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

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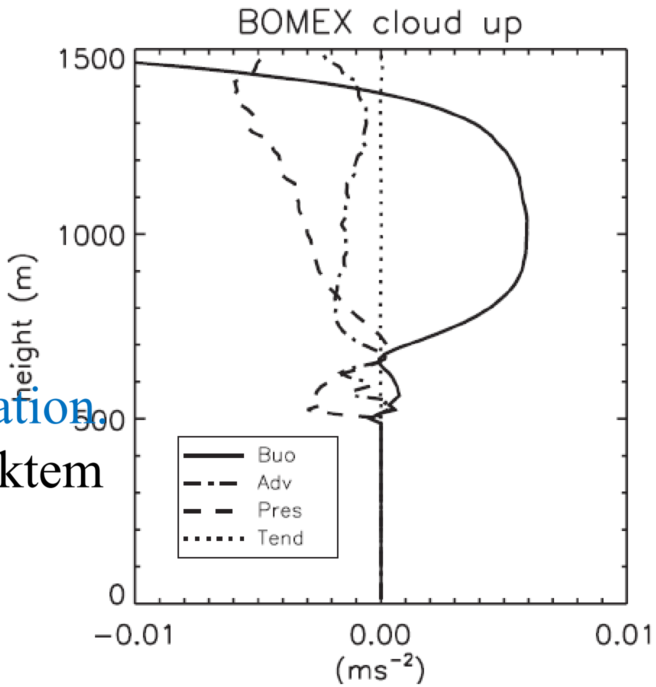
Improvement and calibration of clouds in models
Toulouse, France, 12-16 April, 2021

Parameterization of vertical velocity in a plume model

DeRoode et al. 2012



Buoyancy and entrainment are two major balanced terms

Effect of pressure perturbation is incorporated into the reduced buoyancy term

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

It is the pressure drag, not the entrainment, that balances most the buoyancy acceleration (DeRoode et al. 2012; Sherwood et al. 2013; Romps and Charn 2015; Romps and Oktem 2015)

Parameterization of pressure gradient force

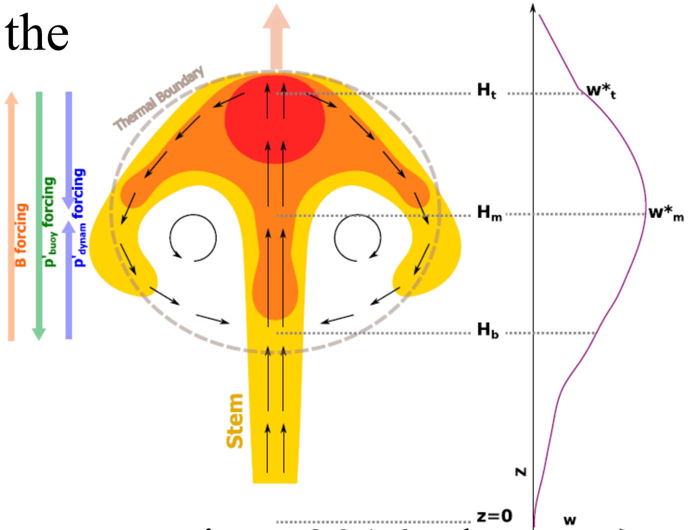
Thermodynamic pressure perturbation accounts for most of the pressure drag on the central axis of updrafts

$$\frac{1}{2}\frac{\partial (w^2)}{\partial z} = \left(1+\frac{\alpha^2 R^2}{H_1^2}\right)^{-1} B - b\varepsilon w^2 \quad z \le z_M \quad \text{and} \tag{5}$$

$$\frac{1}{2}\frac{\partial (w^2)}{\partial z} = \left[1+\gamma_1+\frac{(z-z_M)}{H_2}(\gamma_2-\gamma_1)\right]^{-1} B - \left[1+\gamma_1+\frac{(z-z_M)}{H_2}(\gamma_2-\gamma_1)\right]^{-2}\frac{(\gamma_2-\gamma_1)}{H_2}\int_{z_F}^{z} B\,dz - b\varepsilon w^2 \quad z > z_M, \tag{6}$$

$$\boxed{\nabla^2 p \approx \nabla^2 p_D + \nabla^2 p_B \ ; \ \nabla^2 p_D = -\nabla\cdot(\rho\mathbf{u}\cdot\nabla\mathbf{u}) \ ; \ \nabla^2 p_B = \frac{\partial(\rho B)}{\partial z},}$$

$$\nabla^2 p = \nabla^2 p_D + \nabla^2 p_B \approx \frac{\partial(\rho B)}{\partial z},$$



Morrison 2016a, b

Motivation

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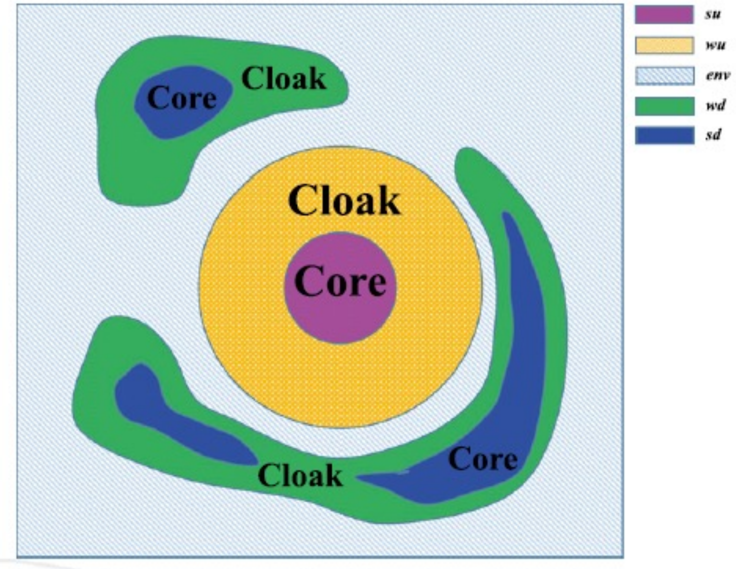
1. How the pressure drag of the cloud ensemble can be related to that of a single cloud or successive rising thermals within the cloud?

2. What about the pressure gradient force off the central axis ?

(Gu et al. 2020)



3. Does it always serve as a drag?

(He et al. 2021, under review)

Methodology

- **Large eddy simulation**
- **BOMEX** (MONC model)

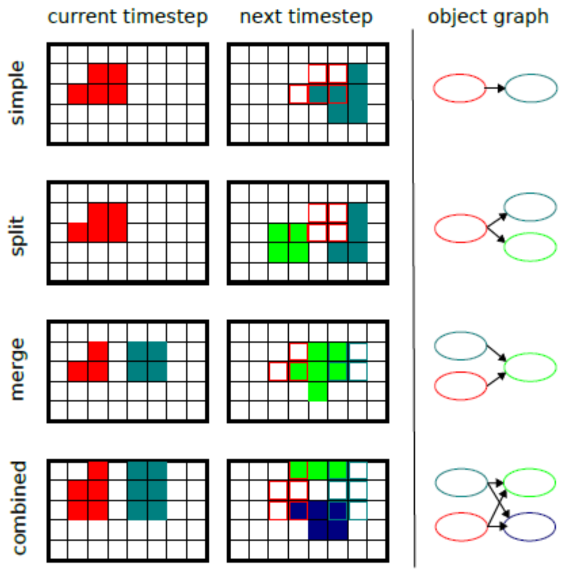
15 km × 15 km × 3 km @ 25 m resolution (both horizontal and vertical)

Most configurations follow the inter-comparison study of BOMEX (Siebesma et al. 2003)

3D Smagorinsky turbulence scheme

6 hour simulation, last hour simulation (equilibrium state, 1 min output frequency) is taken for analysis

- **3D Cloud tracking**
- An extension of Muetzelfeldt's 2D cloud tracking algorithm
- For complicated life cycles, only the cloud object that has the closest cloud depth with previous time is kept.
- A total of 4448 cloud objects have been tracked



Muetzelfeldt 2020

Constructing the vertical momentum budget for cloud ensemble from single cloud

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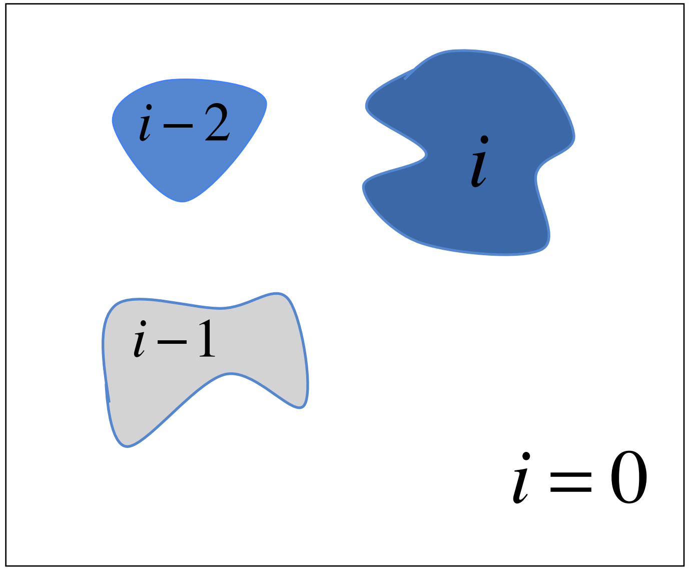
Single cloud

$$\frac{\partial(\rho a_i)}{\partial t} + \frac{\partial(\rho a_i \overline{w_i})}{\partial z} = E_i - D_i$$

$$\frac{\partial(\rho a_i \overline{w_i})}{\partial t} + \frac{\partial(\rho a_i \overline{w_i}^2)}{\partial z} + \frac{\partial \rho a_i \overline{w_i'^2}}{\partial z} = E_i \overline{w_0} - D_i \overline{w_i} + \rho a_i \overline{B_i} - a_i \overline{\left(\frac{\partial p}{\partial z}\right)_i} + \rho a_i \overline{S_i}$$

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



Cloud ensemble

$$\frac{\partial a}{\partial t} + \frac{\partial \sum_i a_i \overline{w_i}}{\partial z} = \frac{1}{\rho}\sum_i E_i - \frac{1}{\rho}\sum_i D_i$$

$$\frac{\partial(\sum_i a_i \overline{w_i})}{\partial t} + \frac{\partial(\sum_i a_i \overline{w_i}^2)}{\partial z} + \frac{\partial \sum_i a_i \overline{w_i'^2}}{\partial z} = \frac{1}{\rho}\sum_i E_i \overline{w_0} - \frac{1}{\rho}\sum_i D_i \overline{w_i} + \sum_i a_i \overline{B_i} - \frac{1}{\rho}\sum_i a_i \overline{\left(\frac{\partial p}{\partial z}\right)_i} + \sum_i a_i \overline{S_i}$$

$$\boxed{\begin{aligned} \underbrace{\frac{\partial \overline{w_c}}{\partial t}}_{\text{Tendency}} = & -\underbrace{\frac{\partial(\frac{1}{2} a \overline{w_c}^2)}{a \partial z}}_{\text{Advection}} - \underbrace{\frac{1}{a}\frac{\partial}{\partial z}\sum_i a_i(\overline{w_i} - \overline{w_c})^2 - \frac{1}{a}\frac{\partial \sum_i a_i \overline{w_i'^2}}{\partial z}}_{\text{Subplume transport}} + \underbrace{\frac{1}{a\rho}\sum_i E_i(\overline{w_0} - \overline{w_c})}_{\text{Entrainment}} \\ & - \underbrace{\frac{1}{a\rho}\sum_i D_i(\overline{w_i} - \overline{w_c})}_{\text{Detrainment}} + \frac{1}{a}\underbrace{\sum_i a_i \overline{B_i}}_{\text{Buoyancy source}} - \underbrace{\frac{1}{a\rho}\sum_i a_i \overline{\left(\frac{\partial p}{\partial z}\right)_i}}_{\text{Pressure}} + \underbrace{\sum_i a_i \overline{S_i}}_{\text{Other sources/sinks}} \qquad (8) \end{aligned}}$$

Budget of cloud ensemble

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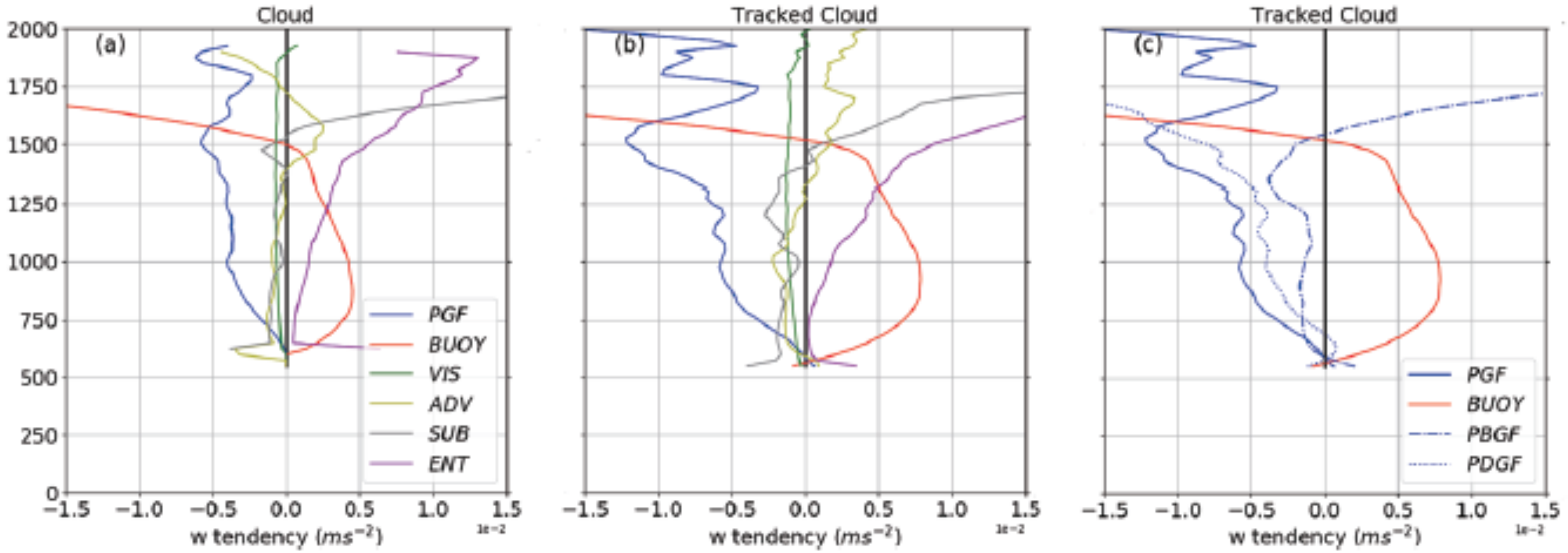


Pressure gradient force (PGF)
Buoyancy force (BUOY)
Viscosity (VIS)
Advection (ADV)
Subplume term (SUB)
Entrainment (ENT)

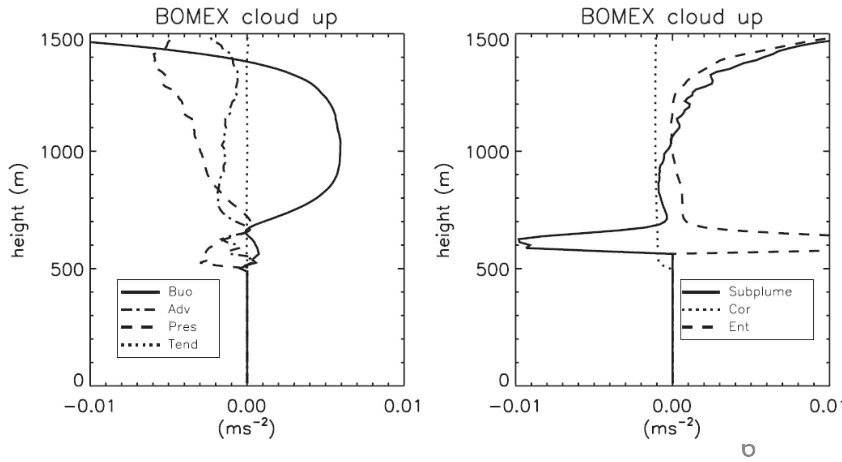
Thermodynamic pressure gradient force (PBGF)

Dynamical pressure gradient force (PDGF)

Despite the vertical extent, our budget results capture reasonable vertical distribution of each terms and also their values, being consistent with DeRoode et al. (2012).

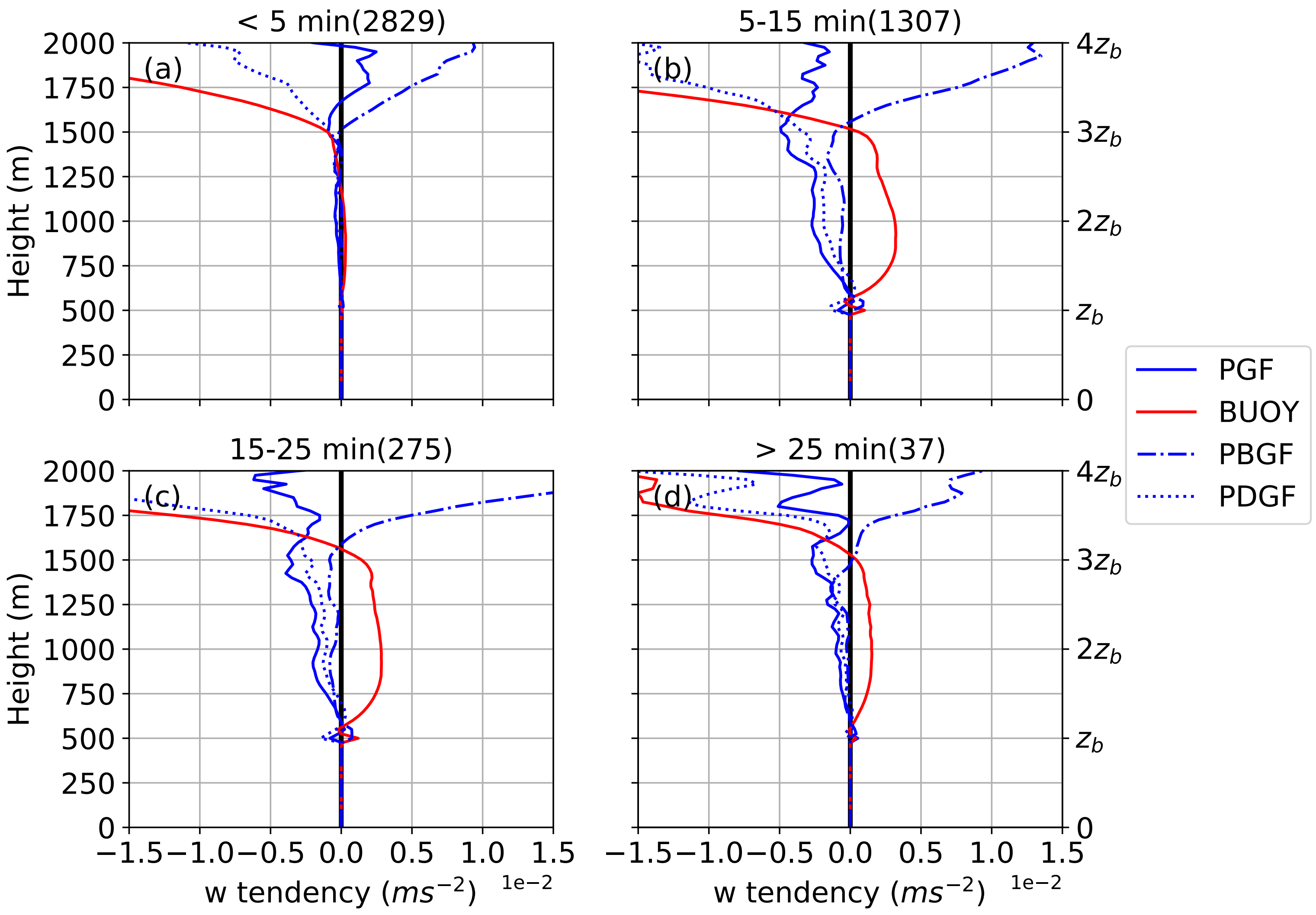
Main points:

1. Thermodynamic pressure gradient force changes consistently with buoyancy source but in an opposite phase;
2. Dynamical pressure gradient force dominates the pressure gradient force, both in terms of magnitude and vertical variations;



DeRoode et al. 2012

Budget for tracked clouds with different life time



Budget for single cloud

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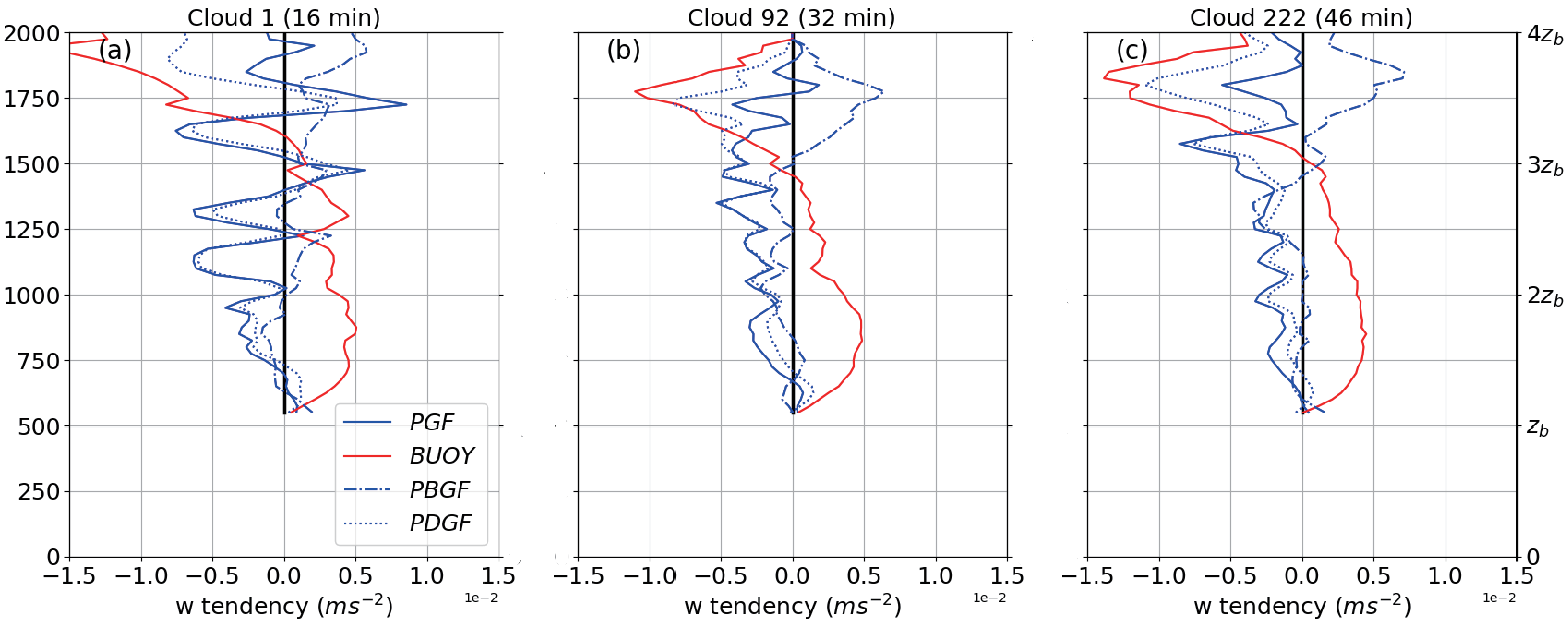
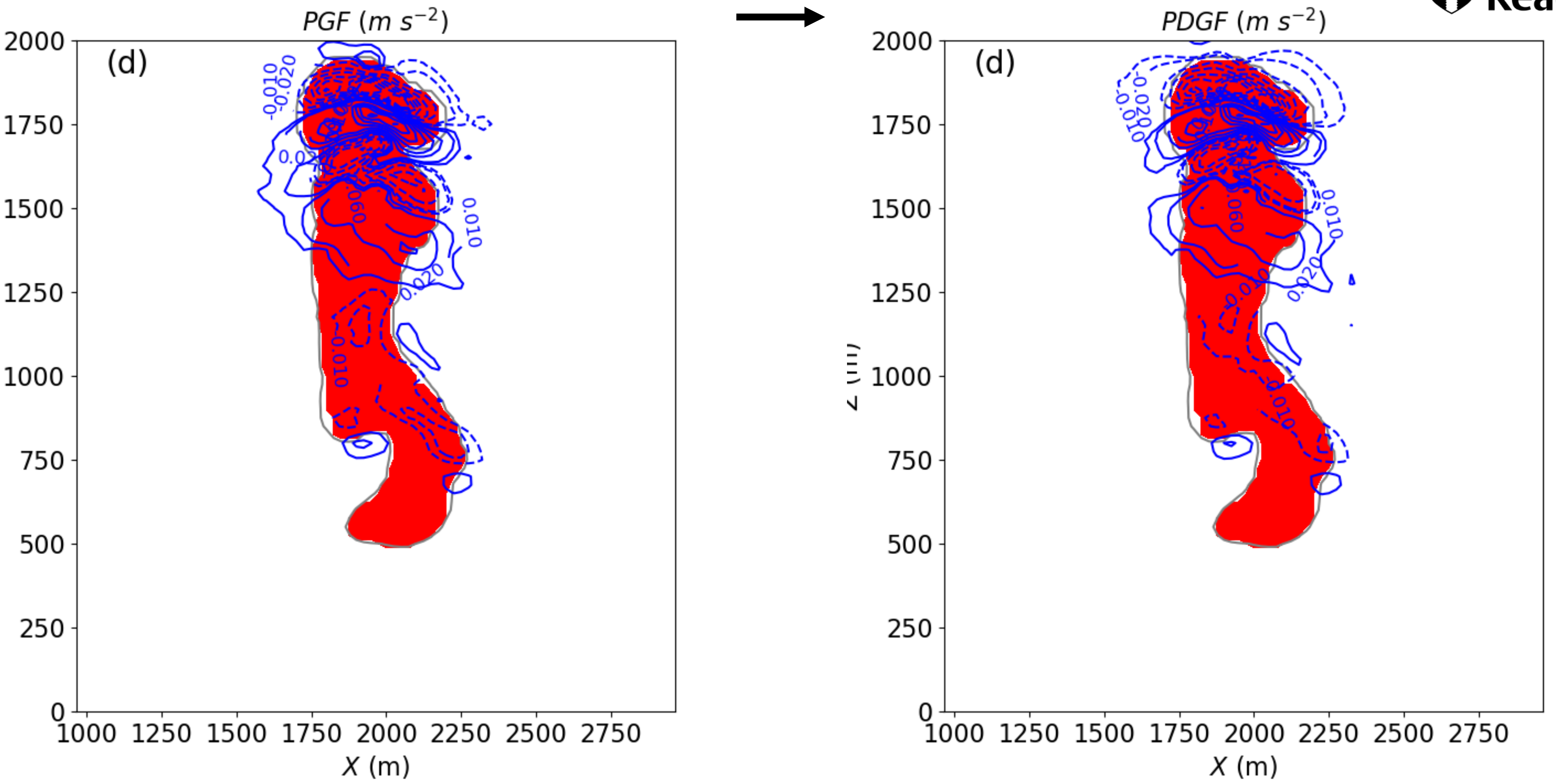
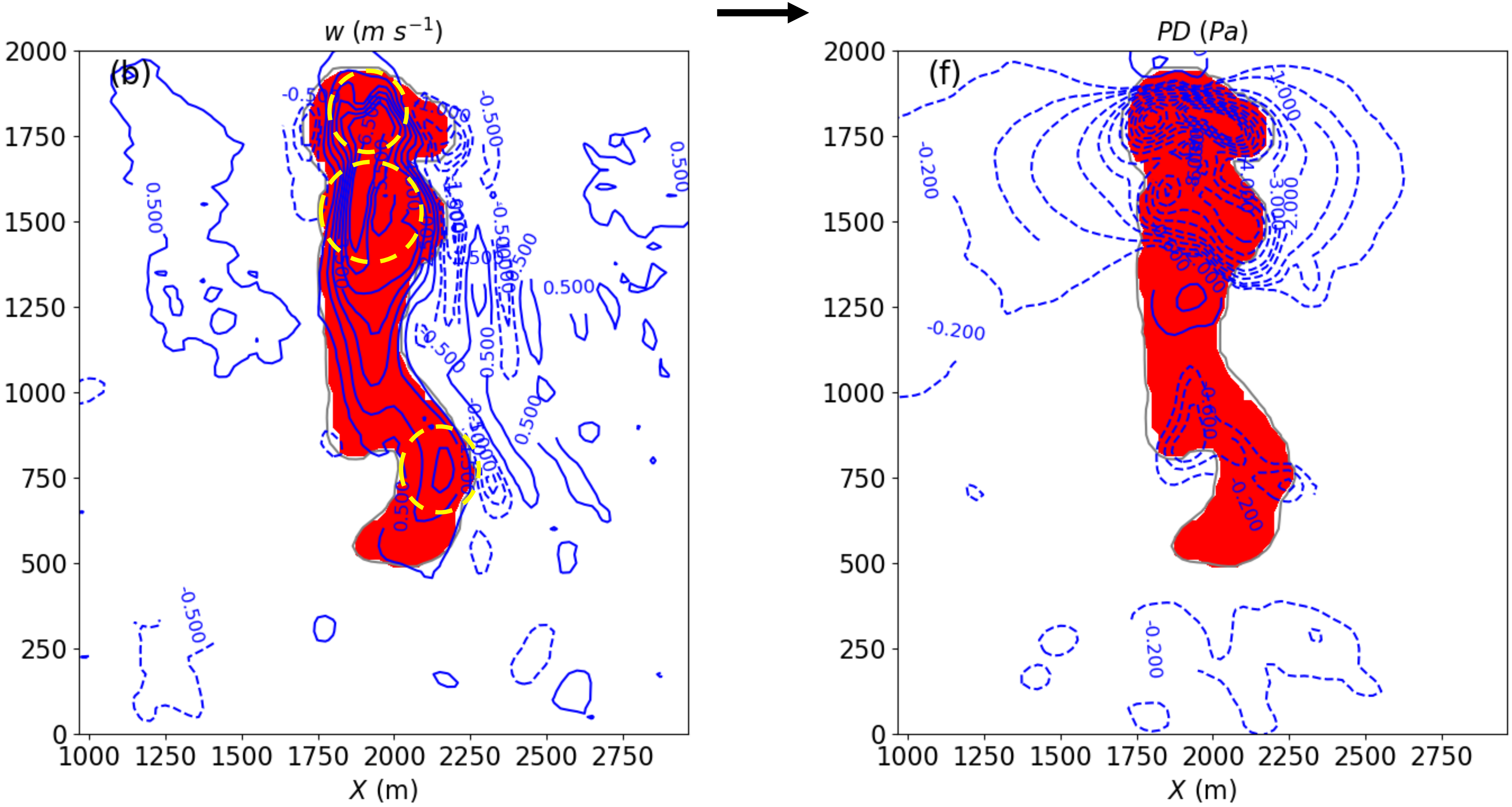


Physical interpretation



Multiple couplets of pressure perturbation in the vertical results in the frequent oscillation of pressure gradient force
Increased magnitude of pressure perturbation leads to the increased negative tendency of pressure gradient force.

Physical interpretation



The couplets of pressure perturbations off the central axis is closely related with successive thermals within the cloud
Downdrafts on the downshear side further complicated the distribution of pressure perturbation

How can we explain the distribution of pressure perturbation using the circulations of thermals?

Decomposition of dynamical pressure perturbation

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The dynamical pressure perturbation can be further decomposed into two components: deformation and rotation

$$\frac{1}{\rho}\nabla^2 p_D = -e_{ij}^2 + \frac{1}{2}|\boldsymbol{\omega}|^2, \tag{5}$$

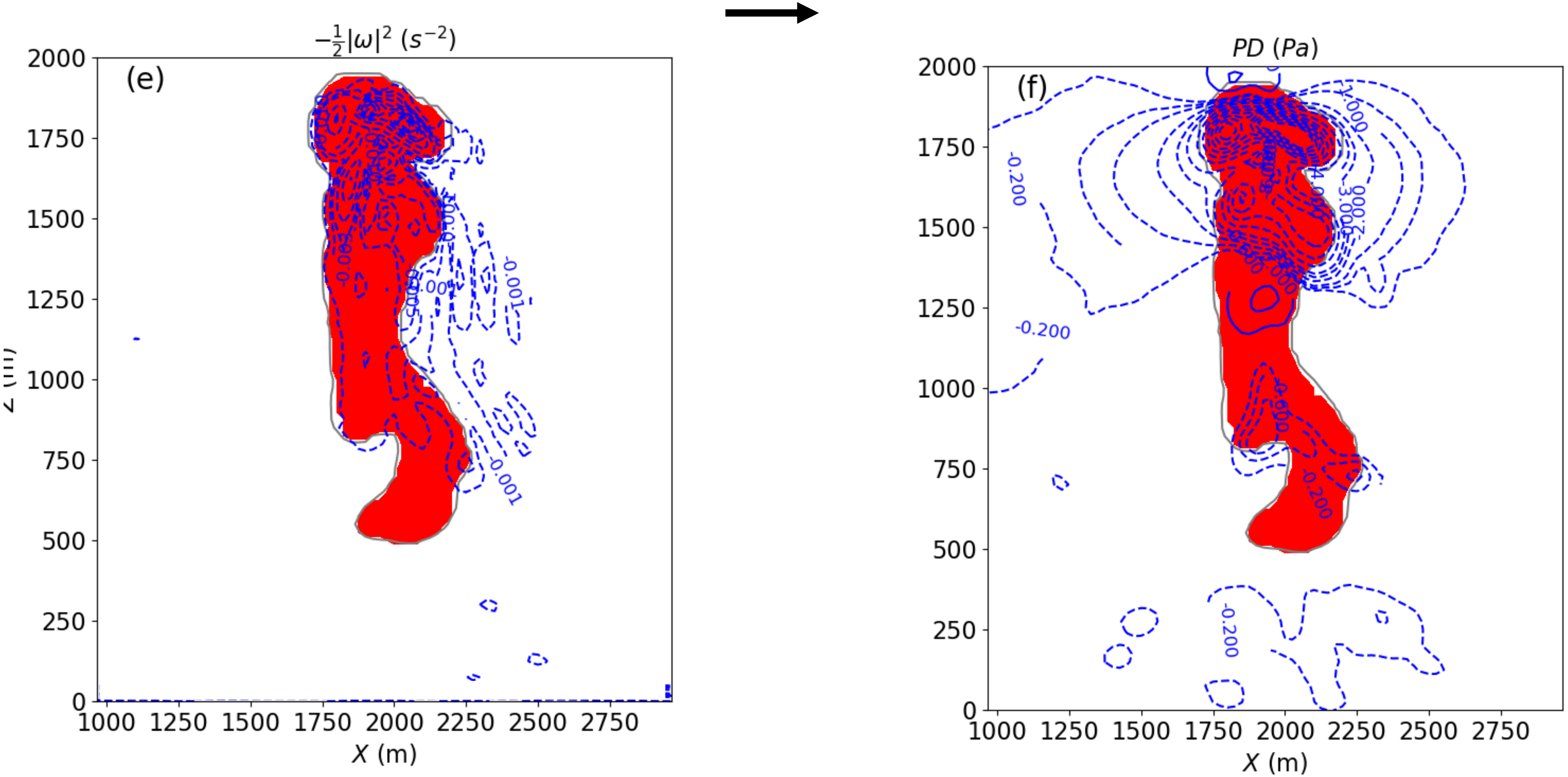
where e_{ij} is the deformation tensor and $\boldsymbol{\omega}$ is the vorticity, such that

$$e_{ij}^2 = \frac{1}{4}\sum_{ij}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2, \tag{6}$$

$$\boldsymbol{\omega} = \nabla \times \mathbf{u}, \tag{7}$$

where $u_1 = u,\ u_2 = v,\ u_3 = w,\ x_1 = x,\ x_2 = y$, and $x_3 = z$.

Physical interpretation



$$\frac{d\omega}{dt} = \underbrace{(\omega + f k)\cdot\nabla u}_{\text{tilting/stretching}} + \underbrace{\nabla\times Bk}_{\text{baroclinic generation}},$$

$$w\frac{d\omega}{dz} = \underbrace{\nabla\times Bk}_{\text{baroclinic generation}},$$

Summary

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Continuous baroclinic generation of horizontal vorticity associated with rising thermals leads to amplified local minimum of dynamical pressure perturbation.

Within individual cloud, the dynamical pressure drag dominates the total pressure drag off the central axis of updraft. Successive rising thermals within the cloud results in the frequent oscillations. The downdrafts outside the cloud further complicated the picture of oscillation.

The pressure drag of cloud ensemble shares similar features with dominant contribution from dynamical pressure drag and increased magnitude with height, but much smoother behaviour.

For parameterization, the thermodynamic pressure drag can be incorporated into a reduced buoyancy source, but the dynamic pressure drag cannot.