June 2019

Technical Handbook:
Weather Forecasts and Odour Alert Guidance

Written by
Marjolein Ribberink, Dr. Rosie Howard
and Prof. Roland Stull

Weather Forecast Research Team
Dept. of Earth, Ocean & Atmospheric Sciences
University of British Columbia
2020-2207 Main Mall
Vancouver, BC V6T 1Z4
Canada

Contact info for Prof. Stull:
rstull@eoas.ubc.ca
604-822-5901.

1. Introduction

This technical handbook describes and explains the forecast graphs provided XXX, at the following URL: <u>XXX.</u>
The graphs provide guidance for the timing of their operations, with estimates of when/if bad odours might reach specified residential areas.

a. Overview of the Goal: Odour Alerts provided to XXX

Fig. 1 shows an hourly forecast of the odour risk in terms of an alert-level index. The NE-winds alert index applies to area-of-interest 1, the City of XXX, while the NW-winds alert applies to area-of-interest 2, to the southeast (see Fig. 2). This alert index is based upon forecasts of wind speed and direction, time of day, boundary-layer depth, Monin-Obukhov (M-O) length, and lower and upper bulk Richardson numbers. These factors are explained later in this handbook.

All variables except for wind speed and direction, and boundary-layer depth, are used to indicate atmospheric stability. Generally, a stable atmosphere near the ground contributes to an odour transport risk. Wind speed and direction (along with *at least one* of the other variables) that fall within specific criteria or thresholds result in an increased alert level.

● Blue dots represent alert index assessed every hour:

- HR = high odour risk (avoid odour production if possible);
- MR = moderate odour risk (monitor odour production);
- LR = low odour risk (consider scheduling higher odour production tasks during this time).

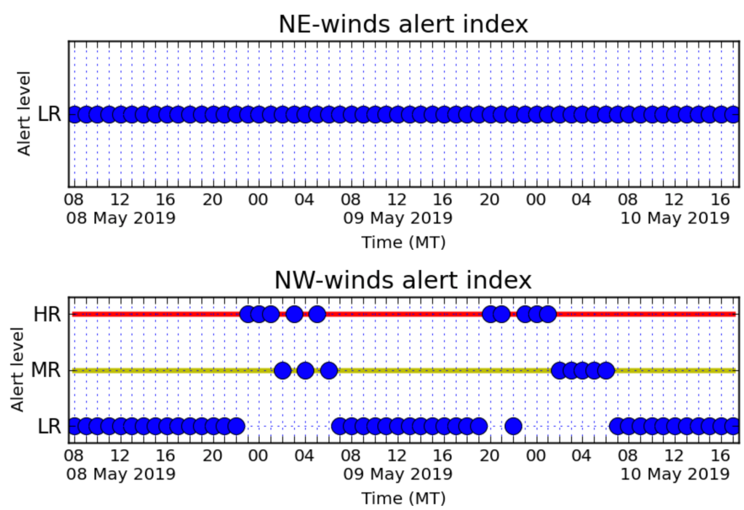

Fig. 1. Hourly forecast of calculated odour alert for 8-10 May 2019. Blue dots represent hourly alert index; HR = high risk, MR = moderate risk, and LR = low risk.

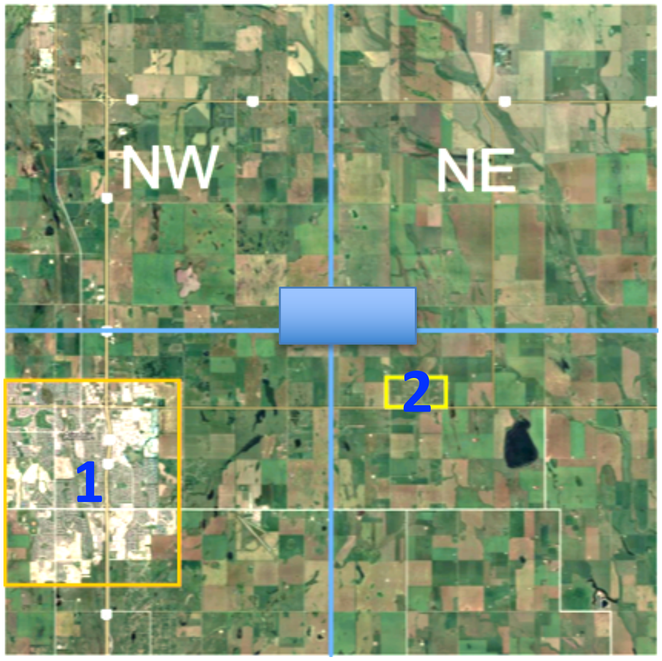

Fig. 2. Map showing the northeast (NE) and northwest (NW) wind regions, corresponding to area-of-interest 1 (outlined in orange) and area-of-interest 2 (outlined in yellow), respectively. (Source: Google Maps, 2019.)

In meteorology, winds are described by the direction they are coming from. For example, a *northeast (NE)* wind blows **from** the northeast to the southwest, and is represented by the numerical value *at the northeast position* on the compass in Fig. 3, i.e. 45°. Similarly, wind coming **from** the northwest (NW; a north-westerly wind) has a wind direction of 315°.

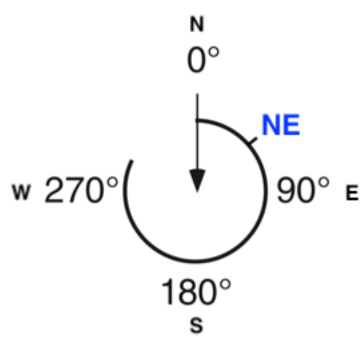

Fig. 3. Compass indicating numerical values of wind direction in meteorology. Northeast (NE) is denoted in blue text, and is represented by the value 45 degrees, halfway between 0 and 90 degrees.

Thus, for area-of-interest 1, we are concerned about north-easterly winds (from the NE), and for area-of-interest 2, we are concerned about north-westerly winds (from the NW).

b. Ensemble Forecasts

All modern weather forecasts are made by computer. This is called Numerical Weather Prediction (NWP). The computer codes that describes the atmosphere (winds, temperature, clouds, etc.) are called NWP models. Different models have slightly different representations of the atmosphere, and result in slightly different forecasts (blue lines in Fig. 4). Due to the chaotic nature of the atmosphere, no forecast is perfect, regardless of which model produced it.

But forecast skill can be improved by running multiple models to produce an ensemble of forecasts for the same locations and times. Although no individual model forecast is perfect, the average of all the ensemble members is usually the best forecast, as verified with statistics over many days of operation. The ensemble average (Fig. 4) is still not perfect, but it often has less error than any individual-model forecast.

Also, the spread of the ensemble members from each other provides an estimate of forecast uncertainty. Greater spread implies greater uncertainty and reduced forecast skill. Nonetheless, if a majority of the ensemble members produce forecasts that reach an alert threshold, then there is greater confidence that the true atmosphere will reach the same threshold value.

We run an ensemble of XXX NWP models to produce XXX slightly different forecasts. The description that follows shows how these ensemble data are used to create Alerts.

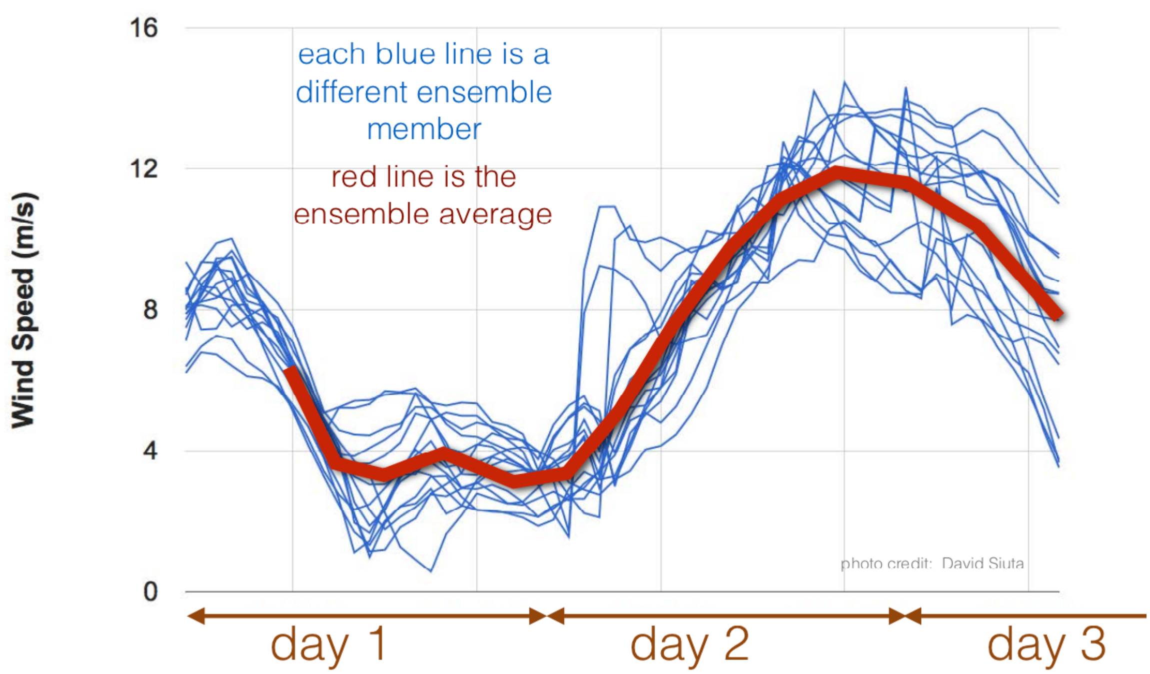

Fig. 4. Illustration of an ensemble of wind-speed forecasts (blue lines) from different NWP models, and resulting ensemble average (thick red line) which usually verifies as the best (even though it is still not perfect).

2. Guidance from wind speed and direction forecasts

Quick look:

- *We anticipate an alert whenever 4 or more out of 8 ensemble members have wind **speeds** that fall between the red lines (0-16 km/h) in Figs. 5a and 6a -AND-*
  *have wind **directions** between the red lines (approx. 20-95° in Fig. 5b and 275-335° in Fig. 6b);*
- *We anticipate a caution whenever 4 or more out of 8 ensemble members have wind **speeds** that fall between the green lines (16-24 km/h in Figs. 5a and 6a) -AND-*
  *have wind **directions** between the green lines (approx. 5-110° in Fig. 5b and 265-350° in Fig. 6b) .*

Explanation:

Examples of wind speed and wind direction forecasts for XXX, as they relate to areas-of-interest 1 and 2, are given in Figs. 5 and 6, respectively. The “NE-winds” in the title (Figs. 5a-b) applies to area-of-interest 1, and “NW-winds” (Figs. 6a-b) applies to area-of-interest 2, since winds from these directions would transport odour towards those areas.

At each hour in the forecast, the blue-triangle data-points in Figs. 5 & 6 represent the forecast values from 8 different ensemble members. (Some of the triangles are on top of each other, so you might not see 8 separate triangles). The two solid red lines indicate the window of values where high-risk is considered. The green dashed lines indicate the window of values for a moderate risk. The green-red dashed line is plotted where the above thresholds overlap.

Despite the periodically higher risk indicated by slow winds in the wind-**speed** forecast (Fig. 5a), the majority of forecast wind **directions** relating to area-of-interest 1 (NE-wind sector, Fig. 5b) do NOT fall into the red or the green-dashed threshold windows. They are between about 270-360 degrees, making them north-westerly winds: not a concern for area-of-interest 1. Thus, the combined risk for this forecast is low (see Fig. 1, top panel).

For area-of-interest 2 (Figs. 6a-b), the majority of the winds are north-westerly, just like for area-of-interest 1. In this case, unlike in the NE-sector, the risk of northwest winds blowing odour into area-of-interest 2 is high. When combined with periodic slow, high-risk wind speeds (Fig. 6a), this makes for periodic high/moderate odour risk overall (Fig. 1).

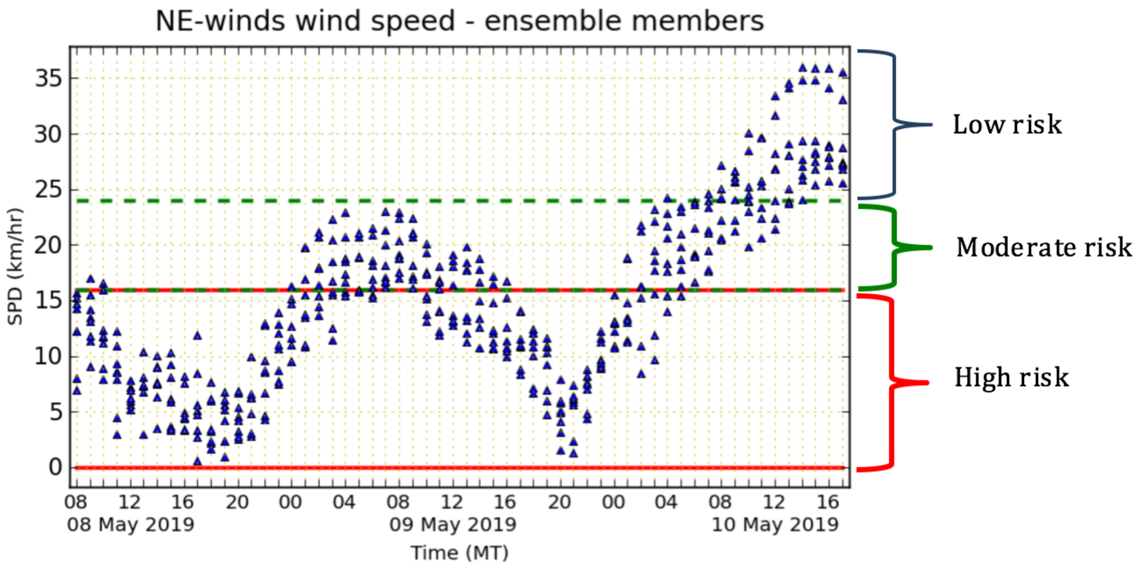

Fig. 5a. Hourly wind-speed (km h-1) forecast for 8-10 May 2019, from 8 different ensemble members, for area-of-interest 1 (affected by winds from NE-wind sector). High- and moderate-risk wind speed values for area-of-interest 1 are enclosed by red solid and green dashed lines respectively.
Although many of the data points show high-risk in wind speed, those same hours have low-risk wind directions in the figure below, and thus would not trigger an alert in Fig 1(top).

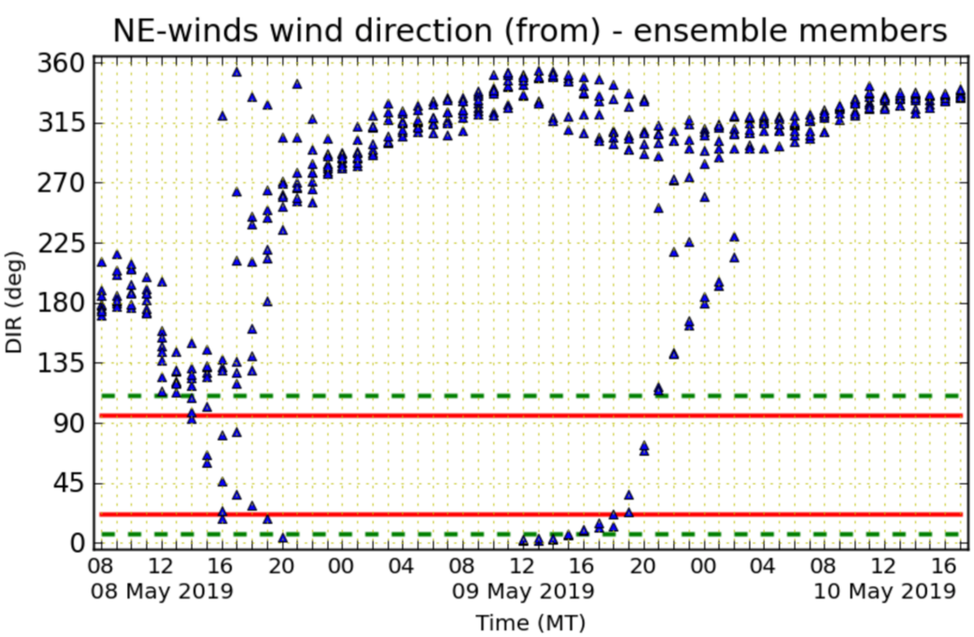

Fig. 5b. Hourly wind-direction (degrees) forecast for 8-10 May 2019, from 8 different ensemble members, for area-of-interest 1 (affected by winds from NE-wind sector). High- and moderate-risk wind direction values for area-of-interest 1 are enclosed by red solid and green dashed lines, respectively.

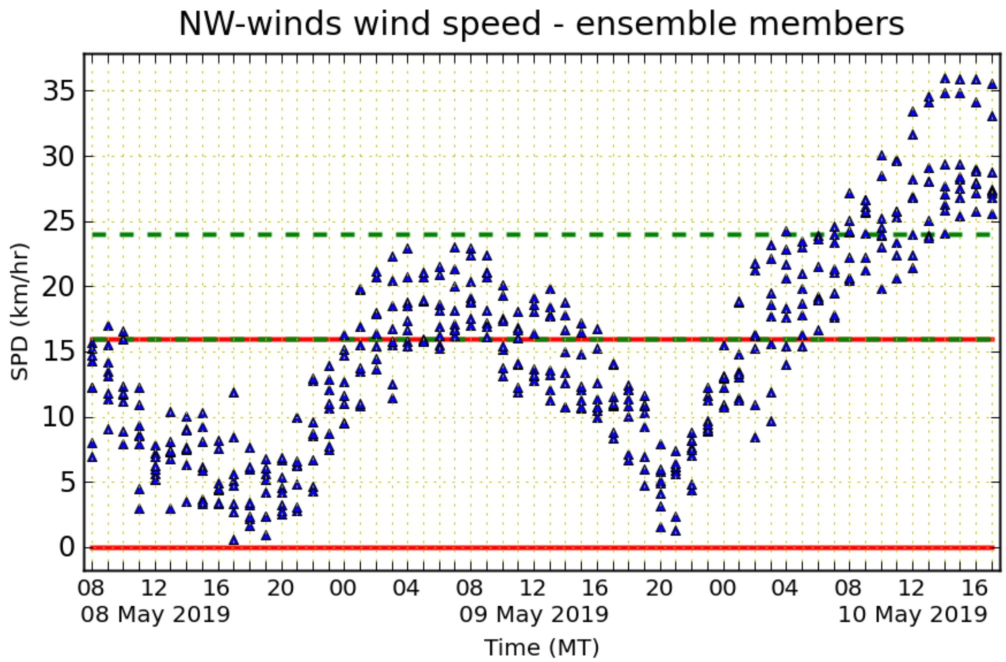

Fig. 6a. Hourly wind-speed (km h-1) forecast for 8-10 May 2019, from 8 different ensemble members, for area-of-interest 2 (affected by winds from NW-wind sector). High- and moderate-risk wind speed values for area-of-interest 2 are enclosed by red solid and green dashed lines respectively, as before.
Some of the data points show high-risk in both wind speed (above) and wind direction (below), and would trigger an alert (Fig 1 bottom).

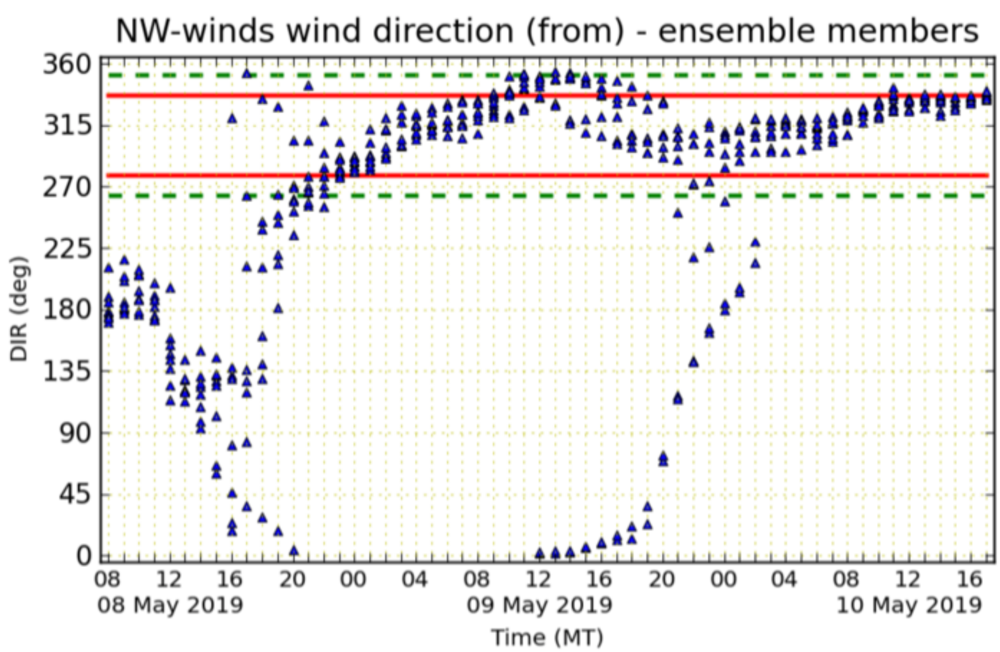

Fig. 6b. Hourly wind-direction (degrees) forecast for 8-10 May 2019, from 8 different ensemble members, for area-of-interest 2 (affected by winds from NW-wind sector). High- and moderate-risk wind direction values for area-of-interest 2 are enclosed by red solid and green dashed lines respectively, as before.

3. Guidance from boundary-layer-variable forecasts

3.1. Time of day

Quick look:

- *We issue an alert whenever 4 or more out of 8 ensemble members are forecasting downwelling (incoming) solar radiation to be 0 W m^{-2} (marked by red-green dashed line in Fig. 7);*
- *We issue a caution whenever 3 out of 8 ensemble members are forecasting downwelling solar radiation to be 0 W m^{-2} (marked by red-green dashed line in Fig. 7).*

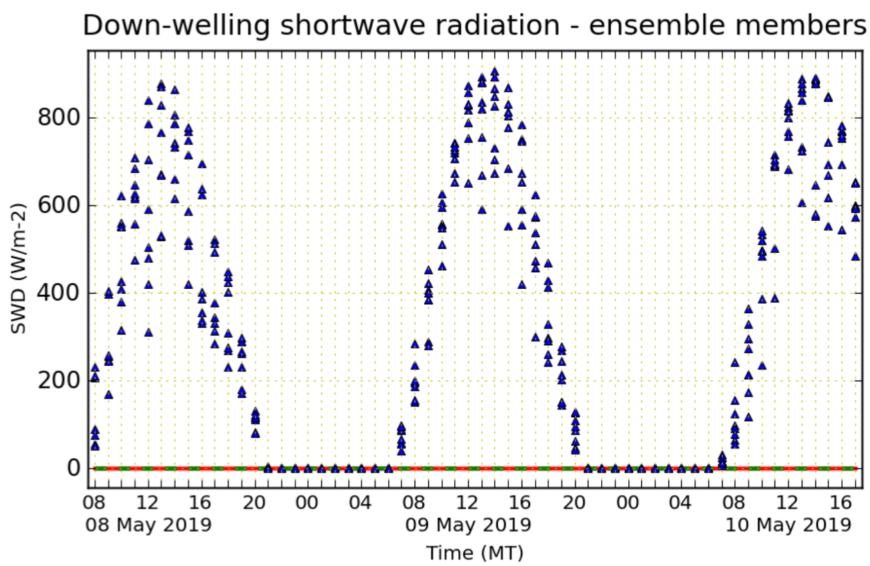

Fig. 7. Hourly forecast of downwelling shortwave radiation (W m^{-2}) for 8-10 May 2019, from 8 different ensemble members.

Explanation:

Fig. 7 shows an hourly forecast of the intensity of downwelling shortwave radiation, i.e. sunlight reaching the surface of the Earth (for the same time period as Figs. 5 and 6). The daily cycle is evident, with radiation increasing in the morning as the sun rises, peaking at solar noon, which is displaced from "clock" noon due to daylight savings time and XXX location within the time zone. Incoming solar radiation decreases throughout the afternoon and becomes zero after sunsets.

During the daytime, most sunlight gets transmitted through the atmosphere, and is then absorbed by the Earth, warming it up. In turn, the Earth radiates some of that heat back into the air near the surface. The newly warmed air near the surface is a higher temperature than its surroundings (especially early in the morning) so it is buoyant and begins to rise vertically through the atmosphere, making convective thermals.

These thermals work to create the layer of turbulence and very vigorous mixing of air in the bottom 100 to 4000 m of the atmosphere (closest to the Earth's surface) that we call the boundary layer (sometimes referred to as the planetary boundary layer, or PBL). Within the boundary layer, we generally experience daily cycles of temperature, humidity, and wind speed. The boundary layer itself is actually composed of several parts (Fig. 8).

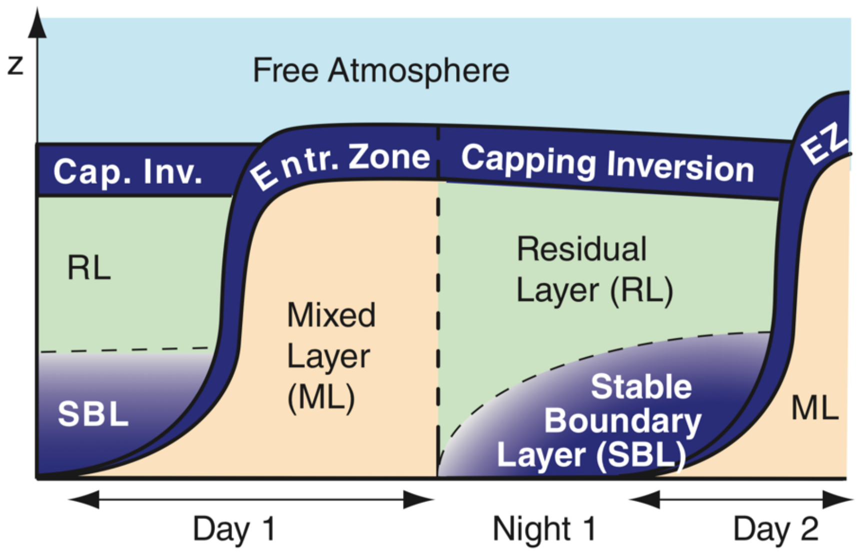

Fig. 8. The evolution and growth of the boundary layer, showing the mixed layer (ML) that develops during the daytime, the stable boundary layer (SBL) that grows overnight, the residual layer (RL) that remains into the nighttime from the previous day's mixed layer, the entrainment zone (EZ) where growth at the top of the mixed layer occurs, and the capping inversion, which marks the top of the boundary layer, with the free atmosphere above this. (Source: Stull, 2017.) The tan-shaded region (ML) provides good dilution of odours over a deep layer of the atmosphere, while the dark-blue-shaded regions (SBL) cause high concentrations of odour to be trapped near the ground.

The ***mixed layer*** is named after the mixing (or stirring) that occurs during the daytime when warm thermals rise, and cooler, more dense air sinks. At the top of the mixed layer there is an ***entrainment zone***, where air from the free atmosphere is entrained or mixed into the mixed layer; this is how the boundary layer gradually increases in height during the day. At nighttime, the sun is no longer heating the Earth so the ground temperature cools down, thermals are no longer created, and the mixing stops.

When the mixing stops, entrainment stops, and this quasi-stationary layer is now referred to as a ***capping inversion*** layer within which the temperature increases with height. Above this, we have the ***free atmosphere*** (not part of the boundary layer). The capping inversion is *stable*, meaning that if air from this layer were to rise above it, it would be colder and denser than the surrounding environment, and would sink back down again.

When the ground temperature cools down, this gradually cools down the air just above the ground surface, and a cool, stable boundary layer (SBL) develops (Fig. 8). This stable layer also prevents air from "escaping", like with the capping inversion at the top of the boundary layer. The relevance of this is that inversions, or stable layers, tend to trap odours and pollutants below the height they are at. During the daytime, the mixing dilutes any odour/pollutants up to the boundary layer depth, therefore ground concentrations tend to decrease as this depth increases.

This cycle repeats every day. *When the downwelling radiation forecast (Fig. 7) is equal to zero (i.e. nighttime), we expect a stable boundary layer (SBL) at the Earth's surface, potentially trapping any odours near the ground.*

3.2. Planetary boundary layer depth

Quick look:

- *We issue an alert when 4 or more out of 8 ensemble members are forecasting a PBL depth < 60 metres, i.e. they are below the red-green dashed line in Fig. 9.*
- *We issue a caution when 3 out of 8 ensemble members are forecasting a PBL depth < 60 metres. i.e. they are below the red-green dashed line in Fig. 9.*

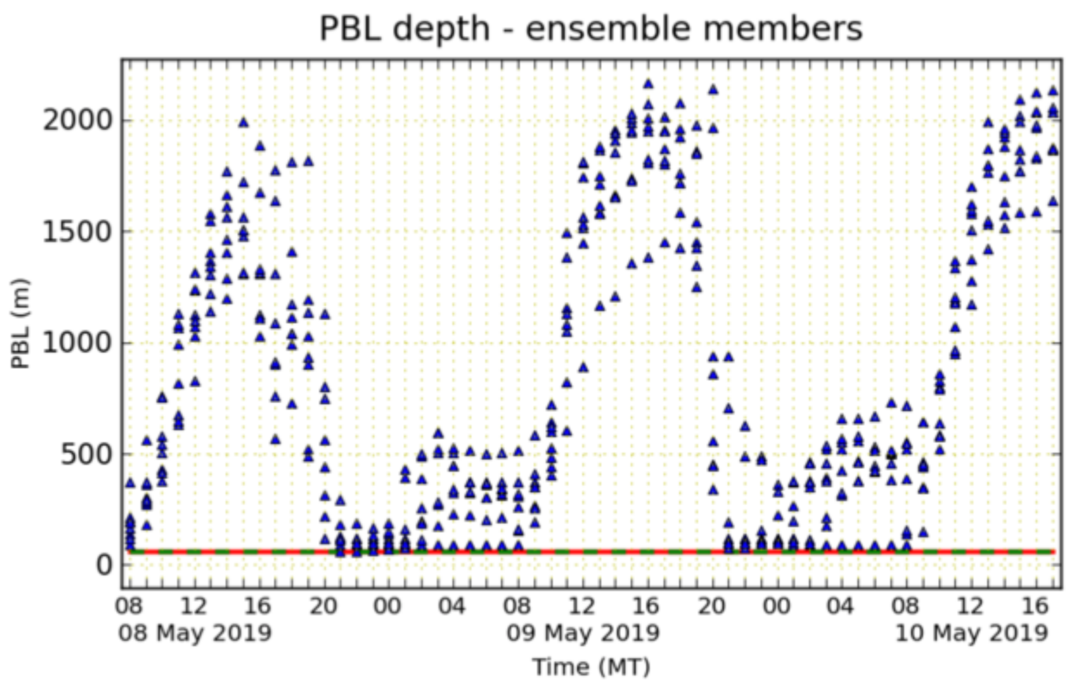

Fig. 9. Hourly forecast of planetary boundary layer depth (metres) for 8-10 May 2019, from 8 different ensemble members. The green-red dashed line shows the PBL depth threshold at 60-m height.

Explanation:

We use the forecast of planetary boundary layer depth (Fig. 9) as an indicator of how deep a layer that odours are mixed into the atmosphere. Deeper layers are better, because odours will become more diluted and weaker. *If the PBL is less than a threshold of 60 m then the risk of odour transport is high, as the odour will be contained within a shallow depth near the ground.* As the PBL grows above 60 m and up to much larger depths, mixing is occurring (by definition), the odour is diluted, and the risk decreases.

3.3. Monin-Obukhov length

Quick look:

- *We issue an alert whenever 4 or more out of 8 ensemble members are forecasting an M-O length > 0 metres, i.e. they are above the red-green dashed line in Fig. 10.*
- *We issue a caution whenever 3 out of 8 ensemble members are forecasting an M-O length > 0 metres, i.e. they are above the red-green dashed line in Fig. 10.*

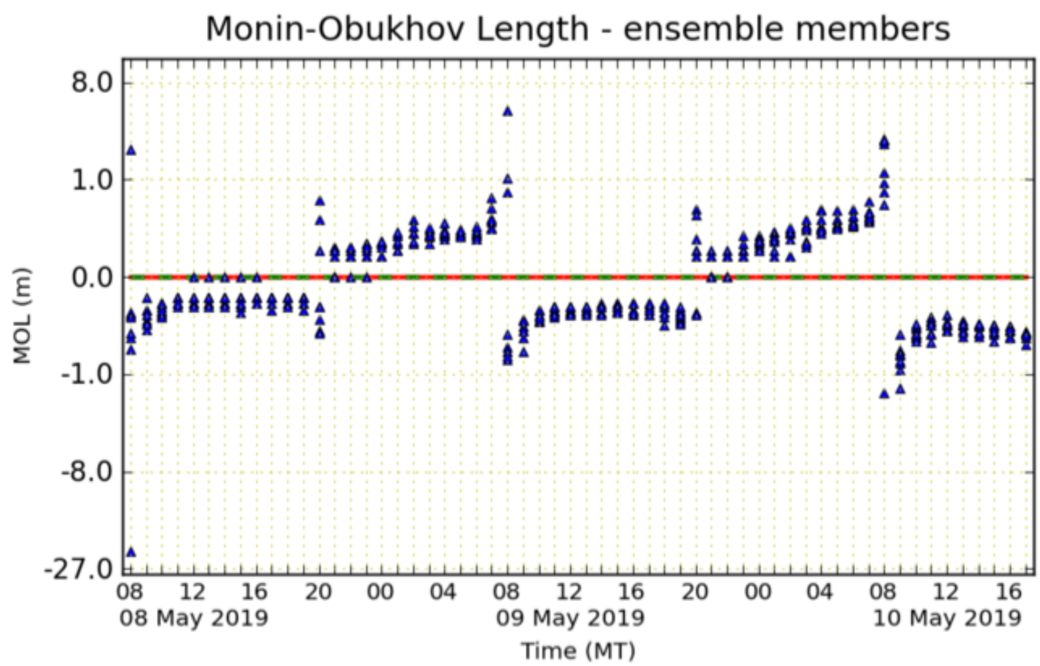

Fig. 10. Hourly forecast of Monin-Obukhov (M-O) length (metres) for 8-10 May 2019, from 8 different ensemble members. The green-red dashed line indicates the threshold of M-O length equal to 0 m.

Explanation:
As the wind blows, the air that comes into contact with the surface of the Earth is subject to a drag force. This causes the wind to slow down near the surface, and gradually increase with height, i.e. further away from the surface (Fig. 11). This change in wind speed with height is called *wind shear*, and it creates turbulence/mixing in the atmosphere. This is a mechanical process, whereas before, the mixing described was driven by buoyancy.

In the interests of comparing these processes and their effects within the boundary layer, meteorologists use a parameter called the Monin-Obukhov length. This can be interpreted as the height above the surface at which the turbulence from the buoyant thermals is equal to that due to mechanical mixing. More importantly, *if the M-O length is positive, the atmosphere near the surface is considered stable* and turbulent mixing in the vertical is weak. If it is negative, then the atmosphere is unstable and turbulent mixing is effective at diluting odors into a deeper layer of air. Therefore, we have indicated a threshold of zero metres (green-red dashed line, Fig. 10).

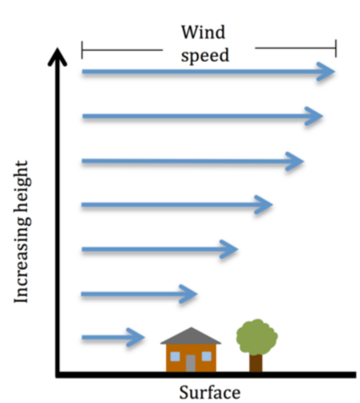

Fig. 11. Schematic showing how wind speed increases with height above the Earth's surface. (Figure by Marjolein Ribberink.)

3.4. Bulk Richardson number

Quick look:

- *We issue an alert whenever 4 or more out of 8 ensemble members are forecasting a Richardson number > 0.25, i.e. they are above the red-green dashed line in Figs. 12a-b.*
- *We issue a caution whenever 3 out of 8 ensemble members are forecasting a Richardson number > 0.25, i.e. they are above the red-green dashed line in Figs. 12a-b.*

Explanation:
The bulk Richardson number is essentially the ratio of turbulence-due-to-buoyancy to turbulence-due-to-wind-shear. It is used as a measure to see whether there will be any turbulence in the atmosphere, and we can see whether turbulence grows or decays by calculating this number. *If the bulk Richardson number is greater than 0.25 (the so-called Critical Richardson number), the atmosphere is stable.* If it is less than 0.25, the flow will be turbulent. We calculate the Richardson number for two layers near the ground surface:

1. Between 0 and 10 metres, denoted GR1, the lower bulk Richardson number (Fig. 12a);
2. Between 10 metres and the next highest model level (~100 m, but could be more or less), denoted GR2, the upper bulk Richardson number (Fig. 12b).

The daytime is mainly turbulent (with good dispersion of pollutants and odour), and the nighttime is mostly stable (with poor dispersal of odours), see Figs. 12a-b.

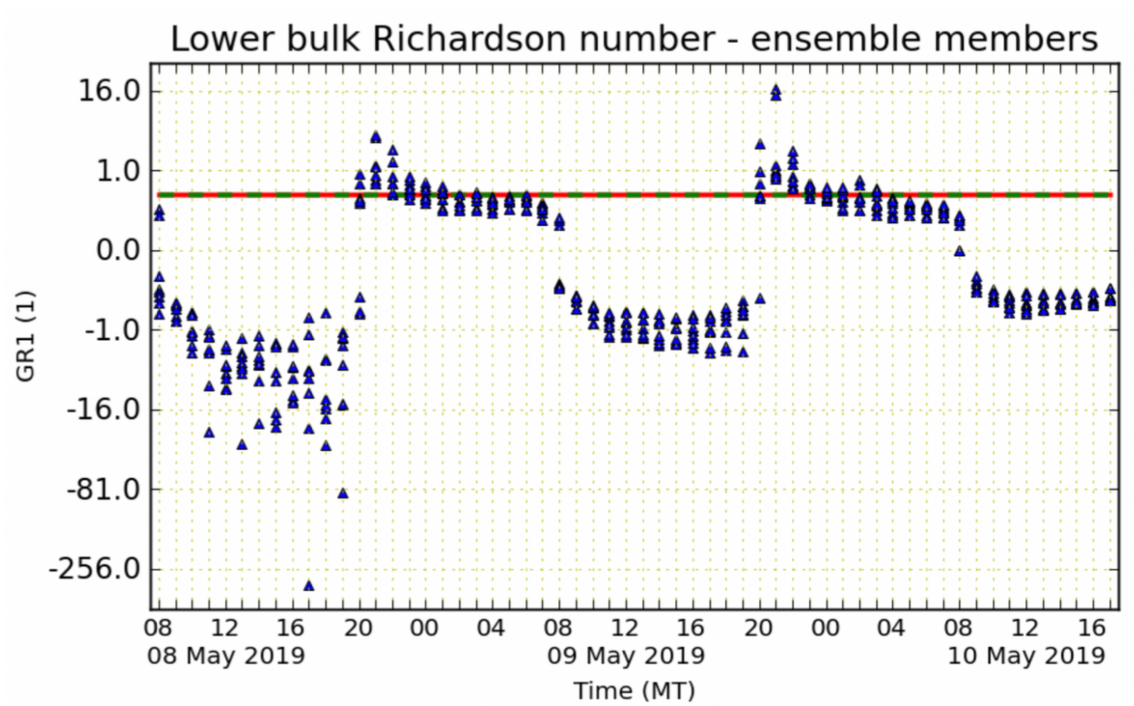

Fig. 12a. Hourly forecast of lower bulk Richardson number (GR1) for 8-10 May 2019, calculated between 0 and 10 m above the ground, from 8 different ensemble members.

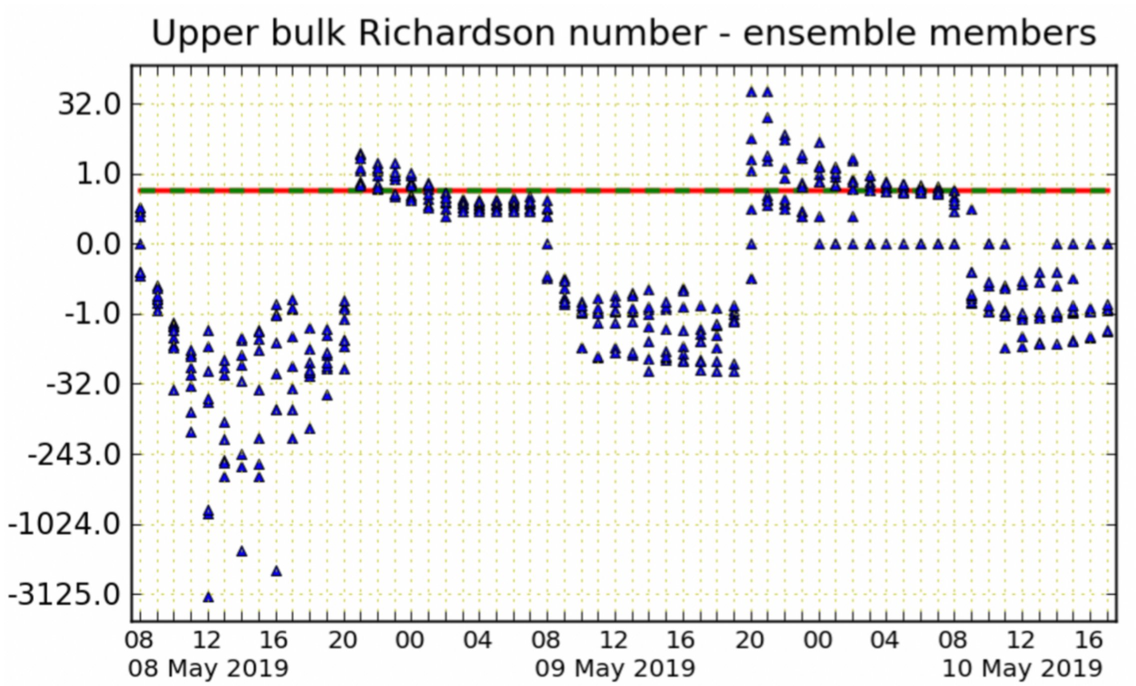

Fig. 12b. Hourly forecast of upper bulk Richardson number (GR2) for 8-10 May 2019, calculated between 10 m above the ground and the next highest model level (~100 m), from 8 different ensemble members.

4. Summary

For an alert to be issued at any one time (HR in Fig. 1), the following conditions must be met:

- The high-risk categories for wind speed AND wind direction must contain 4 or more out of 8 ensemble members;
- PBL depth must be below 60 metres for 4 or more out of 8 ensemble members;
- AT LEAST ONE of the four other boundary layer tests must have 4 or more out of 8 members showing as *stable*.

For a caution to be issued at any one time (MR in Fig. 1), the following conditions must be met:

- The moderate-risk categories for wind speed AND wind direction must contain 4 or more out of 8 ensemble members;
- PBL depth must be below 60 metres for 3 or more out of 8 ensemble members;
- AT LEAST ONE of the four others boundary layer tests must have 3 or more out of 8 members showing as *stable*.
- It is not already designated as an "Alert".

--End--