Quantifying moisture perturbations leading to stacked lenticular clouds

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The origin of horizontal striations in lenticular clouds was qualitatively described by Richard Scorer as being due to a vertically layered moisture field, although the magnitude of the required moisture perturbations has not previously been quantified. Sensitivity tests using high-resolution numerical simulations of these clouds are used here to confirm Scorer's hypothesis, and show that only minute and essentially unmeasurable variations in moisture with height are required to generate striations of the size observed in nature. Relative humidity (RH) perturbations of only ±0.25% can create an indentation into the cloud of approximately 170 m. RH perturbations of this scale are likely to be commonplace in nature, and are an order of magnitude smaller than the accuracy of standard measuring equipment.

Key Words: lenticular clouds; lee waves; piles of plates

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1. Introduction

Lenticular clouds in the lee of terrain are a common sight. Depending upon the availability of moisture, and given sufficiently high-amplitude waves, these clouds may consist of a single thin cloud-filled layer, or a deeper cloud deck (Larsson, 1954). Vertically extensive lenticular clouds almost always have visible striations along their lateral boundaries, leading Scorer (1972) to describe them as 'Piles of Plates' (also Woodley, 1991). Scorer suggested that these striations are produced by vertical variations in the humidity profile, and that the vertical variations in humidity were caused by directional vertical shearing of decaying cumulus towers. Figure 5.I.i of Scorer (1972) illustrates how perturbations in relative humidity (RH) might be associated with striations. However, he did not provide a quantitative analysis of the magnitude of the humidity perturbations required to generate realistic layering.

One attempt to quantity the moisture perturbations responsible for layering in lenticular clouds was included as a complimentary scientific issue in the Terrain-induced Rotors EXperiment (T-REX) field campaign (Grubišić *et al.*, 2004, p. 13). Nevertheless, as far as the authors are aware, no results pertaining to this question have been published. In fact, it would be very difficult to carry out appropriate humidity measurements in a field campaign because, as will be demonstrated below, the magnitude of the moisture perturbations required to create visible layering is so small that it cannot be reliably measured by current humidity sensors.

Our objectives are: (i) to confirm and quantify Scorer's hypothesis that layering in lenticular clouds may be generated through moisture perturbations alone, and (ii) to determine whether moisture-induced layering might feed back on the cloud dynamics in a manner that amplifies the striations. To reach these objectives, we use a high-resolution two-dimensional numerical model to quantify the relationship between the indentations in striated lenticular clouds and the magnitude of the associated humidity perturbations.

2. Numerical model and simulation parameters

Simulations of lenticular clouds are performed using the non-hydrostatic, fully nonlinear model initially described by Durran and Klemp (1983) and updated with tracer advection computed using the piecewise parabolic method and the Blossey–Durran selective limiter (Blossey and Durran, 2008). The Coriolis force is neglected because the Rossby number associated with the flow across our narrow terrain is large.

Resolving the layered structure in lenticular clouds necessitates the use of high resolution in both the horizontal ($\Delta x = 50$ m) and the vertical ($\Delta z = 5$ m for $z < 2$ km, smoothly stretching to $\Delta z = 250$ m for $z > 6$ km). The domain is 400 km and periodic in the x-direction, with an upper boundary at $z = 16$ km. Reflections from the upper boundary are minimized using the gravity-wave radiating KDB boundary condition (Klemp and Durran, 1983; Bougeault, 1983). The model is started impulsively from rest and run for 3 h, terminating before perturbations can wrap around our periodic domain.

The large-scale environment for our waves is modified from an operational sounding taken upwind of an event of well-defined stacked lenticular clouds that formed in a westnorthwesterly airflow across the Pennines in northern England on 22 December 2011. Above an elevation of 2 km, the environment matches the thermodynamic and cross-ridge wind components in the 0000 UTC 22 December 2011 sounding from Castor Bay, Northern Ireland. Below 2 km, the observed temperature and wind profiles are smoothed to ensure the environmental

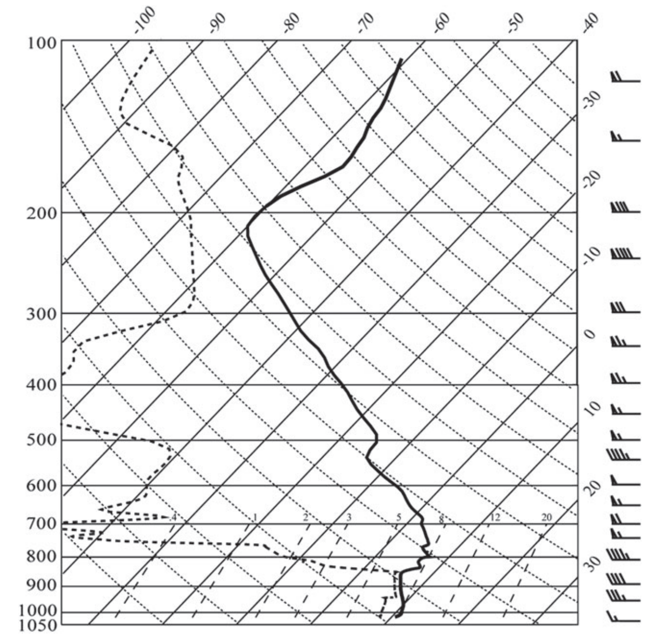

Figure 1. Sounding used to initialise model simulations, modified from the operational sounding taken at Castor Bay, Northern Ireland, at 0000 UTC on 22 December 2011. Wind speeds shown represent the cross-ridge flow (knots).

Richardson number is large enough to avoid triggering the subgrid-scale mixing parametrization and to give a simple smoothly varying profile of specific humidity. This environmental sounding is plotted in Figure 1.

As a specific example of lenticular cloud layering, Figure 2 shows clouds that formed on 22 December 2011 near Sowerby, West Yorkshire. However, we are not attempting to exactly simulate the cloud structure generated on this day. The humidity perturbations required to create the observed striations turn out to be much too small to be captured by the humidity sensor in the sonde, and Castor Bay is too far upstream to offer a reliable sample of the air that passes through the cloud shown in Figure 2.

To approximate the impact of the terrain on the inviscid flow above the boundary layer, we force the waves with smooth terrain $h(x)$, having half-width at half-height $a = 10$ km, and maximum height $h_0 = 400$ m, such that

$$h(x) = \begin{cases} \dfrac{h_0}{16}\left\{1+\cos\left(\dfrac{\pi b}{4a}\right)\right\}^4 & \text{if } b \le 4a, \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

where

$$b^2 = (x - x_0)^2 . \tag{2}$$

The 400 m height of our ridge is similar to that of the section of the Pennines that forced the cloud shown in Figure 2. The terrain is centred at $x_0 = 150$ km.

3. Quantifying the effects of humidity perturbations

The RH is set to 95% throughout the 650–1500 m layer in the sounding in Figure 1, and simulations with this uniform RH profile produce the 975 m-deep lenticular cloud without striations shown in Figure 3(a).* The uniform edges of the cloud shown in Figure 3(a) provide a sharply defined boundary against which we can accurately measure any changes in cloud width arising from vertical variations introduced to the environmental RH profile.

*Throughout this study, regions of cloud-water mixing ratio greater than 1×10^{-5} kg kg^{-1} are considered to be cloud-filled. As a point of reference, the RH values measured within the same layer in the Castor Bay sounding ranged from 86 to 99%.

Note that the lenticular clouds in Figure 3 are plotted with a one-to-one horizontal-to-vertical aspect ratio.

To quantify the indentation distance of the striations produced by moisture layering, two layers will receive dry perturbations. Drier layer 1 (DL1) is located between $z = 800$ and 900 m, and drier layer 2 (DL2) is located between $z = 1100$ and 1200 m, while the top, bottom and centres of the 650–1500 m layer will be moistened by RH perturbations having equal magnitude but opposite sign.

Figure 3(b–d) shows the cloud structure when RH perturbations are ±0.25, ±0.5, and ±0.75%. Despite the very slight changes in upstream moisture content, all the clouds develop a distinct layered structure. The maximum indentations in the side of the cloud in DL1 are 170, 350, and 540 m for the cases shown in Figure 3(b–d) respectively. The increase in indentation width per unit change in RH increases with perturbation size due to the weaker ascent near the centre of the cloud. Indentations associated with DL2 are 140, 290, and 450 m respectively, slightly smaller than those for DL1 due to the steeper parcel trajectories aloft.

These changes in moisture could potentially impact the wave dynamics by changing the moist Brunt–Väisälä frequency (Durran and Klemp, 1982a) and thereby the resonance condition for the trapped waves (Durran and Klemp, 1982b). It turns out that the preceding perturbations influence the wave properties by less than 5%, and do not modify the lenticular cloud structure, except for a very slight shift in its location.

Additionally, the vertical displacement field surrounding the lenticular cloud can be examined to determine whether the layering seen in Figure 3 is the result of any significant changes in dynamical structure. Figure 4 shows the outline of the cloud produced using ±0.75% RH perturbations (as in Figure 3(d)), overlaid with contours of vertical displacement (net change in height of an air parcel from its initial upstream elevation). Clearly no layering in the vertical displacement field is present which might account for the cloud striations.

The results from our simulations may be generalised by considering the trajectory which air parcels follow to become saturated in lenticular clouds. The upward displacement required to reach saturation may be calculated using the definition of the lifted condensation level (LCL) from Emanuel (1994; his Eq. (4.6.23), p. 130), simplifed using the expression for the saturation temperature from Bolton (1980),

$$z^* - z = \frac{c_{pd}}{g}\,\frac{1 + r\frac{c_{pv}}{c_{pd}}}{1+r} \times \left\{T - \left(\frac{2840}{3.5\ln T - \ln e - 4.805} + 55\right)\right\}, \tag{3}$$

where z^* is the LCL, z is the initial parcel height, c_{pd} and c_{pv} are the specific heat capacities at constant pressure of dry air and water vapour respectively, r is the initial parcel mixing ratio, T is the initial parcel temperature, and e is the vapour pressure. Using this equation, we can estimate the extra distance that the relatively drier air parcels must rise to reach saturation, compared to that required for more moist regions of the upstream flow. Combining this with an approximation of the air parcel trajectory through the cloud, we can estimate the indentation of a striation as equal to the extra horizontal distance over which the drier air must transit before reaching its level of condensation.

In our simulation with ±0.25% humidity perturbations, using the preceding to evaluate the difference in the LCLs suggests the parcels within the drier layers must rise an additional 9.5 m to reach saturation compared with the more moist adjacent regions. This corresponds to a 172 m indentation when applied to the centre of DL1, and to a 129 m indentation applied to DL2, values which agree well with those from the full numerical simulations.

The trapped waves in our simulations have wavelengths ($\lambda = 20$ km), vertical velocities ($w = \pm 3$ m s^{-1}), and therefore

Figure 2. An example of a stacked lenticular cloud over Sowerby, West Yorkshire, UK, looking northeast on 22 December 2011. Photograph reproduced with permission from Sheila and John Dickinson.

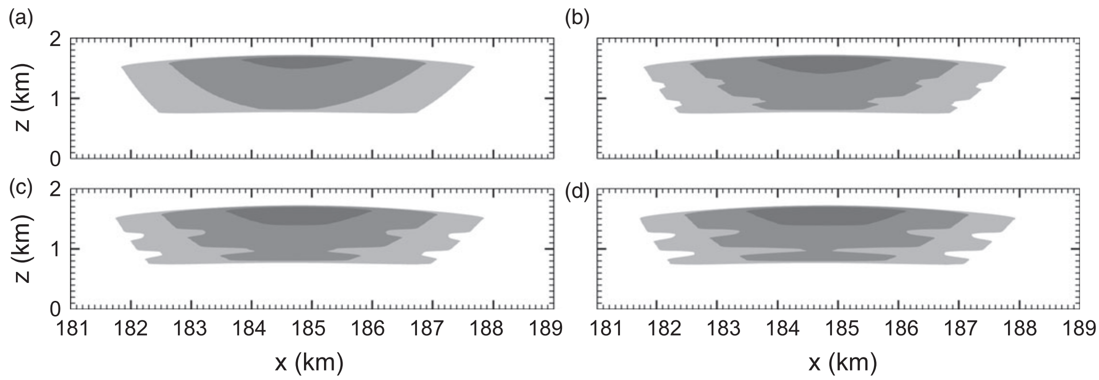

Figure 3. Cloud water content (q_c) after 2.5 h in simulations in which the RH in the 650–1500 m layer is (a) a uniform 95%, or contains perturbations of (b) ±0.25%, (c) ±0.5%, and (d) ±0.75%. Shading shows q_c above values 0.01, 0.11, and 0.21 g kg^{-1}.

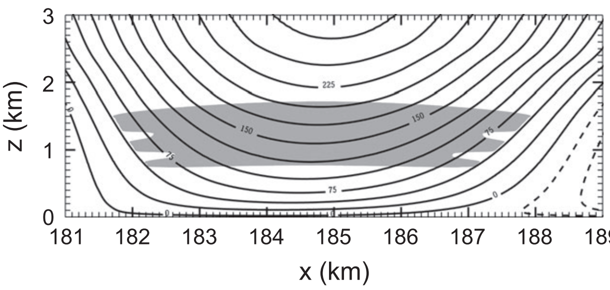

Figure 4. Vertical displacement field (contours at 25 m intervals; dashed lines are negative) and lenticular cloud outline (shaded) after 2.5 h for the case using ±0.75% RH perturbations (case shown in Figure 3(d)).

trajectory slopes, typical of those measured during observational campaigns. For example, Shutts and Broad (1993) measured waves downwind of the Pennines with $\lambda = 20$ km and $w = \pm 3$ m s^{-1}, and Smith and Broad (2003) observed trapped waves downwind of Mont Blanc during the Mesoscale Alpine Programme having $\lambda = 18$ km and $w = \pm 2$ m s^{-1}. It follows from Eq. (3) that typical trapped waves should be expected to develop easily discernible striations when the RH perturbations in the upstream flow are as small as ±0.25%.

4. Conclusions

Our findings confirm the moisture-layering hypothesis proposed by Scorer, although the sensitivity of the layers to very weak perturbations in the vertical humidity profile does not seem to have been previously anticipated. In particular, our numerical simulations have demonstrated that vertically layered RH perturbations as small as ±0.25% can produce lenticular clouds with a layered structure similar to that frequently seen in nature. Slightly larger perturbations of ±0.75% generated pronounced indentations in excess of 0.5 km. These striations in the cloud field were *not* accompanied by any layering in the vertical displacement field – showing that, at least in our simulations, piles of plates are a passive response to the moisture perturbations and not of dynamical origin.

RH perturbations of ±0.5% are an order of magnitude too small to be measured by radiosonde sensors whose RH measurements are only accurate to ±5% (Vaisala, 2010). The presence of such small perturbations in the upstream humidity profile does not appear to demand much of an explanation (such as the shearing of cumulus towers); indeed it might be harder to explain those circumstances in which they might be absent. The sensitivity of lenticular clouds to small changes in moisture content helps explain the rarity of deep lenticular clouds that do not display striations.

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