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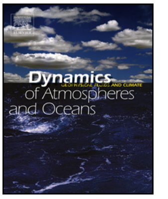

Formulation structure of the mass-flux convection parameterization

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ABSTRACT

Structure of the mass-flux convection parameterization formulation is re-examined. Many of the equations associated with this formulation are derived in systematic manner with various intermediate steps explicitly presented. The nonhydrostatic anelastic model (NAM) is taken as a starting point of all the derivations.

Segmentally constant approximation (SCA) is a basic geometrical constraint imposed on a full system (e.g., NAM) as a first step for deriving the mass-flux formulation. The standard mass-flux convection parameterization, as originally formulated by Ooyama, Fraedrich, Arakawa and Schubert, is re-derived under the two additional hypotheses concerning entrainment–detrainment and environment, and an asymptotic limit of vanishing areas occupied by convection.

A model derived at each step of the deduction constitutes a stand-alone subgrid-scale representation by itself, leading to a hierarchy of subgrid-scale schemes. A backward tracing of this deduction process provides paths for generalizing mass-flux convection parameterization. Issues of the high-resolution limit for parameterization are also understood as those of relaxing various traditional constraints. The generalization presented herein can include various other subgrid-scale processes under a mass-flux framework.

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1. Introduction

The seminal works by Ooyama (1971), followed by Fraedrich (1973, 1974), Arakawa and Schubert (1974) lay foundations for the formulation of mass-flux convection parameterization (cf., Emanuel and Raymond, 1993). This formulation is currently adopted in the majority of atmospheric circulation models both global and regional, and those both for operational forecasts and climate projections (e.g., Tiedtke, 1989; Gregory and Rowntree, 1990; Emanuel, 1991; Moorthi and Suarez, 1992; Donner, 1993; Zhang and McFarlane, 1995; Bechtold et al., 2001). Thus, the importance of their original work is hardly overemphasized (cf., McFarlane, 2011).

The present paper calls the original, common formulation developed by Ooyama, Fraedrich, and Arakawa and Schubert the standard formulation, because all the subsequently-developed mass-flux convection parameterizations closely follow their original formulation. The goal here is to expose the structure of mass-flux convection parameterization formulation in lucid manner. The present paper does not intend any systematic review of existing mass-flux convection parameterizations.

There are several reasons for such an exposition. Most importantly, a systematic derivation of the mass-flux convection parameterization is missing in the literature. The original papers sited above only provide outlines of their derivations with many equations presented without derivations. Sketches for such systematic derivations found, for example, in Siebesma (1998), Yano et al. (2005a), are expanded by the present paper. Many of the equations presented herein are originally derived.

A lucid presentation of the mass-flux convection parameterization formulation also much facilitates its generalization. The original mass-flux parameterization was formulated by assuming that the atmospheric convective system consists solely of an ensemble of convective updrafts (cf., Yano, 2009). However, the observed atmospheric convective system is more complex: presence of downdrafts as well as an organization into mesoscale, intrinsic interactions of convective dynamics with boundary-layer processes (e.g., cold pools), cloud physics, radiative transfer processes, *etc*. Modifications of convection parameterization for incorporating these elements have rather been slow (cf., Randall et al., 2003; Arakawa, 2004). Its formulation structure must first be elucidated for this purpose.

For example, although the majority of current operational mass-flux convection parameterizations includes convective downdrafts in one way or another (e.g., Fritsch and Chappell, 1980; Tiedtke, 1989; Zhang and McFarlane, 1995; Bechtold et al., 2001), they are implemented in a rather *ad hoc* manner (Kerry Emanuel, personal communication, 1992: cf., Section 8.3.5) below). The operational versions of convection parameterizations are slow in including more convection-related processes. Presently, only the Donner (1993) scheme includes mesoscale downdraft as a part of a deep convection parameterization. In order to make these generalizations easier, needed first is a lucid exposition of the formulation structure.

More urgently, with a rapid increase of the model resolutions, especially for the regional forecasts, there is a need for relaxing the basic constraints of the standard mass-flux convection parameterization in order to adopt it in more general contexts (Yano et al., 2010a). Under the high-resolution limit, the scale of deep moist convection is no longer considered distinctively smaller than the grid size, but it begins to be resolved. As a result, the traditional assumption of scale separation is no longer applicable. Various exploratory attempts already exist towards the high-resolution limit (cf., Gerard and Geleyn, 2005; Gerard, 2007; Kuell et al., 2007; Gerard et al., 2009), however, without general consensus on a systematic procedure. The basic structure of the problem must be exposed in order to place it into a wider perspective.

With these needs in mind, this paper presents the structure of the mass-flux convection parameterization formulation in mathematically lucid and general manner. This paper also suggests how to develop a parameterization with fewer constraints by generalizing the standard mass-flux parameterization.

As an important basic perspective, the paper regards the subgrid-scale parameterization as that of a systematic reduction from a full physical system, such as a cloud-resolving model (CRM) and a large-eddy simulation (LES). Yano et al. (2005a) propose the mode decomposition as such a general procedure. Under this perspective, the mass-flux convection parameterization is a special case based on a segmentally-constant mode decomposition: subdividing the grid-box domain into subdomains