Observation and modelling of fog at Cold Lake, Alberta, Canada

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Google earth map of Cold Lake (54° N, 110° W, 541 m ASL) and ECCC’s ground instruments site
DND METAR station and ECCC’s ground instruments site
Ground instruments at Cold Lake, Alberta

The ground-based surface and remote sensing instruments that include a Vaisala PWD22 present weather sensor, multi-channel microwave profiling radiometer (PMWR), Jenoptik CHM15k ceilometer, and WXT520 weather transmitter are used for. The PWD22 measures visibility, and both precipitation type and intensity. A fog detector (FMD), meteorological particle spectrometer (MPS), and Sunphotometer have been added on the extended platform. Further analysis of these data will provide the fall velocity, and size distribution and shape of the falling fog hydrometeors.
The classification of fog types, defined as precipitation fog, advection fog, cloud base lowering fog, radiation fog and evaporation fog, is based on the methodology followed by Tardif and Rasmussen (2006) (Table 2 and Figure 4).
The classification of fog (visibility < 1 km) types, defined as radiation fog (frequency 69%), precipitation fog (17%), cloud base lowering fog (7%), advection fog (5%), and one unknown fog (2%) in 2015-2016, is based on the methodology followed by Tardif and Rasmussen (2007). Note MST = UTC - 7 hrs
The frequency of observed visibility, ceiling, surface level temperature, RH, wind speed and direction distribution in 2015-2016

Case study: Oct 24, 2016
20161024 fog case (advection fog)

- Rate (mm/h)
- Temperature (°C)
- Relative Humidity (%)
- Wind Speed (m/s)
- Wind Direction (°)
- BGL (Cd m⁻²)
- LWP MWR (mm)
- Visibility (km)
- Type

Time (UTC)
Vertical profiles measured by MWR and simulated by HRDPS (EC High Resolution Deterministic Prediction System) at time of fog conditions (7am MDT)
Upstream/initial conditions: a 1-D time dependent model.

Surface cooling, \( dT_s(t)/dt < 0 \), so \( q_s(T_s) \) also decreasing. Water surface is a water droplet sink, \( Q_l = 0 \), and potential source or sink of \( Q_v \). Settling velocity (Nakanishi, 2000 proposes \( V_T = 10^6(Q_l/N_0)^{2/3} \text{ ms}^{-1} \) - an empirical equation! with \( N_0 \) fixed at \( 10^8 \text{m}^{-3} \)). Typical values, \( Q_l = 10^{-4}, V_T = 0.01 \text{ms}^{-1} \).
Θ_l, Θ_v and Q_w

Θ_l[≡ Θ - (Θ/T)(L_v/c_p)Q_l] the liquid-water potential temperature

potential temperature of dry air with same density as moist air + water droplets - needed for stability considerations and TKE equation.

Θ_v ≡ Θ(1 + 0.61Q_v - Q_l)

Q_w(≡ Q_v + Q_l) the total water content, Q_v the specific humidity, Q_l the liquid-water content.
1-D equations

Based on Weng and Taylor (2003), in the Planetary Boundary Layer, 1D PBL model equations are

\[
\frac{\partial U}{\partial t} = -\frac{\partial \langle uw \rangle}{\partial z} + f(V - V_g), \tag{1}
\]

\[
\frac{\partial V}{\partial t} = -\frac{\partial \langle vw \rangle}{\partial z} - f(U - U_g), \tag{2}
\]

\[
\frac{\partial \Theta_l}{\partial t} = -\frac{\partial \langle w \theta_l \rangle}{\partial z} - \frac{\Theta}{T} \left( \frac{1}{c_p \rho} \frac{\partial R_{net}}{\partial z} + \frac{L}{c_p} \frac{\partial G}{\partial z} \right), \tag{3}
\]

\[
\frac{\partial Q_w}{\partial t} = -\frac{\partial \langle wq_w \rangle}{\partial z} + \frac{\partial G}{\partial z}, \tag{4}
\]

where $U$ and $V$ are the horizontal wind components, $\langle uw \rangle$ and $\langle vw \rangle$ the (kinematic) shear stress components, $f$ the Coriolis parameter, $U_g$ and $V_g$ the geostrophic wind components, $\Theta_l[\equiv \Theta - (\Theta/T)(L_v/c_p)Q_l]$ the liquid-water potential temperature, $\Theta$ the potential temperature, $T$ the absolute temperature, $c_p$ the specific heat of dry air at constant pressure, $L_v$ is the latent heat of vaporization, $R_{net}$ the net radiative flux (solar and thermal), $G$ the gravitational settling flux (positive downward) of fog droplets, $Q_w(\equiv Q_v + Q_l)$ the total-water content, $Q_v$ the specific humidity, $Q_l$ the liquid-water content, $\langle w \theta_l \rangle$ the (kinematic) liquid-water potential temperature flux (positive upwards) and $\langle wq_w \rangle$ the total-water content flux ($\langle wq_v \rangle$ and $\langle wq_l \rangle$ the (kinematic) moisture and liquid-water fluxes respectively).
TKE and closure

\[
\langle uw \rangle = -K_m \frac{\partial U}{\partial z}, \quad \langle vw \rangle = -K_m \frac{\partial V}{\partial z},
\]

\[
\langle w\theta_t \rangle = -K_h \frac{\partial \Theta_t}{\partial z}, \quad \langle wq_w \rangle = -K_q \frac{\partial Q_w}{\partial z},
\]

\[
K_m = (\alpha E)^{1/2} \ell_m, \quad K_h = K_q = (\alpha E)^{1/2} \ell_m / Pr,
\]

\[
\frac{\partial E}{\partial t} = -\langle uw \rangle \frac{\partial U}{\partial z} - \langle vw \rangle \frac{\partial V}{\partial z} + \beta g \langle w\theta_v \rangle - \epsilon + \frac{\partial}{\partial z} \left( K_m \frac{\partial E}{\partial z} \right),
\]

for neutral and unstable conditions,

\[
\frac{1}{\ell_m} = \frac{1}{\ell_d} = \frac{\phi_m}{\kappa(z + z_0)} + \frac{1}{\ell_0},
\]

for stably stratified flow,

\[
\frac{1}{\ell_m} = \frac{1}{\kappa(z + z_0)} + \frac{1}{\ell_0} + \frac{\beta_c}{\kappa L_0},
\]

\[
\frac{1}{\ell_d} = \frac{1}{\kappa(z + z_0)} + \frac{1}{\ell_0} + \frac{\beta_c - 1}{\kappa L_0},
\]
4.1 Longwave radiation

For simplicity, the upward ($F^\uparrow$) and downward ($F^\downarrow$) longwave radiations are calculated by suing the emissivity or grey-body approximation following Duynkerke and Driedonks (1989), Barker (1977). They are

$$F^\downarrow = \int_z^\infty B[T(z')] \frac{\partial \epsilon(z', z)}{\partial z'} dz'$$

(24)

$$= \int_z^{z_T} B[T(z')] \frac{\partial \epsilon(z', z)}{\partial z'} dz' + C_R F^\uparrow(z_T) [1 - \epsilon(z_T, z)]$$

(25)

$$F^\uparrow = B(T_B) [1 - \epsilon(z, 0)] + \int_z^0 B[T(z')] \frac{\partial \epsilon(z, z')}{\partial z'} dz'$$

(26)

where $B$ is the Planck function $\sigma T^4$ ($\sigma = 5.67 \times 10^{-8}$, Stefan-Boltzmann constant), $\epsilon(z, z')$ is the emissivity for corrected mass of absorber $u(z, z')$ corresponding to vertical path from $z$ to $z'$, $z_T$ is the model top, $C_R$ depends on the structure of the atmosphere above the boundary layer and has a value (usually between 0.75 and 1.00), and $T_B$ is the equivalent blackbody temperature, which will take as equal to the surface temperature $T_s$.

The emissivity is computed as

$$(1 - \epsilon) = (1 - \epsilon_v)(1 - \epsilon_{CO_2})(1 - \epsilon_W),$$

(27)

where subscript $v$ denotes for water vapour, CO$_2$ for carbon dioxide and $W$ for cloud or liquid water.
1-D model has 201 grid points, uniform spacing after log-linear z to $\zeta$ transform. Top of model at 3 km.

Surface cooled at 2°K per hour for 6 hours, 100% RH at surface
Linear scale in z

Results with Long Wave radiation, More Ql due to radiative cooling.
No LW radiation in model, less fog, later start.
Next Model Development Steps
(somewhat funding dependent!)

- Add solar radiation terms.
- Resolve issues with lower boundary condition for $Q_l$ – include surface energy budget
- Get better data on profiles with/without fog.
- Get the advective case running
- Use the model to determine combinations of conditions (upstream/initial profiles, wind speeds, cloud cover, rate of change of surface temperature, etc. etc.) under which fog forms, and dissipates.
Still struggling to clear the fog but slowly making progress in understanding the conditions that allow fog to form. It is not an easy problem!
Slides I do not have time for!
Case study: Surface measurements on a fog day
Oct 24, 2016 (Advection fog)
1-D Fog modelling

The condensation of water vapour into droplets and the formation of fog in the Earth's atmospheric boundary layer involves a complex balance between horizontal advection and vertical turbulent mixing of heat and water vapour, cloud microphysical processes involving the numbers and size of available condensation nuclei and radiative transfers of heat, plus the impact of water droplets, and sometimes ice crystals, on visibility. It is a phenomenon which has been studied for many years in a variety of contexts. Over the waters offshore from Newfoundland (Grand Banks) a key factor is the advection of moist air from over warm gulf stream waters to colder Labrador current water - an internal boundary-layer problem. Some basic fog properties and the sensitivity to model parameters, initial and boundary conditions, can be learned from 1-D time dependent (z,t) and 2-D steady state (x-z) models.

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Models we have learnt from.


Nakanishi, 2000, Large eddy simulation of radiation fog, Boundary-Layer Meteorology 94: 461–493, 


More closure details

\[ \phi_m = \begin{cases} 
1 + \beta_c z / L_0, & \text{for } z / L_0 \geq 0; \\
(1 - \gamma_1 z / L_0)^{-1/4}, & \text{for } z / L_0 < 0,
\end{cases} \quad (12) \]

where constants \( \beta_c = 4.7 \), \( \gamma_1 = 15 \) and \( L_0 \) is the Obukhov length, which is defined as

\[ L_0 = -\frac{u_*^3}{\kappa \beta g \langle w \theta_v \rangle}. \quad (13) \]

\[ Q_l = \begin{cases} 
a (Q_w - Q_{sl}), & \text{for } Q_w > Q_{sl}; \\
0, & \text{for } Q_w \leq Q_{sl},
\end{cases} \quad (14) \]

\[ a = \frac{1}{1 + \delta Q_{sl} L_v / c_p} \quad \text{and} \quad \delta Q_{sl} = \frac{\partial Q_s}{\partial T} \bigg|_{T=T_l} = 0.622 \frac{L_v Q_{sl}}{R_d T_l^2}, \quad (15) \]

\( Q_s \) is the saturation specific humidity, \( Q_{sl} \equiv Q_s(T_l) \) and \( T_l = \Theta_l T / \Theta \).
For $\epsilon_c(W)$, we have used the formula given by Stephens (1978) in which

$$ W = \left| \int_{z}^{z'} \rho Q_1 dz \right|, $$

where $W$ is in g m$^{-2}$ and the emissivity is

$$ \epsilon_c^{\downarrow\uparrow}(W) = 1 - \exp(-a_0^{\downarrow\uparrow}W), $$

where the fitted absorption coefficients (m$^2$ g$^{-1}$) are $a_0^{\downarrow} = 0.158$ and $a_0^{\uparrow} = 0.130$.

Running procedures:
For a given site, $f$, surface roughness length, $z_0$ and geostrophic wind speed, $|U_g|$, the 1D neutral PBL model (Weng & Taylor, 2003) is run for 4 inertial cycles to obtain a quasi-steady state, neutral planetary boundary layer (NPBL) and wind direction is 0 at $z = 10$ m. With this NPBL, we add the prescribed virtual potential temperature ($\Theta_v$) and the specific humidity ($Q_v$) profiles. The fog model is running for further 6 hours with surface cooling rate of 2 K hr$^{-1}$. The surface is assumed saturated (wet/water surface).

The prescribed $\Theta_v$ and $Q_v$ are

$$ \Theta_v = \begin{cases} 275.15 \text{ K}, & \text{for } z \leq 1000 \text{ m;} \\ 275.15 + 0.0003 \times (z - 1000) \text{ K}, & \text{otherwise.} \end{cases} $$

$$ Q_v = \begin{cases} 0.98 \times Q_{sat}(T, P) \text{ g kg}^{-1}, & \text{for } z \leq 750 \text{ m;} \\ 0.5 \times Q_{sat}(T, P) \text{ g kg}^{-1}, & \text{otherwise.} \end{cases} $$

We have applied a simple 3-points smooth method to these original profiles to smooth out the discontinuity.

In the model runs, the site is specified at 54.41 N and $|U_g| = 10 \text{ m s}^{-1}$. We use $z_0 = 0.05 \text{ m}$. We have switched on/off the long-wave radiation schemes. Therefore, 2 cases are carried out.