High-Resolution GEM-LAM Application in Marine Fog Prediction: Evaluation and Diagnosis

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ABSTRACT

A three-level nested rendering of a high-resolution limited-area model version of the Global Environment Multiscale configuration (GEM-LAM), running quasi-operationally at the Canadian Meteorological Centre, is evaluated for its capabilities in marine fog prediction. The model shows a general underestimation of the cloud water content at lower levels that is utilized as one of the proxies for fog and/or low stratus. A warm and dry tendency also appears at the lowest layer (a few hundreds of meters above the surface) of the vertical profiles and at screen level.

The condensation scheme directly generates/dissipates the cloud water content (or fog) while boundary layer processes [such as moist turbulent kinetic energy (MoisTKE)] vertically redistribute it. However, the results presented here emphasize the significance of the accurate initial and vertical velocity fields, as well as the interactions between the condensation scheme and the radiation scheme that interacts fully with clouds. These conclusions suggest that a delicate balance among the different physical processes and dynamics is needed for a successful fog forecast.

1. Introduction

Fog is defined as a suspension of tiny water droplets (or ice crystals) in the atmosphere near the earth’s surface, lowering the visibility to less than 1 km; it is referred to as mist if the visibility is between 1 and 5 km (WMO 1992). The base of the layer resting on the ground distinguishes fog from cloud. Fog near the surface typically contains a liquid water content of from 0.005 to 0.35 g m⁻³ (Gultepe et al. 2009). It forms by cooling the air to its dewpoint, by moistening until saturation, or by combining the two processes. Advection marine fog typically occurs when regions with cold sea surface temperatures (SSTs) are adjacent to a warm current (Lewis et al. 2004). When the weather pattern is favorable, warm moist air is brought in contact with the cold surface and condensation occurs. Marine fog off the east coast of Canada has its highest frequency during the months of June, July, and August (e.g., in Shearwater, Nova Scotia, Canada) (Gultepe et al. 2009). This type of fog accounts for most of the fog observations at stations in Atlantic Canada (Bowyer 1995), due to cold coastal SSTs resulting from local upwelling, tides, and the vicinity of the cold Labrador current, together with the proximity of the warm Gulf Stream farther to the south. Fog is a hindrance to mariners, military operations, aviation,
and transportation activities, emphasizing the importance of accurate fog predictions.

Regardless of the notable improvement of numerical weather prediction models, numerical prediction of marine fog remains a challenging task that could be attributable to a few factors. First, observations demonstrate that fog formation and evolution involve complicated processes occurring in the boundary layer such as microphysics, turbulent exchange, radiation, and surface processes (e.g., Dyunkerke 1991; Guedalia and Bergot 1994) that need to be appropriately represented in a numerical model. A high vertical resolution grid close to the surface is also desirable (Tardif 2007) but is computationally expensive, in particular for a 3D model having a fine horizontal resolution. Lack of a valid parameterization of turbulence under stable conditions that would lead to the heavily biased temperature is another concern for an operational model running at high vertical resolution. Second, hazardous thick marine fog (fog bank) can cover an area over land and/or ocean with a thickness extending upward to 400 m (Leipper 1994). The meteorological observation network, however, provides sparse data for model verification with most automatic stations not capable of reporting fog. Even sparser are the vertical temperature and moisture profiles measured by radiosondes. Third, the occurrence of marine fog depends to a great extent on the advection of warm moist air coming from the south, which is also a favorable synoptic condition for higher-level cloud formation and, frequently, precipitation. The resultant limited number of “pure” cases (i.e., fog uncontaminated by high-level clouds) therefore often restricts the usage of satellite images in fog observation. Ground-truthed satellite images based on vertical profiles are even rarer although microwave-sounding-based retrieval of atmospheric temperature profiles (Shi 2001) shows promise in the near future.

Application of numerical models in fog studies started with one-dimensional boundary layer models (e.g., Fisher and Caplan 1963; Zdunkowski and Nielsen 1969; Zdunkowski and Barr 1972; Brown and Roach 1976). In spite of ignoring both orography and horizontal heterogeneity, this group of models has become a useful tool in examining the relative importance of the processes that affect fog formation and evolution, as well as in predicting fog, especially with its low computational cost to implement a dense vertical grid close to the surface. For example, Musson-Genon (1987) stressed the significance of turbulence in fog formation and evolution. Bott et al. (1990) investigated the interaction between radiative transfer and fog microphysics. Bergot and Guedalia (1994) emphasized the importance of precise knowledge of initial humidity profiles as well as the sensitivity of fog formation to the low and midlevel clouds through radiation balance. Bergot et al. (2005) further emphasized the importance of initial conditions and hence an accurate local assimilation scheme. Using a one-column version of the model developed at the European Centre for Medium-Range Weather Forecasts (ECMWF) with a prognostic cloud scheme, Teixeira (1999) simulated a case of radiation fog and suggested that a successful forecast of fog needed a delicate balance among all of the different physical processes such as turbulent mixing, radiation, clouds, condensation, and interaction with the surface. In addition, some 3D mesoscale numerical weather prediction models have also been employed for fog case studies (e.g., Ballard et al. 1991; Golding 1993; Pagowski et al. 2004; Fu et al. 2006). A detailed summary of the fog forecasting models can be found in Gultepe et al. (2007). These modeling applications, however, aim at fog physics, focus less on marine fog, and do not directly evaluate and diagnose an operational forecast model.

The operational short-range regional forecast system at the Canadian Meteorological Centre (CMC) is presently based upon the Global Environment Multiscale (GEM) model that has a variable-resolution capability. It is therefore possible to use either a uniform-resolution latitude and longitude mesh or a variable-resolution grid that uses a rotated-coordinate system with a high-resolution subdomain that can be located over any portion of the globe. The current operational short-range forecast product (model) has a global variable resolution with a 15-km uniform core over North America (hereafter regGEM), implemented at CMC since 18 May 2004 (Mailhot et al. 2006). De la Fuente et al. (2007) evaluated the suitability of the regGEM forecast fields for inferring advective marine fog occurrence. The authors concluded that the forecasts show a general underestimation of fog likely owing to the poorly resolved objectively analyzed moisture fields that were used as initial and boundary conditions, as well as the model’s condensation scheme.

As a component of the Lunenburg Bay Multidisciplinary Modeling System (Yang et al. 2006), a limited-area version of the GEM model with a high resolution of 2.5 km (hereafter LAM2.5) was configured and implemented for a demonstration project in June 2007, running quasi-operationally on a daily basis at CMC, and undergoing evaluation by the Meteorological Service of Canada (MSC) Atlantic Storm Prediction Centre (ASPC). The model configuration is designed for routine forecasting and is not specifically intended for fog forecasts, as described in the following section. As such, it is important to specifically assess the model’s capabilities in forecasting marine fog, including its physical processes and some dynamical aspects, to accommodate...
the needs for operational fog forecasting. This assessment constitutes the first step toward enhanced diagnosis and improved lower boundary processes representing more realistic fog formation.

This paper is organized into five sections. This introduction is followed by our methodology in section 2, which includes model configuration, as well as data and verification criteria. The observation summaries, the LAM2.5 performance, and the impacts of driving fields for three marine fog cases are described, respectively, in the subsections of section 3. A diagnosis of LAM2.5 dryness, including a comparison with observations from the Fog Remote Sensing and Modeling (FRAM) project that performed its second stage of fog measurements at Lunenburg Bay in Nova Scotia during the summer of 2006 (Gultepe et al. 2009), is presented in section 4, followed by conclusions and a discussion in section 5.

2. Methodology

a. Model configuration

LAM2.5 is a nonhydrostatic model with 58 variable vertical sigma pressure hybrid levels up to 10 hPa concentrated in the boundary layer (10 below 850 hPa; see Table 1). The time step of integration is 60 s. A surface modeling system based upon a mosaic approach is applied containing four types of surfaces: vegetated land with the Interactions between Soil, Biosphere, and Atmosphere (ISBA) scheme; open water; sea ice with a thermodynamic ice model; and glacier and ice sheets (Mailhot et al. 2006). The geophysical fields used are generated from global high-resolution databases such as the 1-km-resolution U.S. Geological Survey vegetation data (Belair et al. 2003). The topographic field generated on the model domain (Fig. 1) is filtered using a 2 delta-x filter.

The condensation package contains three different schemes. The grid-scale condensation is represented by fully explicit microphysics (Kong and Yau 1997), which includes the most important microphysical processes for each hydrometeor type including mixing ratios of water vapor ($q_v$), cloud water ($q_c$), rainwater ($q_r$), ice and snow ($q_s$), and graupel or snowflakes ($q_g$), but without explicit calculation of the number concentration of the particles. Nevertheless, it is worthwhile to point out that the droplet number concentration, along with the $q_c$, is a crucial variable for visibility forecasts (Gultepe et al. 2006). This scheme is coupled with a shallow convective scheme, Kuo-Transient, dealing with subgrid-scale overshooting cumulus cloud activity (Belair et al. 2005). The turbulent fluxes of momentum, heat, and moisture are based on a predictive equation for “moist” turbulent kinetic energy (hereafter MoisTKE) in the sense that the vertical diffusion is performed on the conservative thermodynamic variables such as ice–liquid potential temperature and total water content. The MoisTKE scheme hence functions to generate low-level clouds including mixed-phase clouds (Mailhot et al. 2006). In the model code, MoisTKE is implemented only down to the second lowest prognostic model level ($\sigma = 0.985$) on the basis of the parameterization by Bechtold et al. (1995) and Bechtold and Siebesma (1998) that was tested over a wide range of boundary layer cloud conditions (J. Mailhot 2007, personal communication). The scheme is hence not designed specifically to represent foggy conditions. Therefore, a slightly modified MoisTKE scheme was also investigated as briefly discussed in section 5. Note that as theoretically deep convection is implicitly resolved by a resolution finer than 3 km (Jacobson 2005), no deep convection scheme applies. The solar and infrared radiation scheme (Fouquart and Bonnel 1980; Garand 1983) that is fully interactive with the total cloud (Yu et al. 1997) acts on the model hourly. Nevertheless, an experiment with an application of the radiation scheme every 5 min is also briefly documented in section 4.

In routine meteorological observations, fog occurrence is inferred from the visibility and at manned sites explicitly stated in the present weather. Visibility is not currently output by the model when using Kong–Yau microphysics (Kong and Yau 1997). The cloud water mixing ratio $q_c$ that is generated by Kong–Yau microphysics (Kong and Yau 1997) is therefore used as one of the fog proxies. The $q_c$ field is also subject to a vertical redistribution by means of vertical diffusion with the implementation of the MoisTKE scheme. Another proxy for fog is dewpoint depression (ES), defined as the difference between the air temperatures and the dewpoint temperatures that are reported by meteorological stations and used by forecasters on a daily basis. This variable is especially relevant at the first model level or near-surface level ($\sigma = 1.000$) where the variables representing the wind at the anemometer level of 10 m and the temperature and humidity at the Stevenson screen

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**Table 1. Approximate heights of the 10 lowest levels of the model.**

<table>
<thead>
<tr>
<th>$\sigma$ level</th>
<th>1.000</th>
<th>0.9950</th>
<th>0.9850</th>
<th>0.9733</th>
<th>0.9606</th>
<th>0.9467</th>
<th>0.9316</th>
<th>0.9151</th>
<th>0.8973</th>
<th>0.8780</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>2</td>
<td>45</td>
<td>145</td>
<td>260</td>
<td>385</td>
<td>530</td>
<td>685</td>
<td>855</td>
<td>1045</td>
<td>1245</td>
</tr>
</tbody>
</table>
level of 1.5 m are calculated diagnostically in accord with variables at the surface and \( \sigma = 0.995 \), and stability functions of the surface layer following the Monin–Obukhov similarity theory, and where condensation is not taken into account.

Due to a spinup period of 8 h in LAM2.5 identified for some winter Arctic air masses in the absence of strong local forcing, CMC implemented a three-level nested scheme to shorten the spinup length (A. Erfani 2007, personal communication). The distinct feature of the nested scheme is the usage of an intermediate limited-area model with a horizontal resolution of 15 km (hereafter LAM15) that exploits the Kong–Yau explicit microphysics scheme as LAM2.5 does, rather than the Sundqvist condensation scheme (Sundqvist 1978, 1981) routinely used by the model with the same resolution (15 km) and the regGEM. Hence, in this nested scheme the regGEM drives LAM15 and then LAM15 drives LAM2.5. During this process, \( q_c \) is treated as a tracer output from regGEM and used as the initial and boundary conditions for LAM15. LAM15 is then capable of outputting the hydrometeor variables \( (q_c, q_r, q_i, \text{ and } q_g) \), which are used as the initial and boundary conditions for LAM2.5. The major differences in the dynamics and physics of the three models are listed in Table 2. Given that fog usually lifts after the sun rises and we focus on the summer period, the commencing times for running regGEM, LAM15, and LAM2.5 are at 0000, 0300, and 0600 UTC, respectively, which are slightly different from those used at CMC. Readers are referred to CMC (2007) for the detailed rationale of the nested scheme. With this scheme, the spinup is only noticeable at the first hour in this study.

b. Data and verification criteria

Within the model domain (Fig. 1), seven meteorological stations with frequent fog occurrences are categorized, for illustration purposes, into three geographical areas. The Bay of Fundy area includes Grand Manan (XGM) and St. John (YSJ) in New Brunswick and Yarmouth (YQI) in Nova Scotia. The southern Nova Scotia area contains Lunenburg Bay (XLB), Shearwater (YAW), and Halifax International Airport (YHZ) in Nova Scotia. Sable Island (WSA) is a station representative of

![Fig. 1. Model domain with topography denoted by gray scales and weather stations indicated by letters. Letters M are manned surface stations, A are automatic surface stations, and U are manned (or automatic for WSA) and upper-air stations.](image)

| Table 2. Differences in the dynamics and physics in regGEM, LAM15, LAM2.5, and LAM2.5M. |
|---------------------------------|----------------|------------|--------------|----------------|
| Horizontal grids               | RegGEM         | LAM15      | LAM2.5       | LAM2.5M        |
| Horizontal resolution (km)     | 432 × 565      | 140 × 130  | 340 × 205    | 340 × 205     |
| Time steps (min)               | 7.5            | 7.5        | 1            | 1              |
| Horizontal diffusion           | \( \nabla^6 \)  | \( \nabla^6 \) | \( \nabla^8 \) | \( \nabla^8 \) |
| Condensation schemes           | Sundqvist      | Kong–Yau   | Kong–Yau     | Kong–Yau      |
| Deep convection                | Kain–Fritsch   | Kain–Fritsch | None        | None          |
| Radiation interval (min)       | 37.5           | 37.5       | 60           | 60            |
| Boundary layer schemes         | MoisTKE        | MoisTKE    | MoisTKE      | Modified MoisTKE |
conditions over the shelf ocean area. These stations report hourly temperature $T$, dewpoint temperature ($T_d$), visibility (VIS), and, for manned stations, fog in the present weather. The automatic stations (e.g., XLB, XGM, and WSA) do not report present weather, and hence fog is inferred from visibility. Visibility and liquid water content (LWC) observations in Lunenburg Bay, a few hundred meters away from the station XLB, were obtained through the FRAM project implemented from 2 June to 6 July during 2006, while XGM and WSA do have visibility reports. The FRAM project also provided the incoming shortwave broadband radiative flux, as well as wind components at 32 Hz, that were used for diagnostic purpose, as shown in section 4. Note that despite the fog definition given in section 1, fog is sometimes reported from meteorological observations even if the visibility is well above 1 km. We therefore also take this kind of fog into account. YQI and WSA are the only two stations within the model domain providing twice-daily radiosonde profiles at 0000 and 1200 UTC. In addition, High Resolution Picture Transmission (HRPT) images from the National Oceanic and Atmospheric Administration’s (NOAA) polar-orbiting satellites were used to identify the likely occurrence and spatial extent of marine fog and low stratus using the 0.6-μm visible channel and applying standard satellite image interpretive techniques. Potential fog cases were further checked using infrared images (e.g., 10.8 μm) to exclude those cases where high clouds were present, indicating the likelihood of additional fog formation processes. The archived weather maps from Environment Canada provided the synoptic background.

At model ($\sigma$) levels, $q_c$ were output to determine the spatial distribution of fog and low stratus formation and were compared with satellite images. Because of the difficulty in distinguishing fog from low stratus in satellite images, they are not separately discussed. The hourly time series of $T$, $T_d$, and ES at the Stevenson screen level (1.5–2 m) from the observations were utilized to verify the temperature and moisture at the lowest model level ($\sigma = 1.000$). The closest grid points to the seven stations were extracted hourly from LAM2.5 output. The coordinates for the stations and model grid points are listed in Table 3. Note that with the exception of XGM and XLB, LAM2.5 has lower elevations compared to actual station heights. The elevations in LAM15 are even lower than in LAM2.5, with XGM and WSA located over water. Due to the usage of the nested scheme, the 24-h time series, corresponding to forecast hours 0–24 in LAM2.5 and 3–27 in LAM15, range from 0600 UTC of the current day to 0600 UTC of the next day. The variables $T$ and $T_d$ at all pressure levels from the surface to 700 mb corresponding to radiosonde levels were output for level-to-level comparison. The geopotential height fields at the lowest pressure levels were checked to ensure the lowest pressure levels did not cross (below) the surface. The location of the upper-air observation site at YQI is slightly different from the surface station that is also reflected in locating the model grid point (see Table 3). Since the radiosonde profiles have vertical coordinates in both heights (above sea level) and pressure levels, the comparison between the model and the observations is eventually plotted in terms of height rather than pressure coordinates for convenient visualization.

Mean bias (MB) is used for quantitative evaluation and is defined as

$$\text{MB} = \frac{1}{n} \sum_{i=1}^{n} (X_{mi} - X_{oi}),$$

(1)

where $X_m$ is the model output and $X_o$ the observation; $n$ is total sample number, representative of a station/vertical level number in this study. It is necessary to point out that although the samples from our limited fog cases may not be sufficient to make the scores statistically significant, it is a way to quantify the model’s performance.

Based on synoptic weather patterns, visibility and fog reports, and available satellite images, three marine fog cases were chosen. The first case fell within the period of
the FRAM field study (Gultepe et al. 2009). The selection of the other two cases is based on de la Fuente et al. (2007).

3. Results


1) Observation Summary

During 26–29 June 2006, a stationary high pressure system dominated Atlantic Canada with its center located southeast of Newfoundland. Atlantic Canada was provided with a warm moist airflow from the south, along with local cold SSTs, preconditioning the environment for fog formation.

We chose 27 June 2006 for a detailed study because the HRPT visible image at 1555 UTC (Fig. 2a) indicated likely dense fog and/or low stratus in the Bay of Fundy, as well as relatively thickening fog toward the southern and eastern shores of Nova Scotia. At this time, fog had retreated from most of the inland areas around the south coast of Nova Scotia.

The time series of VIS (Fig. 3), combined with fog reports, indicate that fog formed basically within two periods. In the Bay of Fundy area, fog persisted from 0600 to 1000 and from 2200 to 0600 UTC at XGM, all day at YSJ, and for almost the whole day (except 1900–2000 UTC) at YQI. Fog lasted for relatively short periods in the southern Nova Scotia area: during 0600–1100 and 0300–0600 UTC of the next day at YHZ and during 0600–1200 and 0000–0600 UTC of the next day at YAW (note some data were missing during the early mornings). In Lunenburg Bay (indicated by the station code XLB for convenience), based upon FRAM visibility (every minute) observations, fog occurrence almost covered entirely the periods from 0600 to 1300 and from 2200 to 0600 UTC. At WSA, except for 1700–1900 UTC, fog continued for the whole period.

The vertical profile at YQI reveals a moist layer extending from the surface to 220 m at 0000 UTC 27 June (not shown). By 1200 UTC the layer was 170 m thick with less moisture around 50 m (Fig. 4a), indicating thinning fog and less reduced visibility. At 0000 UTC 28 June, the layer thickened to 240 m (Fig. 4b). An inversion, situated 100–200 m above the surface, lifted a bit during the day. This inversion acted as a cap that limited vertical mixing and is favorable for moisture accumulation in low levels and creates an environment suitable for fog formation. Along with the time series (Fig. 3), the vertical profile indicates the fog layer gradually lifting and dissipating toward the daily temperature peak (1600–2200 UTC) followed by a subsequent thickening. This is confirmed by the fog report for almost the entire day, except when mostly cloudy and mainly clear at 1900 and 2000 UTC, respectively, at YQI, despite the fact of visibility exceeding 1 km during 1600–2200 UTC. At WSA, a saturated layer with a strong inversion extended from the surface to a height of 150–250 m at all three available time frames (Figs. 4c and 4d), also consistent with its time series (Fig. 3).

2) LAM2.5 Performance

The liquid water path (LWP), the integrated $q_c$ over the lowest five prognostic model levels ($\sigma = 0.995, 0.985, 0.9733, 0.9606$, and 0.9467, respectively), corresponds to geopotential heights up to roughly 500 m (see Table 1) and covers the vertical extent of the densest fog bank (Leipper 1994). LWP at 1600 UTC (Fig. 2b) illustrates a limited presentation of fog and/or low stratus formation along the coast of New Brunswick, as well as over the waters along the south coast of Nova Scotia. A comparison with the satellite image (Fig. 2a) suggests an underestimation of fog and/or low stratus extent around the Bay of Fundy, south of Cape Breton, and southwest Nova Scotia (Fig. 2b).

The time series of MBs of $T$, Td, and ES at screen level based on the seven stations (Fig. 5) reveal a warm (up to 2.7°C in $T$) and dry (up to 2.4°C in ES) tendency, with two MB peaks appearing in the morning and late afternoon, and minimum MBs during night and early morning. The time series of the ES MB closely following that of the $T$ MB implies that the latter dominates the former. The most evident departure of ES from the observations occurs in the Bay of Fundy area that is dominated by an increasingly positive daily temperature bias commencing with sunrise (not shown). Based upon the observations, this was the area having the densest fog and/or low stratus but is severely underestimated in the model.

The vertical profiles at 1200 UTC 27 June and 0000 UTC 28 June at YQI and WSA (Fig. 4) reveal a warm and dry bias at the lowest layer extending from the surface to 140–240 m, and the dryness is dominated by the positive $T$ bias. Overlaid is a relatively cold and wet layer extending upward to a range of 900–1700 m. As a result, the inversions existing in the observations significantly weaken or disappear in the model. This type of profile is favorable for vertical mixing and hence the dissipation of fog. Farther aloft (not shown), beyond the boundary layer, the temperature profiles seem consistent with the observations. The MBs calculated using all the pressure levels from the surface to 700 mb indicate, overall, small $T$ MBs and large Td MBs that accounts mostly for the ES MBs, in contrast to the lowest layer.

3) Impacts of Driving Fields from LAM15

Taking advantage of the same condensation scheme and hence the same partition of hydrometeors as in
FIG. 2. (a) HRPT visible image at 1555 UTC. (b),(c) LWP (10^{-2} \text{ kg m}^{-2}) from the lowest five prognostic model levels for LAM2.5 and LAM15 at 1600 UTC 27 Jun 2006.
LAM2.5, the results from LAM15 are analyzed in comparison with those from LAM2.5 for the purposes of diagnosing the impacts of LAM15 as driving fields on LAM2.5, as well as being used as a reference for the diagnosis in section 4. Note however that this comparison, strictly speaking, is not representative of an impact from a horizontal resolution difference that would keep all other model parameters unchanged and would not be feasible in reality. For example, a higher-order, more scale-selective diffusion operator is needed to deal with the horizontal diffusion term in a high-resolution model (see Table 2).

The LWP at 1600 UTC in LAM15 (Fig. 2c) displays an extent of fog and/or low stratus that is consistent with the satellite image (Fig. 2a) although with a possible overestimation of the thickness; however, the area over the water around the Bay of Fundy is underestimated (Fig. 2c).

The time series of MBs of $T$, $T_d$, and ES at screen level (Fig. 5) show strong negative MBs in both $T$ and $T_d$ (up to $-2.0^\circ C$), mainly occurring during daylight hours, which constrains the ES MB to fairly small values (within $0.4^\circ C$). The temporal variation of $T_d$ MB in LAM15 ($2.0^\circ C$) is larger than in LAM2.5 ($1.5^\circ C$). Because XGM and WSA in the LAM15 grid are located over water, the evolution of $T$ and $T_d$ at the two islands (not shown) shows little diurnal variation (not shown), reflecting the large heat capacity of water.

The vertical profiles of $T$ at both YQI and WSA show an evident cold bias from at least 950 m down to the

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**FIG. 3.** Time series of VIS (km), up to 10 km, observed at (a) XGM, YSJ, and YQI; (b) YAW, YHZ, and XLB (from the FRAM project); and (c) WSA on 27 Jun 2006.
surface, as opposed to LAM2.5 (Fig. 4), and hence ES is more consistent with observations than is the LAM2.5.

In general, the LAM15 provided fairly reasonable initial and boundary conditions in terms of an abundant amount of LWP. However, the lack of LWP formation over the water around the Bay of Fundy in both the LAM15 and LAM2.5 (Figs. 2b and 2c) suggests that inadequate driving fields may lead to a poor simulation in the higher-resolution model in this area.

b. Case 2: 5 October 2005

1) OBSERVATION SUMMARY

As described in de la Fuente et al. (2007), a high pressure system situated a few hundred kilometers south of Nova Scotia slowly tracked eastward during 4–6 October 2005, and was responsible for an increased southerly flow of warm moist air over Atlantic Canada.

The situation on 5 October was analyzed in detail. The fog bank and/or low stratus was unobscured by higher clouds, as inferred from the satellite image at 1645 UTC (Fig. 6a), and extended eastward from the Bay of Fundy to just south of Newfoundland. At this time, the fog bank south of Nova Scotia was mainly distributed over the ocean.

In spite of the existence of a period of visibility >1.0 km (1500–1900 UTC), continuous fog was reported in the present weather at YSJ and YQI, and visibility <1.0 km lasted except for 1600–1900 UTC at XGM (Fig. 7). At YAW and YHZ, fog was reported only during the early morning with visibility >1.0 km; at WSA, fog appeared only during the late afternoon and evening (2000–0400 UTC) (Fig. 7).

The vertical profiles of $T$ and $T_d$ showed saturated layers nearly 700 m thick at 0000 UTC (not shown), 250 m at 1200 UTC, and 300 m at 0000 UTC 6 October containing an inversion layer nearly 100 m above the surface at YQI, while a saturated layer only appeared at 0000 UTC 6 October at WSA with an inversion extending to about 230 m (Fig. 8). The occurrence of the saturated layers at both stations is consistent with the surface station observations.

2) LAM2.5 PERFORMANCE

An extremely limited area of fog and/or low stratus with only a patch appearing mainly west of XGM was
simulated at 1700 UTC (Fig. 6b), compared with the satellite image (Fig. 6a). Even at XGM, LWP is underestimated during the daytime hours from 1400 to 2100 UTC (not shown). Fog and/or low stratus around the south shore of Nova Scotia is completely missed.

As in case 1, the evolutions of $T$ and ES at screen level are characteristic of general warm and dry MBs with the ES MB dominated by the $T$ MB (Fig. 9). The maximum $T$ departure occurs around the diurnal temperature maximum, up to 3.6°C, while the Td MB is limited to 0.5°C. The positive biases of $T$ and ES during the daytime in the Bay of Fundy, where thick fog and/or low stratus were reported, dominate the MBs of $T$ and ES, particularly around the daily maximum (not shown).

Similar to case 1, there exists a lowest layer with a warm and dry bias in the vertical profiles (Fig. 8) extending to at least 250 m above the surface when fog was reported, and $T$ MB accounts mostly for ES MB, as well as a relatively cold and wet layer aloft and a layer consistent with the observations in temperature beyond the boundary layer (only shown up to 500 m). In contrast, the lowest layer at 1200 UTC at WSA does not have such an evident positive ES bias when fog was not reported and the radiosonde did not indicate the occurrence of condensation. The $T$ MB value accumulated from the surface to 700 mb is small as opposed to Td MB; although the latter is much smaller than in case 1, it still accounts predominantly for ES MB.

### 3) IMPACTS OF DRIVING FIELDS FROM LAM15

In contrast to case 1, fog and/or low stratus along the south and southwest shore of Nova Scotia at 1645 UTC were severely underestimated (Fig. 6c) although the simulation is slightly better than in LAM2.5 over the Bay of Fundy. An animation of the LWP distribution suggests that this feature exists for the entire 24-h integration.

The time series of screen-level MBs of $T$, Td, and ES (Fig. 9) show a positive $T$ MB (up to 1.0°C), contrary to case 1, and Td MB ranging from $-0.9^\circ$ to $0.3^\circ$C. The Td MB in LAM15 is larger than in LAM2.5. ES consequently has positive MB, up to 1.4°C. The positive $T$ bias at YSJ, where fog was reported but not simulated appropriately during the daytime, accounts mostly for the $T$ MB (not shown).

The vertical profiles in Fig. 8 show that the $T$ at the lowest layer has a positive bias compared to the observations, but this bias is smaller than in LAM2.5. Due to the relatively lower $T$, the ES in LAM15 at the lowest layer is more consistent with the observations than in LAM2.5.

This case seems to imply that erroneous initial and boundary conditions could lead to an inferior LAM2.5 simulation, especially over the water southwest and south of Nova Scotia. Notice that the severe underestimation of $q_c$ also appeared in regGEM (see Fig. 10e in de la Fuente et al. 2007).

### c. Case 3: 30 June 2004

#### 1) OBSERVATION SUMMARY

As depicted in de la Fuente et al. (2007), there was a weak cyclone situated north of Nova Scotia on 30 June 2004. The northern portion of our model domain was encompassed in the warm zone between the cold and warm fronts while the weak southwest flow brought warm and moist air into this area.

The visible satellite image at 1731 UTC 30 June showed minimal obscuration from high clouds (Fig. 10a). The fog and/or low stratus formed over the water, extending from Lunenburg Bay to south of Newfoundland. At this time, fog was reported at YAW with visibility $>1.0$ km, as well as inferred from visibility at WSA (Fig. 11). Some fog patches were also indicated by a few ship observations around WSA over the ocean from the weather map at 1800 UTC.

In the Bay of Fundy area, fog was only reported at 0200–0600 UTC 1 July at YSJ and YQI, as well as at 0600–1300 UTC at YQI (Fig. 11). In the southern Nova Scotia area, fog was reported from 2300 to 0600 UTC 1 July and occasionally in the early morning (0900–1000 UTC) and at 1700–1800 UTC at YAW, as well as...
FIG. 6. (a) HRPT visible image at 1645 UTC. (b),(c) LWP (10^{-2} kg m^{-2}) from the lowest five prognostic model levels for LAM2.5 and LAM15 at 1700 UTC 5 Oct 2005.
at 0200–0600 UTC 1 July at YHZ. At WSA, visibility <1.0 km occurred approximately during 0600–1000 and 1600–0300 UTC (Fig. 11).

The vertical profiles of T and Td display a thin saturation layer extending from the surface to 160 m with an inversion between 120 and 459 m at 1200 UTC (Fig. 12a), as well as a relatively moist layer at a height of 100–150 m with an inversion and then neutral layer extending from 150 to 500 m at 0000 UTC 1 July at YQI (Fig. 12b). WSA had a moist layer located from 140 to 765 m with an inversion from the surface to 318 m at 0000 UTC 30 June (not shown), indicating low stratus formation. The layer became thinner (140–177 m), extended toward the surface (consistent with the fog formation indicated by the fog report), and was accompanied by a second saturated layer around 900 m at 1200 UTC (Fig. 12c). By 0000 UTC 1 July, the inversion lifted, and the moist layer extended vertically to 233 m (Fig. 12d).

2) LAM2.5 PERFORMANCE

In comparison with the satellite image at 1731 UTC (Fig. 10a), the LWP at 1700 UTC (Fig. 10b) depicts fog and/or low stratus to the south of Cape Breton, with the area around WSA and the water to its south well simulated, the westward extent to the south of Lunenburg Bay underestimated, and a clear patch to the north of

FIG. 7. Time series of VIS (km), up to 10 km, observed at (a) XGM, YSJ, and YQI; (b) YAW and YHZ; and (c) WSA on 5 Oct 2005.
WSA enlarged. The model does not resolve the fog patch over the Bay of Fundy.

Similar to the previous two cases, the model shows an overall warm and dry bias at the screen level with the ES MB dominated by $T_{MB}$ (Fig. 13). The maximum $T_{MB}$ appears around morning, up to 4.3°C. Based on the time series of $T$ and ES from the individual stations, the stations with observed fog and/or low stratus occurrences contributed to the higher $T_{MB}$, such as YQI and YAW. At WSA, the better simulation of fog and/or low stratus reduces the $T_{MB}$.

Vertical profiles at YQI (Figs. 12a and 12b) display the lowest layer with a warm and dry bias extending to at least 200 m, topped by a layer with a cold and wet bias, similar to those in cases 1 and 2; therefore, the temperature inversion that appeared in the observations does not exist in the model. The bias at the lowest layer seems to extend to a higher height when the layer contains more moisture from the observations (e.g., 1200 UTC). At WSA (Figs. 12c and 12d), the model has a temperature inversion at 1200 UTC although it is much weaker than reported in the observations, but it is still too dry and mainly attributable to the low dewpoint. The positive temperature bias layer still exists at 0000 UTC 1 July accompanied by the relatively realistic ES at the expense of both the positive $T$ and $T_d$ biases. $T_{MB}$ from the surface to 700 mb is larger than $T_{MB}$, as in the previous two cases, except for 1200 UTC at YQI. The relatively large $T_{MB}$ at 1200 UTC reflects the large positive $T$ departure from the observations in the lowest layer (see Fig. 12a), while smaller $T_d$ MB results from the offset of the biases between the upper and lower levels.

3) IMPACTS OF DRIVING FIELDS FROM LAM15

A reasonable depiction of the fog and/or low stratus is represented at 1731 UTC (Fig. 10c) in comparison with the satellite image (Fig. 10a), in spite of a still limited westward extension to the south of Lunenburg Bay and the lack of a fog patch over the Bay of Fundy.

The time series of screen-level MBs of $T$, $T_d$, and ES (Fig. 13) mirror mostly negative $T_d$ MB up to −2.3°C (similar to that in LAM2.5), small $T_{MB}$ ranging from −0.6°C to 0.9°C (better than in LAM2.5), and hence ES
MB dominated by Td MB. The time series of $T$ for the individual stations indicate a much better fit with the observations than those in LAM2.5 except at XGM and WSA where the lack of diurnal variation reflects the grid points being located over the water.

The vertical profiles of $T$ and ES at the lowest layer extending to nearly 200 m at YQI display generally positive biases, but are much smaller (better) than in LAM2.5 (Figs. 12a and 12b). At WSA, both $T$ and Td at the lowest layer show negative biases at 1200 UTC that are worse than in LAM2.5, and positive biases at 0000 UTC 1 July that are better than in LAM2.5 (Figs. 12c and 12d); ES however is consistent with the observations.

In conjunction with the $q_c$ fields at 0600 UTC, LAM15 provided reasonable initial and boundary values of $q_c$ for LAM2.5 over the southern Nova Scotia area and around Sable Island.

4. Diagnosis of LAM2.5 dryness

Section 3 reveals that an underestimation of $q_c$, along with a warm and dry MB at the lowest layer, are common features of the LAM2.5 simulations for all three cases. The 27 June 2006 case was therefore selected to further diagnose the dryness of the LAM2.5 given that the LAM15 does a reasonable job in this case in contrast to the LAM2.5, with the added benefit that the date falls within the period of the FRAM observations.

a. Dissipation of $q_c$

Within the Kong–Yau microphysics scheme, $q_c$ is treated as a prognostic variable and, for warm cloud, is a function of the condensation of cloud droplets ($\text{VD}_{\text{wc}}$), the accretion of cloud water by raindrops ($\text{CL}_{\text{cr}}$), and the autoconversion of cloud water ($\text{CN}_{\text{cr}}$). Through these source (sink) terms, the generation (dissipation) of $q_c$ is closely related to the dissipation (generation) of other hydrometeor types, $q_v$ and $q_r$ (Kong and Yau 1997). Lack of generation of $q_c$ for all three cases throughout indicates that the processes of $\text{CL}_{\text{cr}}$ and $\text{CN}_{\text{cr}}$ do not consume $q_c$ and hence are not responsible for the deficit of $q_c$. Thereby, the condensation (evaporation), $\text{VD}_{\text{wc}}$, constitutes the major source (sink) of $q_c$, which depends on how close the vapor mixing ratio $q_v$ gets to the saturated vapor mixing ratio $q_{vs}$, or in other words, how close $T$ approaches Td (i.e., whether ES approaches 0). Now, let us follow this clue to track the LAM2.5 dryness.

1) Initial reduction of $q_c$

Starting with a detailed examination of the initial fields at 0600 UTC of the LAM2.5 and the driving fields of LAM15, it was noticed that the area where ES $= 0$ that generates $q_c (> 0)$ in LAM15, as expected from the Kong–Yau scheme, corresponds to the area with ES $> 0$ where $q_c$ was interpolated from LAM15 (and hence $> 0$) in LAM2.5 (Fig. 14a). This initial ES $> 0$ in LAM2.5 then inevitably leads to an immediate evaporation and hence a significantly reduced area of $q_c$ right at the second time step (Fig. 14b). The initial reduction of $q_c$ is particularly evident over the Bay of Fundy and southwest Nova Scotia, including ocean and weather stations (over land). The ES $> 0$ at 0600 UTC in LAM2.5 appears to be brought about by the slightly higher $T$ compared with the observations.

2) Impacts of vertical motion and horizontal advection

Regardless of the initial reduction, one could still expect that $q_c$ would be generated by internal processes in the model. However, in LAM2.5, there are a few subsidence (vertical velocity field $\omega > 0$) areas over the areas where $q_c > 0$ (e.g., at 0700 UTC; see Fig. 15a) that are stronger than in LAM15 (Fig. 15b). The subsidence lasts for hours starting from 0600 UTC, especially over the water around the Bay of Fundy and along the southwest tip and the south of Nova Scotia. The subsidence induces the subsequent local warming (Fig. 15c), which exacerbates the $q_c$ decrease (Figs. 15d and 15e). Note that the 1-h $T$ difference in Fig. 15c reflects an accumulated subsidence effect from 0700 to 0800 UTC and a subsidence layer of 400 m. The absence of the cloud longwave cooling effect also appears to take part of the
FIG. 10. (a) HRPT visible image at 1731 UTC. (b),(c) LWP (10^{-2} kg m^{-2}) from the lowest five prognostic model levels for LAM2.5 and LAM15 at 1700 UTC 30 Jun 2004.
responsibility for the maximum warming west of Nova Scotia that is matched well with the area where the strong $q_c$ dissipation happens (cf. Fig. 14b and Figs. 15d and 15e); that is, when fog and/or lower stratus dissipates, its cooling effect dies out and subsequently the temperature increases in time. The longwave cooling rate from lower-level cloud can reach more than 10 K day$^{-1}$ (Li 2002).

In general, horizontal advection in LAM2.5 is just slightly stronger than in LAM15, and the wind direction is slightly more westward (Figs. 16a and 16b). The advection, rather than divergence that is associated with the subsidence, therefore does not seem to play a major role in the difference of $q_c$ between LAM2.5 and LAM15.

3) SOLAR RADIATION EFFECT

It was noted in section 3 that the positive biases of $T$ and ES at the lowest layer are dominated by the stations that experienced prolonged fog events, particularly during the daytime hours when fog was reported but has been severely underestimated, such as in the morning and late afternoon in case1, around the diurnal temperature maximum in case2, and during the morning in case3. An examination of the differences in the solar radiative fluxes arriving at the surface (SW) between LAM2.5 and LAM15 (Fig. 16c) on 27 June 2006 illustrates evident positive values over the large ocean area and area around YSJ and YQI where fog and/or low stratus are
underestimated in LAM2.5 while there is an abundance of $q_c$ in LAM15. (Figs. 2b and 2c). This suggests that the initial/earlier thinning or missing fog and/or low stratus allows abundant solar radiation to arrive at the surface during the daytime hours, increasing the model temperature at the level $\sigma = 0.995$ (and at screen level), which in turn leads to less condensation and fog and/or stratus formation, a positive feedback between the underestimation and the solar radiation scheme that is fully interactive with clouds, as documented in section 2.

b. A comparison with FRAM observations

The FRAM project provided valuable observations for our model verification. In both LAM2.5 and LAM15, the $q_c$ (kg kg$^{-1}$) converted to LWC (g m$^{-3}$) at $\sigma = 0.995$ shows an initial consistency with the FRAM observations (that were interpolated to the $\sigma = 0.995$ level) until 1000 UTC, and then a sharp drop in comparison with the large amount of the observed LWC during 1000–1500 UTC; the LAM15 fits better within the second period of the observed nonzero LWC after 2100 UTC (Fig. 17a). Following the SW increase after sunrise (Fig. 17b), the evident increase in $T$ after 1000 UTC (Fig. 17c) leads to an unsaturated condition (Fig. 17d) and, hence, the evaporation of LWC. The inconsistency between the observations and the models in SW and $T$ during 1000–1500 UTC mirrors the underestimation of fog in the models. It should be considered that the observed LWC above using the TP3000 microwave radiometer (MWR) is about 2 times larger than the fog measuring device (FMD) based on
LWC (Gultepe et al. 2009). However, the LWC daily variation is consistent with changes in SW, $T$, and RH. Note that the observed RH < 100 before 1000 UTC resulted from the interpolation between 0 m (RH = 100) and 100 m (RH < 100), indicating very thin fog at that time. The stronger $T$ increase during the daytime in LAM2.5 appears to be responsible for the subsequent departure from saturation after 2000 UTC (Fig. 17c)—as it takes a longer time to cool down when the daily temperature is high.

An experiment with the radiation scheme acting every 5 min displays slightly stronger SW from 1000 to 1600 UTC (Fig. 17b), and does not change the big picture in terms of the underestimation of fog and/or low stratus (not shown).

The TKE at 2 m was stronger in LAM2.5 than in LAM15 and the observations (Fig. 17e), but may not have a direct effect on LWC due to the MoisTKE scheme that only applies down to the second-lowest prognostic model level.

5. Conclusions and discussion

A three-level nested version of a high-resolution GEM-LAM configuration (LAM2.5) was implemented in June 2007, running quasi-operationally at CMC. This study evaluates its capabilities in marine fog prediction, involving its physical parameterizations for high-resolution modeling and some dynamical processes. Three marine fog cases have been carefully examined in comparison with satellite images and surface and upper-air meteorological observations.

Here $q_c$ is used as one of the proxies of fog and/or low stratus; however, $q_c$ underestimates the fog and/or stratus extent and intensity in LAM2.5 with a warm and dry bias at the lowest layer, extending a few hundreds of meters above the surface. This tendency becomes more pronounced when fog persisted after sunrise. The degree of the underestimation of fog and/or low stratus
varies from case to case. The simulation for 5 October 2005 is the worst depiction among the three cases, missing large areas of fog and/or low stratus reported in the observations and satellite imagery.

The immediate initial and boundary conditions from LAM15 provide a sufficient $q_c$ field for the 27 June 2007 case, severely underestimated $q_c$ in the 5 October 2005 case, and slightly underestimated $q_c$ in the 30 June 2004 case for LAM2.5, demonstrating the dependence of a model on its driving fields. The simulated temperature in LAM15 is generally lower than in LAM2.5, leading to a better simulation of $q_c$. Compared to the observations, the temperature in LAM15 has a negative bias when $q_c$ is well simulated/overestimated and a positive bias when $q_c$ is underestimated. On average, $T_d$ in LAM2.5 is better than in LAM15.

A diagnosis based on the 27 June 2006 case that utilizes the reasonable LAM15 simulation and the FRAM observations as the references reveals a reduction in $q_c$ at the initial time caused by nonzero ES over the area where $q_c > 0$. This nonzero ES appears to be related to the preprocessing. Further dissipation of the reduced $q_c$ is exacerbated by stronger subsidence over the area where $q_c > 0$ (in comparison with LAM15) that lasts for hours and induces the local warming. The already underestimated $q_c$ then allows more solar radiation arriving at the surface after sunrise, which unrealistically increases the temperature, leading to evaporation and further underestimation of $q_c$. The horizontal advection does not seem to play a major role in the difference of $q_c$ between LAM2.5 and LAM15.

A modified version of MoisTKE (experiment LAM2.5M in Table 2) that allows cloud to be generated at the lowest prognostic level ($\sigma = 0.995$) of the model around 40–50 m was tested and evaluated against observations and the routine configuration with MoisTKE, using the same cases and methods as in section 3. However, this modified version produces pros and cons for the different cases: giving a slightly more realistic $q_c$ extent in the 27 June 2006 case, a slightly worse (limited) extent in the 30 June
condensation scheme used in regGEM is likely the reason for the general underestimation of fog. We use the Kong–Yau scheme in LAM15 but obtain very similar results for the two cases common to our study and de la Fuente et al. (2007). The modified MoisTKE does not show a conclusive improvement in terms of the marine fog prediction. The radiation scheme acting every 5 min does not show any noticeable improvement either. On the contrary, our results stress the importance of accurate initial conditions and vertical velocity fields during the first few hours, as well as a significant contribution from the interactions between the condensation scheme and the radiation scheme that interacts fully with clouds; although an adjustment period is generally expected for the model to develop its own scales of motion and generate $q_c$ internally at the later hours, solar radiation after sunrise can burn out the remaining $q_c$ and unrealistically increase the daytime temperature; the insufficient cooling down at later hours (e.g., the following late afternoon–evening; see Fig. 17c) causes difficulty for the next period of fog formation, at least within the context of a 24-h forecast. Teixeira (1999) emphasizes the importance to fog forecasting of the delicate balance among different physical processes. Our findings support his result. There may also be a nonnegligible impact from other input fields including geophysical fields and SST. The latter currently uses the CMC analysis with a resolution of $1/3^\circ$ (Brasnett 1997). These aspects could be further investigated.

As mentioned at the end of section 1, the three-level nested GEM-LAM configuration (LAM2.5) that we examined here was set up as part of the Lunenburg Bay Project on Interdisciplinary Marine Environmental Prediction in the Atlantic Region (Cullen et al. 2008). Although the Lunenburg Bay Project has been concluded, a similar LAM2.5 configuration has been extended to a larger domain covering the Canadian Atlantic region and is running daily in experimental mode at CMC since February 2009, complementing LAM2.5 models that are running for other selected areas across Canada. The assessment presented here suggests aspects for further investigation, particularly for better marine fog prediction, as these models continue to be improved.

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