CONVECTIVE WAVES AND CUMULUS GROWTH

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Summary

Numerical simulations and aircraft measurements show that thermal waves are gravity waves developing under the presence of shear in the stable troposphere above a heated boundary layer. The waves are launched when thermals rise from the ground and impinge into the stable layer where they act as obstacles to the mean flow, thus forcing the air to flow over them. This paper reviews some basic aspects of thermal waves based on the papers of Clark, Hauf and Kuettner (1), Clark and Hauf (2), and Kuettner, Hildebrand and Clark (3).

1. Introduction

Continuous reports on thermal or convective waves among the soaring community and the observational evidence of this phenomenon, as documented in the papers by Jaeckisch (4), (5), Rovesti (6), (7), Kuettner (8) and Lindemann (9), and presented at OSTIV Congresses over the last two decades, led to the initiation of the "Convective Wave Project" at the National Center for Atmospheric Research in Boulder, Colorado in 1984. The project consists of airplane measurements and numerical simulations. The measurements were performed in June/July 1984 and June 1985, partially over Colorado, but mainly over the plains of western and central Nebraska, using the NCAR instrumented Beech King-Air. The results of these measurements are published in Kuettner, Hildebrand, and Clark (3). At the same time Terry Clark conducted numerical simulations of those situations when convective waves were reported and measured with the airplane. Clark's numerical cloud model (10) was run on the CRAY computers at NCAR, but also at the DFVLR in Oberpfaffenhofen (F.R.G.). Results of these calculations are reported in Clark, Hauf, and Kuettner (1). The intention of the present paper is to review the basic results of the calculations and illustrate them, discuss their implications, and outline the future work on convective waves.

2. Observations

Thermal waves, as experienced by gliders, are typical gravity waves and as such are found in the stable tropospheric layer above a heated planetary boundary layer. The thermal waves are observed to reach down into the boundary layer, as well as heights well above the tropopause. Thermal waves typically cover the whole tropopause with maximum updraughts between 1-3 m/s. Lindemann (9) found a moderate to strong environmental wind shear to be necessary for their occurrence. Gliders observed them with and without cumulus convection, but obviously, they are easier to detect when clouds are present. To use the waves for gaining altitude, it is recommended to fly from below the cloud base a distance of typically more than one km against the prevailing wind. If thermal waves are present, a smooth wave lift then allows climbing up to several km above cloud top. Convective waves are found over flat to gentle structured terrain and often far away from mountains. As a special case, thermal waves with strong updraughts are observed over cloud streets, provided there is sufficient wind turning between the ground and cloud base (4), (5). These basic features, so far only reported by gliders, have essentially been confirmed by the measurements of Kuettner, et al. (3). They "found the following characteristics of convection waves:

Wavelength:	5–15 km (9 km average)
Vertical motion amplitude:	± 1 to 3 m/s
Vertical wind shear:	3×10^{-3} to $10^{-2} s^{-1}$
Vertical extent of wave systems:	> 9 km."

Next, we try to understand the basic physics of the thermal wave excitation and, therefore, look at some model results.

3. Model simulations

Clark's model is an anelastic and non-hydrostatic, finite difference numerical model and can be configured in either two or three spatial dimensions. In this study, we performed two-dimensional simulations for economic reasons only. Implications of this will be discussed below. An essential characteristic of the model is the interactive grid-nesting where up to three models can be nested to zoom in on a special feature using higher spatial resolution. A detailed model description is found in Clark (10) and the interested reader is referred to this paper, or to the others cited in (1). A set of numerical experiments was performed studying the effects of (i) shear, (ii) horizontal domain, (iii) condensation and evaporation, and (iv) zooming in on a single cloud. In Figure 1 we show results from one such experiment (DRY1) where condensation was inhibited and consequently no clouds could form. Here, only one model is used with a grid size of 125 m in the

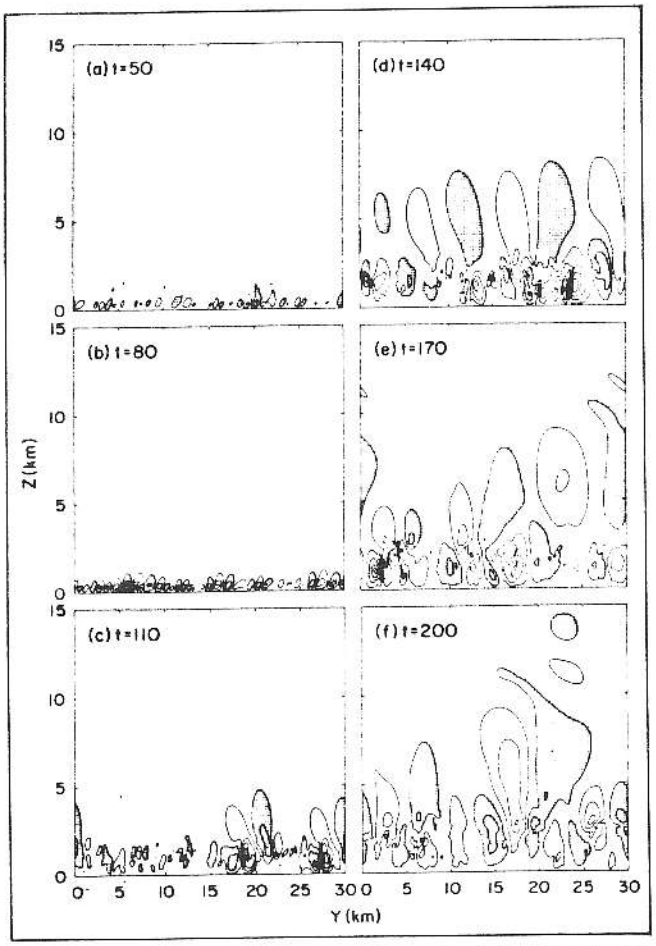

Figure 1. The vertical velocity field w at six time levels (50,80,110,140,170 and 200 min.). The contour interval, Δw, is 0.005 and 0.125 m s^{-1} for plates (a) and (b), respectively, and 1.0 m s^{-1} for plates (c) through (f). The zero contour is not shown. Only odd valued contours are shown, e.g., $\pm\Delta w$, $\pm 3\Delta w$,... Regions where $w \leq -\Delta w$ are stippled. Condensation was not allowed in this experiment. Figure is taken from Clark, Hauf, and Kuettner (1).

horizontal and vertical and using a time step of 5 s. The size of the domain was 30 km in the horizontal and 15 km in the vertical. The shear with a magnitude of $7.0 \times 10^{-3} s^{-1}$ was constant over the depth of 2875 m and zero above. The wind, temperature, and humidity profiles were taken from measurements on June 12, 1984, over the eastern plains of Colorado. A well-developed convective boundary layer of 1.6 km depth was capped by an inversion at ~2.3 km height. Clouds were shallow and developed above 1.6 km with tops extending up to the inversion. Above the inversion, the atmosphere was very dry and unconditionally stable. The tropopause was taken at ~9.5 km. The model starts with the initial profiles assuming horizontal homogeneity, except a 5% white noise variability on top of the surface sensible heat flux, which was assumed to be 140 Wm^{-2}.

4. The basic mechanism

To illustrate the basic mechanism, we look at the six plates (a)–(f) of Figure 1, showing the vertical velocity field at six consecutive time levels, each thirty minutes apart from each other (Experiment DRY1). We see that eddies develop in the convective boundary layer, in the following referred to as CBL, which, in general, are equally spaced. After about 80 minutes, they have reached the top of the CBL and then

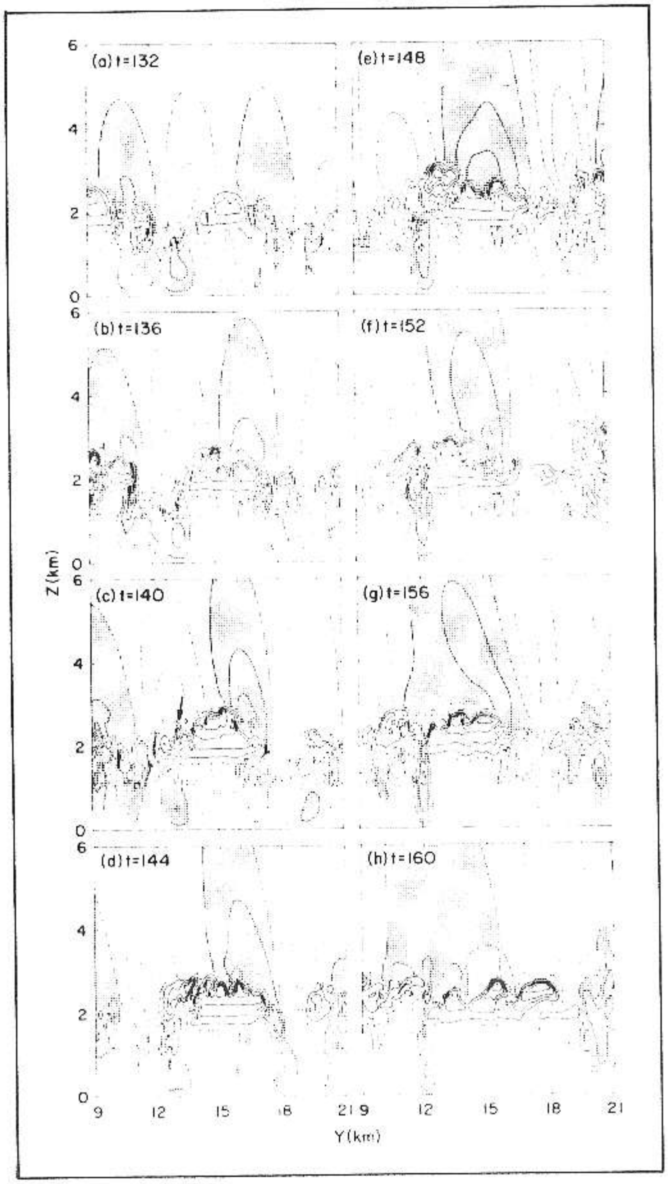

Figure 2. The fields of vertical velocity w and liquid water content q_c at eight time levels (132,136,140,144,148,152,156 and 160 min.). Contour interval for w is 1 m s^{-1} with downdraught areas ($w \leq -1$ m s^{-1}) stippled. Zero contours of w are not drawn, nor are any w contours plotted inside cloud. The contour interval of q_c is 0.2 g kg^{-1} with the 0.01 g kg^{-1} contour plotted as a dotted line, indicating the cloud outline. Only odd valued contours are shown. Figure is taken from Clark, Hauf, and Kuettner. (1).

impinge into the stable layer. Assuming that the thermals conserve part of their horizontal momentum during ascent, we expect to find a considerable difference in wind speed between the thermal and its environment. Consequently, each thermal acts as an obstacle in the flow. The air is forced to flow above each thermal, thus exhibiting an initial wave motion, and, as a result, a gravity wave is launched into the stable layer. The obstacle effect, therefore, provides an excitation mechanism for gravity waves in the stable layer above the CBL. First indications of launched gravity waves appear as soon as thermals penetrate into the stable layer. The waves then grow continuously. They cover the whole troposphere and extend well into the stratosphere as shown on plate (f) after t=200 min. We, therefore, might think in terms of a physical picture where we have two different flow regimes with dynamical structures of different scale in each of them: the thermals in the CBL and the gravity waves in the troposphere above. Both regimes are interacting. As discussed above, thermals penetrate into the stable layer and excite gravity waves. Gravity waves, in turn, act back on the eddies of the CBL. Some eddies get support by upward motion of a gravity wave, some are suppressed by downward motion of another wave. One effect of this support, suppression mechanism, is that the gravity waves force the CBL-thermals to adopt the gravity wave horizontal scale, which is commensurate with the depth of the stable layer between CBL and tropopause ($\sim$7.3 km) and which is obviously larger than the one of the isolated CBL-thermals. This results in an increase of spacing and size of the thermals, as observed from t=110 min on. We can say that the gravity waves tune their own forcing mechanism. From a more mathematical point of view, these CBL eddies and the related gravity waves can be considered as deep forced normal modes. Another feature of this feed back mechanism should be noted. The gravity waves are moving upstream relative to their boundary layer source eddies. Due to this relative velocity, the interaction mechanism gets a non-regular, highly complicated character and can be considered as a statistical interference mechanism.

5. The role of shear

If we reduce the magnitude of the shear to half of its value then two things happen: 1) we observe a broader spectrum of scales within the troposphere, and 2) the amplitude of the dominant gravity wave modes is half of its strong shear value. The broadening of the spectrum is also accomplished by a change of the relative speeds of waves and thermals, thus complicating matter to a greater extent. If the shear layer is confined to the CBL only, and does not reach into the stable layer, we also find gravity waves, but their excitation seems to be less efficient and again, a broader spectrum of scales appears. When there is no shear, the pure thermal forcing still causes some disturbances in the stable layer, but no well defined gravity waves. From our investigations so far, we may conclude that thermals of the CBL launch thermal waves very efficiently if the shear is strong ($\sim 7 \times 10^{-3} s^{-1}$) and if the shear layer extends from the CBL well into the stable layer above.

6. The role of clouds

So far, no condensation was allowed in the simulations. This indicates that the basic mechanism can be considered as the pure dynamical forcing of gravity waves by the obstacle effect of impinging thermals. Thermal waves, therefore, can occur with or without cloud formation. If we allow for condensation, nothing essential changes in the dynamics. Clouds are shallow and their energetic, as well as momentum impact on the waves is negligible. Clouds are strongly correlated to the CBL-thermals, as they need permanent heat and moisture support. Clouds, therefore, mark the thermals. It is important to note that the clouds do not initiate the waves; the latter are initiated by the thermals with which the clouds are associated. Clouds are in the interaction zone between gravity waves and thermals. All their characteristics as their depth, their height, shape, lifetime, etc. are determined in a highly complicated manner by the environmental profiles, which govern essentially cloud base and depth, by the gravity waves, which enhance or suppress the thermals and the cloud as well, by the thermals, which provides the clouds with heat and moisture and at least clouds are affected by their own energetics. Figure 2 illustrates these statements (Experiment XI). Here, only a small portion of the whole domain is shown for a time period of eighteen minutes. We focus on the cloud in the middle of Figure 2a. The eight plates 2a–2h illustrate snapshots of a cloud and its environment at eight stages of its lifecycle. However, neither show the first appearance of the cloud nor its dissolution, but focus on the period of time where the cloud reaches its largest size. During the same period of time, the horizontal scale of the gravity waves is increasing as can be seen by the broadening of the wave up and downdraughts. If we follow the wave downdraught, which at t=132 min. is found to be just on the downwind side of the cloud, over the shown period of time, we can visually identify an upwind motion of this wave downdraught relative to the clouds. At the beginning (t=132 min) the downdraught extends down to half of the CBL. At the next displayed time (t=136 min.) the downwind side of the cloud is surrounded by wave downdraught, which now extends well down to the ground. Later on (t=148) the wave downdraught seems to continue right down through the cloud, at least of its downwind half, but separated from a CBL downdraught. At t=160 min., the wave downdraught has moved further upstream with respect to the cloud catching now another CBL downdraught, which has all the time been upstream of the cloud. Most parts of the cloud now are in an upward motion and the wave downdraught does not pass through the cloud any more. This verbal description of what you can also see on the eight plates of Figure 2 should just indicate that, at least in the case of thermal waves, the spatial relation between up- and downdraughts and a single cloud may be as complicated as wished. In contrast to this, we note that all the time the cloud is supported by a thermal from below. The thermal enters the cloud, not in the middle of the cloud, but a little bit shifted towards the upwind side. Now, we look at the upwind edge of the cloud. This part of the cloud is all the time near to or within the updraught of the CBL-eddy. It is, therefore, also near to the upward flow regions due to the basic obstacle effect. If the upwind side of the cloud gets also wave support from above, then all three conditions lead to an intensive growth of the cloud on its upwind or upshear side, as in our example for the period between t=132 min. and t=148 min. The cloud by now has reached its larrgest extent and it then shrinks in agreement with the fact that only two or three conditions are met now as the cloud is suppressed from the wave above. How does the cloud grow on its upshear side? Plates 2(c)–2(e) give a fine example of cumulus growth in the presence of shear and gravity waves, which is believed to be typical for this situation. Due to the strong updraught on the upwind side of the cloud, new clouds form there (see arrow in place 2c). They grow and finally merge with the main cloud at t=148 min. During the growing stage of the cloud, the maximum wave updraught is found 1–3 km upwind from the cloud in agreement with the observations.

7. The linear model

The same atmospheric situations had been investigated by Clark and Hauf (2) using a linear two-dimensional model. It was found that the excitation of gravity waves by thermals in a sheared environment is essentially a linear process despite differences in details and it was concluded that the overall solution of the air motions can be interpreted as dominant forced normal modes of the whole troposphere, including the CBL.

8. Effects of two dimensions

As in two dimensions, the air has to flow over each thermal and cannot flow around it, the restriction to two dimensions obviously enhances strongly the wave initiation mechanism. We do, however, believe that the basic physical process is the same in 2-D or in 3-D. Numerical simulations in 3-D are currently underway. If the process is basically linear, then the difference between 2-D and 3-D is primarily one of geometry.

9. Conclusions

The numerical simulations and the airplane measurements on thermal waves lead to the following conclusions. Some of them may be considered as preliminary.

1. The measurements and numerical calculations confirm the existence of thermal waves, which had been previously documented by gliders only.

2. Thermal or convective waves are the gravity wave component of the normal modes of the troposphere. Their horizontal wavelength is approximately the depth of the stable layer.

3. Gravity waves are excited by the forced flow of the air over a thermal impinging in the stable layer and acting as an obstacle.

4. Strong or moderate ambient shear provides a sufficient condition for an efficient excitation of gravity waves. The strongest wave growth is found when a strong shear extends into the stable layer.

5. Gravity waves act back on the thermals of the boundary layer, forcing them to adopt a larger scale commensurate with the wave's scale.

6. The boundary layer, under the influence of a heat flux from the ground and in a sheared flow, can no longer be treated as isolated from the stable layer above. Interactions between both layers must be considered taking into account the spatial and temporal variability of these interactions. Solutions of a pure boundary layer flow alone are considerably different in magnitude and scale of the developing modes, compared with those solutions where a stable layer above the CBL is simulated, as well, and is allowed to interact with the CBL. This holds at least for the special atmospheric conditions assumed in our experiments. It may be speculated that the boundary layer/free-atmosphere interactions have to be considered also in situations quite different from the ones presented in this paper.

7. Boundary layer structures, such as clouds or thermals, can be considered as parts of solutions determined for at least the whole troposphere. In particular, this means that a cloud is affected by waves several kilometers above its top and consequently, does not exclusively depend on mean characteristics of the boundary layer alone. Obviously, parcel theories are unable to describe thermal wave clouds. In other words, cloud characteristics in the presence of gravity waves are a result of highly complicated and obviously nonlinear processes.

8. The structures in both regimes can move relative to each other. This gives the interaction mechanism the appearance of a statistical interference.

9. Thermal waves can occur with or without cumulus clouds. The basic wave excitaiton mechanism is dynamical. Small clouds have little impact on the dynamics. They appear as markers in the flow. Clouds, however, seem to have a modifying influence on the relative motion between waves and CBL-eddies. This is presently not yet understood, and is a subject of investigations.

10. Typically, clouds grow on the upshear side, although all kinds of cloud growth and dissolution can appear.

11. If the thermodynamic structure of the atmosphere allows deep convection, energetics of the clouds becomes more important. Clouds then act as a further contributor to the dynamics and thermodynamics of the whole system. First simulations indicate a modifying influence of the release of latent heat on wave characteristics, especially on the phase speeds. Coincidental support by a wave from above and a thermal from below, may lead to development of a deep convective cloud out of a set of apparent similar shallow clouds.

12. Observational efforts will concentrate on the investigations of gravity waves forced by cloud streets.

Last, but not least, it should be stated that the present numerical models, like the one of Terry Clark, are able to simulate not only complicated processes like the thermal waves, but also clouds as they appear to us: lumpy, chaotic, and in a huge variety of shapes.

10. References

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