Using the WRF Model in an Operational Streamflow Forecast System
for the Jordan River

AMIR GIVATI
Israeli Hydrological Service, Israeli Water Authority, Jerusalem, Israel

BARRY LYNN
Weather-It-Is Ltd., Efrat, Israel

YUBAO LIU
National Center for Atmospheric Research,* Boulder, Colorado

ALON RIMMER
The Lake Kinneret Limnological Laboratory, Israel Oceanographic and Limnological Research,
Ltd., Migdal, Israel

(Manuscript received 19 April 2011, in final form 11 September 2011)

ABSTRACT

The Weather Research and Forecasting (WRF) model was employed to provide precipitation forecasts during the 2008/09 and 2009/10 winters (wet season) for Israel and the surrounding region where complex terrain dominates. The WRF precipitation prediction has been coupled with the Hydrological Model for Karst Environment (HYMKE) to forecast the upper Jordan River streamflow. The daily WRF precipitation forecasts were verified against the measurements from a dense network of rain gauges in northern and central Israel, and the simulation results using the high-resolution WRF indicated good agreement with the actual measurements. The daily precipitation amount calculated by WRF at rain gauges located in the upper parts of the Jordan River basin showed good agreement with the actual measurements. Numerical experiments were carried out to test the impact of the WRF model resolution and WRF microphysical schemes, to determine an optimal model configuration for this application. Because of orographic forcing in the region, it is necessary to run WRF with a 4–1.3-km grid increment and with sophisticated microphysical schemes that consider liquid water, ice, snow, and graupel to produce quality precipitation predictions. The hydrological modeling system that ingests the high-resolution WRF forecast precipitation produced good results and improved upon the operational streamflow forecast method for the Jordan River that is now in use. The modeling tools presented in this study are used to support the water-resource-assessment process and studies of seasonal hydroclimatic forecasting in this region.

1. Introduction

Accurate analysis and prediction of precipitation amounts and their spatial distribution are vital for regional- and local-scale hydrological applications. This is especially true for arid and semiarid regions such as in the Middle East, where estimation and prediction of the highly variable precipitation during the rainy season is critical for predicting streamflows and the recharge of reservoirs. The estimates of the streamflow in the Jordan River and the water level of Lake Kinneret play a crucial role in Israeli agricultural and hydrological planning and in flood control. Hydrological forecasts are instrumental for decision-support activities at the Israel Water Authority. Major operational weather forecast centers provide relatively coarse (~16–25-km grid increment) precipitation analyses and forecasts, which are incapable of

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Amir Givati, Israeli Hydrological Service, Israeli Water Authority, P.O. Box 36118, Jerusalem 91360, Israel.
E-mail: amirg@water.gov.il

DOI: 10.1175/JAMC-D-11-082.1

© 2012 American Meteorological Society
resolving the necessary details of the complex precipitation structures that are forced by mesoscale orography, land surface heterogeneities, and land–water contrasts. In the eastern Mediterranean region, strong air–sea interaction and orographic forcing produce precipitation with dramatic gradients that are generally missed by the coarse-grid operational models. In Israel, the precipitation patterns are particularly complex, and large precipitation contrasts occur over a relatively small geographical distance (2–10 km). Large climatological precipitation gradients in Israel are caused by the preferred tracks of extratropical cyclones, the complex orography, and the coastline shape. Rich spatial structures are observed in individual precipitation events as well as in the monthly, seasonal, and annual accumulated precipitation amounts (Saaroni et al. 2009).

Because an objective of this study is to employ a high-horizontal-resolution model to better predict precipitation structures in Israel for streamflow calculations and prediction, it is important to review previous studies of the relationship between horizontal resolution and the predictability of precipitation. In fact, other studies have shown that reducing the horizontal grid spacing of the atmospheric model may enhance the model’s ability to simulate precipitation (Katzfey 1995; Martin 1996; McQueen et al. 1995; Doyle 1997; Colle et al. 1999; Davis and Carr 2000; Petch et al. 2002; Adlerman and Droegemeier 2002; Bryan et al. 2003; Xue and Martin 2006; Schwartz et al. 2009; Kain et al. 2006, 2008; Weisman et al. 2008), and many studies have used high-resolution numerical weather predictions in hydrologic applications. For example, Hay et al. (2002) used daily precipitation and temperature on a grid with 52-km grid spacing as input to a distributed hydrologic model for four basins in the United States. Their results indicated that the coarse-resolution regional-climate-model output could be used reliably for basin-scale hydrological modeling after bias correction; even when bias corrected, however, the regional-climate-model output did not contain the day-to-day variability necessary for hydrologic modeling.

Grell et al. (2000) showed that high-resolution (1-km grid increment) model simulations might be necessary when the complex pattern of the precipitation distribution becomes important. Leung and Qian (2003) examined the sensitivity of precipitation and snowpack simulations in complex terrain to model resolution by employing a nested regional climate model. They found that higher horizontal spatial resolution improves the accuracy of simulated snowpack. Westrick and Mass (2001) looked at a 7-day rain-on-snow event in the Snowqualmie River watershed using the nesting capabilities of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5; 36-, 12-, and 4-km grid spacing) and the Distributed Hydrology–Soil–Vegetation Model (DHSVM) and found that the accuracy of the atmospheric fields increased with higher horizontal resolution, although under-forecasting of precipitation was evident for all three resolutions. The simulated river flows captured 67% (36 km), 75% (12 km), and 72% (4 km) of the total flow and 52% (36 km), 58% (12 km), and 62% (4 km) of the event peak flow.

Mass et al. (2002) used MM5 and DHSVM to show that increasing the spatial resolution improved the forecast in terms of various meteorological variables. Improvement of the forecast from an increase in the atmospheric model resolution was also found by Lin et al. (2002) and Seuffert et al. (2002). Hay et al. (2006) examined the accuracy of high-resolution nested mesoscale-model simulations (MM5 with 5- and 1.7-km grid increments) as an input to the U.S. Geological Survey’s distributed hydrologic model (Precipitation Runoff Modeling System). Their results showed a general increase in the accuracy of simulated runoff with an increase in resolution. Younis et al. (2008) showed the benefit of using high-resolution operational weather forecasts for flash-flood warning in France. Daly et al. (1994) used a statistical–topographical model for mapping climatological precipitation over mountainous terrain in the western United States, and Pandey et al. (1999) and Neiman et al. (2002) related orographic precipitation in California at different elevations to low-level winds and moisture.

2. Existing methods for calculating streamflow in the Jordan River

Another type of regional rainfall analysis, which is especially relevant to the Lake Kinneret watershed, is the regression method of Rimmer and Salinger (2006), which was developed especially for the Hydrological Model of Karst Environment (HYMKE). The model was applied to the Mount Hermon range (70–2800 m MSL) in the upper catchments of the Jordan River, an area with complex karst terrain that contributes most of the water to the Jordan River. At the time of this study, precipitation measurements were not available from most of the Mount Hermon range, especially from the upper parts in Syria and Lebanon. Therefore, precipitation measurements from eight lower-elevation rain gauges in the north of Israel, with elevations between 100 and 960 m MSL, were used to create a linear regression model of precipitation as a function of elevation. The authors extrapolated the precipitation from the lower elevations to the full Mount Hermon range and created maps of monthly and annual precipitation.
Similar regression methods were used in other studies of rainfall and spring river flow in this nonmonitored mountainous region (Simpson and Carmi 1983; Gilad and Bonne 1990; Rosenfeld and Farbstein 1992; Gur et al. 2003). Using this regression analysis, Rimmer and Salingar (2006) showed that the linearity of rainfall versus elevation was slightly weaker and less significant during the beginning of the winter (October), increased toward the middle of the winter (January), and gradually decreased toward its end (April). Halfon (2008) and Saaroni et al. (2009) describe the overall precipitation forcing in Israel, showing that the Cyprus-low storms are associated with strong westerly winds, which enhances the orographic effect, whereas the convective component of precipitation during the autumn and spring is much higher. This can probably explain the difference in correlation strength between precipitation and elevation that was described by Rimmer and Salingar (2006).

The main purpose of this paper is to offer a new tool that will improve the current streamflow calculations and forecasting. By using the high-resolution WRF with improved precipitation prediction for every possible point in the Hermon basin, we can drive the hydrological simulations in a more physical way by representing well the precipitation fields in the basin. This system will allow us to produce improved hydrological predictions, relative to the traditional approach that is based on rainfall extrapolations for high elevation, using the empirical elevation–precipitation relation. This work can also help to develop future scenarios for water availability at the Jordan River under climate-change conditions using dynamical downscaling for existing regional climate models for the twenty-first century.

3. The study areas

The study area in this work includes the Lake Kinneret watershed, located in the central part of the Jordan Rift Valley (northern Israel; see Figs. 1a,b). Lake Kinneret is the most important surface water resource in Israel, providing approximately 35% of the annual drinking water to a population of almost 7.5 million inhabitants. The major water source for the lake is the ~1700-km² upper catchments of the Jordan River (UCJR), including ~920 km² in Israel with the remainder located in Syria and Lebanon. In the north of the UCJR, the higher elevations of the Mount Hermon range (1200–2800 m) are the wettest area in the Lake Kinneret watershed, where the average annual precipitation ranges from 1200 to 1500 mm.

The Mount Hermon basins feed the three major tributaries of the Jordan River: the Dan with ~250 million m³ (Mm³) annually, the Hermon (also known as Banias) with ~110 Mm³, and the Snir (also known as the Hazbani River) with ~115 Mm³. The Mount Hermon area and the surrounding region contribute over 60% of the water to the major rivers in the Kinneret basin. The contribution of the Jordan River and its three tributaries to the national water balance is even higher during dry years. The other part of the Lake Kinneret basin is the direct watershed, located in the immediate vicinity of the lake. The area of the direct watershed is ~965 km², 577 km² of which are in the southern part of the Golan Heights to the east of the lake and the other 388 km² of which are in the eastern Galilee Mountains to the west of the lake. The average annual water flowing into Lake Kinneret over the past decades is 660 Mm³ (for the period 1979–2007) including the Jordan River (455 Mm³), direct rainfall (65 Mm³), direct watershed runoff and artificial diversion (100 Mm³), and springs flowing directly into the lake (40 Mm³). An average of 230 Mm³ evaporates every year (Mekorot Watershed Unit 2008) so that the average annual volume of available water is ~410 Mm³. Most of this volume is pumped out of the lake every year for consumption, while some water occasionally overflows to the Lower Jordan River toward the Dead Sea.

4. Methods

a. The WRF model

WRF, version 3.011, was set up with a 90 × 90 point horizontal-grid outer domain with a 36-km grid interval; a second 136 × 136 point domain at 12-km grid spacing, which is nested in domain 1; and a third 181 × 181 point nested-grid domain at 4-km grid spacing, which is nested in domain 2. To study the impact of model resolution, simulations were carried out individually by dropping the fine-mesh domains in sequence. Also tested is another triply nested model with 27-, 9-, and 3-km grid spacings. Experiments with a 1.3-km grid domain were also performed for selected cases. The model domain is displayed in Figs. 2a,b.

Each simulation was begun at 0000 UTC and had a duration of 30 h. The first 6 h of the forecast were dropped to allow for model spinup. Hence, the precipitation simulations that are valid between 0600 and 0600 UTC of the following day were analyzed in this paper. The WRF simulations were initialized with 0.5° National Oceanic and Atmospheric Administration National Centers for Environmental Prediction Global Forecast System (NCEP GFS) model analysis.

Note that this study has been based on “cold start” initiation WRF forecasts. During the last two decades, several advanced mesoscale data assimilation approaches,
such as the National Center for Atmospheric Research real-time four-dimensional data assimilation (Liu et al. 2008a,b), have been developed to improve short-term quantitative precipitation forecasts.

b. Choosing optimal WRF microphysical schemes and resolution

The first step in the study was to test a variety of WRF microphysical schemes and different horizontal resolutions for a subset of weather events in Israel. WRF allows several choices of microphysical parameterization schemes. The microphysics schemes tested in this study include mp2 and mp6 (WRF single-moment six-class scheme; Hong and Lim 2006), mp7 (the Goddard microphysics scheme), mp8 (the Thompson scheme), and mp10 (the Morrison double-moment scheme, which predicts both mass and number of each category of cloud/precipitation particles). To choose the optimal model configuration for Israel, WRF was run for a few winter storms: 23–25 December 2008, 10–12 February 2009, and 27 February–1 March 2009. The “best” model configuration was determined by comparing the results of the model experiments with a cluster of 17 rain gauge observations in northern and central Israel (see the rain gauge locations and the different aquifers in Israel in Fig. 3).

The Kain–Fritsch convective parameterization scheme was activated in the WRF domains that had grid sizes larger than 4 km. The “Noah” land surface model and the 1.5-moment closure TKE-based boundary layer scheme were used in all model runs. Both schemes are described in detail in the WRF user’s manual. The GFS forecasts were used to update the WRF boundary conditions. The model in its final configuration was run

![Fig. 1. Maps of the (a) eastern Mediterranean sea and adjacent land and (b) the Lake Kinneret watershed, which includes the international borders, the UCJR, and the direct watersheds (east and west).](image)
operationally with 36-, 12-, 4-, and 1.3-km grid-increment domains for the winters of 2008/09 and 2009/10.

c. The hydrological model: HYMKE

HYMKE was developed by Rimmer and Salingar (2006) and is employed in this study. For this study, HYMKE was set up to simulate the hydrological processes in the Mount Hermon region where there are three surface flow catchments and several large karstic springs originating from groundwater. HYMKE contains four main modules (see the model schematic description in Fig. 4): the surface layer (labeled 0), the vadose zone (labeled 1), groundwater (labeled 2), and surface flow (labeled 3). Here, the land surface processes of the entire geographical basin include recharge by precipitation, drying by evaporation, surface runoff, and percolation to deeper layers. A more detailed illustration of HYMKE can be found in Rimmer and Salingar (2006).

The karstic nature of the lands was modeled with a surface layer ("epikarst") composed of both low- and high-permeability sections that feed the karst network. The surface layer is drained continuously as a function of moisture content. Saturation excess is generated when the surface layer is saturated. Part of the excess saturation is then transformed into the surface flow (module 3) while the other part forms a downward preferential flow component. Therefore, the percolation into the vadose zone (module 1) includes both a “slow flow” component through the matrix and a “quick flow” component through the high-permeability section, where the latter is active mainly during the peak of the wet season. The output from the vadose zone (module 1) feeds the groundwater reservoir (module 2). The location of the springs and the differences among the patterns of spring discharge required the separation of module 2 into four groundwater linear reservoirs.

Reservoir (or "tank")-type models (Dooge 1973; Sugawara 1995) are a common way to translate a conceptual model of a groundwater system into mathematical formulations. The linear reservoir concept, in which discharge is linearly dependent on the reservoir storage, is especially useful in karst environments, because the necessary information for physical approaches is usually not available (Jukic and Denic-Jukic 2009). This has become evident in a large number of recently published studies (e.g., Fleury et al. 2007; Hartmann et al. 2011; Jukic and Denic-Jukic 2009; Kessler and Kafri 2007; Le Moine et al. 2008; Rimmer and Salingar 2006).

In the Mount Hermon region, three linear reservoirs feed the Dan, Snir, and Hermon baseflow, and one reservoir contributes to the residual of groundwater to springs in the eastern part of Mount Hermon within Syria. The accumulated output from the surface runoff (module 3) and the baseflow (module 2) for each tributary makes up all of the natural flows in the hydrological model for the region. The sum of all three tributaries creates the flow in the main stream, the Jordan River.
d. Jordan River streamflow prediction

We chose to demonstrate the use of the WRF rainfall to predict daily streamflow in the upper catchments of the Jordan River, using HYMKE and following the procedure described by Rimmer and Salingar (2006). Here, the initial conditions of streamflow in each tributary (Hermon, Snir, and Dan) were determined from the measured discharge on 1 October 2009 (the first day of the 2009/10 rainy season). At this date the soil moisture content in the surface layer (module 0) is set to the minimal (residual) value, the storage and discharge of the surface flow (module 3) and the vadose zone (module 1) are considered to be zero, and therefore the entire streamflow is attributed to the groundwater sources (module 2). The storage of each groundwater reservoir can then be evaluated from the typical discharge–storage relations of each reservoir. These conditions change throughout the season with the application of rainfall.

Three sets of HYMKE runs were done: 1) with measured rainfall, 2) using the WRF-modeled rainfall output, and 3) using the Rimmer and Salingar (2006)
regression-model rainfall output. The measured precipitation input for the latter model was from a rain gauge located at the Hermon base ski resort (1640 m MSL) and operated by the Israeli Hydrological Service since 2009. This location has the highest orographic effect and contributes most of the water in the basin.

WRF daily precipitation forecasts from the 12-, 4-, and 1.3-km grid models were extracted for this station and used as input for HYMKE. In each simulation, HYMKE produced time series of baseflow, surface flow, and full natural flow for the Dan, Snir, Hermon, and Jordan Rivers.

5. Results

a. WRF tests with different microphysical parameterizations

The five previously noted microphysical schemes available in WRF were tested for the three major storms that occurred during 2008/09 in northern and central Israel. Figure 5 displays the accumulated precipitation simulated by WRF with the five microphysical schemes and a comparison with the actual precipitation. Each point in Fig. 5 represents the accumulated precipitation on the 4-km grid. Figure 5 indicates that all of the schemes showed fairly good results but that mp6 produced precipitation with the highest correlation and smallest bias relative to the observations. The mp6 scheme is a WRF single-moment, six-class-hydrometeor microphysical scheme. Note that mp6 is an enhanced version of mp2 (J. Dudhia 2010, personal communication): the advances of mp6 over mp2 appear to be favorable for wintertime precipitation modeling over mountainous regions where cold-cloud microphysical processes are dominant.

b. WRF resolution impacts for precipitation

Another important step for optimizing WRF for the region is to examine the impact of the model resolution. The preferred microphysical scheme (mp6) was used in the WRF runs for these resolution experiments. The correlation between the observed accumulated precipitation and the calculated precipitation with the WRF runs at different resolutions was examined. Also, the GFS-forecast rains at three water-resources basins in Israel were examined: the Kinneret basin, the mountain aquifer, and the coastal aquifer. This was done using the 17 selected representative rain gauges for eight winter storms that occurred during the 2008/09 season (23 December 2008–17 April 2009).

Figure 6 displays the correlation between the observed and the modeled precipitation from the WRF runs with grid increments of 3 (Fig. 6a), 4 (Fig. 6b), 12 (Fig. 6c), and 36 (Fig. 6d) km and from the GFS model (Fig. 6e). It can be seen clearly that the WRF-predicted precipitation at the higher resolutions, with 3- and 4-km grid sizes, correlates very well with the measured rain, with coefficients $r = 0.92$ and 0.96, respectively. The correlation coefficients for the 12- and 36-km forecasts
FIG. 6. WRF-forecast total precipitation from 17 stations during eight storms between 23 Dec 2008 and 17 Apr 2009 running at grid spacings of (a) 3, (b) 4, (c) 12, and (d) 36 km, and (e) the GFS forecast and a comparison with the observed total precipitation for the same period.
were poorer \((r = 0.79\) and 0.69\). The GFS model, although it has coarser resolution (at around 50-km grid size), showed better results than the WRF forecasts at 36 km. More complete results for WRF model-resolution impact are given in Table 1. These findings suggest the importance of using a high-resolution model for operational precipitation forecasts in regions with complex terrain.

Figure 7 displays the correlation of modeled and observed daily precipitation for four rain gauges in the upper part of the Kinneret basin for the full 2009/10 rainy season, in the Hermon range and its foothills. The rain gauges are Hermon base, Majdal Shams, El Rom, and Phicman, with locations shown in Fig. 8. By comparing WRF forecasts at 1.3- and 4-km grid spacing, the high agreement between the calculated and the observed precipitation at both resolutions can be seen again, and the 1.3-km solution shows better results. Figure 9 summarizes the WRF runs for the full 2009/10 rainy season at three different grid increments (12, 4, and 1.3 km) for the cluster of those four rain gauges versus the observed accumulated precipitation. Note that the difference between the observed amount and the forecast precipitation is small, especially for WRF running at 1.3-km grid spacing. The differences between the observed precipitation amounts and the calculated values in Fig. 9 are only \(\sim 3\%\) for the 1.3-km WRF runs and 5% at for the 4-km WRF runs.

<table>
<thead>
<tr>
<th>Storm</th>
<th>Obs precipitation (mm)</th>
<th>3-km WRF</th>
<th>4-km WRF</th>
<th>12-km WRF</th>
<th>36-km WRF</th>
<th>50-km GFS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Kinnert basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 Dec 2008</td>
<td></td>
<td>65</td>
<td>68</td>
<td>60</td>
<td>56</td>
<td>33</td>
</tr>
<tr>
<td>16 Feb 2009</td>
<td></td>
<td>26</td>
<td>21</td>
<td>24</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>3 Mar 2009</td>
<td></td>
<td>27</td>
<td>31</td>
<td>29</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>10–12 Feb 2009</td>
<td></td>
<td>76</td>
<td>62</td>
<td>76</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>16–17 Apr 2009</td>
<td></td>
<td>36</td>
<td>64</td>
<td>28</td>
<td>42</td>
<td>30</td>
</tr>
<tr>
<td>19–21 Feb 2009</td>
<td></td>
<td>94</td>
<td>92</td>
<td>93</td>
<td>57</td>
<td>45</td>
</tr>
<tr>
<td>23–25 Mar 2009</td>
<td></td>
<td>41</td>
<td>48</td>
<td>45</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>27 Feb–1 Mar 2009</td>
<td></td>
<td>70</td>
<td>72</td>
<td>70</td>
<td>48</td>
<td>39</td>
</tr>
<tr>
<td>Tot precipitation</td>
<td></td>
<td>435</td>
<td>459</td>
<td>425</td>
<td>280</td>
<td>218</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yarqon–Taninim</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 Dec 2008</td>
<td></td>
<td>79</td>
<td>94</td>
<td>100</td>
<td>30</td>
<td>18</td>
</tr>
<tr>
<td>16 Feb 2009</td>
<td></td>
<td>11</td>
<td>5</td>
<td>10</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>3 Mar 2009</td>
<td></td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>10–12 Feb 2009</td>
<td></td>
<td>33</td>
<td>15</td>
<td>22</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>16–17 Apr 2009</td>
<td></td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>19–21 Feb 2009</td>
<td></td>
<td>60</td>
<td>61</td>
<td>38</td>
<td>52</td>
<td>14</td>
</tr>
<tr>
<td>23–25 Mar 2009</td>
<td></td>
<td>32</td>
<td>21</td>
<td>38</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>27 Feb–1 Mar 2009</td>
<td></td>
<td>121</td>
<td>86</td>
<td>108</td>
<td>77</td>
<td>48</td>
</tr>
<tr>
<td>Tot precipitation</td>
<td></td>
<td>347</td>
<td>293</td>
<td>327</td>
<td>220</td>
<td>129</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coastal aquifer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 Dec 2008</td>
<td></td>
<td>42</td>
<td>38</td>
<td>41</td>
<td>35</td>
<td>26</td>
</tr>
<tr>
<td>16 Feb 2009</td>
<td></td>
<td>18</td>
<td>19</td>
<td>12</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>3 Mar 2009</td>
<td></td>
<td>10</td>
<td>5</td>
<td>11</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>10–12 Feb 2009</td>
<td></td>
<td>21</td>
<td>4</td>
<td>8</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>16–17 Apr 2009</td>
<td></td>
<td>20</td>
<td>15</td>
<td>2</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>19–21 Feb 2009</td>
<td></td>
<td>58</td>
<td>56</td>
<td>32</td>
<td>55</td>
<td>29</td>
</tr>
<tr>
<td>23–25 Mar 2009</td>
<td></td>
<td>23</td>
<td>12</td>
<td>42</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>27 Feb–1 Mar 2009</td>
<td></td>
<td>82</td>
<td>52</td>
<td>62</td>
<td>66</td>
<td>51</td>
</tr>
<tr>
<td>Tot precipitation</td>
<td></td>
<td>272</td>
<td>201</td>
<td>211</td>
<td>231</td>
<td>161</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Western Galilee</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 Dec 2008</td>
<td></td>
<td>76</td>
<td>48</td>
<td>41</td>
<td>50</td>
<td>34</td>
</tr>
<tr>
<td>16 Feb 2009</td>
<td></td>
<td>26</td>
<td>16</td>
<td>13</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>3 Mar 2009</td>
<td></td>
<td>25</td>
<td>13</td>
<td>10</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>10–12 Feb 2009</td>
<td></td>
<td>37</td>
<td>28</td>
<td>41</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>16–17 Apr 2009</td>
<td></td>
<td>19</td>
<td>19</td>
<td>16</td>
<td>37</td>
<td>29</td>
</tr>
<tr>
<td>19–21 Feb 2009</td>
<td></td>
<td>76</td>
<td>55</td>
<td>49</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>23–25 Mar 2009</td>
<td></td>
<td>33</td>
<td>26</td>
<td>42</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>27 Feb–1 Mar 2009</td>
<td></td>
<td>116</td>
<td>110</td>
<td>102</td>
<td>78</td>
<td>69</td>
</tr>
<tr>
<td>Tot precipitation</td>
<td></td>
<td>408</td>
<td>315</td>
<td>314</td>
<td>296</td>
<td>270</td>
</tr>
</tbody>
</table>
c. WRF versus the linear-regression-calculated precipitation

Rimmer and Salingar (2006) calculated the precipitation for the Hermon range using regression between elevation and precipitation at the lower elevations in the north of Israel, as was described in the first paragraph of section 2. Figure 10 displays the annual precipitation amount that was measured at the Hermon base’s Israeli Hydrological Service rain gauge versus the WRF 1.3- and 4-km precipitation forecasts and versus that calculated for this rain gauge station using the original regression-model equations. It can be seen that the WRF simulations did much better than the regression calculation. The actual precipitation in this gauge was 1306 mm, the WRF 1.3-km simulation calculated 1336 mm, the WRF 4-km simulation calculated 1278 mm, and the regression equation produced just 1022 mm (12%, 22%, and 22% relative to the observed, respectively). Such an underestimation by the regression model would lead to underestimation of the streamflow volumes in the river and its tributaries.

d. Simulations of daily flow in the Jordan River and its tributaries

The actual measured precipitation at Mount Hermon, the amount of precipitation computed by the WRF 1.3-km model, and that computed from the regression model were used to drive the calculations of daily flow volumes in the three major tributaries and at the Jordan River using HYMKE. Figure 11 displays simultaneously the measured and the calculated daily streamflows derived from the WRF 1.3-km rainfall model. Figure 11 indicates that the correlation between the time series of measured and predicted flows for the Hermon stream (Fig. 11a) resulted in $r^2 = 0.74$, as compared with $r^2 = 0.89$ in a 20-yr model calibration with measured rainfall (Rimmer and Salingar 2006). Similar results were found...
for the Snir (Fig. 11b; $r^2 = 0.70$, as compared with $r^2 = 0.84$), the Dan (Fig. 11c; $r^2 = 0.79$, as compared with $r^2 = 0.77$), and the Jordan River itself (Fig. 11d; $r^2 = 0.61$, as compared with $r^2 = 0.94$) at Sede Nehehemia (hydrometric station of the Israeli Hydrological Service). The hydrological model during 2009/10 predicted better the baseflows in this karstic region, whereas the model system needs to be improved for forecasting the very extreme peaks of the streamflows.

Figure 12 compares the daily Jordan River flows simulated by the HYMKE model with 1) measured rainfall and 2) the WRF 1.3-km forecast rainfall. The comparison between flows predicted by the two cases results in $r^2 = 0.93$. The precipitation amount during the rainy season of 2009/10 was about the average climate-mean value. Table 2 summarizes the monthly flow volumes forecast by the hydrological model driven by the rainfall observations, the rainfall forecast by the WRF
1.3-km run, and that computed on the basis of the Rimmer and Salingar (2006) regression approach during the 2009/10 rainy season (from 1 October 2009 to 30 April 2010). The total measured flow volume at the gauge for this period was 354 Mm$^3$: 323 Mm$^3$ at the gauge and another 31 Mm$^3$ consumption upstream that was not able to get into the river. The HYMKE-simulated flow using the actual Hermon precipitation was 362 Mm$^3$, that using the WRF precipitation was 371 Mm$^3$, and that using the regression precipitation was just 294 Mm$^3$. It can be seen in Fig. 12 and Table 2 that using simulated precipitation from WRF is actually almost like using such input from a rain gauge network. The findings presented here have important value for hydrologists, especially in areas where a good network of rain gauges is not available and there is a need for a precipitation forecast such as WRF can provide.

6. Discussion and conclusions

Improving streamflow forecasts for the Jordan River and its tributaries is a highly important task, especially during dry years. This area is disconnected from the national water system (the “National Water Carrier”), and it has to rely on local water sources: direct pumping, mostly from the Dan and the Banias Rivers. During severe drought years like 2000/01 or 2007/08, water shortages occurred and there was scarcely enough water for all of the consumers. This fact is why reliable streamflow forecasting is required throughout the year.

Steep mountains in northern Israel cause complex structures in the spatial distribution of precipitation, especially in the Mount Herman region. Such precipitation features make hydrological forecasting challenging, especially for the Jordan River. In this paper, the use of an advanced mesoscale weather model, the community WRF, has been explored for driving hydrological model forecasts for the Jordan River. Sensitivity experiments were conducted to study the impact of WRF microphysical parameterization schemes and model grid resolution, both of which are crucial for...
wintertime precipitation modeling in regions with steep mountains. The modeling results suggest that WRF is capable of forecasting precipitation amounts and structures in northern Israel reasonably well when high-resolution (4–1.3 km) grids are used.

High-resolution WRF-forecast precipitation is used to drive HYMKE to simulate the Jordan River flow. The verification of the streamflow forecasts for the upper Jordan River, using the WRF rainfall, showed improvement relative to the current hydrological simulations that make use of rainfall from a regression method. WRF is of special value in areas where there are poor surface meteorological observations, such as in the Jordan River basin. The results in Table 2 clearly show that the Jordan River flows forecast using the WRF 1.3-km model precipitation are more accurate than those that are based on the regression approach.

Hydrological modeling using the WRF-simulated precipitation allows us to represent better the important hydrological processes that occur in the northern part of the Jordan basin located in Lebanon, such as daily precipitation–runoff ratios, and the recharge for springs like the Dan and the Banias. Such improved upstream information leads to better predictions for downstream regions.

It can be argued that the high-resolution WRF combined with HYMKE can be used to support hydro-meteorological and hydrogeological applications with dynamical downscaling of global seasonal precipitation forecasts like those from the NCEP GFS model. This would facilitate seasonal streamflow forecasting in the Jordan River. This approach can improve the current method, which uses statistical downscaling for seasonal precipitation forecasting for the Kinneret basin (Wu et al. 2011, manuscript submitted to Int. J. Climatol.).

Using WRF for dynamical downscaling also improves the precipitation input for regional climate models for the upper Jordan River and especially for the Hermon range [as was done for California by Pan et al. (2010)]. In contrast, previous studies used statistical downscaling to evaluate future (2015–35) streamflow volumes and regimes in the Jordan River (Samuels et al. 2010; Rimmer et al. 2011). Thus, the need for interseasonal streamflow simulations is clear.

Further studies to improve the modeling system should be undertaken. A next step will be to extend the WRF domains to cover the full Jordan River region, especially the highest elevations in the Syrian mountains (2800 m), to feed HYMKE with more-complete meteorological input from those areas for basin-flow forecasting.

Acknowledgments. The authors thank Dr. T. T. Warner for reviewing the manuscript and for valuable discussions. The authors also thank Guy Kelman from Weather-It-Is for helping to maintain the WRF operational system at the Israeli Hydrological Service.

REFERENCES


<table>
<thead>
<tr>
<th>Month</th>
<th>Measured streamflow (Mm³)</th>
<th>Calculated streamflow with HYMKE using actual precipitation (Mm³)</th>
<th>Calculated streamflow with HYMKE using WRF 1.3-km precipitation (Mm³)</th>
<th>Calculated streamflow with HYMKE using precipitation calculated with the regression model (Mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 2009</td>
<td>24.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
</tr>
<tr>
<td>Nov 2009</td>
<td>23.3</td>
<td>28.1</td>
<td>23.1</td>
<td>23.0</td>
</tr>
<tr>
<td>Dec 2009</td>
<td>45.3</td>
<td>55.4</td>
<td>50.9</td>
<td>41.2</td>
</tr>
<tr>
<td>Jan 2010</td>
<td>69.2</td>
<td>64.4</td>
<td>72.7</td>
<td>54.3</td>
</tr>
<tr>
<td>Feb 2010</td>
<td>64.4</td>
<td>70.7</td>
<td>69.6</td>
<td>54.6</td>
</tr>
<tr>
<td>Mar 2010</td>
<td>60.6</td>
<td>66.9</td>
<td>76.8</td>
<td>54.5</td>
</tr>
<tr>
<td>Apr 2010</td>
<td>36.6</td>
<td>50.9</td>
<td>52.3</td>
<td>40.6</td>
</tr>
<tr>
<td>1 Oct 2009–30 Apr 2010</td>
<td>354</td>
<td>362</td>
<td>371</td>
<td>294</td>
</tr>
</tbody>
</table>


Martin, G., 1996: A dramatic example of the importance of detailed model terrain in producing accurate quantitative precipitation forecasts for southern California. National Weather Service Western Region Tech. Attachment 96-07, 9 pp. [Available from Western Regional Climate Center, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512.]


