Meteorological Explanation of Wake Clouds at Horns Rev Wind Farm

S. Emeis

S. Emeis; Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology

EXTERNAL ARTICLE

ENGLISH

Abstract

The occurrence of wake clouds at Horns Rev wind farm is explained as mixing fog. Mixing fog forms when two nearly saturated air masses with different temperature are mixed. Due to the non-linearity of the dependence of the saturation water vapour pressure on temperature, the mixed air mass is over-saturated and condensation sets in. On the day in February 2008, when the wake clouds were observed at Horns Rev, cold and very humid air was advected from the nearby land over the warmer North Sea and led to the formation of a shallow layer with sea smoke or fog close above the sea surface. The turbines mixed a much deeper layer and thus provoked the formation of cloud trails in the wakes of the turbines.

Introduction

On February 12, 2008 wake clouds have been observed in the lee of the turbines at Horns Rev wind farm (Fig. 1). This seems to be a rare event since similar photos from other events are not known to the author. In the internet a few further photos can be found which show wind turbines in a deeper pre-existing fog layer, but no distinct wake clouds are visible in the lee of the turbines on those images (see e. g., http://www.dailymail.co.uk/news/article-1251721/Pictured-The-stunning-micro-climate-sea-fog-created-Britains-windfarms.html). The clouds which formed in the lee of the turbines at Horns Rev must be related to the wake turbulence produced by the wind turbines, because they spread exactly in the same way as wakes are supposed to do. Thus, the explanation must involve a condensation process which is fostered by turbulence.

Horns Rev is an offshore wind farm 14 to 20 km off the west coast of Jutland, Denmark, consisting of 80 wind turbines. These turbines are arranged in a regular rhomboidal array of 8 by 10 turbines. The eight rows of 10 turbines are oriented from West to East, the ten columns run from South-Southeast to North-Northwest (Fig. 2). Hub height is 70 m; rotor diameter is 80 m. Thus, the swept area is from 30 m to 110 m above the sea surface. The distance between the turbines is 560 m; the whole area of the wind farm is roughly 20 km². Together with information from a second image (not reproduced here) and the shadows visible in Fig. 1 it is quite clear that the view on Horns Rev wind farm is from the Southeast.

This paper will show that an explanation via the formation of mixing fog can be supported from the available mete-

Fig. 1: Aerial view from the Southeast of wake clouds at Horns Rev on Februray 12, 2008
(© Vattenfall, Horns Rev 1 owned by Vattenfall. Photographer Christian Steiness)

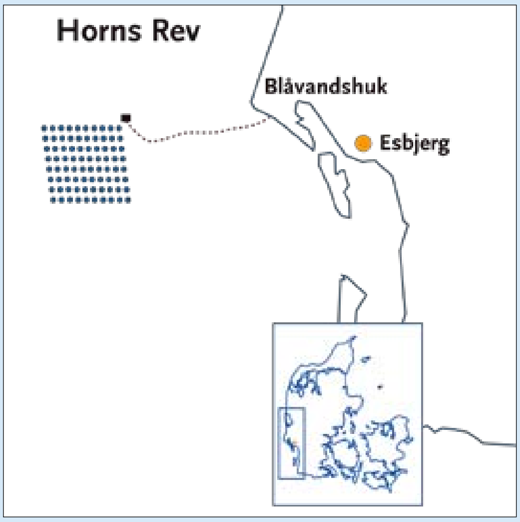

Fig. 2: Horns Rev wind farm
(from: http://www.hornsrev.dk/nyheder/brochurer/Horns_Rev_TY.pdf)

orological data for this event. After a short sketch of the theoretical basis of the formation of mixing fog and a characterization of the weather situation on that day, we will analyse the event depicted in Fig.1.

The Water Vapour Saturation Dependence on Temperature

The amount of water vapour which can exist in a given volume is limited. When the upper bound is reached the vapour is called saturated. The addition of further water vapour then leads to condensation and the formation of small droplets, if a sufficient number of condensation nuclei is available. The upper bound for water vapour content in a given volume is a function of temperature only. The temperature dependence of the saturation water vapour pressure *E* is described theoretically by the Clausius-Clapeyron equation involving the heat of condensation and the gas constant for water vapour. Approximately, the dependence of water vapour saturation pressure in hPa on temperature can be described more simply by Magnus' formula (Emeis 2000):

$$E(t) = 6.107 * 10^{a\ t/(b+t)}$$

Here *t* denotes air temperature in °C. *a* and *b* are two constants (over water: *a*=7.5, *b*=235, over ice: *a*=9.5, *b*=265.5). As a rule of thumb the saturation water vapour pressure doubles every ten degrees between 0°C and 25°C. This means that the saturation water vapour curve in a (*t, E*)-diagram such as Fig. 3 is a steadily increasing upward-bended curve (full line in Fig. 3). This curve separates the under-saturated regime below the curve from the over-saturated regime above the curve. Water boils, if the saturation water vapour pressure reaches the ambient air pressure. This happens at 100°C if the ambient pressure is 1013.25 hPa.
Mixing of two saturated air masses of different temperature leads to a mixed air mass which is always oversaturated, because each straight line which connects two separate points on the saturation water vapour curve runs through the space above the curve between the two points. This is illustrated by the dashed line in Fig. 3.

Weather Situation on February 12, 2008

On February 12, 2008, when the formation of the wake clouds happened, Horns Rev was situated at the western flank of a large wintry high pressure system over the European continent in a weak southeasterly flow with roughly 5 m/s wind speed at 10 m height (Fig. 4). The radiosonde ascent on February

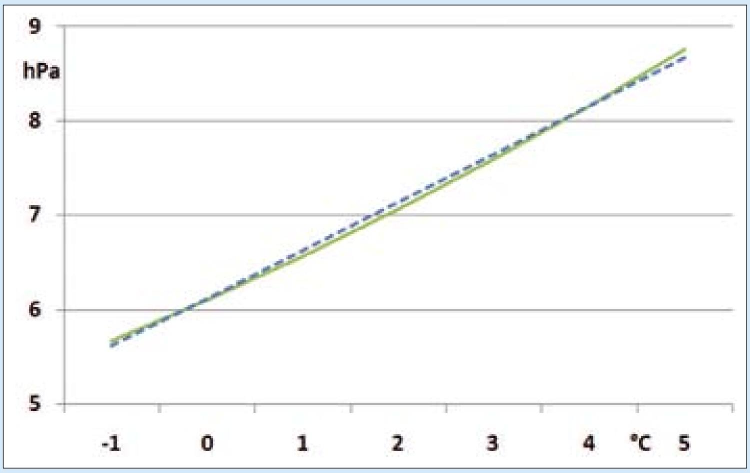

Fig. 3: Dependency of water vapour saturation pressure *E* (y-axis, in hPa) on air temperature *t* (x-axis, in °C) following Magnus' formula (full line) for the temperature range relevant for the present study. The straight dashed line connects the two state points (*t*=-1°C, *rh*=99 %) and (*t*=+5°C, *rh*=99 %) (*rh*: relative humidity). The interval between 0°C and 4°C where over-saturation occurs (the dashed line is above the full curve) is marked with vertical grey bars in Fig. 5.

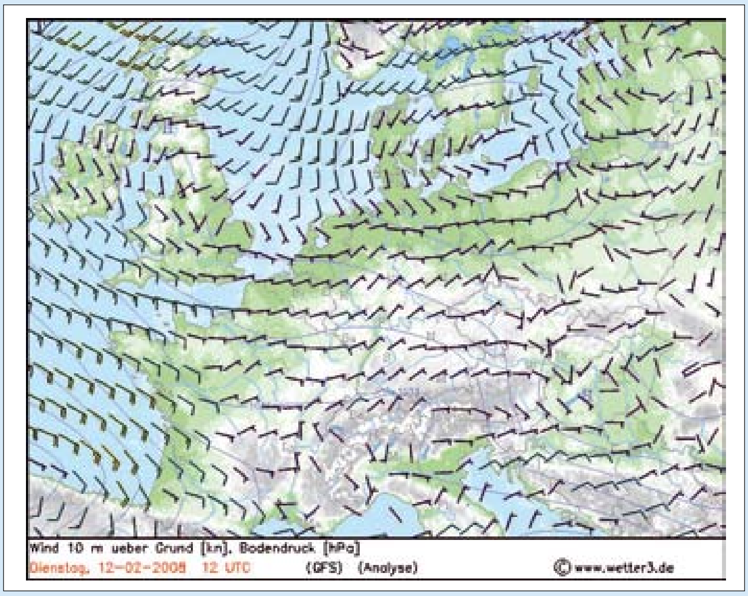

Fig. 4: Surface weather map for February 12, 2008 12 UTC showing 10 m winds in knots (full barb = 10 knots, halb barb = 5 knots) and surface pressure in hPa (thin grey lines).
© www.wetter3.de

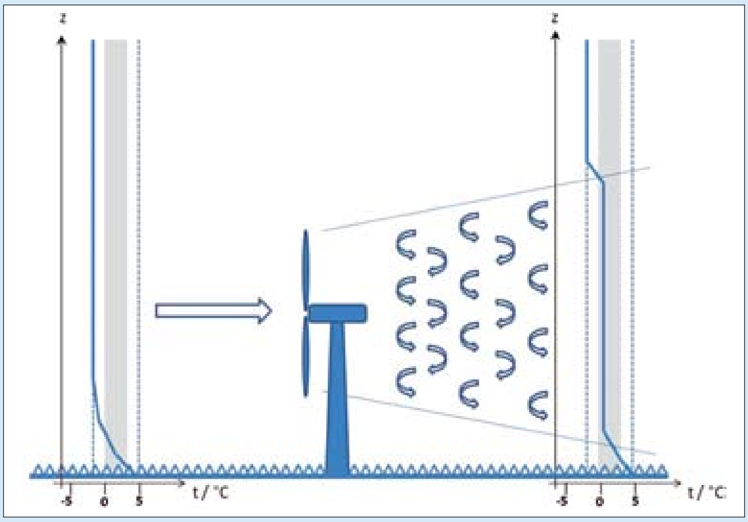

Fig. 5: Simplified sketch of vertical temperature profiles (full line) upstream (left) and downstream (right) of the wind turbines at Horns Rev during the formation of mixing fog. The vertical grey bars indicate the temperature range for which over-saturation and the formation of mixing fog can be expected (see Fig. 3); the dashed vertical lines indicate -1°C and +5°C. The large arrow indicates wind direction; the small bended arrows mark the wake turbulence.

12, 12 UTC at Emden, Germany, at the North Sea coast gave a temperature of -1.5°C and a relative humidity of 99 % 28 m above ground. The ascent at Schleswig at the Baltic Sea coast indicated the presence of a completely saturated air mass up to a height of nearly 600 m above ground on 00 UTC of February 12. The ascent at Ekofisk on 12 UTC of that day gave fully saturated air of 4 °C and southerly flow of 8.5 m/s at 29 m above the sea level. Radiosonde data have been obtained from www.weather.uwyo.edu/upperair/sounding.html. The satellite image for this day showed a large extended fog patch over Denmark, Northern Germany and the eastern part of the North Sea which fitted well to the high relative humidity measured on that day.

The sea surface temperature near Horns Rev was around +5°C in the week ending on February 12, 2008 (data from the German Federal Office on Maritime Travel and Hydrography (BSH) www.bsh.de/de/Meeresdaten/Beobachtungen/Meeresoberflaechentemperatur/). This meant that foggy, nearly saturated cold air with a temperature slightly below freezing point was advected that morning from the Danish and German coast to the about 6 degrees warmer North Sea.

Explanation of the Formation of the Wake Clouds

The advection of this colder air over the warmer sea surface leads to the formation of a shallow layer with sea smoke. This sea smoke is visible all over in Fig. 1 upstream of the wind farm and even between the banners of wake clouds. The left-hand temperature profile in Fig. 5 gives an explanation of this phenomenon. If we assume that nearly saturated air (99 % relative humidity) of -1°C flows over a likewise moist layer directly over the water surface with +5°C and 99 % humidity, then due to buoyancy forces a shallow mixed layer forms within which the temperature decreases with height from 5°C at the sea surface to -1°C in the air above (indicated by the vertical dashed lines in Fig. 5). Within the temperature range between 0°C and 4°C (see Fig. 3 and the vertical grey bars in Fig. 5) the formation of mixing fog or sea smoke can be expected. Comparing blade length and hub height of the turbines visible in Fig. 1, this sea smoke layer is only five to ten metres deep.

Using Magnus' formula given in Section 2 above, it can be calculated that perfect mixing of equal amounts of air with 99 % relative humidity having -1°C (water vapour pressure e = 5.616 hPa) and +5°C (e = 8.664 hPa) leads to a mixed air mass with +2°C and a water vapour pressure of e = (5.616+8.664)/2 = 7.140 hPa). The saturation water vapour pressure E at 2°C from Magnus' formula is only 7.065 hPa (see dashed line in Fig. 3). Therefore the mixed air is over-saturated with 101.1 %.

The situation in Fig. 1 changes dramatically, when the air passes the first row of turbines. A possible temperature profile in the wake region is given by the right-hand temperature profile in Fig. 5. The turbulence produced by the turning turbines leads to a nearly perfect vertical mixing of the air within the wake. When the lower edge of the wake spreads into the warmer air layer below, air from this layer is included into the mixing process and the temperature in the wake starts to rise. When it rises more than about one degree, then the temperature in the wake enters the range marked by the grey bar in Fig. 5 and condensation starts and the wakes become visible. With the spreading of the wakes further away from the turbines the wake clouds become wider. The overall unstable temperature stratification of the air (warmer air underneath colder air) leads to the slightly bumpy nature of the wake clouds. They look like small cumulus clouds.

Conclusions

The analysis above has proven that the weather conditions on February 12, 2008 were sufficient for the formation of mixing fog in the wakes of the turbines of Horns Rev wind farm. This phenomenon requires the existence of two layers of air with two different temperatures and both with very high relative humidity very close to saturation. The separating line between these two layers must be close to the hub height. Then, the mixing of these two layers will lead to the formation of mixing fog. Such a situation is most likely to form during advection of air from land to sea or vice versa. A comparable mixing-fog phenomenon is the formation of cloud banners behind mountain crests shortly after rain events when cold and very humid air aloft mixes with warmer and likewise very humid air which is vented upwards in a lee vortex on the downstream side of the crests.

Due to the necessary requirements for formation (existence of two layers with considerably different temperature with the separation line between the two layers close to the hub height of the turbines and very high relative humidity in both layers), it can be assumed that the formation of such wake clouds is a rather rare event. The most likely area for such phenomena is a stripe on both sides of a coast line with the sea and land having considerably different surface temperatures and winds crossing the coastline.

References

Emeis, S., 2000: Meteorologie in Stichworten. Hirt's Stichwortbücher, Gebrüder Borntraeger Stuttgart. XIV+199 S. ISBN 3-443-03108-0.