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14A.5 AUTOMATED FOG AND STRATUS FORECASTS FROM THE CANADIAN RDPS OPERATIONAL NWP MODEL

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1. INTRODUCTION

Canada is a very large northern country spanned for great distances by air, ship, rail, and highway travel, much of it over remote territory. Surface observations are not available over large portions of the country yet virtually all of the country must be covered by one or more of public, aviation, road, and marine forecasts. Dense fog and low stratus ceilings occur somewhere in the country on most days. There is a need for forecasts of likely areas of dense fog and low stratus ceilings on a national Canadian domain using NWP guidance without requiring direct input of current observations.

Forecasting low visibility in fog and low ceilings in stratus is one of the challenging tasks for a meteorologist. Most of the physical processes that cause fog and low stratus ceilings have been known for a long time (e.g. Petterssen, 1956; Peak and Tag, 1989; Teixeira, 1999; Baker et. al, 2002), but accurate prediction has remained difficult due to the requirement for very high resolution in modeling and initial data observations. Large domain direct prediction of fog and stratus ceilings is not done by the Canadian Regional Deterministic Prediction System (RDPS) (formerly known as the regional GEM model), and will not be for a long time to come. Numerical models for short –term forecasts have been deployed for point-specific forecasts in other countries but these are highly sophisticated models which are not suitable for longer term forecasts over large areas due to computer resource and data observation requirements (e.g. Stoelinga and Warner,1999; Tardiff, 2006). The most effective method for timely production of longer term forecasts of fog and stratus over large areas still remains a diagnostic approach (Zhou and Du, 2010).

There have been various diagnostic methods devised to produce forecasts of fog and stratus over the years, many based on nomograms involving theoretical and observed relations between temperature and dewpoint. As computer capability has increased, recent systems for producing large-area guidance have centered around diagnostic approaches to make forecasts from NWP output using machine learning (e.g. Marzban et al. 2007) and physically-based rules using input from NWP model forecasts (e.g. Peak and Tag,1989; Baker et al., 2002; Zhou and Du, 2010). Our goal was to devise a comprehensive system of rules driven by regional RDPS output to make real time hourly forecasts from 1-48 hr of low visibility fog (½ mile or less) and low stratus (ceiling 500 ft or less) covering all Canadian land and marine areas.

Baker at al. (2002) describe the physical processes that give rise to radiation fog and stratus formation and present a rule-based procedure for diagnosing the likelihood of fog or stratus formation from conditions at the ground and in the near-surface boundary layer. Fog is forecast to occur when the air temperature decreases to a “crossover temperature” which is usually below the dewpoint. This is the temperature where the flux of moisture at the surface reverses sign from upward to downward. The forecast of fog is changed to stratus if it is determined by a bulk Richardson number threshold value that boundary layer turbulent mixing will lift the fog off the ground. The Baker et al. (2002) method is primarily designed to forecast radiation fog over land in relatively warm air masses in areas that receive significant hours of sunlight. These conditions occur over most of Canada in the warmer months. However for much of the year, especially in northern Canada, we deal with cold air masses, little or no daylight, snow and ice covered ground ranging from none to completely covered, vast surface areas of mixed land and water and large open water areas, both frozen and unfrozen, and coastal air flow. While we were able to use the Baker at al. (2002) method to forecast radiation fog, we needed to modify their rules and design additional new rules to cover the many different scenarios under which fog forms over land and marine areas in Canada.

We are concerned primarily with high impact fog and stratus, which we define as fog with 1/2 mile or less visibility and stratus with ceiling 500 ft or less. In Section 2 we show our rules for forecasting dense fog and low-ceiling stratus formed by the several different processes we know about. These rules are formed by comparing direct and derived fields output by the RDPS with observations valid at the same time as the RDPS forecast. Once the likelihood of fog or stratus has been diagnosed from rules of each type, a combined forecast is determined by the union of the fog and stratus forecasts from all rules, thus overlapping of fog and stratus forecast by rules for different processes is not a concern. A final forecast of high impact fog and stratus is made from the combined forecast by post-processing the combined forecast according to the bulk Richardson number. The final forecast has 4 categories: “NO FOG and NO STRATUS”, “STRATUS”, ”FOG or STRATUS”, and ”FOG”. It should be noted throughout this paper that when we say fog and stratus we mean fog with 1/2 mile or less visibility and stratus with ceiling 500 ft or less.

2. PROCESS TYPES and FORECAST RULES

Our rule-based system covers fog and stratus formation over land, water, snow, and ice surfaces. Over large areas of Canada there is a mixture of land and water surfaces. Land surfaces can be fully to partially snow-covered or devoid of snow, water surfaces can be open to fully or partially frozen. The concept of a “crossover temperature” suggested by Baker et al (2002) is adopted in our algorithms for radiation fog advection fog over land. We also adopt their concept of using the modified Richardson number to forecast the possibility that sufficient boundary layer turbulence can cause a low stratus ceiling rather than a ground-based layer of fog. However, fog and low stratus can form from other causes besides radiation cooling at any time of day or night, and modification of the situation at the ground can occur. A brief summary of physical considerations we make for fog and stratus formation follows.

A situation where fog or stratus is likely is diagnosed from the relative air-surface temperature difference, humidity in the air and the vertical gradient of humidity, sources of liquid water at the ground and rain or snow falling from above, the vertical motion component of the air flow near the ground, and the degree of moisture convergence in air near the ground. Together with a large solid land surface Canada has the world’s longest coastline, both saltwater and freshwater. In coastal areas in offshore flow we use rules for fog and stratus formation over land while in coastal areas with onshore flow we use rules for fog formation over a marine surface. The water side of a coastline can be open water or ice-bound, both scenarios requiring separate rules. The Canadian terrain varies from smooth to rugged, so low-level vertical motion is important. Fog or stratus will dissipate in downslope airflow and can form more easily and last longer in upslope airflow, depending on convective stability. A stratus ceiling will lower, sometimes to the ground, in sustained rainfall. If snow is occurring it will scavenge water droplets in the lower boundary layer and can turn a foggy situation at the ground into a stratus ceiling. Existing fog and stratus can be advected from other areas. Fog and stratus are common in warm front situations at any time where mixing of cold air and warm, moist air on the cold side of the surface front can create a zone where the air is saturated. Persistent strong low-level inversions have poor vertical ventilation, allowing trapped moisture in the air to build to levels where dense fog can form which will not dissipate until a complete airmass change occurs. A very cold airmass passing over open water can cause “Arctic sea smoke” (steam fog) formation. Anthropogenic ice-crystal fog occurs in extremely cold temperatures in urban areas due to water vapour emission in petroleum fuel-burning engine exhausts. Over large marine surfaces fog and stratus formation are determined by the relative difference between the dewpoint in the overlying air and the water surface temperature, and this is not diurnally dependent. The surface situation is complicated over Canadian waters by ice cover. Fog is often seen when moist air flows from an open marine surface across the edge of a large ice-covered surface.

In the following sections we stipulate rules for various processes that can produce dense fog and low stratus. Variables that appear in rules are defined in Table 1. Throughout this paper we refer to vertical level numbers in the RDPS. The levels are defined in Table 2. In Table 3 we define solid, liquid, and coastal surfaces; ice and snow surfaces; upslope and downslope flow. Rules for solid surfaces are applied for land, coast with offshore flow, coast with flow onshore from ice-bound shore, and ice-covered water surface. Rules for marine surfaces are applied for open water and coastal points with onshore flow from open water. We start with rules for determining where fog and stratus are *not* likely.

2.1 FOG and STRATUS UNLIKELY

At each grid point we first check for three conditions which, if they occur, make dense fog or low stratus formation unlikely. First, fog is unlikely to form if insufficient moisture is available in the air. Second, Pettersen (1956) noted that fog usually does not form if a vertically decreasing specific humidity profile exists above the surface, and in this case radiational cooling may only result in dew or rime on the ground. Third, fog and stratus are unlikely to form if downslope airflow at or near the surface level is relatively strong. The following rules are for these conditions are:

NO FOG or STRATUS	if	$HU_2 < 4$
	.or.	HU_3 minus $HU_2 < -0.1$
	.or.	$WW_1 > 1.$

These rules are applied for all processes producing fog and stratus that we address.

2.2 RADIATION FOG and STRATUS

We forecast radiation fog and stratus over *solid surfaces* by two different methods described in the following two sections.

2.2.1 UPS-STYLE RULES

Baker et al. (2002) mention three important factors that affect the formation of fog or a low stratus ceiling, and explain the physical reasons:

a. The vertical distribution of humidity in the potential fog layer (surface to 500 feet).
b. The turbulent mixing potential of the boundary layer near the surface.
c. The ground temperature of the surface beneath the potential fog layer.

We adopt the Baker at al. (2002) concept of a *"crossover temperature (Tx)*" for radiation fog. Fog is allowed to form when the air temperature reaches or falls below Tx rather than the dewpoint. The crossover temperature is defined as follows: Under normal atmospheric conditions specific humidity decreases upwards, and in a well-mixed boundary layer the surface dewpoint will decrease during the warmest hours of the day because the flux of water vapor is directed upwards. After the warmest hours have passed the dewpoint will rise a few degrees as the upward moisture flux decreases. As evening and night progress the temperature will fall and at some time become equal to the dewpoint (saturation). The temperature and dewpoint will then fall in tandem without forming fog as long as the specific humidity decreases upwards, that is, the flux of water vapour is still upwards. As the air cools the flux of water vapour eventually reverses direction to downward at Tx. When the temperature falls below Tx there is the possibility of fog formation. Baker et al. (2002) found this temperature is approximately the minimum dewpoint observed during the warmest daytime hours the previous afternoon, assuming no other influences. We check for the possibility of "UPS-style" radiation fog over a solid surface where the maximum afternoon solar angle exceeds 30 degrees above the horizon, so that sufficient diurnal solar heating has occurred. We define Tx as the minimum dewpoint the previous afternoon when forecasting during the time when the sun has not risen more than 15 degrees above the horizon (late evening, night, and early morning). Later in the day when the sun has risen higher we use the minimum dewpoint on the current day from the time the sun rose to 15 degrees above the horizon up to the valid time of the forecast.

Local processes can alter the specification of Tx derived from the simple method described above. We modify T_X by considering five local conditions: 1) a relatively large fraction of open water in the local surface area can act as a source of moisture at the ground; 2) recent or occurring rain can act as a source of moisture from above; 3) ascending (upslope) low-level airflow can saturate the air early before Tx is reached; 4) low-level moisture advection can add to or subtract moisture from the air; 5) where the local terrain elevation is high our experience shows a bias in the RDPS towards cold temperatures, so to activate fog we ask for greater evaporation at the surface and a crossover temperature well below TX. We calculate a modified crossover temperature Tx5 with the following rules applied sequentially:

1) Tx1 = Tx + (10/3 - 10 * MG /3) * (1 - LG)

2) Tx2 = Tx1 if RN6 < 0.1
= Tx1 + 0.5 if $0.1 \le$ RN6 < 1
= Tx1 + 1.5 if $1 \le$ RN6 < 5
= Tx1 + 2.5 if $5 \le$ RN6 < 10
= Tx1 + 3.5 if $10 \le$ RN6

3) Tx3 = Tx2 if $WW_1 >= -1$
= Tx2 + 2 if $WW_1 < -1$

4) Tx4 = Tx3 + (current_θw_2 – previous_afternoon_θw_2)

5) Tx5 = Tx4 if $GZ_1 <= 500$

= Tx4 – 4 if $500 < GZ_1 \le 1000$ .and. FV < 0

= Tx4 – 5 if ($500 < GZ_1 \le 1000$ .and. FV < -2) .or. ($GZ_1 > 1000$ and FV < 0)

= Tx4 – 6 if $GZ_1 > 1000$ .and. FV < -2.

Fog may occur when the temperature falls below Tx5. However, as Baker et al. (2002) point out, if the lower boundary layer is sufficiently turbulent then vertical mixing can cause the fog to lift and form a low stratus ceiling instead. The degree of turbulence can be determined from the RDPS bulk Richardson number RB, which is equivalent to 10 times the modified Richardson number defined by Baker et al. (2002). RB is essentially the ratio of boundary layer potential energy (determined by the convective stability) to kinetic energy. A high Richardson number indicates the lower boundary layer air flow above the surface is decoupled from the air flow at the surface, thus turbulence at the surface is low and fog is more likely. A low Richardson number indicates the surface air flow is coupled with the lower boundary layer airflow, thus turbulence is greater and a low stratus ceiling is more likely. We use the criteria suggested by Baker et al. (2002) for deciding whether fog or stratus is likely over land:

FOG	if	RB ≥ 0.4
FOG or STRATUS	if	0.25 ≤ RB < 0.40
STRATUS	if	RB < 0.25.

2.2.1.1 Modifications to UPS-style Rules

The rules discussed above in this section do not explicitly consider conditions on the ground. Baker at al. (2002) discusses the importance of ground temperature as a factor for adjusting the crossover temperature. They mention that it is easier to get fog if the ground is 3 ºC or more colder than the crossover temperature, and more difficult to get fog if the ground is 3 ºC or more warmer than the crossover temperature. The rules for radiation fog can be enhanced to account for ground conditions favourable for fog or stratus formation, such as ground temperature colder than the overlying air temperature, liquid water lying on the ground or vegetation, or contained within the soil or snow pack. The source of the liquid water could be recent or presently occurring precipitation, or snowmelt. To improve our forecast results when deciding between forecasting fog or stratus we modify the above rules for radiation fog and stratus over solid surfaces. The RDPS model has a surface "skin" temperature (I0 over land, I7 over sea ice), which is the temperature on the ground. There are also water content variables I1, I3, and I4 for surface soil, vegetation, and snow pack, respectively. In flow with neutral vertical motion over solid surfaces fog or stratus are possible

if TT1 ≤ Tx5 .and. -1 ≤ WW_1 ≤ 1

.and. ((liquidI1 > 0.3 .or. liquidI3 > 0.8) .and. SD < 2) .or. (I4 > 1 .and. SD >= 2)).

If the above condition is true we forecast

FOG	if	(I0/I7 < Tx5 - 3 .and. RB ≥ .10)
	.or.	(Tx5 - 3 ≤ I0/I7 ≤ Tx5 + 3 .and. RB ≥ .25)
	.or.	(I0/I7 > Tx5 + 3 .and. RB ≥ .40)
STRATUS	if	(I0/I7 < Tx5 - 3 .and. RB < .10)
	.or.	(Tx5 – 3 ≤ I0/I7 ≤ Tx5 + 3 .and. RB <.25)
	or.	(I0/I7 > Tx5 + 3 .and. RB < .40).

Another modification to the UPS-style rules stems from consideration of the convective stability of upslope boundary layer flow over land or coastal onshore flow. If the air is convectively unstable then no fog or stratus will form because air parcels will move away from the surface. However when the air is convectively neutral or stable air parcels will be constrained to remain near the surface, and the air can become saturated due to cooling while being lifted. Our rule for *convectively neutral or stable upslope flow* uses the Monin-Obukhov length to determine the static stability of the surface layer (Stull, 1997, pp 180-182). Fog is possible in *upslope flow*

if TT1 ≤ Tx5 .and. WW_1 ≤ -1

.and. ((liquidI1 > 0.3 .or. liquidI3 > 0.8) .and. SD < 2) .or. (I4 > 1 .and. SD >= 2)).

If this condition is true we forecast

<u>FOG</u> if $OL \geq 0$ (i.e. the surface layer is stable).

We found all of the above rules combined gave too much fog and stratus at higher elevations if the relative humidity at level 1 is below 95%. Therefore before applying the UPS-style radiation fog and stratus rules at higher elevations the following rule is applied:

<u>NO FOG</u> if $GZ_1 > 500$ .and. $RH_1 < 95\%$.

2.2.2 OUTGOING LONGWAVE RADIATION AND LATENT HEAT FLUX at the SURFACE

We also forecast radiation fog and stratus over solid surfaces, whether snow-covered or not, where the RDPS model has a light wind speed at level 1 and "enough" outgoing long wave radiation at the surface using variable SI combined with "enough" evaporation at the surface using variable FV. This process is also known as evaporation fog (Pettersen, 1956). Due to a possible cold temperature bias in minimum temperatures in RDPS at higher elevations more outgoing long wave radiation is needed there to trigger fog or stratus. The RDPS also has a dry bias in the lowest levels of the boundary layer that becomes more acute with warmer, moister air masses, so we relax the requirement to trigger fog and stratus for outgoing long wave radiation depending on the value of Θw_2. Our rules are

If $0 \leq UV1 \leq 6$ kt

.and. (($\Theta w_2 \leq 5$ .and. $ES_2 \leq 3$ .and. $SI \leq -100$ .and. $FV < -2$)

.or. ($5 < \Theta w_2 < 16$ .and. $ES_2 \leq 5$ .and. $GZ_1 < 650$ .and $SI \leq -60$ .and. $FV < -2$)

.or. ($5 < \Theta w_2 < 16$ .and. $ES_2 \leq 5$ .and. $GZ_1 \geq 650$ .and $SI \leq -80$ .and. $FV < -2$)

.or. ($\Theta w_2 \geq 16$ .and. $ES_2 \leq 10$ .and. $SI \leq -50$ .and. $FV < -1$)

.or. ($.7 \leq DPN_1 \leq 2$ .and. $SI \leq -75$ .and. $FV < -2$)).

When one of these rules is satisfied we forecast

<u>FOG</u> <u>if</u> $RB \geq .25$

<u>STRATUS</u> if $RB < .25$.

The rule involving the one-hour MSL pressure change DPN1 is an attempt to forecast fog or stratus just after a weak cold front has passed, where MSL pressure is slowly rising, the ground surface is wet, and the air is still warmer than the ground.

2.3 ADVECTION FOG and STRATUS

Advection fog occurs when air moves over a surface whose temperature is colder than the dewpoint of the air. We also apply the term advection fog to the situation of evaporation into the air of liquid water lying on the ground, on vegetation, or in the snow pack. In the following rules I0/I7 means to use the surface skin temperature (I0) over land and coast with offshore flow, and to use the sea ice temperature (I7) for ice-covered sea and onshore flow on an ice-bound coast.

If the skin temperature (I0/I7) is *considerably colder* than the dewpoint of the air at level 1 we forecast

FOG   if $I0/I7 < TD_1 – 4$.

If the skin temperature is *moderately colder* than the dewpoint of the air at level 1 we consider other conditions as well in order to assess if fog or stratus is likely to form. If there is abundant water available on the ground either as water in the snow pack or liquid water on snow-free ground and vegetation, then there is an additional moisture source available to saturate the air. Another consideration is the vertical motion of the air at ground level. In *stable upslope flow* at level 1 the air can become saturated because it cools as it is lifted, and fog or stratus can develop because convective inhibition within the flow of air does not allow condensed moisture to escape. Thus

If   WW1 < -1

.and. TD_1 - 4 ≤ I0/I7 ≤ TD_1 - 1) .and. (I4 > 1 .or. liquidI1 > 0.3 .or. liquidI3 > 0.8)

we forecast

FOG   if   OL ≥ 0.

In *neutral vertical motion* at level 1 the rule is more complicated because it is harder for the air to achieve saturation. The crossover temperature concept is used here.

If   -1 ≤ WW_1 ≤ 1

.and. TD_1 -4 ≤ I0/I7 ≤ TD_1 -1 .and. (I4 > 1 .or. liquidI1 > 0.3 .or. liquidI3 > 0.8)

we forecast

FOG	if	(I0/I7 < TX5 – 3 .and. RB ≥ 0.10)
	.or.	(TX5 – 3 ≤ I0/I7 ≤ TX5 + 3 .and. RB ≥ 0.25)
	.or.	(I0/I7 > TX5 + 3 .and. RB ≥ 0.40)
STRATUS	if	(I0/I7 < TX5 - 3 .and. RB < 0.10)
	.or.	(TX5 – 3 ≤ I0/I7 ≤ TX5 + 3 .and. RB < 0.25)
	.or.	(I0/I7 > TX5 + 3 .and. RB < 0.40) .

2.4 FOG AND STRATUS OVER MARINE SURFACES

The main factors considered here are the air dewpoint temperature at level 1 relative to the underlying water surface, the relative humidity at level 2, the vertical motion at level 1, and boundary layer convergence. The separation of stratus from fog occurs at a lower Richardson number than over land because the marine surface tends to be relatively smooth with higher wind speeds than over land. For flow over open water, the basic rules for forecasting fog or stratus are:

FOG	if	TM ≤ TD_1 < TM + 2 .and. RH_2 ≥ 90% .and. RB ≥ 0.10
	.or.	TD_1 ≥ TM + 2 .and. RH_2 ≥ 90%

<u>STRATUS</u> if $TM \le TD_1 < TM + 2$ .and. $RH_2 \ge 90\%$ .and. $RB < 0.10$

These marine surface rules are also applied for coastal flow onshore from open water with neutral vertical motion. In the presence of strong enough *low-level convergence* ($DIV_1 < -.0002\ s^{-1}$) we relax these rules since moisture in the air is enhanced by converging into the local area. The *relaxed forecast rules* are

<u>FOG</u> if ($DIV_1 < -.0002$ .and. $TM - 2 \le TD_1 < TM$ .and. $RH_2 \ge 88\%$ .and. $RB \ge 0.10$)

.or. ($DIV_1 < -.0002$ .and. $TD_1 \ge TM$ .and. $RH_2 \ge 88\%$)

<u>STRATUS</u> if $DIV_1 < -.0002$ .and. $TM - 2 \le TD_1 < TM$ .and. $RH_2 \ge 88\%$ .and. $RB < 0.10$

For *ascending convectively stable coastal flow onshore from open water* (WW1 < -1) we apply a separate rule to forecast fog. There is no stratus in this case.

<u>FOG</u> if $WW1 < -1$ .and. $TD_1 \ge TM - 3$ .and. $OL \ge 0$.

If in addition there is strong enough low-level convergence ($DIV_2 < -.0002$), we relax the above rule since moisture in the air is enhanced by converging into the local area. In this case the rule to forecast fog is

<u>FOG</u> if $WW1 < -1$ .and. $DIV_2 < -.0002$ .and. $TD_1 \ge TM - 4$ .and. $OL \ge 0$.

2.4.1 Ice Edge Fog

Canada has plenty of sea ice on both the sea and fresh water bodies and there are several large lakes. We include a rule for <u>"ice-edge fog"</u> in open water areas, in which is fog caused by movement of moist air from open water across an ice edge.

If $MG < 0.3$ .and. $0.5 \le LG \le 0.95$

.and. the wind is off-water on to the ice

we forecast

<u>FOG</u> if $TD_1 > I7$.

We use $LG \le 0.95$ in this rule rather than $LG \le 1.0$ in order to weed out large areas of sea ice where $.95 < LG < 1$ but there is not a well defined ice edge.

2.4.2 Arctic Sea Smoke

Where very cold air passes from land to open water there can be a phenomenon known as Arctic sea smoke, or steam fog, due to the extreme vapour pressure gradient between the water surface and the air. Our rule for this is

<u>FOG</u> if $TT_1 < TM - 15$ .and.

(($0.3 \le MG \le 0.7$ .and. $LG \le 0.5$).or. ($MG < 0.3$ .and. $0.05 \le LG \le 0.5$))

2.5 INVERSION FOG and STRATUS

These rules apply to both solid and liquid surfaces. All fog is associated with some type of inversion and so there are several situations that can give rise to what we call inversion fog. Inversion fog is common over Canada in all months, especially in the seasonal transition months and the Arctic summer. Inversions are convectively stable, so that vertical movement of air parcels and ventilation are inhibited. A layer of trapped moisture can form and grow deeper with time if the dynamic reasons for the existence of an inversion persist. Strong inversions (temperature is several degrees higher at the top than the bottom) are usually caused by a deep persistent layer of subsiding air aloft, or in persistent cooling at the surface beneath warmer air. Extensive layers of fog and stratus can form in strong low level inversions and persist for days at a time. Weak inversions (close to isothermal) are often seen on the cold side of warm fronts or in air that is slowly rising. Fog can form even if an inversion is shallow, and is a common occurrence at night in warm humid air masses in late summer.

Not all inversions will have fog or stratus associated. Where an inversion is detected we need further analysis to determine if fog or stratus is likely. The process of fog formation in an inversion will be enhanced in the following conditions: 1) in moisture convergence below the base of the inversion; 2) upward vertical motion in the inversion layer; 3) winds remain light. Our rules are designed to detect situations when “enough” moisture is available under a “strong enough” low-level inversion that fog or stratus are likely. We apply separate rules for strong and weak inversions as well as for other types of inversion situations.

2.5.1 Type 1 Inversion Fog and Stratus

These rules apply for strong inversions. Figure 1 shows an example of a Type 1 inversion. We analyze the model output vertical profile for low level temperature inversions beginning at level 2. If an inversion is found it must pass the following four criteria before it qualifies as a Type 1 inversion:

1) If the base of the inversion is above level 11 (approximately 1300 m above ground) it is deemed to be too high above the ground, because the lapse rate below the inversion will allow greater vertical movement of air parcels thus moisture would not be trapped.

2) We analyze the moisture profile in and below the inversion to search for the top of the well-mixed moist layer. If the *top* of the well-mixed moist layer is more than 3 levels *below* the bottom of the temperature inversion then we consider the moist layer to be decoupled from the temperature inversion layer, and fog or stratus are not likely.

3) The temperature difference between the top and bottom of an inversion is calculated to determine if it exceeds a threshold temperature difference shown in Table 4. If the temperature difference does not exceed the threshold then the forecast rules for strong inversions are not applied.

4) The mean relative humidity (ML_RH_mean), mean moisture convergence (ML_MFC_mean), and mean temperature advection (ML_TA _mean) are calculated in the lowest 3 levels of the inversion. If the inversion spans less than 3 levels then these calculations are done for the 1 or 2 levels it has. If the relative humidity at *any* level in the inversion *exceeds* a threshold specified in Table 5 then the inversion is deemed to be suitable for further consideration, otherwise fog or stratus will not occur due to insufficient moisture.

When the above four conditions are all true the diagnosis of fog or stratus is determined by vertical motion at level 1, low-level static stability as determined by the Monin-Obukhov length (OL) (Stull, 1997, pp.180-182), mean relative humidity in the inversion, and mean moisture convergence in the inversion. In the rules for solid surfaces I0/I7 means use the RDPS surface skin temperature (I0) over land or a coast with offshore flow, and use the RDPS sea ice temperature (I7) for ice-covered sea or onshore flow on an ice-bound coast. Separate rules are applied for low-level upslope flow and flow with neutral vertical motion.

In low level *upslope* flow, if the relative humidity is high enough fog can occur in convectively stable or neutral flow and stratus may occur even in unstable flow. For very moist air we require greater humidity than for drier air due to a low-level dry bias in the RDPS. For marginally high relative humidity we require positive moisture convergence to produce fog or stratus. Where a Type 1 inversion has been identified and one of the following conditions is satisfied:

If $WW_1 < -1$

.and. ($\Theta w_2 > 17$

.and. (ML_RH_mean > 90 .or. (85 ≤ ML_RH_mean ≤ 90 .and. ML_MFC_mean > 0))

.or. ($\Theta w_2 \le 17$

.and. (ML_RH_mean > 87.5 .or. (82.5 ≤ ML_RH_mean ≤ 87.5 .and. ML_MFC_mean > 0)))

we forecast

<u>FOG</u>	if	OL ≥ 0
<u>STRATUS</u>	if	OL < 0.

In low-level flow with *neutral vertical motion* we need higher humidity than for upslope flow to forecast fog or stratus. When a Type 1 inversion has been identified and the following condition is true:

If $-1 \le WW_1 \le 1$

.and. (ML_RH_mean > 97

.or. ($\Theta w_2 > 17$ .and. (90 ≤ ML_RH_mean ≤ 97 .and. ML_MFC_mean > 0))

.or. ($\Theta w_2 \le 17$ .and. (87.5 ≤ ML_RH_mean ≤ 97 .and. ML_MFC_mean > 0)))

we forecast fog or stratus by the following rules:

For *solid surfaces:*

<u>FOG</u>	if	$I0/I7 < TD_1 - 3$	.and. RB ≥ .10
	.or.	$TD_1 - 3 \le I0/I7 \le TD_1 + 3$	.and. RB ≥ .25
	.or.	$I0/I7 > TD_1 + 3$	.and. RB ≥ .40
<u>STRATUS</u>	if	$I0/I7 < TD_1 - 3$	.and. RB < .10
	.or.	$TD_1 - 3 \le I0/I7 \le TD_1 + 3$	.and. RB < .25
	.or.	$I0/I7 > TD_1 + 3$	.and. RB < .40

For *liquid surfaces:*

<u>FOG</u>	if	$TM < TD_1 - 2$	.and. RB ≥ .05
	.or.	$TD_1 - 2 \le TM \le TD_1$	.and. RB ≥ .10
	.or.	$TM > TD_1$	.and. RB ≥ .15
<u>STRATUS</u>	if	$TM < TD_1 - 2$	.and. RB < .05
	.or.	$TD_1 - 2 \le TM \le TD_1$	.and. RB < .10

.or. $TM > TD_1$ .and. $RB < .15$

The idea behind the above triplets of rules for is once we determine that we have condensation under a Type 1 inversion (which is a strong inversion) then fog or stratus will occur, but the balance between fog and stratus will vary depending on the skin temperature. For example, in the triplet of rules for solid surfaces, one can consider the second rule as the "usual" case: $TD_1 - 3 \leq I0/I7 \leq TD_1 + 3$. In this case we have fog if RB >= 0.25 and stratus otherwise. Now if the skin is particularly cold ($I0/I7 < TD_1 - 3$) then fog becomes more likely (and stratus less likely), which is accomplished by using a lower RB threshold (in this case, 0.10). In the opposite case occurs when the skin is particularly warm ($I0/I7 > TD_1 + 3$), fog is less likely and stratus is more likely, which follows from using a higher RB threshold (in this case, 0.40).

2.5.2 Type 2 Inversion Fog and Stratus

Another common inversion situation that produces fog and stratus is a convectively stable layer of air in the boundary layer that is mainly saturated or near-saturated. This can occur when a layer of stable air has been gently rising for a long time or if it has become saturated by cooling or evaporation from the surface. The inversion need not be strong, in fact often it is nearly isothermal. An example of a Type 2 inversion is shown Figure 2. We look for the degree of saturation without identifying the cause, the inversion base, or its strength. We count the number of levels where (T – Td) <= 1.2 from level 2 up to the last level in the inversion that is below 1300 m above the ground. If this number is at least 80% of the total number of levels in this layer, for *solid* surfaces we forecast

FOG if $RB \geq 0.25$

STRATUS if $RB < 0.25$

and for *liquid* surfaces we forecast

FOG if $RB \geq 0.10$

STRATUS if $RB < 0.10$.

2.5.3 Inversion Fog and Stratus Rule Modifications

When executing the rules in Section 2.5.1, due to a dry bias in RDPS for warm moist air masses we add 25% to the value of ML_RH_mean used where $\Theta w_2 > 17$ ºC and ML_TA_mean > 0, that is, in warm moist air with warm advection occurring.

In cold temperatures and marginally high relative humidity we found we were forecasting too much fog and stratus so we added an adjustment:

NO FOG OR STRATUS if $TT_1 < -8$ ºC .and. ML_RH_mean ≤ 88

If inversion stratus has been forecast, its base can *build down* to the ground under certain conditions. In the absence of rain the base of stratus located beneath a low level inversion can lower to the ground due to radiational cooling at the cloud top level at night or in low sunlight continually working downwards and saturating the air below the stratus base. Rogers (1988) studied this situation and specified the inversion base should be located 400 m or less above ground. We chose 300 m to be safe. A weak inversion would have temperature increasing about 0.5 ºC per 100 m and be at least 200 m thick. In our case we want the inversion to have a certain minimum strength, say the top has to be about 6ºC warmer than the bottom. This corresponds to about 2ºC per 100 m for a 300 m inversion. We chose these values after examining cases of fog over land under a well-defined inversion. At each grid point we search levels 2 to 5 (a depth of about 300 m) for the inversion maximum temperature (Tmax) and minimum temperature (Tmin), and the vertical level at which they are located (levmax and levmin). Approximate heights of model levels are in Table 2. Our rule is

If no rain is falling change stratus to fog if

STRATUS → FOG if RN6=0 .and. Tmax – Tmin ≥ 6 .and. levmax > levmin .and. SI ≤ 0.

In this rule negative SI indicates net long wave radiation cooling at the ground. We use SI because the long-wave radiation flux at individual model levels above the surface was not available.

If rain is falling into a stratus deck below it can saturate the air below the inversion base, and the base will build downwards toward the ground. After examination of a case of fog under a well-defined inversion we found that the inversion does not have to be as strong as for the no-rain case above, and it can be thicker. If light rain is falling we search over levels 2 to 6 and require a minimum temperature increase of 0.5ºC per 100 m. Our rule is:

If *light rain* is occurring or has occurred in the previous 6 hours change stratus to fog.

STRATUS → FOG if .001 ≤ RN6 ≤ 6 .and. Tmax – Tmin ≥ 2.2 .and. levmax > levmin

If *moderate or heavy rain* is occurring or has occurred in the previous 6 hours the minimum inversion can be even weaker and thicker than for the light rain case. We require the inversion to be at least 300 m thick and have a temperature increase of at least 0.5ºC over the whole layer. We search over levels 2 to 7 and change stratus to fog.

STRATUS → FOG if RN6 ≥ 6 .and. Tmax – Tmin ≥ 2.2 .and. levmax > levmin
.or. RN6 ≥ 6 .and. Tmax – Tmin ≥ 0.5 .and. levmax > levmin + 3

2.5.4 COLD FRONT STRATUS

Frequently we have found there is a narrow band of stratus when light rain is occurring behind a cold front inversion that our other rules do not catch. Our prediction rule for this situation is

STRATUS if ML_TA_mean < -0.4 .and. V_2.DEL (HU_2) > 0.0005 .and. RT > 1 .and. TT_1 > -10.

In this rule the first two terms, cold temperature advection and negative advection of specific humidity at level 2, identify a likely cold front. The third term is the rain rate, the fourth term weeds out very cold air fronts where rain is not likely. The latter would be covered by the augmented rules involving snow amount in Section 2.8.

2.5.5 NEAR-SURFACE SATURATED LAYERS

Low stratus and fog can occur when a thin layer of air is saturated near the surface unless the lapse rate near the surface is greater than dry adiabatic or the air is so much colder than the surface that Arctic sea smoke occurs. Sometimes air at the surface is saturated and sometimes it is not, but it is saturated at a level just above the surface. The following rules attempt to identify such situations through an examination of the forecast dewpoint depression in the lowest model levels.

FOG if $ES_2 < 0.125$ .and. $TT_1 - TT_2 < 0.4$
.or. $ES_2 < ES_1$ .and. $ES_2 < 0.125$ .and. $TT_2 - TT_3 < 0.8$

STRATUS if $ES_3 < ES_2$ .and. $ES_3 < 0.125$

.or. $ES_4 < ES_3$ .and. $ES_4 < 0.125$

.or. $ES_5 < ES_4$ .and. $ES_4 < 0.125$

These rules sometimes overlap rules for Type 1 and Type 2 inversions but this is not always the case. Figure 3 shows an example of this type of situation.

2.6 COLD FOG AND STRATUS POTENTIAL AREAS

2.6.1 Anthropogenic Ice Fog

All engines and power plants burning petroleum fuel emit water vapour in their exhaust. At extremely cold temperatures this water vapour is sufficient to instantly saturate air it is in contact with. In urban areas where many vehicles, aircraft, and power plants exist, their combined water vapour output can create a dense fog composed of ice-crystals that may not dissipate for hours or days. The threshold temperature for anthropogenic fog formation in an urban area depends on the population, that is, on the number of emission sources. Internal Environment Canada operational forecaster notes document this type of fog forming in small urban areas in very light wind at threshold temperatures varying from -38ºC for a small city of population about 20000 (Whitehorse, YT) to between -42ºC and -48ºC for various small cities of population 2000 to 500. In the authors' personal experience for a moderately large urban area of population 800,000 (Edmonton Alberta), a threshold temperature of -33 to -35 ºC in very light wind is sufficient for development of dense anthropogenic ice fog. We don't make a specific forecast but we do outline areas on a forecast chart where dense anthropogenic fog could form in urban centers that lie within an area. Our rules are:

potential FOG small cities if $UV_1 < 3$ .and. $TT_1 \leq -41$

potential FOG large cities if $UV_1 < 3$ .and. $TT_1 \leq -35$

2.6.2 Ice Crystal Fog

At relatively cold temperatures fog composed of mainly or entirely of ice crystals can form in a humid environment. Our rule for this is

potential FOG if $TT_1 < -10$ .and. $QC_2 \geq .05$

This type of fog is not well understood and is the subject of field observation research at this time. We do not include ice crystal fog in the combined forecast chart but we do show areas where the above rule is true in the chart that includes the anthropogenic ice fog forecast.

2.7 VISIBILITY AS A FUNCTION OF RELATIVE HUMIDITY

Gultepe et al. (2006) derived a formula for visibility as a function of relative humidity:

$$VISR = -0.0177RH_2^2 + 1.462RH_2 + 30.8$$

where the unit of VISR is km and the unit of RH_2 is %. We forecast fog or stratus over solid and liquid surfaces with this formula by the following rules:

FOG (solid surface) if $VISR \leq 0.25$

FOG (liquid surface) if $VISR \le 0.10$

STRATUS (solid surface) if $VISR \le 0.5$ .and. $RB \le 0.25$

STRATUS (liquid surface) if $VISR \le 0.5$ .and. $RB \le 0.10$.

2.8 FOG and LOW STRATUS CEILINGS IN SNOW and DRIZZLE

Often there is a low stratus ceiling or dense fog reported when drizzle is occurring, and a low stratus ceiling or obscured ceiling reported when snow or blizzard conditions of snow and blowing snow are occurring. We outline areas of these diagnosed from post-processed RDPS output on our fog and stratus forecast charts although we don't include them when we make a combined forecast with the union of the fog and stratus forecasts derived from the rules discussed above. Where the drizzle or snow areas overlap the forecasts of fog and stratus from the above rules this gives us added confidence in the forecast of dense fog or a low stratus ceiling. Where they do not overlap they can indicate areas of low stratus ceiling or dense fog (in the case of drizzle) that other rules don't catch. For snow we outline areas where the accumulated snowfall forecast in the previous hour up to forecast valid time is 0.5 cm, 1.0 cm, and 2.0 cm respectively. The likelihood of low or obscured snow ceilings or low stratus ceilings within these areas increases with snow amount. We also outline areas of blizzard conditions, defined as average wind speed 30 knots or more in the lowest 6 RDPS levels (approximately 50 mb thickness) combined with snow occurring. For drizzle or freezing drizzle we outline areas where the accumulated precipitation in the previous hour up to the forecast valid time is at least .05 mm water equivalent To determine snow amount the snow-water equivalent is diagnosed with a scheme proposed by Dubé (2003) with some modifications added by William Burrows. Precipitation type is determined by a hybrid algorithm developed by William Burrows from the tephigram area scheme proposed by Bourgouin (2000) and the top-down method by D. Baumgardt discussed in a COMET MetEd study module (2005).

2.9 FOG from LIQUID WATER CONTENT in the AIR

The RDPS outputs liquid water content at each level. The following rule was added as an attempt to forecast some potential dense fog occurrences from liquid droplet concentrations that may not be forecast by any of the above rules:

FOG if $QC_2 \ge .016$ .and. $RH_2 \ge 92$ .and. $\Theta w_2 \ge -6$.

According to Kunkel (1984), the value of 0.016 corresponds approximately to a visibility of 1 km. Teixeira (1999) used this value from the lowest level of the ECMWF model to create a fog simulation.

2.10 POST-PROCESSING the FORECASTS

A combined forecast is made from the union of all the forecasts made from the rules shown above, where a forecast of "fog" is ranked highest, a forecast of "stratus" is ranked next, and a forecast of "no fog or stratus" is ranked lowest. We found this still resulted in forecasting areas of fog that were too large, in particular there were often substantial areas where either fog or stratus was observed but the forecast was fog. *We post-process the combined forecasts of fog* by the following rules:

for *solid surfaces*

FOG if $RB > .25$

FOG or STRATUS if $RB \le .25$

for *liquid surfaces*

FOG	if	RB > .02
FOG or STRATUS	if	RB ≤ .02

The combined forecasts of STRATUS are not post-processed.

We find the RDPS usually dries out too quickly in the low levels after sunrise, particularly in the warmer months, thus our forecast areas of fog and stratus were dissipating too quickly as morning progressed. We devised a simple patch for this by extending existing morning forecast of fog and stratus from the previous hour's forecast but using the current forecast hour's RB value. This allows a forecast area of fog and stratus to retain its shape but allows fog within it to lift to stratus as RB changes. This extension is applied where the sun is less than 25º above the horizon and the sun angle is increasing with time where there is no Type 1 inversion, or if there is a Type 1 inversion, where ML_RH_mean is < 92.5%. Where there is a Type 1 inversion and 92.5% ≤ ML_RH_mean ≤ 97.5% (that is, a strong, moist inversion layer), we apply this extension until the sun angle is 30º above the horizon since it will take longer for fog to burn off.

3. EXAMPLES of FORECASTS

3.1 1400 UTC 30 DECEMBER 2010

Figure 4 shows the 14-hour forecast generated from the 0000 UTC 30 December 2010 RDPS run, valid at 1400 UTC 30 December 2010. The resolution of all forecasts is 15 km. In the western Great Lakes region there is a large organized area of low stratus and dense fog predicted in the warm sector of a low pressure system approaching from the southwest. Another zone of fog and stratus is predicted along the warm front trough line extending northeast from the low pressure center to James Bay, with snow areas on the north side. This pattern of low cloud and fog predicted by our rules for his synoptic situation is often seen with large organized weather systems over eastern North America. Large areas of dense fog and low stratus are seen in Figure 4 in the Atlantic Ocean associated with low pressure systems east of Newfoundland and Greenland. In the Pacific Ocean a large area of fog and stratus is associated with a low pressure trough. All of the predicted fog and low ceiling stratus areas are in reasonable positions relative to the MSL pressure pattern according to conceptual models of where they should be. Drizzle is predicted within in all of the predicted fog and stratus areas, giving us more confidence in those predictions. Figure 5 is a plot of the observations at 1400 UTC 30 December 2010. The overall agreement between forecasts and observations is reasonably good. The large fog and stratus areas were mostly caught by a combination of the forecasts from Type 2 Inversion, Near-Surface Saturated Layer, and Marine fog and stratus rules. Most of the fog and stratus reports in Washington and Oregon were caught by spotty areas of fog forecast by the Radiation fog rules in Section 2.2.2. Drizzle forecasts coincided with the rule forecasts over much of the area. Ice edge fog can be seen off the southwest shore of Hudson Bay.

There are many more stations than can be seen in Fig. 5 because the circles cover them up. A contingency table verification of the forecasts in Figure 4 is shown in Table 6, where we count "stratus" as ceiling 600 ft or less and "fog" as visibility ¾ mile or less. Where "fog or stratus" was forecast we call the forecast fog if fog was observed and stratus if stratus was observed. Results in this table are comprised of observations from both manned and machine stations. The nearest grid point forecast is taken as the forecast to pair with each observation. The CSI of .48 for stratus forecasts is quite good, although the probability of detection is 54%. The CSI of .24 for fog forecasts is alright but not remarkable, however the probability of detection is 79%. Overall there about the same number of forecasts of "no fog or stratus" as were observed, but there are too many forecasts of "stratus" and too few forecasts of "fog" compared to the numbers observed. Agreement of forecasts and observations is reasonably good except when fog was observed there were too many forecasts of "stratus" and too many forecasts of "no fog or stratus", and when stratus was observed there were too many forecasts of “no fog or stratus”. An examination was made of cases where an observing station had one or more neighbouring observing stations within a 50 km radius. Of the 42 stations for which the forecast was “stratus” but “no stratus and no fog” was reported, 20 had a ceiling between 600 ft and 1000 ft, 16 had a neighbour station with ceiling 600 ft or less, and 21 had a neighbour with a ceiling of 1000 ft or less. Of the 6 stations where “no fog or stratus” was reported and “fog” was forecast, 2 reported visibility between ¾ mile and 3 miles. A 6x6 grid of the forecasts at each grid point was centered over each station to check for the number of points where a particular category was forecast. Of the 42 stations for which the forecast was “stratus” but “no stratus and no fog” was reported, for 18 stations there were 9 or more of the 36 points where “no fog or stratus” was forecast. Of the 6 stations where “fog” was forecast but “no stratus and no fog” was reported, at all 6 stations there were 9 or more of the 36 points where “no fog or stratus” was forecast.

3.2 1200 UTC 09 NOVEMBER 2010

Figure 6 shows a 24-hr forecast generated from the 1200 UTC 08 November 2010 RDPS run, valid at 1200 UTC 09 November 2010. A large organized area of dense fog and low stratus is forecast to lie off New England and the Atlantic provinces, associated with a large weak low pressure system northeast of Newfoundland and a second low pressure system east of New England. Another large area of dense fog and low stratus is predicted in the center of the continent associated with a low pressure system located over North Dakota and southern Manitoba. An area of mostly dense fog is forecast through the center of the Great Lakes region. Smaller patchy areas of dense fog and low stratus are forecast over central and northwestern Canada, and Alaska. Figure 7 is a plot of the land observations at 1200 UTC 09 November 2010. Figure 8 shows ship observations for the same time. The overall agreement between forecasts and observations is reasonably good although there are some areas where dense fog and low stratus was forecast but not observed. It should be noted that over much of central and northern Canada there are no observing stations. The large area of marine fog and stratus forecast over the ocean east of the Atlantic Provinces appears to have been well forecast, although the stratus and fog were forecast to remain too long over in eastern Quebec and western New Brunswick. This may be because the actual low pressure system that caused the fog and stratus moved eastward faster than was predicted by the RDPS.

Table 7 shows a contingency table verification of the forecasts in Fig. 6. The probability of detection for stratus observations was 49% and 33% for fog observations, although 4% of the stratus observations were forecast as fog and 11% of the fog observations were forecast as stratus. The CSIs for both stratus and fog forecasts were .23, which is not high, but not insignificant either considering that this is a 24-hr forecast. Of the 70 stations where the forecast was “no fog or stratus” but stratus was observed, 8 had a neighbour who did report a stratus ceiling below 600 ft and 24 had a neighbour who reported a ceiling 1000 ft or less but greater than 600 ft. Of the 28 stations who reported “no fog or stratus” but fog was forecast, 5 had a neighbour who did report a visibility less than ¾ mile in fog. A 6x6 grid of the forecasts at each grid point was centered over each station to check for the number of points where a particular category was forecast. Of the 70 stations for which the forecast was “stratus” but “no stratus and no fog” was reported, for 43 stations there were 9 or more of the 36 points where “no fog or stratus” was forecast. Of the 28 stations where “fog” was forecast but “no stratus and no fog” was reported, at 25 stations there were 9 or more of the 36 points where “no fog or stratus” was forecast. Of the 37 stations where “no fog or stratus” was forecast but fog was observed, at 9 stations there were 9 or more of the 36 points where fog was forecast.

3.3 1300 UTC 16 SEPTEMBER 2010

Figure 9 shows a 13-hr forecast generated from the 0000 UTC 16 September 2010 RDPS run, valid at 1300 UTC 16 September 2010. Large areas of fog and stratus are forecast for several regions. Figures 10 and 11 show land and ship observations, respectively, from 1230 to 1330 UTC 16 September 2010. Figure 12 shows land observations between 1430 and 1530 UTC 16 September 2010. The forecast verifies well overall. The areas of dense fog and low-ceiling stratus over the oceans, Great Lakes, northern Quebec, the eastern Arctic, British Columbia, and the Canadian prairies were caught mostly by a combination of the forecasts from Type 1 and 2 inversion rules, Near-Surface Saturated Layer, Visibility as a Function of Relative Humidity, and the Marine fog and stratus rules. The areas of fog over Alaska and North Dakota - Minnesota were caught only by the UPS-style Radiation fog and stratus rules, while the area of fog over extreme western Ontario was caught only by the rules for outgoing long wave radiation and latent heat flux at the surface. Fig. 10 does not show any dense fog observations over central and western Alaska, but the fog developed shortly after, as can be seen in Fig. 12. Fig. 12 also shows the area of fog over North Dakota – Minnesota - western Ontario had lifted by 1430-1530 UTC. The 15-hr forecast (not shown) correctly predicted this.

Table 8 shows the contingency table verification for the forecasts in Fig. 9. The probability of detection for stratus observations was 69% and for fog observations it was 33%. The CSIs for stratus and fog observations were .26 and .22 which is not high. However of the 166 stations for which stratus was forecast but no fog or stratus was observed, 32 had a neighbour that reported a ceiling in fog below 600 ft, 82 had a neighbour that reported a ceiling greater than 600 ft but less than 1000 ft. There were 48 of these same stations which had a neighbour that mentioned fog in the report. Of the 25 stations that reported "no fog or stratus" but fog was forecast, only 1 had a neighbour who did report a visibility less than ¾ mile in fog, however 6 of these stations reported a 0 temperature-dewpoint spread and wind less than 5 kt. A 6x6 grid of the forecasts at each grid point was centered over each station to check for the number of points where a particular category was forecast. Of the 166 stations for which the forecast was "stratus" but "no stratus and no fog" was reported, for only 17 stations were there 9 or more of the 36 points where "no fog or stratus" was forecast. Of the 25 stations where "fog" was forecast but "no stratus and no fog" was reported, at 9 stations there were 9 or more of the 36 points where "no fog or stratus" was forecast. Of the 37 stations where "no fog or stratus" was forecast but fog was observed, at 9 stations there were 9 or more of the 36 points where fog was forecast. At the 28 stations which reported visibility less than ¾ mile in fog but the forecast was "no fog or stratus", at 9 stations there were 9 or more of the 36 surrounding grid points where the forecast was stratus or fog.

3.4 1200 UTC 14 JANUARY 2011

Figure 13 shows the 21-hr forecast of potential areas of cold fog and stratus from the 1200 UTC 14 January 2011 RDPS run. A large area of potential for anthropogenic ice fog is forecast to lie over the Yukon Territory extending into eastern Alaska. Ice fog may develop in populated areas within this region. Figure 14 shows a plot of the observations between 0830 and 0930 UTC 15 January 2011. Fog and stratus are reported in the Yukon and Alaska in the area of the anthropogenic ice fog potential forecast in Figure 13. None of the other rules were forecasting fog in this region at that time.

4. CONCLUSIONS

We have devised rules to forecast fog and stratus produced by all the processes we are aware of. Real-time forecast charts are for 1-48 hour projections are produced twice daily from RDPS output generated at 0000 UTC and 1200 UTC and distributed in graphical form via an Environment Canada internal website. Forecaster response has been positive for the more than two years that these forecasts have been produced, and the forecasts are widely used. Real-time verification of areal forecasts by eye with plots of current observations of the type such as Figs. 10 and 11 shows that locations of forecast fog and stratus areas match conceptual models and our past experience of where they should be for both land and marine surfaces. Numerical verification of forecasts with observations over land by contingency tables shows a tendency for over-forecasting stratus. The critical success index (CSI) of forecasts over land tends to be in the range of about .25 to .50 for stratus forecasts and .20 to .30 for fog forecasts, depending on synoptic situations. While not remarkable, we feel this is fairly good skill considering the difficulty of daily forecasting of fog and stratus for a wide variety of localities with local effects. These forecasts are suitable for forecasts of the location and extent of areas where fog and stratus are likely to occur and are useful to many users, even out to 48 hours. However forecasters still need to pay attention to local observations at individual stations to make accurate detailed forecasts of low ceiling and visibility because of the profound influence that local conditions exert on fog and stratus occurrence.

These rules are dependent on the RDPS model configuration as of the time of writing. In the future, as models change some of the threshold values in the rules may need to be modified. The principles in the rules will remain the same though. New model versions are not made operational until they have been tested for a considerable time in parallel runs, allowing ample time to make modifications if needed.

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DIV_n	divergence at RDPS level n.
dPN1	RDPS one-hour change of MSL pressure (hPa)
ES_n	RDPS (temperature – dewpoint) difference at model level n=1, 2, 3, etc (ºC)
FV	RDPS upward surface latent heat flux (watt m^{-2})
GZ_n	RDPS geopotential height at model level n=1, 2, 3, etc (m)
HU_n	RDPS specific humidity at model level n=1, 2, 3, etc (g kg^{-1})
I0	RDPS surface “skin” temperature (ºC)
I1	RDPS soil volumetric water content (m^3m^{-3})
I3	RDPS water retained on vegetation (kgm^2)
I4	RDPS water in the snow pack (kg m^{-2})
I7	RDPS sea ice temperature (ºC)
I9	RDPS glacier (land ice) temperature (ºC)
liquidI1	I1 where I0 > 0 ºC
liquidI3	I3 where I3 > 0 ºC
MG	RDPS land/water fraction (0 - 1)
OL	RDPS Monin-Obukhov length (m)
QC_n	RDPS mixing ratio of liquid water at model level n (gkg^{-1})
RB	RDPS bulk Richardson number
RN6	RDPS rainfall in the past 6 hours (mm)
RH_n	RDPS relative humidity at model level n=1, 2, 3, etc (%)
RH_mean	mean relative humidity in the lowest 3 model levels for a Type 1 inversion
RT	RDPS rain rate ($mmhr^{-1}$)
SD	RDPS surface snow depth (cm)
SI	RDPS net infrared radiation flux at the ground (watt m^{-1})
TM	RDPS sea surface temperature (ºC)
TT_n	RDPS air temperature at model level n=1, 2, 3, etc (ºC)
Tx	crossover temperature where fog begins to form at the ground (ºC)
UV_1	RDPS surface wind speed (kt)
V	wind vector
V_2.DEL(HU_2)	dot product of wind and specific humidity at level 2
WW_n	RDPS vertical motion at model level n=1, 2, 3, etc (Pas^{-1})
2F	RDPS glacier (land ice) fraction (0 – 1)
θw_2	RDPS wet bulb potential temperature at model level 2 (ºC)

Table 1. Definition of variables referred to in the main text. The acronym RDPS in front of a variable name means it is a direct output variable from the RDPS operational NWP model at the Canadian Meteorological Center. Model levels are defined in Table 2.

LEVEL	eta	sigma	pressure (mb)	height above ground (m)
1	12000	1.0000	1013	0
2	11950	.9950	1008	42
3	11850	.9850	998	125
4	11733	.9733	986	225
5	11606	.9606	974	334
6	11467	.9467	960	455
7	11316	.9316	945	588
8	11151	.9151	928	734
9	10973	.8973	910	895
10	10780	.8780	891	1073
11	10571	.8571	870	1270
12	10346	.8346	847	1480
13	10104	.8104	823	1720
14	9845	.7845	797	1980
15	9567	.7567	769	2260
16	9272	.7272	740	2580

Table 2. RDPS model vertical levels used in this study. eta = $(2000 + 10000*(P - P_t)/ (P_S-P_t))$, and sigma = P/P_S where Ps is surface pressure, and P_t is 10 mb. Pressure and height above ground are approximate values for a standard atmosphere.

Land	MG ≥ 0.7
Open water	MG < 0.3 and LG < 0.5
Coast	0.3 ≤ MG < 0.7
Ice covered water surface	LG ≥ 0.5
Ice covered land surface	2F ≥ 0.5
Snow on ground	SD > 2 cm
Downslope flow	WW1 ≥ 1 pa s^{-1}
Neutral flow	-1 ≤ WW1 ≤ 1 pa s^{-1}
Upslope flow	WW1 < -1 pa s^{-1}

Table 3. Definitions used in rules. Variable names are described in Table 1.

Number of Levels	1	2	3	4	5	6	7	8	9	10	11
Threshold1	1	1	1.1	1.2	1.3	1.5	1.7	1.9	2.1	2.3	2.5
Threshold2	2.5	2.5	2.6	2.7	2.8	3.0	3.2	3.4	3.6	3.8	4.0

Table 4. Inversion threshold temperature difference as a function of number of mode levels spanned by the inversion up to a maximum of 11. Threshold1 set is for air masses with Td2 < 16 ºC and threshold2 is set for air masses with Td2 >= 16 ºC.

TT1 ≥ -10 ºC	RH ≥ 87.5%
TT1 < -10 ºC	RH ≥ 97%
TT1 < -15 ºC	RH ≥ 99%

Table 5. Threshold minimum relative humidity that at least one level in the inversion must exceed in order for fog or stratus to occur, as a function of the surface temperature.

OBS ↓ FCST →	**No Fog or Stratus**	**Stratus**	**Fog**
No fog or stratus	536	42	6
Stratus	30	118	1
Fog	23	57	27
CSI	*.84*	*.48*	*.24*

Table 6. Contingency table verification of 14-hr forecasts valid 1400 UTC 30 December 2010 in Figure 4. Orientation is observations in rows, forecasts in columns. CSI is the critical success index. Fog is defined as visibility < ¾ mile in fog, stratus is defined as ceiling < 600 ft.

OBS ↓ FCST →	**No Fog or Stratus**	**Stratus**	**Fog**
No fog or stratus	577	70	28
Stratus	31	33	3
Fog	37	7	22
CSI	*.78*	*.23*	*.23*

Table 7. Contingency table verification of 24-hr forecasts valid 1200 UTC 09 November 2010 in Figure 6. Orientation is observations in rows, forecasts in columns. CSI is the critical success index. Fog is defined as visibility < ¾ mile in fog, stratus is defined as ceiling < 600 ft.

OBS ↓ FCST →	No Fog or Stratus	Stratus	Fog
No fog or stratus	507	166	25
Stratus	30	72	3
Fog	28	6	17
CSI	*.67*	*.26*	*.22*

Table 8. Contingency table verification of 13-hr forecasts valid 1300 UTC 16 September 2010 in Figure 9. Orientation is observations in rows, forecasts in columns. CSI is the critical success index. Fog is defined as visibility < ¾ mile in fog, stratus is defined as ceiling < 600 ft.

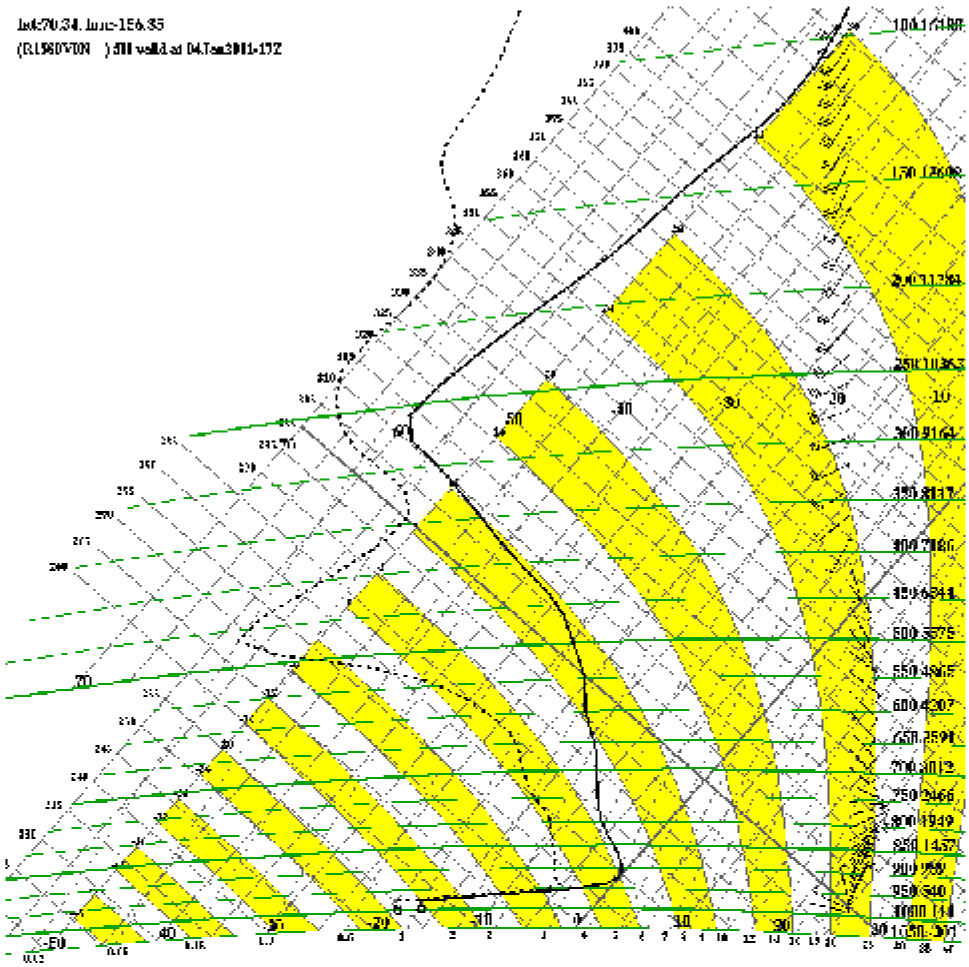

Figure 1. Tephigram plot of a Type 1 inversion. Solid black line is temperature, dashed black line is dewpoint.

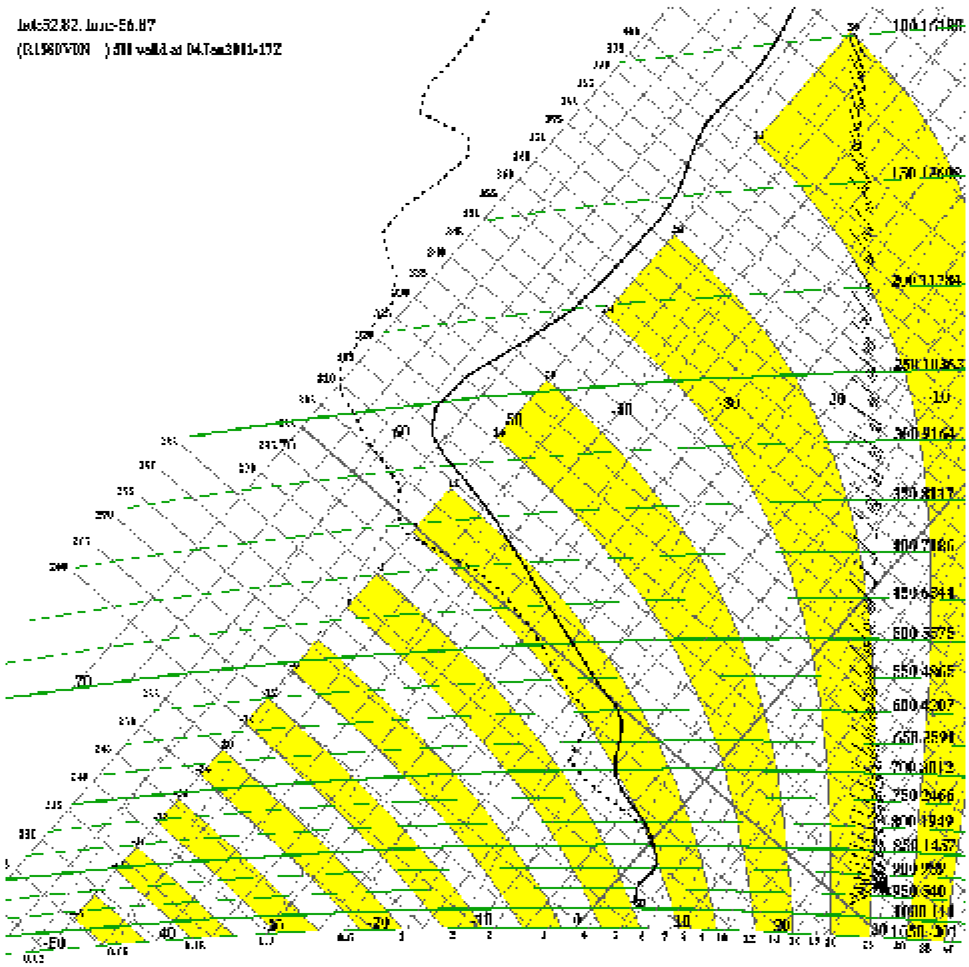

Figure 2. Tephigram plot of a Type 2 inversion. Solid black line is temperature, dashed black line is dewpoint.

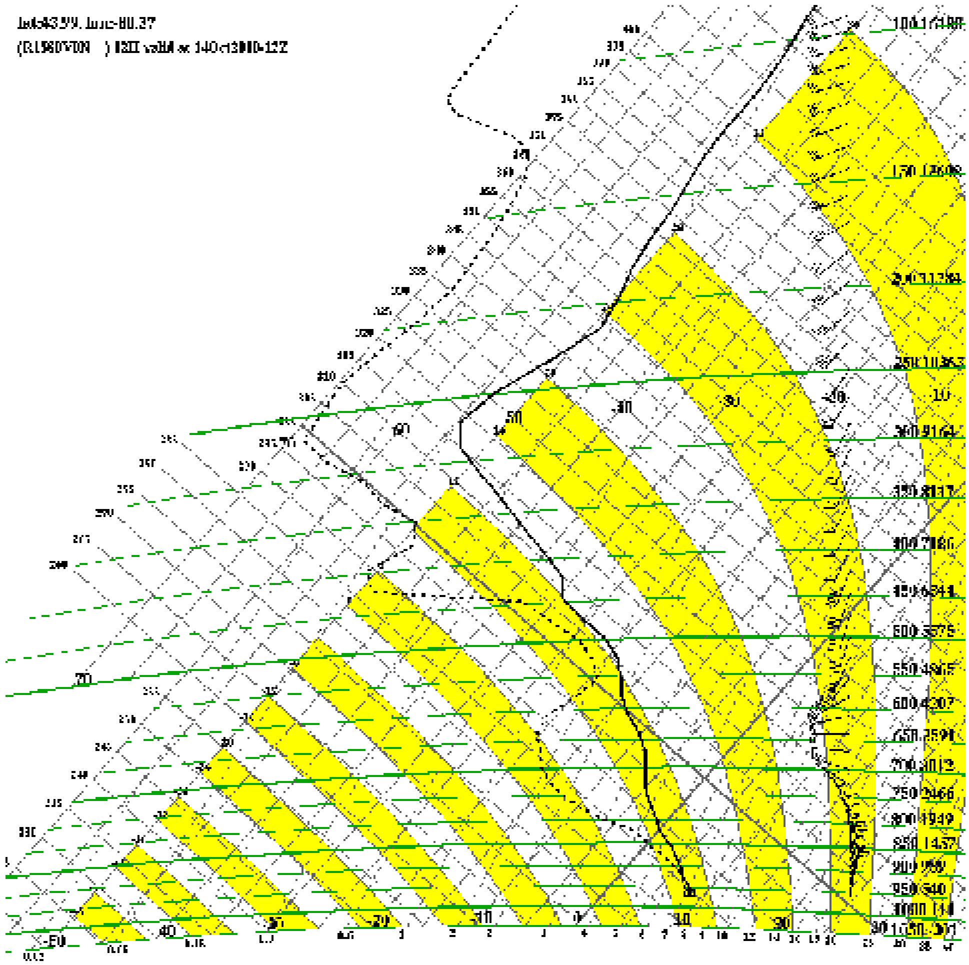

Figure 3. Tephigram plot of a low-level saturation example. Solid black line is temperature, dashed black line is dewpoint.

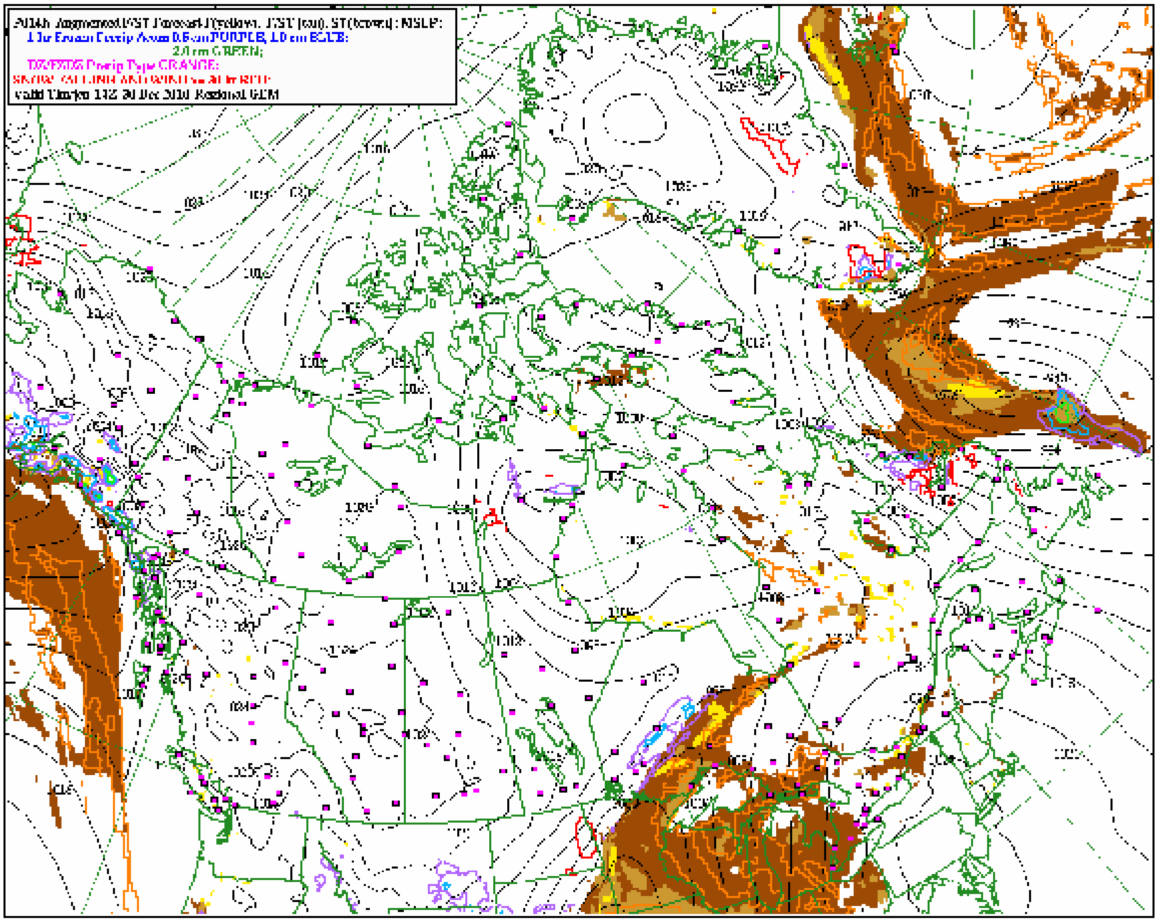

Figure 4. 14-hour forecast generated from the 0000 UTC 30 December 2010 RDPS run, valid at 1400 UTC 30 December 2010. The brown shaded area is the forecast of stratus with ceiling 500 feet or less, the yellow shaded area is fog with visibility ½ mile or less, and the tan shaded area is either fog with visibility ½ mile or less or stratus with ceiling 500 feet or less. The blue, purple and green contours outline the areas with forecast accumulation of frozen precipitation in the past hour of 0.5 cm, 1.0 cm, and 2.0 cm or more, respectively. The red contours outline areas where snow is falling and the average of the wind speed forecasts for the lowest 6 RDPS levels (approximately the lowest 50 mb in the boundary layer) is 30 kt or more. The orange contours show areas where drizzle or freezing drizzle with at least .05 mm accumulated water equivalent are forecast to have occurred in the previous hour up to forecast valid time. The black contours are MSL pressure contours in 4 hPa intervals. The magenta squares are airport locations. Mid-green contours show coast and political boundaries.

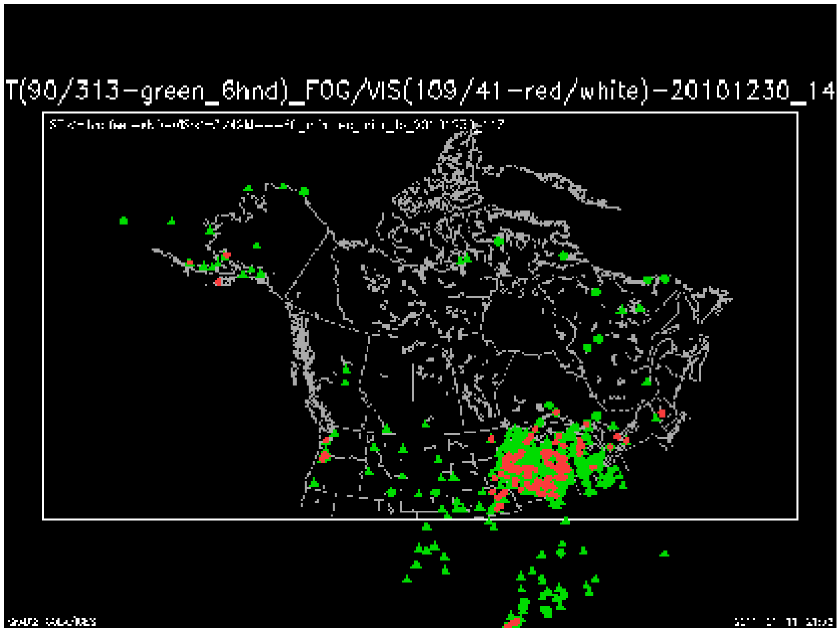

Figure 5. Plot of land observations between 1330 and 1430 UTC 30 December 2010. Green circles are stations reporting stratus ceiling 600 ft or less in fog, red circles are stations reporting visibility ¾ mile or less. Circles are manned observing stations, triangles are machine observing stations. Courtesy of Andrew Giles of Environment Canada.

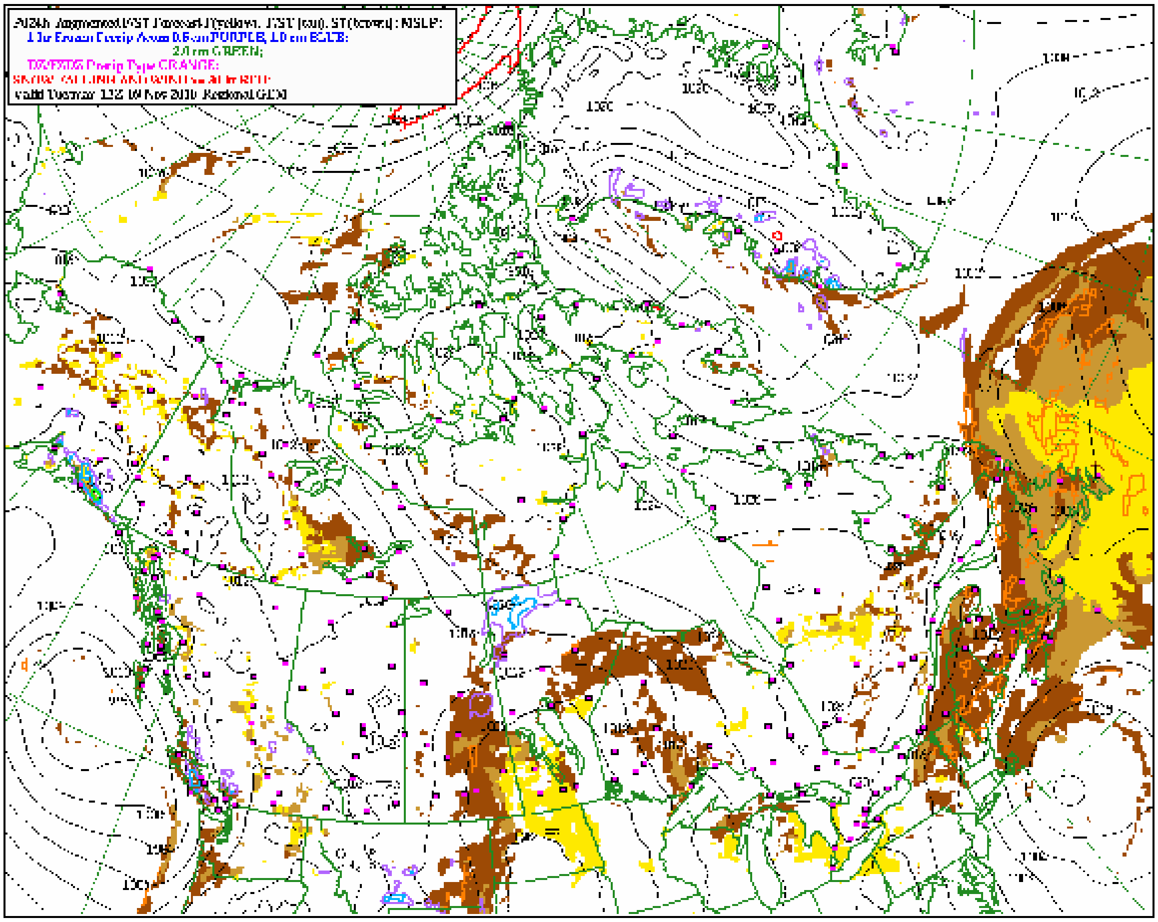

Figure 6. 24-hour forecast generated from the 1200 UTC 08 November 2010 RDPS run, valid at 1200 UTC 09 November 2010. Field descriptions are the same as for Fig. 4.

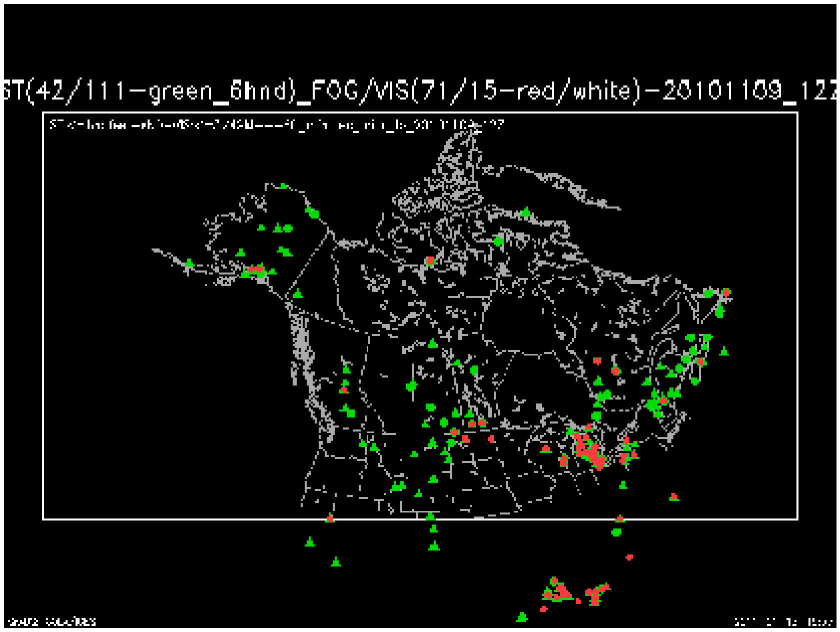

Figure 7. Plot of land observations between 1130 and 1230 UTC 09 November 2010. Field descriptions are the same as for Fig. 5. Courtesy of Andrew Giles of Environment Canada.

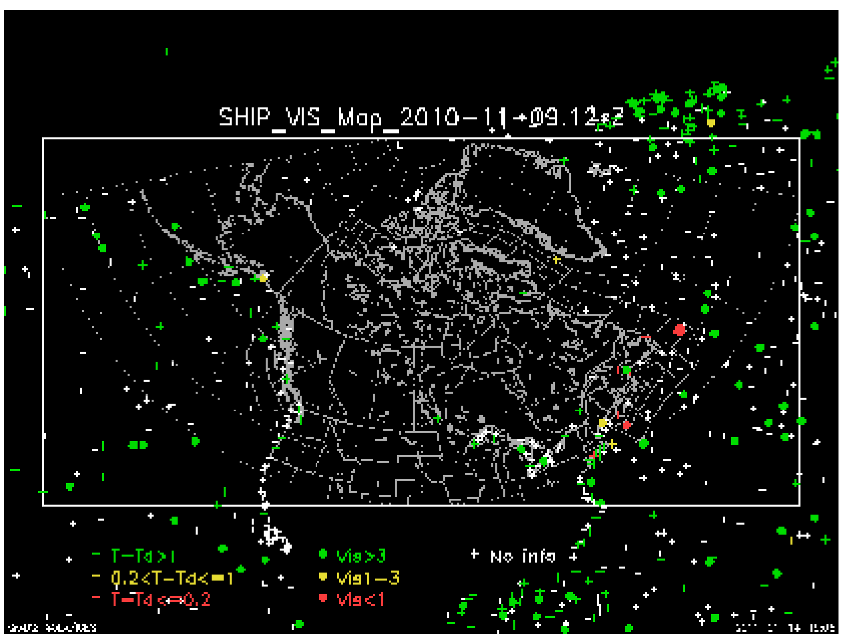

Figure 8. Ship observations between 1130 and 1230 UTC 09 November 2010. Circles: red, yellow, green are visibility < 1 mile, 1 – 3 miles, and > 3 miles respectively. Plus signs: red, yellow, green are temperature minus dewpoint ≤ 1 mile, 1 – 3 miles, and > 3 miles, respectively. White plus signs are “no information”. Irregular polygons in ocean areas show Canadian marine forecast area boundaries. Courtesy of Andrew Giles of Environment Canada.

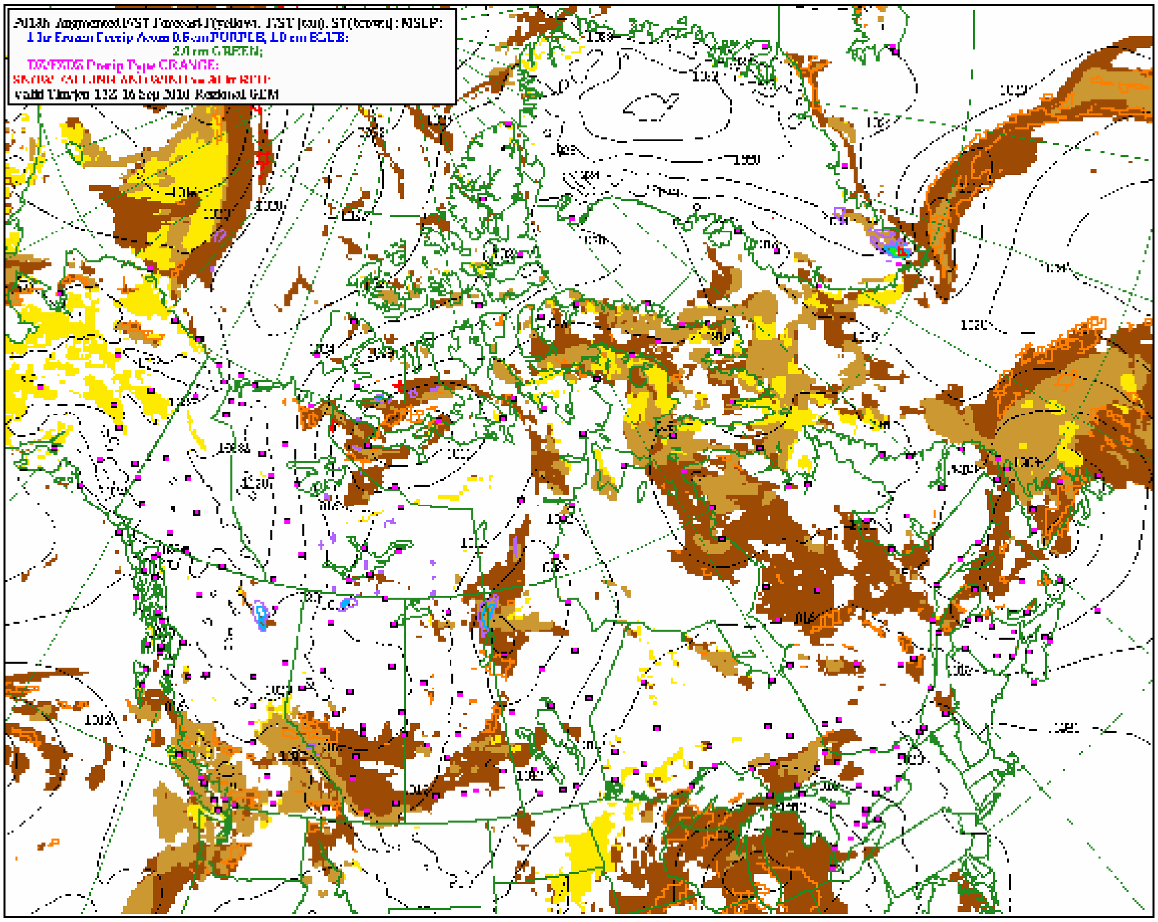

Figure 9. 13-hour forecast generated from the 0000 UTC 16 September 2010 RDPS run, valid at 1300 UTC 16 September 2010. Field descriptions are the same as for Fig. 4.

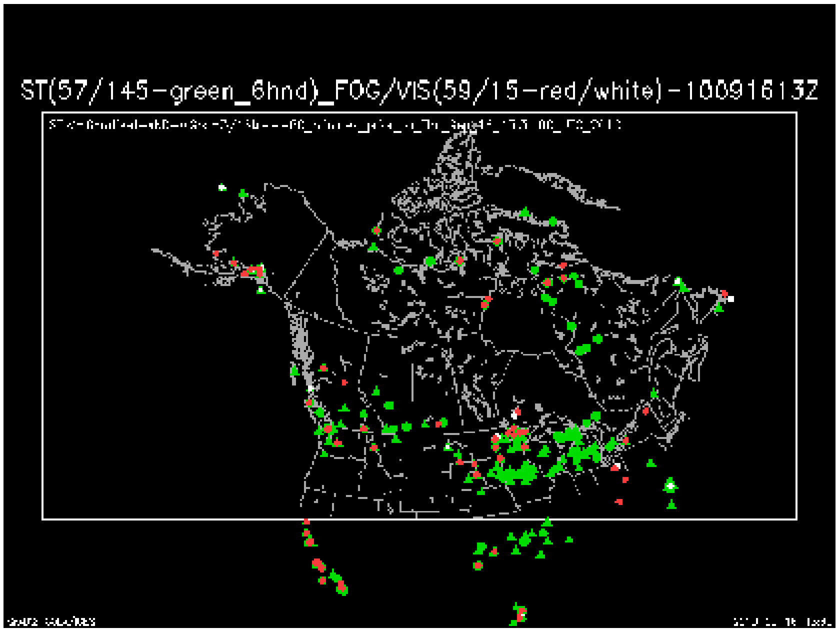

Figure 10. Plot of land observations between 1230 and 1330 UTC 16 September 2010. Field descriptions are the same as for Fig. 5, with the addition of white circles and triangles that represent stations reporting visibility ¾ mile or less with no reason identified. Courtesy of Andrew Giles of Environment Canada.

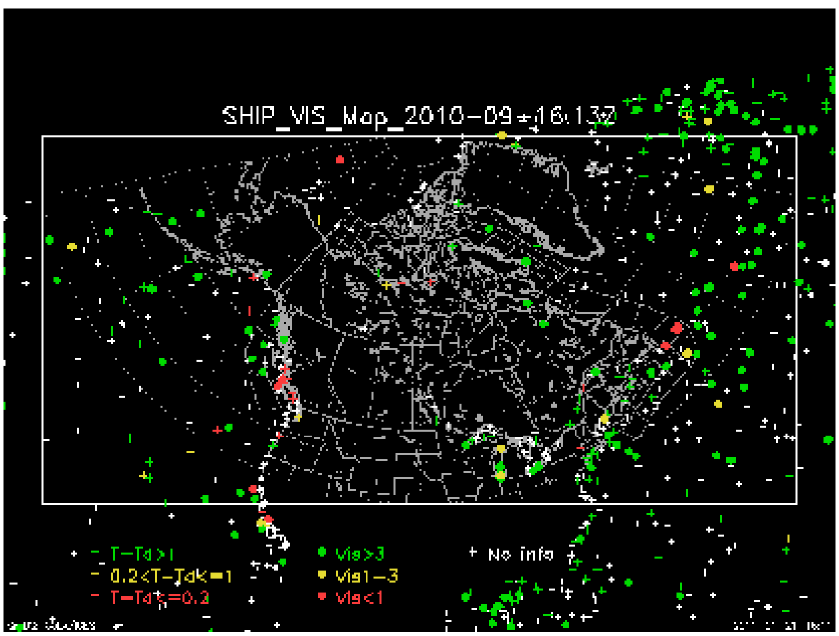

Figure 11. Plot of ship observations between 1230 and 1330 UTC 16 September 2010. Field descriptions are the same as for Fig. 8. Courtesy of Andrew Giles of Environment Canada.

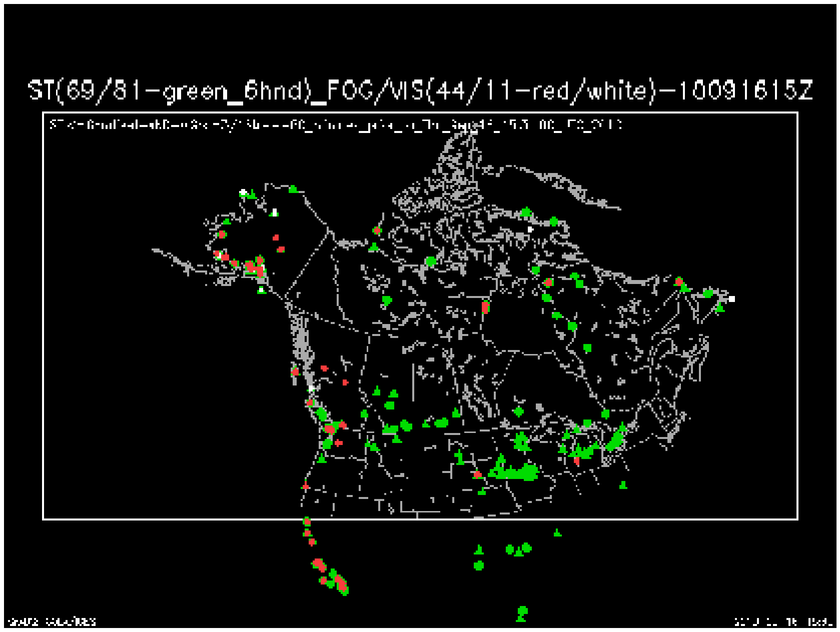

Figure 12. Plot of land observations between 1530 and 1530 UTC 16 September 2010. Field descriptions are the same as for Fig. 10.Courtesy of Andrew Giles of Environment Canada.

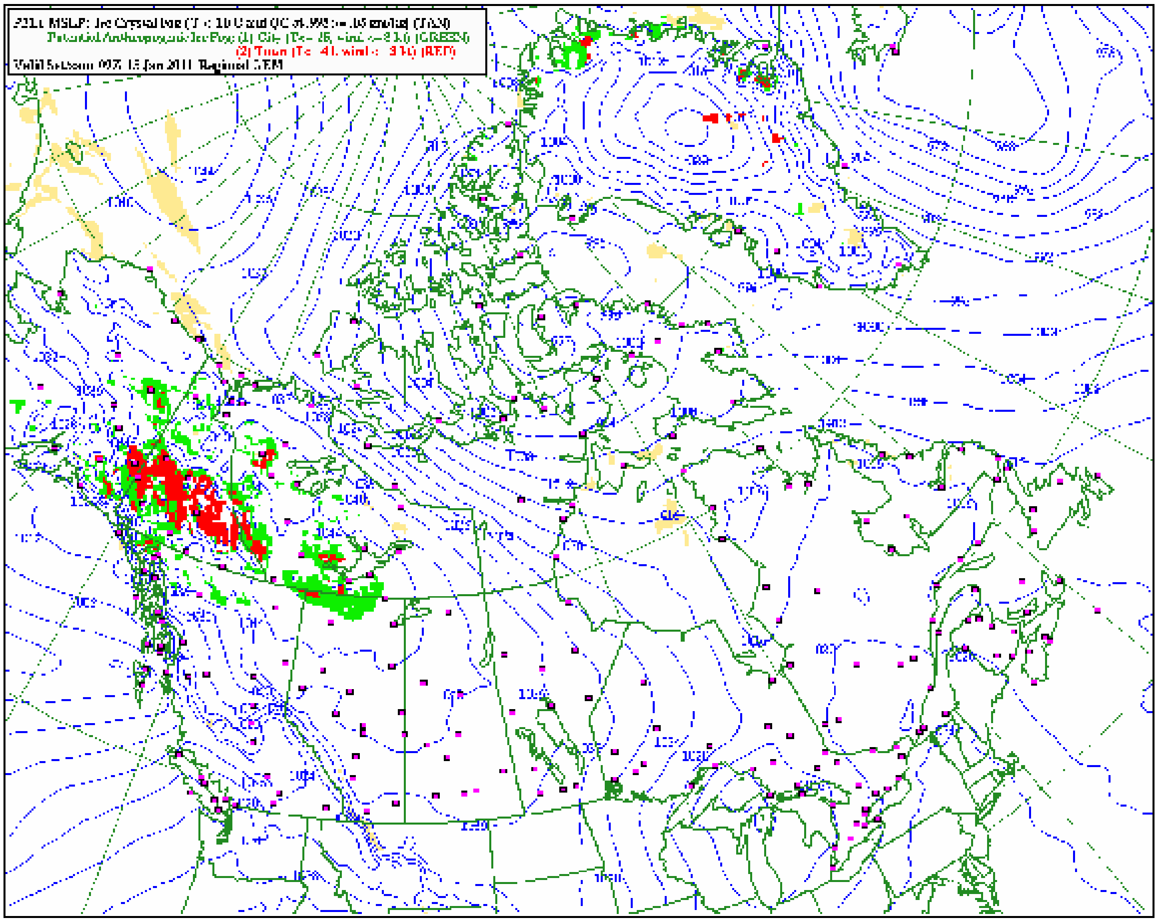

Figure 13. 21-hr forecast of cold fog and stratus potential generated from the 1200 UTC 14 January 2011 RDPS run valid 0900 UTC 15 January 2011. Red shaded area is where surface wind is ≤ 3 kt and temperature is ≤ -41º C. Green shaded area is where surface wind is ≤ 3 kt and temperature is ≤ -35º C. Tan shaded area is where temperature is area of potential ice crystal fog, where surface temperature is < -10º C and QC ≥ .05 gkg^{-1}.

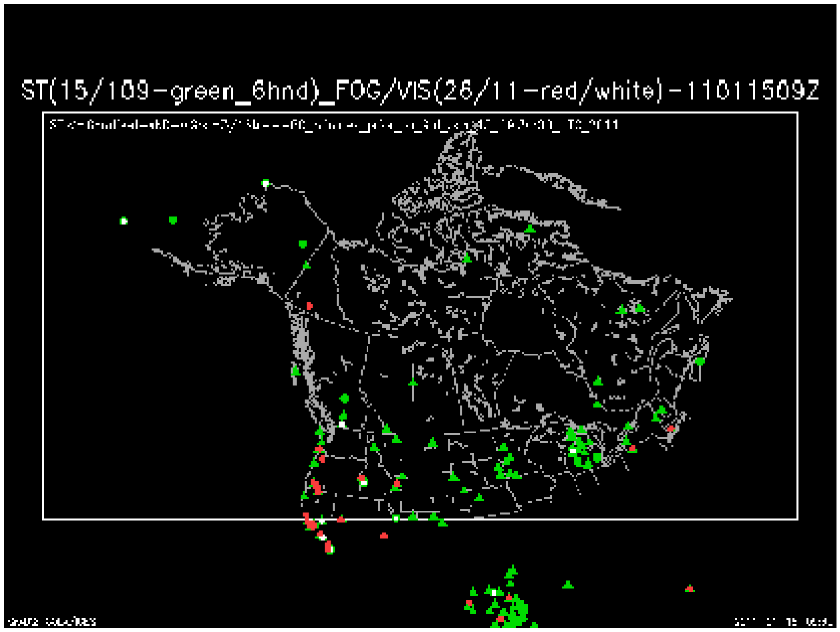

Figure 14. Plot of land observations between 0830 and 0930 UTC 15 January 2011. Green circles are stations reporting stratus ceiling 600 ft or less, red circles are stations reporting visibility ¾ mile or less in fog. Explanation of symbols is the same as for Fig. 10. Courtesy of Andrew Giles of Environment Canada.