On self-maintenance of clear-air turbulence

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Abstract. It is shown that thin patches of clear-air turbulence (CAT) of limited horizontal extent may be a self-maintaining phenomenon due to the relative decrease of Richardson number at the lower and upper edge of the patch.

1. Introduction

Clear-air turbulence (CAT) i. e. turbulence encountered mostly at higher altitudes (over 3000m up to tropopause) in cloudless air or inside thin cirrus clouds creates considerable problems for air traffic. It has rather complex physics and may result from various reasons. Literature on this subject is fairly extensive, but mostly refers to various observational data and empirical or statistical studies directed towards practical applications like CAT forecasting or warnings for pilots. Most of it can be found in various technical reports, conference preprints or pilot manuals rather than in regular scientific periodicals and seldom try to go deeper into theoretical aspects of this phenomenon. The most typical mechanism taken into account is vertical (sometimes also horizontal) shear instability resulting either from larger scale phenomena like jet stream or some more local processes like short gravity waves of surface origin (e.g. mountain waves) or connected with disturbances around thunderstorms. In such a case Richardson number is the most typical criterion of CAT formation. The present author Haman (1962) proposed gravity waves generated by low level convection which propagate upwards with height-increasing amplitude (what may happen for certain vertical temperature and wind profiles) until breaking and overturning appears. Another source of CAT may follow from deformation fields of frontogenetic processes. Atmospheric indices used as predictors for practical, statistical CAT forecasting usually include various forms of Richardson number Ri,(e.g. Colson & Panofsky (1965)) or certain parameters of frontogenetic function equation (e.g. Elrod & Knapp (1992)) or combination of both (e.g. Dutton (1980)); their performance (mostly rather problematic) is usually empirically tested against pilot (PIREP) reports. CAT is often observed in patches which are only few hundreds (or even tens) of meters thick and extend over several kilometers in horizontal. This patchy structure can result from small inhomogeneities in forcing or from other mechanisms which introduce intermittence to chaotic phenomena, but it seems that there may also be some internal feedbacks tending to maintain such patches when once formed. One of such feedbacks is presented in the present paper. Idea of its existence follows from aircraft observations of cooling tower and stack plumes and subsequent tuning a model of stack plume with respect to parametrization of entrainment Haman & Malinowski (1989). Such a plume can be divided into an active part dominated by buoyant eddies and a passive one which drifts with the wind at the level of zero average buoyancy. The passive part retains fairly strong turbulence generated by decay of buoyant eddies and undergoes mixing with environmental air. The best fit between the observed and computed size of the plume has been achieved under assumption that turbulent energy in the passive part is not merely advected from the active one but also produced at place more intensively than in the surrounding air. This suggested that the preexisting turbulence (formed by decay of buoyant eddies) may improve the conditions for generation of turbulence by other factors like e.g. external wind shear. The same mechanisms may be present in self-maintaining of the patches of CAT. The following reasoning based upon a simple conceptual model indicates that this is in fact possible, at least in situations when Richardson number Ri can be treated as a plausible criterion of onset and maintenance of turbulence. It is noticed, that thin patches of CAT of limited horizontal extent may be a self-maintaining phenomenon due to the fact, that the value of Richardson number at the lower and upper edge of the patch is relatively smaller than in its undisturbed environment. For simplicity sake this is shown below first for an idealized case with linear vertical distribution of potential (or rather virtual-potential) temperature θ and wind speed U but can be easily extended to more realistic stratifications as shown in the next step.

2. Idealized case

Let us assume a turbulent patch, generated by some unspecified factors, occupying certain limited area (but wide enough to permit hydrostatic approximation within it) and forming a mixed layer of thickness H, small enough to permit disregarding non-linearity of vertical pressure distribution over it Let us consider an ideal case in which this layer consists of a central, perfectly mixed layer of constant θ and zero shear, bounded from above and below by equally thick transition layers of thickness Δ (Fig. 1a - dashed lines). Vertical distribution of all parameters in the undisturbed atmosphere out of the patch as well as in all sublayers of the patch is assumed linear. Let us consider Richardson numbers for these layers and compare them with Richardson number for undisturbed atmosphere. The undisturbed environment has Richardson number $\mathrm{Ri_e}$ given by the expression:

$$\mathrm{Ri_e} = \frac{\mathrm{gH}}{\overline{\theta}} \frac{\theta_2 - \theta_1}{(U_2 - U_1)^2} \tag{1}$$

where g denotes gravity acceleration and indices 1 and 2 refer respectively to the lower and upper boundaries of the patch and upper dash to its well mixed central layer. This central layer has indefinite Richardson number but it is simply hydrostatically neutral. Disregarding small difference of average θ between the central and transition layers and noting that:

$$\theta_2 - \overline{\theta} = \overline{\theta} - \theta_1 = \frac{1}{2}(\theta_2 - \theta_1) \tag{2}$$

$$U_2 - \overline{U} = \overline{U} - U_1 = \frac{1}{2}(U_2 - U_1) \tag{3}$$

Richardson number for the transition layers Ri_t can be written as:

$$\mathrm{Ri_t} = \frac{2\mathrm{g}\Delta}{\overline{\theta}} \frac{\theta_2 - \theta_1}{(U_2 - U_1)^2} = \frac{2\Delta}{\mathrm{H}} \mathrm{Ri_e} \tag{4}$$

Obviously $2\Delta/\mathrm{H} < 1$, what means that Richardson number for the transition layers is smaller than that for the undisturbed atmosphere; thus turbulence generated by shear instability is more likely to appear there than in the undisturbed air and eventually it may penetrate the neutral central layer, maintaining its well mixed character. Thus, a patch of CAT once formed, may in such a way maintain its existence, provided that the critical value of Ri is between $\mathrm{Ri_e}$ and $\mathrm{Ri_t}$.

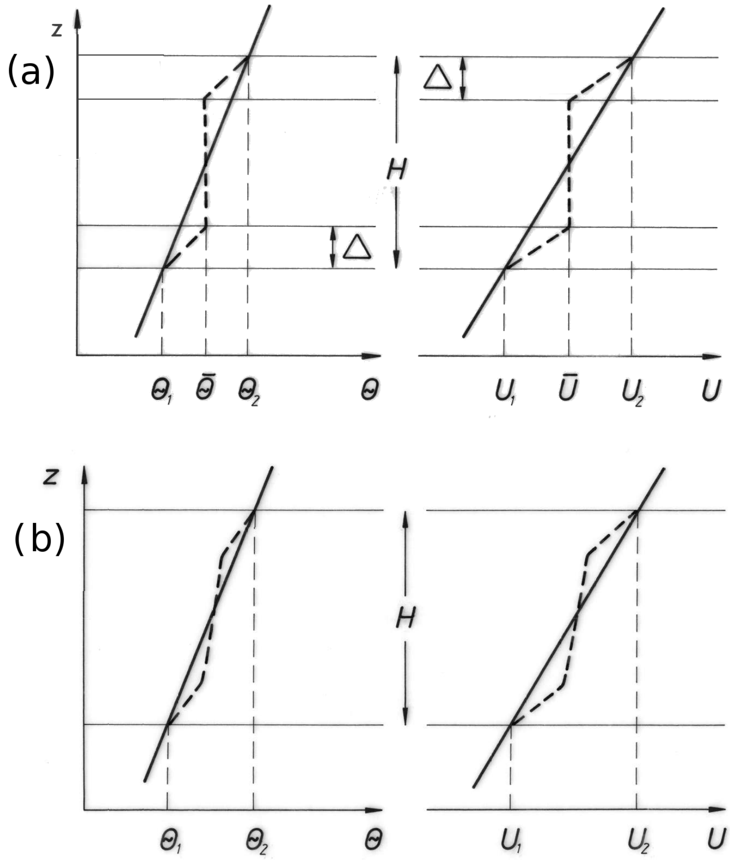

Figure 1. (a) Schematic vertical distribution of potential temperature θ and wind velocity U for undisturbed atmosphere (thick continuous) and turbulent patch (thick dashed) - an idealized case. (b) The same for more realistic case. See text for details.

3. Realistic case

The former result can be at least qualitatively extended to a more realistic case of a turbulent patch with less symmetric geometry and vertical gradients of conservative properties in its central parts reduced with respect to undisturbed environment but not necessarily vanishing (Fig. 1b). Under plausible assumption that the mechanism of mixing for θ and U are identical, the local values of these parameters can be written as:

$$\frac{\partial\theta}{\partial z} = \alpha(z)\frac{\theta_2-\theta_1}{\mathrm{H}} \tag{5}$$

$$\frac{\partial U}{\partial z} = \alpha(z)\frac{U_2-U_1}{\mathrm{H}} \tag{6}$$

where $\alpha(z)$ is a certain dimensionless factor identical for θ and U. Thus Richardson number in the mixed layer $\mathrm{Ri_m}(z)$ can be written in the form:

$$\mathrm{Ri_m} = \frac{\mathrm{g}}{\theta}\frac{\frac{\partial\theta}{\partial z}}{\left(\frac{\partial U}{\partial z}\right)^2} = \frac{\mathrm{Ri_e}}{\alpha(z)} \tag{7}$$

in which small vertical variability of θ over the turbulent layer has been disregarded again and assumption of linear distribution of θ and U in undisturbed environment retained (what seems acceptable). Noting, that vertically averaged θ and U within the turbulent patch and outer atmosphere must be practically the same, it is obvious that in the transition layers of the patch $\alpha(z) > 1$ so that $\mathrm{Ri_m}(z) < \mathrm{Ri_e}$ must hold there, creating there more convenient conditions for generation of turbulence than in the undisturbed environment.

Observational verification of the above hypothesis seems to be very difficult, since resolution of standard aerological measurements, the most abundant source of upper air data, is for this purpose insufficient while special airborne experiments would not be easy to arrange. Nevertheless the problem seems worth of announcing, since suitable data may be incidentally found as a by-product of some in-flight observations of turbulent processes and persons involved in their conduction should be aware of this possibility. Taking it into account may also give some improvement in CAT forecasting.

References

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