



Basic convective element: bubble or plume?

J.-I. Yano

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

Basic convective element: bubble or plume? A historical review

J.-I. Yano

GAME/CNRS, URA1357, CNRS-INSU-Météo France, Toulouse, France

Received: 8 December 2013 – Accepted: 16 January 2014 – Published: 5 February 2014

Correspondence to: J.-I. Yano (jiy.gfder@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

During the 1950s and the 60s, when intensive investigations on atmospheric convection were launched, the two possibilities were identified for the basic element of convection: bubble and plume. The present paper reviews the investigations of this period, and suggests how the mass-flux convection parameterization formulation emerged from these early investigations. Especially the choice of the steady-plume model is a key ingredient of the mass-flux formulation. Some historical lessons are suggested.

1 Introduction

Majority of the current operational as well as climate-projection models adopt mass-flux based convection parameterization, thus a good understanding of its physical basis is imperative for better understanding their model behaviors. The core of the mass-flux formulation is, geometrically speaking, in placing either an ensemble of plumes or a single plume over a grid box domain. Arakawa and Schubert (1974) more specifically adopted an entraining-plume model for this purpose. In order to understand the reason for this specific choice, we need to trace back the investigations on plume dynamics prior to Arakawa and Schubert. The purpose of the present paper is to present such a critical historical review on the convection studies before Arakawa and Schubert, in the years 1950s and 60s.

Intensive investigations on atmospheric convection were initiated over a post-war period, partially due to a rapid development of aeronautic transports and associated safety concerns, as well as for military reasons, but also from interests in fluid dynamics, considering atmospheric convection as a natural laboratory of convection. From these investigations during a period of 1940s to 1950s, the concept of entraining plume gradually emerged. Especially, extensive laboratory experiments were performed in Cambridge in order to mimic atmospheric convection as a part of their efforts for developing an analytical description of atmospheric convection.

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



In order to understand the style of the investigations of the period, a state of art of the technology at the time must also be understood. Digital computers were still in their infancy and they were not widely available, thus people were forced to resort to analytical methods. Simpler analytical theories were always preferred. Combined with an established tradition of fluid mechanics, a persuasion of a similarity solution (or dimensional analysis) was an obvious way to go (Batchelor, 1954).

Under such a circumstance, a natural desire was to identify basic elements for atmospheric convection (cf., Morton, 1997a), in analogy with eddies in three-dimensional turbulence, or vortices in two-dimensional flows, so that advancement could be made by studying dynamics of these basic elements. Bubble and plume were identified as the two major candidates (cf., Turner, 1969).

The main purpose of the present paper is to review these historical processes of the period with three more specific goals in mind. First is to provide a systematic literature survey on this subject, because such a self-contained reference list is hard to find in literature, although reviews on specific subjects exist as going to be pointed out. Second is to examine the implications for the mass-flux convection parameterization developed as an outgrowth of this series of research. Our last goal is, by performing a historical review, to try to assess a future direction of research for convection parameterization.

The next two sections review the research from points of view of bubble and plume, respectively. Observational studies of this period are reviewed in Sect. 4. Consequences and further evolution after the 60s are outlined in Sect. 5. Issues of stratification is reviewed separately in Sect. 6. The role of the steady-plume hypothesis in mass-flux convection parameterization is examined in Sect. 7, and some future perspectives are remarked in Sect. 8.

2 Bubble

The bubble theory is to a certain extent, more intuitive, because by simply looking at convective clouds, bubble-like structures are easily identified moving up and down with

**Basic convective
element: bubble or
plume?**

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



time. We may argue the cumulus clouds look like cauliflower exactly for this reason. Thermals (essentially another name for bubbles) are long since identified by gliding people for a favorable spot for boosting their gliders. Experiments on air bubbles in water tank by Davies and Taylor (1950) originally inspired the idea of bubbles as basic elements of atmospheric convection for an Imperial College group (Ludlam and Scorer, 1953; Scorer and Ludlam, 1953). In order to make bubbles miscible with the environment, they took salty water, instead of air, as source of bubbles. In their experiments (Scorer and Ronne, 1956; Scorer, 1957; Woodward, 1959), 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. Detailed measurements of the velocity around a bubble was reported by Woodward (1959). Saunders (1962) examined the behavior of the bubble intruding into a stable “inversion” layer above. Turner (1963a) tried to mimic the latent heat effect by chemical reaction between hydrochloric acid (HCl) inside a bubble and sodium bicarbonate (NaHCO_3) in the environment. The reaction generated carbon dioxide that boosted the bubble by associated buoyancy. Under this set-up, the light bubbles are injected from the bottom.

Ludlam and Scorer (1953) reviewed atmospheric convection as a whole from a point of view of bubbles as its basic elements. Scorer and Ludlam (1953) tried to establish the bubble concept for atmospheric convection by examining cloud photo sequences as well as a basic theoretical analysis. Malkus and Scorer (1955) attempted the same for the observed clouds more systematically. Simpson (1983b) provides a personal historical retrospect on her involvements, which also led to her decision of choosing a plume model after considerations of both possibilities. In this retrospect, it appears that Malkus and Scorer (1955) were rather looking for starting plumes, as later conceptualized by Turner (1962), than the isolated bubbles.

For the theoretical side, Turner (1957) examined the interplay of the vortex-ring dynamics and the role of buoyancy. Turner (1963b) extended the analysis to the case with a bubble (thermal) surrounded by turbulent flows. Here, a magnitude of the surrounding turbulence is measured by a velocity scale.

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Levine (1959) was one of the firsts to consider an idealized bubble model for atmospheric convection in self-contained manner. More specifically, he considered a 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. Turner (1964) expanded Levine's work to the case when the bubble increased in size with time, and examined the detailed structure of flows inside the bubble.

In spite of its strongly intuitive nature, and also intensive research during the 50s and the 60s, somehow the bubble theory was eventually taken over by the plume theory. A reason for this shift is hard to say simply from existing literature. Clearly no final verdict was issued in any published references. It is most likely that the investigations simply shifted away due to a difficulty of casting a bubble theory into a self-consistent steady theory.

Here, as a historically unfortunate legacy of the bubble theory, the formulation by Levine (1959) for the vertical momentum equation was uncritically taken into plume models, originally by Simpson et al. (1965), and this tradition still continues (e.g., Donner, 1993; Bechtold et al., 2001; Siebesma et al., 2003; Bretherton et al., 2004; Zhang et al., 2005). In the plume dynamics, the dynamic pressure is certainly not negligible. However, the term is systematically neglected in the literature by quoting Levine (1959) but with a rather ad hoc adjustment such as introduction of "effective mass".

3 Plume: entraining plume model

The plume model essentially tries to approximate a single convective tower by a single plume, traditionally under a steady approximation. Note that a steady problem is much less computationally intensive than a time dependent problem. That was considered to be an advantage at that time.

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Laboratory experiments of convective plumes, generated by a steady buoyancy source at a bottom of an experimental tank, supported similarity theory originally proposed by Batchelor (1954). Batchelor's similarity theory predicted a constant entrainment rate, thus a tradition of entraining plume models for convection parameterization begun. Influence of Batchelor's original work has been considerable. 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 et al., 2013).

These laboratory experiments were typically initiated by placing a mass of warm water at a bottom of water tank (e.g., Batchelor, 1954; Morton et al., 1956) in contrast with typical bubble experiments in which a mass of heavy salt water was released from the top. This set-up led to a raising plume with its volume increasing with height by taking in surrounding water. In combination with the persuasion of a similarity solution, it naturally led to a theory of entrainment plume.

Morton (1957) took a next theoretical step by introducing humidity into the plume model of Morton et al. (1956). This paper is particularly illuminating, because it already points to an inherent limit of taking a plume model for moist convection. To quote from the last paragraph of this paper: "When a cloud grows past the critical size ... The cloud is then no longer properly a part of the plume. ... A completely new model will be necessary in order to investigate the behaviour of these developed clouds." In my own knowledge, such a theory is still to be developed. Existence of the stratification is a major obstacle for further pursuing the plume theory based on the similarity theory. The issue of stratification is further discussed separately in Sect. 6.

A final important addition was to consider an evolving process of a convective plume. Such a notion was tagged by Turner (1962) a "starting plume". The basic idea of this conceptualization was to add a cap of bubble at a top of a evolving entraining plume. However, only an outline for this formulation was presented, and the idea was never fully developed in the literature. In the subsequent applications, a starting plume was

often interpreted as a prototype for cumulus convection, but with Morton et al. (1956)'s steady plume theory simply taken as an approximation for it.

4 Observations

Note that plume theories were steady with time. Good agreements with the laboratory experiments were reported in all the literature cited above. Many of them also emphasized applicability to atmospheric convection.

In this historical development, Stommel's (1947; 1951) work on entrainment in trade cumuli stands out as a singular achievement. By mistake or negligence, his papers were not cited by Morton et al. (1956). Stommel's point was that we simply have to assume a lateral mixing with surrounding as cloud air ascends, because otherwise the computed buoyancy far exceeds the observed values. Here, he invoked the notion of "entrainment". However, a link of his "entrainment" to entrainment observed in water tank is not straight.

Then the weather modification experiments came to the scene in 1960s. For a review on observational studies prior to these experiments, see Malkus (1952). The decade of 1960s was a pinnacle of human trusts on technology. Everything was believed to be achievable by technology, culminated into a landing of human on the moon. It was believed that the weathers would be under perfect control in the next century, and the serious investments were made towards this direction. A very interesting historical paper to read through, in this respect, is Ludlam (1958).

The basic idea of weather modification was relatively simple: we just sprinkle a small but critical amount of particles, which function as ice condensation nuclei, such as silver-iodide or dry-ice into convective clouds, then a catalytic effect is induced in precipitation process, and the cloud would die. Extensive field experiments were performed in order to test this possibility.

In order to verify the experimental results, they must be compared against a result from a numerical model. For this purpose, the entraining plume model was adopted

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



(Simpson et al., 1965; Simpson and Wiggert, 1969). A preliminary study towards this goal was already taken by Malkus (1954). A good agreement between observed unseeded clouds and numerical predictions was considered as an evidence that the entrainment plume was a good model for convective clouds. So we arrive to the point of work by Arakawa and Schubert (1974).

5 Historical retrospect: after Arakawa and Schubert

So was the history up to the point of Arakawa and Schubert (1974). Arguably, at the moment that Arakawa and Schubert presented their mass-flux formulation, the entrainment plume was probably the most natural choice, though it was far from a unique choice. Here, history is never simply linear. The entraining plume model was already much criticized in various occasions even before Arakawa and Schubert (1974).

Telford (1966, see also Telford, 1968) pointed out the limits of similarity concepts, especially considering the fact that the experimental plumes are not perfectly steady but associated with extensive transient turbulence, and suggested an importance of “turbulent mixing”. This work rectified earlier proposals (e.g., Houghton and Cramer, 1951) for introducing “turbulent” entrainment in addition to a standard dynamical entrainment. Here, Telford was not clear on the point whether he was actually criticizing Morton et al. (1956)’s original similarity theory or its application to atmospheric convection.

Morton (1968), in turn, replied to this critics by focusing on the original similarity theory itself rather than its atmospheric applications. By emphasizing the fact that the theory was based on a time-averaged picture of a plume rather than a transient one, he defended the consistency of his similarity theory. This “time-average” concept is likely to be more important in interpreting atmospheric convection as a steady plume, because the former is highly transient (S. Turner, personal communication, 2009). In case of atmospheric convection, such transient process is also likely to contribute significantly to the bulk entrainment rate.

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Warner (1970) raised extensive criticisms on the entraining plume model. The main criticism was that the model cannot correctly predict both the cloud top (thermal profile of the plume) and liquid water contents at the same time by adjusting the entrainment rate (Warner, 1972). Although the work is often considered a final blow to the entraining-plume hypothesis for atmospheric convection, readers should carefully read the response by an original author (Simpson, 1971, 1972) before convincing themselves.

A major counter mechanism was proposed by Squires (1958a, b) and Paluch (1979; see also Blyth et al., 1988). They argued based on their “mixing line” analysis that a dominant mixing process is due to penetrative downdrafts from the cloud top (a type of “cloud-top entrainment”). Telford (1975) further argued that a single “cloud” element may detrain at multiple levels. The last idea led to a proposal of the “stochastic mixing” model by Raymond and Blyth (1986). They argued that, especially for nonprecipitating clouds, aggregates of many parcels move towards buoyancy equilibrium from the cloud bottom. These parcels follow different eventual fates by mixing with the environment with different rates. This model was further extended by Taylor and Baker (1991). Emanuel (1991) developed a full convection parameterization based on stochastic mixing.

A similar, but somehow simpler mixing formulation called “buoyancy sorting” was proposed by Kain and Fritsch (1990). This scheme performs similar multiple mixing with the environment at every vertical level as for stochastic mixing. However, the parcel does not multiply under this formulation. This parameterization was further elaborated by Bechtold et al. (2001). The role of this mechanism is under investigations by various large-eddy simulations (cf., de Rooy et al., 2013).

As the whole, the present convective parameterizations is gradually drifting away from the entraining plume model by equally introducing detrainment. See for example, Derbyshire et al. (2011), which is considered one of the most recent efforts towards the latter goal. Nevertheless, it may seem surprising to find that the basic notions of entrainment and detrainment are hardly given up even after half century.

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Morton (1997b) presents the following historical retrospect: “Early works looked at lateral entrainment and took jets and plumes as models for atmospheric convection. Each requires a maintained source, each rises without limit in a homogeneous environment, but has bounded rise in stable environments where the rising stream overshoots and falls back before spreading laterally, and each has similarity structure determined by source strength alone, at least up to the level where the mean buoyancy falls to zero. The jet is an unrealistic model in an atmosphere where convection is normally buoyant and compact sources of momentum are uncommon; the plume is not a great deal more realistic as its motion and similarity structure up to the level of zero mean buoyancy is determined primarily by the strength of its maintained source, possibly involving both buoyancy and momentum fluxes. The plume appears even less appropriate as latent heat of condensation and the environment is normally stable. A further deficiency of the plume model is that lateral entrainment with its associated turbulent mixing should produce gaussian profiles. There is, however, some evidence from airplane traverses that cloud properties such as liquid water content, droplet populations and droplet spectra are relatively uniform over considerable parts of cloud sections, but change with height, and only narrow zones of gradient and observed near cloud edges. Such profiles are inconsistent with lateral diffusion.”

For many, the first half of the above statement may sound trivial, and argue that these limitations of the original plume models are now well known. However, the fact still remains that even today, we somehow stay with this original framework of the steady-plume model, but by modifying in details. We have to consider carefully how long we can keep going under such a “revisionist” stance. The latter half is, I am afraid, not well appreciated, and this is related to the fact that a distinction between stirring and diffusion (cf., Ottino, 1989) is not well recognized in the context of atmospheric convection.

Physical bases for the entrainment concept applied to the jets and the laboratory-experiment plumes are systematically discussed by Turner (1986: see also Townsend, 1970; List, 1982; Reuter, 1986). Turner suggests that the entrainment concept would

also be relevant to some of the outdoor processes such as volcano eruptions, atomic bomb explosion, and possibly for bush fires. However, a direct relevance of this concept to atmospheric convection is questionable. In this respect, Malkus and Scorer (1955) foresaw that the bubble dynamics would be the “mechanism of entrainment” in cumulus convection.

6 Buoyancy parameter: issues of stratification

As discussed in Sect. 3, the entraining plume model naturally arises under a dimensional analysis for a fluid without stratification. However, once a stratification is introduced to the system, the similarity theory based on dimensional analysis becomes no longer available. For this reason, it would be important to consider the role of stratification in the context of the plume dynamics specifically.

An important nondimensional parameter playing a key role is the buoyancy parameter introduced by Baines (2001):

$$B = \frac{QN^3}{g'^2}, \quad (1)$$

where Q is the initial volume flux per unit area, [$\text{m}^2 \text{s}^{-1}$], N the buoyancy frequency (Brunt–Vaisala frequency), [s^{-1}], and g' the initial buoyancy (reduced-gravity), [ms^{-2}]. Note that the Q is a measure of the initial vertical velocity.

In typical plume experiments in the laboratory (cf, Baines, 2002), this parameter B is more than often set to the order of unity by introducing a finite vertical velocity initially. This point must be emphasized: though the literature argues that the initial momentum source is small, it is indeed finite.

This situation is in great deal of contrast with typical atmospheric situations, in which the initial velocity of a plume is expected to be virtually nonexistent. Note that a typical atmospheric value for the buoyancy parameter may be estimated as $B \sim 10^{-3}$ as a possible maximum. Here, we use the parameters $g' \sim g\theta'/\theta \sim 10^{-1} \text{ms}^{-2}$, $N \sim 10^{-2} \text{s}^{-1}$,

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and $Q \sim dw \sim 10 \text{ m}^2 \text{ s}^{-1}$, assuming $g \sim 10 \text{ ms}^{-2}$, $\theta' \sim 1 \text{ K}$, $\theta \sim 10^2 \text{ K}$, an initial vertical scale $d \sim 10^2 \text{ m}$, an initial vertical velocity $w \sim 10^{-1} \text{ ms}^{-1}$. Thus, the buoyancy parameter is extremely small in typical atmospheric situations.

Another parameter relevant for this purpose is the so-called lazy parameter, Γ (assumed to be positive), introduced by Morton (1959, see also Scase et al., 2006). The definition is rather involved so is not reproduced here, but it is defined in such manner that we have $\Gamma = 1$ when a plume satisfies a similarity solution of Morton et al. (1956). Here, again, it is important to realize that the classical similarity solution assumes a finite vertical velocity (momentum) at a source. Only when the initial ratio between the momentum and the mass satisfies a particular value (i.e., $\Gamma = 1$), the similarity solution is obtained. Otherwise, the plume evolution does not follow that of the similarity solution. For this reason, the regime with $\Gamma = 1$ is proposed to be called “pure plume”. When $\Gamma > 1$ (disturbed or lazy), the mass source dominates. When $\Gamma < 1$ (forced), the momentum source dominates. The “lazy” situation is expected to be more relevant to the atmospheric plumes for the reason just discussed.

These short considerations suggest that classical laboratory-plume experiments are not necessarily relevant for atmospheric plumes. Here, atmospheric convection is in a qualitatively different regime than for the typical laboratory-experiment convective plumes.

7 Role of the plume hypothesis in the mass-flux formulation

As a historical review so far suggests, it may even be argued that the steady-plume model is introduced into the mass-flux convection parameterization more by a historical “accident”. We may point out a strong role of Joanne Malkus Simpson in this process. Then how strongly the mass-flux formulation is constrained by this steady-plume hypothesis?

The steady-plume hypothesis has two major consequences in the standard mass-flux parameterization formulation. These are:

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1. separation of the variables;
2. determination of its vertical structure by a entrainment-detrainment hypothesis

In order to critically examine these consequences, a short summary on the mass-flux formulation is warranted. As its name suggests, a key variable in its formulation is the convective mass flux, M . Once this variable is determined, all the output variables for mass-flux convection parameterization can be evaluated more or less in straightforward manner (cf., Yano et al., 2005).

The mass flux, M , is in turn, determined by two steps by assuming a separation of variables into time and vertical dependences:

$$M(z, t) = M_B(t)\eta(z). \quad (2)$$

Here, a subscript, B, is added to the time-dependent part, because it is customarily defined as the mass-flux value at the convection base.

We may trace the separation of the variables to the steady-plume hypothesis introduced to the mass-flux convection parameterization under a historical process as reviewed so far. This hypothesis allows us to assume that the vertical structure, $\eta(z)$, is defined under a steady-plume model, whereas its time-dependent amplitude, $M_B(t)$, is determined by a large-scale environment to which convective processes are slaved, in a similar manner as a gradually modified stratification within a water tank changes the behavior of the plume. The latter is defined under a formal procedure called “closure” (cf., Yano et al., 2013).

However, we should also realize that separation of the variables also naturally comes into the mass-flux formulation when an asymptotic limit of vanishing fractional area for convection is introduced, as a standard limit. It may also be emphasized that the separation of variables is essentially introduced in Arakawa and Schubert (1974) in the latter manner. Discussions on the plume only comes later in this paper. Thus, as a logical construction of the mass-flux formulation, the separation of variables does not hang on the plume hypothesis. The idea can be treated in a more abstract manner, probably keeping a term “plume” only as a metaphor.

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



On the other hand, the vertical structure of the mass flux, $\eta(z)$, is, without exception, determined by invoking the plume dynamics in the current operational schemes. Recall that Morton et al. (1956) proposed an entraining plume, whose vertical structure is determined by

$$5 \quad \frac{1}{\eta} \frac{d\eta}{dz} = \frac{1}{M} E \quad (3)$$

with the entrainment rate, E , assumed to be proportional to the mass flux, M . The above formulation can be generalized by adding the detrainment, D , so that

$$\frac{1}{\eta} \frac{d\eta}{dz} = \frac{1}{M} (E - D). \quad (4)$$

10 From a point of view of the plume dynamics, this is the most general manner for determining a vertical structure of convection. There are extensive debates on the procedure of determining the convection profile under this framework, as already discussed in Sect. 5.

15 However, once we accept the fact that the entrainment–detrainment formalism is merely a historical “accident”, there is no longer a strong reason for upholding it. A vertical structure of mass flux may be determined by any other different manners.

Unfortunately, there are not many alternative options immediately visible, but a one clear choice is to adopt a spectrum representation for the mass flux, M_i , with the subscript i stands for a convection type. The principle of separation of variables becomes

$$20 \quad M_i(z, t) = M_{i,B}(t) \eta_i(z) \quad (5)$$

with $i = 1, \dots, N$ when N convection types are considered. Once such a spectrum formulation is adopted, we can avoid an issue of determining a vertical structure for each type by simply introducing an enough number of *prescribed* vertical profiles, $\{\eta_i\}$. An

Basic convective element: bubble or plume?

J.-I. Yano

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



easiest choice could be simply a series of half-sinusoidal shapes with varying heights, for example.

The key issue is, then, turned into that of determining the mass-flux spectrum, $\{M_{i,B}\}$, by a closure condition. Arakawa and Schubert's original convective quasi-equilibrium hypothesis is exactly designed to address the problem in this manner. Unfortunately, not much formal investigation on this formulation is reported in the literature (cf., Yano and Plant, 2012).

8 Future perspectives: rediscovery of bubble?

After this long historical tour, it appears to me that we are turning to a period of rediscovery of bubble. With dramatic progress of the digital computational power, it is now possible to simulate details of the atmospheric convective dynamics in relative ease. At such a level of details, convection is clearly not steady, but rather transient. As a result, it is far easier to recognize atmospheric convection as consisting of an ensemble of bubbles, rather than as a quasi-steady plume.

Under this trend, extensive process studies focused on bubbles have begun to appear (e.g., Sherwood et al., 2013), and likely more to follow. A recent development with laboratory experiments may equally remarked with sophisticated measurements based on laser technology (cf., Korczyk et al., 2012). Clearly, we would learn a lot along this line in the years to come. Here, we may even say that we came a long way to correctly recognize again that convection consists of bubbles. However, this is with ironies after years of efforts developing convection parameterization based on a steady plume hypothesis.

Keep in mind that generally it is not legitimate to simply criticize a certain parameterization by saying that it neglects a key element for a given process, such as transient nature of real atmospheric convection consisting of bubbles. The goal of a parametrization is not to reproduce the whole structure of a given process accurately. Its only concern is to provide the feedback of the given process in grid-box average (i.e., large scale).

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Though a given element may well be important for reconstructing a whole structure of a given process, say in explicit simulations, it may not be as important for a feedback to the large scale. Said it differently, the feedback itself may be well described without taking into account such a feature (cf., Yano et al., 2012).

Importance of transient nature of convection in parameterization must also be considered in this manner. Though everyone would agree that atmospheric convection is highly transient, there is not robust evidence to believe that it is crucial to implement this aspect into a parameterization.

As reviewed in the last section, the current convection parameterization based on the steady plume hypothesis is developed in a self-consistent manner. Thus, such a critic is like trying to discredit the quasi-geostrophic theory based on the fact that it neglects gravity waves. Most of the dynamists would agree that the value of the quasi-geostrophic theory hardly diminishes by the fact that it neglects gravity waves. The same could be equally true with the mass-flux convection parameterization: its neglect of convective transiency does not necessarily automatically discredit its value. In this very respect, it is not quite clear how the bubble-dynamics studies contribute to the improvements of mass-flux convection parameterization.

If we are going to re-adopt the bubbles as basic elements of convection, then we need to develop a completely new framework for convection parameterization, other than a one based on mass flux. Recall that though Ooyama (1971) claimed to take the bubbles, only under a steady environment. Thus, his formalism reduces to that of the steady plumes in the end (see also Ooyama, 1972). If the bubble paradigm is to be fully accepted, a fully transient description of convection must be developed for a parameterization purpose. In order to deal with many bubbles within a convective cloud in a compact, parameterizable manner, a statistical theory for convective bubbles must first be developed.

Here, we face dichotomous choices. We may stay with a traditional mass-flux formulation originated from the steady-plume hypothesis, but treating the plume more as a metaphor. Alternatively, we may pursue a completely new theory based on a statisti-

cal dynamics for a bubble ensemble. A final answer may turn out to be a mathematical analogue to a steady-plume formulation. However, that is exactly what we still have to find out.

Yet, it would be better to conclude the present review in a cautious manner rather than maintaining a misleading optimism. A good parallel would be a question of reducing a spectrum of convective plumes under mass-flux formulation into a bulk plume. Though a bulk model is often considered an ensemble-averaged version of a spectrum model (e.g., Gregory and Rowntree, 1990), such an interpretation turns out to be difficult to maintain literally (Plant, 2010).

A stepwise generalization of a plume-based formulation could be a third path to take. A general system with such plume dynamics can be constructed by introducing a geometrical constraint consistent with the mass-flux formulation, which may be called segmentally-constant approximation (SCA), into a cloud-resolving model (CRM: Yano et al., 2005, 2010; Yano, 2012). Especially, when only a single plume is placed over a grid box, a fully-prognostic bulk mass flux model can be derived without any further approximations, nor closures (Yano and Baizig, 2012).

An important lesson from the present historical review is to avoid to repeat a mistake of uncritically adopting a formulation already developed for a particular purpose into something else. The bubble vertical-velocity formulation by Levine (1959) was uncritically introduced into the steady-plume problem in this manner. We should avoid the same mistake of reapplying the steady-plume formulation back into an unsteady bubble problem.

Acknowledgements. The context of the COST Action ES0905 is acknowledged.

References

Arakawa, A. and Schubert, W. H.: Interaction of a cumulus cloud ensemble with the large-scale environment, Part I, *J. Atmos. Sci.*, 31, 674–701, 1974. 3338, 3344, 3349

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Baines, P. G.: Mixing in flows down gentle slopes into stratified environments, *J. Fluid Mech.*, 443, 237–270, 2001. 3347
- Baines, P. G.: Two-dimensional plumes in stratified environment, *J. Fluid Mech.*, 471, 315–337, 2002. 3347
- 5 Batchelor, G. K.: Heat convection and buoyancy effects in fluids, *Q. J. Roy. Meteor. Soc.*, 80, 339–358, 1954. 3339, 3342
- Bechtold, P., Bazile, E., Guichard, F., Mascart, P., and Richard, E.: A mass-flux convection scheme for regional and global models, *Q. J. Roy. Meteor. Soc.*, 127, 869–889, 2001. 3341, 3345
- 10 Bretherton, C. S., McCaa, J. R., and Grenier, H.: A new parameterization for shallow cumulus convection and its application to marine subtropical cloud-topped boundary layers, Part I: Description and 1-D results, *Mon. Weather Rev.*, 132, 864–882, 2004. 3341
- Blyth, A. M., Cooper, W. A., and Jensen, J. B.: A study of the source of entrained air in Montana cumuli, *J. Atmos. Sci.*, 45, 3944–3964, 1988. 3345
- 15 Davies, R. M. and Taylor, G. K.: The mechanics of large bubbles rising through extended liquids and through liquids in tubes, *P. R. Soc. London*, 200, 375–390, 1950. 3340
- de Rooy, W. C., Bechtold, P., Frohlich, K., Hohenegger, C., Jonker, H., Mironov, D., Pier Siebesma, A., Teixeira, J., and Yano, J.-I.: Entrainment and detrainment in cumulus convection: an overview, *Q. J. Roy. Meteor. Soc.*, 139, 1–19, doi:10.1002/qj.1959, 2013. 3342, 3345
- 20 Derbyshire, S. H., Maidens, A. V., Milton, S. F., Stratton, R. A., and Willett, M. R.: Adaptive detrainment in a convective parameterization, *Q. J. Roy. Meteor. Soc.*, 137, 1856–1871, 2011. 3345
- Donner, L. J.: A cumulus parameterization including mass fluxes, vertical momentum dynamics, and mesoscale effects, *J. Atmos. Sci.*, 50, 889–906, 1993. 3341
- 25 Emanuel, K. A.: A scheme for representing cumulus convection in large-scale models, *J. Atmos. Sci.*, 48, 2313–2335, 1991. 3345
- Gregory, D. and Rowntree, P. R.: A mass flux scheme with representation of cloud ensemble characteristics and stability-dependent closure, *Mon. Weather Rev.*, 118, 1483–1506, 1990. 3353
- 30 Houghton, H. and Cramer, H.: A theory of entrainment in convective currents, *J. Meteorol.*, 8, 95–102, 1951. 3344

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Kain, J. S. and Fritsch, J. L.: A one-dimensional entraining/detraining plume model and its application in convective parameterization, *J. Atmos. Sci.*, 47, 2784–2802, 1990. 3345
- Kasahara, A. and Asai, T.: Effects of an ensemble of convective elements on the large-scale motions of the atmosphere, *J. Meteorol. Soc. Jpn.*, 45, 280–291, 1967.
- 5 Korczyk, P. M., Kowalewski, T. A., and Malinowski, S. P.: Turbulent mixing of clouds with the environment: Small scale two phase evaporating flow investigated in a laboratory by particle image velocimetry, *Physica D*, 241, 288–296, 2012. 3351
- Levine, J.: Spherical vortex theory of bubble-like motion in cumulus clouds, *J. Meteorol.*, 16, 653–662, 1959. 3341, 3353
- 10 List, E. J.: Turbulent jets and plumes, *Annu. Rev. Fluid Mech.*, 14, 189–212, 1982. 3346
- Ludlam, F. H.: The hail problem, *Nublia*, 1, 13–96, 1958. 3343
- Ludlam, F. H. and Scorer, R. S.: Reviews of modern meteorology – 10, Convection in the atmosphere, *Q. J. Roy. Meteor. Soc.*, 79, 317–341, 1953. 3340
- Malkus, J. S.: Recent advances in the study of convective clouds and their interaction with the environment, *Tellus*, 4, 71–87, 1952. 3343
- 15 Malkus, J. S.: Some results of a trade-cumulus cloud investigation, *J. Meteorol.*, 11, 220–237, 1954. 3344
- Malkus, J. S. and Scorer, R. S.: The erosion of cumulus towers, *J. Meteorol.*, 12, 43–57, 1955. 3340, 3347
- 20 Morton, B. R.: Buoyant plumes in a moist atmosphere, *J. Fluid Mech.*, 2, 127–144, 1957. 3342
- Morton, B. R.: Forced plumes, *J. Fluid Mech.*, 5, 151–163, 1959. 3348
- Morton, B. R.: On Telford's model for clear air convection, *J. Atmos. Sci.*, 25, 135–138, 1968. 3344
- Morton, B. R.: Discreet dry convective entities, I: Review, in: *The Physics and Parameterization of Moist Atmospheric Convection*, edited by: Smith, R. K., NATO ASI, Kloster Seeon, Kluwer Academic Publishers, Dordrecht, 143–173, 1997a. 3339
- 25 Morton, B. R.: Discreet dry convective entities, II: thermals and deflected jets, in: *The Physics and Parameterization of Moist Atmospheric Convection*, edited by: Smith, R. K., NATO ASI, Kloster Seeon, Kluwer Academic Publishers, Dordrecht, 175–210, 1997b. 3346
- 30 Morton, B. R., Taylor, G. I., and Turner, J. S.: Turbulent gravitational convection from maintained and instantaneous sources, *P. Phys. Soc.*, 74, 744–754, 1956. 3342, 3343, 3348, 3350
- Ooyama, V. K.: A theory on parameterization of cumulus convection, *J. Meteorol. Soc. Jpn.*, 26, 3–40, 1971. 3352

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Ooyama, V. K.: On parameterization of cumulus convection, in: Dynamics of the Tropical Atmosphere, Notes from a Colloquium: Summer 1972: National Center for Atmospheric Research, Boulder, Colorado, 11 July 1972, 496–505, 1972. 3352

Ottino, J. M.: The Kinematics of Mixing: Stretching, Chaos, and Transport, Cambridge Texts in Applied Mathematics, Cambridge University Press, 364 pp., 1989. 3346

Paluch, I. R.: The entrainment mechanism of Colorado cumuli, *J. Atmos. Sci.*, 36, 2467–2478, 1979. 3345

Plant, R. S.: A review of the theoretical basis for bulk mass flux convective parameterization, *Atmos. Chem. Phys.*, 10, 3529–3544, doi:10.5194/acp-10-3529-2010, 2010. 3353

Raymond, D. J. and Blyth, A. M.: A stochastic mixing model for nonprecipitating cumulus clouds, *J. Atmos. Sci.*, 43, 2708–2718, 1986. 3345

Reuter, G. W.: A historical review of cumulus entrainment studies, *B. Am. Meteor. Soc.*, 67, 151–154, 1986. 3346

Saunders, P. M.: Penetrative convection in stably stratified fluids, *Tellus*, 16, 177–194, 1962. 3340

Scase, M. M., Caufield, C. P., Dalziel, S. B., and Hunt, J. C. R.: Time-dependent plumes and jets with decreasing source strengths, *J. Fluid Mech.*, 563, 443–461, 2006. 3348

Scorer, R. S.: Experiments on convection of isolated masses of buoyancy fluid, *J. Fluid Mech.*, 2, 583–594, 1957. 3340

Scorer, R. S. and Ludlam, F. H.: Bubble theory of penetrative convection, *Q. J. Roy. Meteor. Soc.*, 79, 94–103, 1953. 3340

Scorer, R. S. and Ronne, C.: Experiments with convection bubbles, *Weather*, 11, 151–154, 1956. 3340

Sherwood, S. C., Hernández-Deckers, D., Colin, M., and Robinson, F.: Slippery thermals and the cumulus entrainment paradox, *J. Atmos. Sci.*, 70, 2426–2442, 2013. 3351

Siebesma, A. P., Bretherton, C. S., Brown, A., Chlond, A., Cuxart, J., Duynkerke, P. G., Jiang, H., Khairoutdinov, M., Lewellen, D., Moeng, C.-H., Sanchez, E., Stevens, B., and Stevens, D. E.: A large eddy simulation intercomparison study of shallow cumulus convection, *J. Atmos. Sci.*, 60, 1201–1219, 2003. 3341

Simpson, J.: On cumulus entrainment and one-dimensional models, *J. Atmos. Sci.*, 28, 449–455, 1971. 3345

Simpson, J.: Reply, *J. Atmos. Sci.*, 29, 220–225, 1972. 3345

**Basic convective
element: bubble or
plume?**

J.-I. Yano

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Simpson, J.: Cumulus clouds: early aircraft observations and entrainment hypotheses, in: Mesoscale Meteorology – Theories, Observations and Models, edited by: Lilly, D. K. and Gal-Chen, T., 355–373, Reidel, Dordrecht, the Netherlands, 1983a.

Simpson, J.: Cumulus clouds: interactions between laboratory experiments and observations as foundations for models, in: Mesoscale Meteorology – Theories, Observations and Models, edited by: Lilly, D. K. and Gal-Chen, T., 399–412, Dordrecht, the Netherlands, 1983b. 3340

Simpson, J. and Wiggert, V.: Models of precipitating cumulus towers, Mon. Weather Rev., 97, 471–489, 1969. 3344

Simpson, J., Simpson, R. H., Andrews, D. A., and Eaton, M. A.: Experimental cumulus dynamics, Rev. Geophys., 3, 387–431, 1965. 3341, 3344

Squires, P.: The spatial variation of liquid water content and droplet concentration in cumuli, Tellus, 10, 372–380, 1958a. 3345

Squires, P.: Penetrative downdraughts in cumuli, Tellus, 10, 381–389, 1958b. 3345

Stommel, H.: Entrainment of air into a cumulus cloud, J. Meteorol., 4, 91–94, 1947. 3343

Stommel, H.: Entrainment of air into a cumulus cloud II, J. Meteorol., 8, 127–129, 1951. 3343

Sud, Y. C. and Walker, G. K.: Microphysics of clouds with relaxed Arakawa–Schubert scheme (McRAS), Part I: Design and evaluation with GATE Phase III data, J. Atmos. Sci., 56, 3196–3220, 1999.

Taylor, G. R. and Baker, M. B.: Entrainment and detrainment in cumulus clouds, J. Atmos. Sci., 48, 112–121, 1991. 3345

Telford, J. W.: The convective mechanism in clear air, J. Atmos. Sci., 23, 652–666, 1966. 3344

Telford, J. W.: Reply, J. Atmos. Sci., 25, 138–139, 1968. 3344

Telford, J. W.: Turbulence, entrainment and mixing in cloud dynamics, Pure Appl. Geophys., 113, 1067–1084, 1975. 3345

Townsend, A. A.: Entrainment and the structure of turbulent flow, J. Fluid Mech., 41, 13–46, 1970. 3346

Turner, J. S.: Buoyant vortex rings, P. R. Soc. London, 239, 61–75, 1957. 3340

Turner, J. S.: The “starting plume” in neutral surroundings, J. Atmos. Sci., 13, 356–368, 1962. 3340, 3342

Turner, J. S.: Model experiments relating to thermal with increasing buoyancy, Q. J. Roy. Meteor. Soc., 89, 62–74, 1963a. 3340

Turner, J. S.: The motion of buoyancy elements in turbulent surroundings, J. Fluid Mech., 16, 1–16, 1963b. 3340

**Basic convective
element: bubble or
plume?**

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Turner, J. S.: The flow into an expanding spherical vortex, *J. Fluid Mech.*, 18, 195–208, 1964. 3341
- Turner, J. S.: Buoyant plumes and thermals, *Annu. Rev. Fluid Mech.*, 1, 29–44, 1969. 3339
- Turner, J. S.: Turbulent entrainment: the development of the entrainment assumption, and its
5 application to geophysical flows, *J. Fluid Mech.*, 173, 431–471, 1986. 3346
- Warner, J.: On steady-state one-dimensional models of cumulus convection, *J. Atmos. Sci.*, 27, 1035–1040, 1970. 3345
- Warner, J.: Comments “On cumulus entrainment and one-dimensional models”, *J. Atmos. Sci.*, 29, 218–219, 1972. 3345
- 10 Woodward, B.: The motion in and around isolated thermals, *Q. J. Roy. Meteor. Soc.*, 85, 144–151, 1959. 3340
- Yano, J.-I.: Mass-flux subgrid-scale parameterization in analogy with multi-component flows: a formulation towards scale independence, *Geosci. Model Dev.*, 5, 1425–1440, doi:10.5194/gmd-5-1425-2012, 2012. 3353
- 15 Yano, J.-I. and Baizig, H.: Single SCA-plume dynamics, *Dyn. Atmos. Ocean*, 58, 62–94, 2012. 3353
- Yano, J.-I. and Plant, R. S.: Convective quasi-equilibrium, *Rev. Geophys.*, 50, RG4004, doi:10.1029/2011RG000378, 2012. 3351
- Yano, J.-I., Redelsperger, J.-L., Guichard, F., and Bechtold, P.: Mode decomposition as
20 a methodology for developing convective-scale representations in global models, *Q. J. Roy. Meteor. Soc.*, 131, 2313–2336, 2005. 3349, 3353
- Yano, J.-I., Benard, P., Couvreux, F., and Lahellec, A.: NAM-SCA: Nonhydrostatic Anelastic Model under Segmentally-Constant Approximation, *Mon. Weather Rev.*, 138, 1957–1974, 2010. 3353
- 25 Yano, J.-I., Cheedela, S. K., and Roff, G. L.: A compressed super-parameterization: test of NAM-SCA under single-column GCM configurations, *Atmos. Chem. Phys. Discuss.*, 12, 28237–28303, doi:10.5194/acpd-12-28237-2012, 2012. 3352
- Yano, J.-I., Bister, M., Fuchs, Ž., Gerard, L., Phillips, V. T. J., Barkidija, S., and Piriou, J.-M.: Phenomenology of convection-parameterization closure, *Atmos. Chem. Phys.*, 13, 4111–4131, doi:10.5194/acp-13-4111-2013, 2013. 3349
- 30 Zhang, J., Lohmann, U., and Stier, P.: A microphysical parameterization for convective clouds in the ECHAM5 climate model: single-column model results evaluated at the Ok-

ACPD

14, 3337–3359, 2014

Basic convective element: bubble or plume?

J.-I. Yano

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

