Pressure drag for shallow cumulus clouds – from thermals to the cloud ensemble

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1. Introduction

Representation of vertical velocity within the shallow cumulus clouds is important for the parameterization of convective mixing that is critical to explain the climate sensitivity in climate models. Current parameterization of in-cloud vertical velocity is based on a conditionally averaged, steady state vertical momentum equation in the form of:

$$\frac{1}{2}\frac{\partial w_c^2}{\partial z} = aB_c - b\epsilon w_c^2,$$

in which the buoyancy source and entrainment are two major balanced terms. The effects of pressure perturbation is incorporated into the reduced buoyancy term. However, recent studies have shown that it is the pressure gradient force, not the entrainment, that balances most of the buoyancy source (DeRoode et al. 2012; Sherwood et al. 2013; Romps and Charn 2015).

Based on a single updraft, theoretical studies (Morrison 2016a, b) suggested the pressure gradient force along the central axis is mainly due to the thermodynamic pressure perturbation, and its parameterization can be absorbed in the buoyancy source term with virtual mass coefficients.

2. Motivation

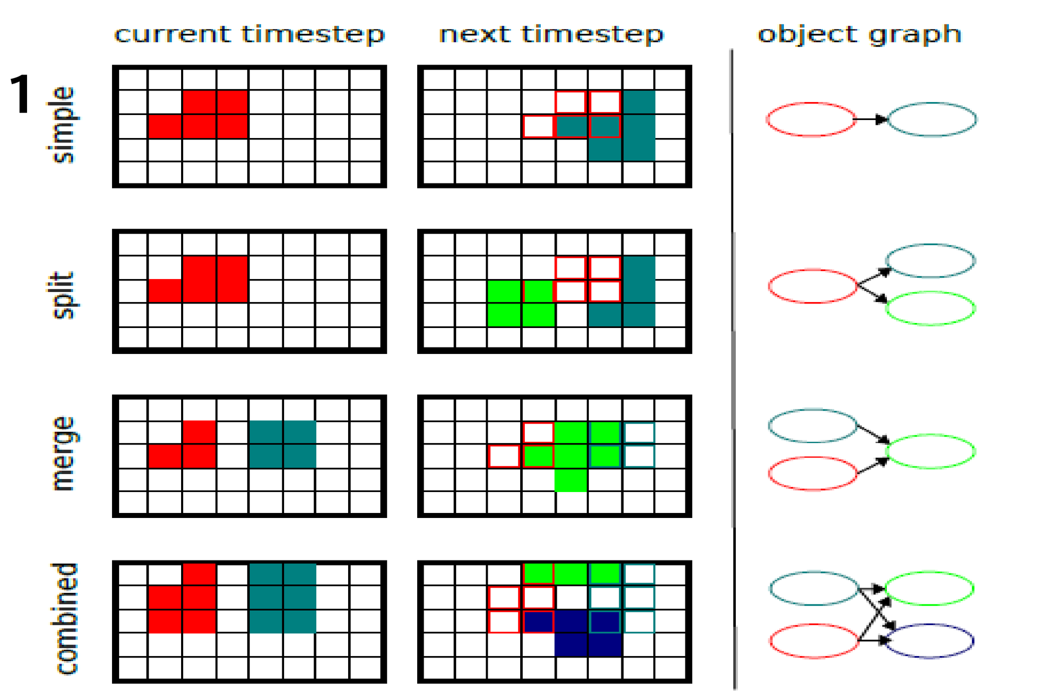
- How does the pressure drag of the cloud ensemble relate to that of a single cloud or successive rising thermals within the cloud?
- Does the thermodynamic pressure perturbation always dominate the pressure gradient force within clouds?
- What about the pressure gradient force off the central axis?
- Does the pressure gradient force always serve as a drag?

3. Methodology

3.1. Large eddy simulation

a. Model: Met Office-NERC Cloud (MONC) model
b. Simulation setup:
BOMEX case;
Domain: 15 X 15 X 3 (km)³ domain size @ 25 m;
Microphysics: Simple cloud scheme with saturation adjustment;
Sub-grid turbulence: Smagorinsky-Lilly;
Output: 6 hours simulation, last hour (at equilibrium state) data for analysis, 1 min output frequency

3.2. Cloud tracking

Fig. 1


A cloud tracking algorithm is performed to record life cycles of each cloud and the vertical momentum tendencies during the period.

3.2. Vertical momentum budget

Conditional averaged vertical momentum equation for a single cloud and the cloud ensemble are derived and used to understand the vertical velocity budget.

Single cloud:

$$\frac{\partial \overline{w_i}}{\partial t} = -\frac{1}{a_i}\frac{\partial\left(\frac{1}{2}a_i\overline{w_i}^2\right)}{\partial z} - \frac{1}{a_i}\frac{\partial a_i\overline{w_i'^2}}{\partial z} + \epsilon_i w_i(\overline{w_0}-\overline{w_i}) + \overline{B_i} - \frac{1}{\rho}\overline{\left(\frac{\partial p_{nh}}{\partial z}\right)_i} + \overline{S_i},$$

Cloud ensemble:

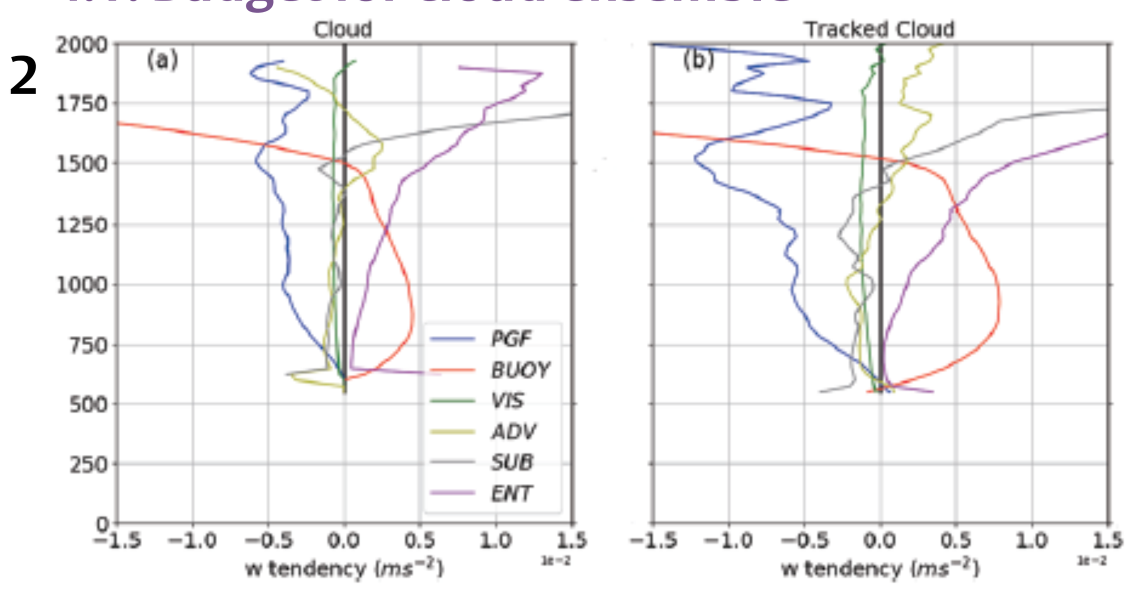
$$\underbrace{\frac{\partial \overline{w_c}}{\partial t}}_{\text{Tendency}} = \underbrace{-\frac{1}{a}\frac{\partial\left(\frac{1}{2}a\overline{w_c}^2\right)}{\partial z}}_{\text{Advection}} \underbrace{-\frac{1}{a}\frac{\partial}{\partial z}\sum_i a_i(\overline{w_i}-\overline{w_c})^2 - \frac{1}{a}\frac{\partial \sum_i a_i\overline{w_i'^2}}{\partial z}}_{\text{Subplume transport}} + \underbrace{\frac{1}{a\rho}\sum_i E_i(\overline{w_0}-\overline{w_c})}_{\text{Entrainment}}$$
$$\underbrace{-\frac{1}{a\rho}\sum_i D_i(\overline{w_i}-\overline{w_c})}_{\text{Detrainment}} + \underbrace{\frac{1}{a}\sum_i a_i\overline{B_i}}_{\text{Buoyancy source}} \underbrace{-\frac{1}{a\rho}\sum_i a_i\overline{\left(\frac{\partial p_{nh}}{\partial z}\right)_i}}_{\text{Pressure}} + \underbrace{\frac{1}{a}\sum_i a_i\overline{S_i}}_{\text{Other sources/sinks}},$$

The vertical momentum equations have components of advection (ADV), sub-plume transport (SUB), entrainment/detrainment (ENT), buoyancy source (BUOY), and pressure gradient force (PGF).

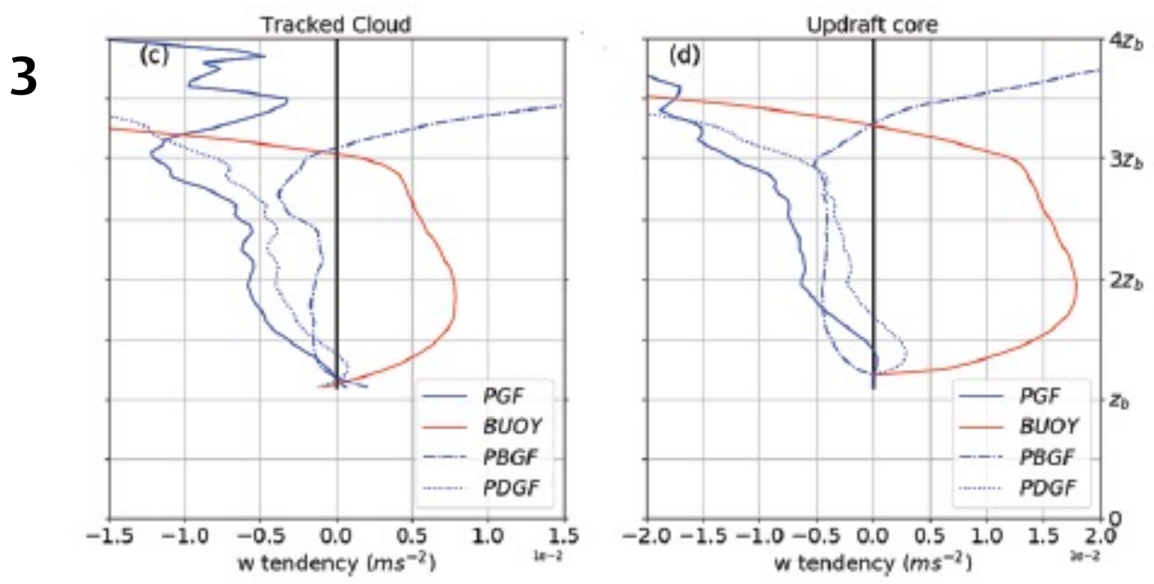
The vertical momentum budgets are performed for each single cloud over its lifecycle and for the cloud ensemble consisting of all the tracked clouds. A budget for all clouds (including the non-tracked) is also performed to have a direct comparison.

4. Results

4.1. Budget for cloud ensemble

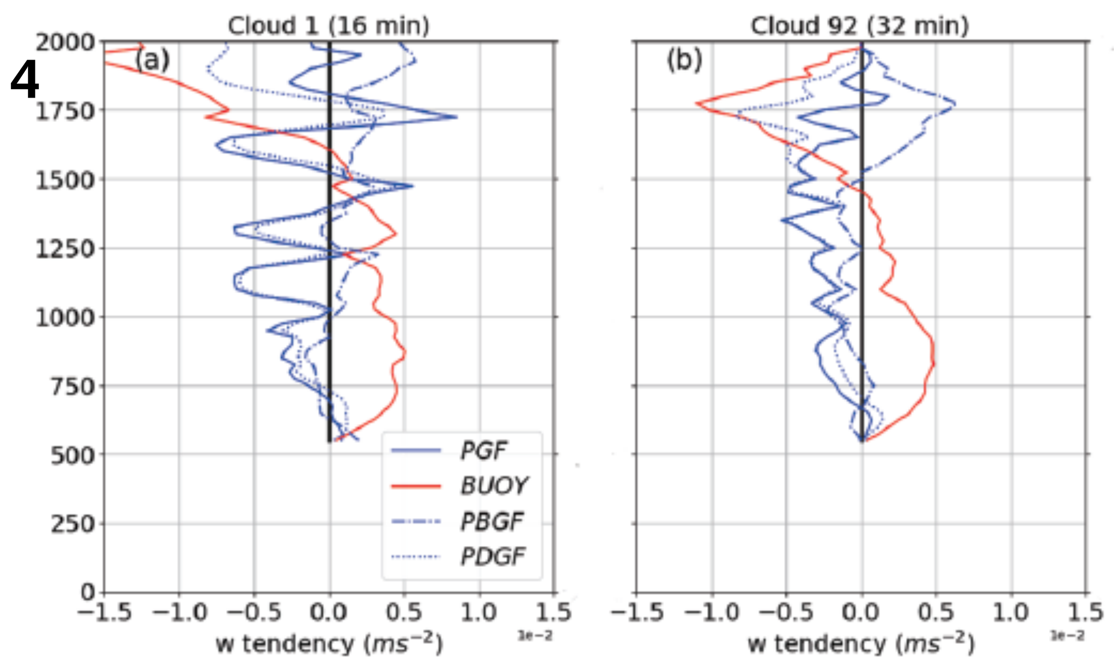
Fig. 2


1. Pressure gradient force mainly serves as drag to balance the buoyancy source and increases with height till cloud top. It does not vary consistently in opposite phase with buoyancy term.
2. Entrainment term does not decelerate the vertical velocity;

Fig. 3


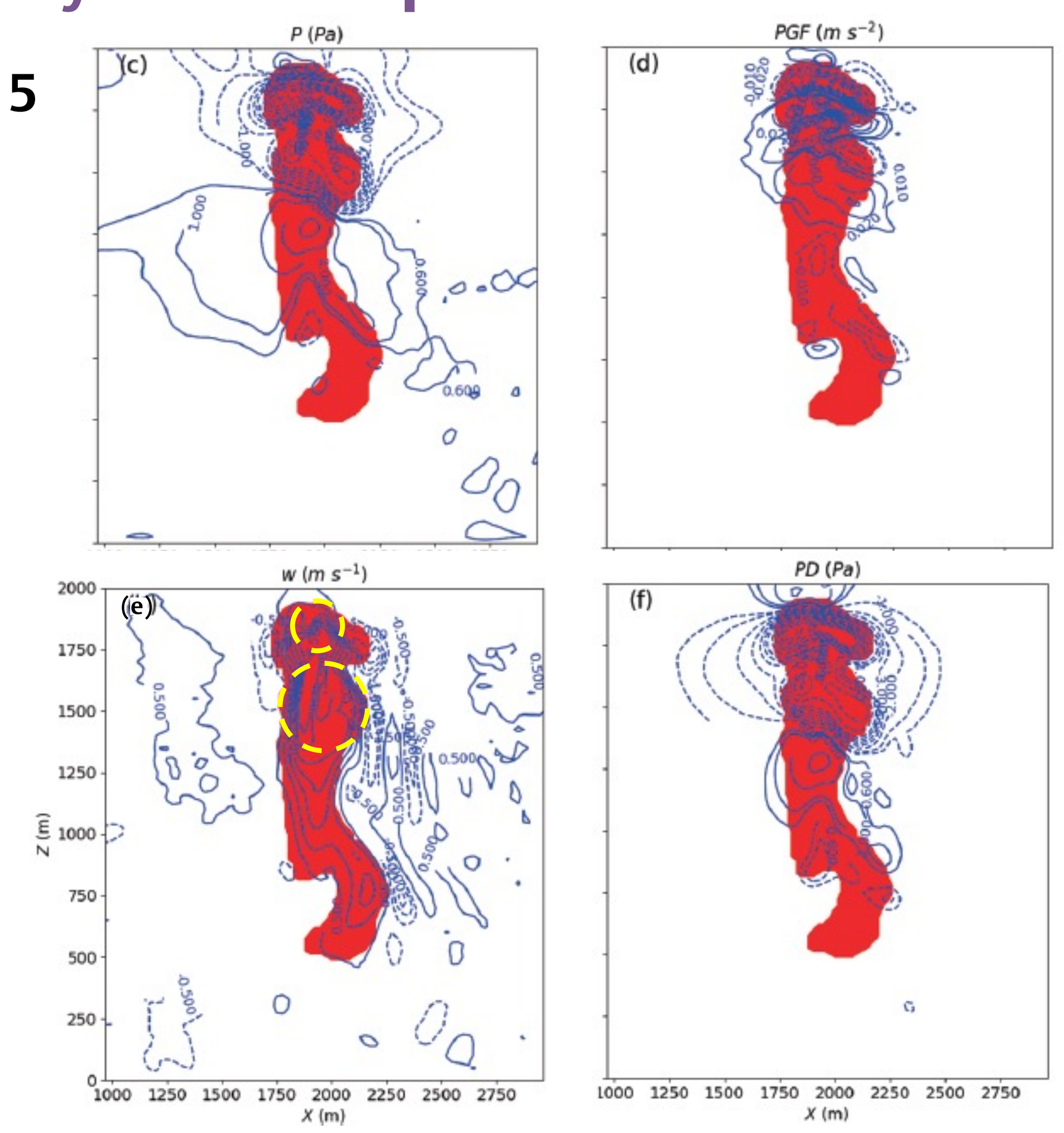
3. Dynamical pressure gradient force dominates the total drag, in terms of magnitude and vertical profile, for whole clouds (3c). It has weak acceleration near cloud base;
4. Thermodynamic component is the stronger one in cloud core (3d), consistent with Morrison et al. 2016a, b;

4.2. Budget for single cloud

Fig. 4


1. Dynamical component dominates the total pressure gradient force but with frequent oscillations in the vertical, sometimes even accelerating the updraft;
2. Magnitude of local minimum negative dynamical pressure gradient force has a tendency to increase with height.

5. Physical interpretation

Fig. 5


(blue solid = positive, dashed = negative; red shading = cloud object)

1. Pressure perturbation pattern (5c) is dominated by dynamical pressure perturbation (5f);
2. Successive rising thermals (5e, yellow circles) are responsible for the couplets of local minima dynamical pressure perturbation (5f), leading to frequent oscillation of pressure gradient force in the vertical (5d);
3. The local minima of the dynamical pressure perturbation are amplified with height, resulting in increased dynamical pressure drag;
4. The increased magnitude of dynamical pressure perturbation is mostly contributed through enhanced horizontal vorticity that is the result of baroclinic generation due to the buoyancy distribution within clouds:

$$\frac{1}{\rho}\nabla^2 p_D = -e_{ij}^2 + \frac{1}{2}|\boldsymbol{\omega}|^2, \qquad \frac{d\boldsymbol{\omega}}{dt} = \underbrace{(\boldsymbol{\omega}+f\mathbf{k})\cdot\nabla\mathbf{u}}_{\text{tilting/stretching}} + \underbrace{\nabla\times B\mathbf{k}}_{\text{baroclinic generation}},$$

6. Summary

1. Dynamical pressure drag dominates the total pressure drag for cloud ensemble, with increased magnitude with height till cloud top, also true for individual cloud but with frequent oscillation in the vertical.
2. The oscillations come from the impact of successive rising thermals within clouds and are further complicated by the downdrafts outside the clouds.
3. Continuous baroclinic generation of horizontal vorticity associated with rising thermals leads to amplified local minima of dynamical pressure perturbation, and thus amplified dynamical pressure drag.
4. For parameterization, the thermodynamic pressure drag can be incorporated into a reduced buoyancy source, but the dynamic pressure drag cannot.