MESOSCALE CONVERGENCE AND CUMULUS CONVECTION

by Krzysztof E. Haman

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Summary

The paper deals with physical mechanisms by which mesoscale convergence of order $10^{-4}\ s^{-1}$ can enhance development of convective clouds. After recalling some long known processes like direct triggering of convective updrafts or activation of latent instability, the effectiveness of which may be often problematic, the paper turns attention to less known mechanisms like lifting of the top of planetary boundary layer and prolongation of activity of surface sources of updrafts. Effectiveness of these mechanisms is quantitatively estimated and their relation to feedback with mesoscale convective structures and gravity waves is shortly mentioned.

1. Introduction

The fact that low level mesoscale convergence of β-scale (20-200km) or sometimes even α-scale (200-2000km) enhances convective activity is known for a long time. It is documented in numerous papers (e.g. Matsumoto [1], Pennel and LeMone [2], Coulman and Wamer [3], Cooper et al. [4] and, many others) as well as on satellite and aerial photographs where differentiation of cloud top heights in form of more or less regular patterns is often observed and attributed to convergence connected with mesoscale convection or gravity (buoyancy) waves activity. However the exact physical mechanisms responsible for this effects with respect to a single, individual convective cloud are not always clear, and not all are well understood. There is evidently more than one such a mechanism and sometimes they may be acting jointly. It seems that only few of them have been identified until now.

A fairly common belief that upward motions connected with horizontal convergence directly trigger the development of convective clouds by lifting the low-level air its free convection level (FCL) can hardly be considered valid. It can refer to a γ-scale (2-20km) convergence of order $10^{-3}\ S^{-1}$ enforced e.g. by small scale terrain features or thunderstorm outflow currents (Simpson et. al. [5]), which at the cloud base level of about 1000m can create updrafts of about 1m/s. It seems much less probable in the case of β-scale convergence of order $10^{-4}\ s^{-1}$, which in similar conditions will create upward motions in only dcm/s range. In addition these motions are usually quasi-hydrostatic and effect rather the general environment than individual developing clouds. In the latter case, only certain particular variety of this mechanism can work. This occurs when an upward motion of humid and potentially (convectively) unstable air leads to the release of potential instability. In such situation the stratiform condensation pattern formed by the β-scale lifting becomes decomposed into γ-scale convective cells and clouds. A slightly different kind of this process may be observed shortly before the saturation is reached, when the development of convective clouds in nearly saturated layer can be triggered by weak, random impulses of various origin. A well-documented case of action of this long known and probably fairly common mechanism has been presented by Wilson et al. [6]. Numerical experiments by Crook and Moncrieff [7] and more recently by Xin and Reuter [8] give a more artificial examples of its efficiency. Nevertheless far not all cases of convergence-enhanced convection can be attributed to its operation.

Another long known mechanism, sometimes regarded as a cause of enhancement of Cumulus convection in areas where mesoscale convergence is being observed, is increasing the vertical separation of isentropic surfaces (and hence decrease of hydrostatic stability) by ascending quasi-hydrostatic motions related to horizontal convergence This mechanism may occasionally help, but in the case of relatively short lasting β-scale motions its effect will be usually negligible (may be more important in longer lasting synoptic scale motions). Convergence of low level moisture is also often believed to intensify development of convective cloudiness (this concept is fundamental to classic CISK - conditional instability of the second kind). There is also empirical evidence of correlation between these two phenomena in various meteorological situations (e.g. Hudson [9]). In fact this may be an important factor with respect to the general moisture balance of a cloud system, but Radziwill [10] has shown that with respect to dynamics of a single cloud effectiveness of this mechanism is relatively poor.

There is also a hypothesis connected with the fact, that Cumulus updrafts result from coalescence and merging of smaller scale currents or bubbles developing within planetary boundary layer (PBL). There is a suspicion, following from certain numerical experiments (e.g. Chen and Orville [11]) that horizontal convergence may sometimes enhance this process of coalescence, but details of this mechanism need further studies. Also Simpson et al. [5] points out the role of horizontal convergence in merging Cumulonimbus clouds into bigger clusters, but this case doesn't refer to the problem of smaller Cumulus convection which is our main object of interest.

The aim of the present paper is to tum attention to two other less known mechanisms by means of which the low-level convergence may enhance development of individual convective clouds in certain types of convective weather. First of them - "lifting of the capping lid mechanism" (LCLM) has been described in the just mentioned paper by Radziwill [10]. Since "Zeitschrift fuer Meteorologie" in which it was published in 1989 is not easily available, a fairly detailed presentation of his results is given in the next Section 2. The second one - "cloud life extension mechanism" (CLEM), which seems to be not considered until now, is presented in Section 3. Some complementary comments as well as conclusions and recommendations are given in Section 4.

2. Lifting Of The "Capping Lid" Mechanism (LCLM)

The "capping lid" in form of a thin inversion or at least strongly stable layer at the top of convective boundary layer is a characteristic feature of the summer fair weather stratification. Radziwill [10] found that even small upward displacement of this stable layer which is close to the cloud base may dramatically change the conditions of vertical development of Cumulus clouds. For example convergence of the order 10^{-4} s^{-1} in an about 1 km thick boundary layer will move "the capping lid" in half an hour by about 200m. Such a displacement close to sharp bends of temperature stratification curve (which are characteristic for the "capping lid") can dramatically increase the net value of the convective available potential energy (CAPE) below the free convection level (FCL) and facilitate reaching the latter by an incipient Cumulus cloud. In favorable conditions this may be enough to change the convective pattern from Cumulus humilis to Cumulus congestus or even Cumulonimbus.

The essence of this mechanism can be understood even in framework of the classical "parcel method" and is illustrated on Figure 1. If the temperature stratification curve has sharp bends close to the condensation (LCL) and free convection (FCL) levels, the proportion of the so called "positive area" to "negative area" on the aerological thermodynamic chart becomes very sensitive to small vertical displacements of the stable layer. Such a displacement can thus dramatically increase the value of the convective available potential energy (CAPE) below FCL and facilitate reaching the latter by an incipient Cumulus cloud.

of the well mixed layer. Changes of the altitude reached by the thermals in course of this process modeled the variation of vertical extension of Cumulus clouds caused by the conver Radziwill [10] tested this idea be means of a one-dimensional entraining parcel model of Cumulus cloud, developing in environment which is slowly transformed by an upward, vertical hydrostatic motions. De-

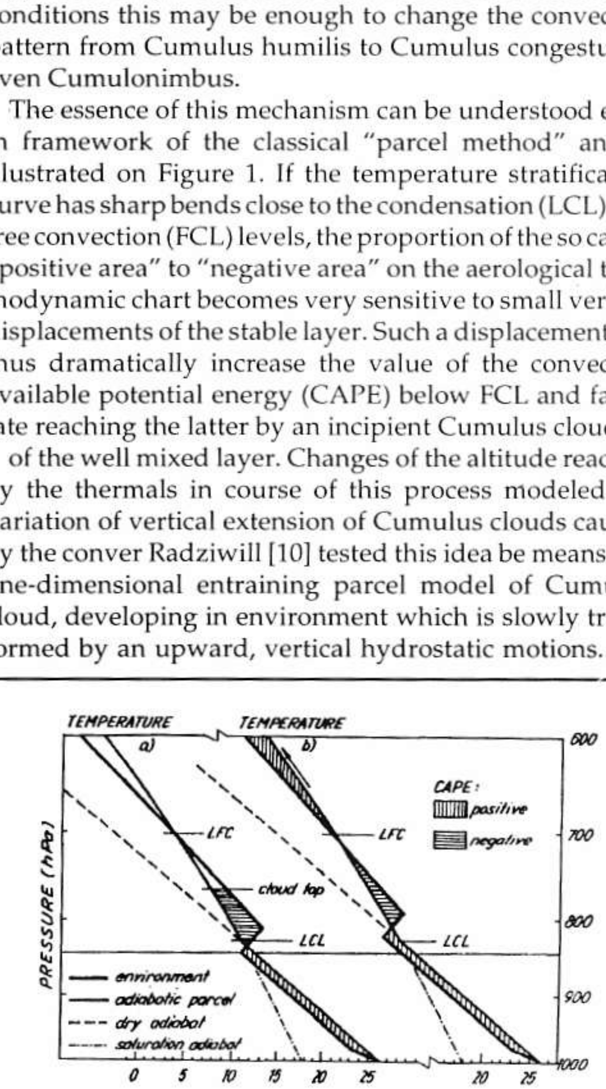

Figure 1. Example of a typical temperature profile in the lower troposphere and thermodynamic diagram of a parcel moving adiabatically from the surface level: (a) initial, (b) modified by a low-level convergence (after Radziwill [10]).

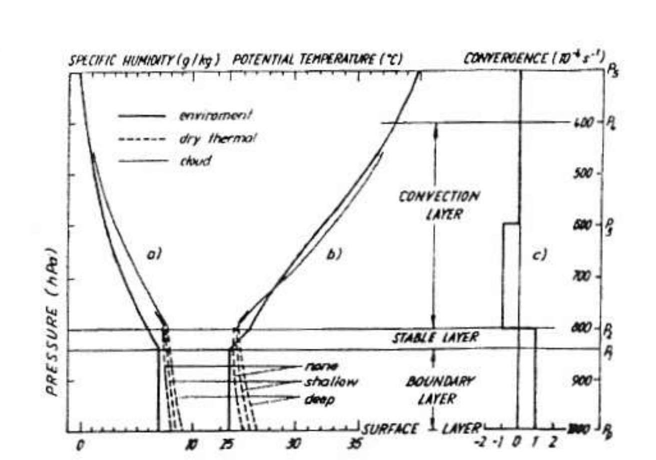

Figure 2. Initial environmental stratification of potential temperature, humidity and mesoscale convergence in experiment, the results of which are shown on Fig. 3. Broken lines present behavior of temperature and specific humidity in thermals starting with various values of ΔT and Δq (after Radziwill [10]).

spite of their oversimplifications, entraining parcel models are often good tools for determining the base and top levels of convective clouds, and due just to their simplicity they permit extensive numerical experimentation over a big ensemble of various environmental and initial conditions at low computational cost.

Radziwill [10] assumed an atmosphere consisting of a well-mixed layer of constant mixing ratio and constant potential temperature, and conditionally unstable layer of constant relative humidity, separated by thin, stable transition layer ("capping lid"). Through such atmosphere he released entraining thermals with constant entrainment coefficient. These thermals were starting at the surface with initial temperature and specific humidity differing from that of the environmental value by ΔT and Δq respectively. These differences simulate the close-to-the-surface thin, superadiabatic layer which is believed to be the main supplier of air for the core of Cumulus updraft. In the well mixed layer constant horizontal convergence C was assumed compensated by horizontal divergence above the "capping lid" what caused slow adiabatic, vertical movement of the latter and increase of the thickness gence. Results of one of such experiments performed for stratification visible on Figure 2 is presented on Figure 3.

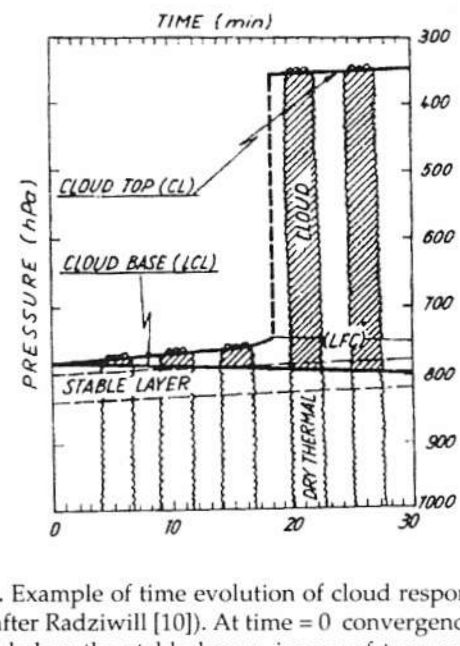

Figure 3. Example of time evolution of cloud response under LCLM (after Radziwill [10]). At time = 0 convergence 10^{-4} s^{-1} is imposed below the stable layer; jumps of temperature and water vapor mixing ratio at the surface are $\Delta T = 1°C$ and Δq = lg/kg respectively. No clouds develop during first 2 minutes, shallow clouds appear after 2 minutes, deep clouds after 20 minutes from the start of convergence.

Experiments were repeated many times, with various reasonable values of constant parameters included in the basic scheme, giving qualitatively similar results. Separate experiments proved that artificial removing of the moisture convergence within the well-mixed layer has little effect on the behavior of thermals, while leaving this convergence without lifting the "capping lid" results in lack of enhancement of convective activity. Removal of compensating divergence from above the "capping lid" can only increase the effect of its lifting. All this seems to show that the role of LCLM might be of particular importance for local enhancement of convective activity.

3. Cloud-Life Extension Mechanism (CLEM)

The main idea of the "cloud-life extension mechanism" - CLEM - is that not all developing Cumulus clouds live long enough to make use of all convective available potential energy (CAPE) present in the large scale stratification. Local low-level mesoscale convergence may help to extend this life and hence produce clouds taller than elsewhere. In order to understand the operation of CLEM let us recall that developing Cumulus clouds build their most vigorous updrafts of the air which comes from the superadiabatic surface layer (first 100m or so); it has the highest values of the equivalent-potential temperature (Θe) and thus can produce the greatest buoyancy. A particular convective cloud extracts this air from above a certain area which we call here the surface convection source (SCS) of this cloud. The high Θe air is permanently produced at this source by the sensible and latent heat flux from the surface, but if this production is not fast enough to meet the needs of the developing updraft, that air may eventually become exhausted and replaced by descending air of lower Θe. When the latter enters the cloud the updraft becomes weaker, the cloud top starts to collapse and eventually the activity of SCS stops until the surface layer above it is rebuilt. This stop may happen before the top had reached the convection level corresponding to the highest value of Θe so that there is still a certain potential for further development of the cloud; it could be used provided that there is a continuing supply of the high Θe air. Horizontal β-scale convergence, which seemingly "pumps" such air into the SCS may play this role. So areas in which such a convergence is present may contain convective clouds taller than those where it is absent.

Realistic, estimation of the effectiveness of CLEM is very difficult, since its operation evidently depends upon various details of cloud dynamics like entrainment rate or cloud separation distance, and may additionally be obscured by the presence of wind which displaces the SCS area. However, we can get a certain general idea and even rough quantitative estimate of this effectiveness by means of the following simple model illustrated on Figure 4.

Let us imagine a volume of homogenous fluid rising within a cylindrical pipe of cross-section S with constant velocity W from a shallow vessel of volume V. Let T denote the time necessary for complete extraction of the fluid from the vessel. Then the column in the pipe has maximal height $H = WT = V/S$. Let us now assume that the fluid is permanently supplied from an additional source of intensity Q proportional to the volume of the vessel: $Q = CV$, where C is a constant. The new maximal height H_1 in the moment the vessel is empty (T_1) would be now:

$$(1)\ H_1 = W \bullet T_1 + V(1 + C \bullet T_1)/S = H(1 + C \bullet T_1) = VT(1 + C \bullet T_1)$$

and hence:

$$(2)\ T_1 = CT/(1 - C \bullet T_1)$$

so the relative increase of the maximal height of the column due o the existence of additional source of fluid is:

$$(3)\ (H_1 - H)/H = C \bullet T/(1 - C \bullet T)$$

i.e. it can be expressed in terms of C and T only.

This simple model can serve as an analogue of interaction between low level convergence and developing Cumulus. The column of fluid may be interpreted as the core updraft of Cumulus cloud formed from the high Θe air, the vessel as its convection source, W as the average speed of rise of the top and C as the β-scale convergence. T is here the time-span of the cloud growth in the absence of convergence. Notice that the analogy remains valid independently of whether there is creation of the high Θe air by the surface heat flux, or not. H should be measured in the units of pressure rather than length, since it should be proportional to the mass of the air within the updraft. The formula (3) can be used for tentative evaluation how effective the discussed mechanism can be for a given aerological situation and value of convergence. T can be only very roughly estimated through heuristic analysis of sounding, since it depends on many factors; usually it can be expected to be of order 10^3s. This means that a typical low level β-scale convergence ($1 - 2 \bullet 10^{-4}$) can increase the height of a cloud top by as much as about 30% (provided that there is such a potential left). It is worth of noticing that this effectiveness increases with time T, i.e. it is best when development of clouds is slow. One can thus expect that CLEM might be particularly well suited for the tropical air masses with nearly wet-adiabatic stratification over a thick layer of troposphere, which permits development of tall but not very vigorous clouds. In contrast, the LCLM seems to be most effective in the fresh polar air within strong conditional instability and developed capping inversion over the well-mixed PBL.

As noticed before the pure, convergence-generated CLEM can occur only in absence of wind, because similar extension of the life of Cumulus cloud can be achieved not by mesoscale convergence but by sweeping the surface by the roots of Cumulus cloud moving with the wind. The source in this case ceases to work when the cloud roots come to the place already exhausted by an another cloud and its effective surface may be much bigger than in no-wind conditions.

Few remarks referring to the sources of β -scale convergence should be made. The most common of them are related to well known mesoscale convective cells or rolls developing in PBL. Breeze phenomena of maritime, lake or orographic origin may also create such convergence, as well as collision of outflows from mature or dissipating thunderstorms. Other possibility is due to gravity waves. In general, interaction between Cumulus convection and gravity waves may be a complicated process (Clark et al [12], Kuettner et al. [13]), but a relatively simple case of gravity waves wandering on the top of PBL is of particular interest. Unpublished studies by the present author and his collaborators on solution of certain modified form of Taylor-Goldstein equation for real atmospheric soundings indicate that eigenmodes of this equation have often sharp maxima of amplitude at the top of PBL . With frequencies of 10 -20 min and wavelengths of several kilometers they are good candidates for activating both LCLM and CLEM. In certain situations one can expect a sort of feedback or resonance between these waves and convection, leading to mesoscale waveform structures in the fields of cumulus clouds.

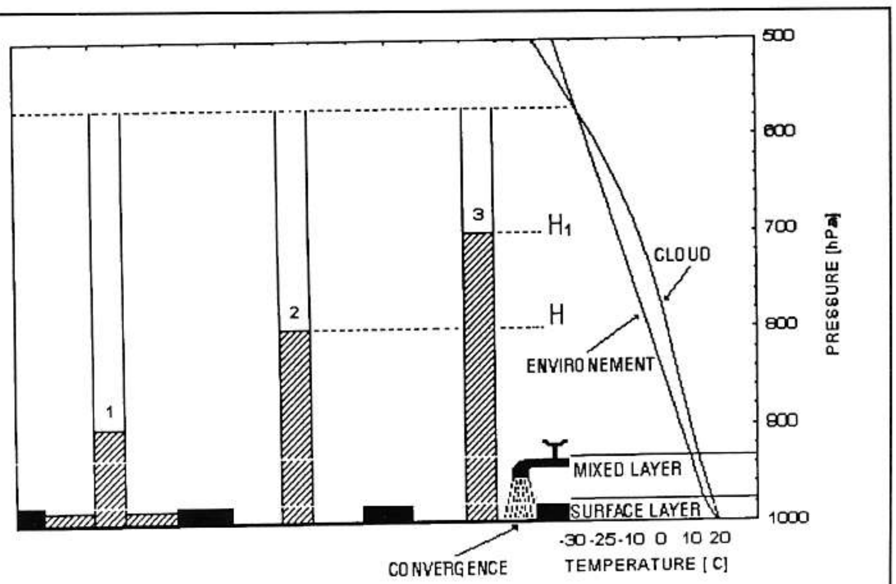

Figure 4. Conceptual model of CLEM. See text for explanation.

4. Conclusions And Recommendations.

Understanding the physics of interaction of mesoscale convergence with individual convective clouds is important not only as a challenging, purely scientific question, but may be valuable for practical problem of correct parametri~ation of convection in mesoscale forecasting models as well as in nowcasting of convective phenomena. For sailplane pilots this knowledge may perhaps be of limited direct value, but better understanding of what is going on in the atmosphere, particularly in the scale of a single updraft, may indirectly improve their qualifications. The mechanisms of enhancement of local convective activity presented in this paper may; perhaps be often met in nature but at the present state of meteorological science must still be treated as hypothetical. Regrettably, evidence available from standard observations is usually insufficient to judge which of the mechanisms discussed in this paper is active in a particular case, nor what is their relative importance in a climatological sense. However operators of sodars or lidar profilers which become more and more common equipment of various research or even operational units, may collect some empirical evidence concerning this question provided that they will perform parallel observations of development of convective cloudiness. Also observations made by sailplane pilots acquainted with the problem, (particularly if equipped with GPS - Global Positioning System - recorders), referring to local variations of cloud base and top altitudes may help. Thus turning attention of these communities to such a possibility seems important.

An interesting task may be the reconstruction of LCLM and CLEM in frames of fairly realistic 3-dimensional mesoscale models which are now available in some research centers but this would require costly computations made on very fine mesh and within a relatively wide area. The latter is necessary for avoiding artefacts from lateral boundary conditions (particularly in the case of CLEM). Such experiments has not been performed until now.

5. Acknowledgements

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6. References

[1]. Matsumoto, S. K., K. Ninimiya and T. Akiyama, 1967: Cumulus activities in relation to the mesoscale convergence field. J. Meteor. Soc. Japan, 45, 291305.

[2]. Pennel, W. T. and M. A. LeMone, 1974: An experimental study of turbulence structure in the fair-weather trade wind boundary layer. J. Atmos.Sci., 31, 1308-1323.

[3]. Coulman, C. E. and J. Warner, 1977: Temperature and humidity structure of the subcloud layer over land. Bound. Layer. Meteor., 11, 467-484.

[4]. Cooper, H. J., M. Garstang and J. Simpson, 1982: The diurnal interaction between convection and peninsular-scale forcing over South Florida. Mon. Wea. Rev., 110, 486-503.

[5]. Simpson, J. S., N. E. Westcott, R. J. Clerman, and R. A. Pielke, 1980: On Cumulus mergers. Arch. Met. Geoph. Biokl. Ser. A., 29, 1-40.

[6]. Wilson, J. W., J. A. Moore, G. B. Foote, B. Martner, A. R. Rodi, T. Uttal, J. M. Wilczak, 1988: Convection initiation and downburst experiment (CINDE). Bull. Amer. Meteor. Soc., 69, 1328-1348.

[7]. Crook, N. A. and M. W. Moncrieff, 1988: The effect of large scale convergence on generation and maintenance of deep moist convection. J. Atmos. Sci., 45, 3606-3624.

[8]. Xin, L. and G. W. Reuter, 1996: Numerical simulation of the effects of mesoscale convergence on convective rain showers. Mon. Wea. Rev., 124,2828-2842.

[9]. Hudson, H. R., 1971: On the relationship between horizontal moisture convergence and cloud formation. J. Appl. Meteor., 21, 953-977.

[10]. Radziwill, J. M., 1989: Effect of mesoscale convergence on single convective cloud development. Zeit. Meteor., 39, 94-99.

[11]. Chen, C. H., and H. D. Orville, 1980: Effects of mesoscale on cloud convection. J. Appl. Meteorol., 19, 256-274.

[12]. Clark, T.L., T. Hauf and J. P. Kuettner, 1986: Convectively forced gravity waves: Results from two-dimensional numerical experiments. Quart. J. Roy. Meteor. Soc., 112,899-925.

[13]. Kuettner, J. P., Hildebrand, P.A. and T. L. Clark, 1987: Convection waves: Observations of gravity waves systems over convectively active boundary layers. Quart. J. Roy. Meteor. Soc., 113, 445-467.