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A Seasonal Statistical Evaluation of COAMPS® over the Arabian Gulf Region

REBECCA E. EAGER,[1] SETHU RAMAN,[1] TEDDY R. HOLT,[2] DOUGLAS WESTPHAL,[2] JEFFREY REID,[2] JASON NACHAMKIN,[2] MING LIU,[2] and ABDULLA AL MANDOOS[3]

Abstract—A statistical evaluation of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) was performed over the Arabian Gulf region for the period, 1 August to 5 October, 2004. Verification skill scores of bias and root-mean-square error were estimated for surface variables and for vertical profiles to investigate any diurnal variations. The model predictions of boundary-layer heights are compared with the observations at Abu Dhabi, United Arab Emirates. The Middle East presents challenges to numerical weather prediction due to complex land-ocean-land mesoscale processes. An independent data set of surface measurements from 50 stations in the UAE was available from the Department of Water Resources Studies, Abu Dhabi for model verification. The results indicate a diurnal variation in the model errors. The errors are small considering the magnitudes of the observed variables. Errors in the coastal region can be attributed to the differences in the timing of the onset of sea and land breeze circulations in the simulations as compared to the observations. Errors are relatively smaller in the offshore locations.

Key words: Statistical evaluation, UAE, COAMPS, verification.

1. Introduction

The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) (HODUR, 1997) developed by the U.S. Naval Research Laboratory, provided weather and dust forecasts for the Arabian Gulf region in support of the United Arab Emirates Unified Aerosol Experiment (2004) (UAE^2). Verification of COAMPS® has been done for winter months in the Mediterranean (NACHAMKIN and HODUR, 2000) and in the Middle East (SHI *et al.*, 2004). SHI *et al.* (2004) performed a model verification of COAMPS® for January-March 1991 on a 15-km grid centered over Iraq. They found bias errors of near zero at the analysis time for levels below

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[1] Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina, U.S.A.
[2] Naval Research Laboratory, Monterey, California, U.S.A.
[3] Department of Atmospheric Studies, Ministry of Presidential Affairs, United Arab Emirates.

200 hPa. At the 12-hour forecast below 200 hPa there was a negative temperature bias error of 0.2–0.7°C, a negative geopotential height bias of 3 m to 9 m, and a positive wind bias of 0.5 m s^{-1}, which are similar to the bias errors of the models listed in WHITE *et al.* (1999). NACHAMKIN and HODUR (2000) found the wind and temperature fields to be underpredicted and relative humidity to be overpredicted, with magnitudes similar to the bias errors in SHI *et al.* (2004) and WHITE *et al.* (1999).

This paper describes a statistical evaluation of 48-hour COAMPS® forecasts performed in the Arabian Gulf region during the summer and early fall, from 1 August to 5 October, 2004. Section 2 discusses the model, available data, verification methods and gives a brief synoptic overview of the period; Section 3 discusses the verification of surface variables across the region; Section 4 includes the model verification for upper-level variables; and Section 5 gives a summary of the results. Throughout the paper, both UTC and local time (LT; UTC + 4 hours) are used when referring to forecast valid time, because mesoscale circulations driven by land-sea temperature contrasts are the dominant weather features during most of the verification period.

2. Model, Verification Methods, and Data

2.1. Model Description

The atmospheric component of COAMPS® with non-hydrostatic dynamics was used in this study. The atmospheric model contains physical parameterizations for subgrid scale mixing, sub-grid scale convection, short- and longwave radiation, and explicit moist physics. A full description of the model physics and the equations can be found in CHEN *et al.* (2003) and on the COAMPS® website (http://www.nrlmry.navy.mil/coamps-web/web/home). Three one-way nested grids are used (Fig. 1). The outer grid is 92 × 68 grid points with 81-km resolution, grid 2 is 127 × 109 grid points with 27-km resolution, and grid 3 is 181 × 181 grid points with 9-km resolution. The domain has 30 vertical sigma levels, with increased vertical resolution (50 to 100 m) in the lower levels. For this study the 9-km grid domain is used for verification. Boundary conditions are provided by the Navy Operational Global Atmospheric Prediction System (NOGAPS) model, as are the first-guess fields for the first model run. Subsequent model runs use the previous COAMPS® 12-hr forecast for the first-guess field. Data assimilation was performed using multivariate optimum interpolation analysis every 12 hours at 0000 UTC and 1200 UTC.

2.2. Observed Data

Three data sets are used for verification of surface variables. The first data set is the ADP data set, consisting of all the observations contained within the 9-km model

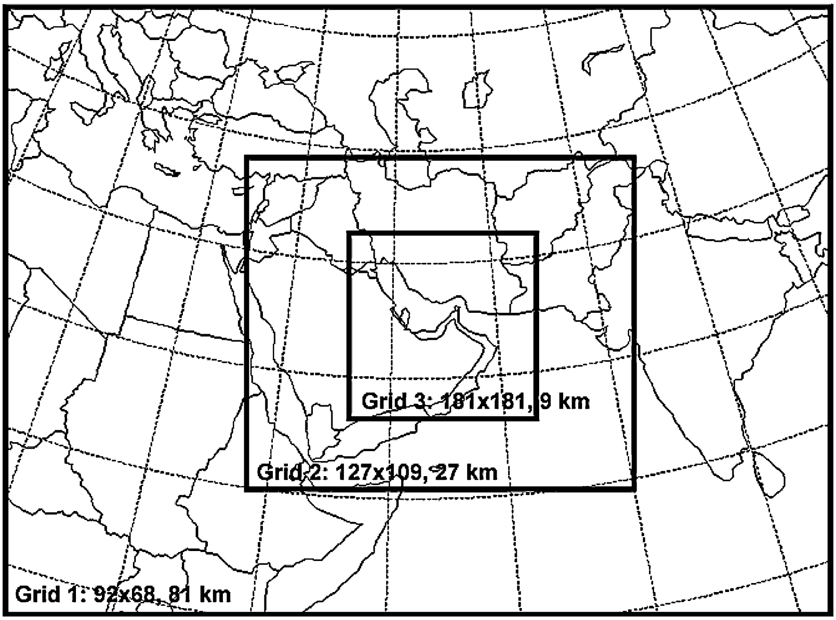

Figure 1
COAMPS® model triple nested domain with grid points and horizontal resolution given for each nest.

grid that were available for model analysis, including surface station, radiosonde, buoy, and satellite data. This data set undergoes a complete data quality process (Baker, 1992) prior to assimilation into the model. The second data set, the UAE data set, is the independent data set not used in the analysis, consisting of the Department of Water Resources Studies (DWRS) surface weather station data. The status of the quality control on the DWRS data is unknown. Thirty-six DWRS stations are located in the interior of the UAE, nine are coastal stations, and seven are on islands. Sixteen stations are excluded for the entire period for one of two reasons: (1) model terrain height for the station was more than 100 m different than the actual terrain height, or (2) the model designated the location of a coastal or island station as water instead of land. Single hours of data at a station are excluded from the calculations of skill scores when any one of the variables was not present; for example, if the wind speed was missing at a particular hour, the other variables at that hour were not included. Locations of the stations used in the model verification are given in Figure 2. The third data set, designated as BOTH, consisted of the combined ADP and UAE data sets. Visibility is not measured at the DWRS stations and therefore model surface visibility is only verified against the ADP data set. The ADP data set is also used for verification of the upper-level variables. Radiosonde soundings from Abu Dhabi, available from the Department of Atmospheric Science at the University of Wyoming from their website (http://weather.uwyo.edu/upperair/

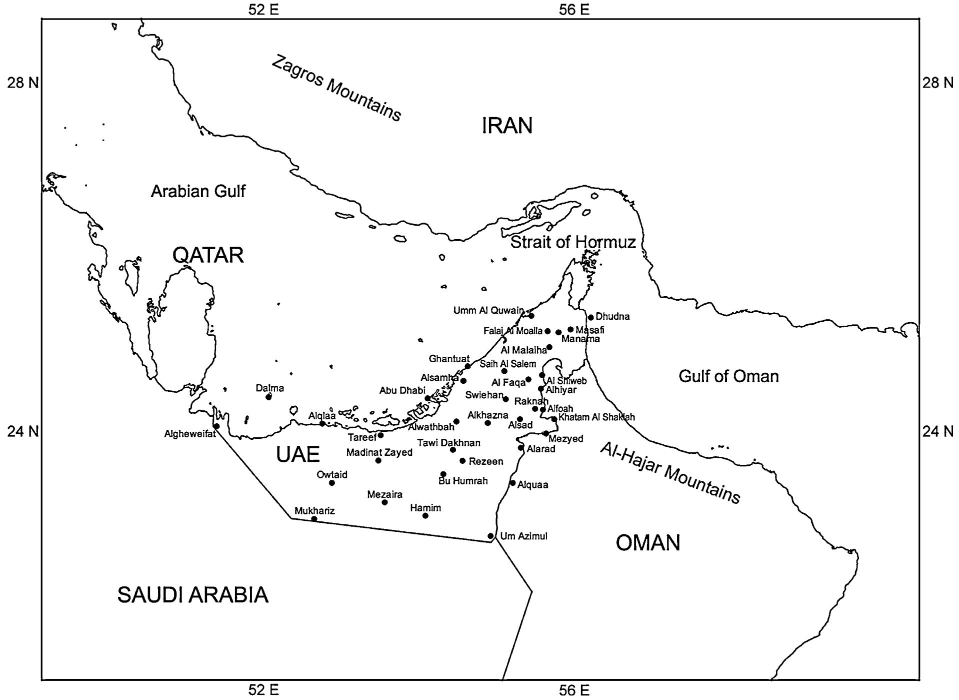

Figure 2

Surface meteorological stations included in the verification of surface parameters. These stations are operated by the UAE Department of Water Resources.

sounding.html) are used in the verification of model boundary layer heights. Radiosonde data are available every 12 hours at 0000 UTC (0400 LT) and 1200 UTC (1600 LT) for 1 August to 5 October, 2004 except for seven soundings.

2.3. Verification Techniques

Verification skill scores of bias error and root-mean-square (RMS) error are estimated for air temperature, dew point temperature, wind speed, wind direction, surface visibility, and geopotential height. COAMPS® model output of dew point depression is converted to dew point temperature. Visibility, in kilometers, is estimated from the COAMPS® output of surface dust concentration (*sfdscc*), with units of mg m^{-3}, using the following relation:

$$\text{visibility (km)} = \frac{0.16}{(sfdscc)^2}. \tag{6.1}$$

This equation is derived from the Koschmeider Equation (Seinfeld, 1986). The bias error measures the model's tendency to underpredict or overpredict a value. The

RMS error measures the magnitude of the model error. The bias error is estimated for any given variable x, as

$$\text{bias}\,(x) = \frac{1}{N}\sum_{n=1}^{N}\left(x_n^f - x_n^o\right), \tag{6.2}$$

and the RMS error using

$$\text{rmse}\,(x) = \left[\frac{1}{N}\sum_{n=1}^{N}\left(x_n^f - x_n^o\right)^2\right]^{1/2}, \tag{6.3}$$

where N is the number of locations, $x_n{}^f$ is the value of the forecast variable and $x_n{}^o$ is the value of the observed variable. Bias and RMS errors are estimated for each model-observation pair and then averaged over all available pairs.

2.4. Verification Procedure

A cold start model simulation was begun on 25 July, 2004 with 48-hour forecasts produced every 12 hours through 1200 UTC 5 October, 2004. Model output was stored every three hours. The statistical evaluation period for the 9-km domain is from 0000 UTC 1 August to 1200 UTC 5 October, 2004. The model performance skill scores for the region are calculated every 6 hours for all surface variables for both the 0000 UTC (0400 LT) and 1200 UTC (1600 LT) model initialization times. Bias and RMS errors are also determined for upper-level variables, and the model predicted boundary-layer height is verified against observations at Abu Dhabi.

2.5. Synoptic Overview

During most of the verification period, the area of interest is dominated by the southwest monsoon, which causes light northwesterly winds of 2 to 4 m s^{-1} over the Arabian Gulf. Mesoscale features, such as the sea and land breeze circulations, are the main influences on the weather during the monsoon. The surface winds near the coast can increase to approximately 10 m s^{-1} due to the sea and land breeze circulations. Observed hodographs from several stations throughout the UAE region are available in EAGER (2005). Occasionally, stronger winds due to synoptic features over the Gulf overwhelm the coastal circulations; however, these periods only last for about one to two days. The summer monsoon ended between 23 and 27 September, 2004, followed by a tropical disturbance that moved westward across the northern Arabian Sea.

The typical diurnal range of air temperature is from about 32° to 40°C at island and coastal locations, and 26° to 40°C at inland sites. The dew point temperature ranges from 20° to 28°C offshore, 18° to 26°C at coastal stations, and 8° to 16°C at inland stations, with more moist conditions at night. The wind speed varies from about 8 to 10 m s^{-1} for all stations (EAGER, 2005).

3. Surface Verification

The model temperature bias and RMS errors for the 0000 UTC (0400 LT) and 1200 UTC (1600 LT) initialization runs are shown in Figures 3a and 3b. For both times, an average of 32 model-observation pairs are used to estimate the bias and RMS errors. COAMPS® generally underpredicts the temperature at each time period with a 0 to 1°C cold bias in the late morning (1000 LT) and afternoon (1600 LT) and a 2.5°C cold bias during the night (2200 LT) and early morning (0400 LT). When verified against the BOTH data set, the nighttime cold bias decreases to values

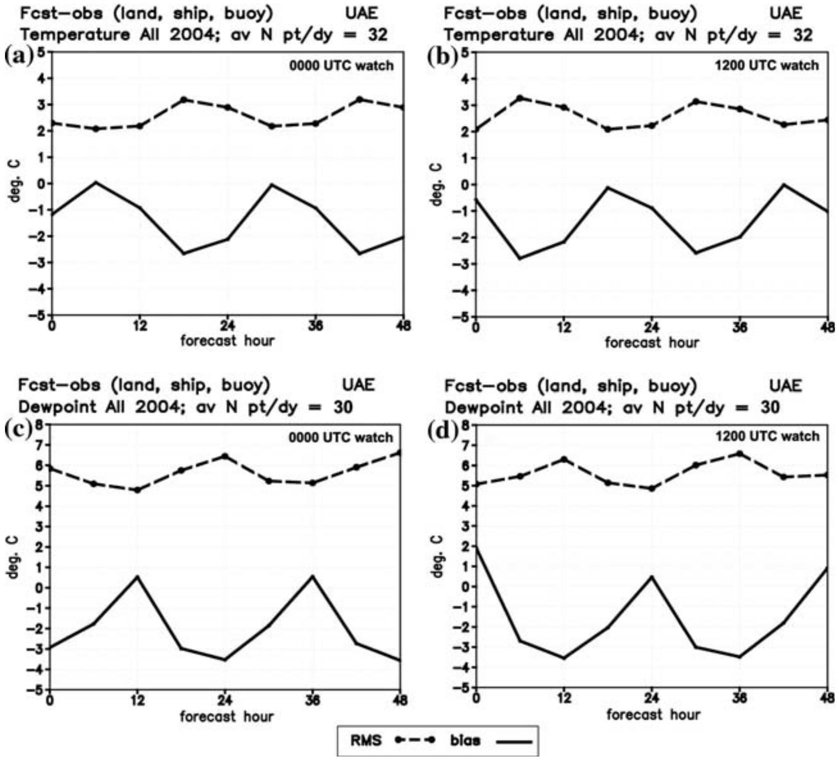

Figure 3
The 2 m air temperature RMS and bias errors at (a) 0000 UTC (0400 LT) and (b) 1200 UTC (1600 LT) initialization times. The 2 m dew point temperature RMS and bias errors at (c) 0000 UTC (0400 LT) and (d) 1200 UTC (1600 LT) initialization times. UAE data set was used for verification. Watch refers to model initialization time.

between 0°C and –2°C. As mentioned, typical daytime maximum temperature is approximately 40°C and minimum around 26°C inland. This translates to about 2.5% in the daytime and 8% during night time for bias errors. The RMS errors show little diurnal variation and vary from about 5% during nights to about 8% during the day. It is interesting to note the reversal in magnitudes of errors between the bias and the RMS errors. These errors are possibly caused by errors in the model prediction of sea breeze and land breeze circulations.

Model dew point temperature bias and RMS errors are shown in Figures 3c and 3d for the 0000 UTC and 1200 UTC (0400 LT and 1600 LT) initialization times. An average of 30 pairs per day are used. COAMPS® has a 2 to 4°C dry bias during the night (2200 LT) and morning hours (0400–1000 LT). The model bias in the afternoon (1600 LT) is very slightly moist. When COAMPS® is verified against BOTH, the model dew point bias improves at all forecast time periods, but still ranges between a 0°C to + 1°C in the afternoon to a bias of about –2°C at night and in the early morning. When compared to typical observed values of dew point temperatures of 18 to 26°C at the coast, the bias errors are of the order of 5 to 10%. The RMS errors are relatively larger (about 20%), possibly due to low moisture conditions of the atmosphere in this location.

The wind speed bias and RMS errors are shown in Figures 4a and 4b for the 0000 UTC and 1200 UTC (0400 LT and 1600 LT) model initialization time. An average of 32 pairs per day is available for verification. For both the 0000 UTC (0400 LT) and 1200 UTC (1600 LT) initialization times, the model winds are 0.5–1 m s^{-1} too fast in the morning hours (0400–1000 LT) and 0.5 m s^{-1} too slow during the afternoon (1600 LT) and night (2200 LT). The model wind speed bias error slightly improves to –0.5 m s^{-1} to 0.5 m s^{-1} when verified against the BOTH data set. The most improvement in the forecasts occurs during the late morning (1000 LT; not shown). RMS errors are about 2 m s^{-1}. Typical observed near-surface wind speeds are of the order of 10 m s^{-1} due to sea and land breeze circulations (EAGER, 2005), indicating an RMS error of 20%. Some of this error can be attributed to observational errors related to averaging time and instrument response and model errors related to horizontal inhomogeneity and prediction of the onset of sea and land breezes.

The model wind direction bias and RMS errors are plotted in Figures 4c and 4d for the 0000 UTC (0400 LT) and 1200 UTC (1600 LT) initialization times. An average of 32 grid points per day was available to estimate the bias and RMS errors. The wind direction errors are estimated accounting for the zero crossing. For both model initialization times there is a 10–20° bias error in the forecasts valid in the night (2200 LT) and morning (0400 LT and 1000 LT). For the afternoon (1600 LT) forecast integration times there are no wind direction bias errors. The wind direction bias improves to 0° to 10° at both initialization times for the forecasts verified against BOTH (not shown). The RMS errors vary from 70° to 80°. and are rather large. It is interesting to note that the bias is small and the RMS error is large. The possible reason for this difference is that the model is not

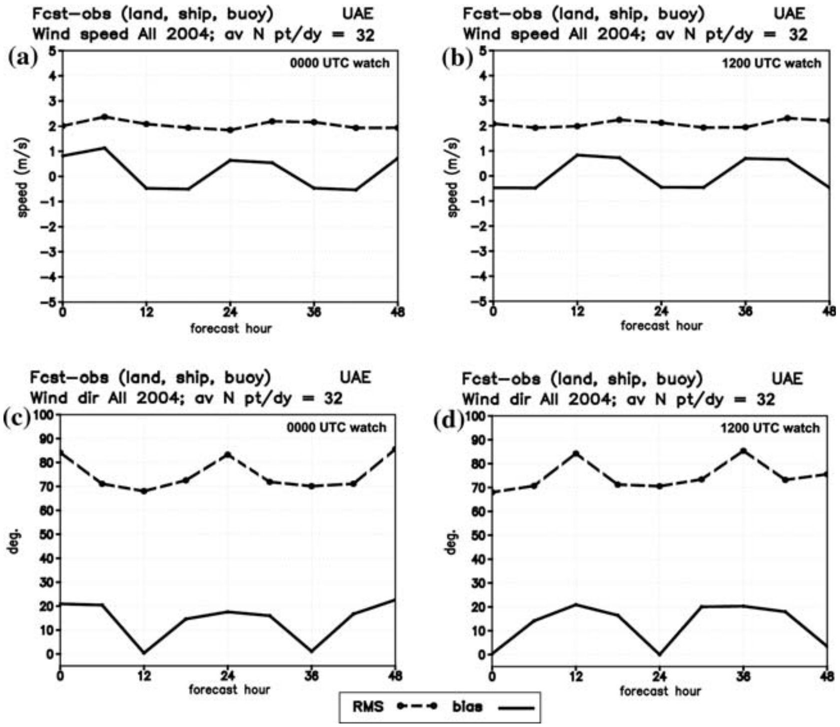

Figure 4
Wind speed RMS and bias errors at (a) 0000 UTC (0400 LT) and (b) 1200 UTC (1600 LT) initialization times. Wind direction RMS and bias error at (c) 0000 UTC (0400 LT) and (d) 1200 UTC (1600 LT) initialization times. UAE data set was used for verification. Watch refers to model initialization time.

able to accurately predict the location of the sea and land breeze fronts with the result that at a given location the model forecast would be southerly (offshore) winds and the observed winds northerly (onshore). This produces an error of 180°. However, while estimating the bias error, the errors cancel out giving a small net value. Predicting the circulation and the sea breeze and land breeze fronts has always been a challenge for the mesoscale models.

Visibility is not measured at the DWRS stations, but was available in the ADP data set. An average of 38 model-observation pairs is available per day. The model visibility bias and RMS errors are shown in Figure 5. The bias at the initialization time improves from 4 km in the 0000 UTC (0400 LT) runs to 3 km in the 1200 UTC (1600 LT) runs. The visibility bias error decreases in the afternoon, and increases during the morning and night. The RMS error is between 6–7 km at all forecast integration times. The large bias error may be due to the inherent problem of model visibility versus observed visibility that arises from the visibility observations typically being less than the model-determined values, particularly for clear sky

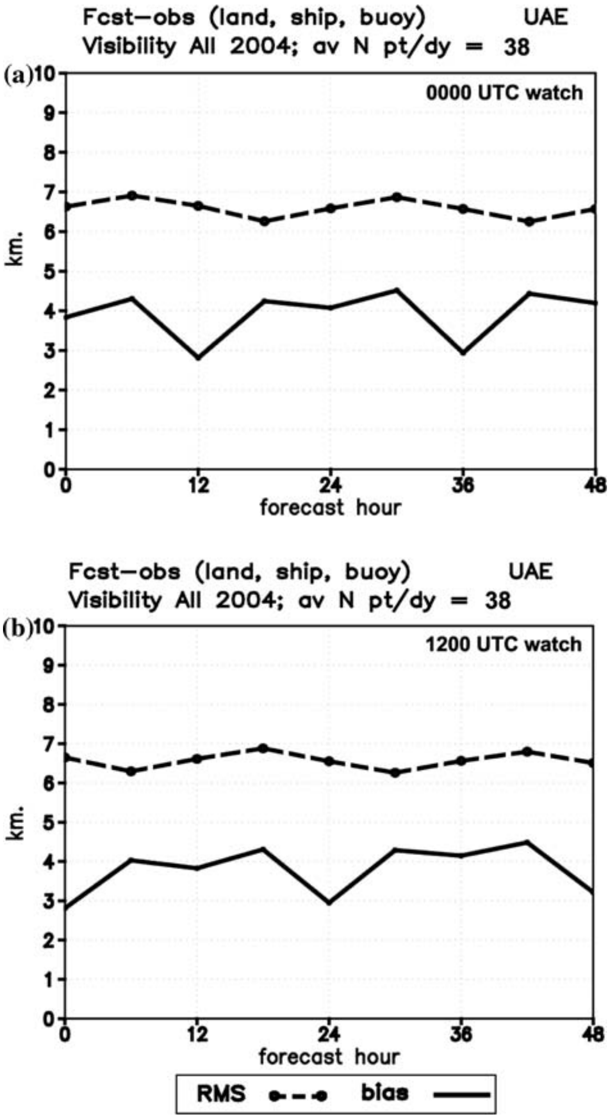

Figure 5
Visibility RMS and bias errors at (a) 0000 UTC (0400 LT) and (b) 1200 UTC (1600 LT) initialization times. ADP data set was used for verification. Watch refers to model initialization time.

conditions. In addition, observations of visibility are typically given qualitatively instead of exact values as determined by the model.

Summaries of the bias and RMS error values calculated using the UAE data set at each forecast valid time are given in Table 1 (0000 UTC simulations) and Table 2 (1200 UTC simulations) for temperature, dew point temperature, wind direction, and

Table 1

Summary of RMS and bias error values for COAMPS® verified against the UAE data set for the 0000 UTC (0400 LT) initialized simulations

	Temperature (°C)		Dewpoint (°C)		Wind Speed (m s^{-1})		Wind Direction (°)	
Tau	RMS	Bias	RMS	Bias	RMS	Bias	RMS	Bias
0	2.2	−1.2	5.7	−3.0	1.9	0.8	82.4	20.8
6	2.0	0	4.7	−1.8	2.3	1.1	67.0	20.0
12	2.1	−0.9	4.6	0.6	2.0	−0.5	66.3	0.4
18	3.1	−2.7	5.6	−3.0	1.9	−0.5	70.6	14.5
24	2.8	−2.2	6.3	−3.7	1.8	0.6	80.8	17.1
30	2.1	0	4.9	−2.0	2.1	0.5	69.5	15.5
36	2.2	−0.9	4.9	0.6	2.1	−0.5	68.1	0.7
42	3.1	−2.7	5.7	−2.8	1.9	−0.5	69.4	16.3
48	2.8	−2.1	6.5	−3.7	1.9	0.7	83.6	22.2

Table 2

Summary of RMS and bias error values for COAMPS® verified against the UAE data set for the 1200 UTC (1600 LT) initialized simulations

	Temperature (°C)		Dewpoint (°C)		Wind Speed (m s^{-1})		Wind Direction (°)	
Tau	RMS	Bias	RMS	Bias	RMS	Bias	RMS	Bias
0	2.0	−0.6	4.9	1.9	2.0	−0.5	66.0	0.4
6	3.2	−2.8	5.3	−2.7	1.9	−0.5	68.5	13.9
12	2.8	−2.2	6.2	−3.6	1.9	0.8	82.5	20.8
18	2.0	−0.1	4.8	−2.1	2.2	0.7	68.0	16.1
24	2.2	−0.9	4.7	0.5	2.1	−0.4	68.5	−0.2
30	3.1	−2.6	5.9	−3.0	1.9	−0.5	71.2	19.8
36	2.8	−2.0	6.5	−3.6	1.9	0.7	83.5	20.0
42	2.2	0	5.2	−1.9	2.2	0.6	70.3	17.5
48	2.3	−1.0	5.3	1.0	2.1	−0.5	72.9	3.4

wind speed. The model bias and RMS errors are smallest at forecast integration times in the afternoon, and largest in the early morning (0400 LT). Air temperature RMS errors are between 2°C and 3.25°C and the bias errors are between −3°C and 0°C. The daytime temperature bias is typically underpredicted by 2.5% and by 7.7% during the night. The RMS error during the day is about 5% of the temperature and about 11.5% during the night. The dew point temperature RMS errors are 4.6°C to 6.5°C and bias errors are −3.7°C to 1.9°C. The dew point temperature is overpredicted by about 1.9% during the day and underpredicted by 16.7% during the night at coastal stations. The RMS error is about 19.2% during the daytime and 33.3% during the nighttime. The wind speed errors are small, with RMS errors of up to 2.5 m s^{-1} and bias errors between -0.5 and 1 m s^{-1}. The wind direction RMS errors are between 65° and 85° with bias errors of 0° to 25°.

RMS and bias error values at individual stations are different than the errors summed over all the stations. On the island station used for verification, the temperature bias was smaller during the night and the dew point temperature bias was positive during all forecast integration times, both contrasting to the errors calculated for all the stations. COAMPS® predicts the dew point temperature better at this offshore location than at stations on the coast or inland. Stations along the coast show similar bias and RMS error tendencies as the errors for all the stations. Inland stations show similar temperature bias errors as for all the stations. The dew point temperature and wind speed bias errors vary between the inland and coastal stations (EAGER, 2005).

4. Comparison of Vertical Profiles

Bias and RMS errors are calculated every 12 hours for the 0000 and 1200 UTC (0400 and 1600 LT) soundings using 11 available observed soundings from the ADP data set. Geopotential height, temperature, dew point temperature, wind direction, and wind speed are verified at pressure levels of 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, and 100 hPa. Model vertical soundings at Abu Dhabi are also verified against observations to determine the ability of the model to predict the boundary-layer height.

4.1. Vertical Verification—All Stations

The model temperature bias and RMS errors in the vertical soundings are shown in Figure 6. The smallest RMS error of 1–2°C occurs at the 700 hPa level while the largest RMS error is at the 100 hPa level (12°C). COAMPS® performs well in the lower layers with only a slight warm bias. Above 850 hPa there is a cold bias that increases with height and forecast integration time.

The model dew point temperature bias in the upper levels is shown in Figure 7. The RMS error is between 5°C and 8°C from 1000 to 700 hPa, and error values increase with forecast integration time. The model dew point temperature has a moist bias at all levels, which increases with height and forecast valid time. Below 700 hPa the bias is 0°C to 4°C too moist, but above this level the dew point bias increases to a maximum of 14°C too moist at the 48-hr forecast. The moist dew point temperature bias and cold air temperature bias means that the model dew point depression is too small and that too much moisture is predicted at all levels. Larger errors in higher altitudes could be due to the problems associated with the model initialization and boundary conditions.

The geopotential height bias error and RMS error are shown in Figure 8. The smallest RMS error (15–30 m) is at 1000 hPa. The largest RMS error is at the 200 hPa level, where it increases from 40 m in the 0-hr forecast to 80 m in the 48-hr

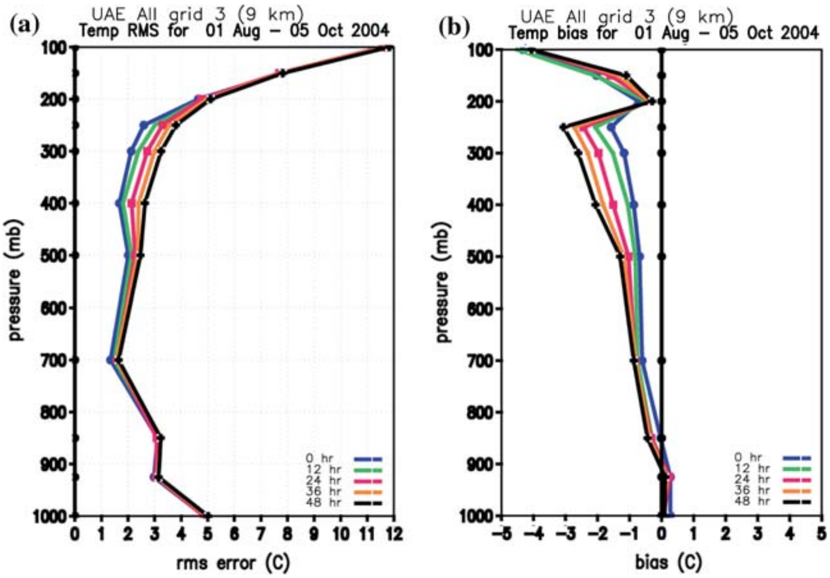

Figure 6
Temperature RMS and bias errors for all vertical soundings available on grid 3.

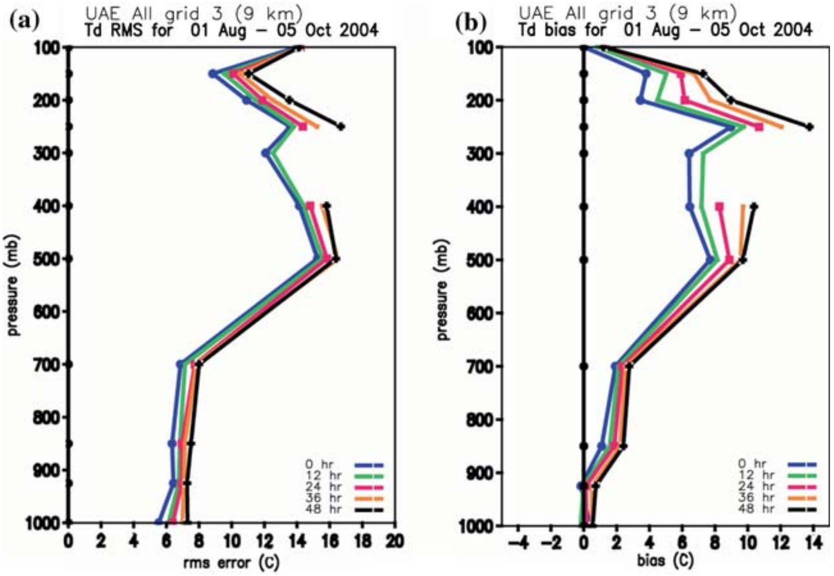

Figure 7
Dew point temperature RMS and bias errors for all vertical soundings available on grid 3.

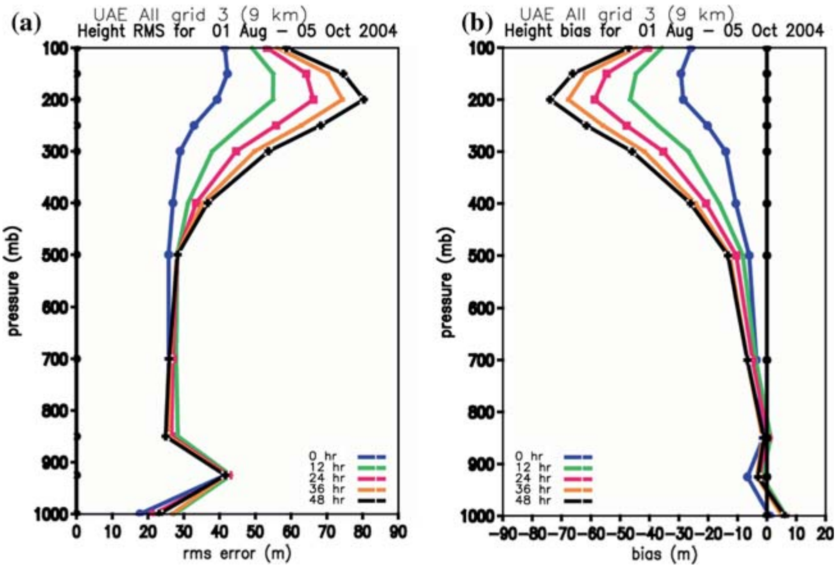

Figure 8
Geopotential height RMS and bias error for all vertical soundings available on grid 3.

forecast. The geopotential height is initialized well with a bias of ± 10 m for all levels up to the 400 hPa level and -10 to -30 m above 400 hPa. The model geopotential height bias increases with each forecast valid time, most notably at 500 hPa and above, where the bias error increases to a maximum of about −75 m.

COAMPS® upper-level wind speed bias error and RMS error are shown in Figure 9. An RMS error of 2 m s^{-1} occurs at 1000 hPa and increases with height to 6 m s^{-1} at 200 hPa. RMS errors increase in each subsequent forecast time. The model wind speed bias indicates an underprediction of 0–1.5 m s^{-1}. From 250–150 hPa, the model overpredicts the wind speed by up to 1 m s^{-1}. Wind speeds are 0–1.5 m s^{-1} too slow from the surface to 250 hPa.

COAMPS® upper-level wind direction bias and RMS error are shown in Figure 10. The RMS errors decrease with height, from an error of 60° at 1000 hPa to an error of 40° at 100 hPa. RMS errors increase in each subsequent forecast integration time. The wind direction bias error is about 0°–10° from 1000 hPa to 200 hPa. Above 200 hPa, the wind direction bias error is −5° to −15°.

4.2. Vertical Verification – Boundary-Layer Height

The model derived boundary-layer height is compared with observed soundings at Abu Dhabi, a coastal site. The observed boundary-layer height is determined by the location of the base of the elevated inversion using the virtual potential temperature. The boundary-layer depth is derived in COAMPS® based on the

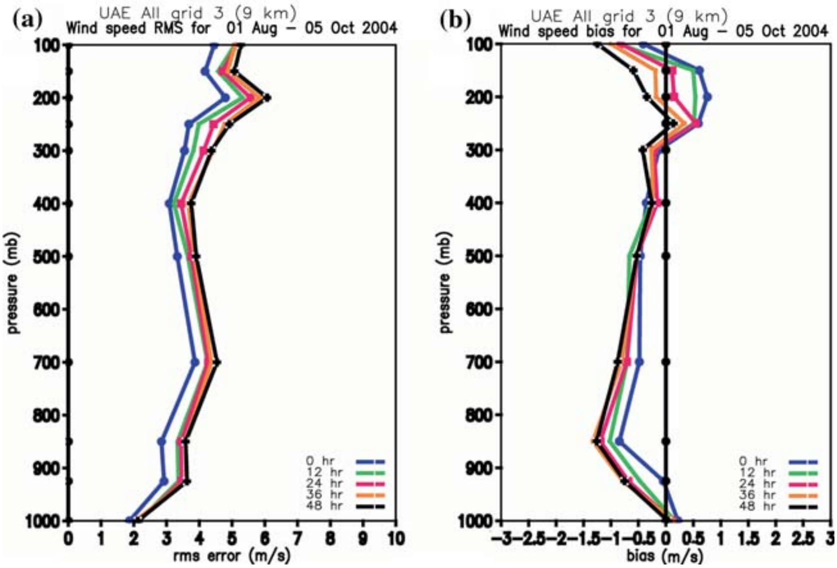

Figure 9
Wind speed RMS and bias error for all vertical soundings available on grid 3.

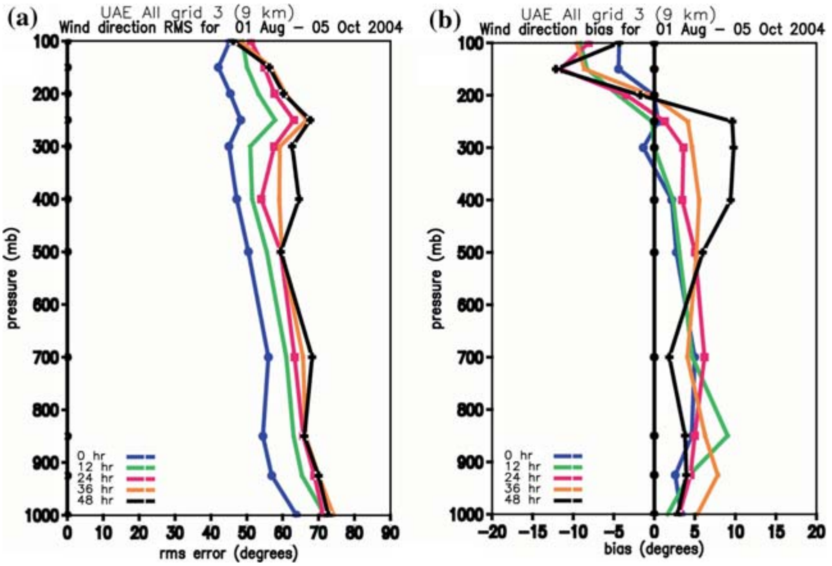

Figure 10
Wind direction RMS and bias error for all vertical soundings available on grid 3.

Richardson number (*Ri*), and is defined as the lowest level at which *Ri* exceeds a value of 0.5 (CHEN *et al.*, 2003). The model-determined boundary-layer height is compared with the boundary-layer height as determined from the model potential temperature profile. This also shows how the potential temperature inversion that signifies the top of the boundary layer was resolved in the model. The dates of 3 and 24 August and 15 September were chosen to illustrate the differences in the two methods of estimating the boundary-layer height.

On both 3 and 24 August, 2004, the boundary layer height was better predicted by the model potential temperature profile as compared to the *Ri* method. The observed boundary layer height on 3 August, 2004 at 1200 UTC (1600 LT) was 676 m. The boundary-layer height as determined by the *Ri* method was 2240 m, while the height estimated from the model potential temperature was 676 m. The observed boundary-layer height on 24 August, 2004 at 1200 UTC (1600 LT) is 1510 m. The model boundary layer height determined by the *Ri* method was 2257 m, but when estimated from the model potential temperature profile, the boundary layer height is 1489 m, a value similar to the observed boundary layer height as shown in Figure 11.

Better agreement between the observed boundary-layer height and the model-determined height using the *Ri* method is found on a few days. For example, on 15 September, 2004, the observed boundary-layer height at Abu Dhabi was 540 m at 1200 UTC (1600 LT). The model boundary-layer height determined by the *Ri* method was 520 m, while the value estimated from the model potential temperature profile was 731 m.

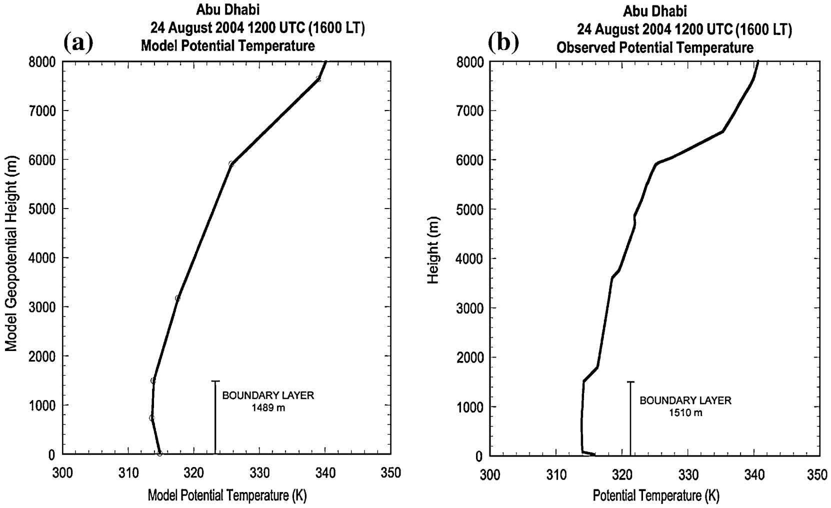

Figure 11
(a) Modeled and (b) observed potential temperature soundings for 1200 UTC (1600 LT) 24 August, 2004. Model sounding is from the initialization time.

The coarse vertical resolution of the model is a problem at higher altitudes (above 1 km) which makes comparisons of the *Ri* method and the potential temperature method difficult; however, the *Ri* method also poses problems at altitudes below 1 km, where there is higher vertical resolution. Some of the overprediction by COAMPS® of the boundary-layer height may be due to the location of the site of the radiosonde station. Abu Dhabi is located on the coast, and therefore slight differences between the modeled and observed wind direction would cause the air mass over Abu Dhabi to be very different: dry continental air due to southerly winds or maritime air due to northerly winds. This in turn may lead to errors in the boundary layer height due to the different stabilities in the modeled and observed boundary-layer air mass.

5. Summary and Conclusions

A statistical evaluation of COAMPS® using the verification skill scores of bias and RMS error was performed for the 1 August to 5 October, 2004 time period. This time period included the days of the UAE^2 experiment. Model output fields of 2 m air temperature, 2 m dew point temperature, 10 m wind speed, and 10 m wind direction were verified against three data sets. Surface visibility was verified against the ADP dataset only because no measurements were available in the UAE data set. RMS and bias errors were calculated for modeled upper-level variables of temperature, dew point temperature, geopotential height, wind speed, and wind direction. The predicted height of the boundary layer was verified against soundings at Abu Dhabi.

The initial analysis and model forecast errors are well within the bounds of mesoscale models, and are similar to the RMS and bias errors shown in SHI *et al.* (2004) and WHITE *et al.* (1999) for the winter season. In the verification of the vertical profiles, bias and RMS errors do not grow significantly with time as compared to the values at the initial time (0-hour forecast). The study location is in a region of weak synoptic forcing during the summer. Forecast errors grow slowly with time because of the mesoscale features rather than the synoptic features. The mesoscale features in the Arabian Gulf region are driven by diurnal variations. This may lead to the forecasts valid at similar times of day exhibiting similar forecast errors. This makes it ideal for model validation.

For bias and RMS errors averaged over the region, model 2 m air temperatures are cooler at all forecast integration times except in the late morning when there is no bias. Model 2 m dew point temperatures are too dry in the morning, and too moist in the afternoon and night. The observed wind speeds are underpredicted during the afternoon and night and overpredicted during the morning. Differences in bias errors over land and over water will cause differences in the model temperature gradient, which in turn could produce differences in wind speed. At night the air temperatures are too cool, and the modeled temperature gradient between land and water is too small. This results in a smaller modeled pressure gradient and weaker winds. Later during the night, the model temperature over land has continued to cool and is now much cooler than the sea-surface temperature, resulting in a large temperature difference between land and water. This in turn causes the larger wind speed bias. In the late morning there is no temperature bias, so there should also be minimal bias in the modeled horizontal temperature gradient between land and water. In the afternoon there is a cold temperature bias, resulting in a small temperature difference between land and water. This causes a smaller modeled pressure gradient and lighter modeled wind speeds, as shown in the negative wind speed bias.

The wind direction bias is 10–20° at most forecast times, with little bias in the afternoon. Individual stations show a wind direction bias of 35–70°, which could be due to incorrect predictions of the timing and development of the sea and land breeze circulations. The 3–4 km surface visibility bias indicates that COAMPS® is not predicting as much aerosol loading in the near-surface layer as that which is actually there. This may be due to the lighter simulated wind speeds in the afternoon not causing enough aerosols to be lifted or remain suspended. This error may have important practical implications for real-time forecasting in desert regions. The model boundary-layer height error at Abu Dhabi may be due to the method used to calculate the boundary-layer height, and errors may decrease by estimating the boundary-layer height from the modeled potential temperature. In summary, in spite of the biases and errors discussed here, the model does well in predicting the diurnal variations over water and over land, such as the development of the sea and land breezes and the thermal internal boundary layers. Large RMS errors in wind direction indicate that the model is not able to predict the time and location of the sea and land breeze fronts. This is a problem with the present mesoscale models and needs to be addressed through improved surface and land use parameterizations.

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