Satellite-Based Estimation of Convective and Large-Scale Mass Fluxes: New Diagnostics for Evaluating GCM Cumulus Parameterization

Hiro Masunaga[1] *and* ***Johnny Luo***[2]

[1]*Nagoya University, Nagoya Japan;*
[2]*City University of New York, City College, New York, USA*

GEWEX UTCC PROES meeting, April 29 2016, Paris

Determination of Bulk Properties of Tropical Cloud Clusters from Large-Scale Heat and Moisture Budgets

MICHIO YANAI, STEVEN ESBENSEN AND JAN-HWA CHU

Dept. of Meteorology, University of California, Los Angeles 90024

(Manuscript received 29 December 1972)

Yanai et al. 1973

Interaction of a Cumulus Cloud Ensemble with the Large-Scale Environment, Part I

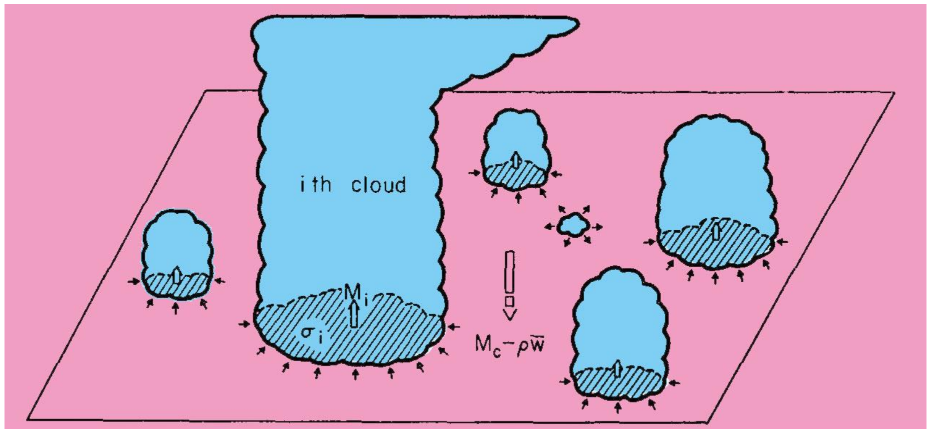
AKIO ARAKAWA AND WAYNE HOWARD SCHUBERT[1]

Dept. of Meteorology, University of California, Los Angeles 90024

(Manuscript received 10 August 1973, in revised form 7 November 1973)

Arakawa and Schubert 1974

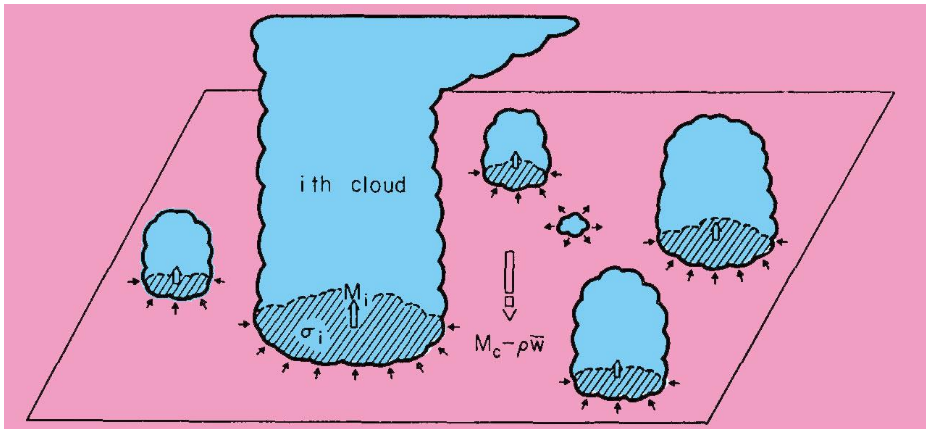
These seminal papers in 1970s defined the framework of GCM cumulus parameterizations that most of us still use today - ***mass flux-based formulation***.



Total large-scale mass flux

Convective mass flux

$$\bar{M} = M_c + \tilde{M},$$



Total large-scale mass flux

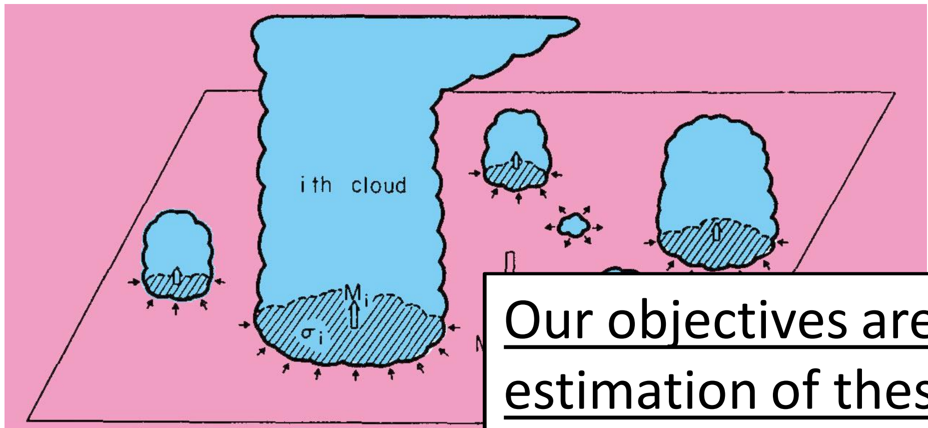
Convective mass flux

$$\bar{M} = M_c + \tilde{M},$$

$$M_c = -\sigma\omega_c$$

Coverage of convective cores

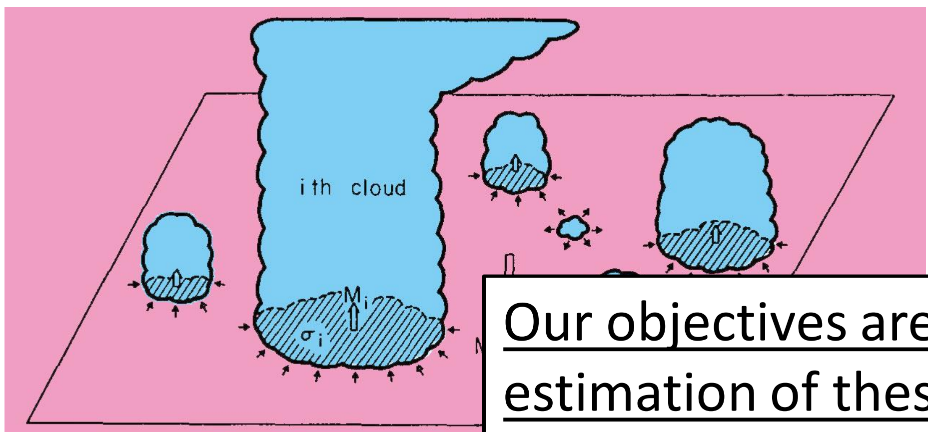
Vertical velocity



Our objectives are to 1) present a satellite-based estimation of these mass fluxes, and 2) project them onto a meaningful envelop of dynamic context

Outlines

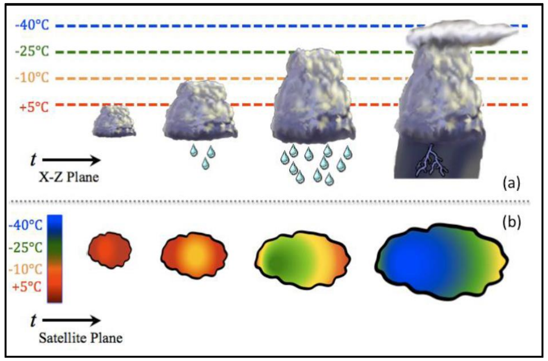
1. *Estimation of* M_c *: A-Train observations + 1D plume model*
2. *Estimation of* $\overline{M}$ *(Masunaga & L'Ecuyer 2014)*
3. *Projecting mass fluxes unto a composite convective life cycle*
4. *Summary & future plans*



Our objectives are to 1) present a satellite-based estimation of these mass fluxes, and 2) project them onto a meaningful envelop of dynamic context

A-Train data provide pieces for putting together the whole "jigsaw puzzle" of M_c profile

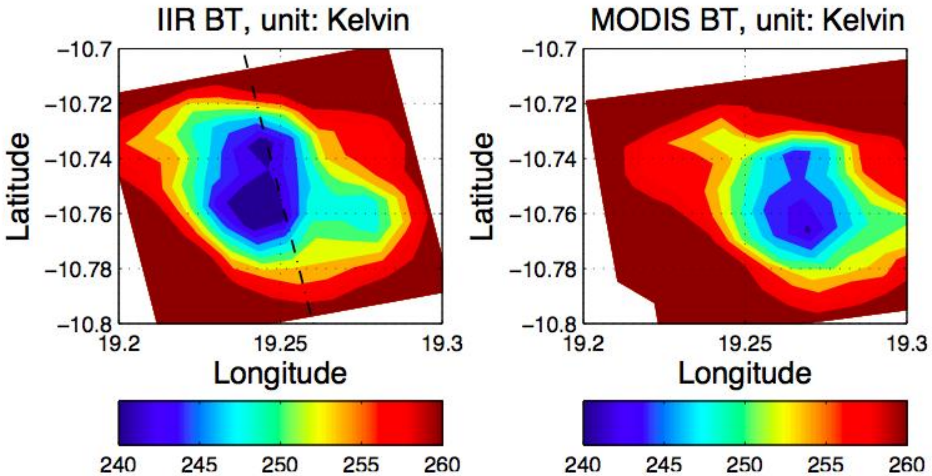
A-Train data provide pieces for putting together the whole "jigsaw puzzle" of M_c profile



Cloud-top w

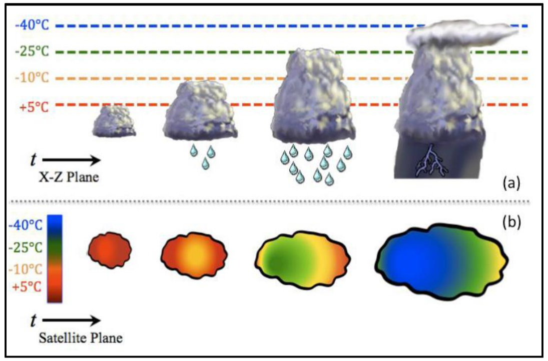
$$w = \left(\frac{\partial T}{\partial z}\right)^{-1} \frac{dT_{BB}}{dt}$$

← ~ 2 min →



Luo et al. (2014)

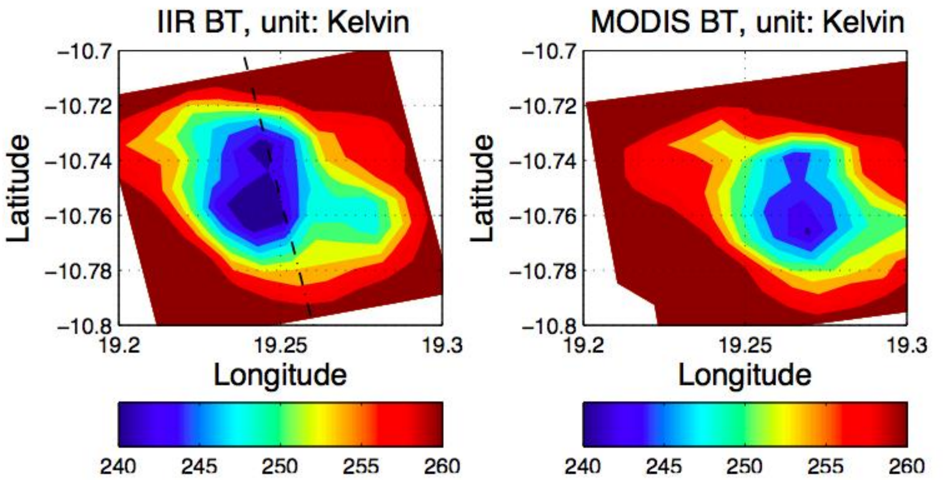
A-Train data provide pieces for putting together the whole "jigsaw puzzle" of M_c profile



Cloud-top w

$$w = \left(\frac{\partial T}{\partial z}\right)^{-1} \frac{dT_{BB}}{dt}$$

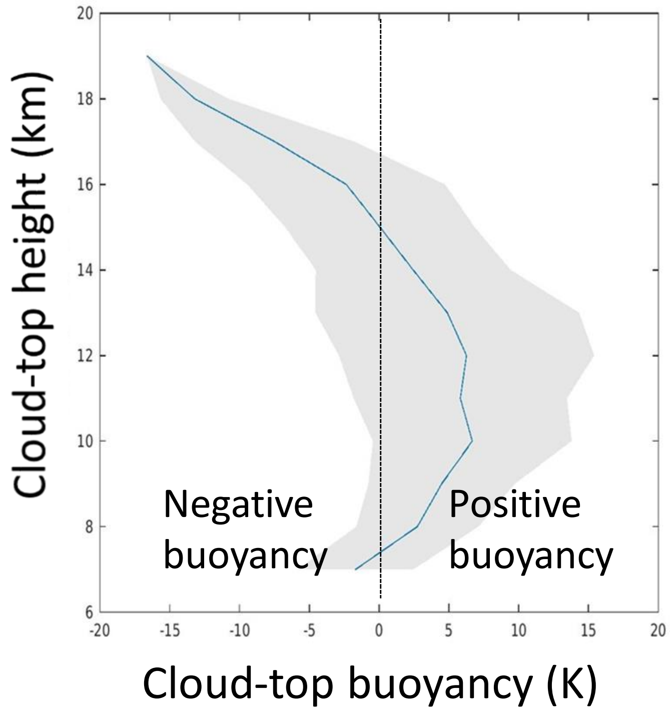
← ~ 2 min →



Luo et al. (2014)

Cloud-top buoyancy

$$B = g\frac{T_{parcel} - T_{env}}{T_{env}}$$



Luo et al. (2010); Wang et al. (2011)

A single-column plume model

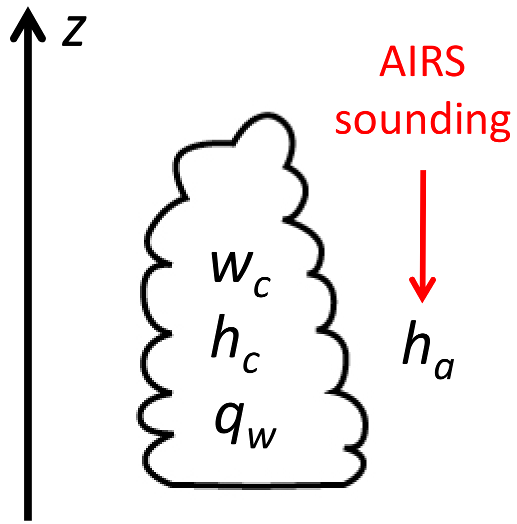
Å Basic equations

Basic equations

$$\frac{1}{2}\frac{\partial w_c^2}{\partial z} = a_B B - \epsilon w_c^2 - c_D w_c^2,$$

$$\frac{\partial (h_c - L_i q_i)}{\partial z} = -\epsilon (h_c - L_i q_i - h_a),$$

$$\frac{\partial q_w}{\partial z} = -\epsilon q_w + \frac{1}{w_c}(\dot{q}_{\mathrm{cond}} - \dot{q}_{\mathrm{auto}}),$$



As far as w_c is concerned, the most important parameter is the entrainment rate (ε). Entraining ambient air will slow down convective updraft.

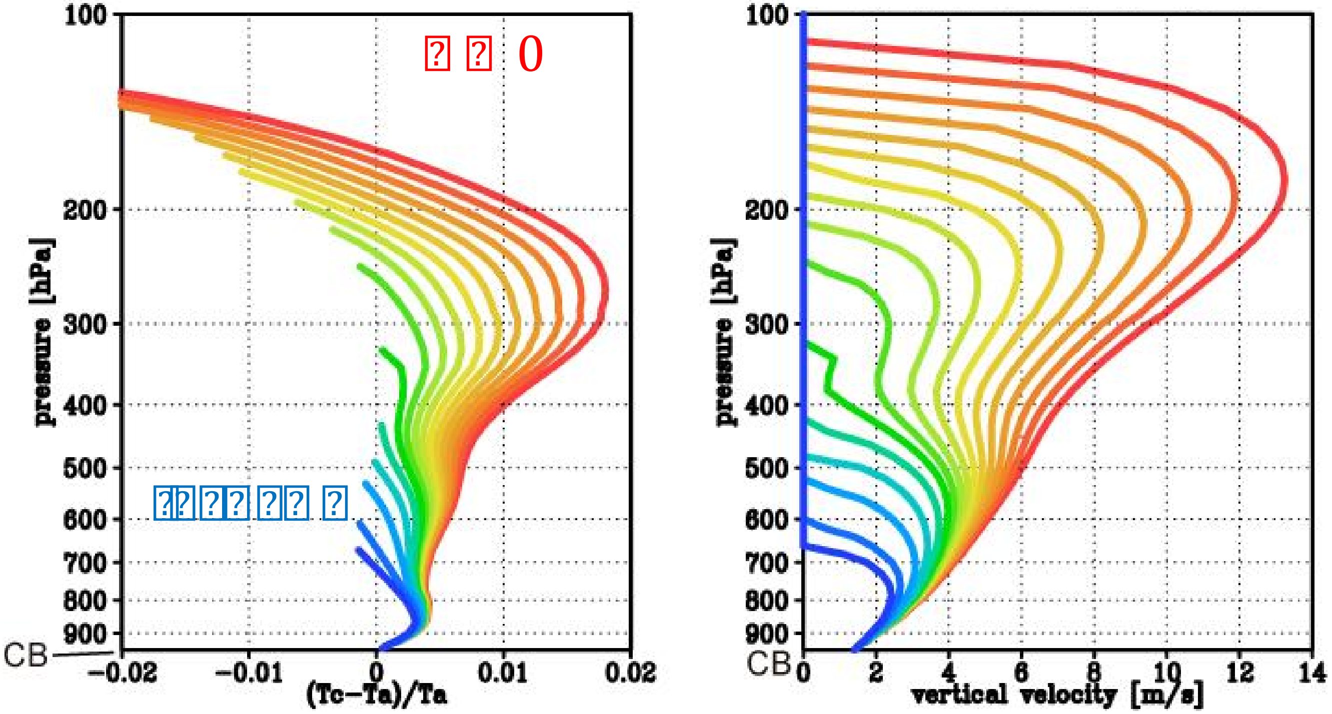
Masunaga and Luo (2016)

Simulated buoyancy ($\Delta T/T$) and w_c *profiles* under different ε

ε: 0 – 0.4/km (red to blue)

Buoyancy Profile

Vertical velocity Profile

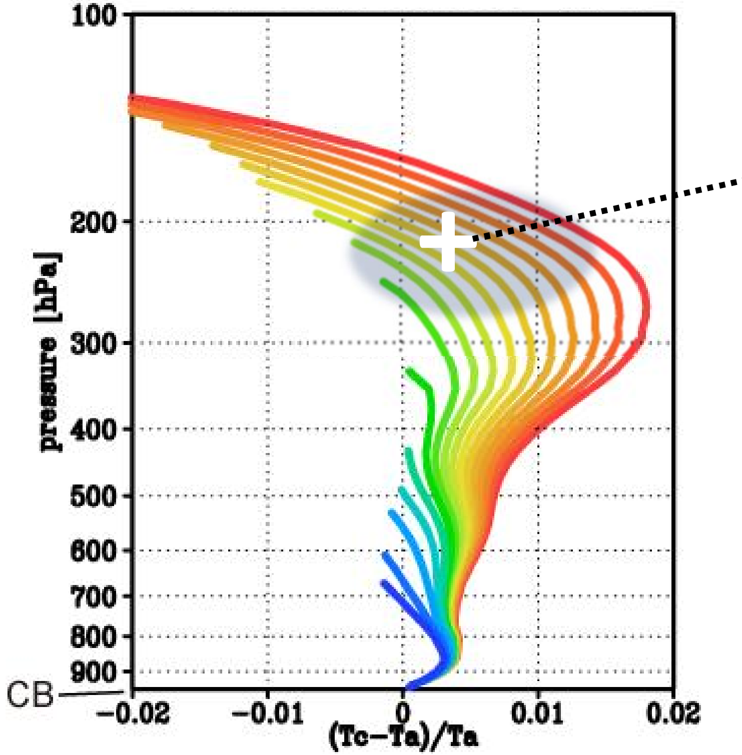


Forced by AIRS sounding

Masunaga and Luo (2016)

Observations (cloud-top buoyancy and w_c) are used to constrain different possibilities

Buoyancy Profile

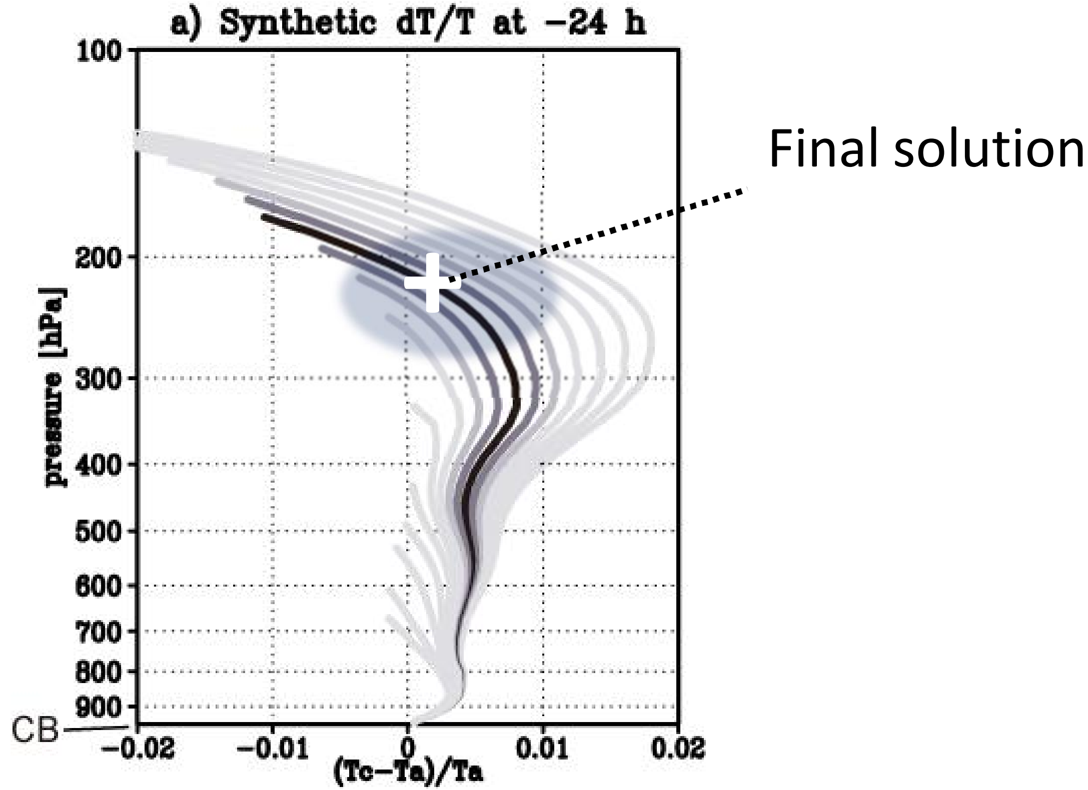


Hundreds of thousands of observed data points are used to weigh these different profiles.

Masunaga and Luo (2016)

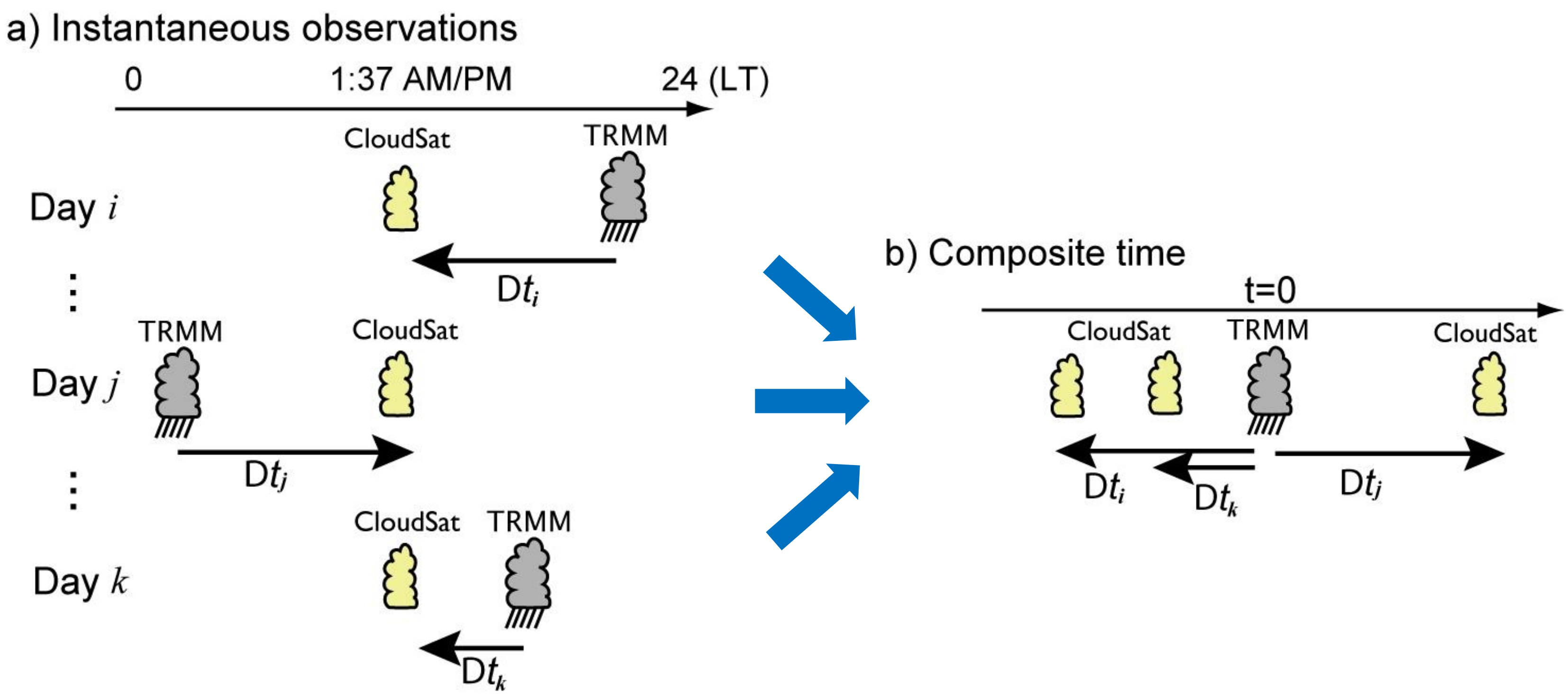
Nail down the final solution

$$\hat{w}_c(z) \equiv \sum_i p(\epsilon_{\mathrm{tur},i}|z_T, \Delta T_T) w_{c,i}(z) = \sum_i p(\epsilon_{\mathrm{tur},i}) p(z_T, \Delta T_T|\epsilon_{\mathrm{tur},i}) w_{c,i}(z),$$



Masunaga and Luo (2016)

Composite Observations w.r.t. Convective Life Stages

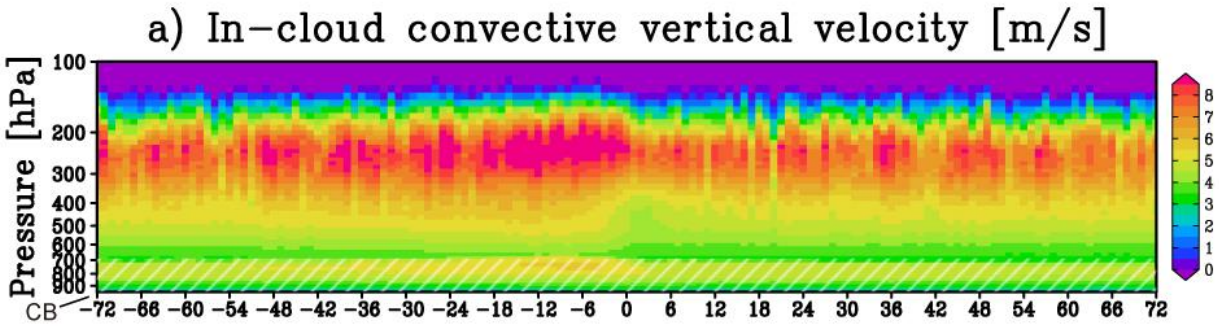


Masunaga (2012; 2013),
Masunaga and L'Ecuyer (2014)

Global tropical (15^{o}S-15^{o}N) oceans

2 years of Jan 2008 – Dec 2009

Masunaga and Luo (2016)



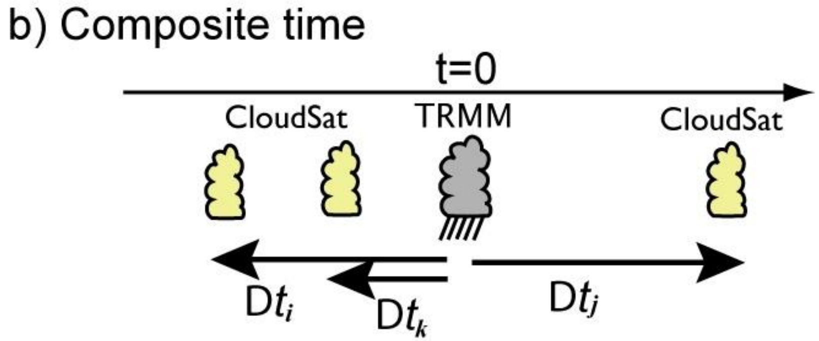
72 hrs before

peak

72 hrs after

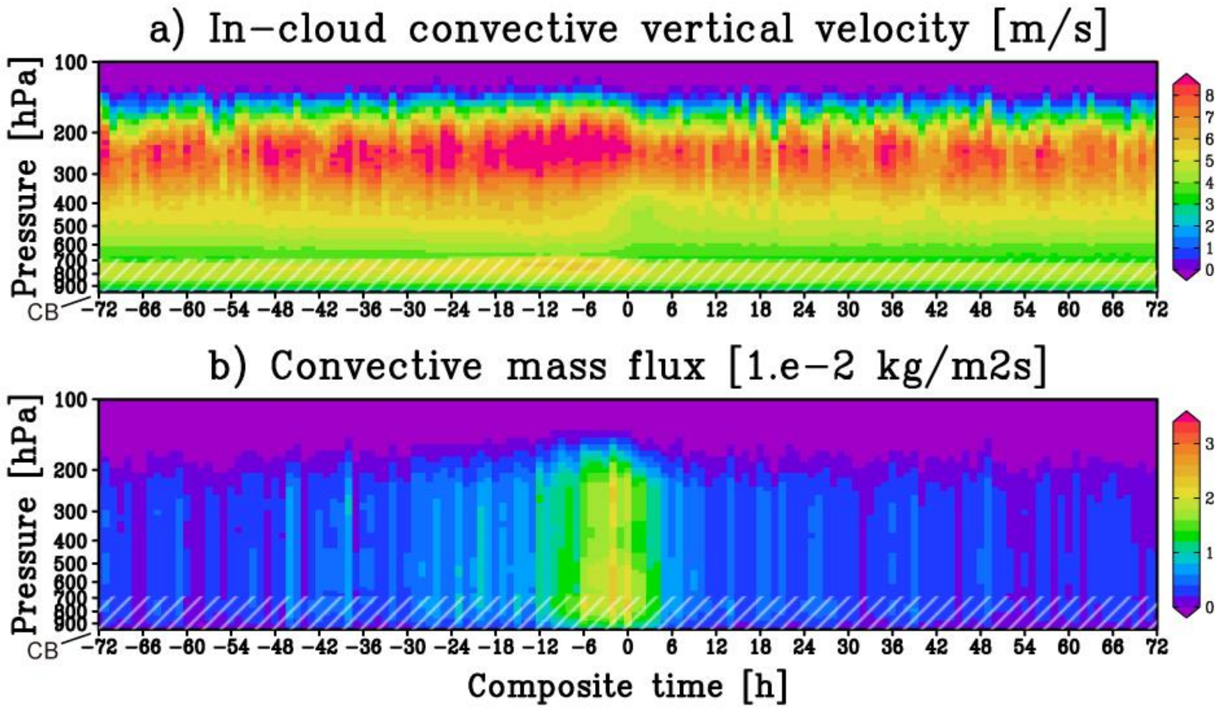
W$_c$ peaks at around 300-200 hPa

Relatively invariant over time



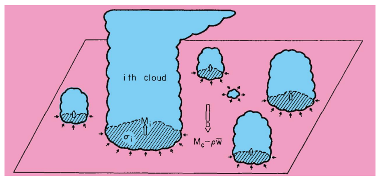
W_c relatively invariant over time

M_c follows convective life cycle, controlled by convective coverage (or *level of convective organization*)



Masunaga and Luo (2016)

$$M_c = \sigma W_c$$



Total large-scale mass flux ($\overline{M}$) is derived based on thermodynamics budget considerations *independent of M_c estimation*

$$\frac{\partial}{\partial t}\overline{\langle q \rangle} + \qquad = E - P_s - \overline{\langle \nabla \cdot q\mathbf{v} \rangle}_{SC}$$

Obs.

FT moisture convergence

Obs. + Bulk formula

Obs.

Obs. from QuikSCAT

Masunaga (2013); Masunaga and L'Ecuyer (2014)

Estimation of large-scale vertical motion

Moisture Budget

$$\frac{\partial}{\partial t}\overline{\langle q \rangle} + \quad = E - P_s - \overline{\langle \nabla \cdot q\mathbf{v} \rangle}_{SC}$$

$$\approx -\langle \overline{q} \nabla \cdot \overline{\mathbf{v}} \rangle_{FT} =$$

Masunaga (2013); Masunaga and L'Ecuyer (2014)

Estimation of large-scale vertical motion

Moisture Budget

$$\frac{\partial}{\partial t}\overline{\langle q \rangle} + \quad = E - P_s - \overline{\langle \nabla \cdot q\mathbf{v} \rangle}_{SC}$$

$$\approx -\langle \overline{q} \nabla \cdot \overline{\mathbf{v}} \rangle_{FT} =$$

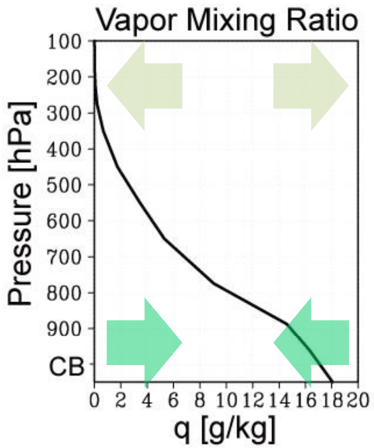
Dry Static Energy (DSE) Budget

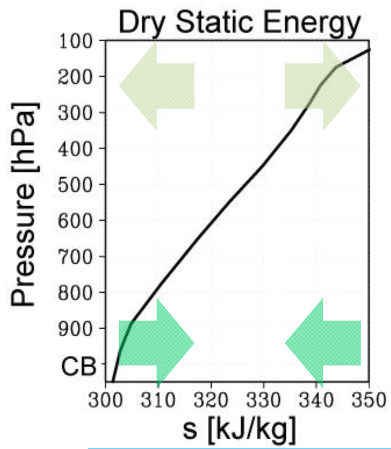
$$\frac{\partial}{\partial t}\overline{\langle s \rangle} + \quad = S + LP_s - \overline{\langle \nabla \cdot s\mathbf{v} \rangle}_{SC} + \overline{\langle Q_R \rangle}$$

$$\approx -\langle \overline{s} \nabla \cdot \overline{\mathbf{v}} \rangle_{FT} =$$

Masunaga (2013); Masunaga and L'Ecuyer (2014)

Estimation of χ : underlying concept





$$-\left\langle \bar{q} \frac{\partial \omega}{\partial p} \right\rangle_{FT}$$

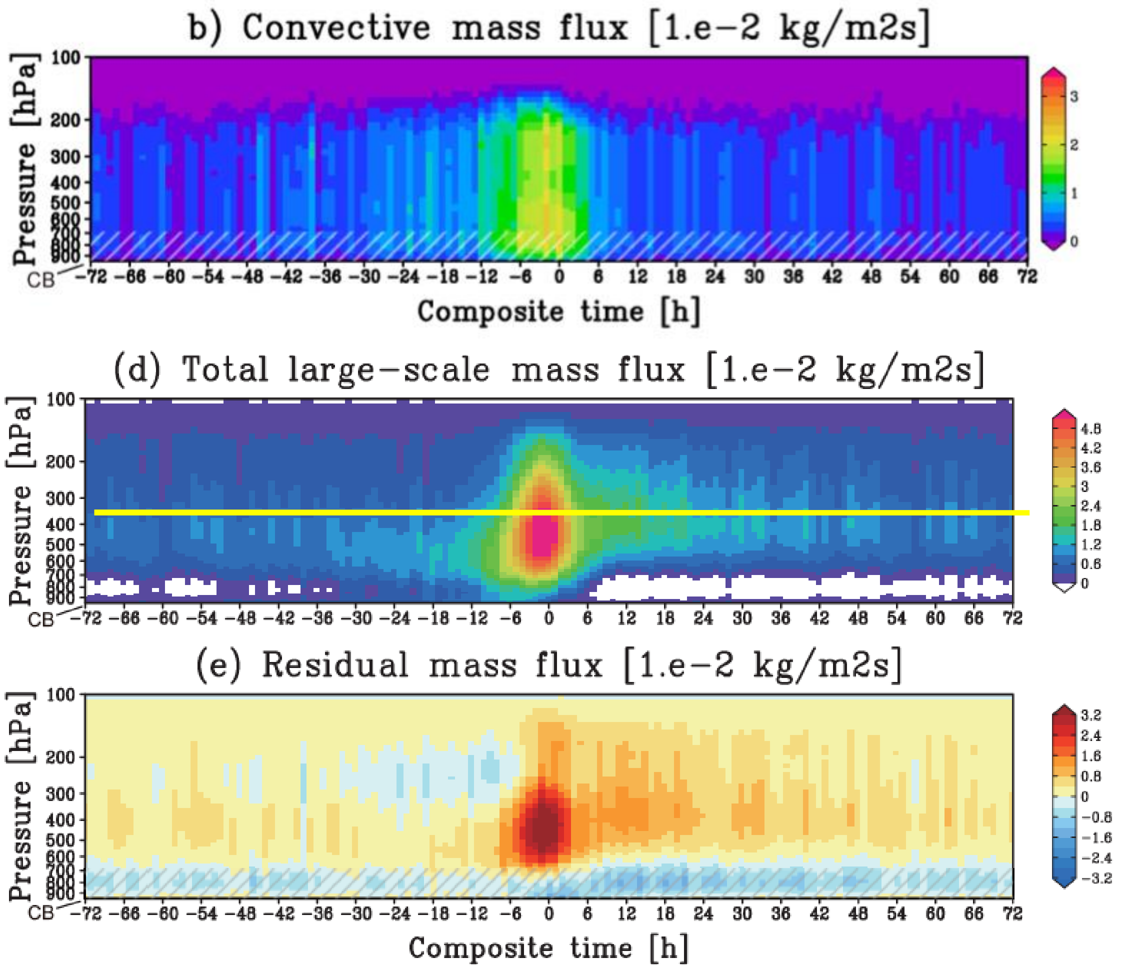
Lower-troposphere weighted convergence

$$-\left\langle \bar{s} \frac{\partial \omega}{\partial p} \right\rangle_{FT}$$

Upper-troposphere weighted convergence

Masunaga (2013); Masunaga and L'Ecuyer (2014)

$$\overline{M} = M_c + M_R + M_*$$, where $\overline{M_R \frac{\partial s_a}{\partial p}} = \frac{\overline{Q}_R}{g}$



M_c

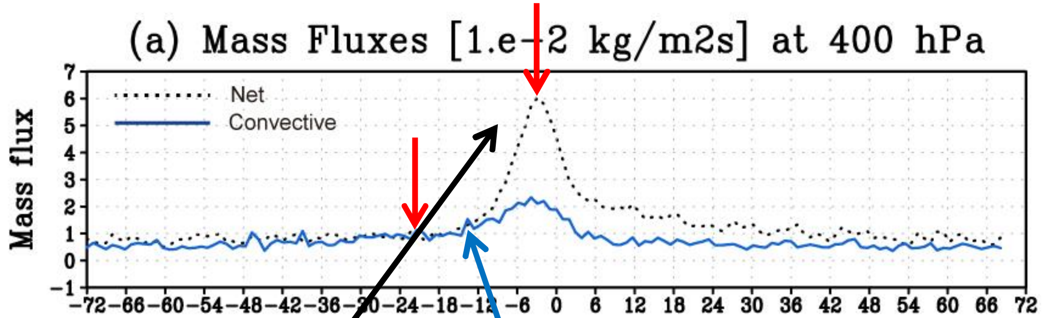
$\overline{M}$

M_*

Masunaga and Luo (2016)

Composite time series of mass fluxes

At 400 hPa



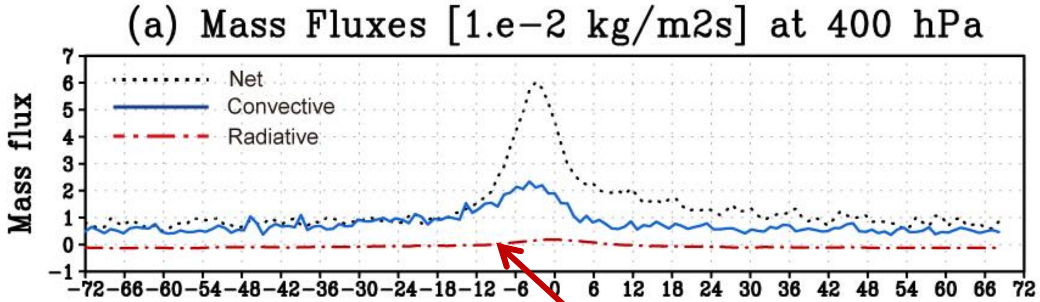
Mass budget: $$\overline{M_0} \equiv \frac{\overline{\omega}}{g} = \overline{M_c} + \overline{M_R} + \overline{M_*},$$

$\square_{\square} \approx \square_{\square}$ before convection intensifies.

$\square_{\square} < \square_{\square}$ during the peak convection.

Composite time series of mass fluxes

At 400 hPa



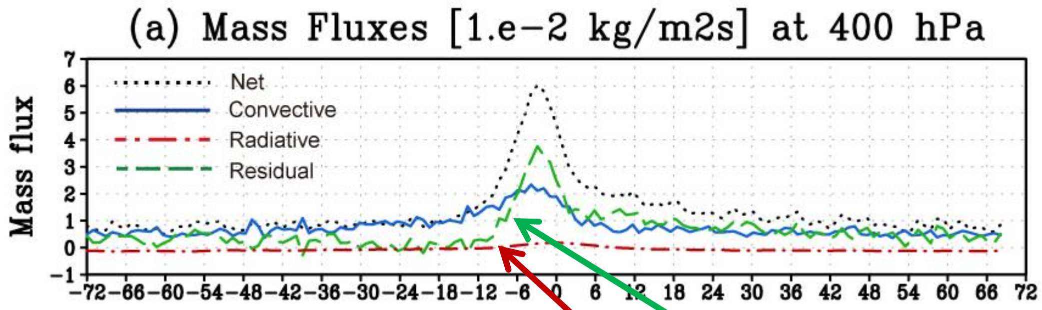
Mass budget: $$\overline{M_0} \equiv \frac{\overline{\omega}}{g} = \overline{M_c} + \overline{M_R} + \overline{M_*},$$

L-scale subsidence balanced against radiative cooling

$$\overline{M_R \frac{\partial s_a}{\partial p}} = \frac{\overline{Q}_R}{g}$$

Composite time series of mass fluxes

At 400 hPa



"Residual"

Mass budget:

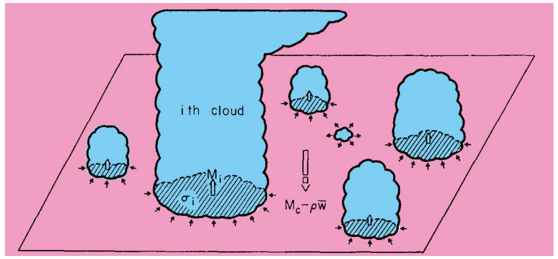
$$\overline{M_0} \equiv \frac{\overline{\omega}}{g} = \overline{M_c} + \overline{M_R} + \overline{M_*},$$

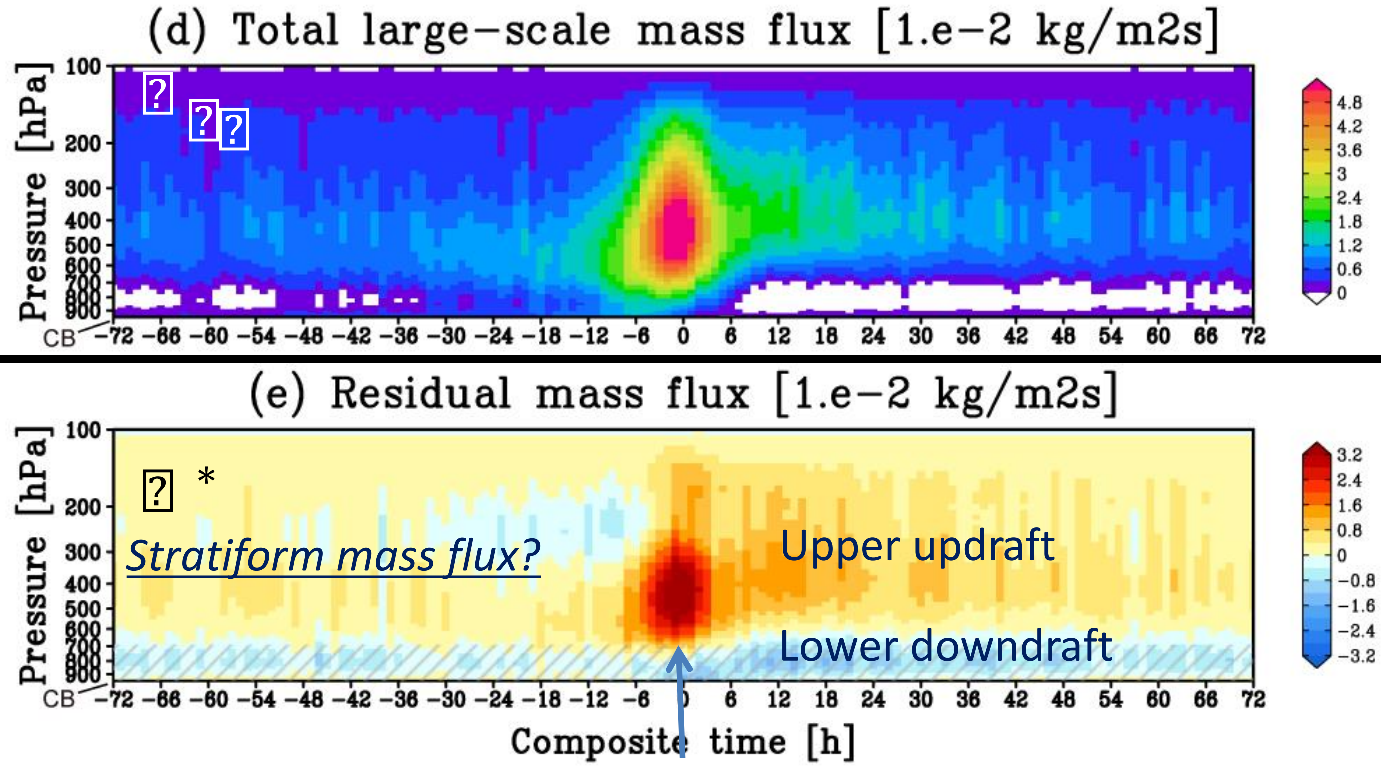
L-scale subsidence balanced against radiative cooling

$$\overline{M_R}\frac{\partial \overline{s_a}}{\partial p} = \frac{\overline{Q}_R}{g}$$

The residual flux makes a significant contribution near t ~ 0.

Composite time series of total & residual fluxes





Enhanced updraft during organized convection

Summary

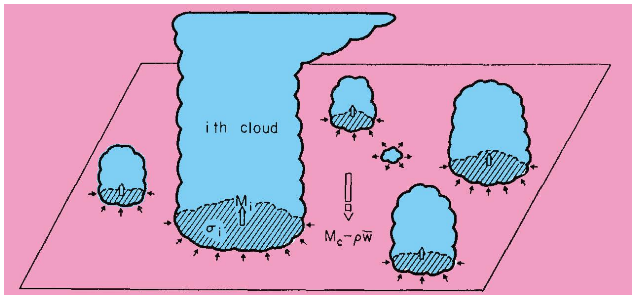
- A new satellite method for convective mass flux
  - ❑ A-Train observations provide the observational pieces (cloud-top w and B) for putting together the whole M_c "jigsaw puzzle"
  - ❑ A 1D cloud model provide candidate profiles of in-cloud w, narrowed down to the final solution via a Bayesian approach

Summary

- A new satellite method for convective mass flux
  - A-Train observations provide the observational pieces (cloud-top w and B) for putting together the whole M_c "jigsaw puzzle"
  - A 1D cloud model provide candidate profiles of in-cloud w, narrowed down to the final solution via a Bayesian approach
- Projecting the mass fluxes onto convective life cycle
  - Convective mass flux (M_c) is primarily controlled by the level of organization of the convective system (coverage of active cores)
  - M_c dominates the total mass flux only during the early hrs of the convective evolution before the system is well organized
  - A residual mass flux reminiscent of the stratiform dynamics builds up as the convection system matures up.

What next?

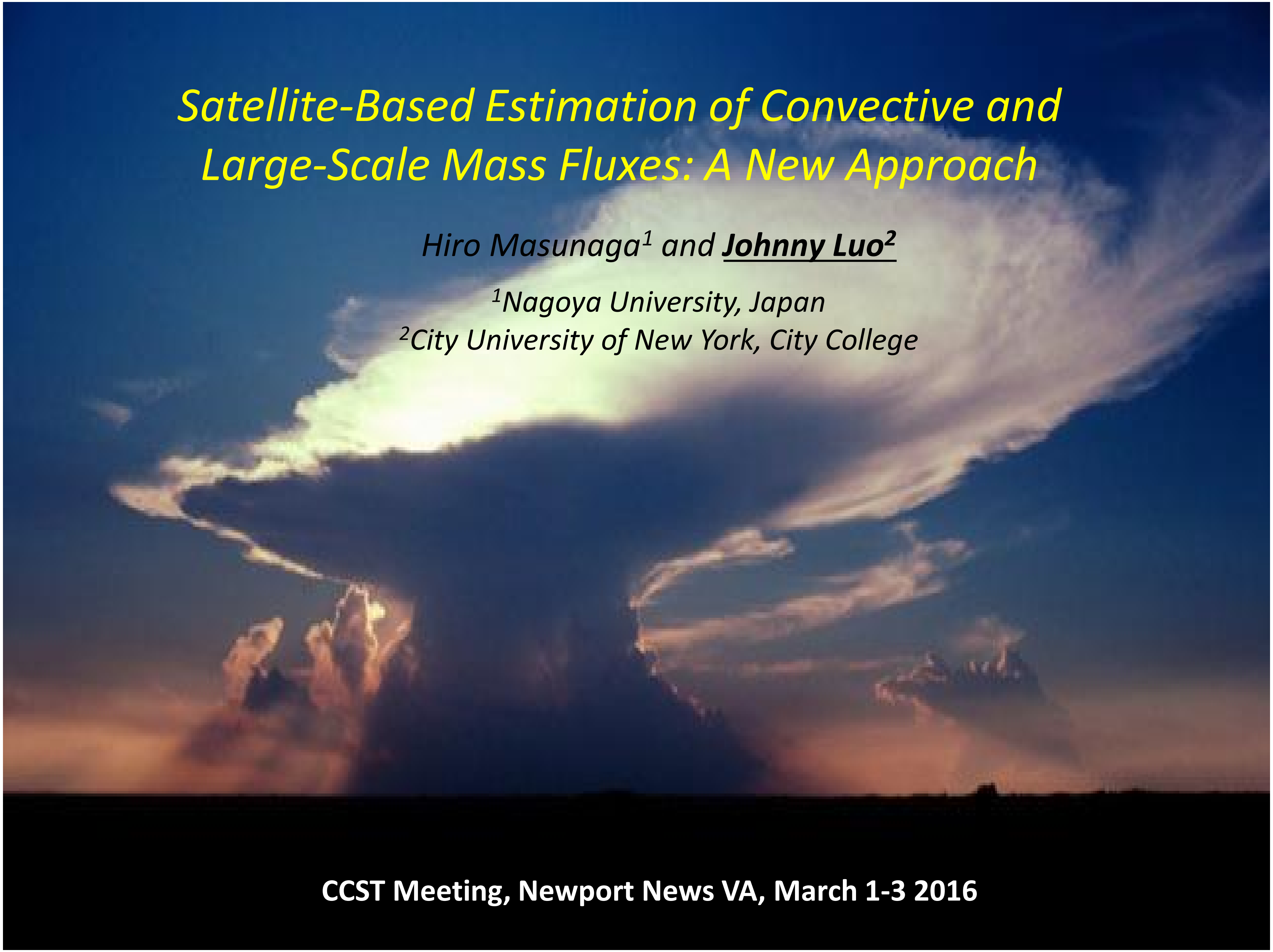
1. Improve the methodology: using a CRM instead of a 1D plume model.
2. Projecting upon an envelop of dynamic context: MJO, African Easterly Wave, etc … This will be a powerful diagnostic tool for evaluating GCM cumulus parameterizations
3. Validation: we are desperately in need of a global capability of measuring convection vertical velocity profile. Without this, our fallback at this point is ground-based radar measurements (e.g., ARM).



Our objectives are to:

1) present a satellite-based estimation of these mass fluxes, and 2) project them onto a meaningful envelop of dynamic context

Backup slides



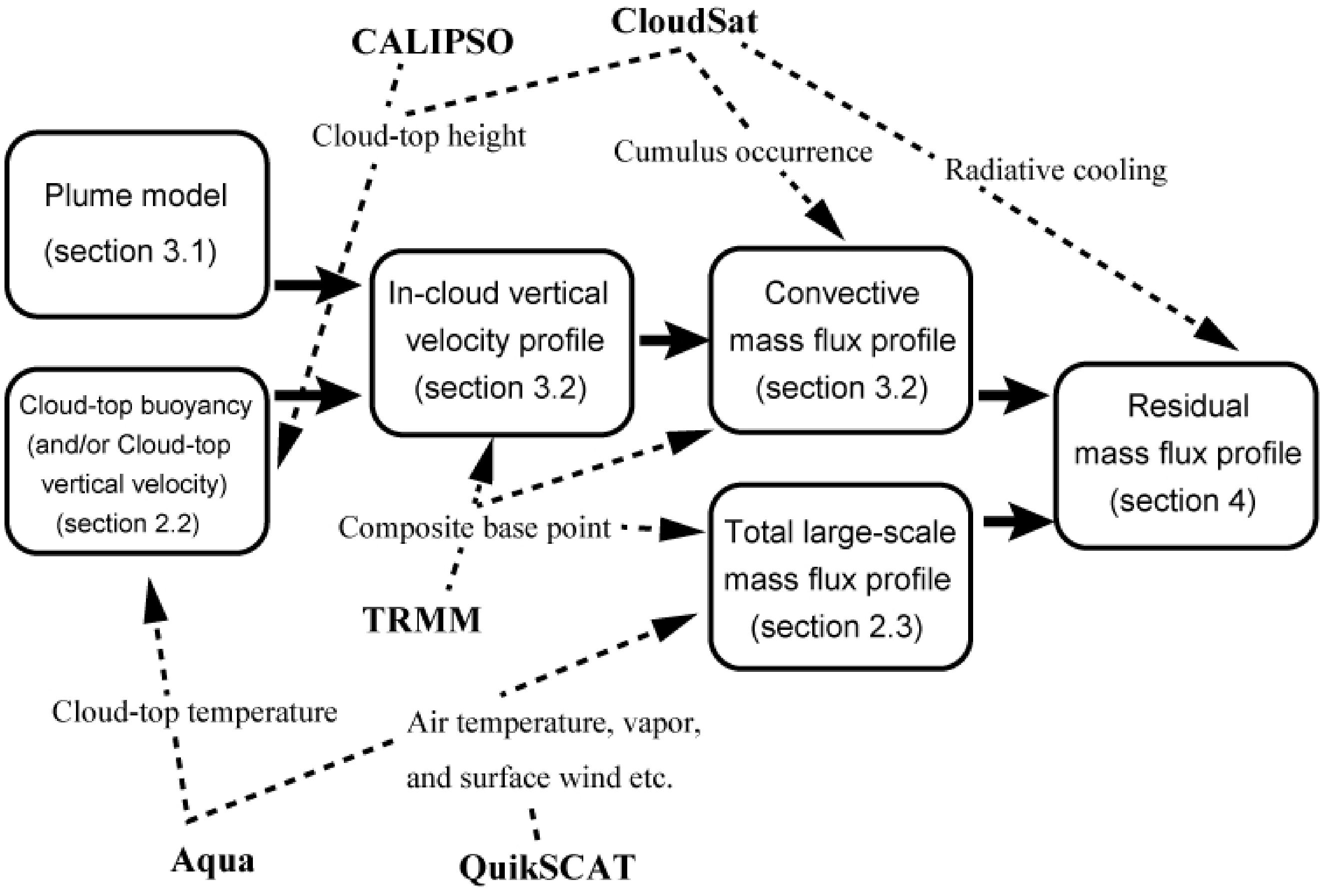
Satellite-Based Estimation of Convective and Large-Scale Mass Fluxes: A New Approach

Hiro Masunaga[1] *and* ***Johnny Luo***[2]

[1]*Nagoya University, Japan*
[2]*City University of New York, City College*

CCST Meeting, Newport News VA, March 1-3 2016

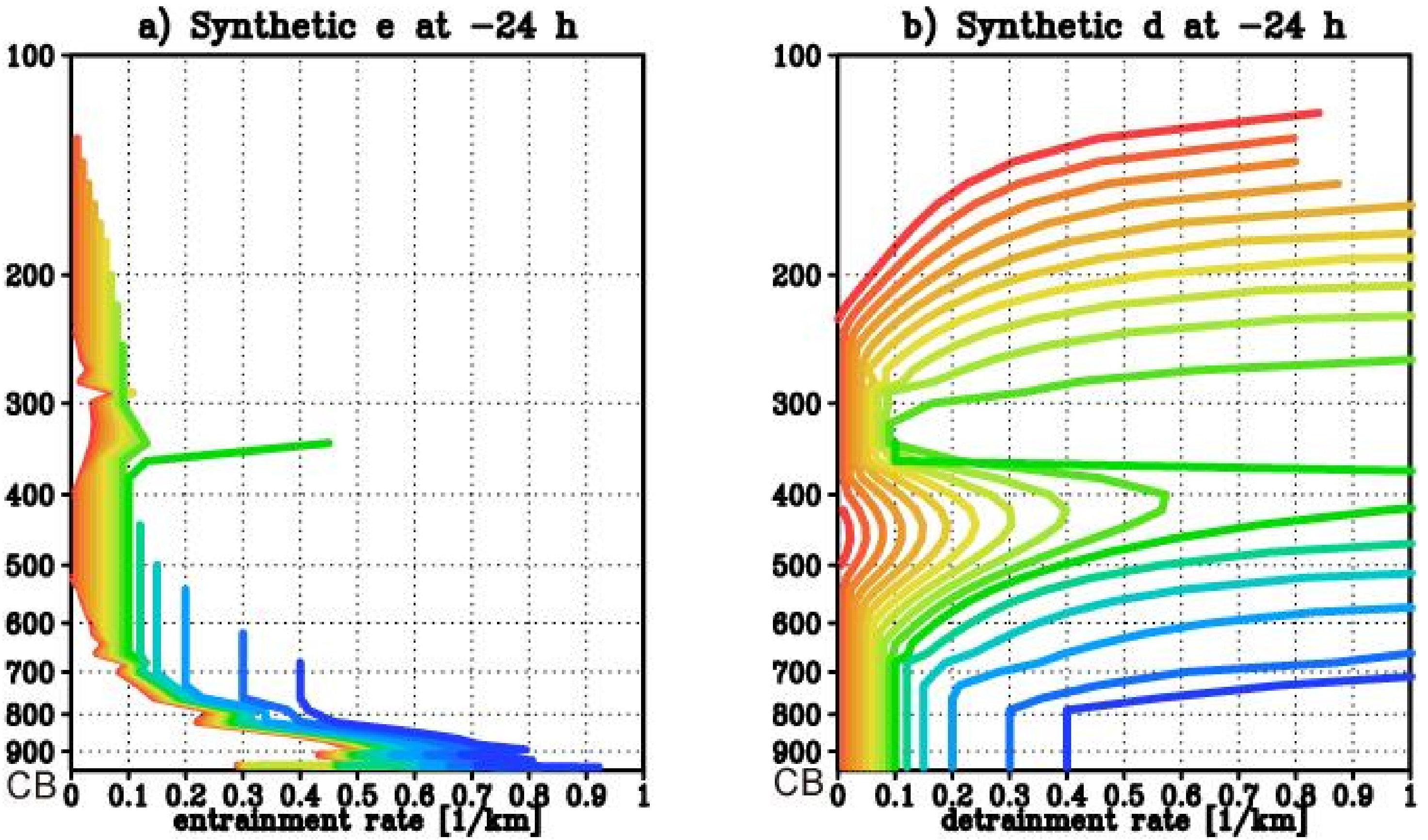
Flowchart



CALIPSO
CloudSat
Cloud-top height
Cumulus occurrence
Radiative cooling
Plume model
(section 3.1)
In-cloud vertical
velocity profile
(section 3.2)
Convective
mass flux profile
(section 3.2)
Residual
mass flux profile
(section 4)
Cloud-top buoyancy
(and/or Cloud-top
vertical velocity)
(section 2.2)
Composite base point
Total large-scale
mass flux profile
(section 2.3)
TRMM
Cloud-top temperature
Air temperature, vapor,
and surface wind etc.
Aqua
QuikSCAT

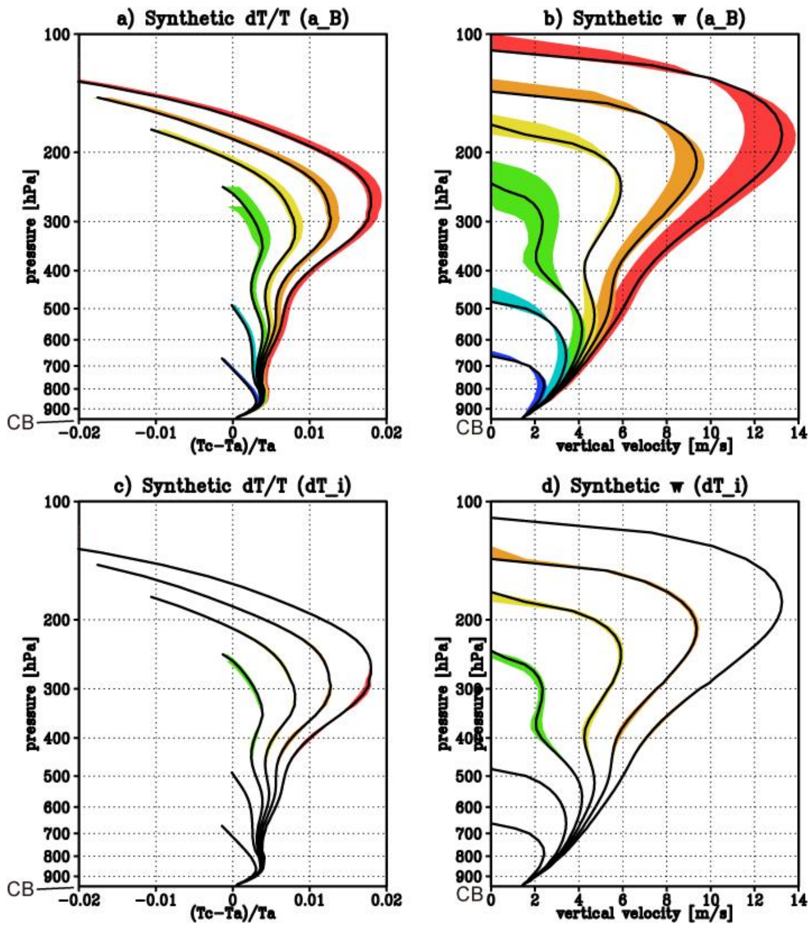
Entrainment and detrainment rates

Å ε and δ from the plume model



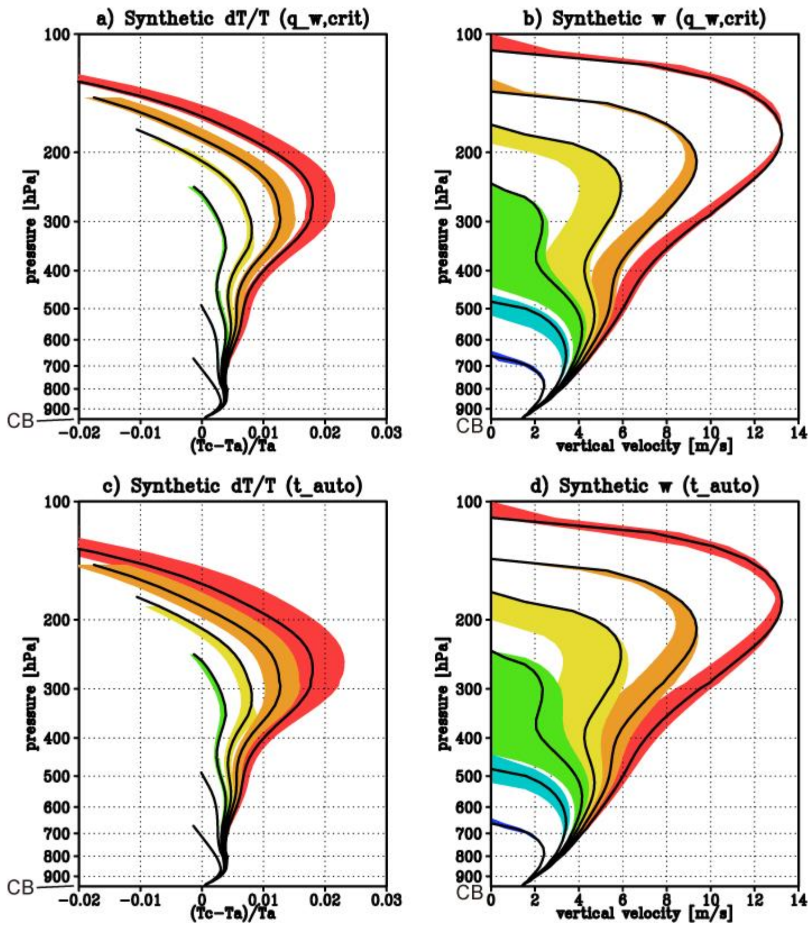
Error analysis: Single-column plume model

Å Uncertainties associated with the plume model -1



Error analysis: Single-column plume model

Å Uncertainties associated with the plume model -2



Error analysis: Composite time series

Å Uncertainties in convective mass flux