A Satellite-Based Fog Detection Scheme Using Screen Air Temperature

I. GULTEPE
Science and Technology Branch, Cloud Physics and Severe Weather Research Section, Environment Canada, Toronto, Ontario, Canada

M. PAGOWSKI
NOAA/Earth System Research Laboratory, Boulder, Colorado

J. REID
Science and Technology Branch, Cloud Physics and Severe Weather Research Section, Environment Canada, Toronto, Ontario, Canada

(Manuscript received 5 April 2006, in final form 28 September 2006)

ABSTRACT

A warm fog detection (air temperature > −5°C) algorithm using a combination of Geostationary Operational Environmental Satellite-12 (GOES-12) observations and screen temperature data based on an operational numerical model has been developed. This algorithm was tested on a large number of daytime cases during the spring and summer of 2004. Results from the scheme were compared with surface observations from four manned Canadian weather stations in Ontario, including Ottawa, Windsor, Sudbury, and Toronto. Initially, when all cases were included, fog detection (hit rate) by the satellite scheme ranged between 0.26 and 0.32. It is suggested that mid- or high-level clouds within the satellite imagery during the observed foggy periods affected the scheme’s performance in detecting surface-level fog for the majority of the cases. When cases with mid- and high-level clouds were removed using model-based screen temperatures, the hit rate ranged between 0.55 and 1.0. With an average false alarm rate of 0.10, the inclusion of model-based sounding values can be seen to improve results from the satellite-based algorithms by an average of 0.42. Average differences between the screen temperature and the surface-observed air temperature were found to be up to 2°C and this can likely account for some discrepancies in detecting fog. Finally, averaging GOES and model data to scales representing single data-point observations likely resulted in some of the failure of the fog algorithm.

1. Introduction

Fog formation is related to thermodynamical, dynamical, radiative, aerosol, and microphysical processes, as well as surface conditions. Within fog, the extinction of radiation at visible ranges results in low visibilities that can affect low-level flight conditions, marine traveling, shipping, and transportation. The high frequency of fog occurrence, experienced greater than 10% of the time in some regions of Canada (Whiffen 2001), requires improvements in fog nowcasting and/or forecasting models. Particularly, visibility (Vis), which is related to fog intensity, should be more accurately simulated to reduce the costs of fog-related accidents and delays at airports and in marine environments. Pagowski et al. (2004) studied a fog episode related to a major traffic accident in Canada and suggested that the forecasting of fog can be very difficult because of its high variability and its complicated physical processes occurring in the boundary layer, for example, microphysics and turbulent fluxes. In their analysis, they emphasized the importance of land surface schemes in obtaining screen temperatures at the surface (over 2-m height) that were used to predict fog formation and development.

Using NWP for fog prediction is an important issue in part because of limitations in observational techniques in detecting fog. Satellite observations cannot be used accurately for fog detection when visible channels are not available (nighttime or otherwise). When high-level clouds exist, satellite-based analyses alone cannot be used for fog detection. Surface observations over
land are also insufficient to determine the true extent of fog (Ellrod 1995) because of the scarcity of surface stations. In these situations, the integration of observations and other data are needed.

The use of satellite observations for fog studies has been discussed in many earlier studies (Ellrod 1995; Wetzel et al. 1996; Lee et al. 1997; Bendix 2002). In these studies, differencing between channel 2 (ch2; 3.9 \( \mu m \)) and channel 4 (ch4; 11.2 \( \mu m \)) from Geostationary Operational Environmental Satellite (GOES) observations, and between the channel-3 IR component (3.7 \( \mu m \)) and ch4 (11.0 \( \mu m \)) data from National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer observations, has been used to detect fog regions. Fog microphysical parameters can also be obtained using satellite observations. Using a detailed radiative transfer model together with satellite observations, fog microphysical parameters based on lookup tables were retrieved by Wetzel et al. (1996) but were not used for visibility calculations.

During the night, although fog regions can be defined (Eyre et al. 1984), fog physical characteristics (e.g., particle effective size) cannot be obtained adequately in part due to inversion layers above, where the temperature is higher than the surface temperature. Ellrod (2002) developed a method to study nighttime low cloud-base ceiling and visibility that used the difference between the GOES ch2 and ch4 temperatures, and between observed surface and ch4 temperatures. He found that the latter criterion was a better indication of low cloud products. The results from the present work also show that fog detection hit rates range between 0.55 and 1.0 when model-based screen temperatures are used to filter mid- and high-level clouds, compared with 0.26–0.32 when clouds are not removed.

Satellite retrievals can be used to estimate liquid water content (LWC) and droplet number concentration \( (N_d) \), and then for visibility if fog physical thickness is calculated accurately. Increasing \( N_d \) in warm fog conditions \( (T > 0^\circ C) \) for a fixed LWC results in a decrease in visibility. Increasing LWC also results in decreasing visibility. Visibility in most NWP models (Stoelinga and Warner 1999) is calculated using Vis–LWC relationships. However, Meyer et al. (1980) and Gultepe (2006b) showed that both \( N_d \) and LWC should be included in visibility parameterizations for warm fog conditions. These studies suggested that if \( N_d \) is not known accurately, visibility calculations cannot be obtained correctly from satellite observations or predicted from numerical models.

Many cloud forecast models, in general, use a microphysical parameterization developed by Kunkel (1984, hereafter K84), which is based on the relationship between the extinction parameter \( (\beta_{ext}) \) and LWC. For example, Bergot and Guedalia (1994a,b) used the 1D Couche Brouillard Eau Liquide model for studying fog in which they utilized the K84 relationship. The Rapid Update Cycle (RUC) model that is used commonly for operational forecasting in North America also utilizes the K84 parameterization (Benjamin et al. 2004) for visibility calculations. Stoelinga and Warner (1999) extensively studied the extinction of hydrometeors as a function of their condensed water content in which the K84 parameterization was used for warm fog conditions and liquid clouds. In contrast, Bott and Trautmann (2002) developed a model that predicted both \( N_d \) and LWC. Their work showed that droplet number concentration should be a prognostic variable used to calculate visibility. The latter study suggested that fog physics is very important and LWC alone is not be sufficient to calculate Vis in numerical forecast models.

In this study, the operational regional Global Environmental Multiscale (GEM) model (Belair et al. 2003; Côté et al. 1998) is used to obtain the screen temperatures to be included in the analysis of a satellite-based daytime fog algorithm. The objective is to develop an algorithm that uses both operational model data and GOES observations to detect fog regions. Presently, the GOES-based algorithms use only channel differencing between channels 2 and 4 observed at the cloud (fog) top. The results are verified using surface observations collected at the four stations in the Ontario, Canada, region from 1 March to 30 September 2004. The results are then evaluated using forecasting statistics such as hit rate and false alarm rate.

2. Data

Data extracted from 1) GOES-12 observations, 2) the GEM regional operational model, and 3) surface station observations were used in the analysis and are summarized below.

a. GOES-12 satellite observations

Satellite imagery was obtained from GOES-12 observations. Reflected radiances measured at five channels are available from the multispectral imager instrument aboard the GOES-12. The time resolution of the imagery is approximately every 15 min. Channel-1 (visible; 0.5–0.7 \( \mu m \)), -2 (near IR; 3.8–4.0 \( \mu m \)), and -4 (thermal IR; 10.2–11.2 \( \mu m \)) albedos and brightness temperatures are used here, with native ground resolutions of 1, 4, and 4 km, respectively. Details of the GOES-12 observations can be found in Schmit et al. (2001).

This study uses a satellite sector covering south-central Ontario and Quebec, Canada, centered at (45°N, 77°W). During postprocessing procedures, chan-
channel data are registered to approximate 5 km² pixels, creating an image over the study area approximately 900 × 1200 km² in size.

b. Operational model data

The operational numerical model data were obtained from the Canadian Meteorological Centre (CMC). In this analysis, forecast screen-level temperature (Tsc) and relative humidity with respect to water (RHw) data from the 0000 UTC run of the regional GEM model were used. Prior to 18 May 2004, the regional GEM model had a horizontal resolution of 24 km. After this date, upgrades to the operational model by CMC increased the resolution to 15 km. The time resolution was 450 s (Mailhot et al. 2006; Bélair et al. 2003) and the model output was obtained every eight time steps (instantaneous, not averaged).

c. Surface observations

Hourly surface observations were retrieved from Environment Canada climate archives for four weather stations in south and central Ontario. These stations are listed in Table 1. A map of their locations is shown in Fig. 1. This area has fog occurrence about 10% of the time per year and is consistent with work by Whiffen (2001). The main observations used in the analysis from the surface observations are temperature (Tso), relative humidity with respect to water, and visibility. Visibility is obtained based on human observers that report “prevailing visibility,” which is an “average” value of the horizontal visibility around the airport determined by identifying specified targets at known distances as defined by Atmospheric Environment Service (1977).

3. Method

In this section, the analysis is divided into four sections relating to surface observations, satellite data, model data, and statistical data analysis, and they are given below.

a. Surface observations analysis

Hourly observations from each of the four weather stations were examined between the dates of 1 March and 30 September 2004 for warm fog events (T > −5°C). Off-hour “special” reports were not included. For this comparison, only daytime events were selected; that is, solar zenith angles in the satellite images were <70°. Observed fog events at the surface were categorized as those that had, at minimum, three consecutive hours of fog (listed under the “weather” column of the station reports) with at least some of those hours being in the daytime. After matching these times with the available satellite and NWP data, 19, 25, 31, and 24 cases of fog (total of 99 cases) were identified at Ottawa (YOW), Windsor (YQG), Sudbury (YSB), and Toronto (YYZ), Ontario, respectively. The same number of random no-fog hours (99 h) out of the 198 cases was also selected at each station to balance the comparison statistics with foggy cases. In this selection, it is assumed that the random sample of 99 no-fog events has the same distribution as the whole sample of 198 cases.

b. Satellite data analysis

The 198 events, including 99 foggy and 99 no-fog cases, were processed using the warm fog satellite detection scheme described below. Model data from the closest forecast hour were used in the algorithm. For example, when a satellite image at 1615 UTC is processed, model data from the 16-h forecast are chosen and so forth. A 3 × 3 pixel (15 km × 15 km) area centered at each of the four weather stations was extracted for comparison against the surface observations for the corresponding hour. Results from the satellite scheme were considered “foggy” if at least one out of nine pixels were classified as foggy by the detection scheme. If a large uncertainty occurs in an input parameter, the criteria given in Table 2 can likely eliminate the pixel from being considered foggy. The comparisons between surface observations and model values are made by using the model output, representing a 15-km scale, over each weather station.

Warm daytime fog regions were identified in GOES-12 imagery using the criteria given in Table 2. On a pixel-by-pixel basis, each satellite pixel was individually checked for the conditions specified in Table 2. In order for the scheme to detect the presence of low cloud/fog, tests 1, 3, and 4 in Table 2 must be satisfied. The first test is an indicator of reflectance from cloud tops. The second test is an indicator of mid- and high-level clouds. The third test is a condition to specifically check for liquid water clouds. For this criterion, daytime ch2 data are first separated into their shortwave (SW) albedo and IR components. This separation is applied using the method given in Welch et al. (1992). This method is effective in discriminating the water phase from the ice phase using the SW albedo, although it is a rough ap-
proximation to the true ch2 albedo. Then, the SW albedo component is used to identify liquid water phase clouds. For the fourth criterion, the ch2−ch4 IR temperature difference test is used as an indicator of liquid water phase.

Following the cloud mask tests, criteria 5–8 in Table 2 all need to be satisfied for the satellite pixel to be considered foggy. The solar zenith angle (SZA) condition simply confirms daytime conditions. In test 6, it is assumed that $|T_{ch4} - T_{sc}| < 10^\circ C$ approximately represents a maximum height of 1000 m if the dry-adiabatic lapse rate is assumed. This assumption is made to increase the chance of detecting fog formation.

It is clear that if the air is saturated and well mixed, the fog-layer thickness can become more than 1000 m. The $T_{ch4} > -5^\circ C$ condition is used to represent the liquid phase of fog because droplets are very commonly found at temperatures warmer than $-5^\circ C$ (Gultepe and Isaac 2004).

c. Model data analysis

The occurrence of fog over small scales is possible when RHw (~80%) from a large-scale model (e.g., <50 km) is less than 100% (as shown later; see Fig. 3). This value (80%) can be increased when high-resolution models (with grid sizes of less than 1 km) are applied for fog forecasting.

Screen-level temperature was obtained from an interpolation between the surface skin temperature estimated using surface–land schemes (Bélaïr et al. 2003) and the air temperature at the first atmospheric model level around 50 m. The interpolation is done using surface-layer stability functions. Surface screen temperature comparisons between two model runs with 15- and 24-km resolutions have been studied and related information can be found online (http://www.msc.ec.gc.ca/cmc/op_systems/). These comparisons indicate that differences in Tsc were negligible. For this work, using a Lagrangian bicubic interpolation method, numerical model data were interpolated to the same ground resolution as the postprocessed satellite data (5 km).

d. Statistical analysis

The following statistical descriptions, including hit rate (HR), false alarm rate (FAR), and true skill sta-
tistics (TSS), are used to evaluate the success of the fog algorithm. Here, HR is a measure of the accuracy of the validation. FAR is the fraction of predictions of fog that were not actually observed. TSS is the measure of relative forecasting accuracy; a value close to 0 or 1 represents a forecast with no skill or a perfect forecast, respectively. Details on statistical analysis and definitions are well known and they can be found in the works of Stanski et al. (1989), Tapp et al. (1986), Woodcooke (1976), and Saseendran et al. (2002).

4. Results

In this section, two examples, representing a good case and a bad case, are described. A good case refers to the availability of low-visibility values for a specific location from the surface and satellite observations, and operational model data. A bad case refers to the failure of fog detection and forecasting at a particular location. After describing these case studies, an overall evaluation of the results for all of the 198 events, including foggy and no-fog cases, based on the statistical concepts is provided and discussed.

a. Case studies

1) 3 September case (no high-level clouds)

For this case, the average model surface temperature was 19.6°C and the observed dry-bulb temperature was 17.1°C at 1300 UTC at YYZ. Figure 2 is a digital picture of the fog conditions at approximately 1140 UTC taken in the greater Toronto area (GTA), just north of the city limits. Figure 3a shows the observed surface temperature, visibility, and averaged GEM operational model-based screen surface temperature. The observed visibility was 1.6 km and fog was recorded in the hourly surface report at 1300 UTC. Averaged model-based RHw during fog episode was 82% (Fig. 3b) and the observed RHw was 100%. Based on this result, a low RHw value criterion for the fog algorithm was chosen. Figure 4 depicts a series of GOES-related images. The time of the satellite data is 1315 UTC, while the model data are for the 1300 UTC forecast hour. Figure 4a shows that the ch2 IR cloud-top temperature (Tt) indicates some clouds were near Toronto. The IR image from ch4 (Fig. 4b) did not indicate any fog/low clouds over the Lake Ontario region, specifically at YYZ. Figure 4c shows the Tch2 – Tch4 difference. When it is greater than 10°C, the pixel is accepted as containing liquid water. For this case, this test was able to identify liquid water clouds in southern Ontario. The fog regions are also identified in the channel-2 albedo (Ach2) image (albedo ≥ 0.08 indicates a likelihood of liquid water) in green (Fig. 4d). The operational GEM re-

2) 31 July case (with high-level clouds)

In the case of mid- and high-level clouds, satellite-based algorithms do not work but summarizing this condition here helps to show the applicability of an operational model. For this case, the results are summarized similarly to those for the 3 September case. The time series of surface observations and GEM model data at YYZ are shown in Fig. 6. The RHw and T values from the GEM model and the observations were found to be comparable. Reported visibility was 2.4 km, and fog and rainshowers were recorded in the hourly surface report at YYZ at 1300 UTC. Figure 7
The satellite data were collected at 1315 UTC, while the model data are for the 1300 UTC. A swath of cold cloud is seen across the image covering Lake Ontario and the GTA. This is indicated by the white-colored clouds in ch2 and ch4 (Figs. 7a and 7b). The average Tt over YYZ from GOES ch4 was 30.8°C. Figure 7c shows Tch2 > Tch4 > 10°C areas of liquid water cloud or fog in the vicinity of YYZ. Liquid water cloud regions are also identified in the Ach2 image in areas west of the GTA, but not at YYZ (Fig. 7d). High-level clouds, indicated by dark blue color, with smaller albedo values are seen in and around the GTA. The model surface screen temperature was about 20°C at YYZ (Fig. 7e) and the observed dry-bulb temperature was 19.6°C at 1300 UTC at YYZ (Fig. 6). The model RHw was 95% (Fig. 7f) and the observed RHw was 98%.

The derived GOES fog product indicates cloudy regions over most of the study area (Fig. 8). Fog was not detected at YYZ, over which the cold clouds were seen. In this case, high-level clouds obscured the fog conditions below, making fog undetectable by the satellite algorithm. Some fog areas are seen farther west, indicating that foggy layers were likely to exist below the low-level clouds over the YYZ area, and this is verified with low visibility values observed at YYZ (Fig. 6) and high RHw values from the GEM model. If high- and midlevel clouds exist, then a high-resolution GEM model together with surface observations should be used for fog forecasting rather than a satellite-based algorithm.

b. Statistical evaluations

The results for the 198 cases were analyzed by HR, FAR, and TSS. Here, HR is computed as the fraction of GOES foggy samples by the total number of foggy observations reported at the surface. FAR is the fraction of GOES fog predictions by the total number of reported nonfoggy observations. The true skill score is HR – FAR. These results are summarized in Table 3. The HR for the four stations ranged between 0.26 and 0.32 and for all cases combined was 0.28. The FAR reached up to 0.20 for individual stations.

When all cases with |Tt – Tsc| > 10°C were removed (implying mid- or high-level clouds) from the initial dataset, a total of 63 (out of 198) cases remained. Similar skill statistics as in Table 3 were generated and are shown in Table 4. When cases with suspected mid- or high-level clouds are removed, the HR at each of the stations was improved significantly from those in Table 3. The HR ranged from 0.55 in Windsor, Ontario, to 1.00 in Ottawa. The FAR values were less than 0.17. Overall the TSS ranged between 0.55 and 0.86, and the TSS was 0.59 for all four stations combined. The average improvement in the TSS was found to be 0.42, indicating that the inclusion of model-based data in the algorithms could significantly improve fog forecasting.

5. Discussion

In this section, uncertainties related to the GOES-based algorithm and screen temperatures obtained from the GEM operational model runs are discussed.

a. Model-based screen temperature (Tsc) – observed surface temperature (Tso)

Because surface temperatures play an important part in the satellite detection scheme, the ability of the numerical model to forecast this parameter plays an important factor in the satellite algorithm’s overall performance. For this reason, a comparison was made between the model screen temperatures (Tsc) against the values actually observed (Tso) at the stations. Average model screen temperatures across the 3 × 3 pixel grid were computed for each of the cases at each station and then differenced from the reported dry-bulb temperature at that hour. Absolute average, and minimum and maximum differences were computed and are shown in Table 5.

The average absolute temperature difference (ΔTso) between the model and surface observations was between 1.4° and 1.8°C. Some of these differences are
likely in part due to comparisons made between point observations and scaled averaged values from the model runs (Gultepe and Isaac 1999). A cold bias can also contribute to this uncertainty and this is explained in section 5c. Generally, it was found that the model and observations gave comparable values during this analysis and thus it was unlikely a large factor in any differences seen between the satellite scheme and the observations. Wilson and Vallée (2002, 2003) have developed a method to correct Tsc values across Canada. Using CMC’s updateable model output statistics procedure, surface temperatures at land stations (at approximately 700 sites across Canada) were corrected at the lowest level of the model (eta level = 1 correspond-
ing to ~50 m) with statistical postprocessing. This correction was done at every 3 h out to 48 h based on the GEM regional model. Although the same technique can be used for correcting Tsc in this work, because of differences in time resolution, their method is not included in this analysis.

b. GOES fog-top temperature (Tt) – observed surface temperature (Tso)

One of the caveats of a satellite-based algorithm is the potential for mid- or high-level clouds to obscure fog conditions underneath. If this situation occurs, then the fog scheme would result in a report of nonfoggy conditions. This may in part account for the high number of occurrences in Table 3 when the satellite scheme deduced no-fog conditions while fog was reported at the surface.

A simple test for mid- and high-level cloud identification is differencing the temperature between the surface and the cloud tops (test 2 in Table 2). If the temperature difference is relatively large (e.g., \( >10 \, ^\circ C \)), then there may be evidence of these types of clouds. For cases when the stations reported fog and GOES produced nonfoggy results, absolute Tt – Tsc differences were examined. Averages of these differences for the 3 \times 3\ pixel grid were calculated and are shown in Table 6 for all four stations. The calculations show an absolute average temperature difference of between 31\(^\circ\) and 35\(^\circ\) C across the four stations for such cases. Maximum temperature differences were greater than 60\(^\circ\) C on several occasions, indicating that there were likely cold, high-level clouds in the satellite image. The average \( |Tt - Tsc| \) difference for only 3 out of 71 of these cases was below 10\(^\circ\) C (once for YOW and twice for YSB). Because the model surface temperatures are unlikely in question (see previous section), it is suggested that mid- or high-level clouds existed for the majority of cases when fog was observed at the surface but was not determined by the satellite method.

c. Overall discussion and future work

Fog detection using satellite observations has been studied in previous works by Ellrod (1995), Bendix (2002), and Lee et al. (1997). Ellrod (1995) showed that cloud physical thickness can be obtained using tem-

![Figure 5](http://journals.ametsoc.org/waf/article-pdf/22/3/444/4640196/waf1011_1.pdf)
perature differences from GOES ch2 and ch4. This method will not work, however, when mid- and high-level clouds are present. Their method can be compared with the method given here, which is based on both numerical model output and satellite observations. It is clear that when satellite observations are not applicable to a case with mid- and high-level clouds, model-based LWC values together with other surface observations should be used to estimate visibility as described in Gultepe et al. (2006b) and Gultepe and Isaac (2004).

Using a high-resolution model run for a given grid point, the fog’s physical thickness can be easily obtained from the results of the present work, which utilizes both Tsc and Tt parameters. Using both the fog physical thickness and model-based heating rate, the dissipation time of a fog layer can be calculated. This result could then be used for aviation and transportation applications.

Using operational models, fog regions and visibility in the BL can be determined. The RUC model presently uses physical parameterizations to calcu-
late visibility (Benjamin et al. 2004; Smirnova et al. 2000). Their visibility calculations were based on LWC values obtained using the parameterized equations given in Stoelinga and Warner (1999). They also calculated visibility using RHw values when clouds did not occur. These parameterizations were not available in GEM simulations that could have been used for further validations for the method presented here.

The relationships between visibility and $N_d$ were studied by Gultepe et al. (2006a,b), who showed that $N_d$ should be used in visibility parameterizations that include only LWC. This study suggested that visibility could be obtained as a function of both LWC and $N_d$, and therefore the new parameterizations together with satellite-based algorithms that use high-resolution numerical model output can directly be used to obtain visibility. Integration of the satellite-based algorithms and regional high-resolution (e.g., 2.5 km in the horizontal scale) operational forecast model outputs can be utilized for fog nowcasting. The use of surface observations to predict foggy conditions for a short-time period (<3 h) integrated with satellite- and model-based data can improve fog-related prediction skills. This suggests that better forecasting skills could improve fog nowcasting at airports and remote unmanned airfield areas, as well as marine environments, in which observations are not usually available.

<table>
<thead>
<tr>
<th>Station name</th>
<th>GOES algorithm</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>YOW</td>
<td>Surface obs fog: yes</td>
<td>5 14 19 0.26 0.05 0.21</td>
</tr>
<tr>
<td></td>
<td>Surface obs fog: no</td>
<td>1 18 19</td>
</tr>
<tr>
<td>YQG</td>
<td>Surface obs fog: yes</td>
<td>8 17 25 0.32 0.20 0.12</td>
</tr>
<tr>
<td></td>
<td>Surface obs fog: no</td>
<td>5 20 25</td>
</tr>
<tr>
<td>YSB</td>
<td>Surface obs fog: yes</td>
<td>8 23 31 0.26 0.06 0.20</td>
</tr>
<tr>
<td></td>
<td>Surface obs fog: no</td>
<td>2 29 31</td>
</tr>
<tr>
<td>YYZ</td>
<td>Surface obs fog: yes</td>
<td>7 17 24 0.29 0.13 0.16</td>
</tr>
<tr>
<td></td>
<td>Surface obs fog: no</td>
<td>3 21 24</td>
</tr>
<tr>
<td>Tot</td>
<td>Surface obs fog: yes</td>
<td>28 71 99 0.28 0.11 0.17</td>
</tr>
<tr>
<td></td>
<td>Surface obs fog: no</td>
<td>11 88 99</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station name</th>
<th>GOES algorithm</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>YOW</td>
<td>Surface obs fog: yes</td>
<td>5 0 5 1.0 0.14 0.86</td>
</tr>
<tr>
<td></td>
<td>Surface obs fog: no</td>
<td>1 6 7</td>
</tr>
<tr>
<td>YQG</td>
<td>Surface obs fog: yes</td>
<td>6 5 11 0.55 0.0 0.55</td>
</tr>
<tr>
<td></td>
<td>Surface obs fog: no</td>
<td>0 5 5</td>
</tr>
<tr>
<td>YSB</td>
<td>Surface obs fog: yes</td>
<td>6 2 8 0.75 0.17 0.58</td>
</tr>
<tr>
<td></td>
<td>Surface obs fog: no</td>
<td>2 10 12</td>
</tr>
<tr>
<td>YYZ</td>
<td>Surface obs fog: yes</td>
<td>5 3 8 0.63 0.0 0.63</td>
</tr>
<tr>
<td></td>
<td>Surface obs fog: no</td>
<td>0 7 7</td>
</tr>
<tr>
<td>Tot</td>
<td>Surface obs fog: yes</td>
<td>22 10 32 0.69 0.10 0.59</td>
</tr>
<tr>
<td></td>
<td>Surface obs fog: no</td>
<td>3 28 31</td>
</tr>
</tbody>
</table>
The accuracy of the GEM model screen temperature

A cold bias at the surface from operational GEM runs is usually seen and needs to be improved because $T_{sc} - T_{so}$ in the present work reaches up to 2°C. This may cause some fog detection problems related to RHw and $T$. More information on this topic can be found online (http://www.msc.ec.gc.ca/cmc/op_systems/). A new version of GEM called the GEM Limited Area Model (GEM-LAM) has its horizontal and vertical resolutions set at 0.0225° (~2.5 km) and 58 levels, respectively. The lowest vertical level for the GEM model is at approximately 50 m. The output of the operational GEM-15 run at 0000 UTC is being used to provide the initial and boundary conditions for the two runs. They are being initiated at 1200 UTC and provide hourly forecasts out to 24 h. The aim of the GEM-LAM project is to develop a high-resolution model that offers a better representation of the local conditions (orography, vegetation, etc.), physical processes (cloud microphysics, radiation, etc.), and dynamical organization of weather systems at all scales. Therefore, it will be better suited for fog studies. The GEM-LAM operational/research-oriented versions will be used for fog and visibility analysis. Clearly, state-of-the-art high-resolution model development will be very helpful for fog nowcasting/forecasting. In future studies, use of such a LAM model for short-time forecasting would be very useful in planning field projects such as the Fog Remote Sensing and Modeling program (Gultepe et al. 2006a).

### 6. Conclusions

The case studies analyzed from the spring–summer of 2004 showed that a satellite-based warm fog detection scheme using model-based screen temperature had an average relative forecasting accuracy of 59% when compared with reports from four surface observation stations in Ontario. Model-based screen temperatures were used to remove cases of mid- and high-level clouds that interfered with the satellite-based method. Also, when optically thin fog occurs, a significant contribution from the surface to the reflected radiance in the visible and near-IR channels can complicate the algorithm.

The following conclusions are drawn from this work.

- The mean HR is estimated to be 0.28 when mid- and high-level clouds are considered. When cases with suspected mid- or high-level clouds are removed, the satellite- and model-based scheme’s mean HR increased to 0.69 overall, with individual success rates of between 0.55 and 1.0.
- The accuracy of the GEM model screen temperatures is very crucial for increasing HRs. The comparisons between $T_{so}$ and $T_{sc}$ indicate that differences between them can be up to 2°C.
- Using both GOES observations and model-based sounding data, forecasting results would be improved on average by 0.42.
- It is possible that the use of the RHw > 80% criteria based on a forecasting model can result in higher occurrences of fog conditions and it needs to be improved.
- GOES satellite algorithms based on only channel differencing cannot work accurately when an elevated fog layer occurs. In this case, high-resolution model

### Table 5. Absolute average, and minimum and maximum temperature differences between model-based screen temperatures ($T_{sc}$) and surface-reported values ($T_{so}$) for the 198 cases.

<table>
<thead>
<tr>
<th>Diff (°C)</th>
<th>YOW</th>
<th>YQG</th>
<th>YSB</th>
<th>YYZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg</td>
<td>1.5</td>
<td>1.8</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Min</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Max</td>
<td>5.2</td>
<td>7.2</td>
<td>5.6</td>
<td>7.3</td>
</tr>
</tbody>
</table>

### Table 6. A listing of GOES cloud-top temperature ($T_{t}$) and model screen temperature ($T_{sc}$) absolute differences for cases when the satellite method returned nonfoggy results compared with a reported fog event by the surface station. Average, minimum, and maximum differences are provided in the last three rows from the top to the bottom, respectively.

<table>
<thead>
<tr>
<th>Station name</th>
<th>YOW (14 cases)</th>
<th>YQG (17 cases)</th>
<th>YSB (23 cases)</th>
<th>YYZ (17 cases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>56.1</td>
<td>23.3</td>
<td>16.4</td>
<td>18.0</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>41.8</td>
<td>57.4</td>
<td>5.5</td>
<td>26.2</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>59.3</td>
<td>21.0</td>
<td>38.5</td>
<td>19.4</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>45.7</td>
<td>23.8</td>
<td>4.2</td>
<td>23.0</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>21.7</td>
<td>78.8</td>
<td>33.4</td>
<td>52.9</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>20.1</td>
<td>11.3</td>
<td>31.5</td>
<td>26.4</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>13.2</td>
<td>20.8</td>
<td>35.5</td>
<td>42.6</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>20.9</td>
<td>44.7</td>
<td>59.2</td>
<td>25.5</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>38.9</td>
<td>20.9</td>
<td>49.6</td>
<td>23.4</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>61.2</td>
<td>58.3</td>
<td>30.5</td>
<td>12.7</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>2.8</td>
<td>15.8</td>
<td>39.4</td>
<td>51.5</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>30.7</td>
<td>16.6</td>
<td>15.3</td>
<td>31.0</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>18.9</td>
<td>25.4</td>
<td>23.0</td>
<td>25.5</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>55.4</td>
<td>46.7</td>
<td>65.3</td>
<td>28.7</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>31.0</td>
<td>35.6</td>
<td>55.7</td>
<td>15.7</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>44.9</td>
<td>19.8</td>
<td>51.3</td>
<td>19.8</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>12.9</td>
<td>59.5</td>
<td>56.0</td>
<td>56.0</td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>10.9</td>
<td>30.4</td>
<td>14.6</td>
<td></td>
</tr>
<tr>
<td>$T_{t} - T_{sc}$</td>
<td>43.9</td>
<td>37.8</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>Avg</td>
<td>34.8</td>
<td>32.6</td>
<td>30.9</td>
<td>31.2</td>
</tr>
<tr>
<td>Min</td>
<td>2.8</td>
<td>11.3</td>
<td>4.2</td>
<td>12.7</td>
</tr>
<tr>
<td>Max</td>
<td>61.2</td>
<td>78.8</td>
<td>65.3</td>
<td>56.0</td>
</tr>
</tbody>
</table>
runs should be integrated into a decision-making system.
At times when fog can be properly deduced from the analysis of satellite- and model-based data, microphysical parameters, including liquid water path, mean droplet diameter, and visibility, can also be determined using traditional lookup tables that incorporate radiative transfer equations (Minnis et al. 1998; Wetzel et al. 1996). Satellite data can also be used to derive such fog-related information using parameterizations that have been developed using aircraft measurements (Gultepe and Isaac 2004; Gultepe et al. 2006b).

Acknowledgments. This work was accomplished with continuous discussions and support of many individuals at Environment Canada (EC), and we are especially thankful to Dr. G. A. Isaac of the Cloud Physics and Severe Weather Research Section for scientific discussions during the course of this work. Funding for this work was provided by the Canadian National Search and Rescue Secretariat, Environment Canada, and Transport Canada. Some additional funding was also provided by the European COST-722 fog initiative project office. Technical support for the data collection was provided by the Cloud Physics and Severe Weather Research Section of the Science and Technology Branch, Environment Canada, Toronto, Ontario. The authors are also thankful to J. Milbrandt and S. Belair of RPNI, Environment Canada, Montreal, Quebec, and Dr. W. Jacobs, Langen, Germany for discussions during the course of this work.

REFERENCES


