in this southern area from May through November, and the planetary boundary layer height has increased 200 m or more at the same time. Water vapor is mixed deeper into the atmosphere and, along with increased temperatures, this increases subsequent evaporation from the water bodies. This combination of processes works to substantially increase the water vapor content of the lower atmosphere (below ~800 hPa) during summer and autumn. In addition to causing some local precipitation, this reservoir of atmospheric moisture is also available to be transported elsewhere; when conditions are right, it will be transported northward and cause precipitation in the Fertile Crescent as a class 4 or class 6 event.

The difference between the precipitation decrease projected by the ensemble of GCMs contributing to the IPCC fourth assessment and the precipitation increase projected by this RCM is explained by the large increase in class 4 and class 6 events. These events are generated in part by the formation of a mountain barrier jet along the Zagros Mountains. The relatively small spatial scale of this phenomena means these events are not captured by the GCMs.

This increase in precipitation immediately following the dry season has the potential to improve the seeding and germination stage of rain-fed crops in the region. The fact that the precipitation mostly falls in very large storm events does, however, increase the risk of landslide and localized flash floods. Currently, agricultural practice in the area attempts to cope with the risk of too little rain, particularly at this time of transition from the dry to wet seasons. In this scenario, local farmers would need to adjust their planting strategies to account for the heavy rains and possible flooding.

5. Conclusions

The study presented here attempts to identify storm types in the eastern Fertile Crescent region on the basis of water vapor fluxes, then it investigates the likely changes in the number and size of these different storm types as a result of global warming. The water vapor fluxes were investigated at high temporal and spatial resolution using a regional climate model (MM5–Noah) to downscale the NCEP–NCAR reanalysis for the first five years of the twenty-first century. Similar RCM runs were also performed using boundary conditions from the CCSM3 GCM run using the SRES A2 emission scenario for the first and last five years of the twenty-first century. Using the ISODATA clustering algorithm, the 200 largest precipitation events occurring during the NCEP–NCAR–based simulation and accounting for more than 72% of the entire precipitation, were grouped into classes on the basis of the similarity of their water vapor fluxes. Using these classes and a minimum Euclidean distance algorithm, events from the CCSM3–based simulation were then assigned to their appropriate class.

This precipitation event clustering indicates that westerly fluxes are important in the majority of events, and these events are responsible for most of the precipitation that falls at present. The southerly flux–dominated events do, however, tend to be large such that although they only account for about 9% of the events, they contribute about a fifth of the total precipitation. This ratio changes dramatically in the global warming simulation, with the southerly dominated events occurring more frequently (26% of events) and contributing the majority of the precipitation. This increase is caused by a significant increase in the atmospheric water vapor resident over the Saudi Peninsula, largely during autumn, that is transported northward during these southerly dominated events. According to the climate model simulation performed for this study, the largest changes in precipitation to affect the eastern Fertile Crescent region during the twenty-first century will be an increase in large events occurring during transition seasons, especially autumn. This change is associated with a decrease in the importance of water vapor fluxes from water bodies to the west such as the
Mediterranean Sea and in increase in the importance of water vapor from southern water bodies such as the Red Sea, Persian Gulf, and the Arabian Sea.

Acknowledgments. This study was undertaken with the financial support of NASA (Grant NNG05GB36G) and NSF (Grant ATM-0531212). I appreciate the computer time for model runs provided by the National Center for Atmospheric Research (NCAR). The research was motivated and assisted by many fruitful conversations with other members of the southwest Asia project team including Ron Smith, Roland Geerken, Frank Hole, Ben Zaitchik, and Larry Bonneau. CCSM data for boundary conditions were supplied through Oak Ridge National Lab, with special thanks to David Erickson. I acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and the WCRP’s Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multimodel dataset. Support of this dataset is provided by the Office of Science of the U.S. Department of Energy.

REFERENCES


