First Application of JMA-NHM to Meteorological Simulation over the United Arab Emirates

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Abstract

The Japan Meteorological Agency Non-Hydrostatic Model was applied to meteorological simulations under arid and semi-arid environments of the United Arab Emirates (UAE). A one-year hindcast experiment was conducted with both an original configuration, which is well tuned for mid-latitude humid conditions around Japan, and a new configuration, which represents a much drier land surface condition. The new configuration produced much better results in terms of the diurnal variation of land surface temperature and consequent surface air temperature, as well as cloud and precipitation occurrence. The most effective factors for improving results are the threshold of soil water content and the parameters associated with surface and soil heat flux. The improvement indicates the validity of the model application to the investigation of cloud and precipitation processes over the UAE.

(Citation: Hashimoto, A., M. Murakami, and S. Haginoya, 2017: First application of JMA-NHM to meteorological simulation over the United Arab Emirates. SOLA, 13, 146–150, doi:10.2151/sola.2017-027.)

1. Introduction

In 2015, the UAE Research Program (UAEREP) for Rain Enhancement Science was launched to promote scientific advancement and the development of new technology. In the project “Advanced Study on Precipitation Enhancement in Arid and Semi-Arid Regions,” which was one of the three projects awarded the UAEREP prize in 2016, the authors plan to apply the cloud seeding model (Hashimoto and Murakami 2016) to the assessment of seedability and to the evaluation of cloud seeding effects. The seeding model was developed on the basis of the Japan Meteorological Agency (JMA) Non-Hydrostatic Model (JMA-NHM; Saito et al. 2006). Because the JMA-NHM was originally developed for the prediction of mid-latitude humid weather around Japan, it was necessary to optimize the model configuration, especially in terms of land surface characteristics, for its application to arid and semi-arid environments. This article presents (i) the procedures used for optimizing the model configuration, and (ii) the improvement in simulation results of meteorological fields, including cloud and precipitation, over the UAE.

2. Observation data for validation of the model

For a comparison with simulation results, we used Moderate Resolution Imaging Spectroradiometer (MODIS) products of the Terra and Aqua satellites with 5-km resolution, 11C1 (Version 041, Wan et al. 2015) for land surface temperature (LST), and 06_L2 (Version 051, Platnick et al. 2015) for cloud fraction. For the validation of simulated surface air temperature (SAT), we applied the Aviation Routine Weather Report (METAR) data collected by the National Centers for Environmental Prediction (NCEP Department of Commerce 2004). We also used daily precipitation amount data from the UAE’s domestic automatic weather stations (AWSs), which are provided by the National Center of Meteorology and Seismology (NCMS) of the UAE, to calculate seasonal precipitation amount at the AWS sites.

3. Model configurations

3.1 Numerical simulation

The JMA-NHM was applied to the present numerical experiment with basically the same configuration as that for the operational weather forecast model in Japan, except the following two points: (i) in this study, a double-moment bulk parameterization scheme, which predicts both the mixing ratio and number concentration, was applied to the solid hydrometeors and a single-moment parameterization that predicts only the mixing ratio was applied to the liquid hydrometeors; and (ii) the ice-saturation adjustment scheme (Tao et al. 1989) was turned off to avoid the unrealistic formation of ice clouds in the upper troposphere. Hereafter, the above-mentioned configuration will be termed the “original configuration” in this article.

Figure 1 shows the model domain. The domain size is 2000 km × 2000 km in the horizontal direction and 22 km in the vertical direction. The horizontal grid spacing is 5 km (5km-NHM). The vertical grid spacing is stretched from 40 m at the surface to 866 m at the top of the domain. Fifty variable vertical layers are employed in a terrain-following coordinate system. In each simulation, the model is time-integrated for 30 hours with a timestep of 1 second for the 5km-NHM, and 3 seconds for the 1km-NHM. The model variables are presented on the grid lines.

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12 s. The hourly output data in the last 24 hours were used for the analysis. The initial and boundary conditions of the atmosphere were provided by the global objective analysis data of JMA for air pressure, horizontal wind, air temperature, water vapor mixing ratio. For the initial condition of soil temperature, we adopted a simple mathematical function representing the soil heat conduction forced by the annual variation of surface air temperature centered at its annual-averaged climatic value. A control experiment (CTL) was performed once a day with the original configuration at an initial time of 10:00 LT from 2 February 2015 through 1 February 2016. As will be shown below, the control simulation resulted in a large bias in LST. To improve the bias, we modified the model configuration, as described below, and conducted another experiment with a modified configuration (MDF) in the same time period.

2.2 Modification of land surface model

A slab land surface model is incorporated into JMA-NHM, which simply solves a one-dimensional heat flux equation, expressed as follows

\[ \rho \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2}, \]  

(1)

where \( T \) is the temperature of the soil layer, and \( \rho \) and \( \lambda \) are volumetric heat capacity (J m\(^{-3}\) K\(^{-1}\)) and thermal conductivity (W m\(^{-1}\) K\(^{-1}\)), respectively. The upper boundary condition is given by

\[ -\lambda \frac{\partial T}{\partial z} = \left(1 - \sigma \right) S + \epsilon \left( L - \sigma T^4 \right) - H_l - H_s, \]  

(2)

where \( \sigma \) and \( \epsilon \) are downward shortwave and longwave radiation fluxes, respectively. \( \sigma \) and \( \epsilon \) are albedo, emissivity, and the Stefan-Boltzmann constant, respectively. \( H_l \) and \( H_s \) are sensible and latent heat fluxes, respectively. At the lower boundary (1.2-m depth from the surface), zero-flux is assumed, and the temperature is set as a climatic value.

In the original configuration, the land cover type of each grid is determined by the Global Land Cover Characteristics Data Base Version 2.0 (GLCC), and \((\rho_s, \lambda) = (2.3 \times 10^3, 2.07)\) and \((1.8 \times 10^3, 1.08)\) are adopted for “Barren or Sparsely Vegetated” and “Shrubland,” respectively, based on the USGS Land Use/Land Cover System Legend (Modified Level 2). Kondo (1994) summarized these parameter values in several types of soil including dry sand \((\rho_s, \lambda) = (1.3 \times 10^3, 0.3)\) and wet sand \((\rho_s, \lambda) = (3.0 \times 10^3, 2.0)\). From trial and error during numerical experiments referencing the parameter values of Kondo (1994), we obtained the values \((\rho_s, \lambda) = (1.64 \times 10^3, 0.521)\) for “Barren or Sparsely Vegetated” and \((\rho_s, \lambda) = (2.15 \times 10^3, 0.965)\) for “Shrubland”; these were adopted in the new configuration. The surface roughness length \(z_o\) (m) is 0.1 for “Barren or Sparsely Vegetated” in the original configuration. This is adjusted to \(z_o = 0.024\) for the new configuration. For the “Shrubland,” \(z_o\) is 0.3 and 0.2 in summer and winter, respectively, in the original configuration and are adopted for the new configuration. In addition, a portion of “Shrubland” in the GLCC is changed to “Barren or Sparsely Vegetated” in the new configuration, as shown in Fig. S1, and all the related parameters are accordingly modified, because an unrealistic pattern appeared in the simulated LST with the original configuration due to the distribution pattern of “Shrubland” (not shown).

The latent heat flux \(H_l\) is expressed by the latent heat of evaporation \(L\) (J kg\(^{-1}\)), air density \(\rho\) (kg m\(^{-3}\)), and water vapor flux \(E\) (kg m\(^{-1}\) s\(^{-1}\)):

\[ H_l = L \rho E. \]  

(3)

The water vapor flux is expressed as follows:

\[ E = -C_e \beta \overline{p} (q_a - q_w). \]  

(4)

where \(C_e\) is the bulk coefficient of the surface flux, \(\overline{p}\) and \(q_a\) are the absolute wind velocity (m s\(^{-1}\)) and specific humidity (kg kg\(^{-1}\)), at the lowest layer in the model atmosphere, \(q_w\) is the saturated specific humidity at the soil surface, and \(\beta\) is the evaporation efficiency. \(\beta\) is diagnosed using the volumetric water content at the surface \(w_s\) in the original configuration, as follows (Hara 2008):

\[ \beta = \begin{cases} \frac{w_s}{0.3} & (w_s \leq 0.3) \\ 1 & (w_s > 0.3) \end{cases}. \]  

(5)

This formulation systematically overestimates \(\beta\) in a dry condition when \(w_s\) is less than 0.2 (Hara 2008). In the new configuration, we used the following formulation (Kondo 1994):

\[ \beta = \left( \frac{C_s \pi F(w_s)}{D_s} \right)^{-1}, \]  

(6)

\[ F(w_s) = F_s(w_s) - w_s, \]  

(7)

where \(D_s\) is the molecular diffusivity of water vapor (m\(^{2}\) s\(^{-1}\)). The constants \(F_s\) and \(F_s\) are 0.397, \(7 \times 10^3\), and 11.2, respectively, which correspond to the soil texture “sandy soil” in Kondo (1994).

For predicting \(w_s\), a force-restore equation is solved with two subsurface soil water layers. The time evolution of \(w_s\), which corresponds to the 10-cm depth subsurface layer, is obtained by solving the following equations (Hara 2008):

\[ \frac{\partial w_s}{\partial t} = -\frac{w_s - w_s}{\tau_s} + F_s, \]  

(8)

\[ \frac{\partial w_s}{\partial t} = F_s, \]  

(9)

\[ \tau_s = C_s \tau_1, \]  

(10)

\[ F_s = -C_i \frac{E - P}{\rho \sigma d_1}, \]  

(11)

\[ F_s = \frac{E - P}{\rho \sigma d_1}, \]  

(12)

where \(w_s\) is the volumetric water content of the 50-cm depth subsurface layer, \(\tau_s\) is the \(\tau\)-folding time for the difference between \(w_s^0\) and \(w_s\), \(\tau_1\) is the length of one day (86400 sec), \(\rho\) is the density of water \((1000 \text{ kg m}^{-3})\), \(P\) is the precipitation rate \((\text{kg m}^{-2} \text{s}^{-1})\), and \(d_1 = 0.1 \text{ m}\) and \(d_2 = 0.5 \text{ m}\) are the depths of the two subsurface layers. \(C_i\) and \(C_s\) are formulated following Deardorff (1978) in the original JMA-NHM. In the new configuration, the formulations are altered so as to incorporate the factors of soil texture into these parameters, following Noilhan and Planton (1989). Noilhan and Planton (1989) proposed formulations representing 11 types of soil texture. In our new configuration, the formulation representing silty clay was adopted. The initial value of soil water content is set as 0.4 (summer) or 0.3 (winter) for “Shrubland”, and 0.2 (summer) or 0.1 (winter) for “Barren or Sparsely Vegetated” in each restart of simulation.

In the original configuration, \(w_s\) is forced to be larger than 70% of its initial value during time integration, which brings an unrealistically wet condition to the desert surface. In the new configuration, we altered this threshold value from 70% to 10% to represent the dry condition of the actual desert surface. Although there is arbitrariness in determining the threshold value, this alteration improves reproducibility of LST and SAT.

In the original configuration, the slab land surface model employs four layers within a depth of 1.2 m below the surface. Moving down from the surface, the thickness of each layer \(\Delta z_s\) is 0.04, 0.15, 0.40, and 0.60 m. The vertical gradient of temperature or heat flux in a soil model is generally underestimated with coarse resolution. We increased the number of layers from 4 to 12 to reproduce the large amplitude of diurnal variation in LST over
the desert. In the 12-layer configuration, $\Delta z_i$ is determined with the following equation:

$$\Delta z_i = C \times \Delta z_{i+1},$$

(13)

where $C = 1.488$ and $\Delta z_1 = 0.005$ m.

In addition, we altered the flat distribution of surface emissivity ($= 1.0$) in the original configuration to a spatially variable distribution in the new configuration, based on the emissivity dataset provided by Ren et al. (2013).

Differences between the original and new configurations are summarized in Table 1.

### Table 1. Differences between the original configuration (CTL) and new configuration (MDF).

|                     | CTL                        | MDF                        |
|---------------------|----------------------------|-----------------------------|
| Volumetric heat capacity | $1.8 \times 10^6$ J m$^{-3}$ K$^{-1}$ (08) | $2.15 \times 10^6$ J m$^{-3}$ K$^{-1}$ (08) |
| Thermal conductivity   | $2.3 \times 10^6$ J m$^{-3}$ K$^{-1}$ (08) | $1.64 \times 10^6$ J m$^{-3}$ K$^{-1}$ (19) |
| Roughness length       | 0.08 W m$^{-1}$ K$^{-1}$ (08) | 0.024 W m$^{-1}$ K$^{-1}$ (19) |
| Land cover classification | GLCC                      | Modified GLCC               |
| Evaporation efficiency  | Hara (2008)                | Kondo (1994)                |
| Soil water content     | Deardorff (1978)           | Noilhan and Planton (1989)  |
| Threshold on soil water content | 70% of initial value       | 10% of initial value        |
| Number of soil layers  | 4 layers                   | 12 layers                   |
| Surface emissivity     | 0.3/0.2 m in summer/winter (08) | Spatially variable |

The bracketed numbers in the rows of volumetric heat capacity, thermal conductivity and roughness length indicate the values in the GLCC Land Cover System Legend (Modified level 2); 08 for “Shrubland” and 19 for “Barren or Sparsely Vegetated”

4. Results

Figure 2 shows the mean and standard deviation of LST in the area shown by the blue broken line in Fig. 1. Gray dots indicate the values observed by the MODIS satellites, Aqua and Terra that pass over the Middle East around the noon and the midnight. Colored dots indicate the simulated values in the CTL (Fig. 2a) and MDF (Fig. 2b). The scattering of mean LST roughly indicates the range of diurnal variation. The standard deviation indicates the spatial variation of LST. With the original configuration, the model does not cover the actual LST variation in time and space. By applying the new configuration, the simulated mean LST is clearly improved throughout the year. The standard deviations are also improved (blue dots in Fig. 2b), but are smaller than those in the observations, indicating that the new configuration is still too simple to account for the real variety of land surface characteristics.

Figure 3 shows the daily maximum and minimum values of SAT at Al Ain International Airport. The maximum SAT is underestimated in the CTL (red dots in Fig. 3a), as compared with the observations (gray dots). In the MDF (blue dots in Fig. 3b), the maximum SAT shows good agreement with the observations. The minimum SAT is lower than that of the observations in the CTL. The underestimation of SAT remains in the MDF.

Figure 4 shows the three-month accumulated precipitation amounts in the CTL and MDF. The reproducibility of the observed

![Fig. 2. Areal mean LST $m$ and standard deviation of LST $s$ in the area shown by the blue broken line in Fig. 1 simulated in the (a) CTL and (b) MDF experiments. The gray dots show the LST observed by Aqua and Terra, and the colored dots show the LST simulated by the 5km-NHM. The plots show only the cases swath-covered and clear (no cloud) area is more than 65% of the area.](image)

![Fig. 3. (a) Daily maximum and minimum SAT at Al Ain International Airport for the (a) CTL and (b) MDF experiments. Gray and red/blue dots show observed and simulated values, respectively.](image)
precipitation amount (colored dots) accumulated through winter (from January to March: JFM) is not clearly different between the two experiments (color shading in Figs. 4a and 4b). This is because precipitation is mainly brought by synoptic-scale disturbances regardless the land surface characteristics. During the other seasons, differences in the simulated precipitation distribution mainly appear over the desert area. Especially in the periods from July to September (JAS) and from October to December (OND), reproducibility is clearly improved in the MDF experiment.

5. Discussion

As shown above, the new configuration of land surface processes in JMA-NHM improved the simulation of LST, SAT, and consequently cloud formation and precipitation development over the desert areas in the UAE. However, it is open to discussion whether the combination of new values or formulations adopted for individual components of the configuration offer a unique solution for optimizing the land surface processes. Although this requires more work to provide the solution, it is worth examining the sensitivity of the simulation results to each component for further tuning or developing of model. For this purpose, we additionally conducted five sets of simulations (Ex1–5).

Figure 5 shows the results of sensitivity tests in terms of LST and SAT. To plot Fig. 5, the simulated LST was averaged over the area shown by the blue rectangle in Fig. 1. From the time series of the area-averaged LST, the maximum and minimum values were sampled and averaged for three days (9–11 September 2015) to represent the daily maximum and minimum LST (circles) for the different configurations. The same procedure was applied to the SAT values (triangles). During the three days, clouds formed in daytime firstly over the mountain area and secondly over the desert. Precipitation was seen on the mountain area every day. In the afternoon of 10 and 11 September, some clouds produced precipitation over the desert.

Ex1, in which the number of soil layers was set to the same as that in CTL (4 layers) and the other components were set to the same as those in MDF, shows that the daily maximum and minimum LST and SAT are not sensitive to the number of soil layers. In Ex2, where the lower limit of soil water content is set to the same as that in CTL (wetter soil condition than in MDF), the daily maximum LST decreases, as compared with the MDF. This is due to a greater release of latent heat from the soil surface during the daytime. Also, the daily maximum SAT slightly decreases owing to the decrease in sensible heat flux from the soil surface to the atmosphere. In Ex3, the formulations for evaporation efficiency and soil water content were set to the same as those used originally; the results are not markedly different from Ex2. When the components of the configuration related to soil thermal conductance are returned to the original values in Ex4 (more conductive than in MDF), the daily maximum decreases and the minimum LST increases because LST is more strongly influenced by the bottom soil layer, whose temperature is kept at a climatic value. In Ex5, roughness length is additionally returned to the original value (larger than in the MDF). Daily maximum LST decreases and SAT increases, as compared with Ex4, because of the enhanced exchange of heat between the soil surface and the atmosphere.

Figure 6 shows the time evolution of cloud coverage, as calculated using the gridded cloud fraction data in the model output and the MODIS cloud product over the desert (shown by the blue rectangle in Fig. 1). In the CTL (red broken line and red dots) with 5km-NHM, cloud coverage is quite low during the period, except for the evening of 10 September. In the MDF with 5km-NHM (MDF05, blue broken line and blue dots), cloud coverage increases in the afternoon and evening compared with that in the CTL, but it is lower than the observations (black dots). Another factor (other than the land surface characteristics) that can potentially influence the simulation results is grid spacing. For an examination
of the sensitivity to grid spacing, we performed additional simulations with a horizontal resolution of 1 km (1km-NHM) with the new land surface configuration in the domain shown in Fig. 1 for the same three days (MDF01). Vertical grid spacing, initial time, and integration time are set to the same as those in the 5km-NHM, and the timestep is 8 s. Initial conditions and boundary forcing are provided by the 5km-NHM. The cloud coverage simulated in MDF01 becomes larger than that in MDF05 (Fig. 6) for each day. The enhancement of cloud coverage in MDF01 indicates that the application of a finer grid spacing is an effective approach for realizing a more accurate simulation of cloud formation accompanied by thermal convection over the desert in the UAE, as Takemi et al. (2005) successfully simulates the diurnal variability of boundary-layer convection and cloud development over a desert with a sub-kilometer grid spacing. On the other hand, Fig. 6 shows that substantial underestimation (compared with observations) remains in MDF01. On this point, however, it should be considered that the MODIS cloud fraction has a systematic bias relating to sensor zenith angle (larger cloud fraction for larger sensor zenith angle), as shown by Maddux et al. (2010).

6. Conclusion

We conducted a one-year hindcast experiment over the UAE using JMA-NHM to evaluate the model performance in reproducing cloud and precipitation formation. Changing the land surface configuration from one that represents the mid-latitude humid environment around Japan to a new configuration that represents arid or semi-arid environments, the simulation results were markedly improved in terms of LST, SAT, and consequently cloud and precipitation formation. The sensitivity of the simulation results to the model configuration was examined with respect to individual land surface characteristics and the horizontal resolution of the model. The results demonstrate the usefulness and credibility of the model application to the investigation of cloud and precipitation processes over the UAE, which is critical to precipitation enhancement research.

Acknowledgements

This study was supported by the Ministry of Presidential Affairs and the NCMS, the UAE, under the UAEREP for Rain Enhancement Science. MODIS products were obtained from the Land Processes Distributed Active Archive Center of the United States Geological Survey, Earth Resources Observation and Science Center (http://lpdaac.usgs.gov). METAR data were downloaded from the National Center for Atmospheric Research (http://rda.ucar.edu/datasets/ds461.0/).

Edited by: T. Takemi

Supplement

Figure S1. GLCC land cover system legend in (a) the original configuration and (b) the new configuration.

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Manuscript received 19 May 2017, accepted 24 July 2017
SOLA: https://www.jstage.jst.go.jp/browse/sola/