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Evaluation of bulk mass flux approximation using large eddy simulations

Jian-Feng Gu[1], Robert Plant[1], Chris Holloway[1], Todd Jones[1], Alison Stirling[2], Peter Clark[1] and Steven Woolnough[1]

1. University of Reading

2. Met Office

Convection Parametrization: progress and challenges

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Motivation

- Previous evaluations (Siebesma and Cuijpers 1995, Guichard 1997, Yano 2004) found the bulk mass flux approximation underestimated the total vertical flux by up to 30-50%. These studies used relatively coarse resolution, which does not resolve fine structures (for example, cloud shell) in shallow and deep cumulus clouds. These fine structures are found to be important for vertical fluxes (Heus and Jonker 2008, Glenn and Krueger 2013, Brient et al. 2019).

- The neglected sub-plume variability is parameterized with simple assumptions, such as a down-gradient assumption (Lappen and Randall 2001) or rescaled based on the shape of mass flux. These assumptions need to be examined carefully.

- **Questions:**
- 1. Do the fine structures of clouds matter in the bulk mass-flux approximation?
- 2. What are the components of sub-plume variability and what features do they have?
- 3. What are the key components of cloud that needs to be considered in the mass flux approach in order to get the right vertical fluxes?

Large eddy simulations

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- **BOMEX**

Met Office-NERC Cloud (MONC) model: 13 km × 13 km × 3 km @ 25 m resolution (both horizontal and vertical)

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

6 hour simulation (10 minutes output frequency), last hour simulation (equilibrium state) is taken for analysis

- **RCE**

Met Office-NERC Cloud (MONC) model: 132 km × 132 km × 40 km @ 200 m resolution, 99 vertical levels

Prescribed radiative cooling (1.5 K/day below 12 km), SST=300K, U=-5m/s, 3D Smagorinsky turbulence scheme, CASIM microphysics

54 days simulation (6 hours output frequency), last five days simulation (equilibrium) is taken for analysis

Decomposition of vertical fluxes

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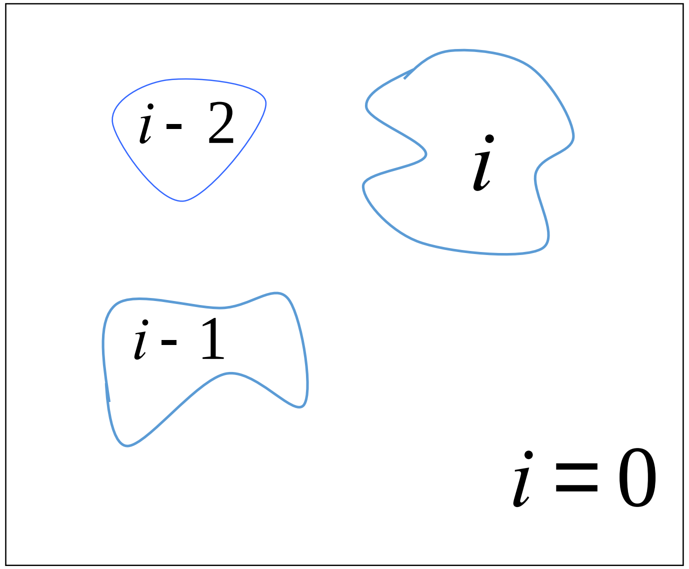
- The whole domain is decomposed into cloud objects (*i*>0) and environment (*i*=0);
- Variable within the object: ϕ_i
- Average over the object: $\overline{\phi}_i$
- Perturbation with respect to the object average: $\phi'_i = \phi_i - \overline{\phi}_i$
- Domain averaged mean: $<\phi> = \sum_i a_i \overline{\phi}_i$
- Perturbation with respect to the domain average: $\phi^*_i = \phi_i - <\phi>$
- Difference between the object average and the domain average: $\overline{\phi}^*_i = \overline{\phi}_i - <\phi>$
- Total turbulent flux:

$$
\begin{aligned}
&<w^*\phi^*> \\
&= <w\phi> - <w><\phi> \\
&= \sum_i a_i(\overline{w^*_i}\,\overline{\phi^*_i} + \overline{w'_i\phi'_i})
\end{aligned}
$$

Massflux contribution **Intra-cloud and environment variability**



Decomposition of vertical fluxes

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- **Updraft-environment decomposition:**

  Define the average over all clouds objects as: $\overline{\phi^p} = \frac{\sum_{i>0} a_i \overline{\phi_i}}{\sum_{i>0} a_i}$ $\quad \overline{w^p} = \frac{\sum_{i>0} a_i \overline{w_i}}{\sum_{i>0} a_i}$

  The total vertical flux could be rearranged as:

$$
\begin{aligned}
&< w^* \phi^* > \\
&= \overbrace{(1-a_0)(\overline{w^p} - <w>)(\overline{\phi^p} - <\phi>) + a_0(\overline{w_0} - <w>)(\overline{\phi_0} - <\phi>)}^{(4.1)} \\
&+ \overbrace{\sum_{i>0} a_i(\overline{w_i} - \overline{w^p})(\overline{\phi_i} - \overline{\phi^p})}^{(4.2)} \\
&+ \overbrace{\sum_{i>0} \underbrace{a_i \overline{w_i' \phi_i'}}_{(4.3a)} + \underbrace{a_0 \overline{w_0' \phi_0'}}_{(4.3b)}}^{(4.3)}
\end{aligned}
$$

Bulk mass flux approximation:

Inter-object variability

Intra-object variability

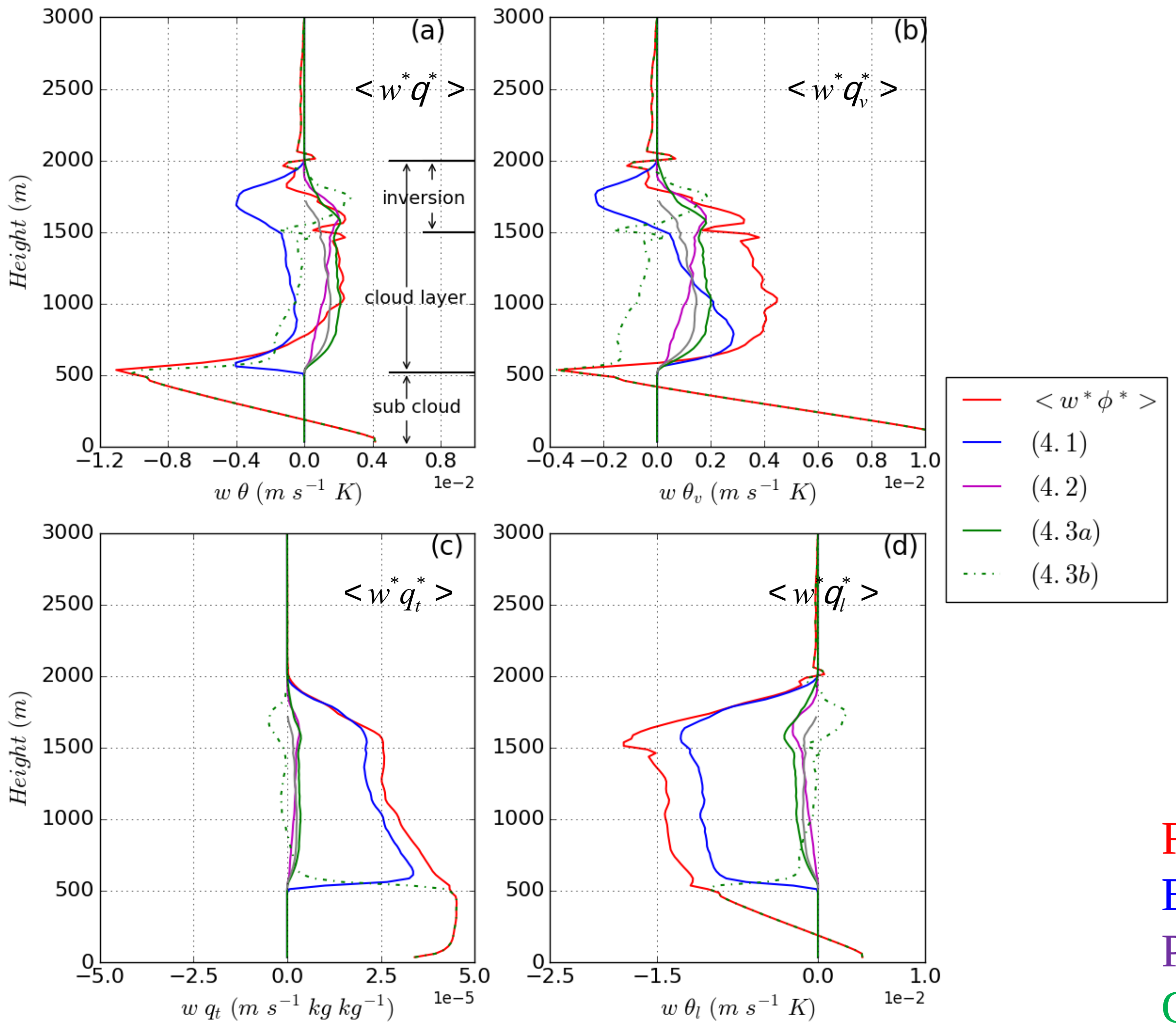
(4.1) **Bulk mass flux approximation:** $(4.1) = a_0(1 - a_0)(\overline{w^p} - \overline{w_0})(\overline{\phi^p} - \overline{\phi_0})$

(4.2) **Inter-object variability:** Differences among clouds objects

(4.3) **Intra-object variability:** Fluctuations within the cloud objects (4.3a) and the environment (4.3b)

Inter- and intra-object variability

BOMEX



Cloud objects are identified with q_l > 1e-5 kg kg^{-1}

The bulk mass flux approximation can capture 80% vertical fluxes of q_t and θ_l, but loses most the vertical fluxes of θ and θ_v because of neglecting the inter- and intra-cloud variability.

This indicates that the distributions of temperature and buoyancy are different from that of cloud liquid water.

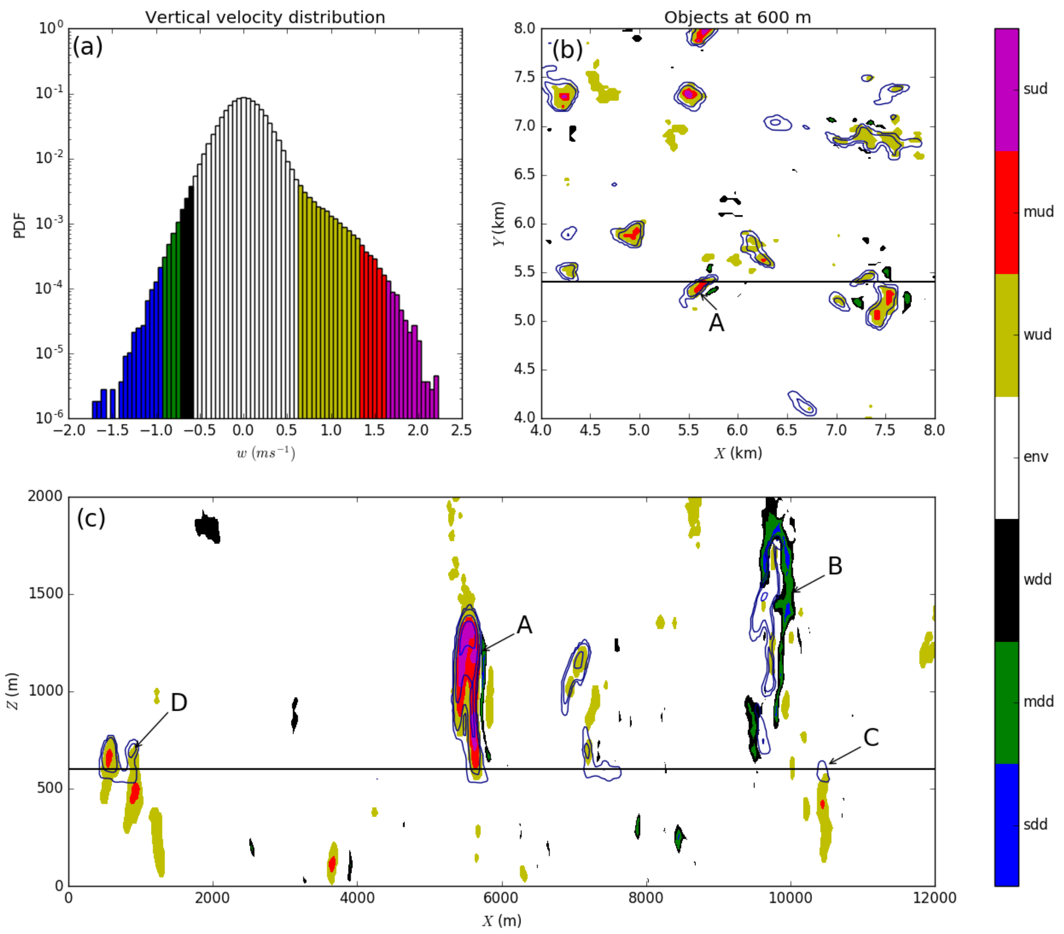
Inter- and intra-cloud variability of θ and θ_v are comparable to the bulk mass flux approximation, but they do not show similarity with it.

Using cloud core for decomposition improves the representation of θ and θ_v, but gives degraded moisture fluxes.

Red line: total vertical flux
Blue line: bulk mass flux approx
Purple line: inter-object variability
Green line: intra-object variability
Green dash line: environmental variability

An alternative decomposition

BOMEX



strong-medium-weak drafts
strong: top 0.1%
medium: top 0.5-0.1%
weak: top 5-0.5%

Decompose the flow based on the distribution of vertical velocities at each vertical level.

Most of the identified updrafts are collocated with clouds.

Advantage:

Capture the complete structure of clouds, including shell structures

Capture developing dry updrafts

Capture decaying clouds combined with cloud liquid water

Could be used to study cloud triggering by tracking thermals that emerge from sub-cloud layer and finally develop into clouds

Updraft-environment decomposition

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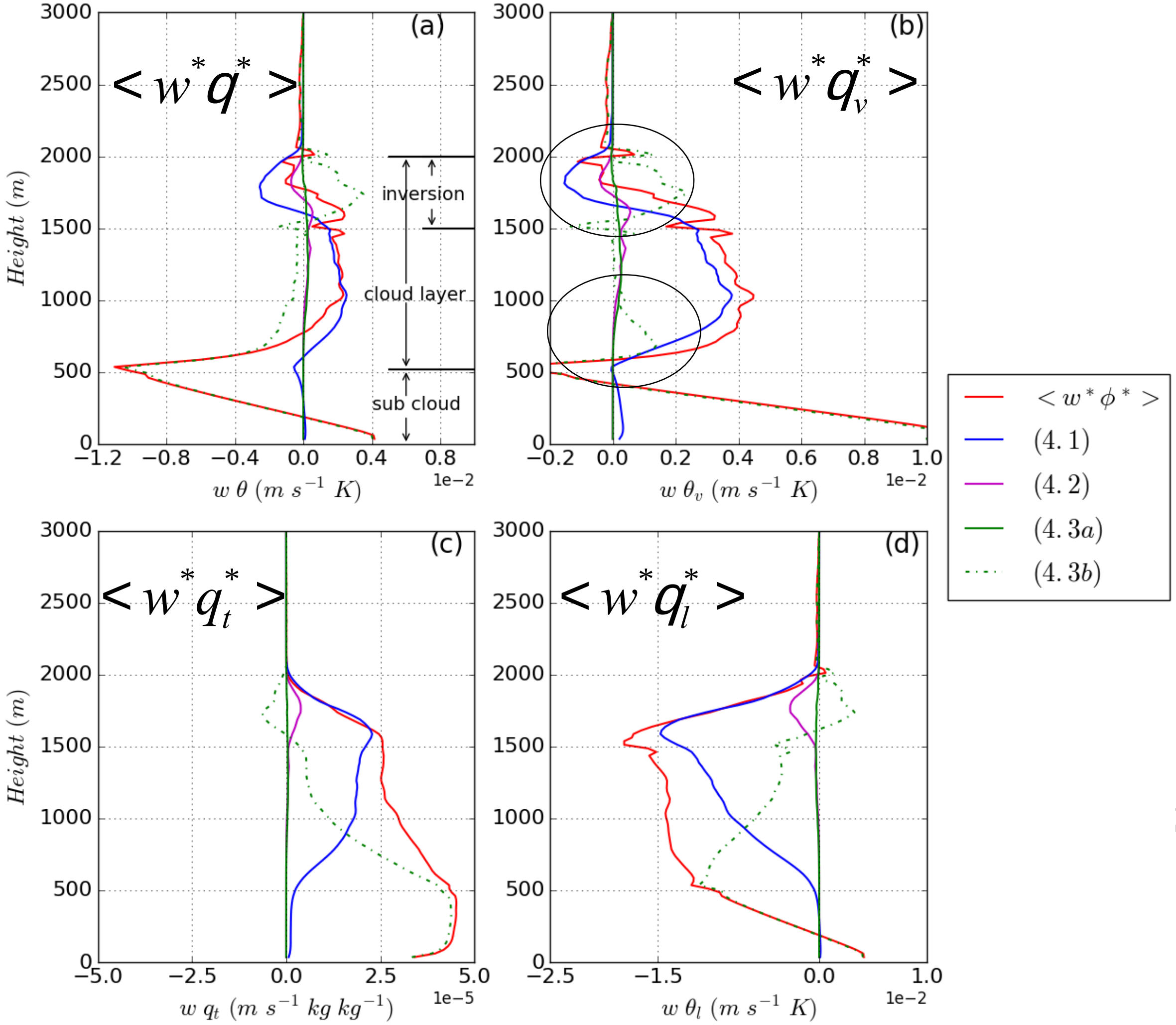

BOMEX

Strong updraft: top 0.5%

Red line: total vertical flux

Blue line: bulk mass flux approx

Purple line: inter-object variability

Green line: intra-object variability

Green dash line: environmental variability

Bulk mass flux approximation lost information near cloud top and at lower part of cloud layer

Decomposition of vertical fluxes

- **Updraft-downdraft-environment decomposition:**

Define the average over updraft and downdraft as: $\overline{f}^{ud} = \dfrac{\sum_{i=ud} a_i \overline{f}_i}{\sum_{i=ud} a_i}$ $\quad \overline{w}^{ud} = \dfrac{\sum_{i=ud} a_i \overline{w}_i}{\sum_{i=ud} a_i}$

The total vertical flux could be rearranged as:

$$< w^* \phi^* >$$

$$= \overbrace{a_{ud}(\overline{w}^{ud} - < w >)(\overline{\phi}^{ud} - < \phi >) + a_{dd}(\overline{w}^{dd} - < w >)(\overline{\phi}^{dd} - < \phi >) + a_0(\overline{w}_0 - < w >)(\overline{\phi}_0 - < \phi >)}^{(6.1)}$$ Bulk mass flux approximation

$$+ \overbrace{\sum_{i=ud} a_i(\overline{w}_i - \overline{w}^{ud})(\overline{\phi}_i - \overline{\phi}^{ud}) + \sum_{i=dd} a_i(\overline{w}_i - \overline{w}^{dd})(\overline{\phi}_i - \overline{\phi}^{dd})}^{(6.2)}$$ Inter-object variability

$$+ \overbrace{\underbrace{\sum_{i=ud} a_i \overline{w_i' \phi_i'} + \sum_{i=dd} a_i \overline{w_i' \phi_i'}}_{(6.3b)} + \underbrace{a_0 \overline{w_0' \phi_0'}}_{(6.3b)}}^{(6.3)}$$ Intra-object variability

(6.1) **Bulk mass flux approximation** Is this the real bulk mass flux approximation?

(6.2) **Inter-object variability:** Differences among updrafts or downdrafts

(6.3) **Intra-object variability:** Fluctuations within the updrafts, downdrafts (6.3a) and the environment (6.3b)

Updraft-downdraft-environment decomposition

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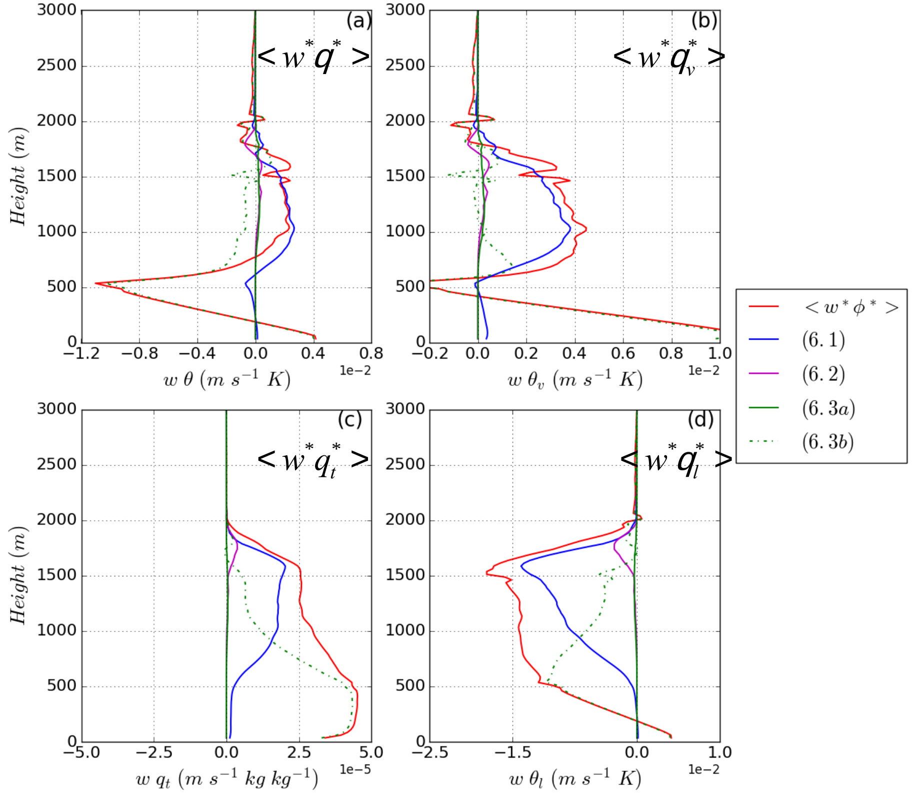

BOMEX

Red line: total vertical flux

Blue line: bulk mass flux approx

Purple line: inter-object variability

Green line: intra-object variability

Green dash line: environmental variability

Improves significantly near cloud top due to the inclusion of downdrafts.

Intra-object variability in the environment still dominates in the lower part of the cloud layer, indicating the contribution from less extreme drafts.

The total vertical fluxes are contributed by different components of the flow: the updraft (strong and weak), the downdraft, the overturning structure near cloud top.

A multi-draft decomposition may help to improve the vertical flux representation.

Multi-draft representation

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- **Multi-draft decomposition:**

The complexity of parameterizing the inter-object and intra-object variability is that physically coherent objects need to be considered explicitly. This complexity could be reduced by collecting similar objects together as abstract drafts.

For example, we can categorize the updrafts or downdrafts into two types: **strong** and **weak**

$$<w^*\phi^*>$$

$$= \overbrace{\sum_{j=sud,wud} a_j(\overline{w_j}-<w>)(\overline{\phi_j}-<\phi>)+\sum_{j=sdd,wdd} a_j(\overline{w_j}-<w>)(\overline{\phi_j}-<\phi>)+a_0(\overline{w_0}-<w>)(\overline{\phi_0}-<\phi>)}^{(7.1)}$$

$$+\overbrace{\sum_{j=sud,wud} a_j\overline{w_j'\phi_j'}+\sum_{i=sdd,wdd} a_j\overline{w_j'\phi_j'}+a_0\overline{w_0'\phi_0'}}^{(7.2)}$$

(7.1) **Mass flux term**

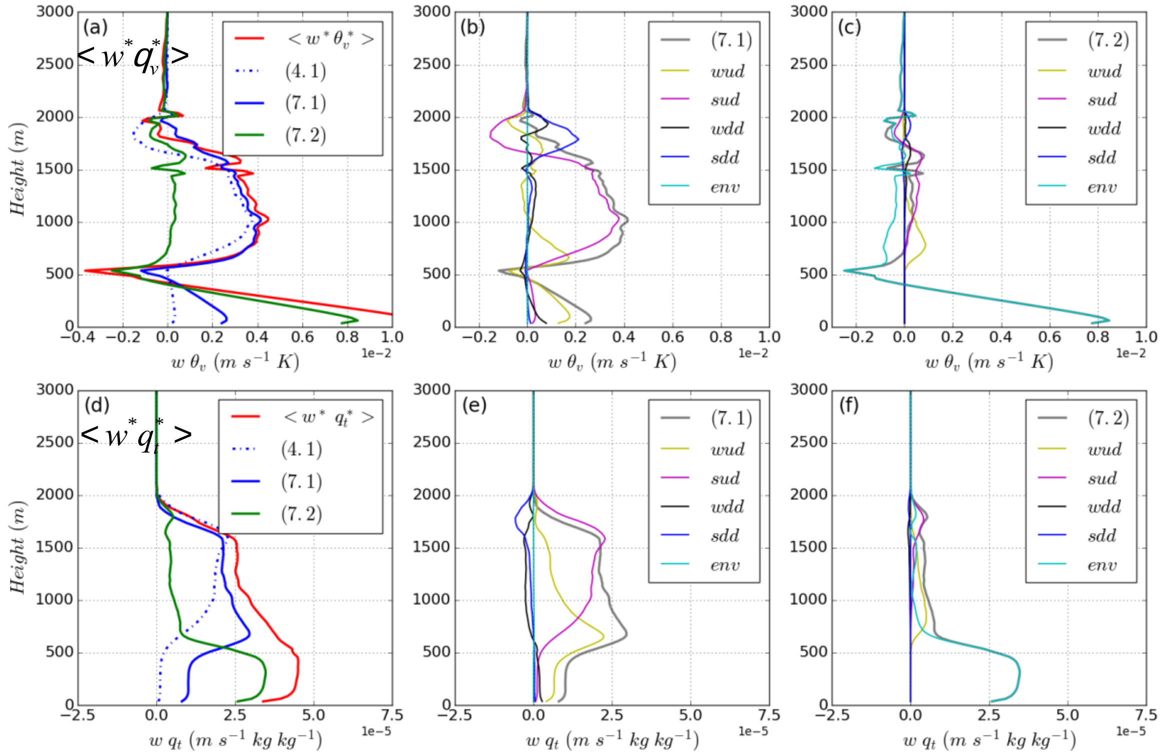
(7.2) **Intra-draft variability:** Fluctuations within the same draft

For simplicity, we will start from a two-draft (strong and weak) representation.

Two-draft representation (BOMEX)

strong drafts: top 0.5%

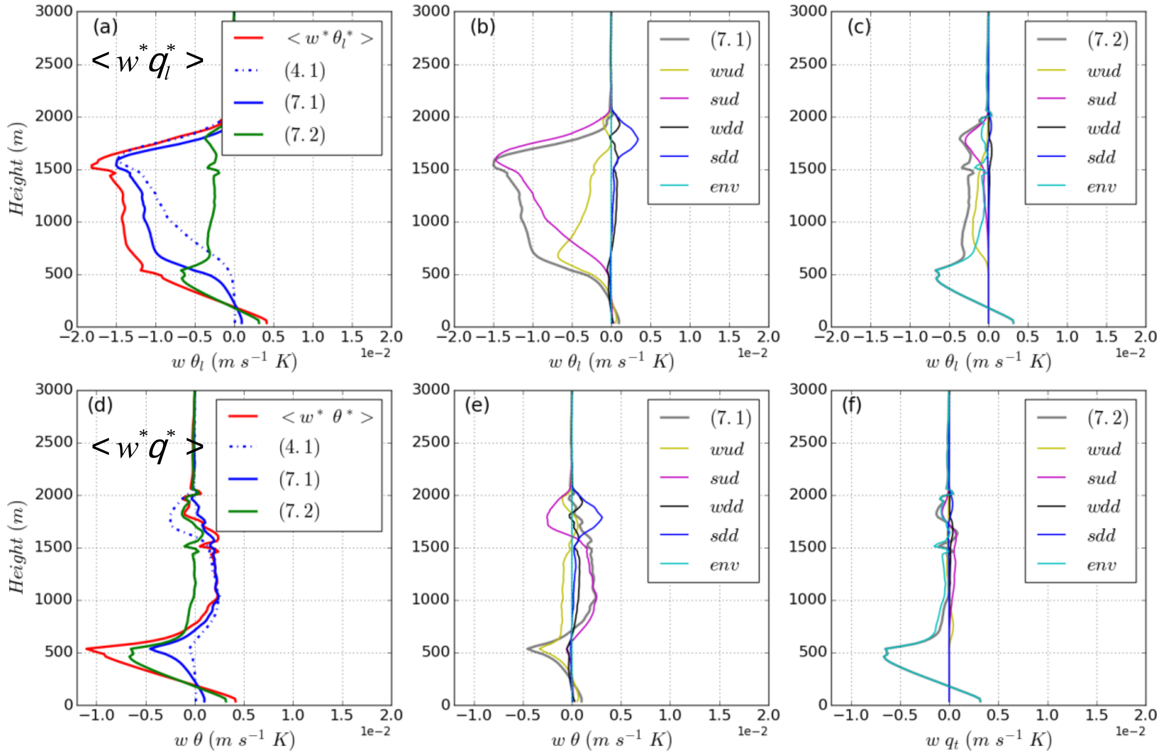
weak drafts: top 5-0.5%



Total flux
Two-draft mass flux contribution
Intra-draft variability
Bulk mass flux approx (dash)

Mass flux contribution
wud
sud
wdd
sdd
env

Intra-draft variability
wud
sud
wdd
sdd
env



Total flux
Two-draft mass flux contribution
Intra-draft variability
Bulk mass flux approx (dash)

Mass flux contribution
wud
sud
wdd
sdd
env

Intra-draft variability
wud
sud
wdd
sdd
env

All fluxes are improved both in magnitude and shapes due to the inclusion of overturning structure near cloud top, weak updraft

Weak updraft: buoyancy flux are zeros above 1 km, indicating transition zone around cloud core. It contributes non-negligible part of moisture transport

Core-cloak conceptual model of convection

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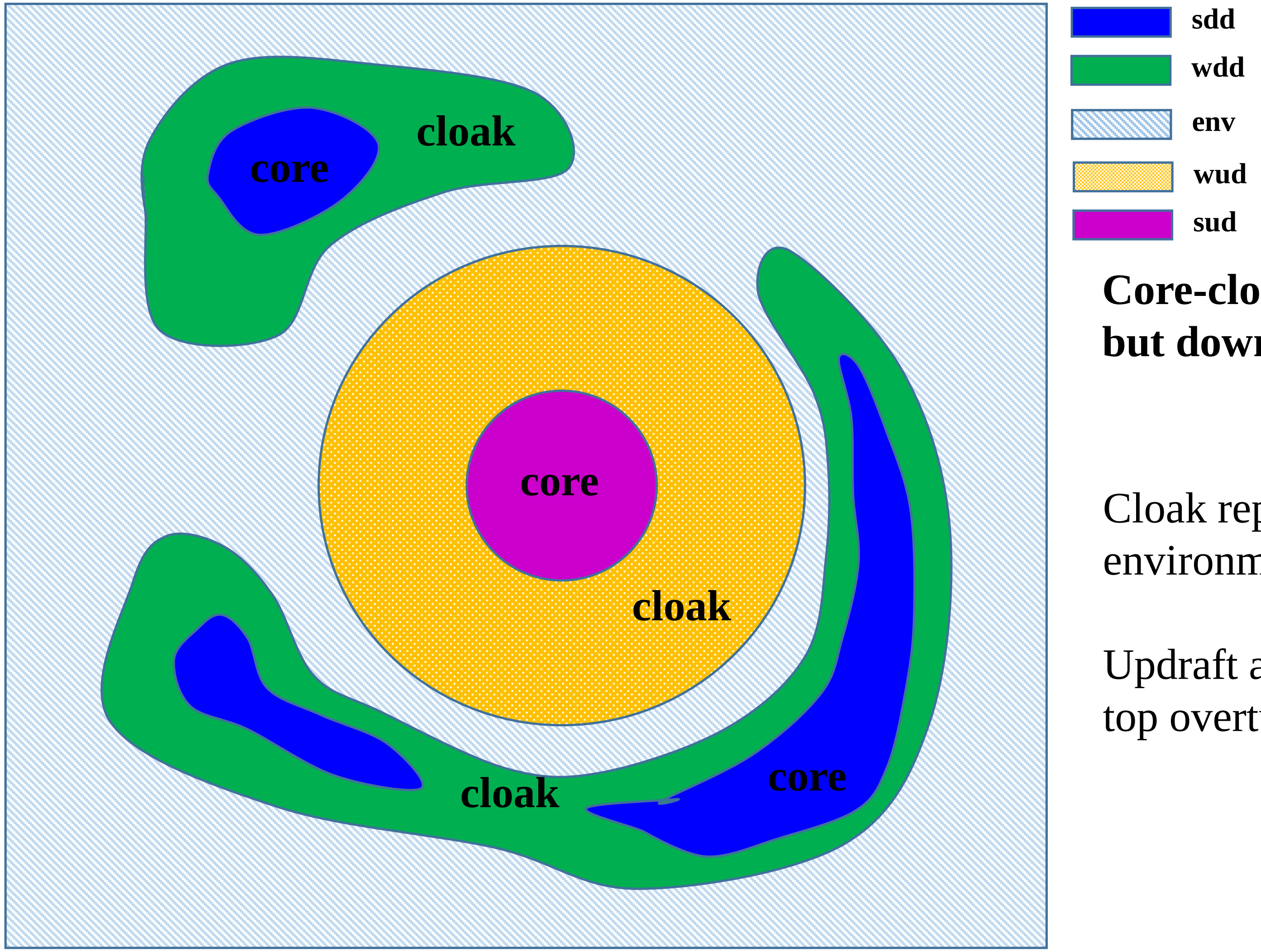


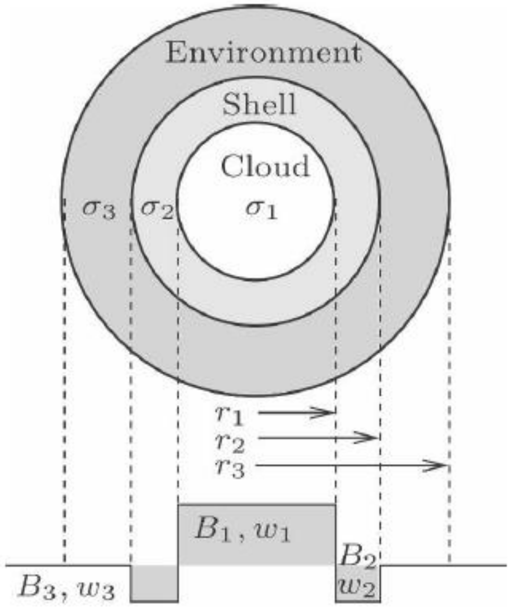
Core-cloak representation for both updraft and downdraft, but downdraft could be simplified as one draft

Cloak represents the transition zone between the core and environment

Updraft and downdraft could be coupled through the cloud top overturning structures.

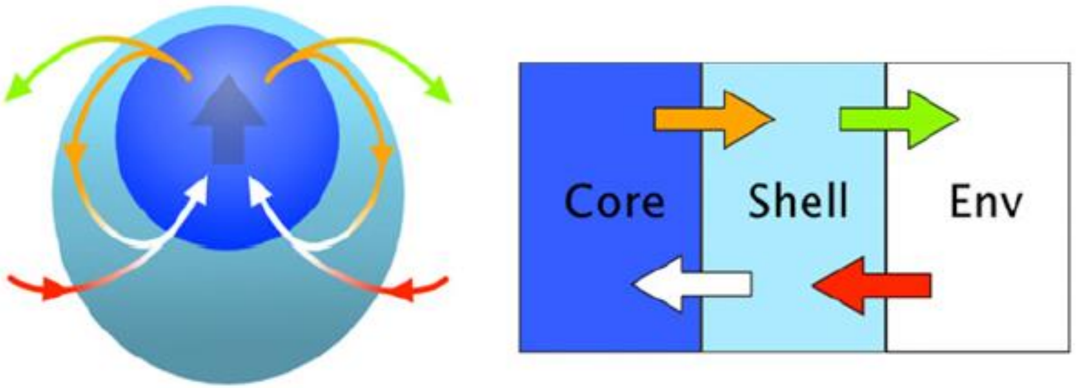
Comparison with other conceptual model

Three layer model (Heus and Jonker 2008)



Negative buoyant downdraft wrapping around the cloud is considered explicitly

Buffered Lagrangian thermal (Hannah 2017)



Shell in this buffered model represents the thermodynamic buffer, where detrained core air and entrained environmental air are mixed.

The core-cloak model has a core (strong updraft) and transition zone (weak updraft) within the cloud, the subsiding shell structure around the cloud and also overturning structure near cloud top.

These components are needed to be included to improve the parameterization of both heat and water vertical fluxes. It can be applied for both shallow and deep cumulus clouds.

Summary

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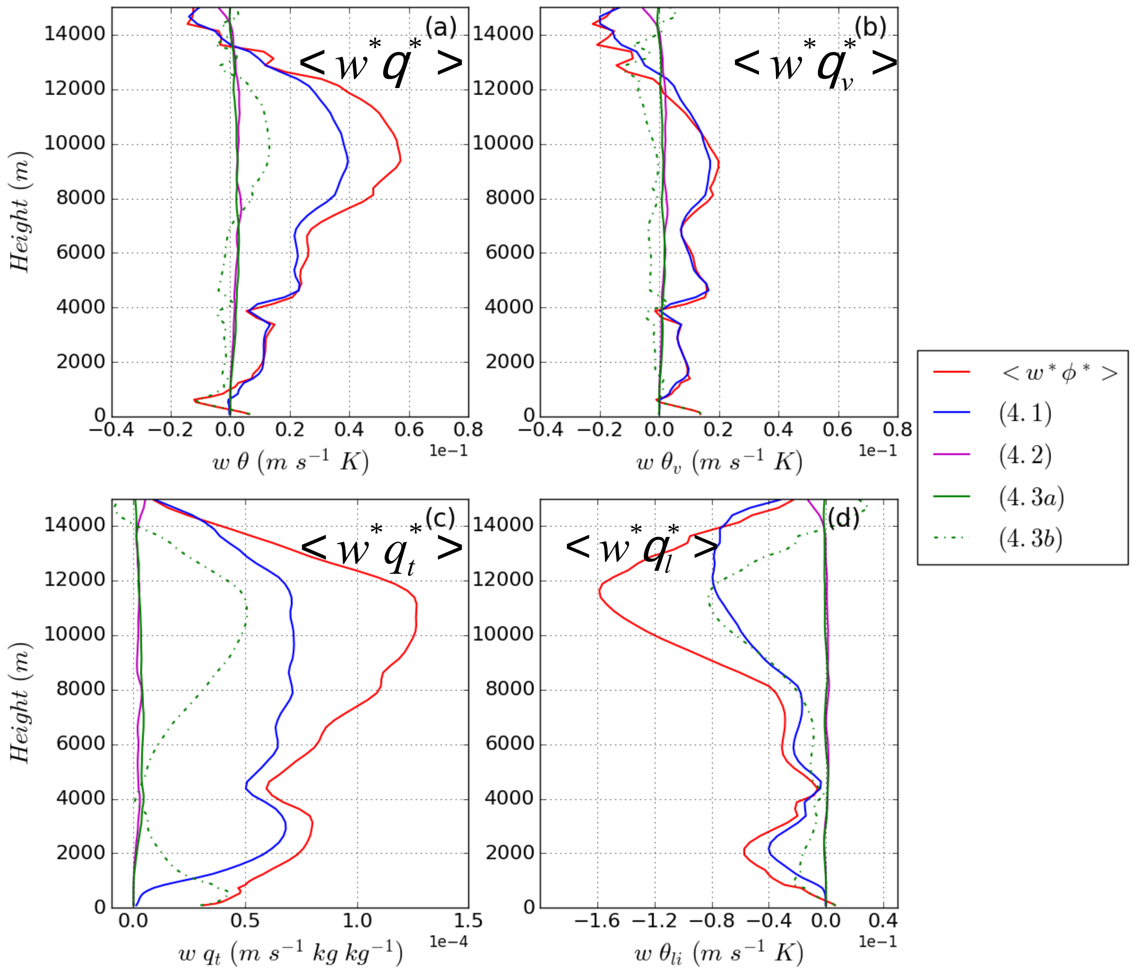
- Bulk mass flux approximation underestimates the total vertical fluxes by neglecting the inter-object and intra-object variability. These two components do not share similar shapes with bulk mass flux contribution, thus can not be simply parameterized by rescaling, especially in shallow cumulus clouds.

- The sub-plume fluxes is dominated by the intra-object variability within buoyant updrafts and thus could not be simply parameterized through down-gradient assumption.

- The overturning structure at cloud top and the weak drafts around the core are important for the total vertical transport and should be considered.

- The core-cloak conceptual model could well capture the total vertical fluxes, both in magnitudes and vertical distribution for shallow and deep cumulus clouds because it includes the key components of clouds (cloud core, transition zone near cloud edge, subsiding shell around the cloud, overturning structures at cloud top).

Updraft-environment decomposition



Strong updraft: top 0.5%

RCE

Red line: total vertical flux

Blue line: bulk mass flux approx

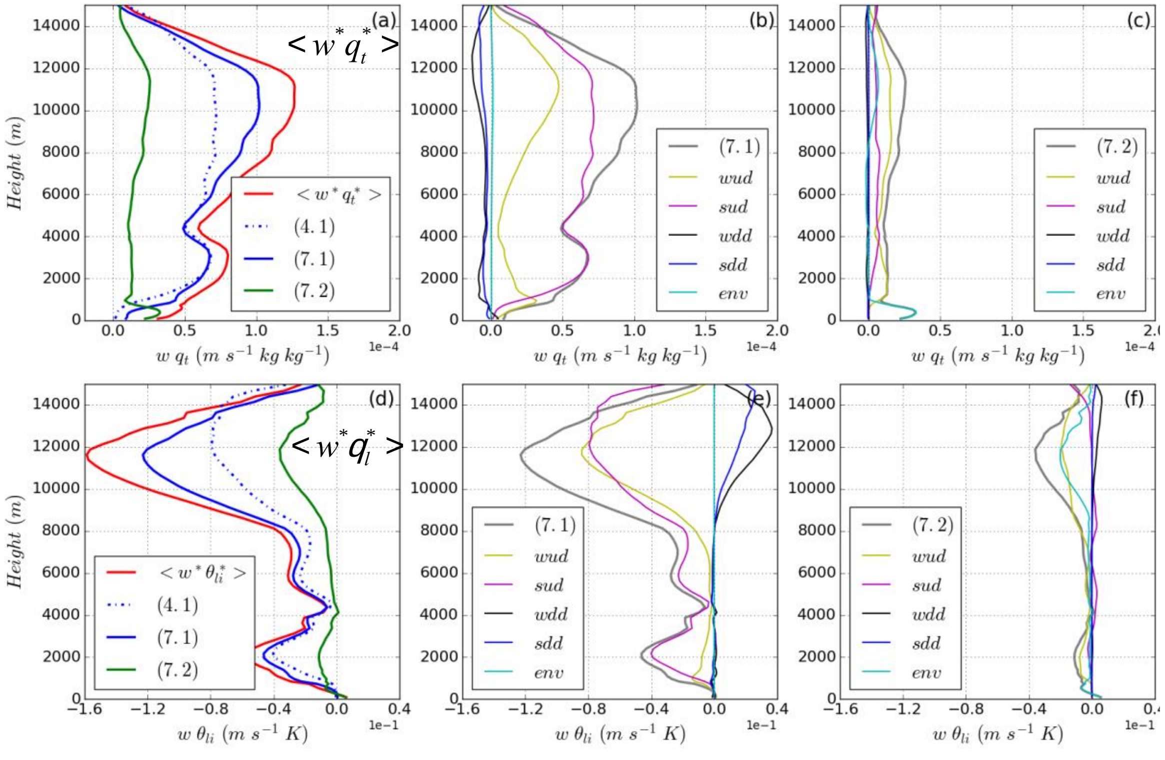
Purple line: inter-object variability

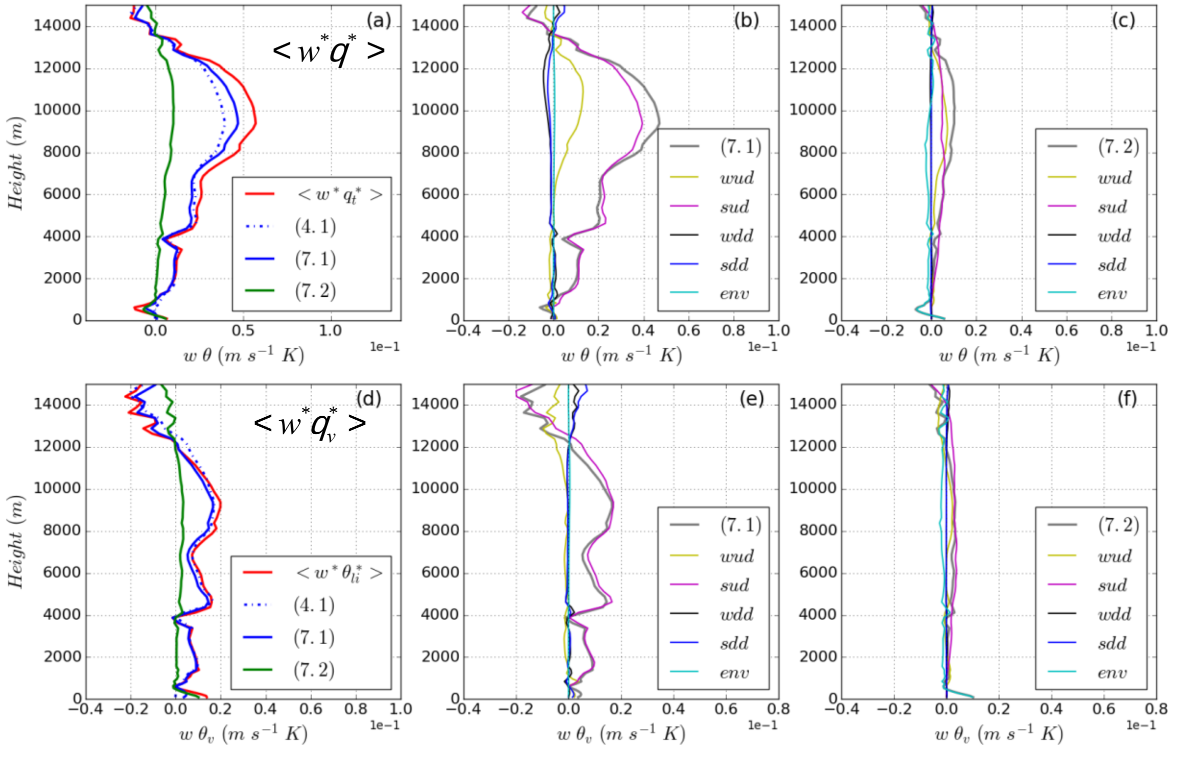
Green line: intra-object variability

Green dash line: environmental variability

Bulk mass flux approximation lost information near cloud top and at lower part of cloud layer

Two-draft representation (RCE)





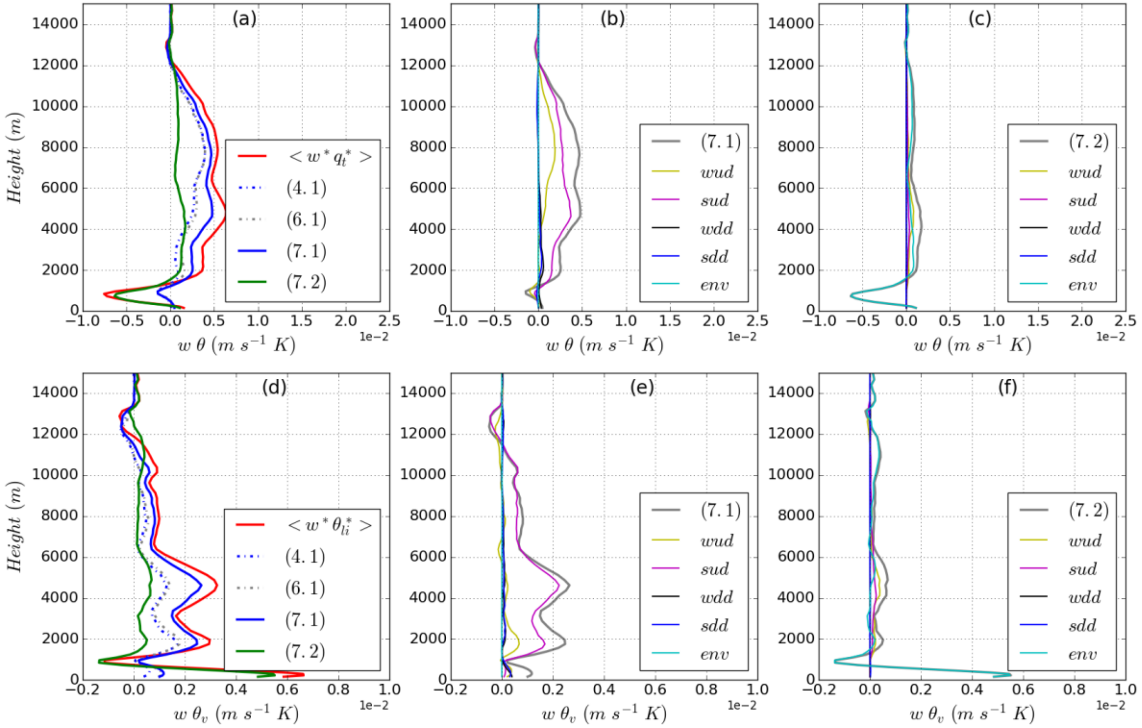
The two-draft representation also gets the right magnitudes and shapes for both heat and moisture fluxes in deep clouds.

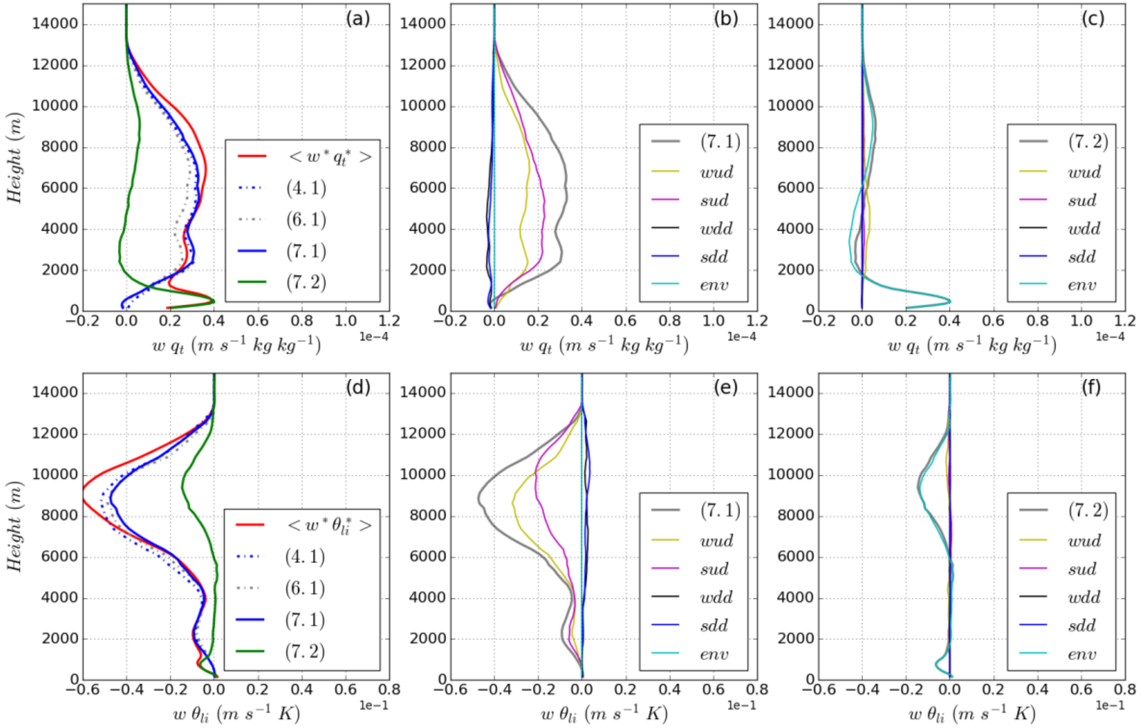
The moisture flux is improved significantly both at low- and high-levels.

The improvement is not obvious for buoyancy flux perhaps because the strong updrafts acquire most of the buoyancy and the horizontal resolution (200 m) is probably still not enough to resolve the cloud boundary in deep clouds.

Organized convection

Can the core-cloak representation well capture the vertical fluxes for system with organized convection?





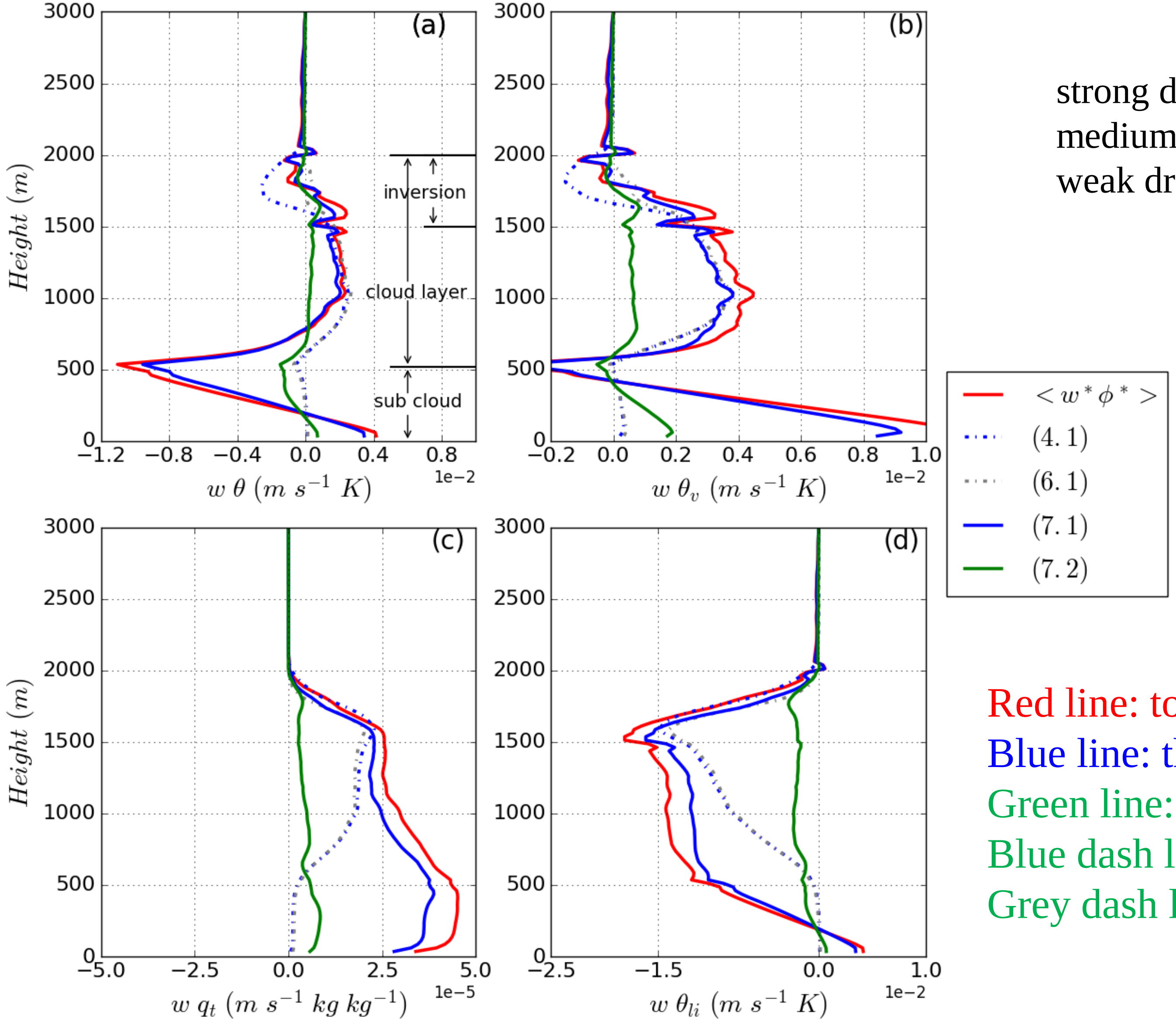
RCEMIP

Met Office Unified Model (UM) model:

Small domain:100 km × 100 km @ 1km resolution, SST = 300 K, interactive radiation

Ends up with self-aggregation.

Three-draft representation

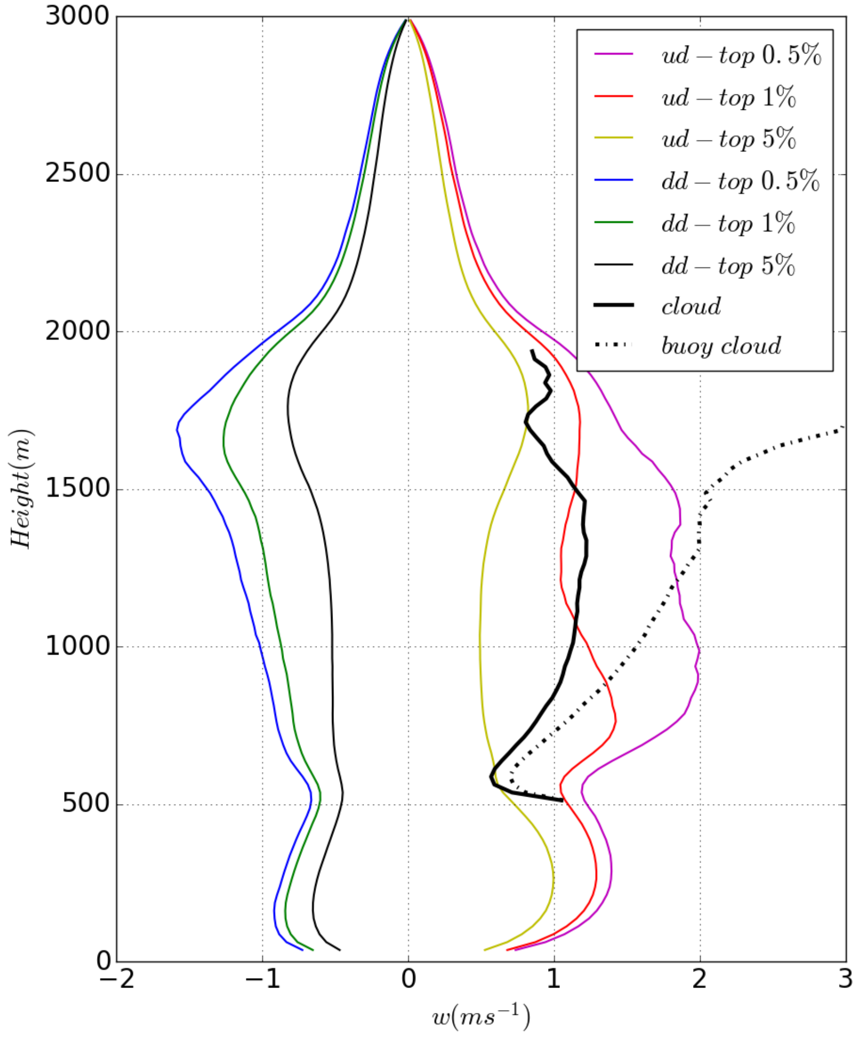


strong drafts: top 0.5%
medium drafts: top 5-0.5%
weak drafts: top 60-5%

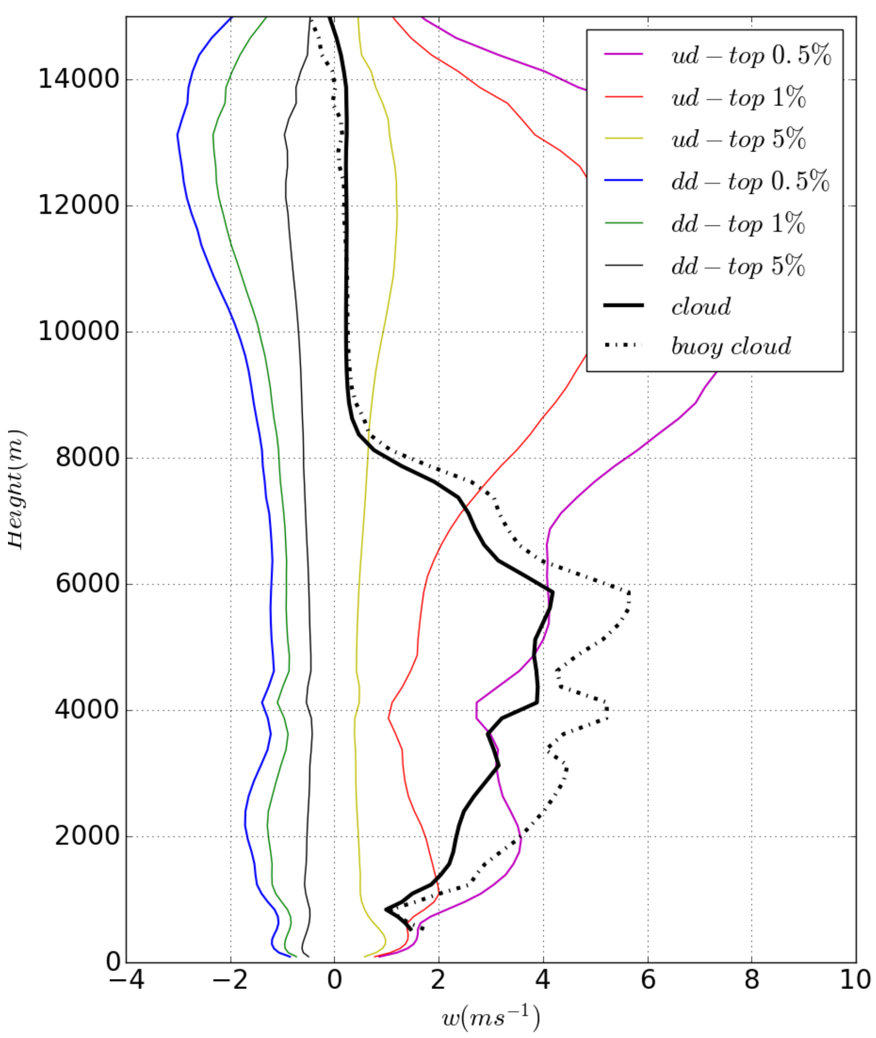
The vertical fluxes within the sub-cloud layer are well captured by the three-draft representation.

Red line: total vertical flux
Blue line: three-draft representation
Green line: intra-draft variability
Blue dash line: updraft-environment representation
Grey dash line: updraft-downdraft-environment representation

Decomposition based on the flow



BOMEX



RCE

Structure for shallow clouds

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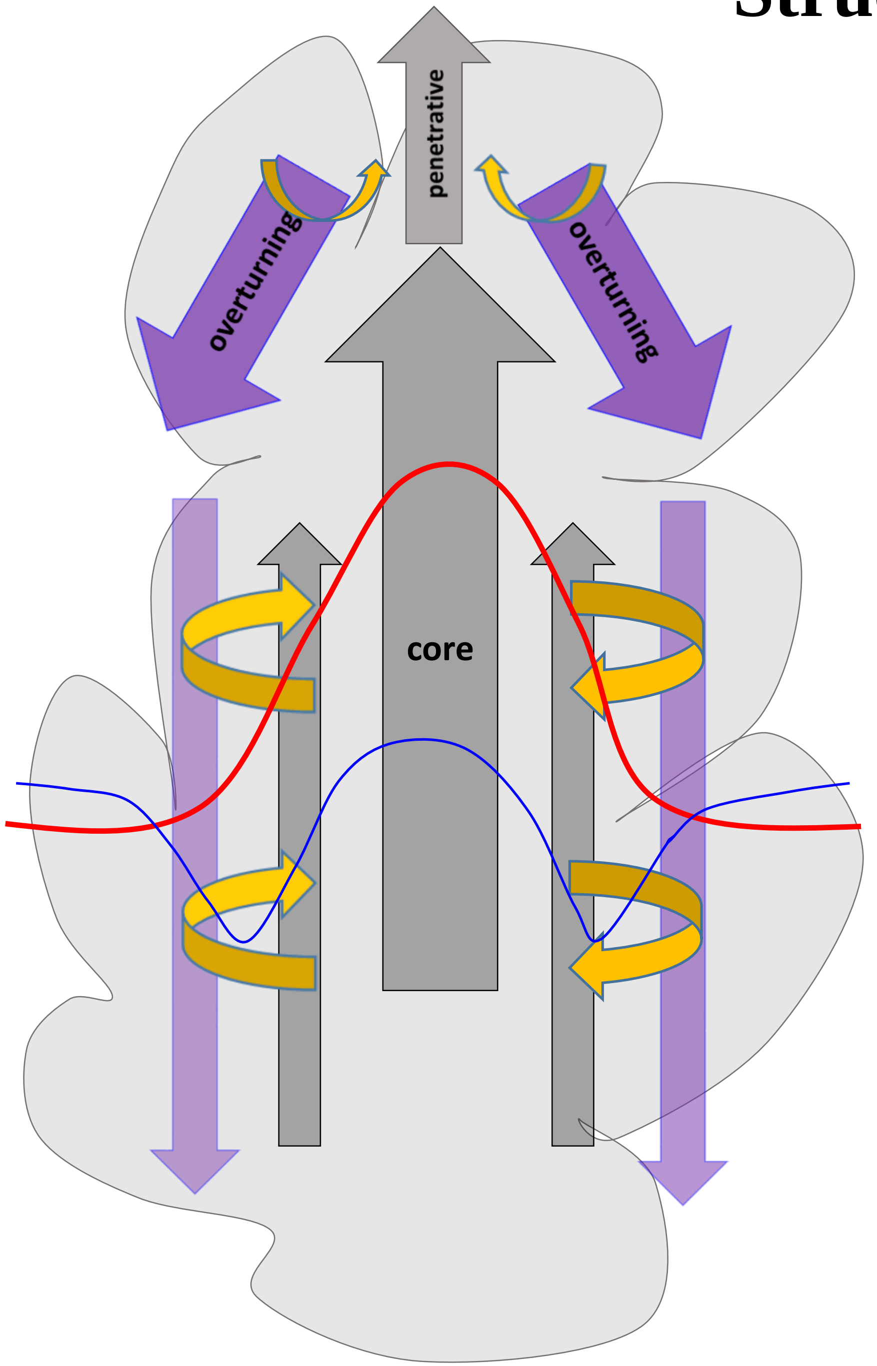

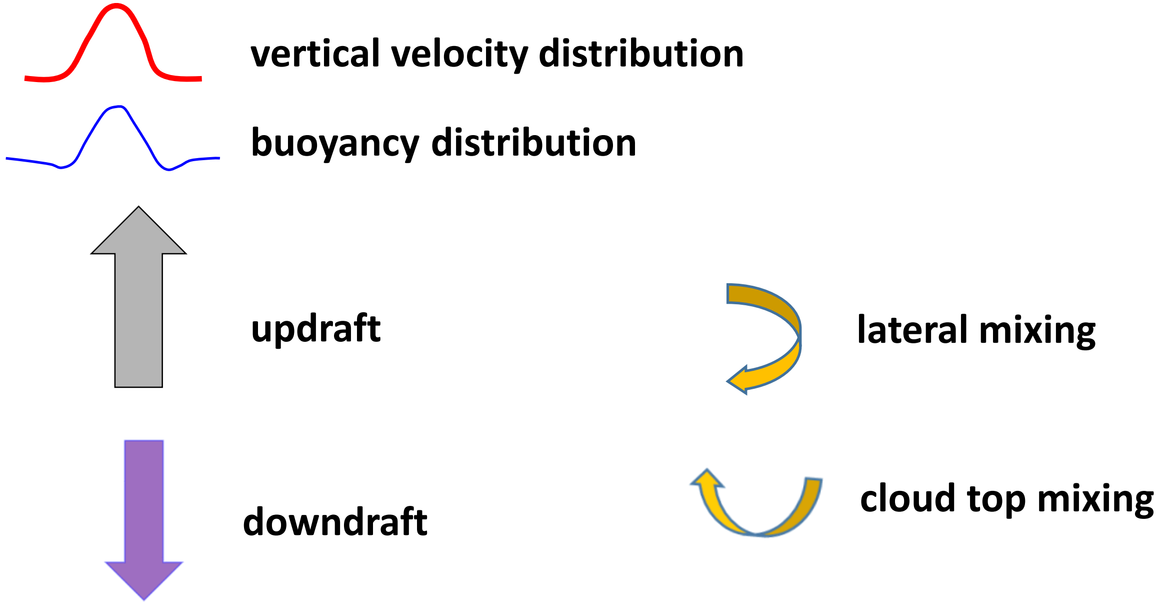

The fine structures of clouds (cloud top overturning, negative subsiding shell, transition zone near cloud boundary and cloud core) are all important for the vertical transport of heat and water.

Spectral representation