Analysis and Modeling of an Extremely Dense Fog Event in Southern Ontario

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ABSTRACT

In this study, a dense fog episode that occurred near Windsor, Ontario, Canada, on 3 September 1999 is investigated. The fog patch, with a spatial scale of several kilometers, reduced visibility on a major highway to a few meters and led to a series of collisions and loss of life. Satellite imagery and surface observations are used to analyze the physics of the event, and several hypotheses on the origin of the fog are presented. A series of simulations of the event with the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) suggest that the fog formed because of convergence of land breezes developing along the shores of a lake and subsequent advection of moisture over the site of the accident. Tests indicate that the small scale of the modeled event contributes to sensitivity of the results to a broad range of factors. Sensitivity to the initial and boundary conditions, including initial soil moisture content and parameterization of turbulence, is discussed.

1. Introduction

Fog presents a serious hazard in areas of intense traffic, such as airports, highways, and harbors, and its prediction is essential for public safety and has a high economic value (Leigh 1995). Thick fog was very likely a factor in a recent (3 November 2002) collision of 194 vehicles on a California highway. These facts stress the importance of fog studies.

Radiative cooling and mixing (humidification) are the two main physical processes responsible for fog formation. Fogs can be classified as radiative when the first mechanism dominates, and as advective when the second is prominent.

Surface observations of fog are common and date back about 200 years (see, e.g., Wells 1814; Taylor 1917; Willet 1928; Duynkerke 1991; Guedalia and Bergot 1994). They demonstrate the processes involved in fog formation and development, including the primary role of radiation, microphysics, turbulence, and moisture transport over heterogeneous terrain.

Numerical models can be used for fog forecasting and to investigate the relative importance of the processes affecting fog formation and evolution. Application of one-dimensional models for fog simulations, despite ignoring horizontal heterogeneities, provides many insights into fog physics. For example, Zdunkowski and Nielsen (1969) and Brown and Roach (1976) showed the importance of radiative cooling at the fog top on surface layer destabilization and on downward propagation of the fog. Brown (1980) and Mason (1982) investigated the effect of radiative cooling on droplet growth and modification of the droplet spectrum. Modeling by Musson-Genon (1987) emphasized the importance of turbulence in fog formation and evolution. Bott et al. (1990) and Bott (1991) studied effects of aerosol activation and composition on fog droplet distribution and visibility. Siebert et al. (1992) and Duynkerke (1991) showed that vegetation and its type strongly influence fog formation by changing the surface heat and moisture budget.

To further illustrate the complexity of fog physics, we present findings of Bergot and Guedalia (1994) who performed a series of experiments with a one-dimensional model. They emphasize the importance of precise knowledge of initial humidity profiles, especially for fogs forming during the second half of the night. They also showed the strong sensitivity of fog simulations to horizontal advection (by assuming a constant gradient in the model) and the effects of low- and midlevel clouds, through radiative balance, on the boundary layer. The effect of atmospheric pollution on fog was demonstrated by shifting the droplet spectrum toward the smaller sizes, causing a decrease in gravitational settling. Authors also pointed out that radiative balance of the surface layer is influenced by the soil heat conductivity, which affects the cooling rate of the surface. Dew
deposition, which leads to the dehydration of the layer, also affects the likelihood of fog formation.

The above summary outlines the potential difficulties in fog modeling and prediction. The lack of accurate initial humidity profiles in the boundary layer and the uncertainties in the parameterization of radiation, microphysics, turbulence, and surface processes make fog modeling and prediction a very challenging task in complex cases.

For regional fog studies and forecasting, the use of three-dimensional models with their computational burden and necessary simplifications in parameterization is unavoidable. Ballard et al. (1991) were the first to attempt fog prediction with a regional model. Experimental forecasts of fog off the coast of northern Scotland, using the United Kingdom Meteorological Office (UKMO) mesoscale model, were relatively successful and showed that results were critically dependent on the model initial conditions and the parameterization of turbulence. In this model an extension of the 1.5-order closure of Mellor and Yamada (1982), to include liquid water and phase changes after Sommeria and Deardorff (1977), was included. More recently, Gayno (1994) and Stauffer et al. (1999) took a similar approach, including vertical mixing corrected for countergradient flux in the convective conditions. Model simulations compared favorably with visibility, wind, temperature, humidity, and radiative fluxes recorded at the 215-m Cabauw, Netherlands, tower during a fog event on 3 August 1977 (Wessels 1984; Musson-Genon 1987).

In the present work we analyze a fog episode that occurred near Windsor, Ontario, Canada, in the early morning of 3 September 1999. The extremely dense, small-scale fog patch reduced visibility to several meters on a stretch of a major highway and led to a series of collisions, involving 82 vehicles, that left 8 people dead and 33 injured. The fog moved or dissipated within several minutes. Observations collected during the fog episode and the results of simulations with the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) were examined to better understand fog formation and development in this case.

We begin by analyzing the physics of the episode and developing hypotheses on the origin of the fog patch. The modeling approach and simulations are then described. The paper concludes with a discussion of the results.

2. Case analysis

For the analysis of the physics of the fog episode, high-resolution satellite imagery provided the most valuable information. Canadian Meteorological Centre (CMC) weather analyses and surface reports of wind, temperature, and dewpoint from stations in the area of interest were also used.

CMC analyses (Fig. 1) show that the weather on 2 and 3 September 1999 was dominated by a stationary high pressure system elongated in northeast (NE)–southwest (SW) direction, with the center in the middle of a triangle bounded by Lakes Erie, Ontario, and Huron. Surface winds over southern Ontario and eastern Michigan were weak—no precipitation was observed and no atmospheric fronts passed over the area. Surface air temperatures over land in this area reached 25°C–30°C on 2 September and dropped by about 10°C overnight.

It can be noted (Fig. 2) that a narrow strip of land between Lakes St. Clair and Erie (star denotes site of the accident) lacks any significant topographical features that could contribute to the fog formation. Also, dominant land use/vegetation (pasture) and soil type (clay) are uniform over the area where the accident occurred. However, we draw attention to the fact that the terrain slopes upward in the northwesterly direction west of Lake St. Clair. We believe that the presence of the ridge seen in Fig. 2 resulted in channeling of the flow toward Lake St. Clair. This will be demonstrated in the analysis of the model simulations (see section 3).

Both lakes are very shallow with depths of the order of 20 m or less within the area shown. Analysis of data from two buoys moored on eastern Lake Erie (no buoys were deployed on Lake St. Clair until June 2000) showed that on the 2 September the average water temperature was about 23°C and had a diurnal amplitude of about 2°C. The average air temperature was about 22°C with a diurnal amplitude of about 4°C. Surface observations for September 2000 showed that the water and air temperature at Lake St. Clair are only slightly warmer (by about 0.5°C) than those measured by the two buoys on Lake Erie.

CMC analyses (Figs. 1c,d) show that at night and in the early morning of 3 September, Lake St. Clair and its surroundings were in the weak NE flow stream. Surface observations [Fig. 3 and Aviation Routine Weather Report (METAR), not included] indicate that the flow stream was modified at the lake shores by thermal gradients between land and water. It can be seen in Fig. 3 that land breezes developed at night along the northwestern and southern shores of the lake as indicated by winds at Mt. Clemens, Michigan (KMETC), Bell River, Ontario, Canada (WDD), and possibly Windsor (YQG) at 0800 and 1000 UTC. At 1200 UTC (0800 LDT), about 1 h after the sunrise, a change in the wind direction at KMETC and YQG signals the onset of lake breezes. After midnight (from 0830 to 1215 UTC, METAR reports) very dense fog with near-zero visibility appeared at KMETC and led to two deadly accidents. From 1100 to 1330 UTC fog was also observed at Detroit, Michigan (KDET), and from 1218 to 1300 UTC at YQG. Because of the wide spacing of surface stations, it is difficult to determine the exact extent of fog banks with time.

Satellite data provide additional information on fog or low clouds and complement the surface observations. During daylight hours fog banks or low clouds can be determined by visible satellite imagery. During night-
time, it is difficult to distinguish fog or low clouds using a single IR channel because the temperature of the fog or low clouds is usually close to the surrounding cloud-free areas. Ellrod (1995) developed a technique based on earlier work by Hunt (1973) to delineate fog or low clouds at night using the difference between the Geostationary Operational Environmental Satellite (GOES) channel 4 (11 μm) and channel 2 (3.7 μm). Because channel 2 also detects reflected solar IR, this method fails during daylight hours. Ellrod (1995) claims that the areas where the difference in brightness temperature between channels 4 and 2 is below 2.5 K can be partially or completely filled with the semitransparent fog. A difference in temperature from 2.5 to 5 K corresponds to clouds from 3 to 400 m thick and above 5 K to clouds from 500 to 700 m thick. Figure 4 shows a sequence of high-resolution (1.5 km) images from GOES-8. Differential infrared and visible images for nighttime and daytime hours, respectively, are displayed in Fig. 4.

In Figs. 4a–c (at 0945, 1032, and 1102 UTC), green areas denote temperature differences greater than 2 K and red areas have differences greater than 4 K. It should be noted that at least a part of the cloudy area extending over the northwestern shore of Lake St. Clair from about 1000 to 1100 UTC corresponds with the ground-level fog as reported by the surface station at KMTC. The sequence of nightly images combined with visible imagery shows southerly propagation of the cloud and its westerly spread. The first usable visible image at 1132 UTC (Fig. 4d) shows the southern edge of the cloud about 6 km northwest of the accident site (shorelines and station locations are accurate within about 2 km).
By 1145 UTC (Fig. 4e, about 15 min before the accident) the edge of the cloud was just north of the accident site. By 1215 UTC (Fig. 4f) the cloud edge appeared to be west of the accident site. At 1227 UTC, near-zero visibility was reported at Windsor Airport, about 10 km westward from the site of the accident where the cloud on the imagery is more opaque (Windsor Airport observations, drivers’ reports).

The formation of the cloud can be explained as a result of wind convergence along the northwestern shore of Lake St. Clair induced by land breezes during the night. Its southerly drift is consistent with the general direction of the synoptic flow and the weakening of land breezes and onset of lake breezes at the southern lake shore at a later time. Dissipation of the cloud most likely occurred because of the warming of the ground, subsequently leading to a change in the breeze circulation pattern and disappearance of the previous convergence zones. It is important to note that the presence of the cloud in the imagery is not equivalent to the existence of ground-level fog. At the time of the accident ground-level visibility was poor only at the easternmost edge of the cloud, while fair visibility conditions were reported several kilometers westward from the site of the accident where the cloud on the imagery is more opaque (Windsor Airport observations, drivers’ reports).

Scarcity of observations and lack of measurements of wind, temperature, and dewpoint in the area where the accident occurred does not allow us to provide a definitive explanation of the physics of the episode, but, rather, to formulate several hypotheses on the possible scenarios.

First, we note that because of the direction of the prevailing flow and proximity of the accident site to Lake St. Clair, it is unlikely that land breezes developing at the shores of Lake Erie had much influence on the fog event under consideration. Second, it is quite possible that the poor air quality, confirmed by smog warnings issued in the Windsor area on 2 and 3 September, could have affected the fog formation and evolution as well as its opacity. Fine atmospheric aerosols (with radii smaller than 2 μm), present on smoggy days, provide cloud condensation nuclei (CCN) for water droplets. High concentrations of CCN under saturated conditions leads to the formation of a large number of small droplets (Gultepe and Isaac 1999), resulting in slower gravitational settling of droplets and thus, fogs with larger liquid water content. As shown by the experimental relation of Jiusto (1981),

\[ V = k \frac{τ}{q_L} \]  

(1)

where \( V \) is visibility, \( τ \) denotes the average cloud droplet radius, \( q_L \) is liquid cloud water content, and \( k \) is a proportionality constant that is in the range of \( 1–3 \times 10^{-3} \)
for SI units, small, average-sized droplets accompanied by increased liquid cloud water content result in drastically decreased visibility.

As shown above, the presence of the cloud seen on the imagery (Fig. 4) might be associated in some areas below it with ground-level fog. It is possible that the low-level cloud was mixed downward in the surface layer, destabilized by radiative cooling at the cloud top and warming of air at the surface (Fleagle et al. 1952; Pilić et al. 1975). This scenario is supported by observations of some witnesses claiming that the fog appeared to “fall from the sky.”

The time of the fog formation over the site of accident (about 1 h after sunrise), as well as its proximity to the lake, suggest that both nighttime radiative cooling and moisture advection contributed to its presence. The role of dew in fog formation and evolution was investigated by Pilić et al. (1975) who noted that evaporation of dew...
after sunrise can saturate the surface layer. To maintain a saturated layer a constant supply of moisture is necessary. Our estimates (see the appendix) suggest that overnight water vapor condensation on vegetation surface elements might have played a certain role in fog formation in the early morning of 3 September.

In the second scenario, the fog would form when warm and moist air from over Lake St. Clair moved southward and became saturated over cooler land. The timing of the event is very much related to the weakening of land breeze circulations at the southern and western shores of Lake St. Clair, the onset of the lake breeze, and the resulting southerly flow. We stress that this hypothesis is not inconsistent with the satellite imagery because the cloud seen in Fig. 4 would obscure any shallow fog layer forming at the ground.

Modeling provides some support to the latter scenario.

3. Modeling

a. Design

To study the event, MM5 (Grell et al. 1994) was employed. It is an Eulerian nonhydrostatic regional model with multinesting capability. It employs a vertical terrain-following pressure-based coordinate system and provides various options for the parameterization of turbulence, grid-resolved and unresolved cloud processes, and radiation, as well as recently included coupling to land surface models. MM5 has been used extensively for modeling studies, and there is a significant body of literature on the model itself and its applications (which was available online at http://www.mmm.ucar.edu/mm5/mm5home.html).

Lateral and initial conditions for MM5 simulations were obtained by interpolation of CMC analyses to the model grid. The analyses are produced in the three-dimensional variational data assimilation cycle, which uses the Global Environmental Model (GEM; Côté et al. 1998a,b) results as the background. Rawinsondes, standard surface measurements, satellite temperature (SATEM) thickness, aircraft reports (AIREP), satellite-observation cloud-drift (SATOB) winds, dewpoint from GOES, Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) radiances, and precipitable water from the Special Sensor Microwave Imager (SSM/I) are also included in the data assimilation (Gauthier et al. 1999; Laroche et al. 1999). GEM is a semi-Lagrangian primitive equation global model, which can be used on a rotated variable resolution mesh. The flexibility of this design allows for high resolution over the area of primary interest, in our simulations approximately 24 km over North America and its surrounding oceans. In the incremental three-dimensional variational data assimilation (3DVAR) al-
algorithm, the innovations are calculated with respect to the high-resolution model grid, while the analysis increments are obtained at the lower resolution on a Gaussian grid. The increments interpolated bilinearly to the original GEM grid provide a high-resolution analyses.

Soil temperature and moisture were initialized using NCAR reanalyses. We allowed the diurnal variation of surface temperature of Lakes Erie and St. Clair based on observations and climatology (see section 2) in all the computational domains.

In the control simulation the Gayno-Seaman parameterization of the boundary layer (Gayno 1994; Stauffer et al. 1999), coupled with a five-layer interactive soil and bucket model was used. At 9-km grid resolution and above, the deep convection parameterization of Kain and Fritsch (1993) was used. Explicit treatment of cloud microphysics of Dudhia (1989) was employed. To account for an important role that longwave and shortwave radiation play in fog formation, the Dudhia scheme (Dudhia 1989) was employed. In this parameterization, effects of water vapor, carbon dioxide, and liquid water on emissivity are included. Clear air, water vapor, and cloud water absorption and scattering are accounted for in the parameterization of shortwave radiative flux.

Four computational grids shown in Fig. 5 have horizontal spacings of 27, 9, 3, and 1 km and mesh sizes of $95 \times 71$, $97 \times 97$, $82 \times 82$, and $85 \times 85$ points, respectively. Two-way nest interaction was employed. Thirty-two vertical levels, stretched monotonically from the surface to 100 hPa, provide high resolution in the boundary layer (18 levels below 850 hPa, with the first wind and temperature level at about 10 m).

b. Control simulation

The control simulation of the event began at 1800 UTC 2 September with the integration in the 1-km-resolution domain delayed by 6 h. Initially, we concentrate only on the analysis of the innermost domain.

In Fig. 6 where winds in this domain at the first and 0.988 sigma level (i.e., at about 10 and 100 m AGL, respectively) are plotted, the effect of topography on the flow west of Lake St. Clair can be identified. It can be seen that the low-level flow in this area was clearly affected by the presence of the ridge (see topography in Fig. 2) as the wind direction changed from NE to N. Direction of the flow was not affected by the topography at the higher level.

In Fig. 7, simulated winds and moisture divergence at the 10-m level are plotted (only a subset of the domain shown). It can be seen that the weak flow was modified further at the western and southern shores of Lake St. Clair by the thermal gradients between water and land. Both influences (topography and thermal) created convergence zones at the shores, which led to the ascent and transport of moisture upward.
Fig. 8. Relative humidity (%) at 200 m at (a) 1130 and (b) 1230 UTC.

Fig. 9. Liquid cloud water content (g kg\(^{-1}\)) at 10 m at (a) 1100, (b) 1130, (c) 1200, (d) 1230, (e) 1300, and (f) 1330 UTC. Accident site is marked with a star.
Fig. 10. (a) Ground temperature (°C) and (b) TKE (J kg⁻¹, scaled by 10⁴) at 10 m at 1130 UTC.

Fig. 11. Vertical cross sections showing (a)–(c) potential temperature (K) and tangential wind vectors and (d)–(f) vertical velocity (cm s⁻¹) and cloud liquid water content (g kg⁻¹) along the line shown in Fig. 10 at (a), (d) 1130, (b), (e) 1200, and (c), (f) 1230 UTC. Arrows indicate shoreline.
In Figs. 8 and 9, relative humidity at about 200 m (0.979 sigma level) and liquid cloud water content at about 10 m are displayed, respectively. It can be seen that, in the current simulation, relative humidity west and south of Lake St. Clair was higher than 90%, though the cloud seen on the satellite imagery was not reproduced. As noted in section 2, it is possible that the formation of the cloud on the western shore of Lake St. Clair did not affect the ground-level fog formation. In this scenario, low-level moisture convergence lead to the formation of a moist blob of air at the ground and its subsequent advection over land with the prevailing northeasterly flow. Cooling of the blob over land through its interaction with a relatively cold surface and radiation lead to saturation and formation of fog over the site of the accident. It can be seen that the narrow strip of land between Lakes St. Clair and Erie was, at 1130 UTC, approximately 4°C cooler than the surface of Lake St. Clair (Fig. 10a). Mechanical turbulence generated by weak winds [see plots of turbulent kinetic energy (TKE) at 10 m in Fig. 10b] was suppressed by the strong static stability above, inhibiting mixing and, thus, creating favorable conditions for the fog formation. The concave shape of the shoreline of Lake St. Clair might have strengthened convergence at the shore. This would occur as a consequence of the fact that the wind acquires an additional component in the direction of the thermal gradient, that is, in the case of the land breeze perpendicular to the shoreline, and toward the lake.

Additional insight can be gained by the analysis of vertical cross sections in Figs. 11 and 12 (along the line shown in Fig. 10). In these figures potential temperature, tangential wind vectors, vertical velocity, liquid cloud water content, radiative tendency, and TKE during the simulation are displayed. Evolution of a shallow front resulting from temperature contrast between lake and land can be seen in Fig. 11. Convergence at the leading edge of the front, which is generated by a land breeze (see also Fig. 7) and enhanced by deceleration of the NE flow over land, leads to the development of vertical motions (Fig. 11d–f). Ascent is compensated by the des-
cent, which originates at the inversion behind the surface front. Downward motions suppress vertical buildup of fog by advecting dryer air from above and increasing stratification in the lower atmosphere behind the front (Figs. 11e and 12e). As the land breeze loses strength after sunrise vertical motions weaken (Fig. 11c). This, combined with radiative cooling due to fog (Figs. 12b and 12c), leads to a less stable surface layer, increased turbulence, and vertical buildup of the fog.

The fog started to dissipate at the surface around 1230 UTC because of the warming of the ground. By 1330 UTC (not shown) dissipation of the fog patch was almost complete.

Simulation within a coarser 3-km-resolution domain (see cloud water at 10 m in Fig. 13, the only subset of the 3-km-domain shown) also shows the presence of the fog patch at the location similar to that in the 1-km-resolution domain. Its cloud liquid water content is, however, lower. Thus, processes leading to the accident were already resolved at 3 km. Simulations in domains 1 and 2 (27- and 9-km resolution), where lake and land breezes along shores of Lake St. Clair were not resolved, do not show the presence of the fog in the area of interest.

Scarcity of observations allows only for limited verification of the model results. Based on the available data it is quite possible that the simulation accurately reproduced the arrival and dissipation of the fog at the site of the accident and correctly represented the sequence of events. However, uncertainty associated with interpreting the cloud feature seen on the satellite imagery in this simulation needs to be acknowledged.

c. Sensitivity studies

Series of simulations were performed with varying physics and initial and boundary conditions. Other boundary layer schemes available in MM5 (Blackadar 1979; Zhang and Anthes 1982; Hong and Pan 1996) yielded poor results even when coupled with the Oregon State University land surface model (Pan and Mahrt 1987; Chen et al. 1996). It was noted that the initialization of soil moisture with NCAR reanalysis improved quality of simulations with the Gayno–Seaman scheme (Gayno 1994; Stauffer et al. 1999), even though the comparison of initial soil moisture obtained from NCAR reanalysis with soil moisture, based on land use type (not shown), revealed differences smaller than 10% over the modeling domains. In Fig. 14 results of the above simulations are shown.

Below, sensitivity of the model results to the initial and boundary conditions is investigated. Table 1 lists the three different numerical experiments.
TABLE 1. List of model simulations.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Starting date</th>
<th>Duration (h)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1800 UTC 2 Sep 1999</td>
<td>24</td>
<td>CMC analyses used to specify initial and lateral boundary conditions</td>
</tr>
<tr>
<td>II</td>
<td>0000 UTC 3 Sep 1999</td>
<td>18</td>
<td>CMC analyses used to specify initial and lateral boundary conditions</td>
</tr>
<tr>
<td>III</td>
<td>1800 UTC 3 Sep 1999</td>
<td>24</td>
<td>GEM forecast results used to specify initial and lateral boundary conditions</td>
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Simulation II had all of the features of the control, except it began in all four nests at 0000 UTC 3 September. In Fig. 15 wind and moisture divergence and liquid cloud water content at about 300 (0.966 sigma level) and 10 m are displayed, respectively. It can be seen that the cloud feature seen on the imagery was reproduced, but the fog patch developed at locations about 10–15 km west of the site of accident. Also, analysis of vertical cross sections at different model levels showed that the cloud- and ground-level fog were decoupled and, thus, formed independently. This is similar to the control simulation where air at 200 m was nearly saturated (Fig. 8) but separate from the ground fog patch. We believe that the sequence of events and salient features of this simulation are very similar to the control run. As mentioned previously, the moist blob of air that formed at the lake shore traveled with the mean flow over the cooler ground where it saturated and formed fog. Because of the small differences in wind direction and location of the convergence zones in comparison with the control case, the location of the fog patch was inaccurate.

We point out that the above runs were not “true” forecasts but rather were diagnostic studies, because weather analyses obtained in the data assimilation cycle were used to specify boundary conditions for the simulations. To obtain a true forecast, a 30-h simulation with GEM starting at 1200 UTC 2 September was performed to obtain initial and lateral boundary conditions for MM5. This MM5 simulation (III) was apparently inferior to the control and simulation II because it produced fog already at 1000 UTC 3 September. The fog spread over the wide area by 1200 UTC, that is, when the accident occurred (Fig. 16).

We are convinced that the scale of the fog event and the number of factors that could possibly affect the results make this study highly suitable for ensemble modeling with a carefully designed set of the initial conditions.

4. Conclusions

An extremely dense fog event that occurred in southern Ontario and led to multiple collisions on a highway was analyzed. Because of the small scale of the event and lack of in situ measurements in the area of the accident, the analysis of the fog is difficult and no definitive answers on fog formation can be given. Satellite imagery provided valuable information on the presence and movement of a cloud feature in the vicinity of the accident site. Downward mixing of this cloud could lead to ground-level fog formation.

Numerical investigation with MM5 favored a scenario in which a moist mass of air formed at the shore of a nearby lake, which was subsequently advected over cooler land, leading to air saturation at the accident site. The role of the land and lake breeze circulations was crucial for the fog formation in this case. Sensitivity of the model results to the initial conditions and physical parameterizations suggest that the authors’ persistence,
and not only the model skill, contributed to the apparent accuracy of simulation of such a small-scale event. Also, different scenarios of the fog formation cannot be excluded, especially because the model lacks comprehensive parameterizations of vegetation and aerosol microphysics. We suggest that further insight into the fog formation in this area could be gained by climatological analysis of fogs in the Windsor region. Such analysis was not attempted in this study.

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APPENDIX

Role of Local Evaporation in Fog Formation on 3 September

Monteith (1957) notes that there are two important processes contributing to dew formation: distillation, when there is an upward flux of water vapor from warmer soil to the top of a vegetation canopy, followed by a condensation on the leaves; and dewfall, which occurs when surface cools to the dewpoint. In addition, when fog is present gravitational settling of droplets on the canopy can occur.

Below, we assess the likelihood of these processes in forming dew on 3 September 1999. Because of the lack of measurements of soil/ground temperature in the area of the accident, certain assumptions based on observations from nearby hourly stations and model simulations are necessary.

First, we note that no precipitation on 1 and 2 September was observed near the site of the accident and, based on NCAR reanalysis, soil moisture availability south of Lake St. Clair was below 40%. According to Garratt (1992, p. 139, their Fig. 5.9a), relative humidity at the surface for clay soil in such conditions is about 40%. Model simulations suggest that soil skin temperature south of Lake St. Clair was about 20°C, while surface stations in the area recorded 2-m air temperature from 17°C to 18°C. Based on the above, and taking into account measurements from Cabauw, Netherlands, for a grass canopy on a summer cloudless night (Duynkerke 1991), we assume that the temperature difference between soil skin temperature and the top of the canopy is about 10°C. These assumptions give specific humidity at the soil surface equal to 5.9 g kg⁻¹ and specific humidity at the top of canopy equal to 7.7 g kg⁻¹, resulting in moisture flux downward toward the soil. Thus, we conclude that distillation did not have, or had very small, contributions to dew formation at the top of the canopy.

Based on dewpoint values at surface stations nearby from 14°C to 17°C, it is possible that vapor condensed on the canopy, which could have cooled down to 10°C (dewfall). Because no fog in the area south of Lake St. Clair was observed during the night, it is unlikely that gravitational settling contributed to droplet deposition on the canopy overnight.

REFERENCES


