Message to the Editor:

The present manuscript has been completely revised by fully considering all the comments by the two referees constructively. Thus, I believe that it is acceptable for ACP.

However, if you think further revisions are required, please let me know. I am more than happy to try another iteration.

Please see the specific modifications by following by point–by–point response to the two referees appended below, which are based on the earlier response to them posted on ACPD Web site.

Reply to the Referee 1:

Summary:

The present referee well summarizes the basic spirit of the present review: a short story on simplified models of convective elements in application to formulation of mass–flux parameterization of moist convection. At the same time, the referee thinks the review is "too compact" to be useful for many readers.

In order to amend this shortcoming, the manuscript is extensively expanded in revision. Especially, the concepts of "plume" and "entrainment" are introduced in the beginning of the revised Sect. 3 in the following manner:

"The idea of a plume can most vividly be seen by a water–tank experiment originally performed by Morton et al. (1956). They placed a constant buoyant–mass source at the bottom of a water tank (with dyed alcohol as a marker), and examined the resulting motion. The result was a plume gradually growing upwards, which may be considered steady after a substantial time (see Fig. 3 in the revised text).

In general, the plume refers to convective flows resulting from a continuous source of buoyancy. They tend to be quasi–steady in contrast to the inherently transient nature of bubbles.

In the case of the original experiment by Morton et al. (1956), the plume grows upwards by sucking the surrounding water at a constant rate, and as a result it also increases its radius at a constant rate with height. Such a 'sucking' process is commonly referred to as *entrainment.* A particular plume solution obtained by them is called the *entraining plume*, because it is characterized by a constant fractional entrainment rate (cf., Eq. 3 below).

Importantly, the obtained laboratory result is consistent with a theoretical result predicted by Batchelor (1954) using a similarity theory. Here, a similarity theory seeks a form of a solution of a given system that is determined solely by examining the dimensionality of the relevant variables and parameters."

The notion of detrainment is introduced in discussing the concept of "starting plume" towards the end of this section.

Many of the responses to the Major Comments below also constitute text segments incorporated into the revised manuscript.

Major Comments:

Abstract:

The adjective "moist" is added to convection throughout the abstract in order to make it clear that the present review is dealing with "moist atmospheric convection".

2. Bubble:

Sect. 2 is modified as follows:

"Atmospheric moist convection may be considered consisting of a series of warm bubbles released from a surface level. A cauliflower–like structure seen in clouds may be considered a visualization of an ensemble of bubbles. Existence of these warm bubbles (or thermals as they were called) was known about by glider pilots for years. By riding over such a thermal, they could substantially boost their gliders.

A good laboratory analogue could be a series of air bubbles released from the bottom of a water tank. Such an experiment was originally performed by Davies and Taylor (1950) from fluid–mechanical interests. Their experiment, in turn, induced interests of an Imperial College group for studying atmospheric moist convection as an ensemble of bubbles.

A major difference from the atmospheric bubbles to air bubbles used in the experiments by Davies and Taylor (1950) is that the former gradually mix with the environment as they ascent, whereas the latter are immiscible. In order to introduce such mixing tendency, the salt water was taken, instead of air, as a source of bubbles within a water tank (Scorer and Ronne 1956, Scorer 1957, Woodward 1959).

In their experiments, a hemispheric copper cup was filled with dense salt water, which was turned over quickly by hand into a water tank in order to generate a bubble, but in an upside-down manner. The focus of the study was the time evolution of a single bubble. Thus only a single bubble is released at one time in all the experiments reported.

An example of such an experiment is shown as Fig. 1 in the revised text: the highly transient nature of the bubble dynamics may be noted.

Detailed measurements of the velocity around a bubble (Woodward 1959) revealed that a doughnut–shaped vortex ring was formed inside the bubble (see Fig. 2 in the revised text).

. . .

Levine (1959) was one of the firsts to consider an idealized bubble model for atmospheric convection in a self-contained manner. More specifically, he considered the vertical motion of an isolated bubble in an infinite domain under a quiescent state at infinity. Under this condition, the most remarkable conclusion is that the dynamic pressure trivially vanishes at the center of the bubble. Thus no effect of the dynamic pressure is found in the total vertical momentum equation.

More precisely, Levine (1959) considered a spherical bubble. Hill's vortex solution (Lamb 1932) is adopted inside the bubble in order to describe a vortex ring structure. The flow outside the spherical bubble is constructed by an irrotational flow assuming a continuity of the tangential velocity at the surface. This inviscid–flow solution is explicitly exploited by Levine in order to derive a drag force acting on the bubble. In order to obtain a drag force, it is assumed that a bottom part of the bubble is open to outside air, where a drag force is inserted.

Turner (1964) expanded Levine's work to the case when the bubble increased in size with time, and examined more detailed structure of flows inside the bubble.

...

The drag force derived under elaborate effort by Levine (1959) also becomes rather irrelevant in applying his formulation to the plume dynamics. In the latter case, it can easily be shown that the drag coefficient simply be equal to the fractional entrainment rate of a given plume."

3. Plume:

The following sentence is moved to the end of Sect. 3 in revision: "In spite of the fact that the original entraining plume model has been much criticized, the notions of the entrainment and the detrainment are hardly given up in current convection parameterizations (cf., de Rooy 2013)."

The "completely new model" in quotation of Morton (1957) has rather been exaggerated. A key point here is that by performing an analysis under a relatively limited setting with a constant potential–temperature profile and no density stratification, he found a tendency of plume to grow to infinity both in size and height when a bottom plume size is above a critical value: See his Fig. 6 and compare it with the case below this critical value shown in his Fig. 5. Unfortunately, no careful followup study exists to investigate how this explosive tendency of plume under water condensation can be tamed under a presence of stratifications. In other words, an emergence of a new theory is still awaited.

Sects. 4 and 5:

Stommel did not examine whether convection observed by him was maintained by a continuing buoyancy source as a condition for constituting a "plume". Thus, a link between his "entrainment" and entrainment observed in water tank is not obvious. Here, we also emphasize that by "entrainment" Stommel merely referred to a lateral mixing of the convective cloudy air with an immediate surrounding even without specifying how to define this "immediate surrounding".

A schematic based on Raymond 1993 is added as Fig. 4 in the revised text, which summarizes three different theories for the atmospheric convective entrainment–detrainment processes.

Morton (1997b): The notion of the "jet" is introduced here in revision.

6. Buoyancy Parameter

Sànchez et al. (1989) is added in revision as a reference addressing issues of initial momentum in thermal experiments.

The initial velocity of the plume: the discussion here simply points out that non–convective momentum source in the atmospheric boundary layer is small in the nondimensional unit. I would suggest to the reviewer to substitute the values she or he would think more appropriate. My best expectation is that we still get the buoyancy parameter substantially smaller than unity.

One may argue that at the cloud base, we may have larger values such as $d \sim 10^3$ m and $w \sim 1$ m/s. However this still merely gives the buoyancy parameter, $B \sim 0.1$.

Minor Remarks:

3338–10: parapetization → parameterization

3342–4: plume theories were steady with time → plume theories were developed under a steady framework

References:

Lamb, H., 1932: Hydrodynamics, 6th Ed., Cambridge University Press, 738pp.

Raymond, D. J., 1993: Observational constraints on cumulus parameterizations. *The Representation of Cumulus Convection in Numerical Models. Meteor. Mono.,* No. 46, Amer. Meteor. Soc., 17–28.

Sànchez, O., D. J. Raymond, L. Libersky, A. G. Petschek, 1989: The development of thermals from rest. J. Atmos. Sci., 46, 2280–2292.

Reply to the Referee 2:

The following is the point–by–point response to the present referee's comments. Most of the remarks below is also incorporated into the revised text at appropriate places.

- Grossing over many important points: This remark clearly resonates with the referee 1's main point. Thus, please also refer to my response to the referee 1 as well.

  In revision, the text is substantially expanded as already described in response to the referee 1 and also described below so that key advantages and disadvantes of plumes vs. bubbles are also better undrstood.

- Rennaisance of Bubble?: I believe more papers are coming out soon on bubbles. In revision I quote oral presentations by George Craig (2012) and Alison Stirling (2013) as personal communications in order to strengthen this point. Furthermore, I strongly believe the laboratory experiments currently performed by Szymon Malinovski's group can potentially elucidate the fine details of the bubble dynamics. In order to demonstrate this point, an image from their experiments is also quoted in the revised manuscript as Fig. 5. Note that these experiments can measure, with a help of particle image velocimetry (PIV: Korczyk et al. 2006), much more fine details of the flows associated with a bubble than current LESs can. A more recent article (Diwan *et al.* 2014) is also added as a reference.

- The following technical terms are more carefully introduced in the revised manuscript (in order of appearance): two–dimensional and three–dimensional flows (a reference textbook added), bubble, vortex ring, plume, entrainment, entraining plume, similarity theory, starting plume, detrainment, mixing line, jet.

  Please refer to my response to the referee 1 in order to see some of the examples.

- Five figures are added in the revised manuscript: the four by following the suggestions of the referee 1, and by following the present response as Fig. 5.

- It is important to note that the plume and the bubble are governed by different sets of equations even in its simplest cases: compare Eq. (2) of Morton et al. (1956) and Eqs. (1), (3), and (4) of Turner (1963b). Note that their systems are described in terms of a vertical coordinate and time, respectively. However, even when the latter system is transformed into a vertical coordinate, it does not reduce to the former, because simply different physics are considered. When a stream of bubbles is considered, one must use the latter. In other words, although both may be arguably based on a certain "parcel" approximation, they are *not* equivalent.

Another way of looking at the issue is a mass–flux equation (Eq. 3 of the manuscript) that defines a vertical structure of the mass flux under a given fractional entrainment rate, which my be generally defined by $E/M = \alpha/R$ with R a radius of a cross section. Here, however, we obtain from the laboratory experiments, qualitatively different values for the fractional entrainment rate for entraining plume and a spherical bubble: $\alpha \simeq 0.2$ and 0.25, respectively ($cf.$, Turner 1969, 1986).

Note that the above argument is made under a hypothesis of non–interactions between the bubbles, as emphasized in the revised Sect. 2. Little study has been performed on the interactions between the bubbles. Whether interacting ensemble bubbles behave as if like an entraining plume is a highly speculative matter.

As also emphasized in the revised Sect. 2, the evolution of a bubble is highly transient in contrast to a quasi–steady nature of plumes. Thus, the most straightforward modification would be to take an ensemble of bubbles described by Turner's (1963b) Eqs. (1), (3), and (4) in place of an ensemble of steady plumes under a spectrum formulation of mass flux.

Under this new formulation, individual bubbles would behave in transient manner by explicitly taking into account of the convective time–scale evolution. [A subtle point that such a generalization is possible under a spectrum representation of mass–flux formulation is carefully discussed in the revised Sect. 7: in the original manuscript, I skipped this subtlity in order to make the argument simple.] Under this formulation, a key constraint is to add a hypothesis of "collective steadiness" of those transient bubbles, which states that a total thermodynamic tendency of bubbles must be steady in convective scale in order to ensure the slow evolution of the large–scale dynamics.

As the referee suggests it may well be possible that ensemble of bubbles can be described under an analogy with a steady plume. However, in this case, the merit of adopting "bubble hypothesis" becomes more sutble and even implicit. Under such a re–interpretation, the entrainment–detrainment simply reduces to a tuning parameter. The question is whether any fundamental bubble theory or extensive measurements of bubbles from laboratory experiments can provide anything useful for this "tuning" exercise.

In other words, if we are going to take a steady–plume system, as described in Sect. 7, merely as a mathematical metaphor, there will be no point for discussing any more which point of view is more central between bubble and plume. The entrainment–detrainment rate would simply becomes a tunable parameter, or something to be estimated from, say, LES without asking any physical mechanism behind.

- It is a very good question whether we really need to worry about nonsteady convection in a parameterization. Many tend to lightly argue for it without reflecting what kind of modifications are required.

Some Minor Comments:

Everywhere: The final manuscript is carefully read by Richard Davy so that many grammatical errors are corrected.

3341:19: Importance of the dynamic pressure in the convective–plume dynamics is demonstrated for example by Holton (1973), Soong (1974), Yau (1979), and Kuo and Raymond (1980). Especially, Fig. 19 of Soon (1974) showed that the dynamic pressure force is substantially balanced out by the buoyancy force. These new references are added in revision.

3342:24–28: A clearer description of starting plume is introduced in revision.

References:

Diwan, S. S., P. Prasanth , K. R. Sreenivas , S. M. Deshpande and R. Narasimha, 2014: Cumulus-type flows in the laboratory and on the computer: Simulating cloud form, evolution and large-scale structure. Bull. Amer. Meteor. Soc., in press. doi: http://dx.doi.org/10.1175/BAMS-D-12-00105.1

Holton, J. R., 1973: A one–dimensional cumulus model including pressure perturbations. Mon. Wea. Rev., 101, 201–205.

Korczyk, P., S. P. Malinowski, T. A. Kowalewski, Mixing of cloud and clear air in centimeter scales observed in laboratory by means of Particle Image Velocimetry. Atmos. Res., 82, 173–182, 2006. DOI:10.1016/j.atmosres.2005.09.009

Kuo, H. L., and W. H. Raymond, 1980: A quasi–one–dimensional cumulus model cloud model and parameterization of cumulus heating and mixing effects. Mon. Wea. Rev., 108, 991–1009.

Soong, S.–T., 1974: Numerical simulation of warm rain development in an axisymmetric cloud model. J. Atmos. Sci., 31, 1262–1285.

Yau, M. K., 1979: Perturbation pressure and cumulus convection. J. Atmos. Sci., 36, 690–694.