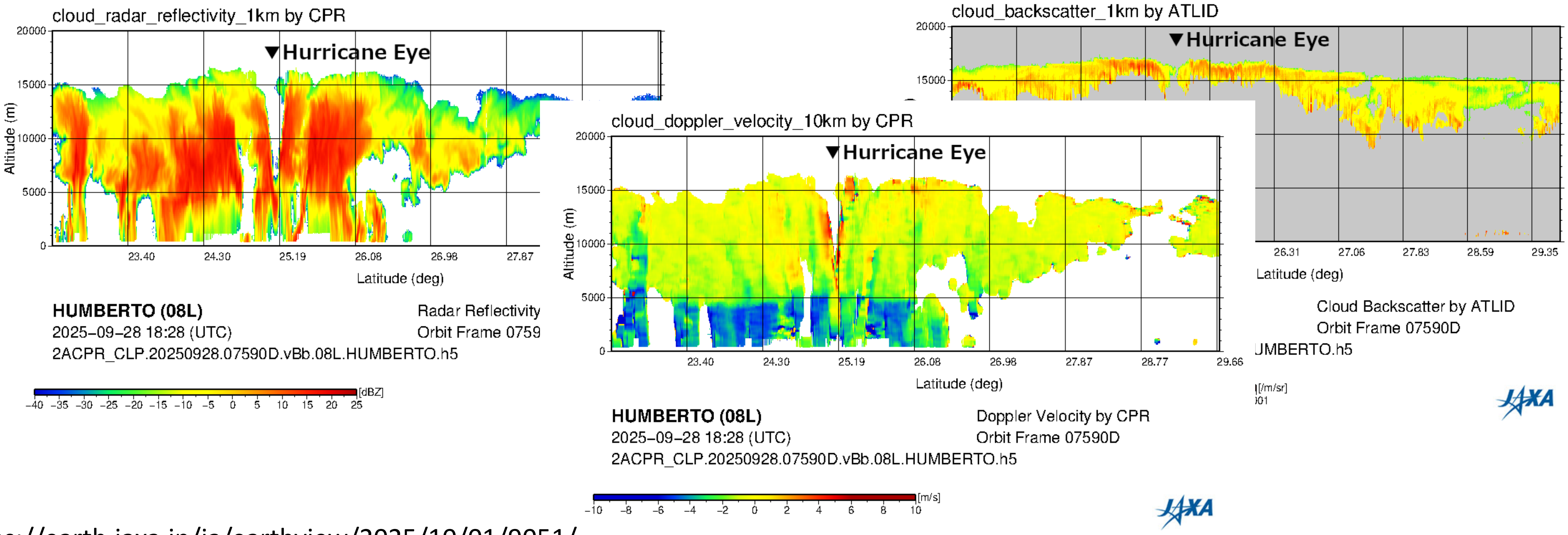
Cloud and convective dynamics revealed from space: multi-platform synergy and EarthCARE

Hiro Masunaga (Nagoya Univ.)

What would clouds look like as seen from space?

The answer of the EarthCARE workshop audience is …



https://earth.jaxa.jp/ja/earthview/2025/10/01/9051/

What would clouds look like as seen from space?

The answer of anyone else may be like …

What would clouds look like as seen from space?

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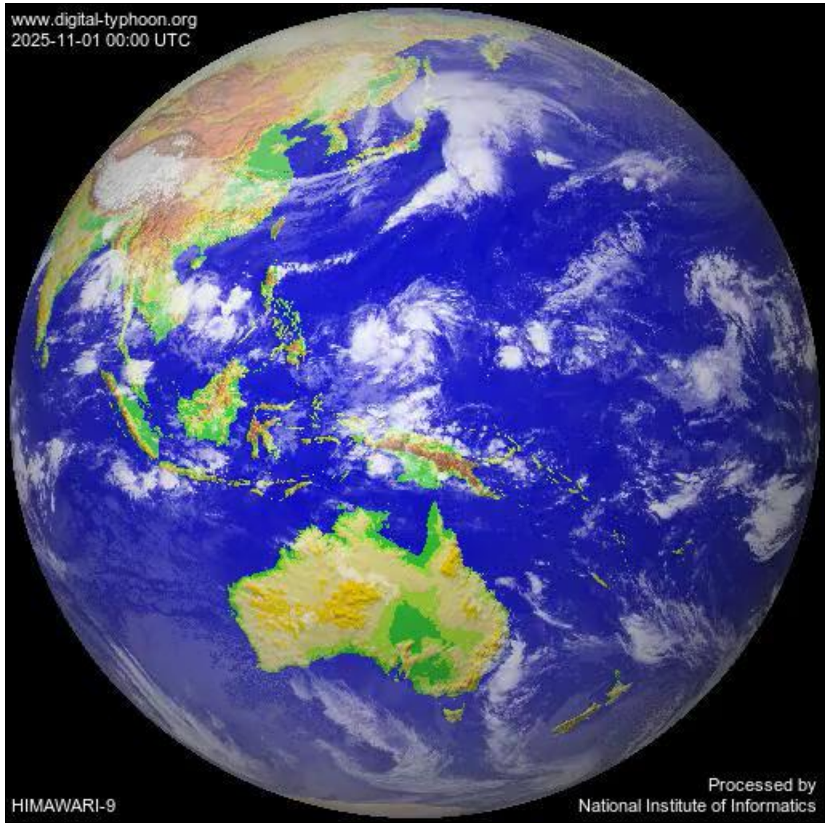
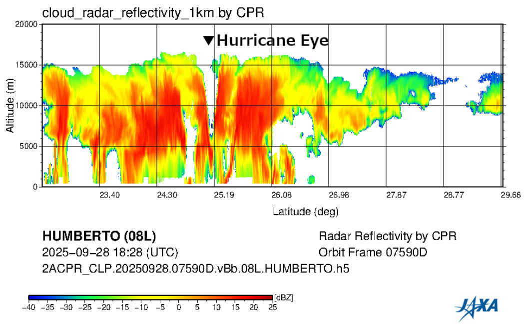


https://agora.ex.nii.ac.jp/digital-typhoon/archive/monthly/

LEO versus GEO

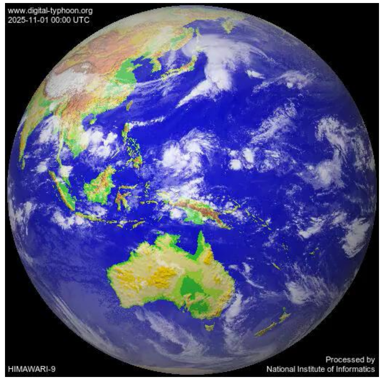
LEO satellites

- ✓ Carry various advanced instruments such as radars and lidars.
- ✓ Capture sporadic snapshots without temporal context.



GEO satellites

- ✓ Carry visible-IR imagers/sounders but no MW or active instruments.
- ✓ Capture the hourly evolution of clouds and convection.



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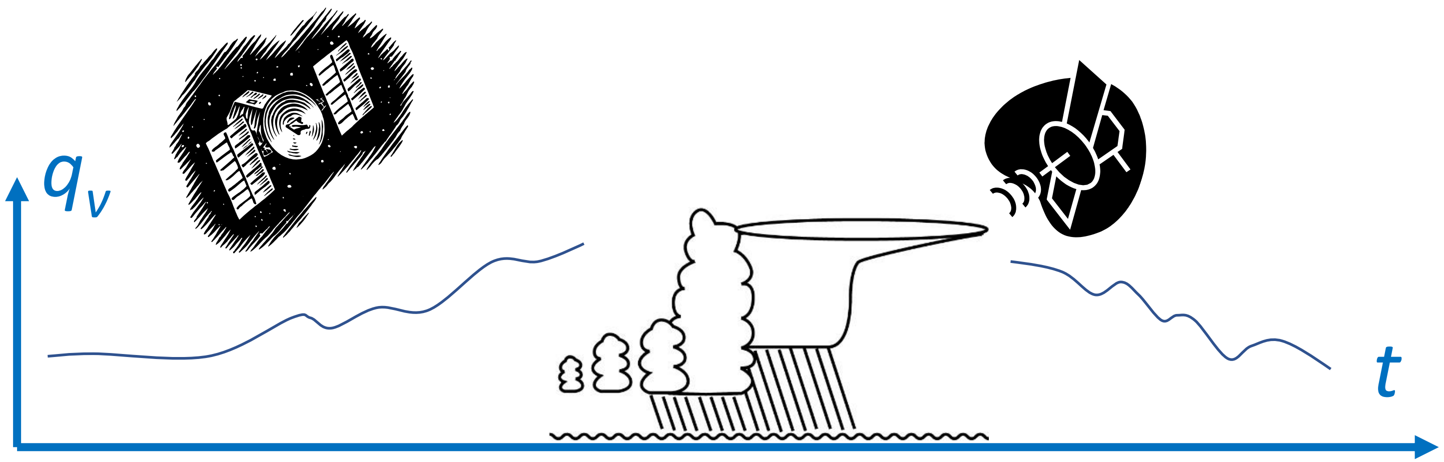

LEO versus GEO

Is it possible to exploit advanced LEO sensors as if they were in the GEO orbit?

- ✓ Carry various advanced instruments such as radars and lidars.
- ✓ Capture sporadic snapshots without temporal context.

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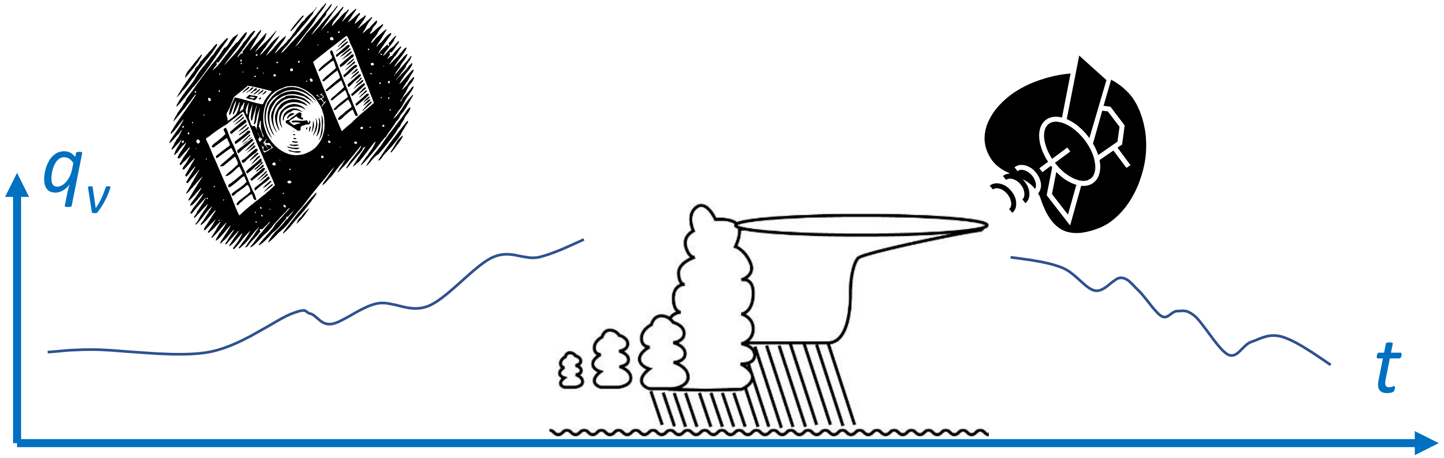


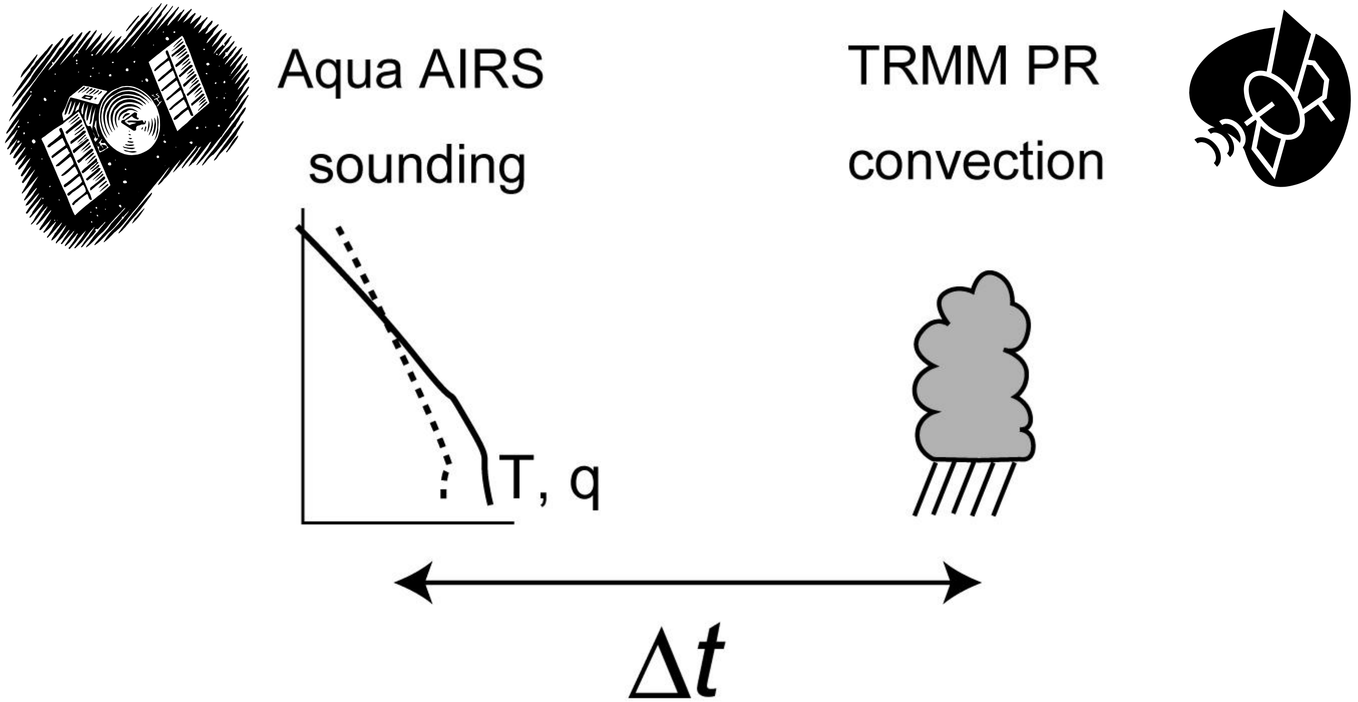
LEO versus GEO

Is it possible to exploit advanced LEO sensors as if they were in the GEO orbit?

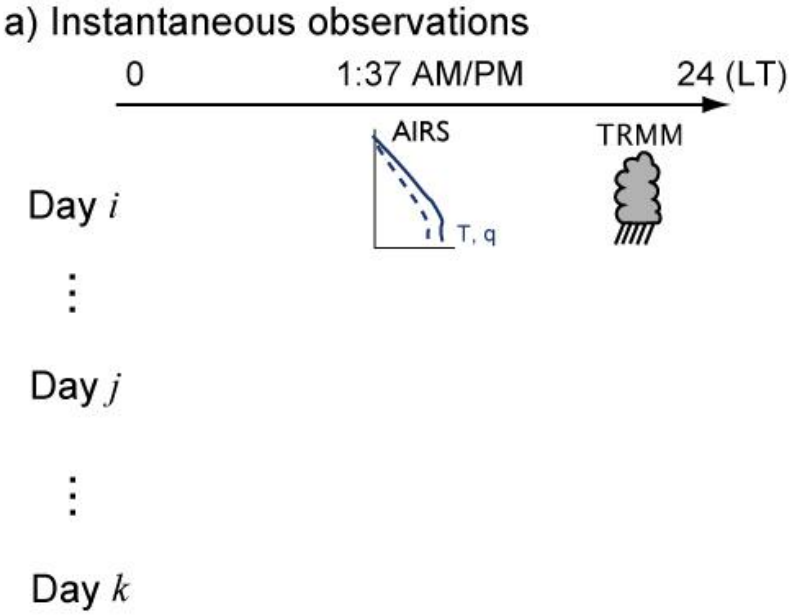
Yes, *by use of composite time series.*

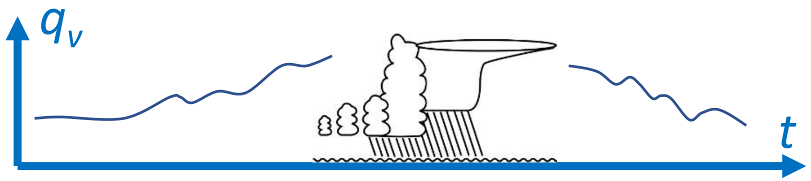
Composite time series: Method

<u>*Polar orbiter*</u> <u>*Sun-asynchronous orbiter*</u>



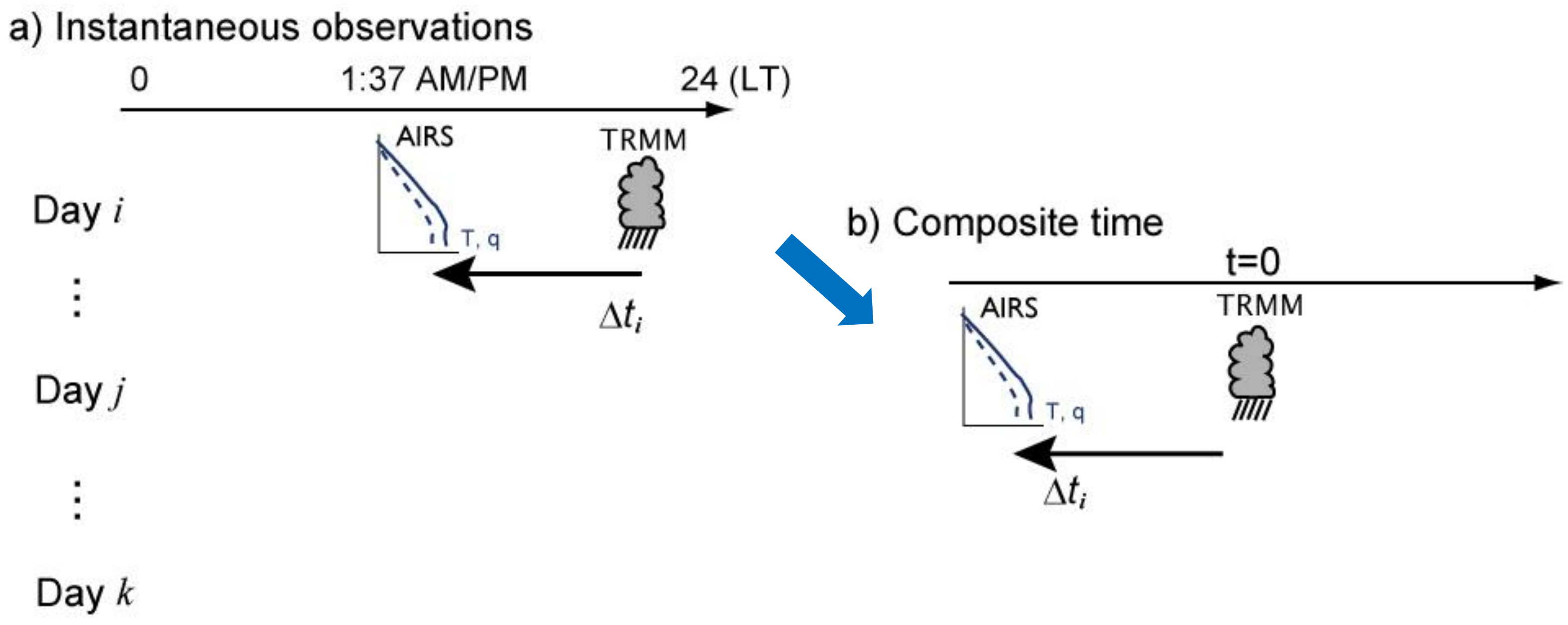
Composite time series: Method





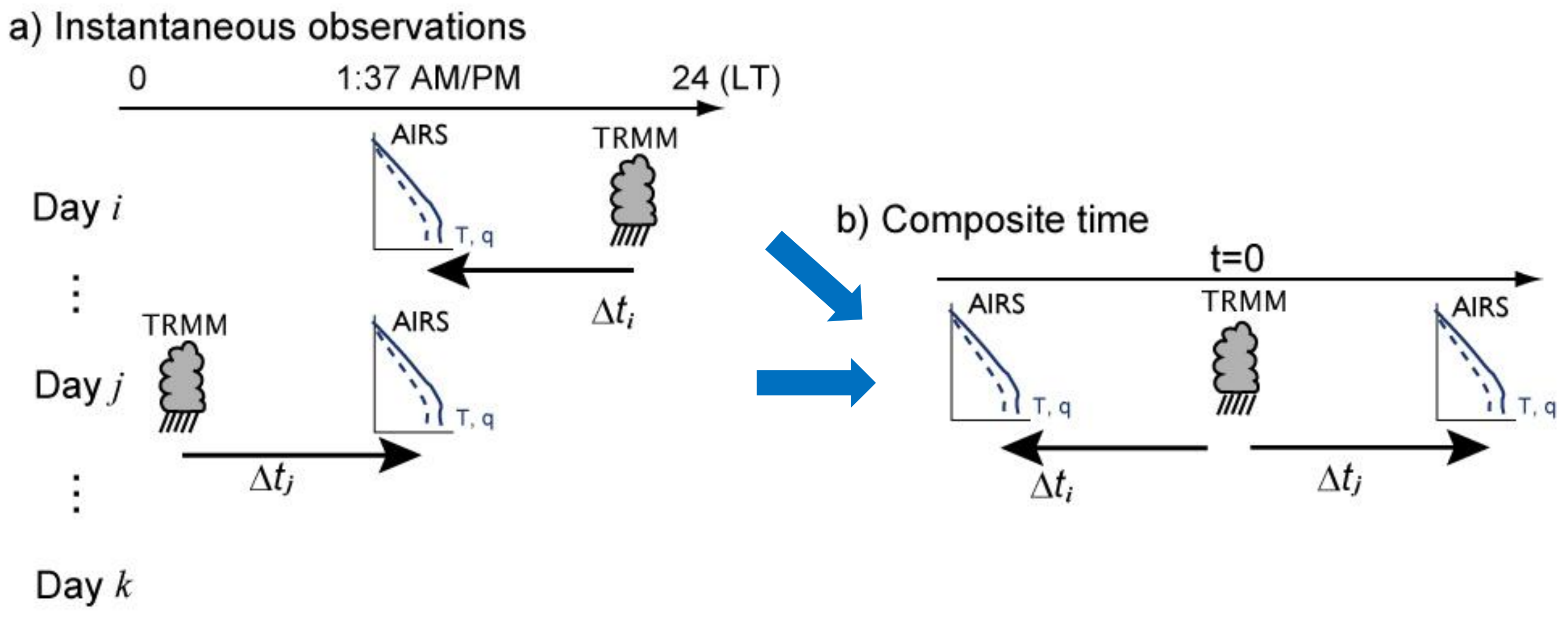
Masunaga, *JAS*, 2012

Composite time series: Method



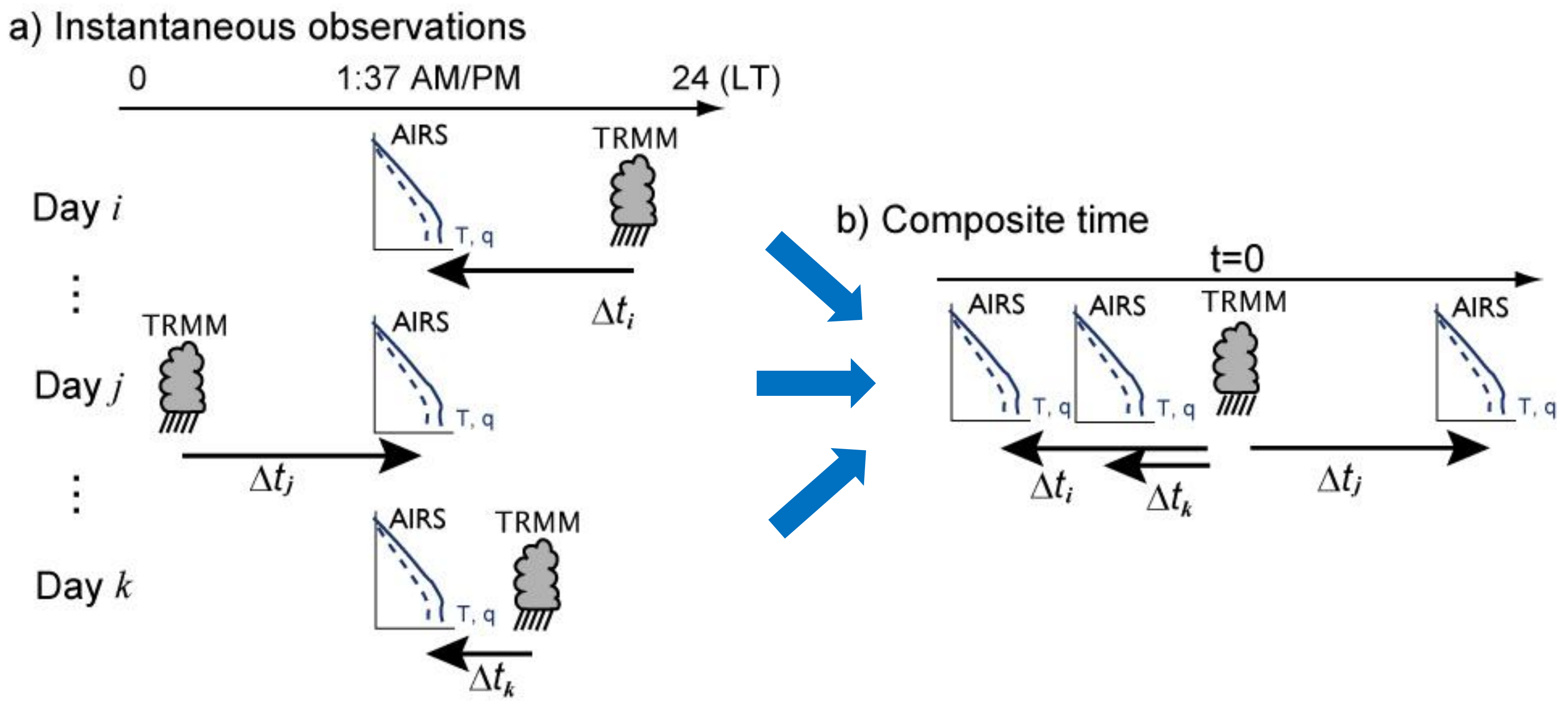
Masunaga, *JAS*, 2012

Composite time series: Method



Masunaga, *JAS*, 2012

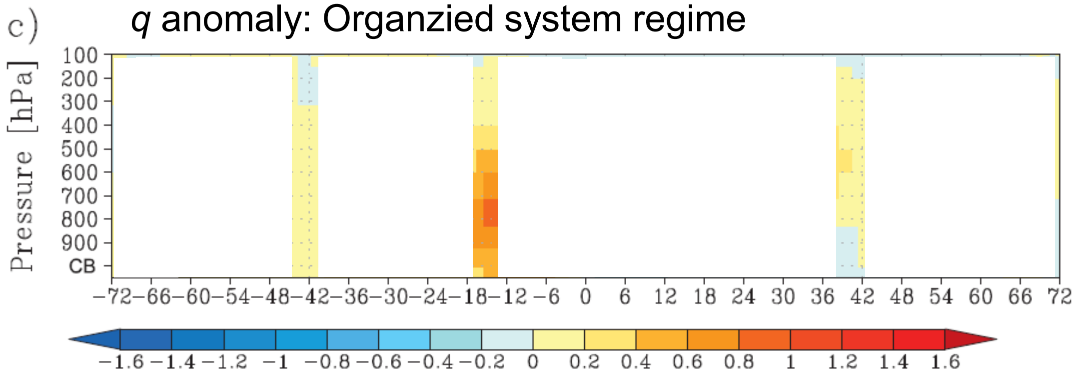
Composite time series: Method

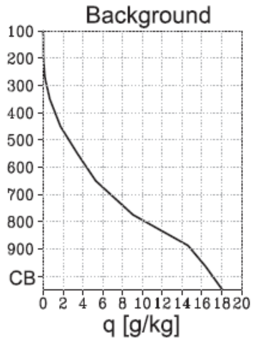


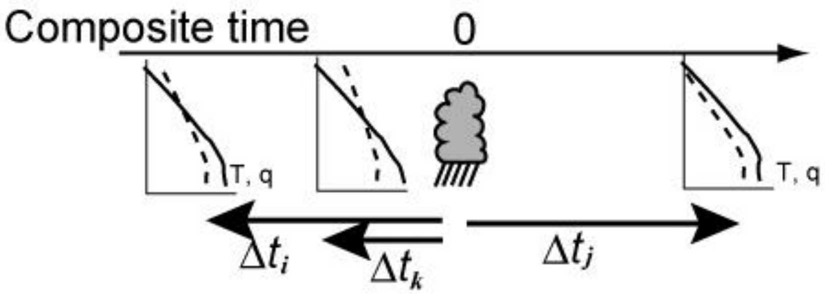
Masunaga, *JAS*, 2012

Composite time series: Method

Vapor mixing ratio q



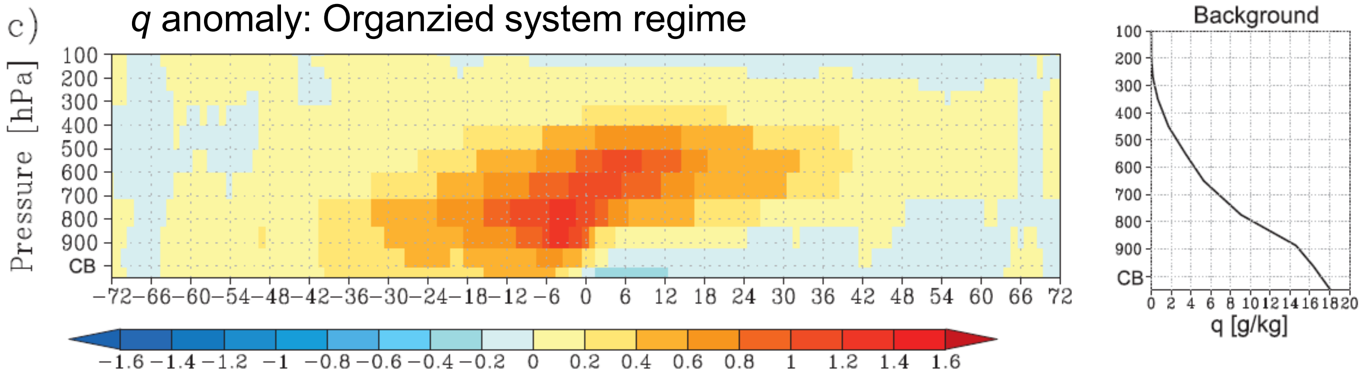




Composite time series: Moisture and DSE

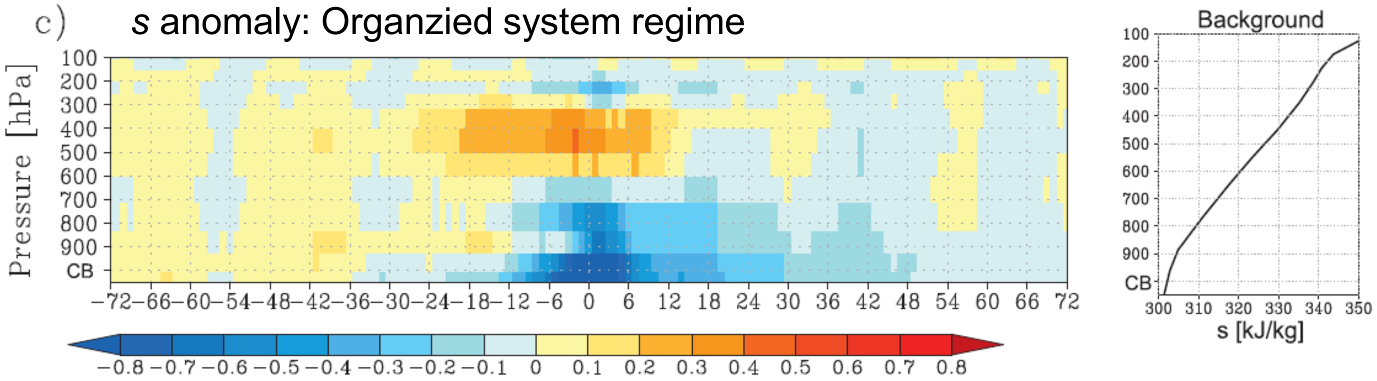
Vapor mixing ratio

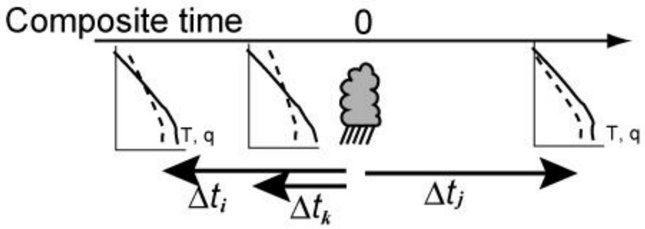
q



Dry static energy

$s = c_p T + gz$





Masunaga, *JAS*, 2013

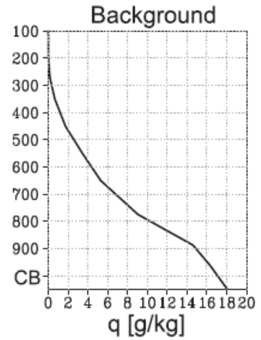
Composite time series: Large-scale vertical motion ($\overline{\omega}$)

JAXA esa

Column-integrated moisture budget equation

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

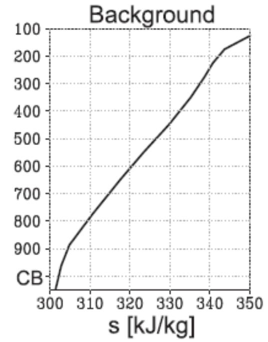
Obs. Obs. Obs.



Column-integrated thermal budget equation

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

Obs. Obs. Obs. Obs.



Mass conservation in the sub-cloud layer

$$\overline{\omega}(p_{CB}) = (\nabla \cdot \mathbf{u}_{10})\Delta p_{CB}$$

Obs.

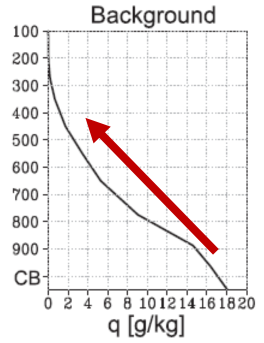
q: vapor mixing ratio
s: dry static energy
ω: vertical p-velocity
E: evaporation
P_s: precipitation
S: sensible heat
Q_R: radiative heating
p_{CB}: p at cloud-base
$\langle \cdots \rangle$: vertical integral

Masunaga and L'Ecuyer, *J. Atmos. Sci.*, 2014

Composite time series: Large-scale vertical motion ($\overline{\omega}$)

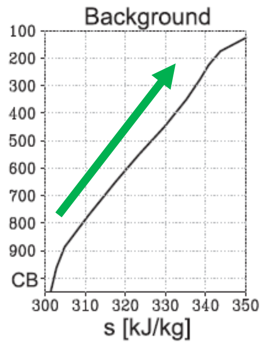
1. *q* convergence → LT dynamics

$$\overline{\langle \nabla \cdot q\mathbf{v} \rangle} \approx -\left\langle \bar{q} \frac{\partial \overline{\omega}}{\partial p} \right\rangle$$



2. *s* convergence → UT dynamics

$$\overline{\langle \nabla \cdot s\mathbf{v} \rangle} \approx -\left\langle \bar{s} \frac{\partial \overline{\omega}}{\partial p} \right\rangle$$



3. Vertical continuity at cloud base

$$\overline{\omega}(p_{CB})$$

Masunaga and L'Ecuyer, *J. Atmos. Sci.*, 2014

Composite time series: Large-scale vertical motion ($\overline{\omega}$)

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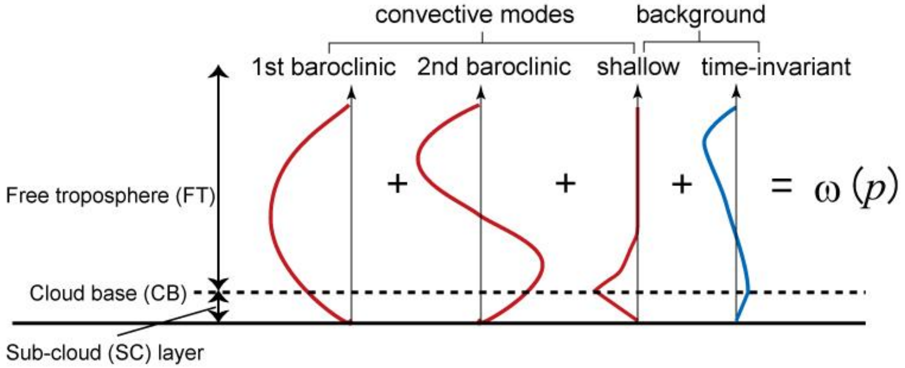
3. Vertical continuity at cloud base

$$\overline{\omega}(p_{CB})$$

$$\overline{\omega'} = \overline{\omega}_{\mathrm{bc1}} + \overline{\omega}_{\mathrm{bc2}} + \overline{\omega}_{\mathrm{shl}}$$

1st baroclinic 2nd baroclinic shallow



Masunaga and L'Ecuyer, *J. Atmos. Sci.*, 2014

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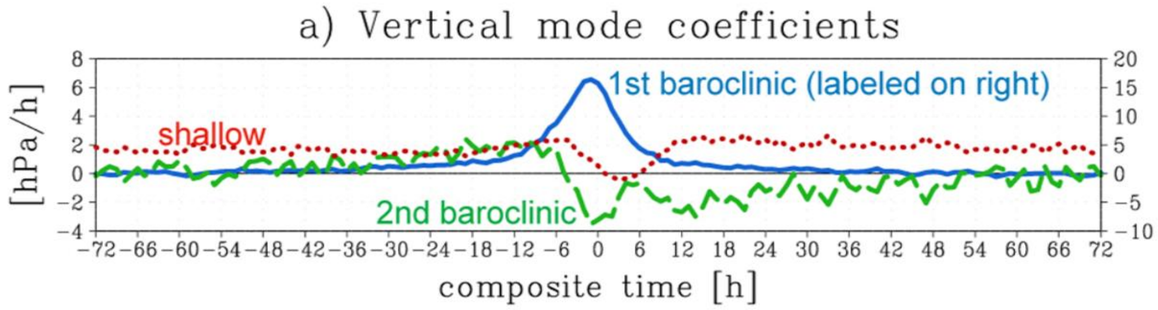
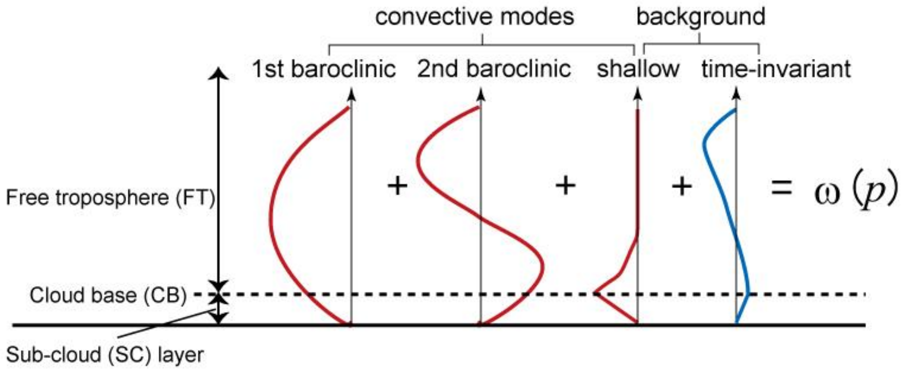


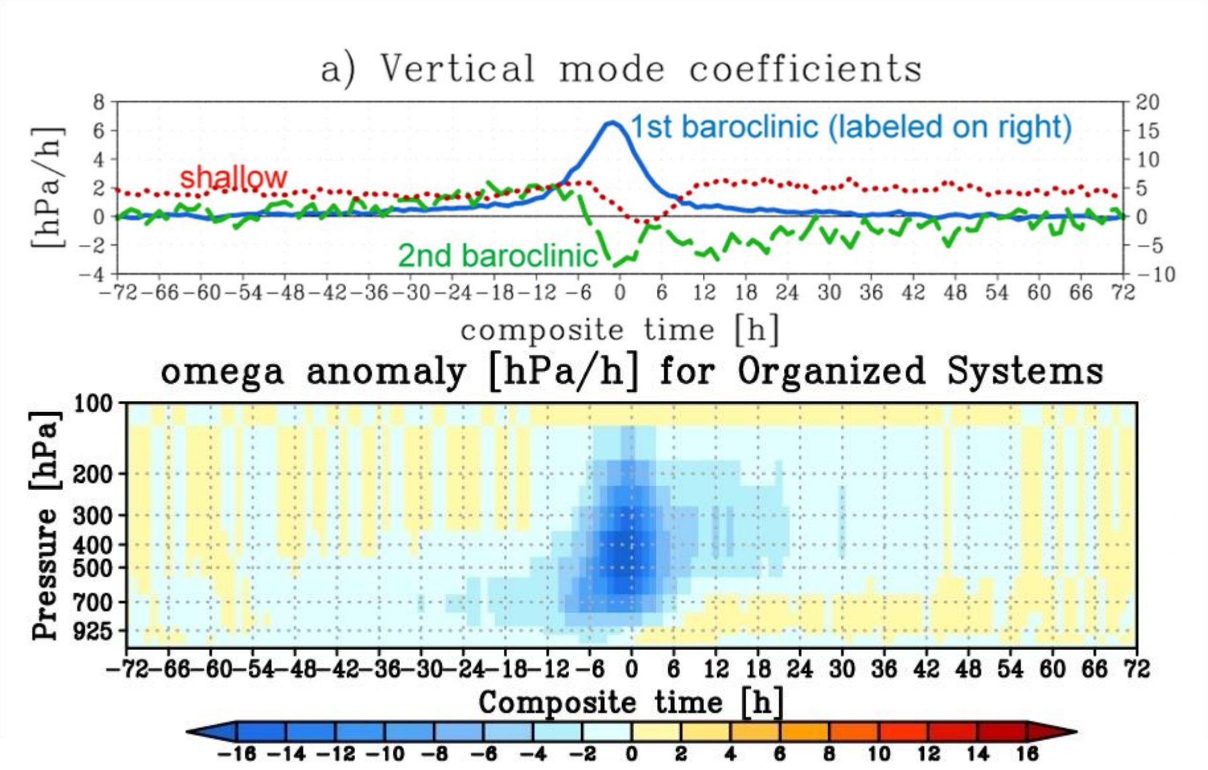
$$\overline{\omega'} = \overline{\omega}_{\mathrm{bc1}} + \overline{\omega}_{\mathrm{bc2}} + \overline{\omega}_{\mathrm{shl}}$$

1st baroclinic   2nd baroclinic   shallow



Masunaga and L'Ecuyer, *JAS*, 2014

Composite time series: Large-scale vertical motion ($\overline{\omega}$)



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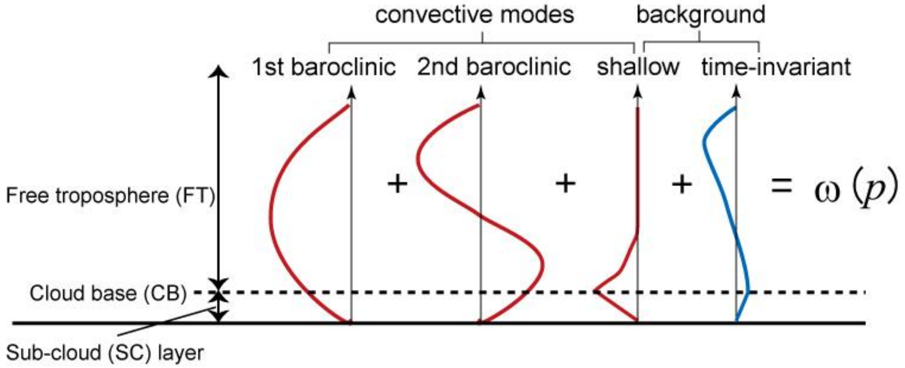
1st baroclinic 2nd baroclinic shallow



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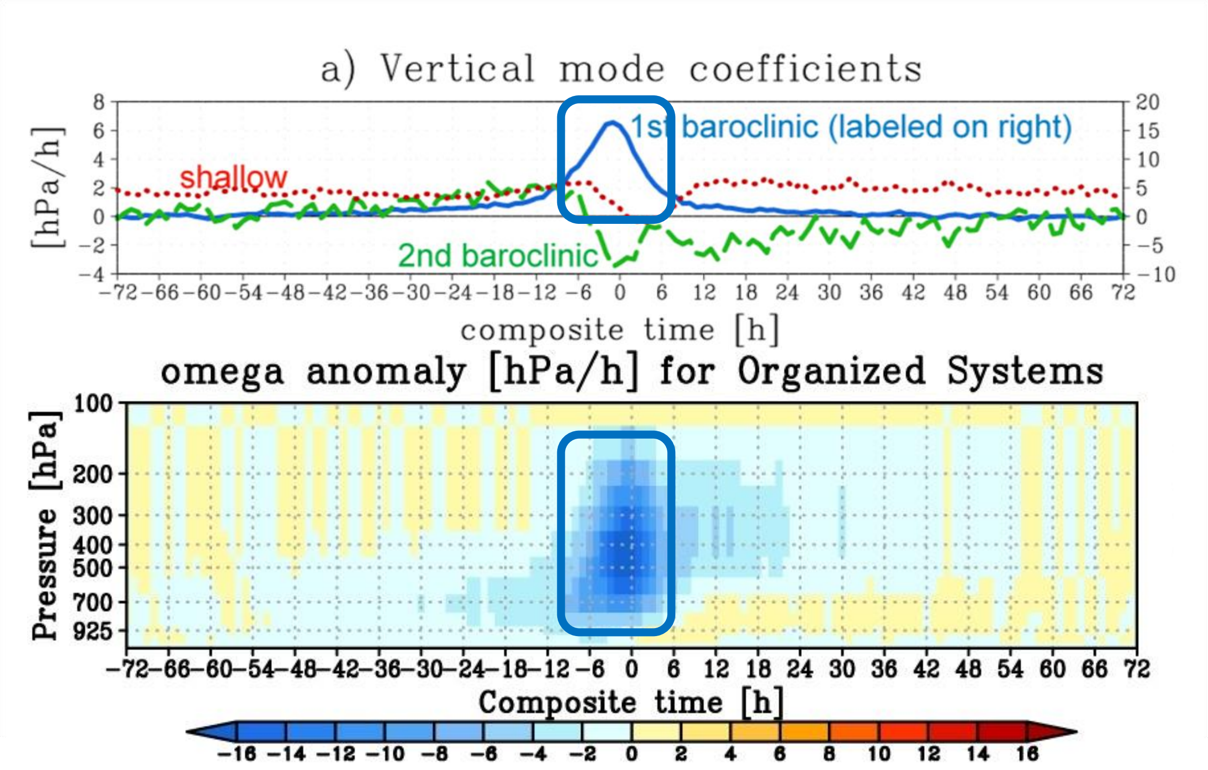


$$\overline{\omega'} = \overline{\omega}_{\mathrm{bc1}} + \overline{\omega}_{\mathrm{bc2}} + \overline{\omega}_{\mathrm{shl}}$$

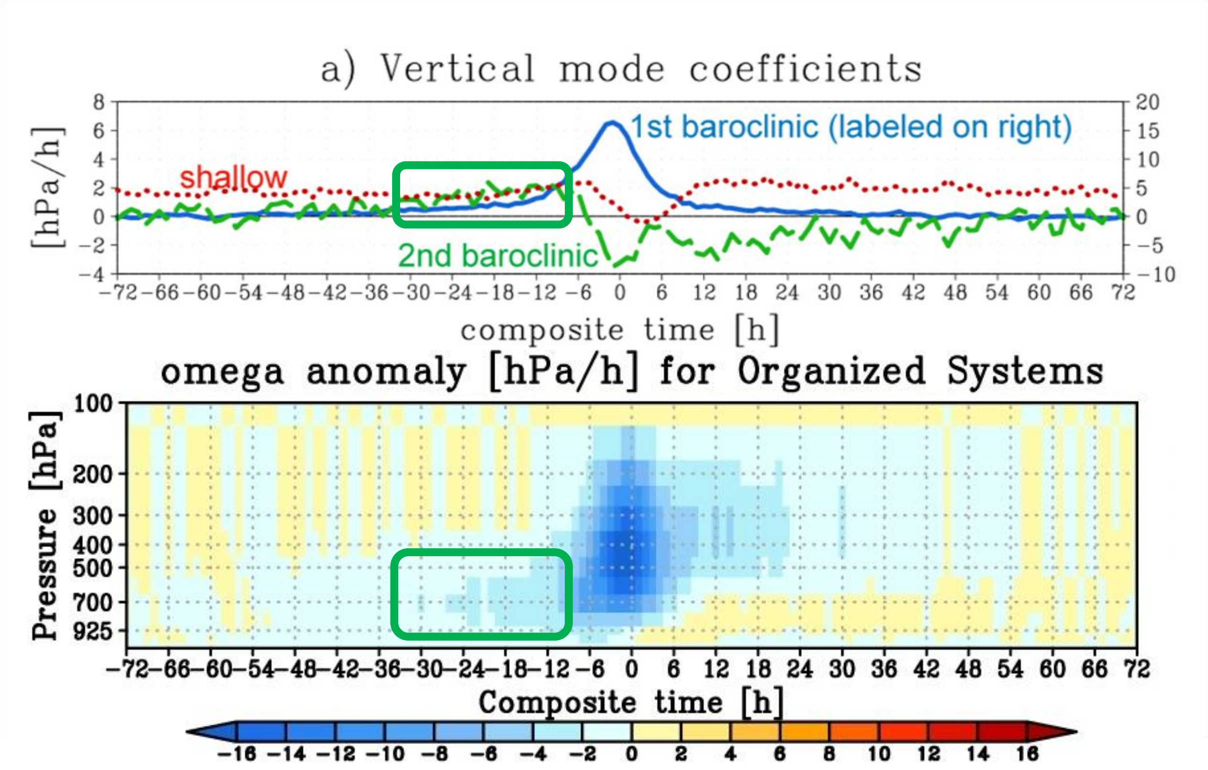
1st baroclinic — 2nd baroclinic — shallow

<u>1st baroclinic mode</u>

- ✓ Deep and intense
- ✓ Unsustainable without external forcing

Masunaga and L'Ecuyer, *JAS*, 2014

Composite time series: Large-scale vertical motion ($\bar{\omega}$)



$$\overline{\omega'} = \bar{\omega}_{\mathrm{bc1}} + \bar{\omega}_{\mathrm{bc2}} + \bar{\omega}_{\mathrm{shl}}$$

1st baroclinic | 2nd baroclinic | shallow

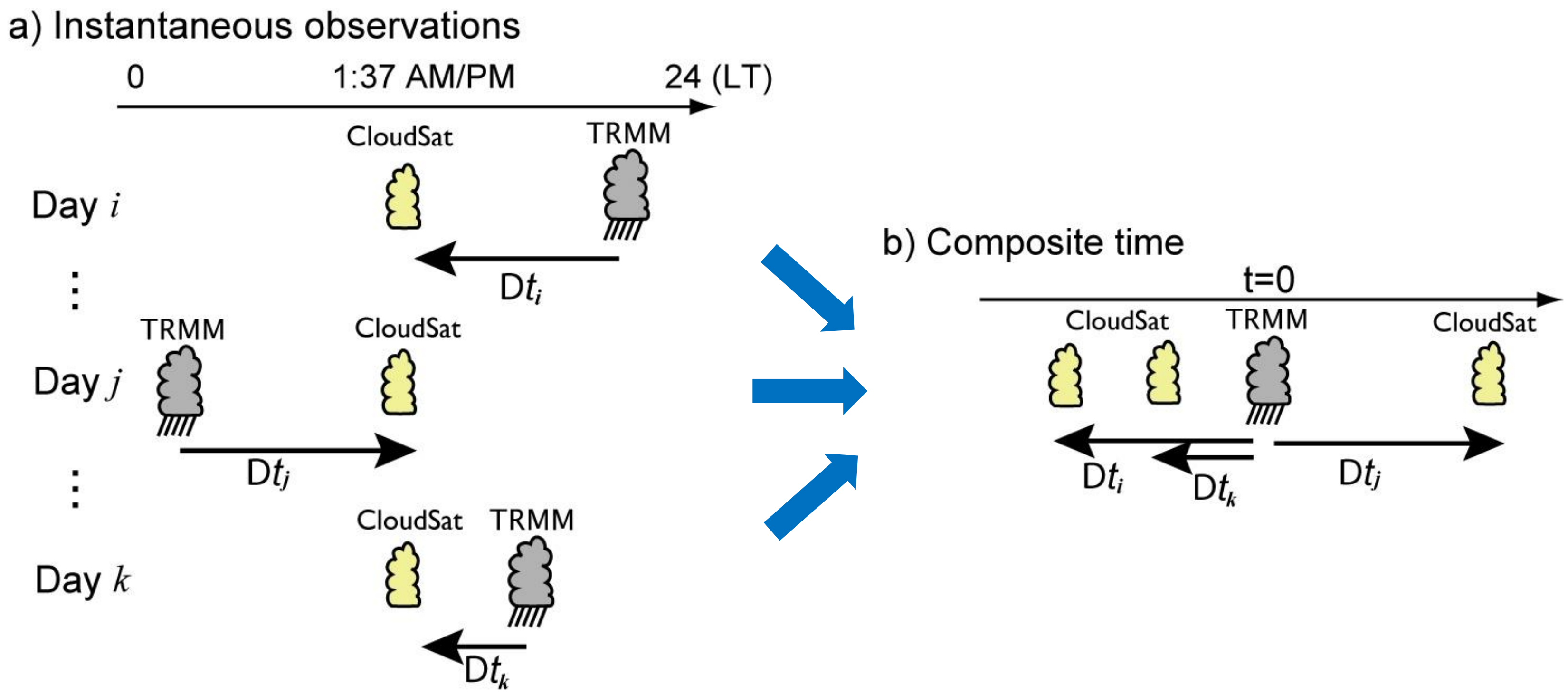
1st baroclinic mode
- ✓ Deep and intense
- ✓ Unsustainable without external forcing

2nd baroclinic mode (when positive in sign)
- ✓ Shallow and modest
- ✓ Capable of growing on its own

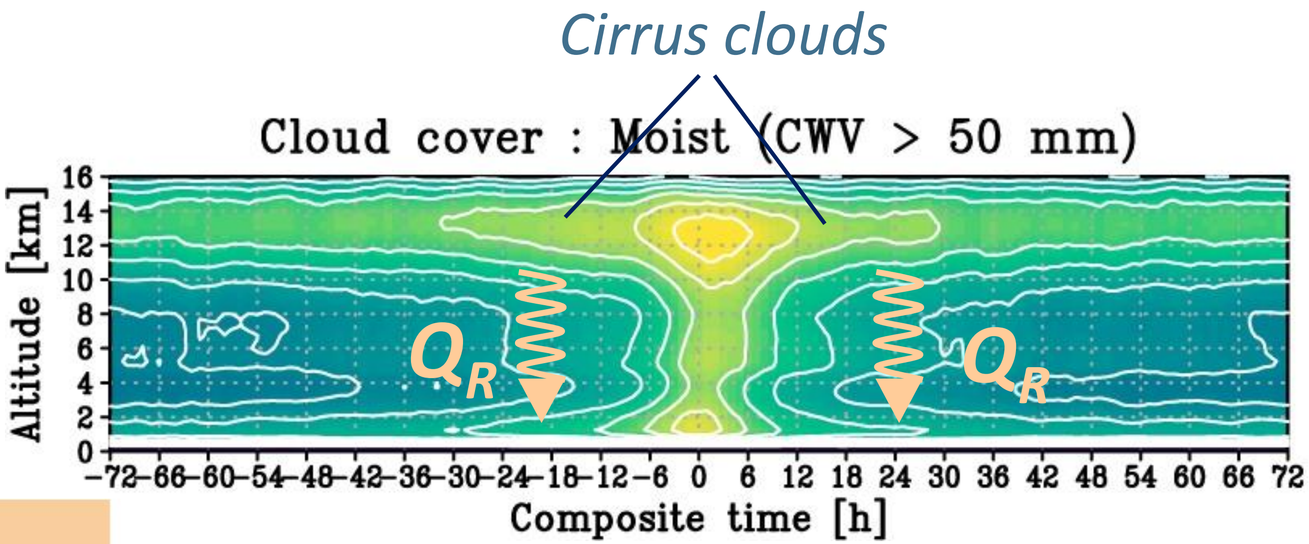
Masunaga and L'Ecuyer, *JAS*, 2014

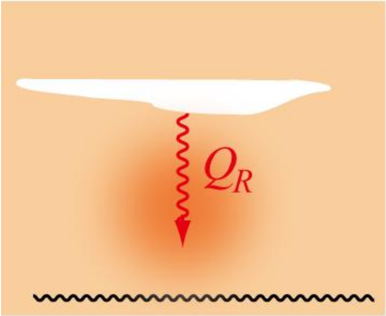
Composite time series: Method with CloudSat/CALIPSO

CloudSat/CALPISO observations are next analyzed to study the evolution of clouds and their radiative effects.

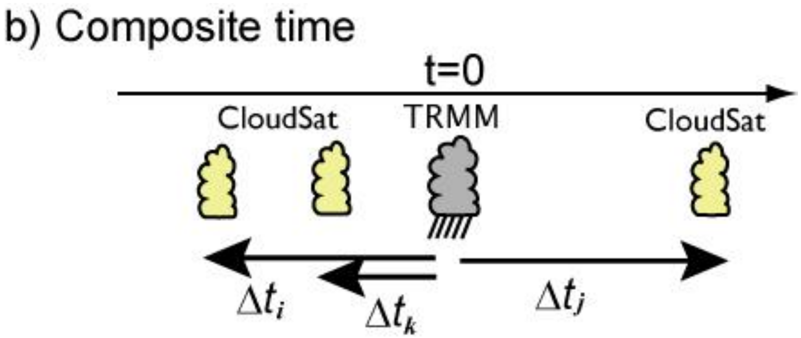


Composite time series: Clouds and radiation



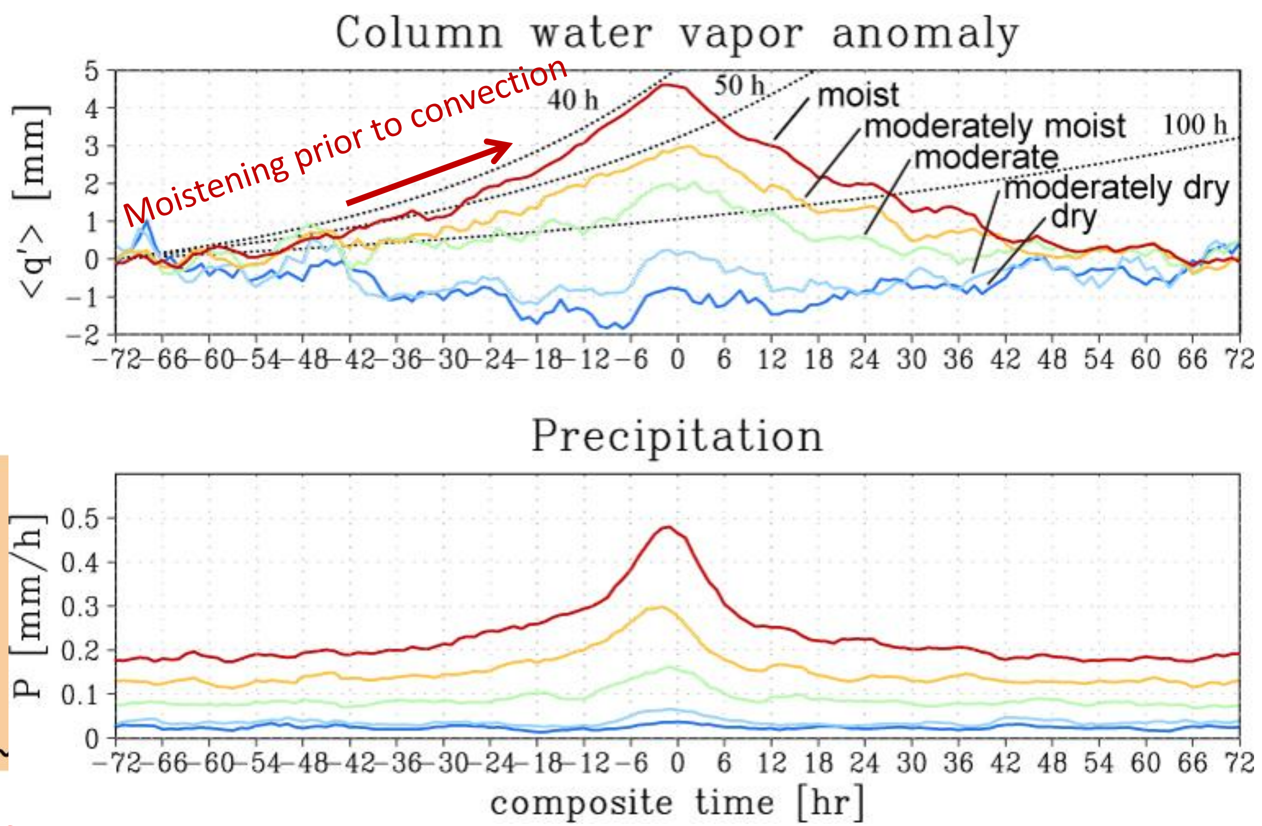


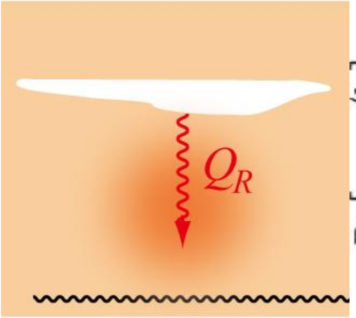
Cirrus LW heating



Masunaga and Bony, *JAS*, 2018

Composite time series: Clouds and radiation

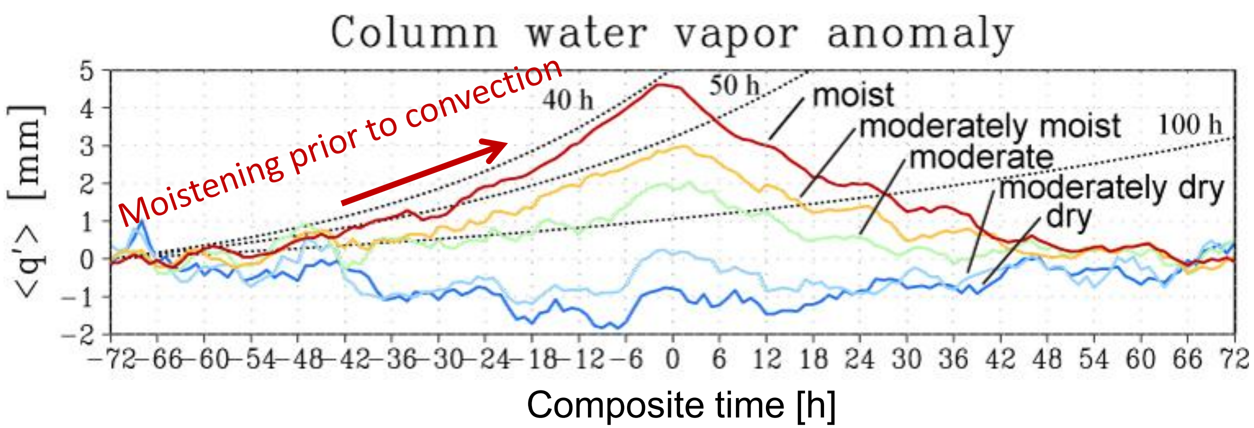


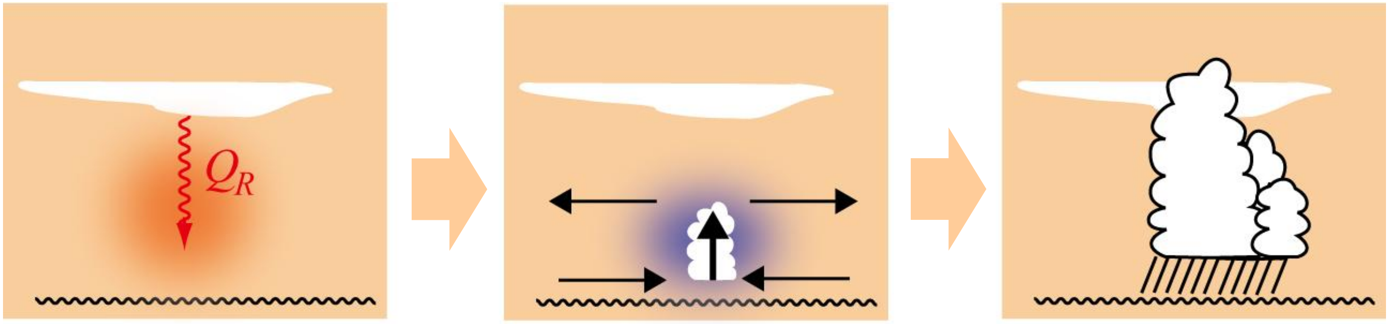


Cirrus LW heating

Masunaga and Bony, *JAS*, 2018

Composite time series: Clouds and radiation





Cirrus LW heating

Moistening by localized shallow circulation

Resulting deepening of convection

2nd baroclinic mode (+)

1st baroclinic mode

Convective dynamics

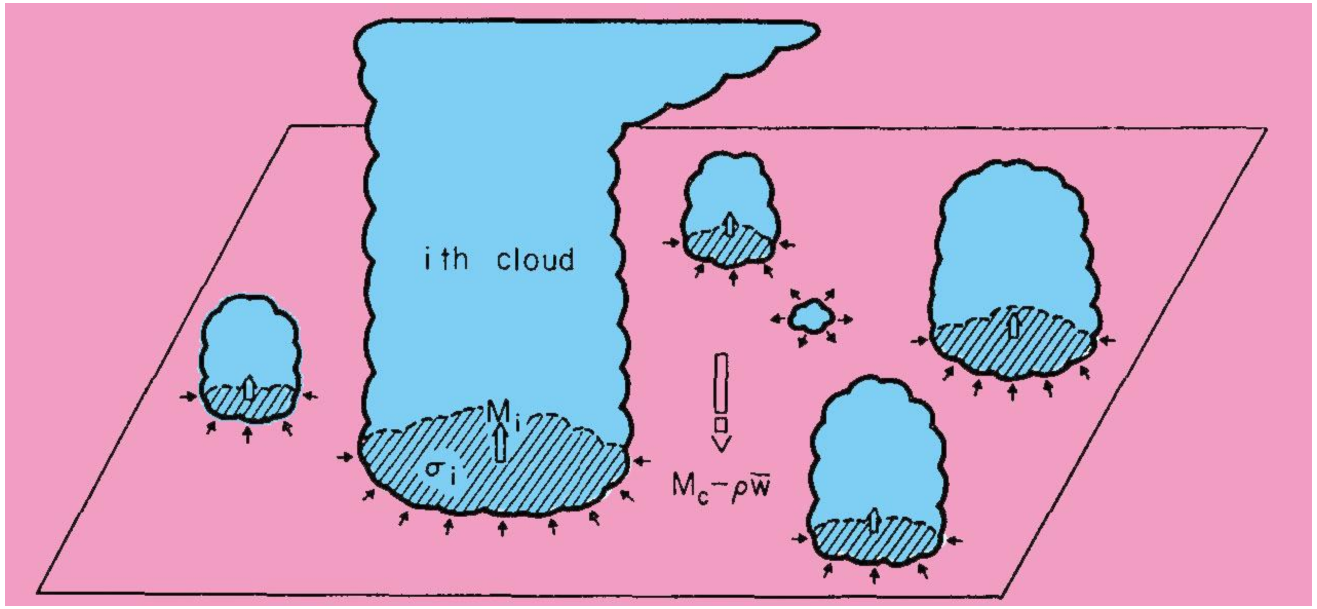
⇕

Large-scale dynamics

Masunaga and Bony, *JAS*, 2018

Old and new problem: vertical motion across scales

Vertical motion spectrum across scales has yet to be understood in more depth.



Arakawa and Schubert, *JAS*, 1974

Convective dynamics

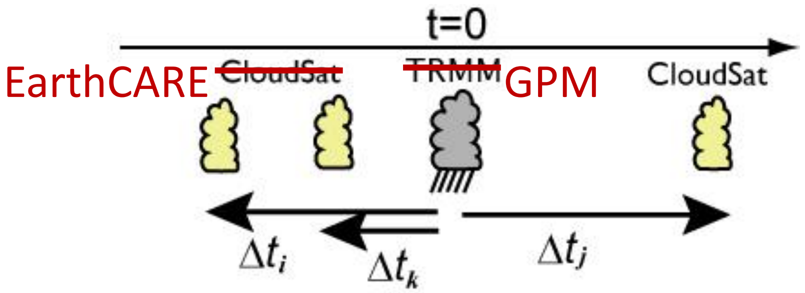
⇕

Large-scale dynamics

Now we have EarthCARE!

EarthCARE CPR/ATLID measurements composited against GPM DPR would illustrate the evolution of

- ✓ Cloud structure including cirrus anvil and cloud radiative effects, just like CloudSat/CALIPSO
- ✓ In-cloud vertical motion derived from Doppler velocity, unlike any other satellites



… but its too early for now to do that.

- ✓ The GPM Core Observatory, whose orbital precession is slower than TRMM, requires a longer period of observations to ensure statistical robustness in composite time series.

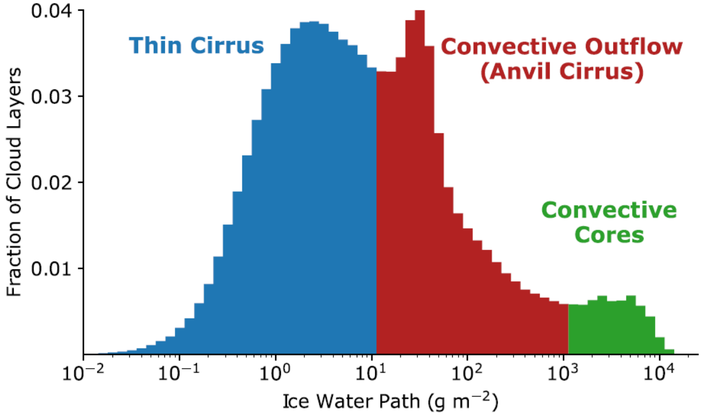
Now we have EarthCARE!

Preliminary analysis of EarthCARE observations

- ✓ Based on the **L2a CPR_CLP** and **L2b CA_CLP** **vBb** products (Sato et al., *AMT*, 2025)
- ✓ 1+ year (Aug. 2024 – Sep. 2025) over global tropical oceans (20°S-20°N)

Targeted mainly on in-cloud vertical air velocity ($w_{a,c}$) in **anvil cirrus clouds**

- ✓ Deep convective $w_{a,c}$ is tricky due to Doppler aliasing (although not excluded from the analysis).
- ✓ Thin cirrus is also challenging because signals are week and $w_{a,c}$ is small.
- ✓ Mirror image echoes can be problematic but are removable (not discussed today).

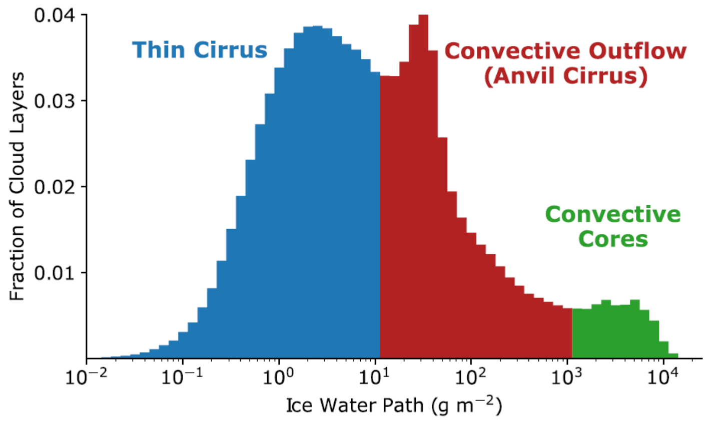


Sokol and Hartmann, *JGR*, 2020

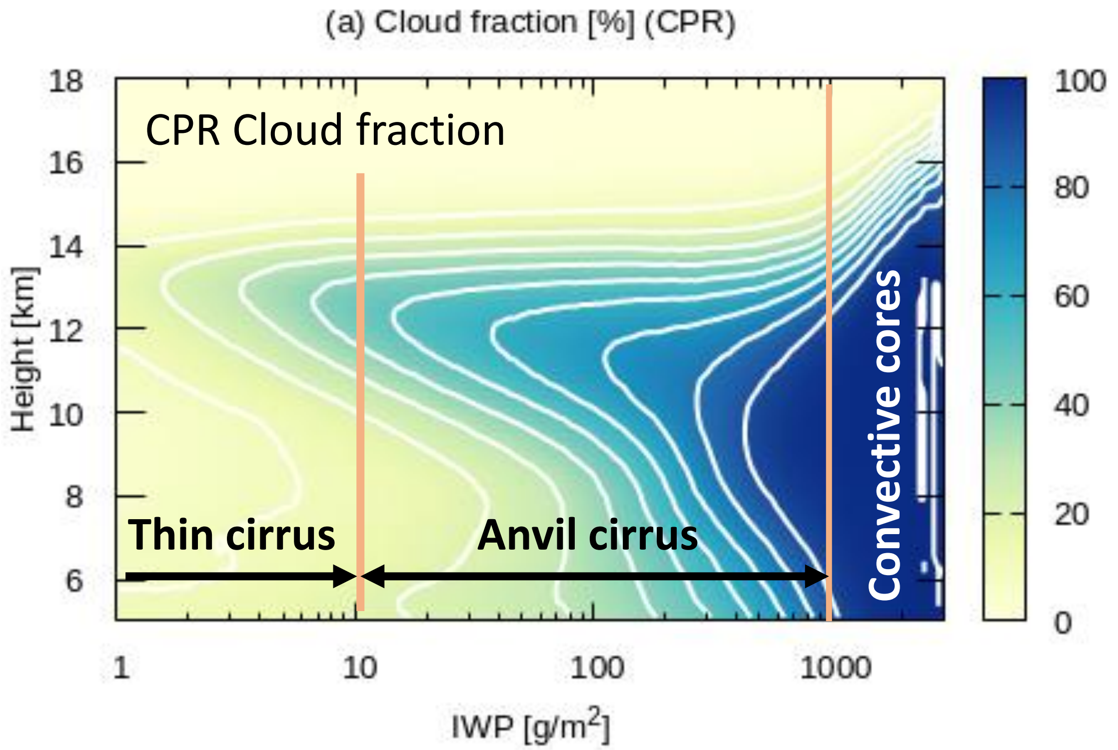
IWP-sorted composite: cloud fraction

Analysis strategy

1. IWP-sorted composite of vertical cloud/$w_{a,c}$ structure (e.g., Gasparini et al., *JAMES*, 2019)
2. Convection-centered composite of vertical cloud/w_{air} structure (e.g., Ito and Masunaga, *GRL*, 2022)



Sokol and Hartmann, *JGR*, 2020



IWP-sorted composite: Doppler velocity

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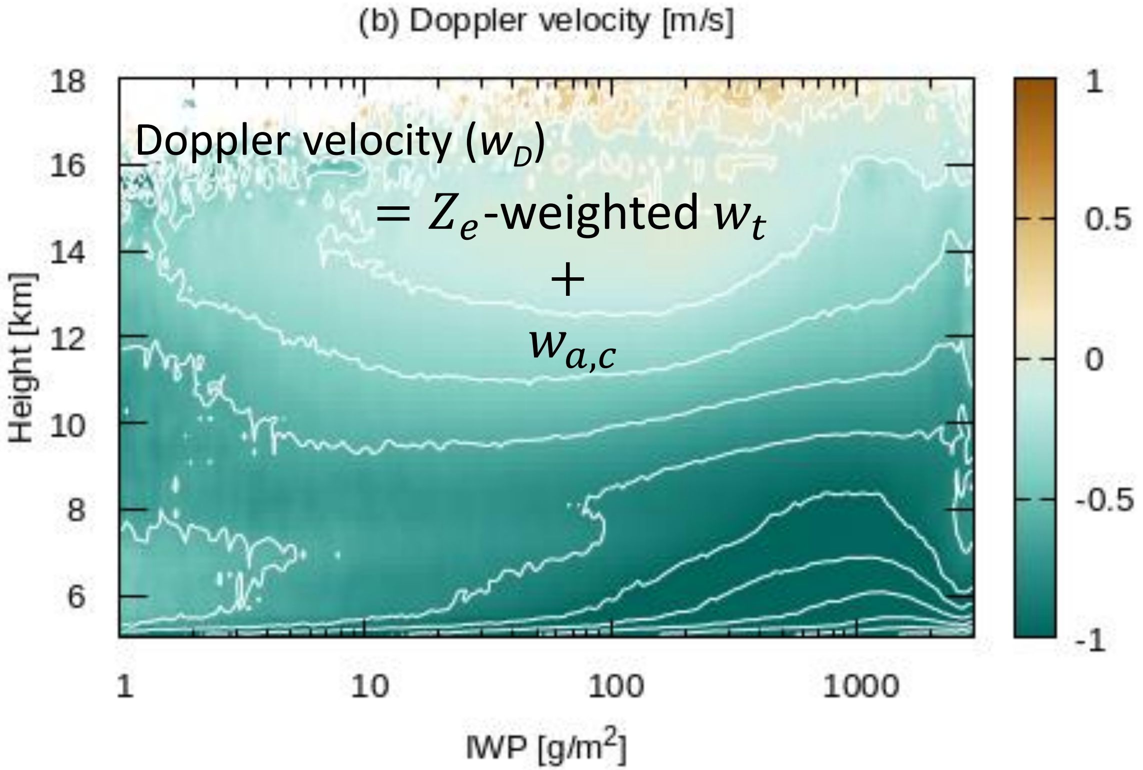
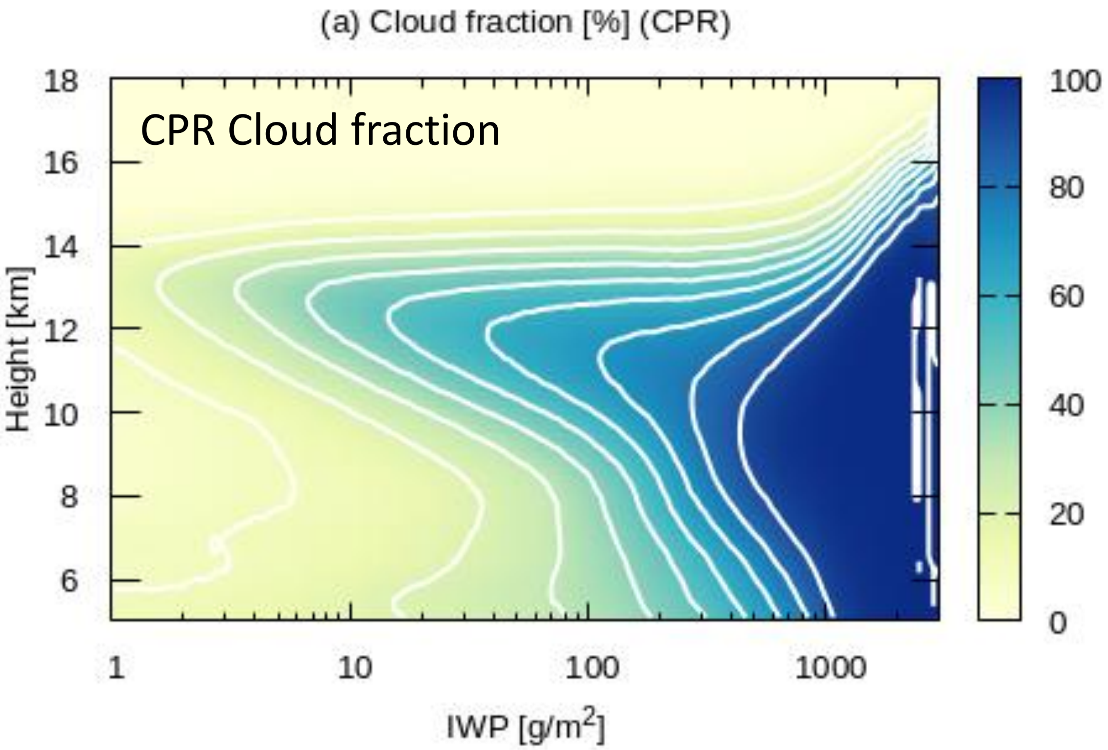
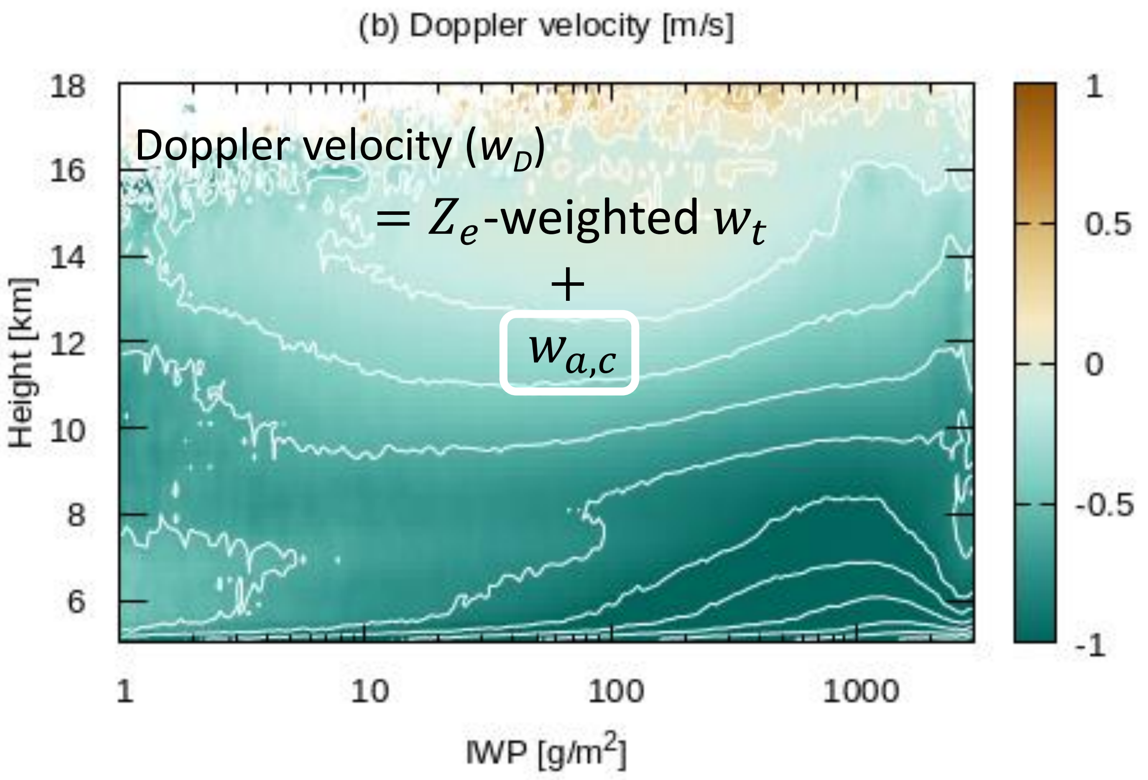


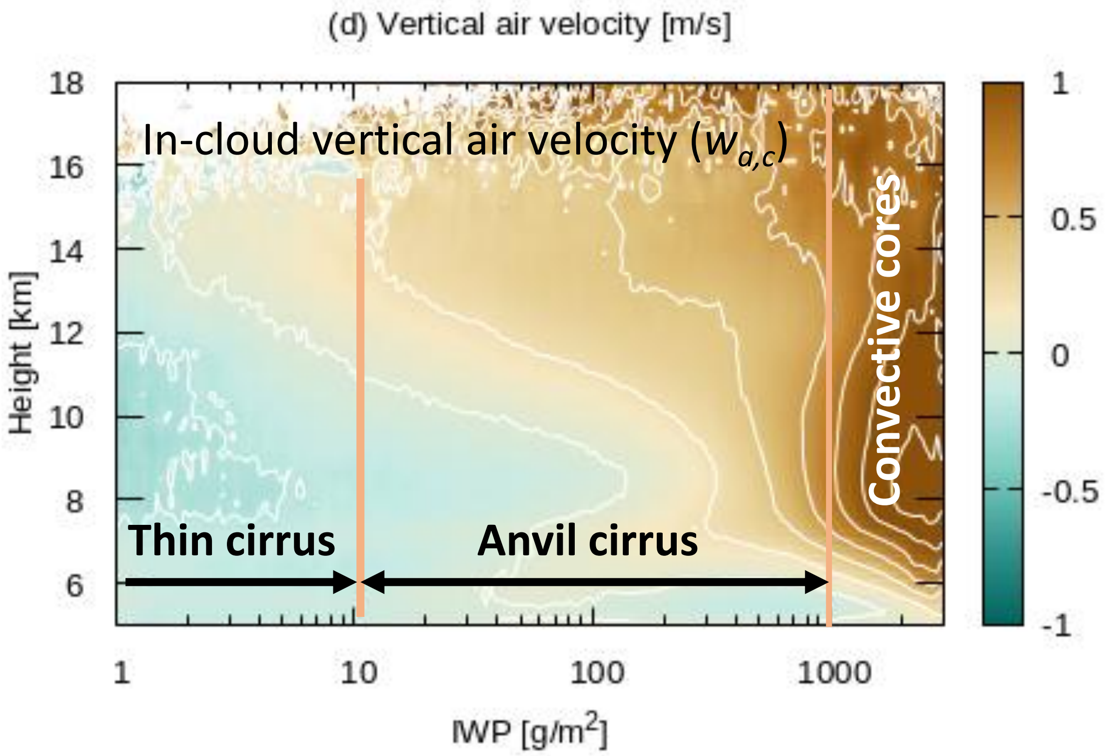


IWP-sorted composite: Doppler velocity and $w_{a,c}$

Analysis strategy

1. IWP-sorted composite of vertical cloud/$w_{a,c}$ structure (e.g., Gasparini et al., *JAMES*, 2019)
2. Convection-centered composite of vertical cloud/w_{air} structure (e.g., Ito and Masunaga, *GRL*, 2022)





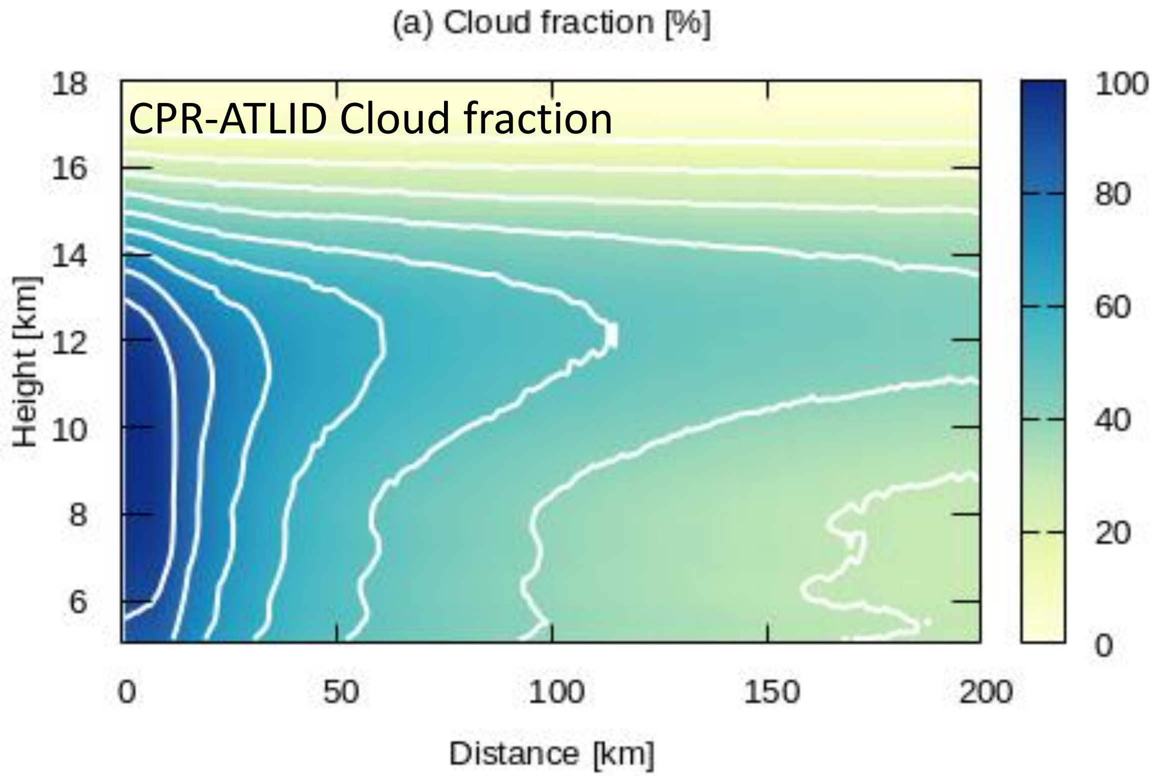
Convection-centered composite: cloud fraction

Analysis strategy

1. IWP-sorted composite of vertical cloud/$w_{a,c}$ structure (e.g., Gasparini et al., *JAMES*, 2019)
2. Convection-centered composite of vertical cloud/w_a structure (e.g., Ito and Masunaga, *GRL*, 2022)

Compositing method

- ✓ A convective core is defined by IWP>10^3 g/m^2.
- ✓ Cloud variables are sorted by the distance from the convective core.
- ✓ IWP must be below 10^3 g/m^2 outside the core.



Convection-centered composite: w_a and divergence

Analysis strategy

1. IWP-sorted composite of vertical cloud/$w_{a,c}$ structure (e.g., Gasparini et al., *JAMES*, 2019)
2. Convection-centered composite of vertical cloud/w_a structure (e.g., Ito and Masunaga, *GRL*, 2022)

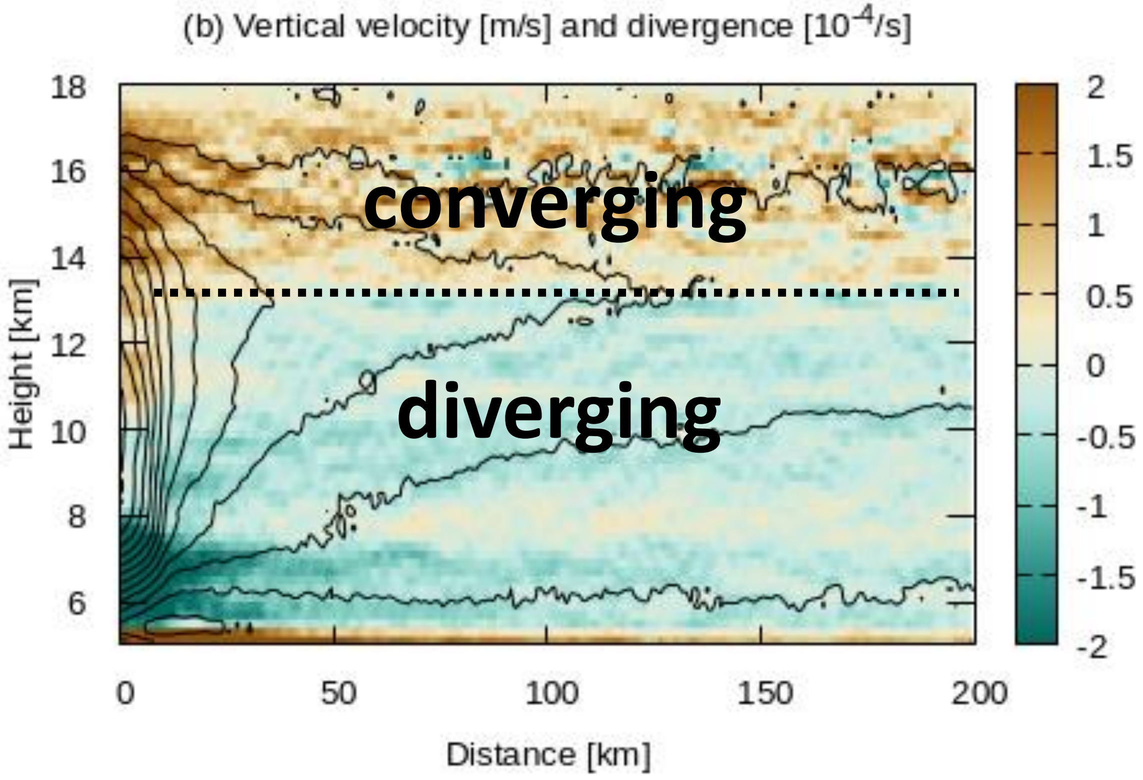
Horizontal divergence, *D*, is estimated by

$$D \equiv -\frac{\partial w_a}{\partial z},$$

where all-sky vertical motion is given as

$$w_a = f_c w_{a,c} + (1 - f_c) w_{a,a}$$

with the observed cloud fraction, f_c.
The ambient velocity $w_{a,a}$ is tentatively assumed to be zero.



Shade: horizontal convergence, Contours: w_a

Convection-centered composite: w_a and divergence

Analysis strategy

1. IWP-sorted composite of vertical cloud/$w_{a,c}$ structure (e.g., Gasparini et al., *JAMES*, 2019)
2. Convection-centered composite of vertical cloud/w_a structure (e.g., Ito and Masunaga, *GRL*, 2022)

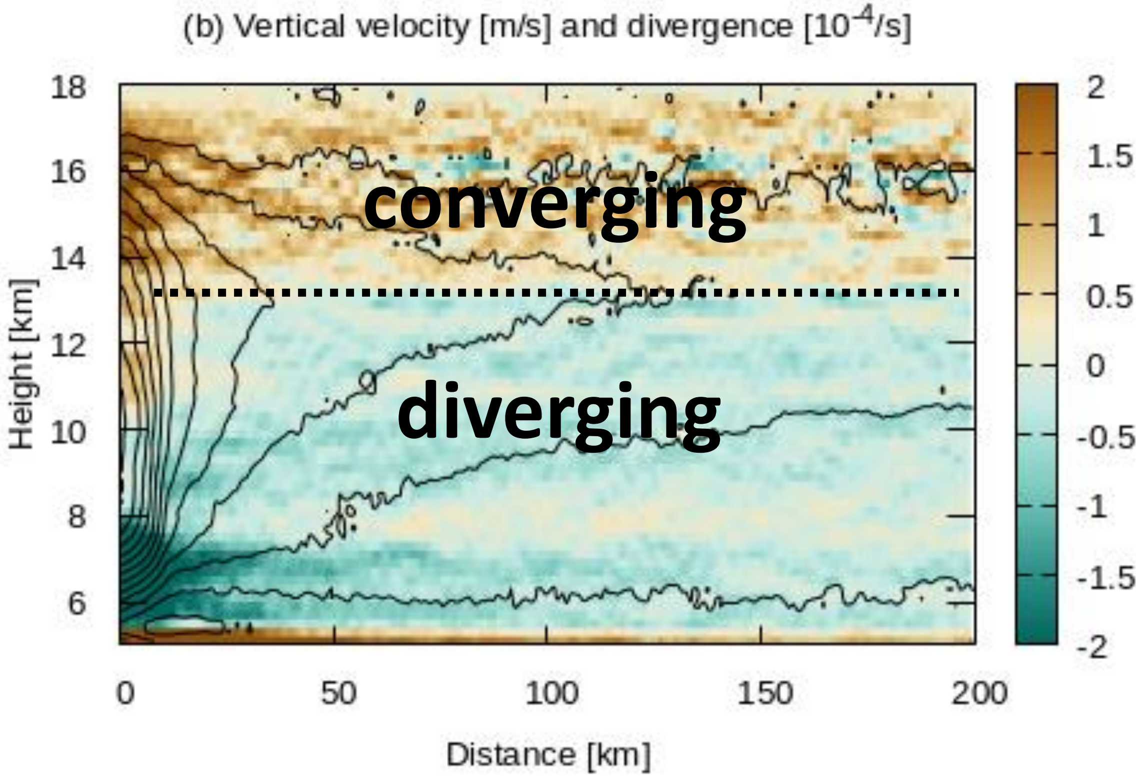
Horizontal wind, u_r, is derived by integrating the axisymmetric continuity equation over distance *r*,

$$\frac{1}{r}\frac{\partial(ru_r)}{\partial r} + \frac{\partial w_a}{\partial z} = 0,$$

or

$$u_r = -\frac{1}{r}\int_0^r r'\frac{\partial w_a}{\partial z}dr'$$

with the boundary condition of $u_r = 0$ at $r = 0$.



Shade: horizontal convergence, Contours: w_a

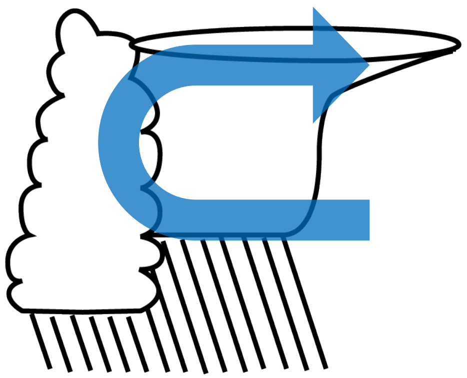
Convection-centered composite: circulation field

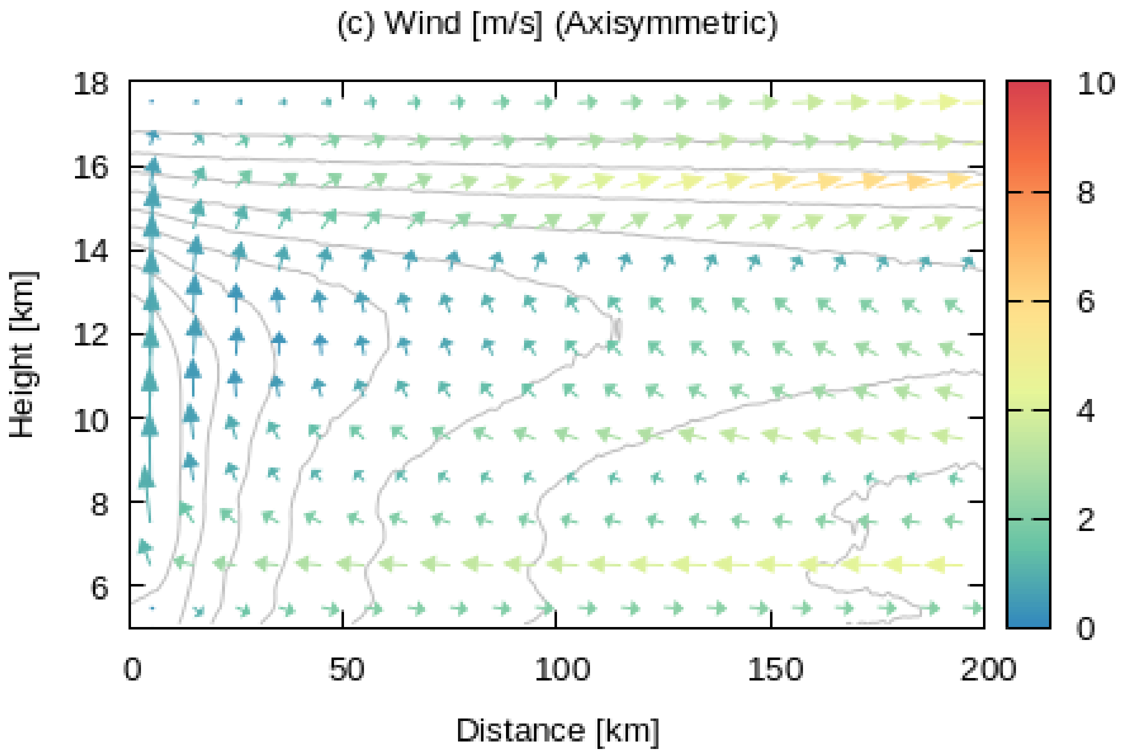
Analysis strategy

1. IWP-sorted composite of vertical cloud/$w_{a,c}$ structure (e.g., Gasparini et al., *JAMES*, 2019)
2. Convection-centered composite of vertical cloud/w_a structure (e.g., Ito and Masunaga, *GRL*, 2022)

Horizontal wind, u_r, is derived by integrating the axisymmetric continuity equation over distance *r*,

$$\frac{1}{r}\frac{\partial(ru_r)}{\partial r} + \frac{\partial w_a}{\partial z} = 0,$$

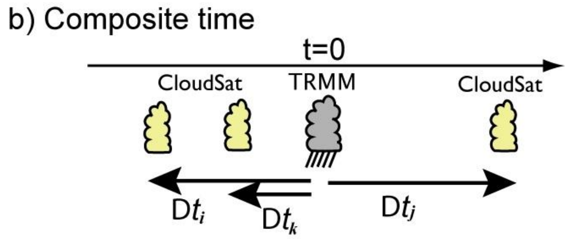


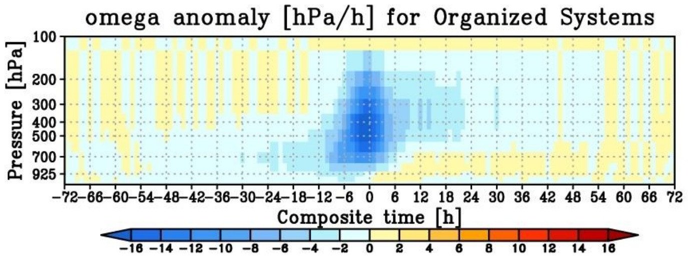


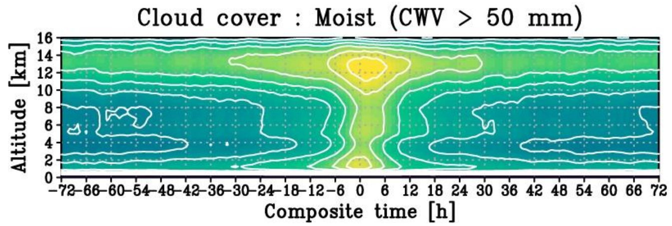
Color: wind speed $= \sqrt{u_r^2 + w_a^2}$

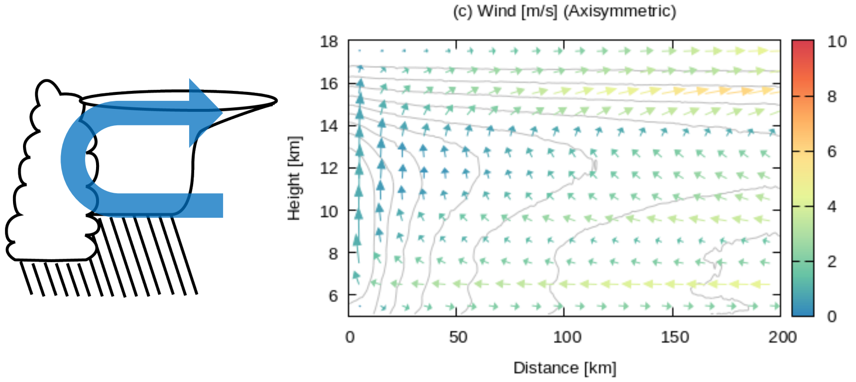
Takeaways

- Mapping Δt between polar and sun-asynchronous orbiters onto composite time series offers a way to study hourly to daily convective variability.
  - AIRS with TRMM → T, q, and derived ω
  - CloudSat/CALIPSO with TRMM → clouds, Q_R
- EarthCARE further boosts the potential of the existing constellation of LEO satellites.
  - Not just vertical air motion but even mesoscale circulation in convective systems can be derived from observations.
- So will future satellite missions.
  - INCUS, AOS PMM/C^2OMODO, …







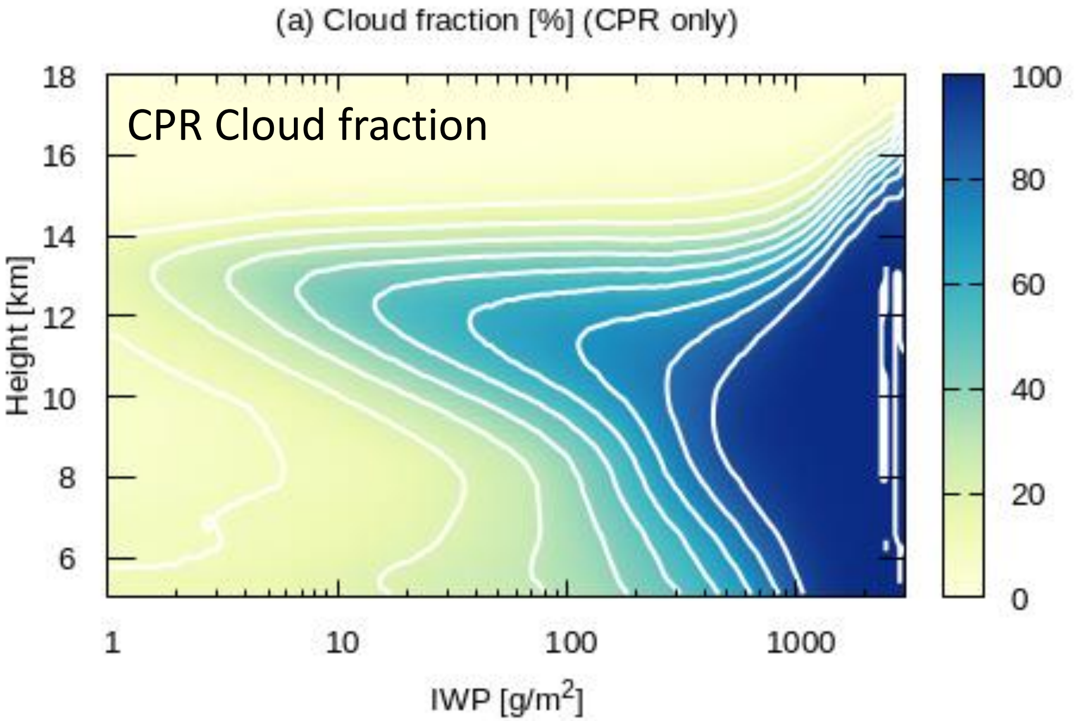


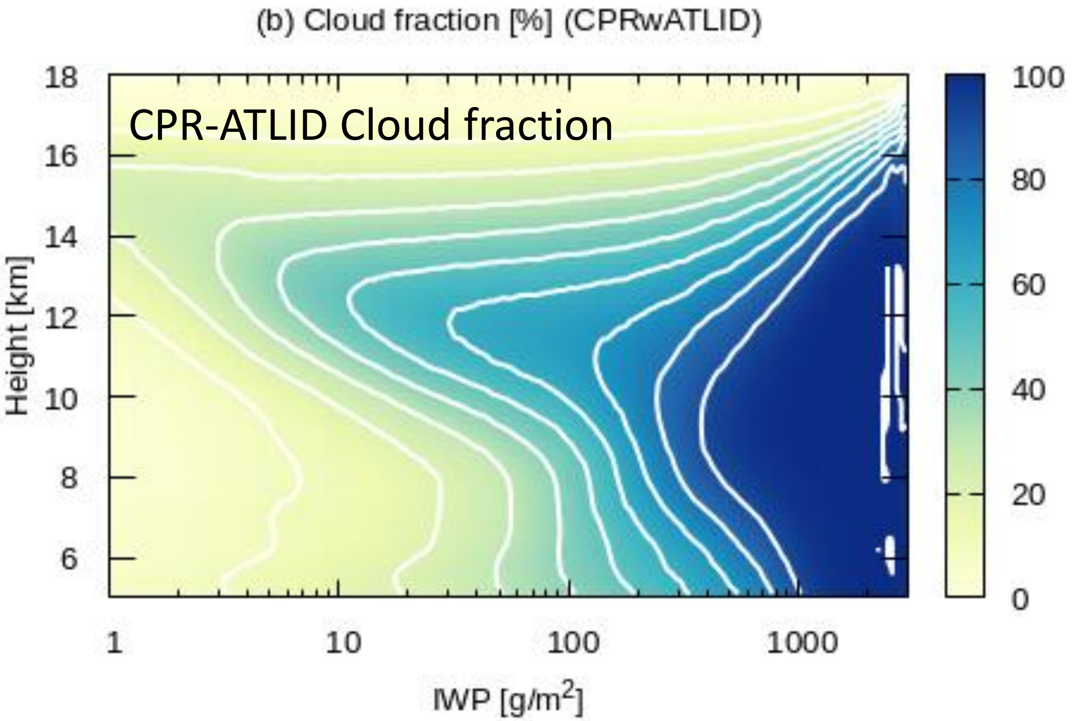
Backup slides

IWP-sorted composite: CPR only versus CPR-ATLID

Analysis strategy

1. IWP-sorted composite of vertical cloud/$w_{a,c}$ structure (e.g., Gasparini et al., *JAMES*, 2019)
2. Convection-centered composite of vertical cloud/w_{air} structure (e.g., Ito and Masunaga, *GRL*, 2022)





IWP-sorted composite: CPR only versus CPR-ATLID

Analysis strategy

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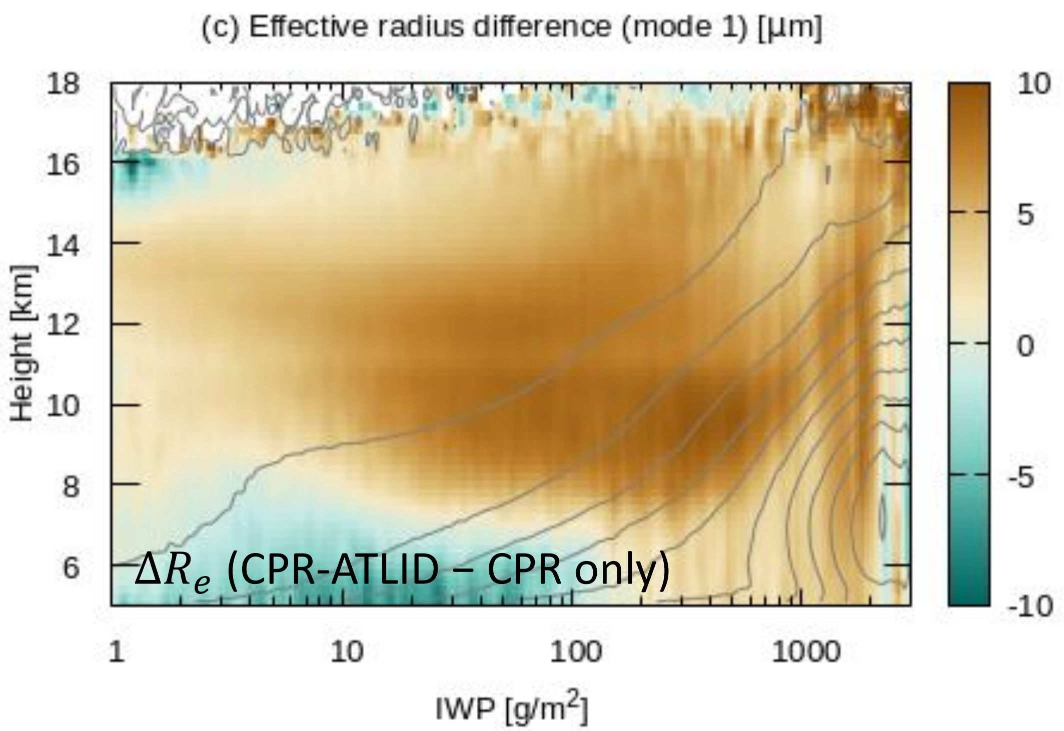
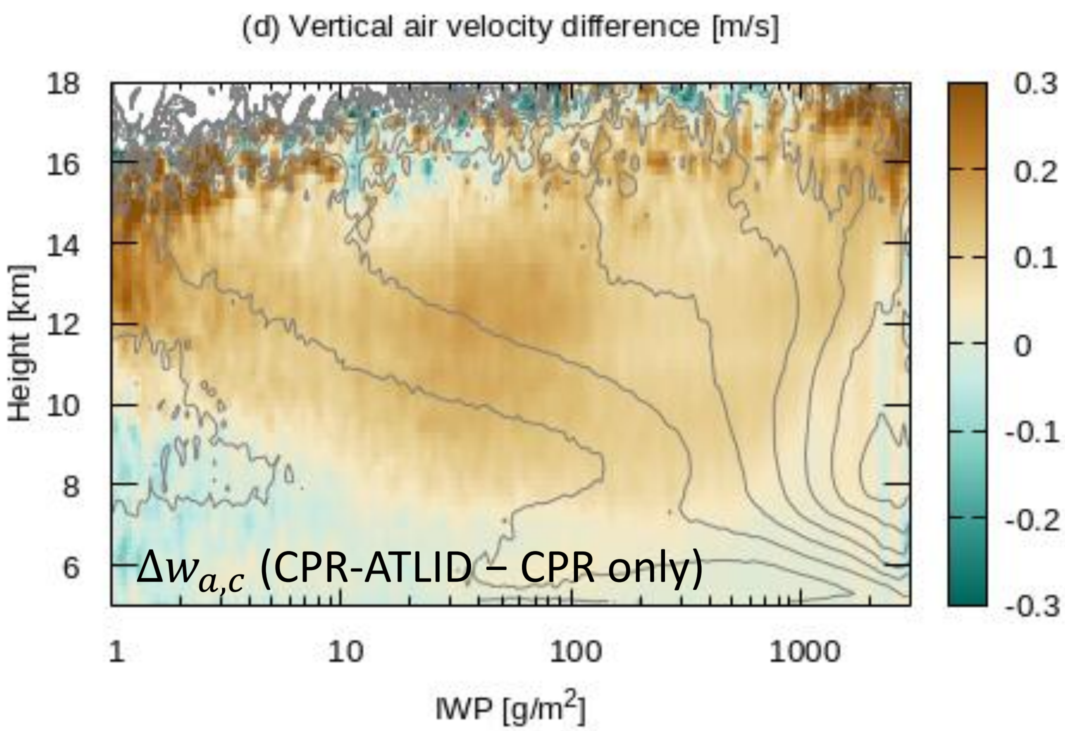


Contours: R_e (CPR only, 20-µm interval)



Contours: $w_{a,c}$ (CPR only, 0.2-m/s interval)

Removal of mirror image echoes

Mirro image