Relating vertical velocity and cloud/precipitation properties: A numerical modeling study of Tropical convection

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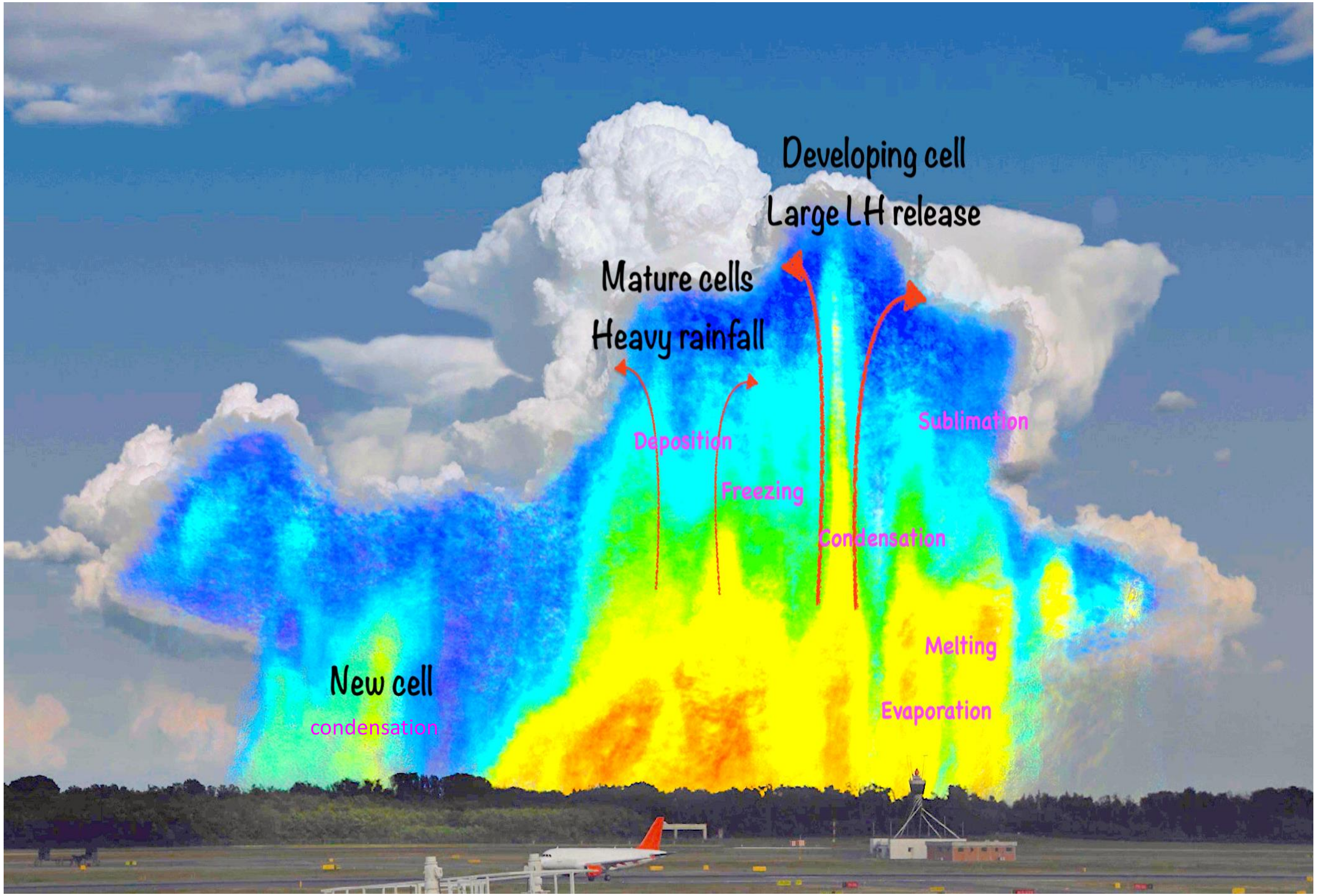
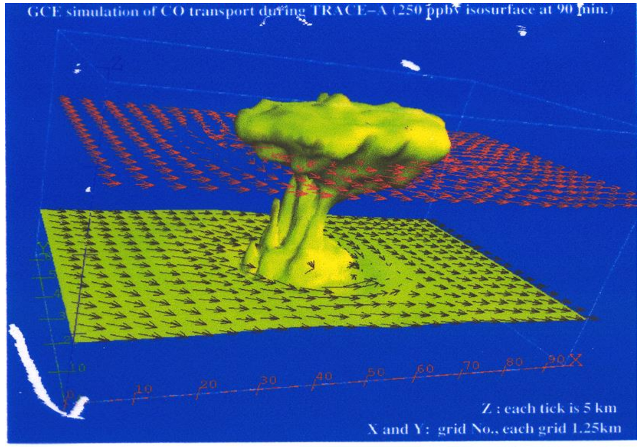
- Background (vertical velocity)
- Model (GCE) and Model set up (Sounding Estimated Forcing)
- Cases (DYNOMO and GOAmazon)
- Results (active updrafts/downdrafts; Microphysical properties ..)
- Summary (discussion)

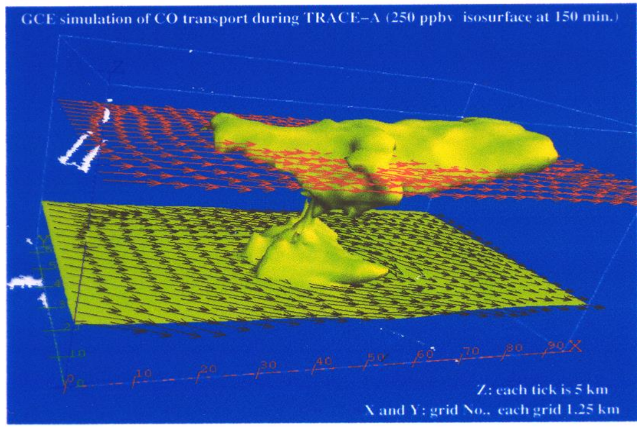
June 2, 7:30 AM
June 6, 11:30 PM

Tao, W.-K., T. Iguchi, S. Lang, X. Li, K. Mohr, T. Matsui, S. C. van den Heever and S. Braun, 2022: Relating Vertical Velocity and Cloud and Precipitation Properties: A Numerical Modeling Study. *J. Adv. Model. Earth Syst., e2021MS002677. https://doi.org/10.1029/2021MS002677*.

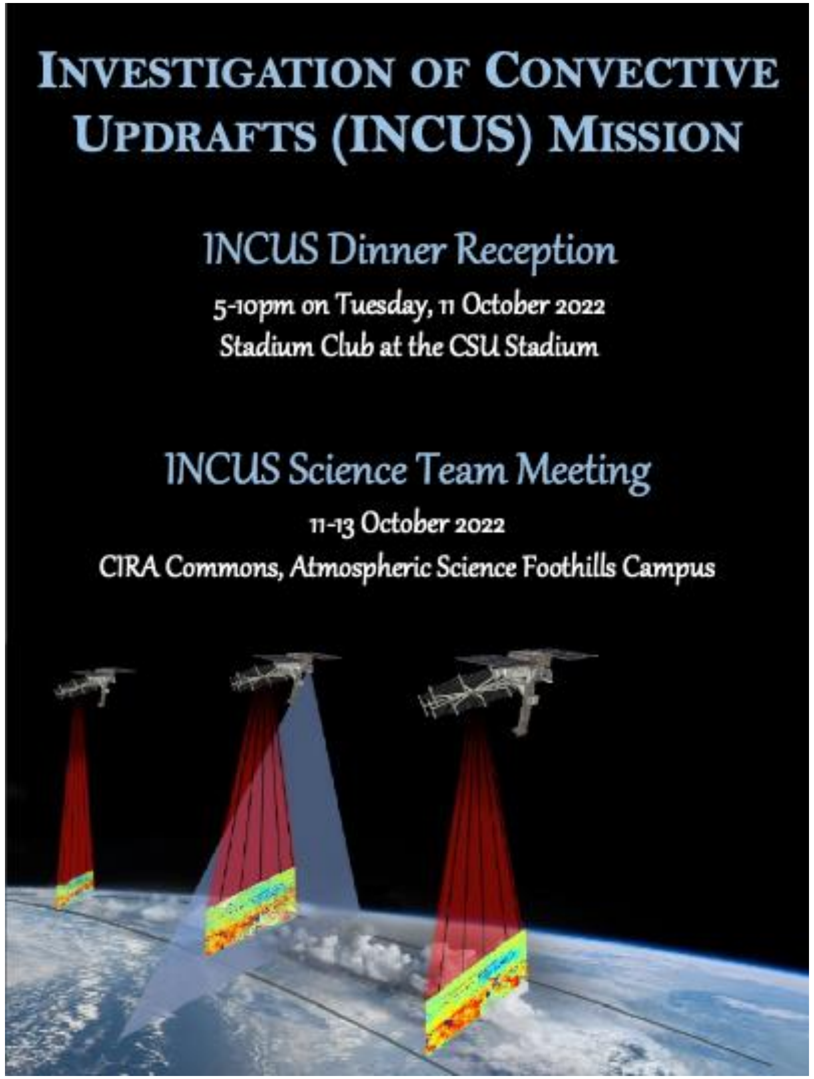


Inert Tracer Calculated from GCE model: Low-level tracer transported to upper atmosphere by convective updraft.

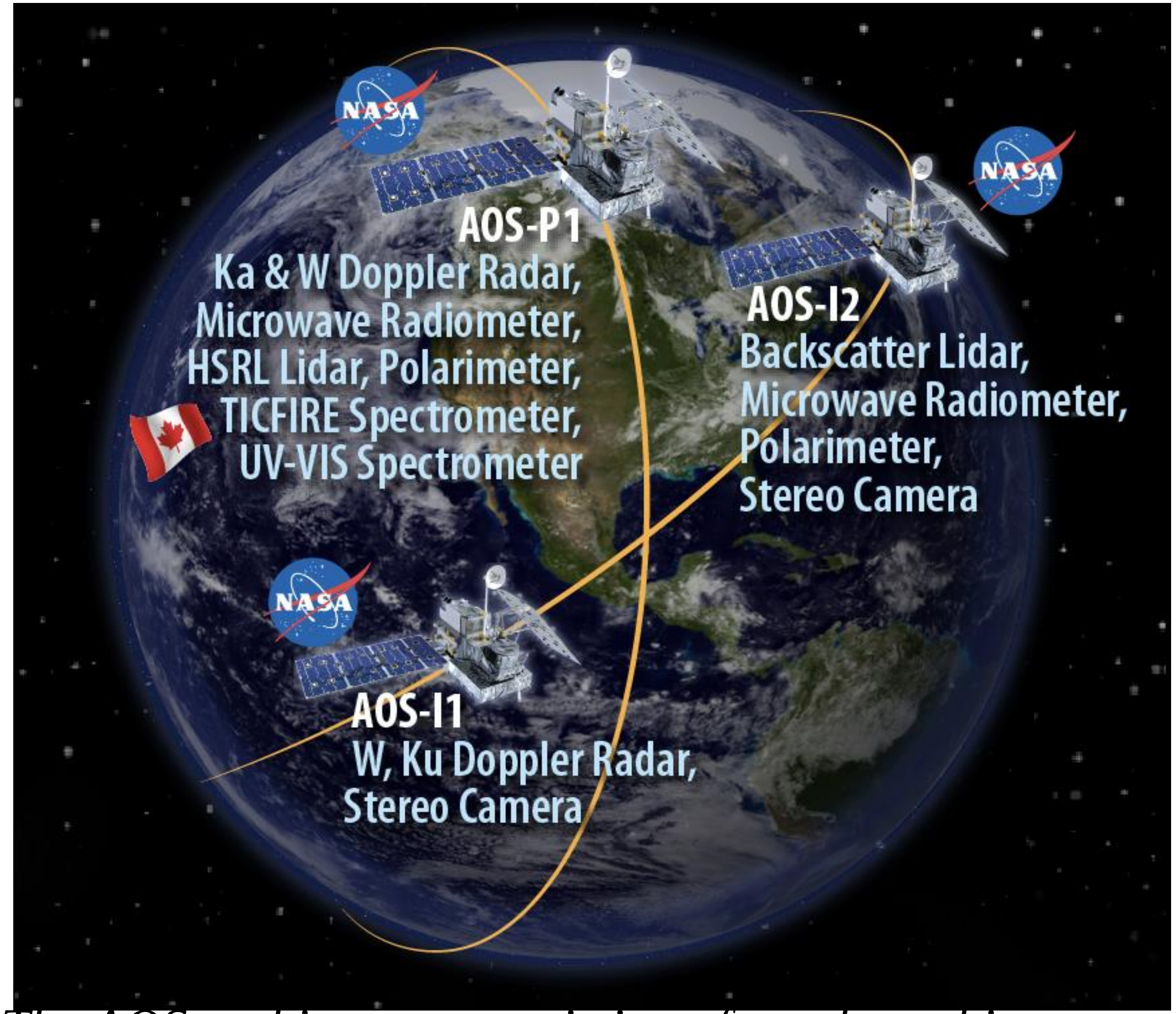




S. C. van den Heever (CSU)



S. Braun (NASA Goddard)



The AOS architecture consisting of a polar orbit (AOS-P1) and inclined orbit (AOS-I1 and AOS-I2).

INCUS: Investigation of Convective Updraft Mission (Launched 2026)

AOS: Atmosphere Observing System (Launched 2028-2029)

The goal of Investigation of Convective Updraft Mission (INCUS) is to quantify relationship between microphysics and storm dynamics linked through updraft/downdraft cores, using cloud-resolving model simulations.

One of the *key Atmosphere Observing System* (AOS) *Mission's* scientific goals is to examine the relationships between vertical velocities and resulting liquid and ice hydrometeor species. The AOS Mission will allow us to address such goals through the first ever: (1) global observations of updraft and downdraft convective storm velocities and (2) global collocated observations of the microphysical and dynamical properties of convective cloud systems.

The goal of this modeling study is to quantify relationship between microphysics and storm dynamics linked through updraft/downdraft cores.

Motivation (W-velocity)

Why do this? Improving weather and climate prediction require our understanding of physical processes (NASA Decadal Survey). Currently we do NOT have a way of directly measuring microphysical processes. Measuring vertical velocities in cloud updrafts and downdrafts will enable us retrieve these processes.

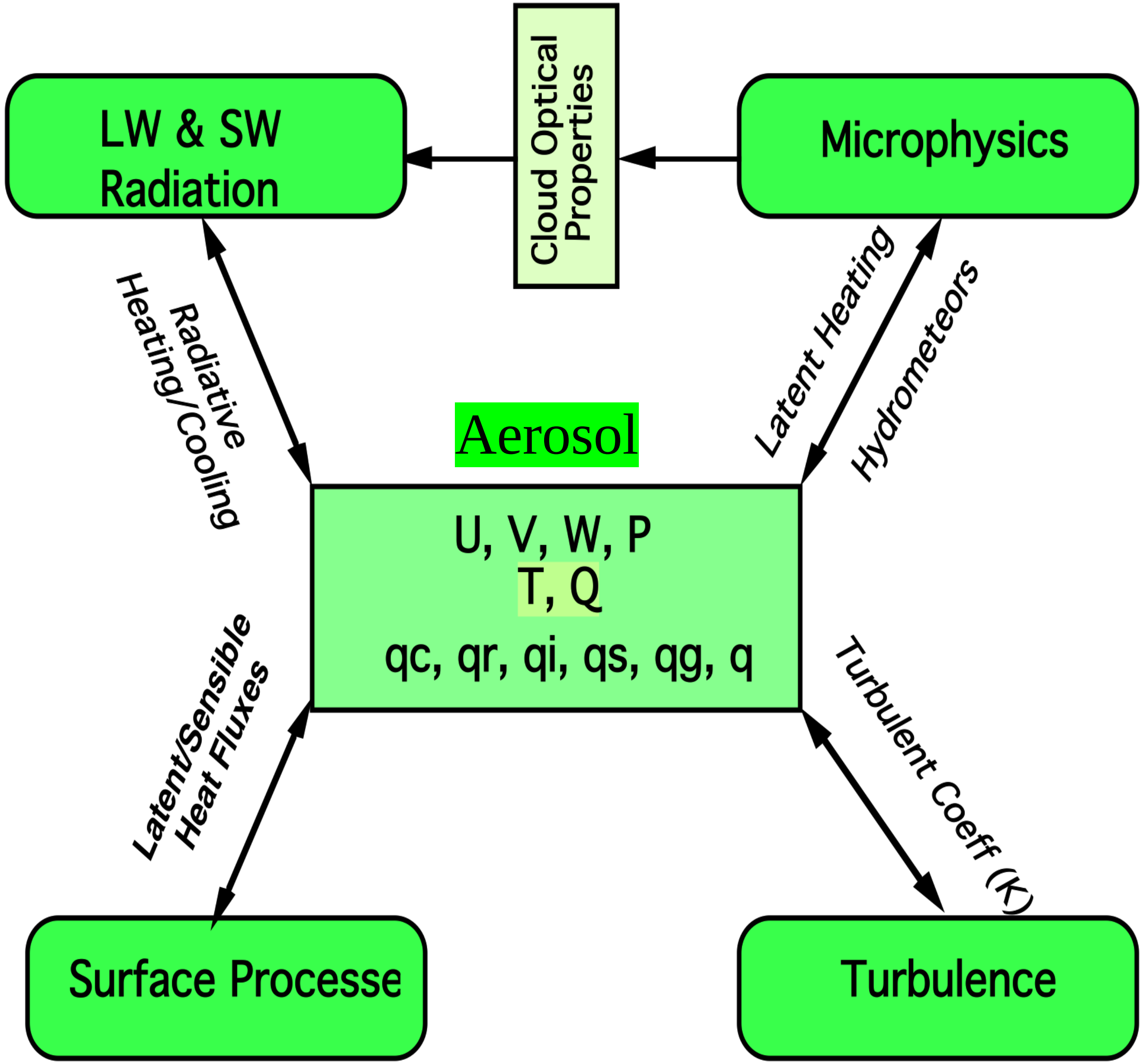
Why now? Doppler Radars, which are the main remote sensing instrument to measure air velocity, are increasing available. EarthCare and NASA's upcoming AOS (Atmosphere Observing System, collaborations with JAXA) Mission will carry a space-borne Doppler Radar and will be able to observed vertical velocity globally.

What is cloud model, cloud ensemble model, cloud resolving model, cloud-system resolving model, or cloud (convective)-permitting model?

- Non-hydrostatic (same order in W and U/V) –

  Anelastic or Compressible
- Horizontal resolution (< 1 km)
- **Cloud and microphysics (liquid/solid)**
- Turbulence (***LES – lower order***)
- Large-domain (MCSs)
- Radiation (**no need for cloud overlap assumption**)
- Surface processes
- Aerosol (indirect and indirect)

Goddard Cumulus Ensemble Model (GCE) (1989-Present; over 150 papers)



GCE Model Description:

Tao and Simpson (1993)

Tao *et al.* (2003),

Tao (2003)

Tao *et al.* (2014)

CRM review paper:

Tao and Moncrieff (1999 – *Geophy Rev*)

Aerosol review paper:

Tao *et al.* (2012 – *Geophy Rev*)

May write a review paper on CRM

Evolution of GCE Model Development and Microphysics Schemes

Year	Development/Improvement	Name
1989	**Saturation Adjustment**	Tao, Simpson, McCumber
1993	2D and 3D Anelastic & Compressible Stretched Grid (V+H)	Tao
1994, 1998, 2007, 2011, 2014	4-Classes Microphysics	S. Lang, B. Ferrier
1996	TOGA COARE Flux Ocean Surface	Y. Wang
1998	Land (PLACE)	B. Lynn
1996	Radiation	Tao, Sui
2007	MPI	H. Juang
2009	**Spectral bin microphysics**	X. Li, D. Johnson
2009, 2013	Aerosol (IN, CCN)	X. Zeng. X. Li
2018	Unified GCE **Added: RAMS, Morrison**	T. Matsui
1998	Coupled to global model	J. Chern
2016	LES mode	X. Li, T. Matsui
1989, 1991, 1993, 1994	Tracer transport & Trajectory	Tao
2024/2025	**2-M 4 Class Ice**	Chung/NCU

CRM Simulated heating (LH, Q_1, Eddy Transport and Q_1-Q_R)

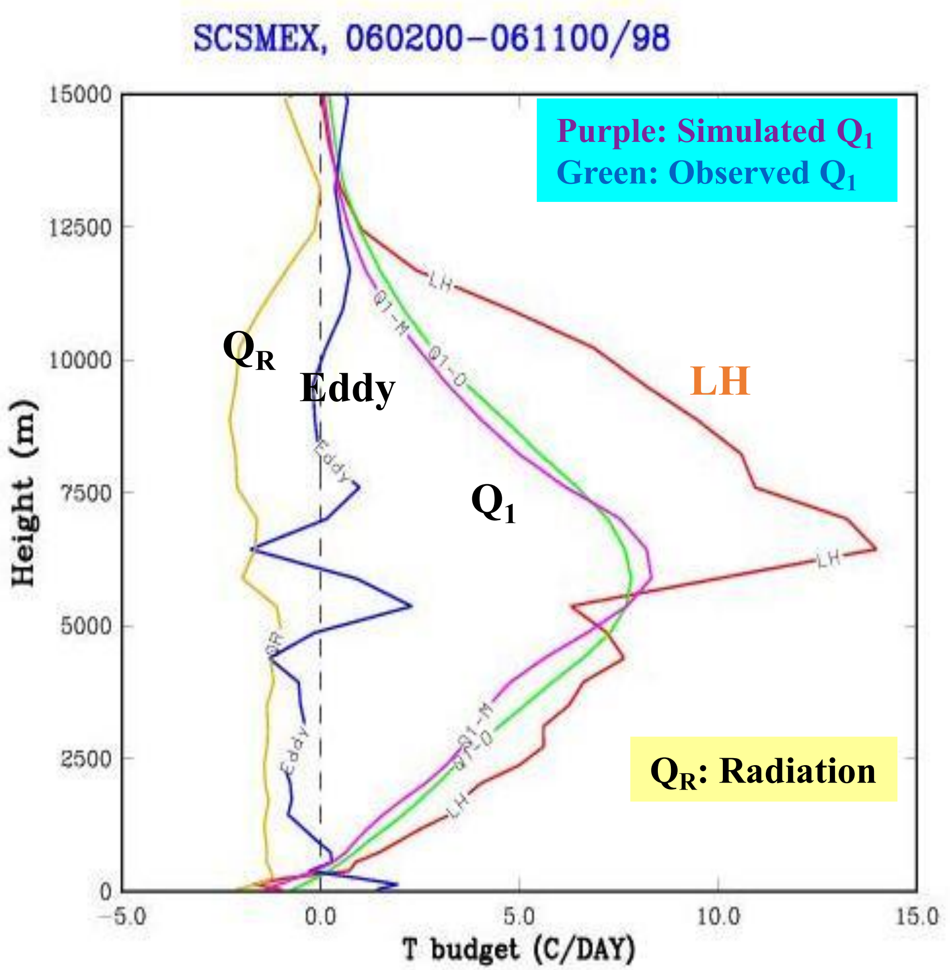
$$Q_1 - Q_R = \bar{\pi}[-\frac{1}{\bar{\rho}}\frac{\partial \bar{\rho} w'\theta'}{\partial z} - \vec{V}' \bullet \nabla\theta'] + \frac{L_v}{C_P}(c-e) + \frac{L_f}{C_P}(f-m) + \frac{L_s}{C_P}(d-s)$$

Eddy heat transport by cloud dynamics

LH: Latent Heat - phase change of water

Heat released/absorbed through phase changes of water and transport by cloud drafts

No Direct Measurements but can be calculated through cloud resolving models



Sounding Estimated Q_1 (apparent heat source)

Indirect measurement using sounding networks

(TRMM and other field campaign)

(Yanai et al. 1973)

$$Q_1 = \bar{p}[\frac{\partial \bar{q}}{\partial t} + \bar{V} \cdot \nabla \bar{q} + \bar{w}\frac{\partial \bar{q}}{\partial z}]$$

Observed large-scale advective tendencies of potential temperature, water vapor mixing ratio, and horizontal momentum were used as the main large-scale forcing in the GCE model in a semi-prognostic manner (Soong & Ogura, 1980; Soong & Tao, 1980; Tao & Soong, 1986). A major characteristic of this approach is that ensembles of clouds can be generated by the "observed-prescribed forcing." The large-scale advective tendencies for potential temperature and water vapor mixing ratio *qv*,

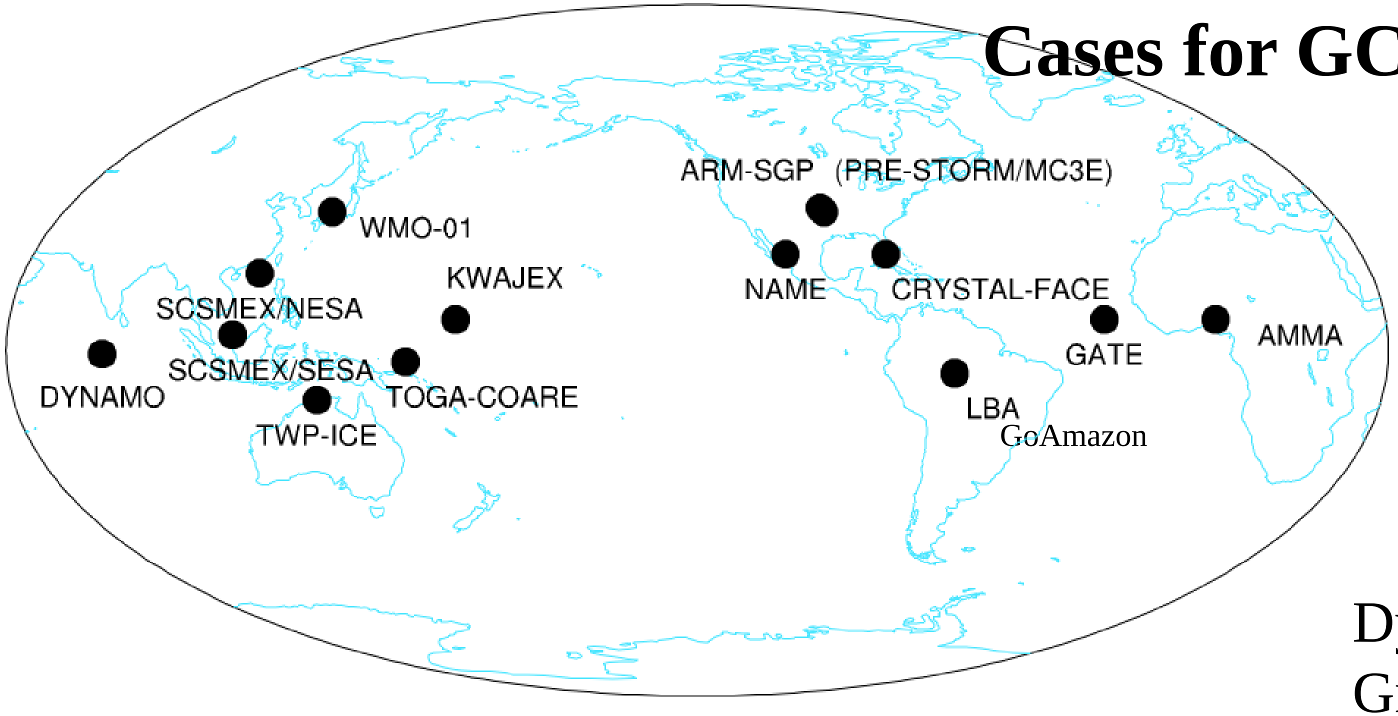
$$\begin{cases} \left(\frac{\partial\bar{\theta}}{\partial t}\right)_l = -\bar{u}\frac{\partial\bar{\theta}}{\partial x} - \bar{v}\frac{\partial\bar{\theta}}{\partial y} - \bar{w}\frac{\partial\bar{\theta}}{\partial z} \\ \left(\frac{\partial\bar{q_v}}{\partial t}\right)_l = -\bar{u}\frac{\partial\bar{q_v}}{\partial x} - \bar{v}\frac{\partial\bar{q_v}}{\partial y} - \bar{w}\frac{\partial\bar{q_v}}{\partial z} \end{cases}$$

were derived every 3 hr from the DYNAMO (Equatorial Indian Ocean) and GOAmazon (Amazon Basin) sounding networks. Since accurate calculations of the large-scale horizontal momentum forcing terms are difficult to obtain from observations in the tropics, these terms were instead replaced by a nudging term:

$$\begin{cases} \left(\frac{\partial\bar{u}}{\partial t}\right)_l = -\frac{\bar{u}-\bar{u}_{obs}}{\tau} \\ \left(\frac{\partial\bar{v}}{\partial t}\right)_l = -\frac{\bar{v}-\bar{v}_{obs}}{\tau} \end{cases}$$

Many other CRMs have also used this approach.

Cases for GCE Model Simulations (globally)

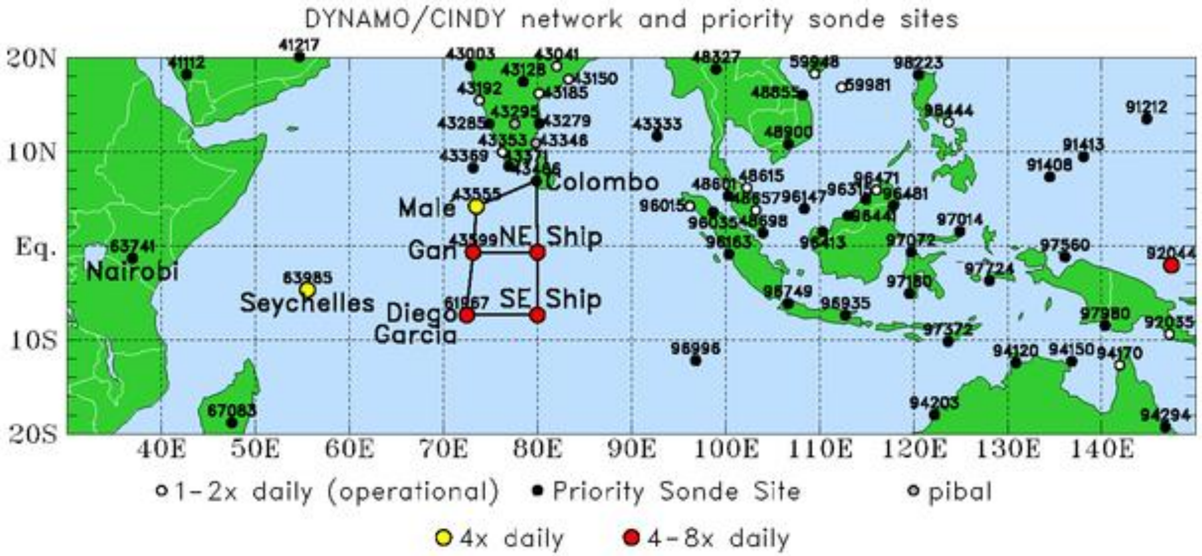


FIELD CAMPAIGNS

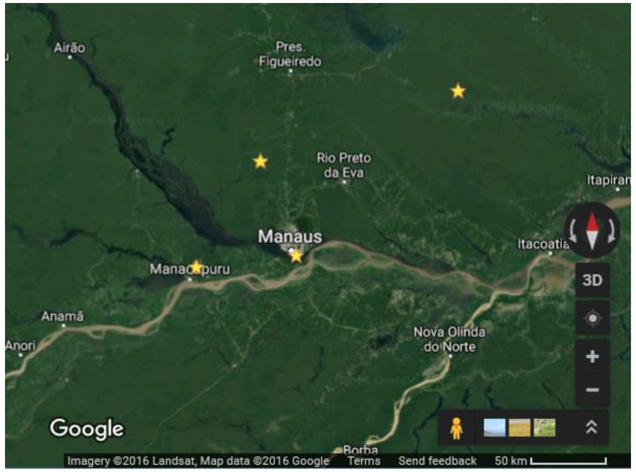
Fifteen-day GCE model simulations for **DYNAMO** (Equatorial Indian Ocean) and **GOAmazon** (Amazon Basin)

Dynamics of the Madden-Julian Oscillation
Green Ocean Amazon Experiment

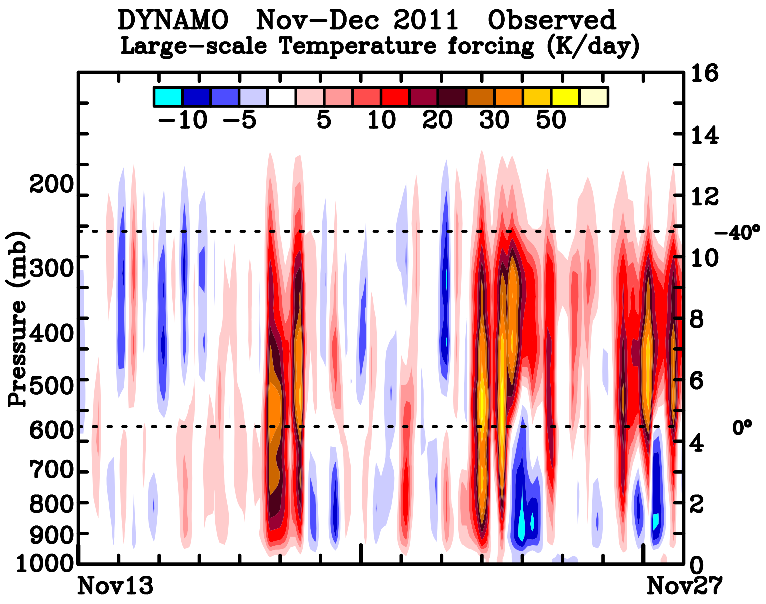
DYNAMO

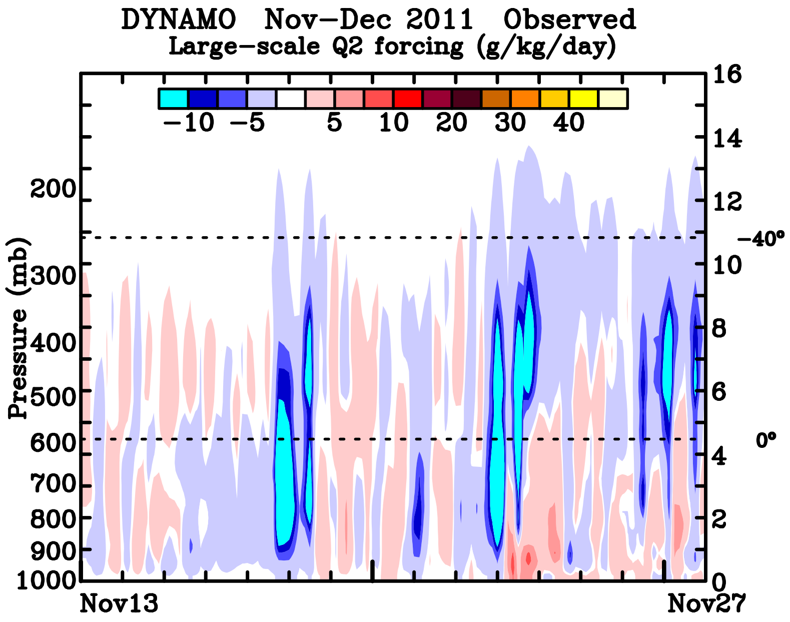


GOAmazon

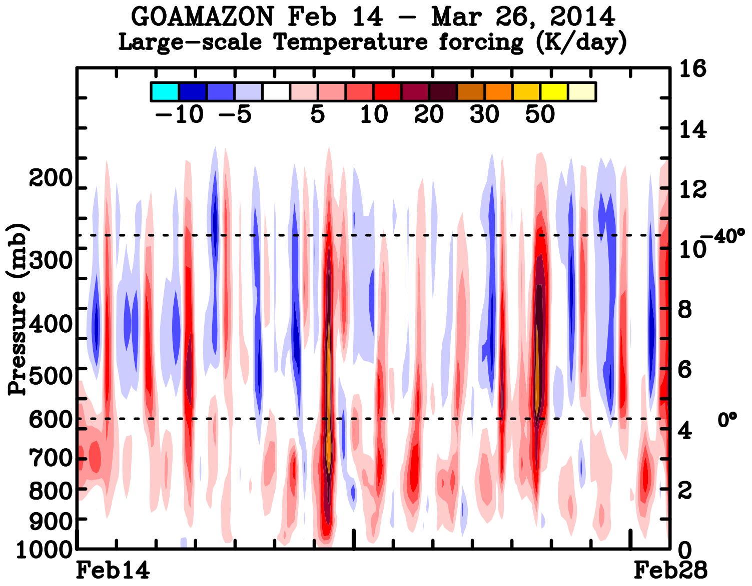


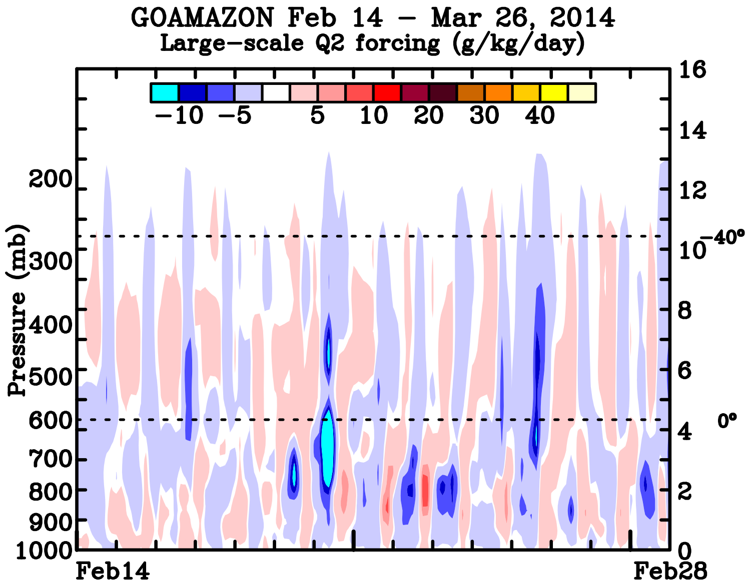
DYNAMO





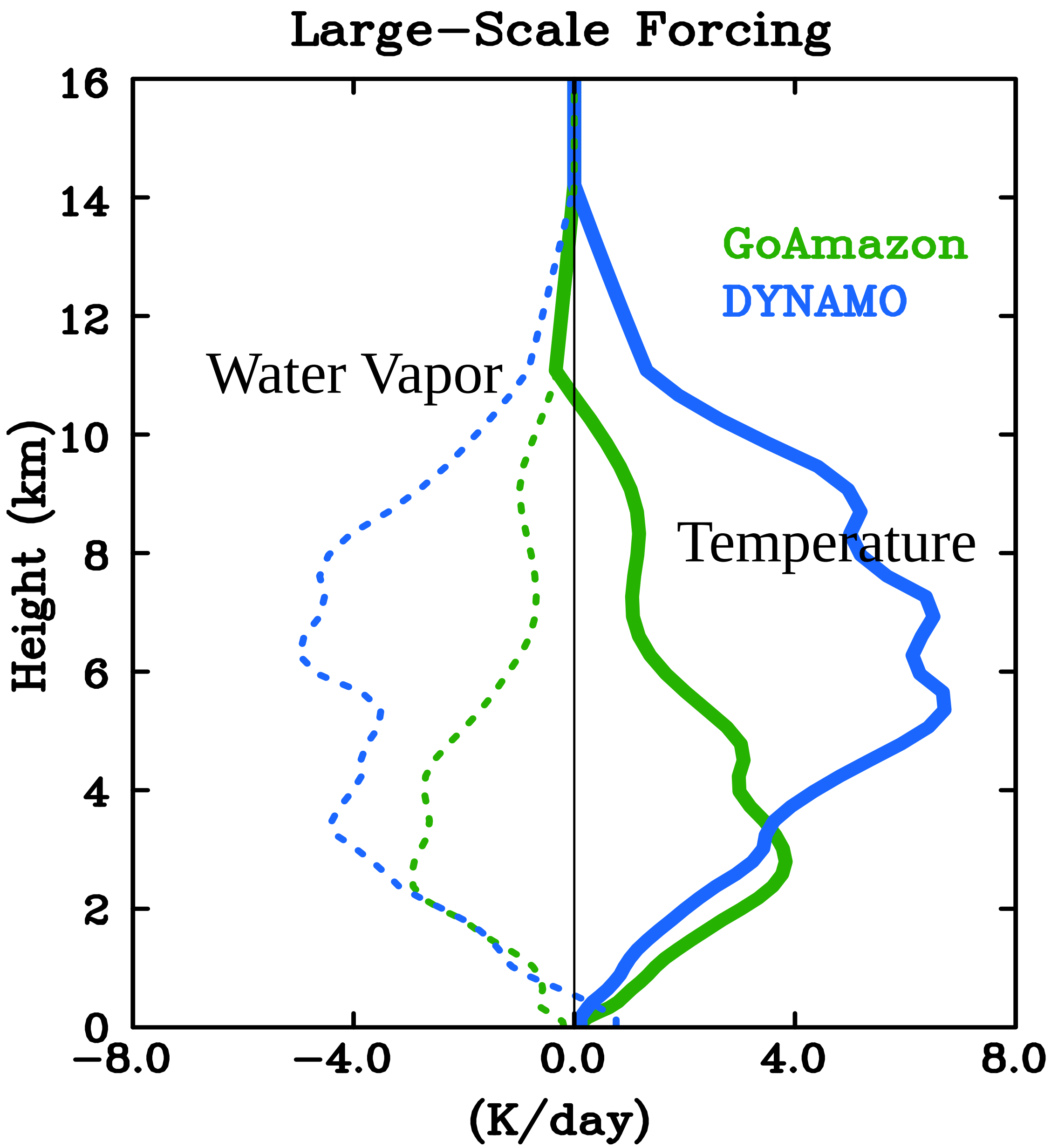
GOAmzon

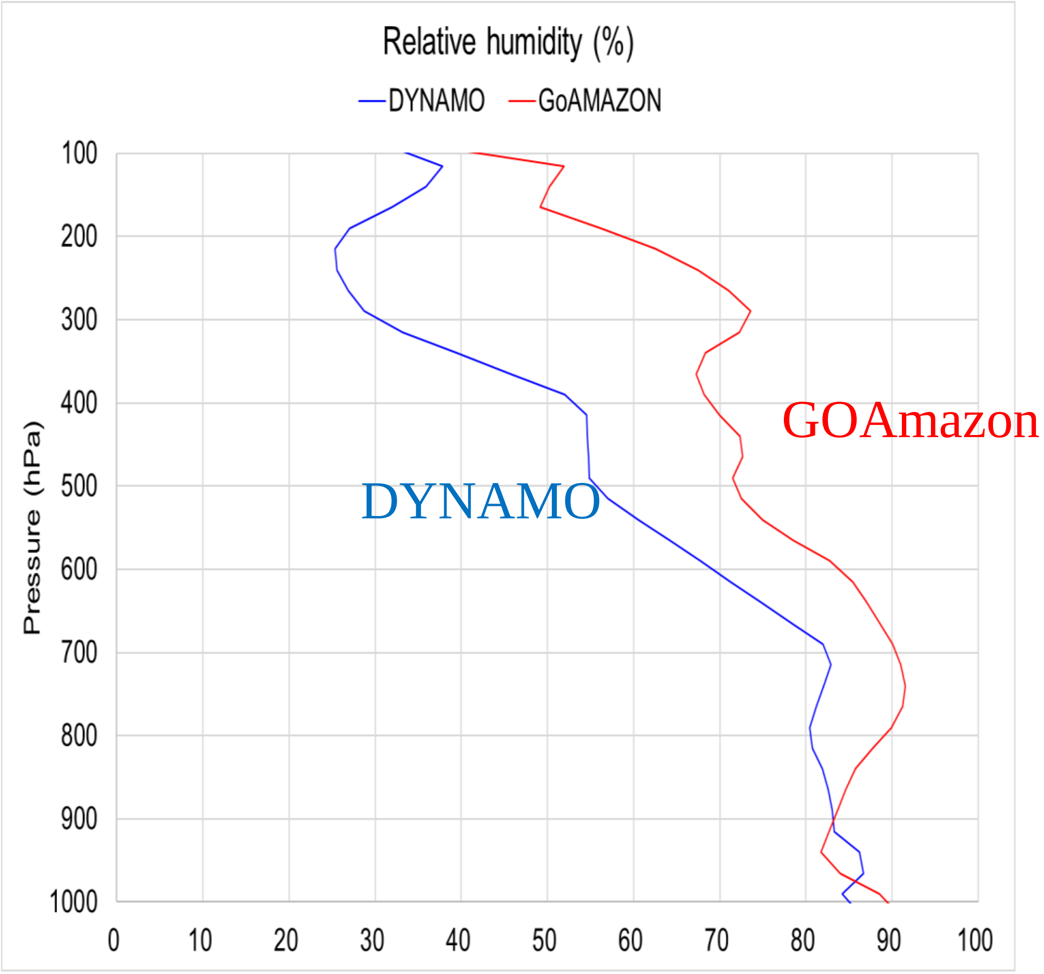




Time series of the observed large-scale advective forcing in (a) temperature and (b) water vapor derived from the sounding network for the **DYNAMO** case. **(c)** and (d) are the same as (a) and (b), respectively, except for the **GOAmazon** case. The black dashed lines are domain mean temperature level 0°C and -40°C.

Differences in large-scale advective forcing and Relative humidity





Relative Humidity

3ICE:
Cloud water
Rain
Cloud ice
Snow
Graupel

4ICE:
Cloud water
Rain
Cloud ice
Snow
Graupel
Hail

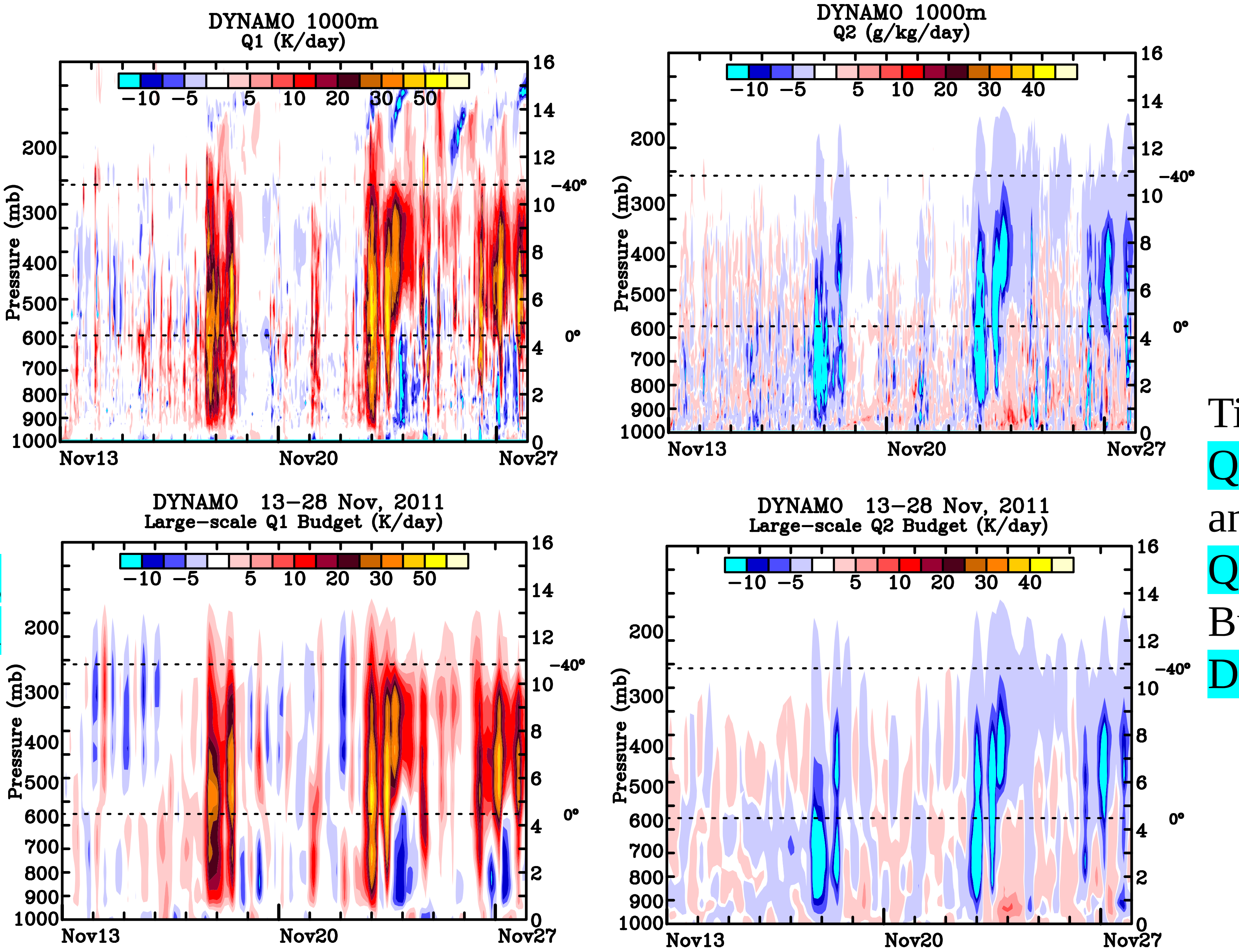
	Case	Resolution	Grid Points	Microphysics
D4ICE	DYNAMO	1000 m	512	4ICE
D4ICEH	DYNAMO	250 m	2048	4ICE
D3ICE	DYNAMO	1000 m	512	3ICE
D3ICEH	DYNAMO	250 m	2048	3ICE
G4ICE	GOAmazon	1000 m	512	4ICE
G4ICEH	GOAmazon	250 m	2048	4ICE
G3ICE	GOAmazon	1000 m	512	3ICE
G3ICEH	GOAmazon	250 m	2048	3ICE

The eight experiments conducted for this study. Experiment nomenclature, cases (**DYNAMO and GOAmazon)**, horizontal model grid resolution (**250 vs 1000 m**) number of grid points (512 vs 2048), and the microphysics parameterization (**3ICE vs 4ICE**) for each experiment is shown.

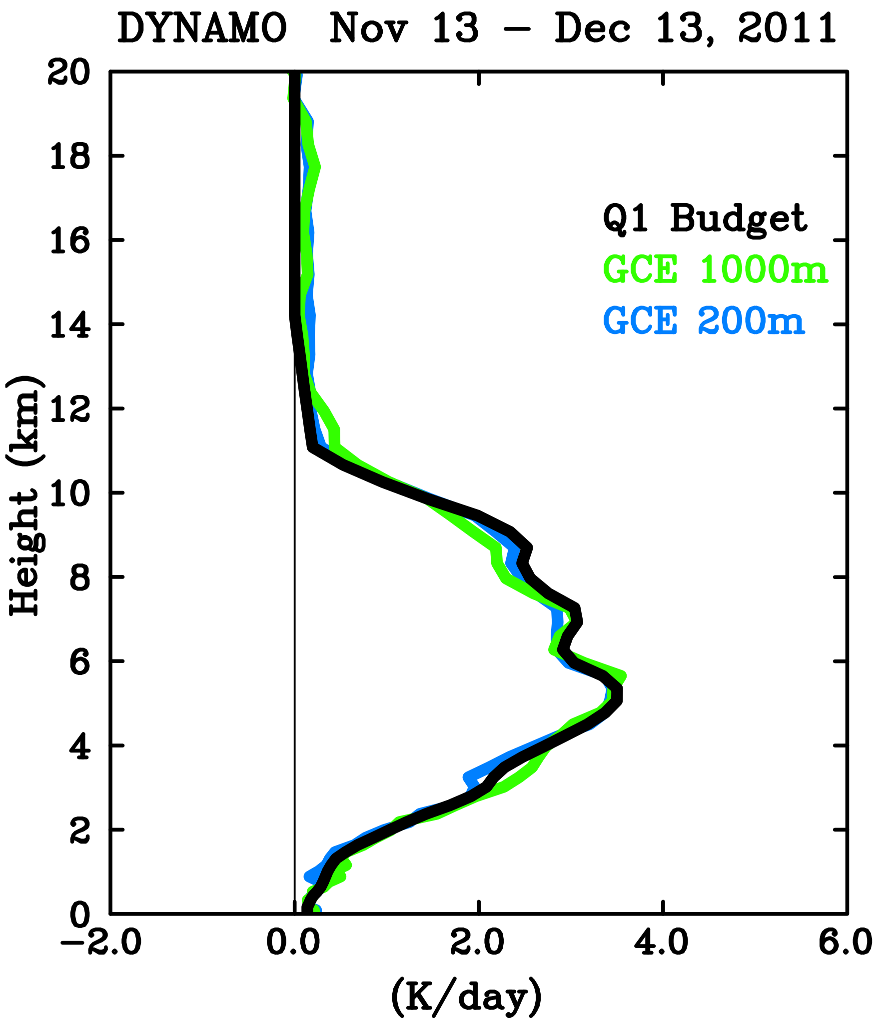
Each Experiment is integrated with a 15-day simulation.

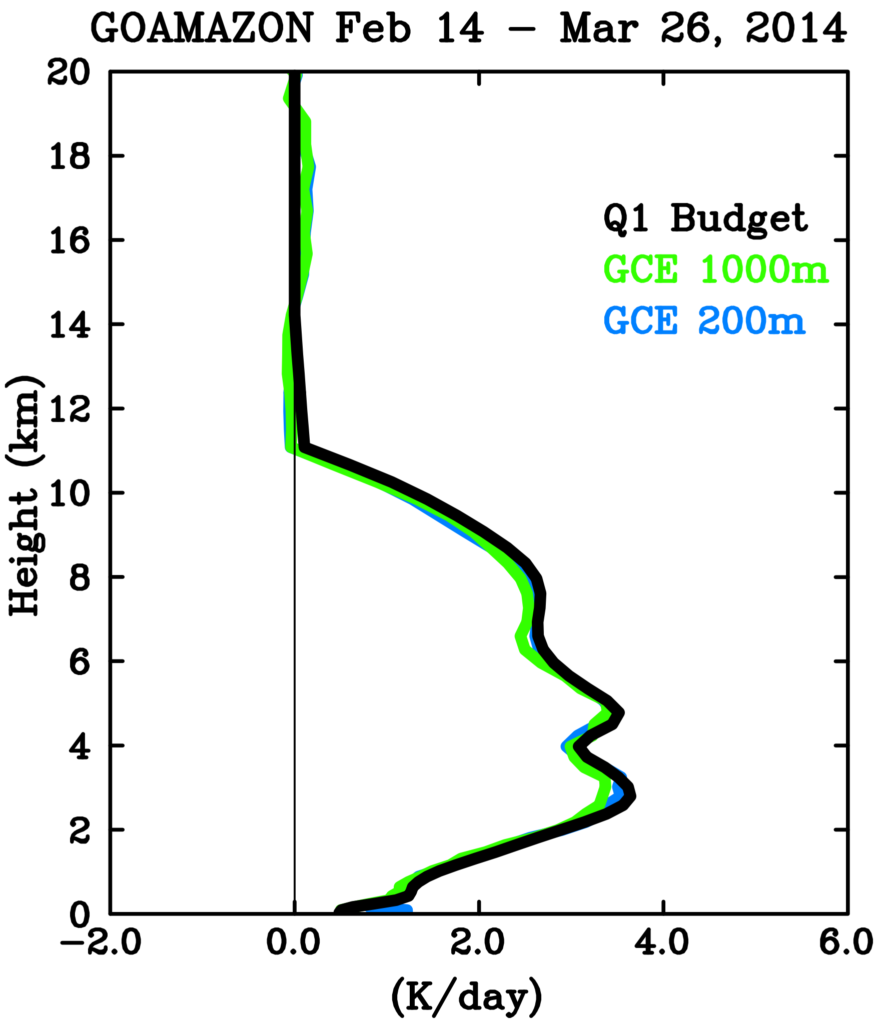
GCE Modeled

Sounding estimated

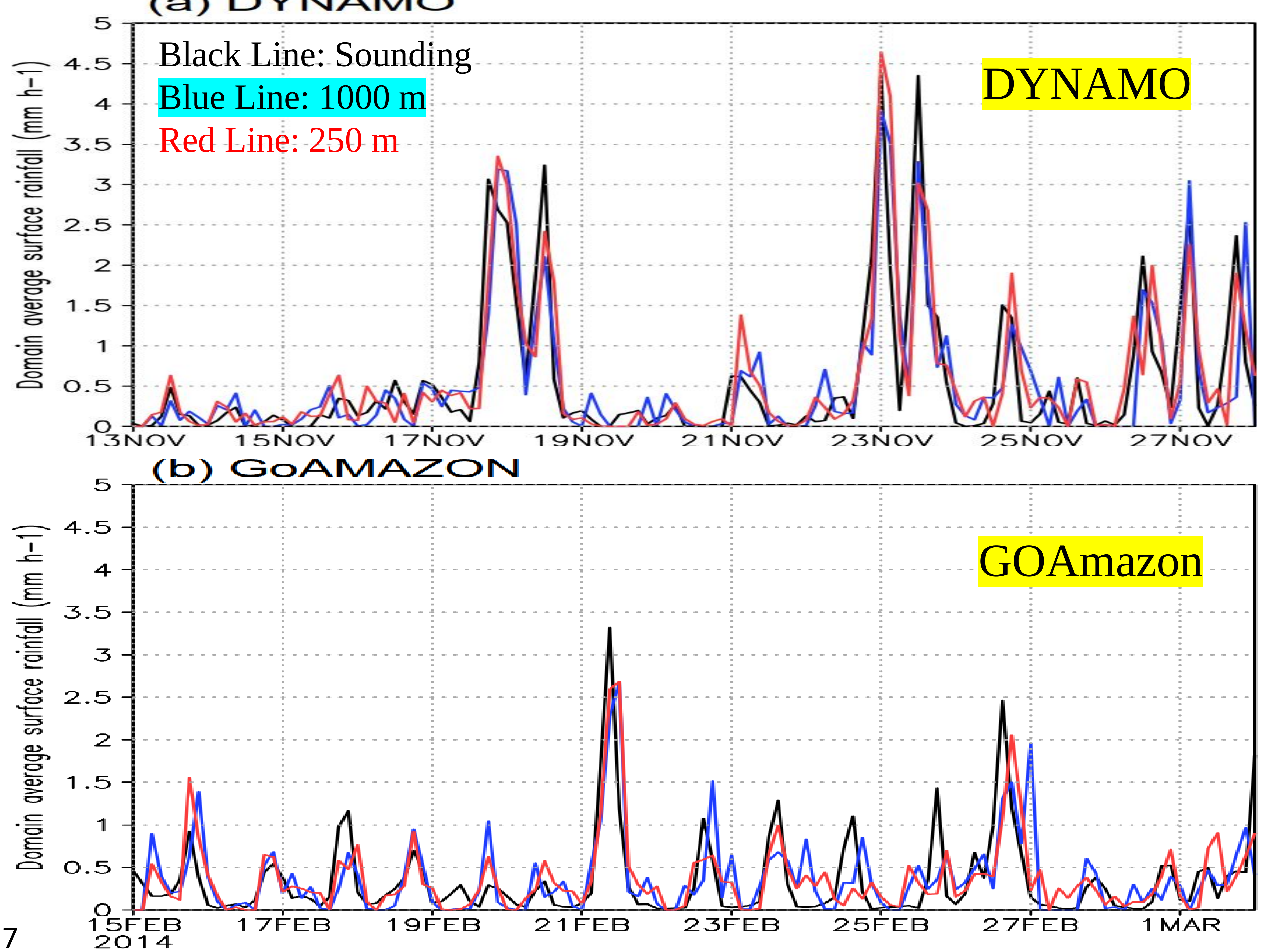


Time series of Q_1 (temperature) and Q_2 (water vapor) Budget for DYNAMO





Good agreement between modeled and sounding estimated Q_1 for both (DYNAMO & GOAmazon) cases

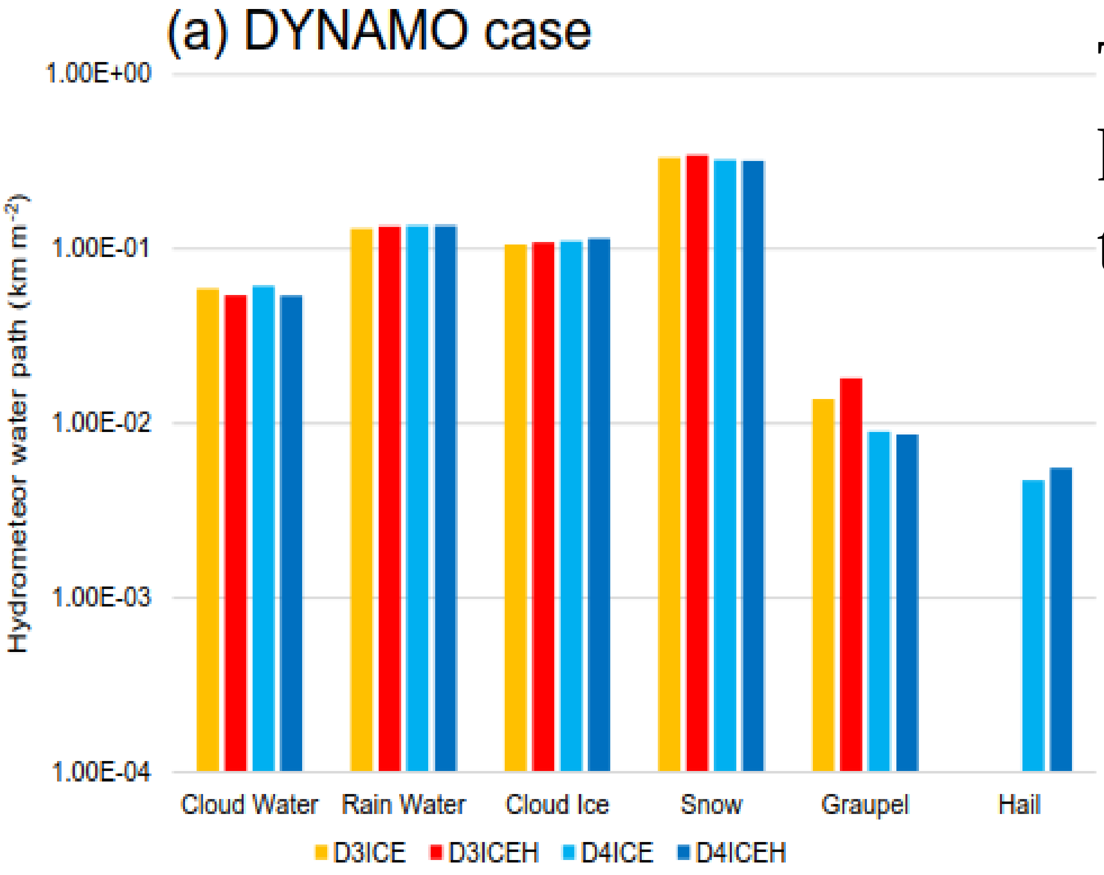


Time series of GCE simulated domain average surface rainfall using 1km (blue) and 250 m horizontal resolution (red) with 4ICE versus surface rainfall derived from the corresponding sounding budget (black) for the (a) DYNAMO and (b) GOAmazon cases. Unit are in mm h^{-1}.

	Total Rain (mm)	Convective Rain (mm)	Stratiform Rain (mm)	Stratiform percentage (%)
D4ICE	204.22	118.33	85.89	42.06
D4ICEH	201.79	118.63	81.16	41.21
D3ICE	202.06	113.63	88.52	43.76
D3ICEH	201.03	116.21	84.82	42.19
G4ICE	129.47	85.80	43.67	33.73
G4ICEH	128.14	86.72	41.42	33.32
G3ICE	128.20	82.53	45.67	35.62
G3ICEH	128.98	85.83	43.15	33.45

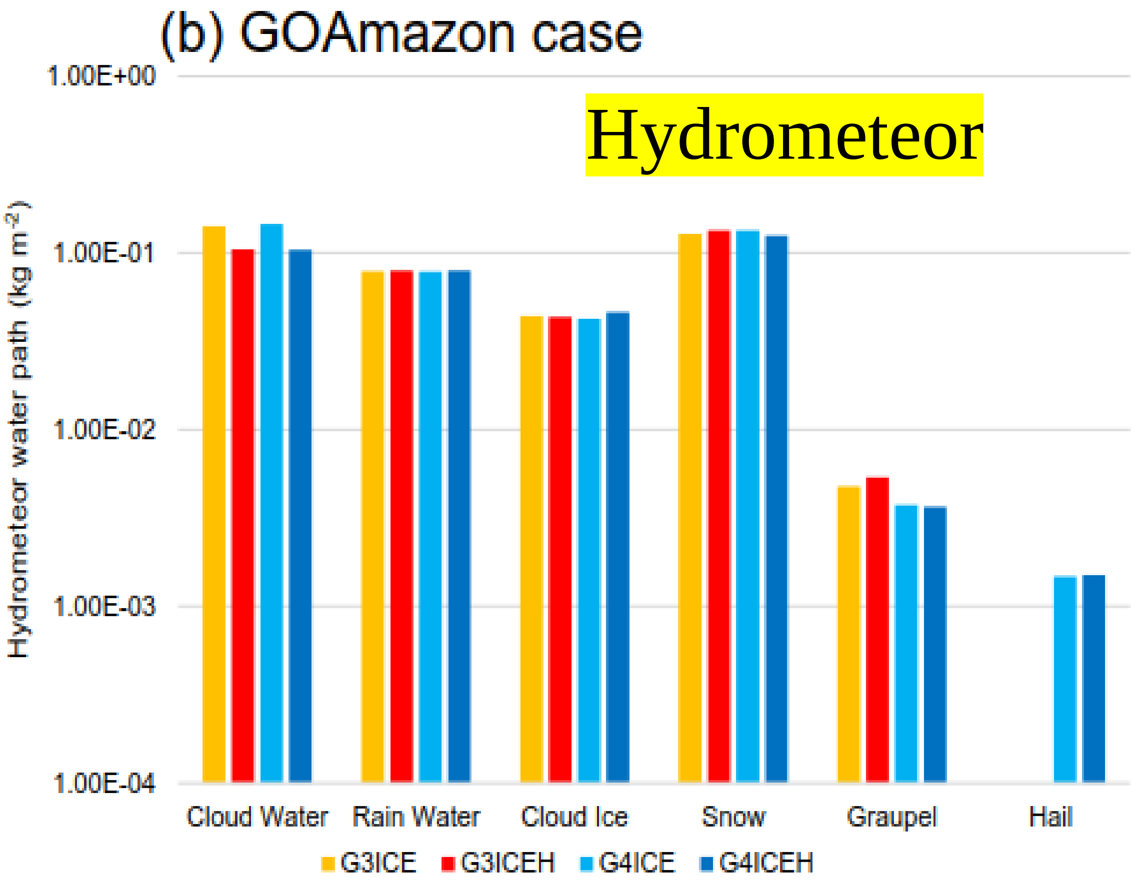
Total, convective and stratiform simulated rainfall for the DYNAMO and GOAmazon cases. Sounding estimated rainfall is 119.36 mm and 197.85 mm for the GOAmazon and DYNAMO case, respectively.

Sensitivity to resolution (250 vs 1000 m) and microphysics (3ICE vs 4ICE)



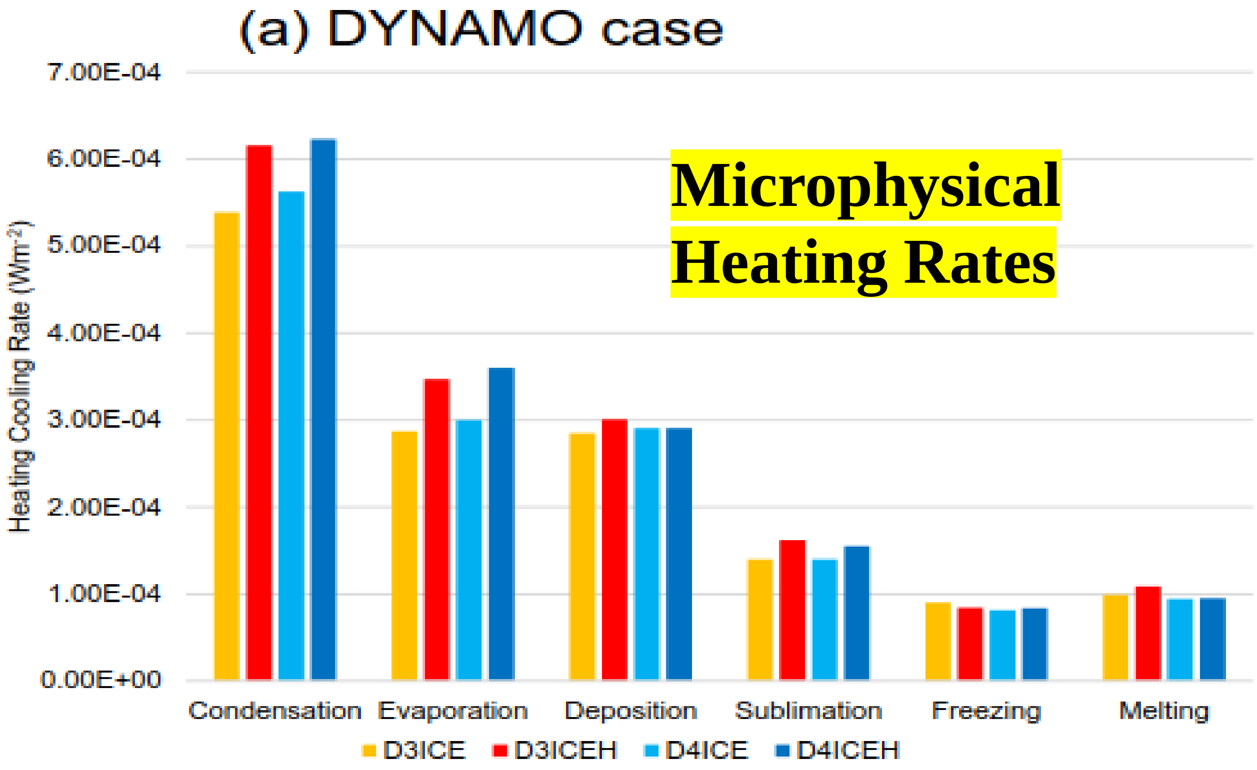
There is small sensitivity in terms of mean hydrometeor (rain, cloud ice, and snow) due to the same large-scale forcing used.

Hydrometeor

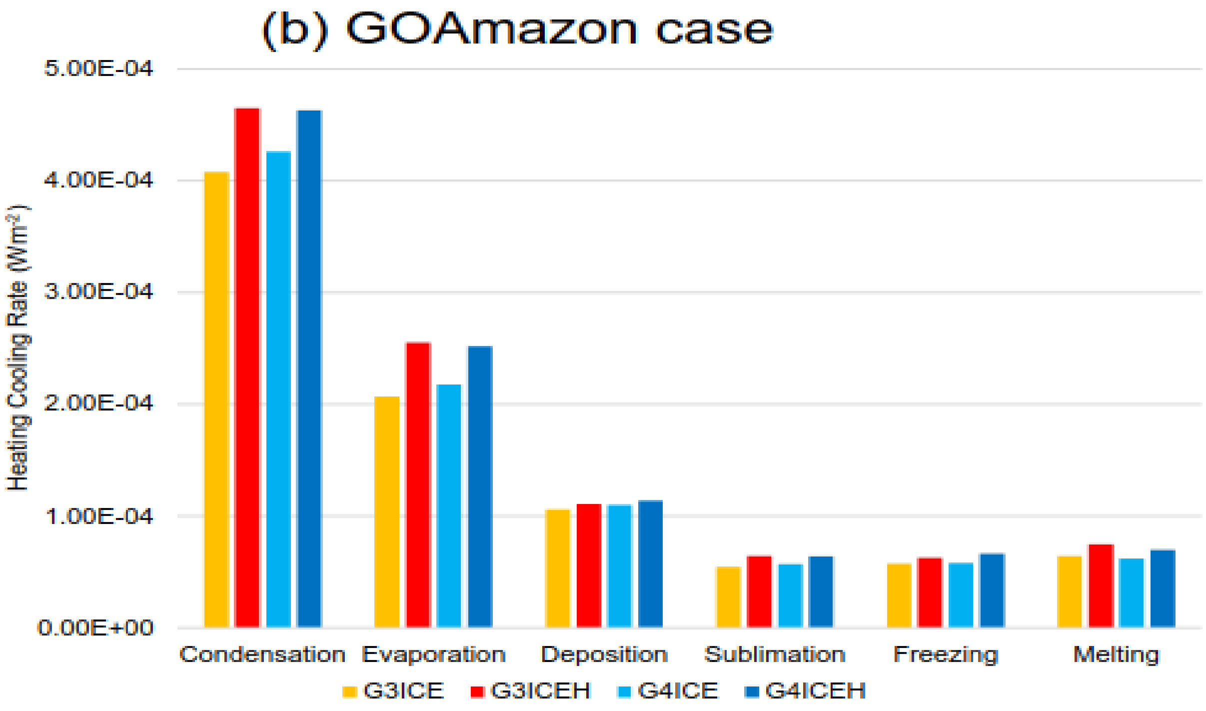


Mean hydrometeor (cloud water and graupel) is sensitivity in model resolution than microphysics.

Sensitivity to resolution (250 vs 1000 m) and microphysics (3ICE vs 4ICE)



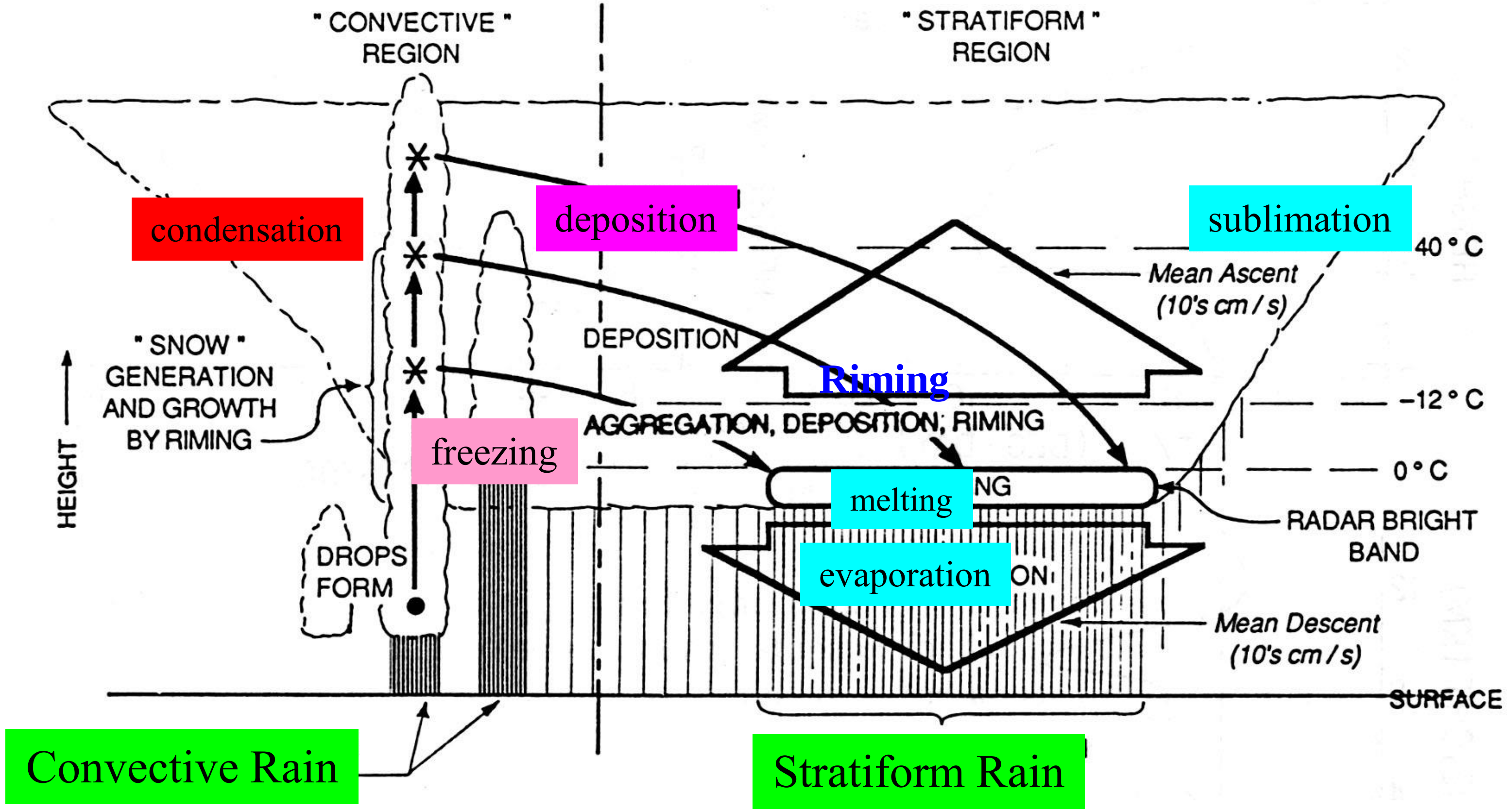
Condensation, evaporation and deposition. rate are dominate; and more sensitivity in model resolution than microphysics



There is some difference in terms of mean microphysical rates (condensation, evaporation, deposition, sublimation, freezing and melting) due to the same large-scale forcing used.

Microphysical Processes in an idealized mesoscale convective system (Convective / Stratiform region)

Houze, 1989: Observed structure of mesoscale convective systems and implications for large-scale heating. *Quart. J. Roy. Meteor. Soc.*, **115**, 425-461.



Schematic of a microphysical processes associated with a tropical mesoscale convective system in its **mature** stages. Straight, solid arrows indicate convective updraft, wide, open arrows indicate mesoscale ascent and subsidence in the stratiform region Where vapor deposition and evaporation occur. Adapted from Houze (1989).

DYNAMO

4ICE, Dx=250m

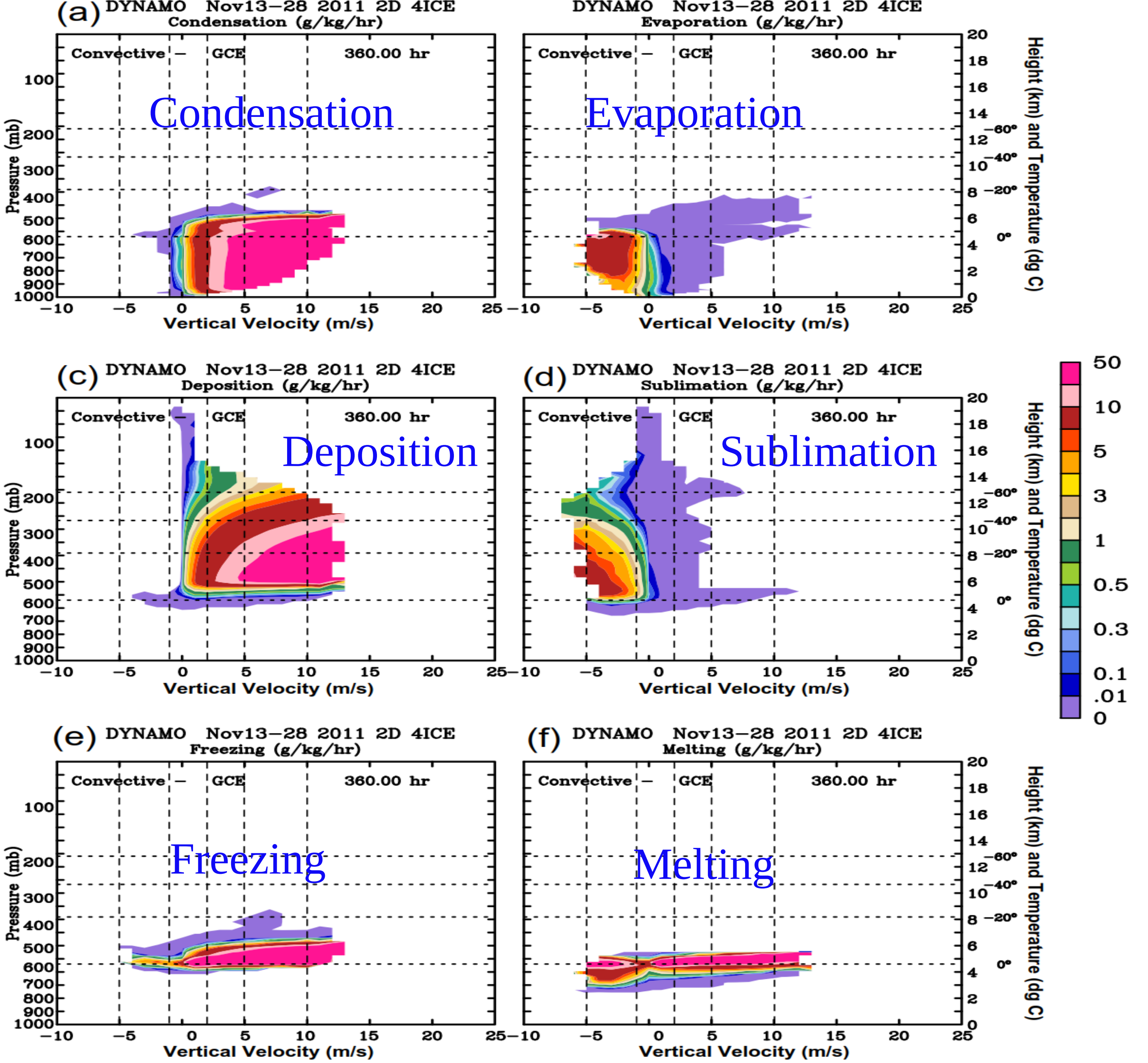
Convective Region

Distribution of microphysical heating rates by vertical velocity bins

Large condensation/deposition in the convective updrafts

Large evaporation/sublimation in the convective downdrifts

Freezing/Melting in both up and downdrafts

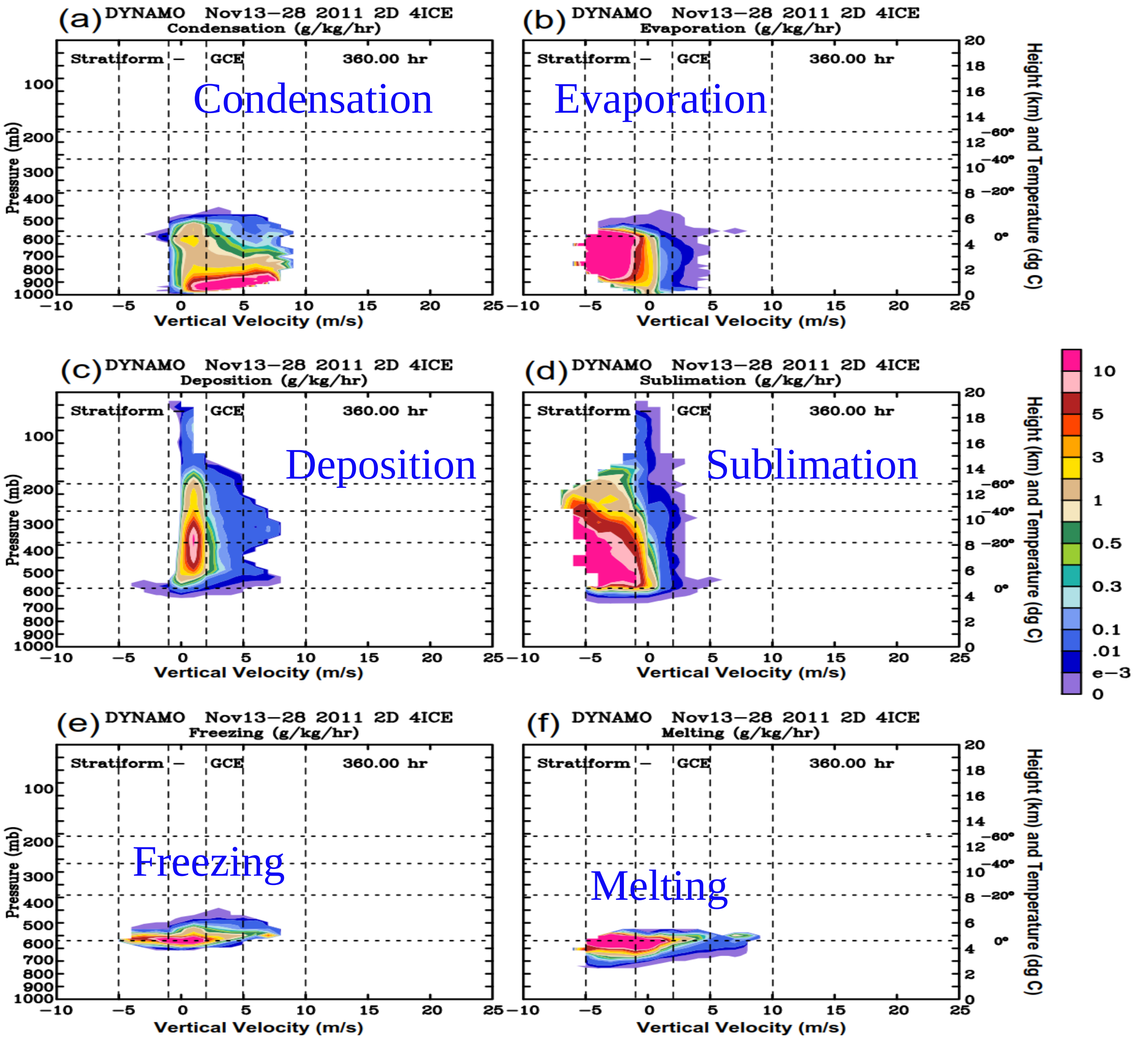


DYNAMO

4ICE, Dx=250m

Stratiform Region

Distribution of microphysical heating rates by vertical velocity bins



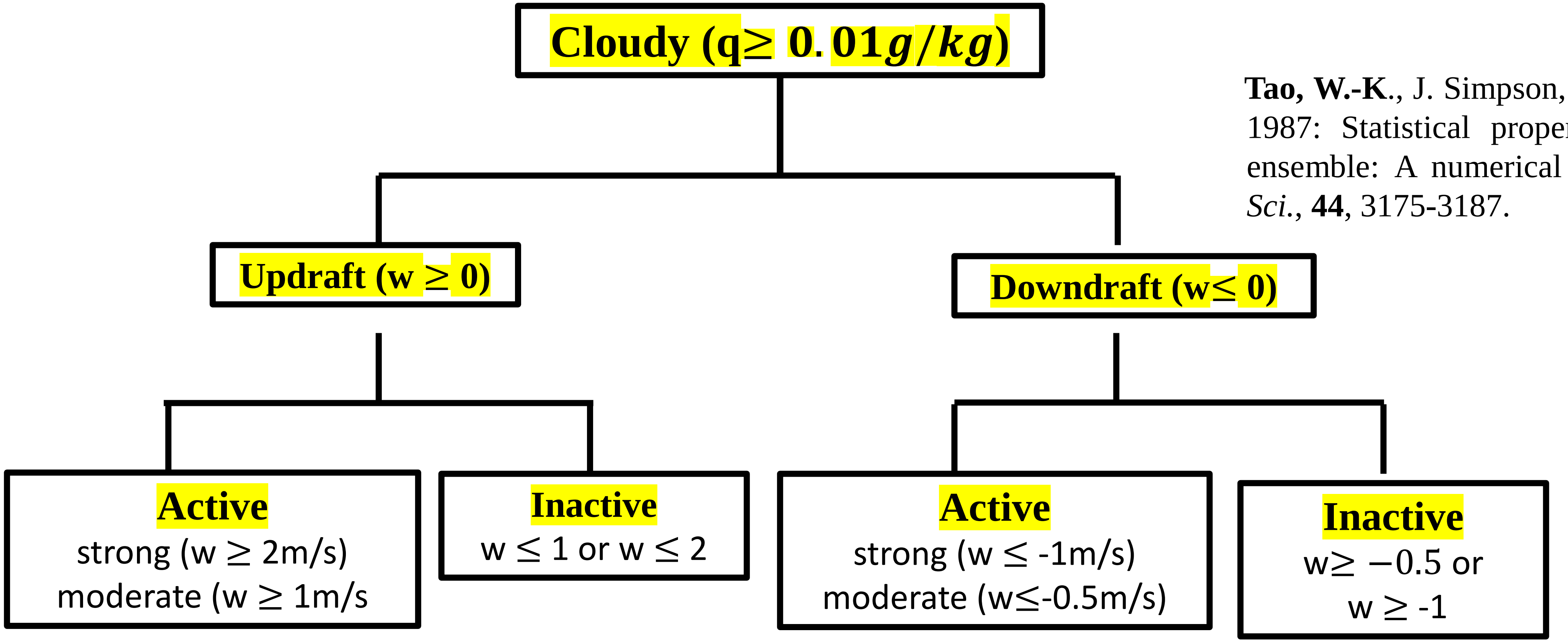
Large evaporation/sublimation in stratiform downdrifts

Most freezing/melting in stratiform downdrafts

Small condensation/deposition in stratiform region

GCE (Goddard Cumulus Ensemble) Model

- 2D model domain of 512 km with observed large-scale forcing
- 15-day simulations for two case studies (DYNAMO and GoAMAZON)
- Two resolutions: 1000 m and 250 m
- Two microphysical schemes: 3ICE (ice, snow, graupel) and 4ICE (+hail)



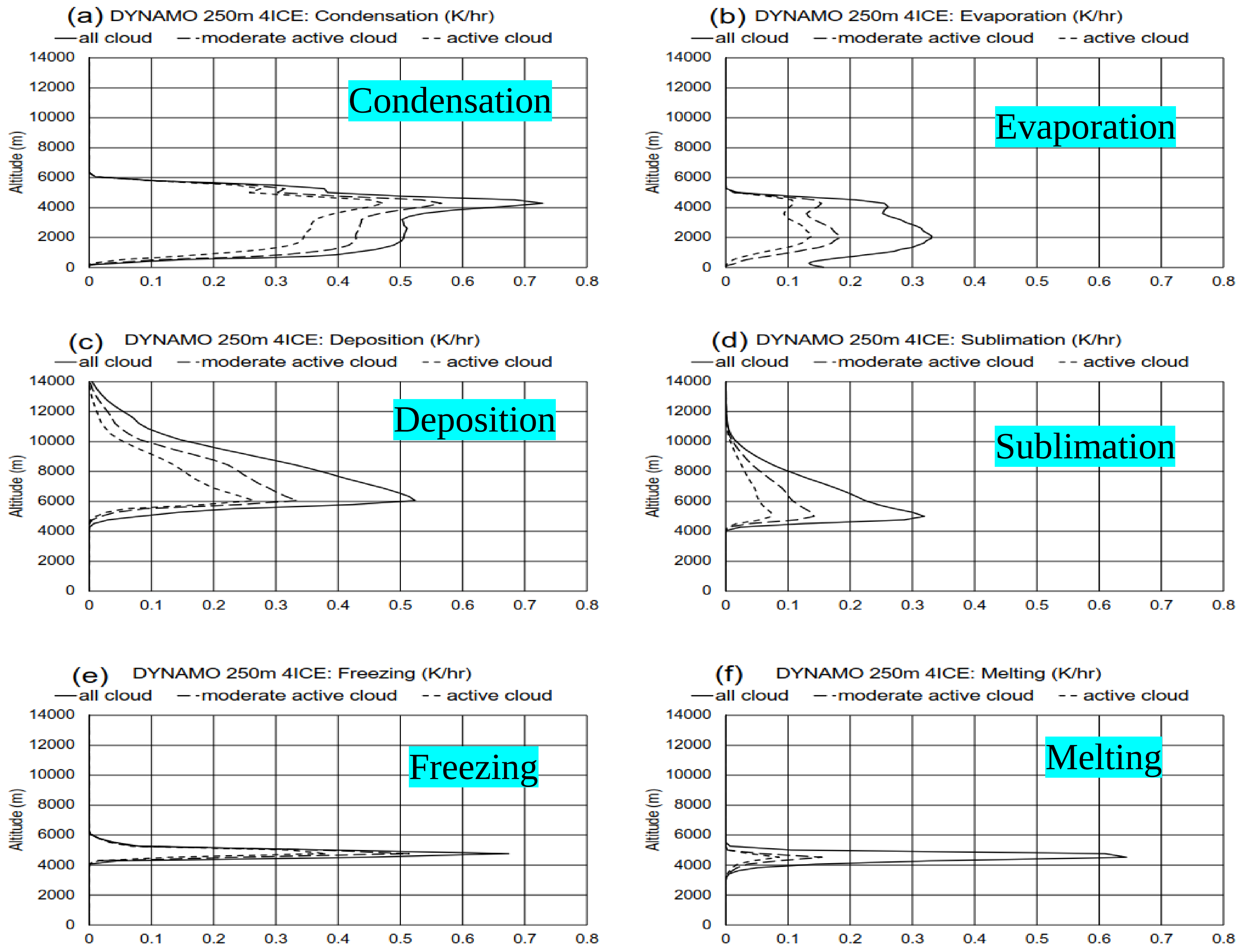
Tao, W.-K., J. Simpson, and S.-T. Soong, 1987: Statistical properties of a cloud ensemble: A numerical study. *J. Atmos. Sci.*, **44**, 3175-3187.

	Condensation	Evaporation	Deposition	Sublimation	Melting	Freezing
Total	6.25E-04	3.22E-04	3.88E-04	2.37E-04	1.03E-04	9.02E-05
Updraft	**99%**	**16%**	**96%**	**9%**	**65%**	**95%**
$w > 1\ ms^{-1}$	**83%**	**1%**	**46%**	**< 0.5%**	**43%**	**75%**
$w > 2\ ms^{-1}$	**66%**	**<0.01%**	**32%**	**< 0.1%**	**29%**	**58%**
Downdraft	**< 1%**	**84%**	**4%**	**90%**	**35%**	**5%**
$w < -.5\ ms^{-1}$	**< 0.01%**	**48%**	**< 0.001%**	**44%**	**17%**	**3%**
$w < -1\ ms^{-1}$	**< 0.001%**	**33%**	**<0.0001%**	**24%**	**9%**	**1%**

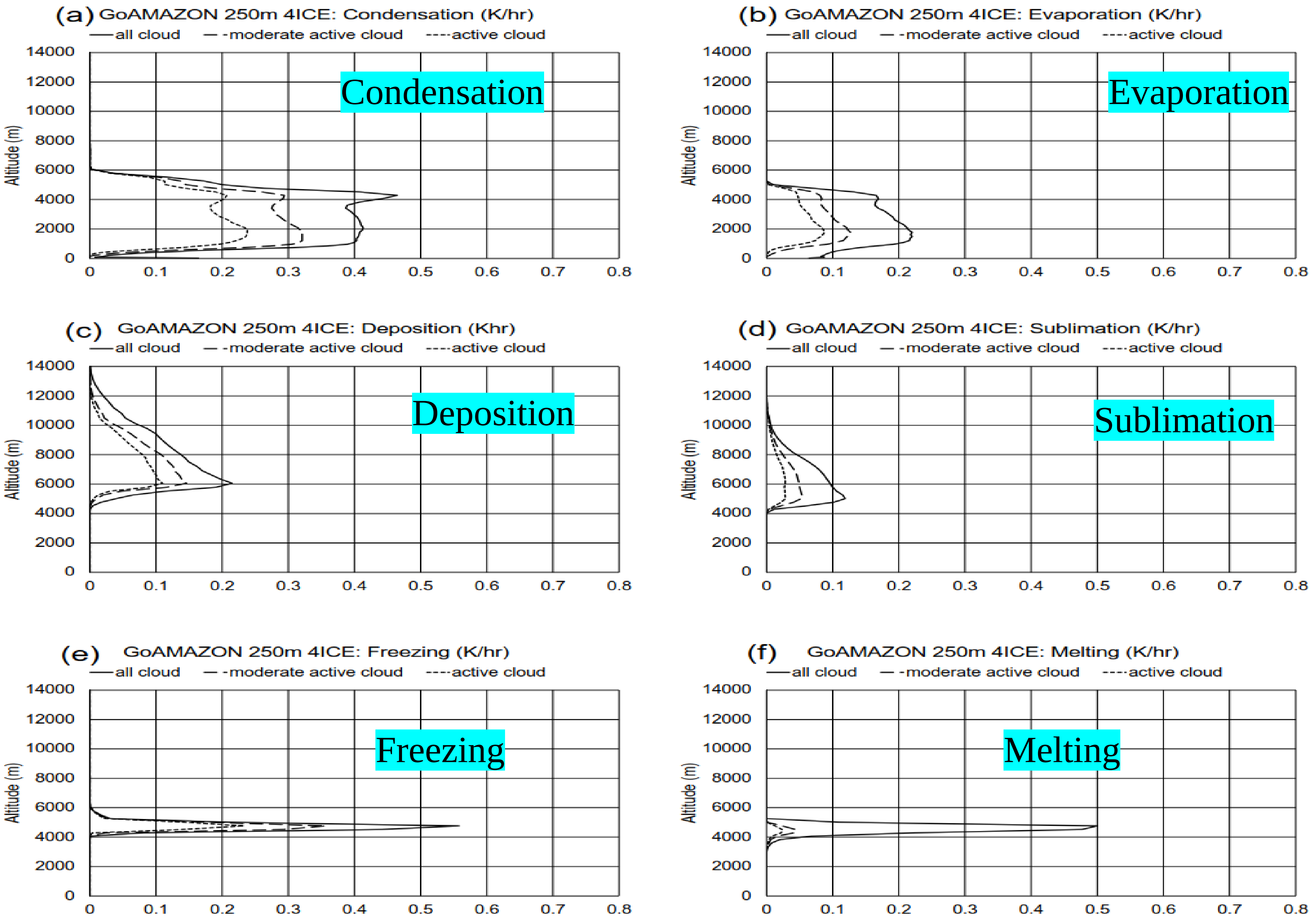
Domain and time averaged vertically-integrated LH change rates (W m^{-2}) for **the whole domain, updraft and downdraft regions** in the DYNAMO 4ICE simulation with 250 m model resolution. **The values for the updraft and downdraft regions are percentages of the total amounts.**

W/m2	Condensation	Evaporation	Deposition	Sublimation	Melting	Freezing
Total	4.57E-04	2.12E-04	1.52E-04	9.48E-05	6.54E-05	6.48E-05
Updraft	**99%**	**11%**	**97%**	**9%**	**77%**	**96%**
$w > 1$ ms^{-1}	**72%**	**< 0.5%**	**52%**	**< 0.5%**	**42%**	**62%**
$w > 2$ ms^{-1}	**51%**	**< 0.1%**	**35%**	**< 0.01%**	**23%**	**36%**
Downdraft	**1%**	**89%**	**3%**	**93%**	**23%**	**4%**
$w < -.5$ ms^{-1}	**< 0.01%**	**49%**	**< 0.1%**	**43%**	**10%**	**2%**
$w < -1$ ms^{-1}	< 0.001%	31%	< 0.01%	23%	5%	1%

Same as previous table except for the GOAmazon **case**.



Vertical profiles of mean LH production rate due to the phase changes of water within cloud and active updraft and downdraft areas for the DYNAMO case. **Solid line is for all cloud**, **long-dashed line is for moderate active cloud** ($w > 1$ m s^{-1} for condensation, deposition, and freezing, and $w < -0.5$ m s^{-1} for evaporation, sublimation, and melting) and **short-dashed line is active cloud** ($w > 2$ m s^{-1} and $w < -1$ m s^{-1}).

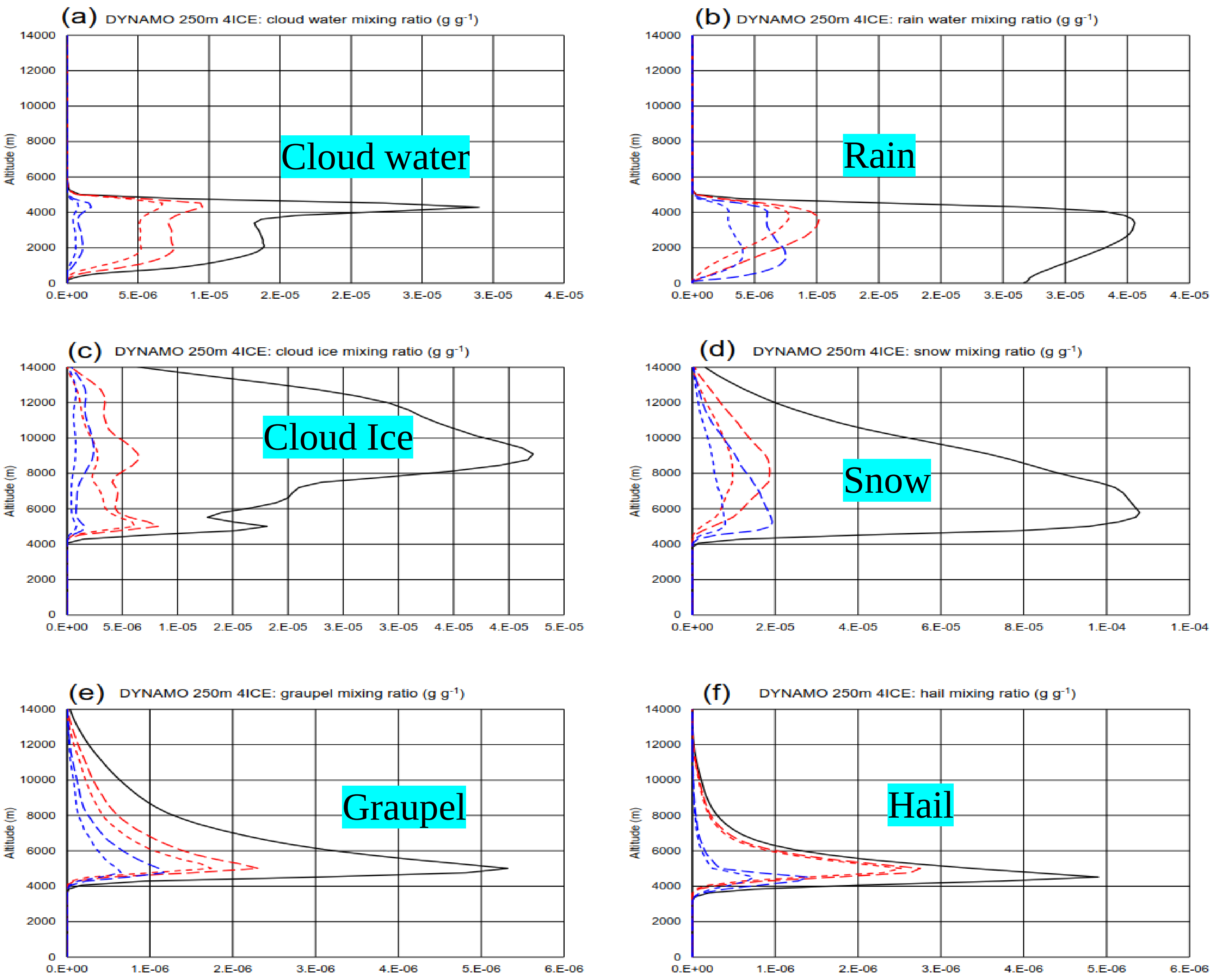


Vertical profiles of mean LH production rate due to the phase changes of water within cloud and active updraft and downdraft areas for the GOAmzon case. **Solid line is for all cloud, long-dashed line is for moderate active cloud** (w > 1 m s^{-1} for condensation, deposition, and freezing, and w < -0.5 m s^{-1} for evaporation, sublimation, and melting) and **short-dashed line is active cloud** (w > 2 m s^{-1} and w < -1 m s^{-1}).

Vertical profiles of hydrometeor for DYNAMO case.
Red: Updraft
Blue: Downdraft

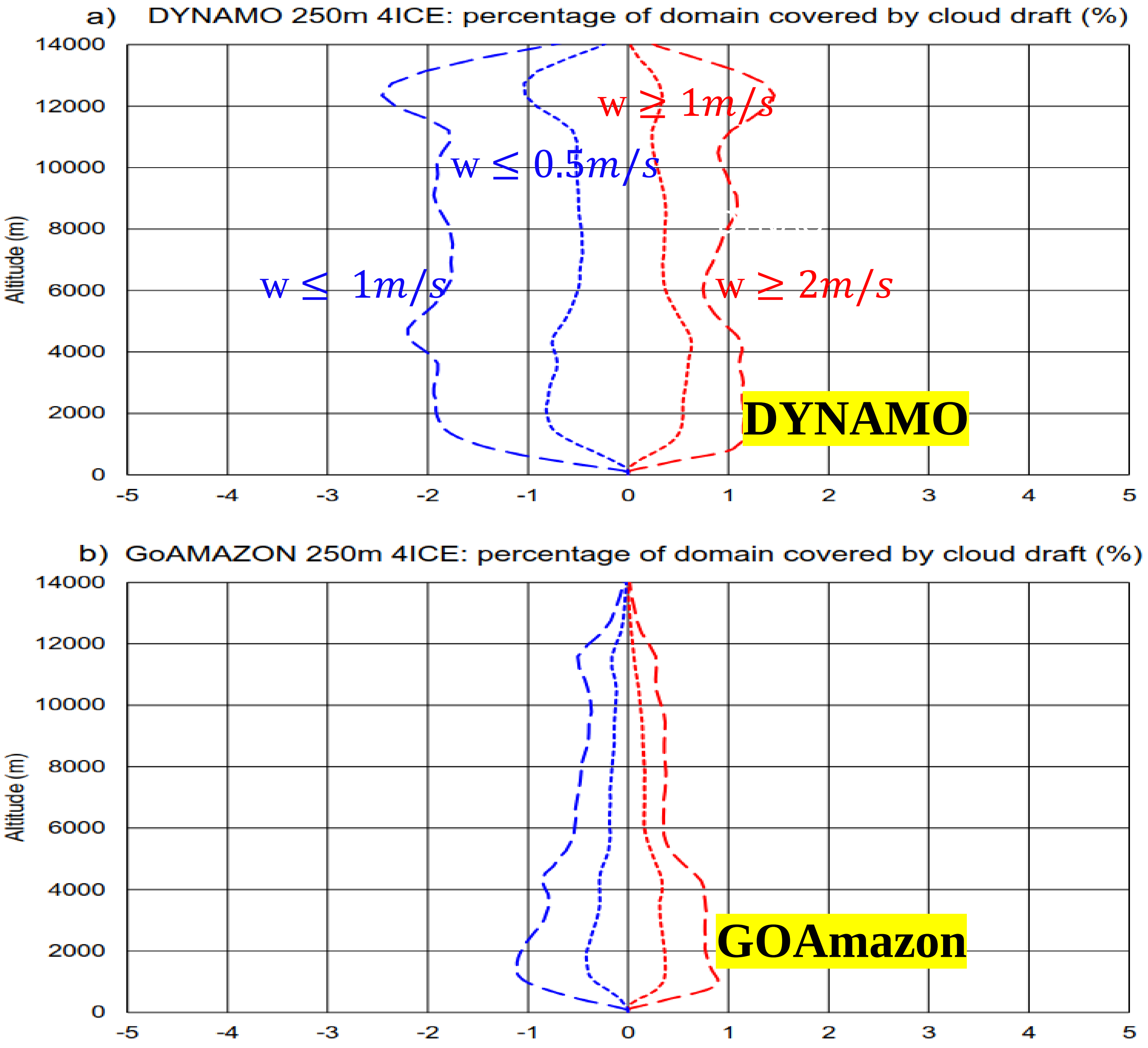
Growth/heating (condensation, deposition) terms occurs mainly in active updraft cores,

but the hydrometeors are much more spread in space

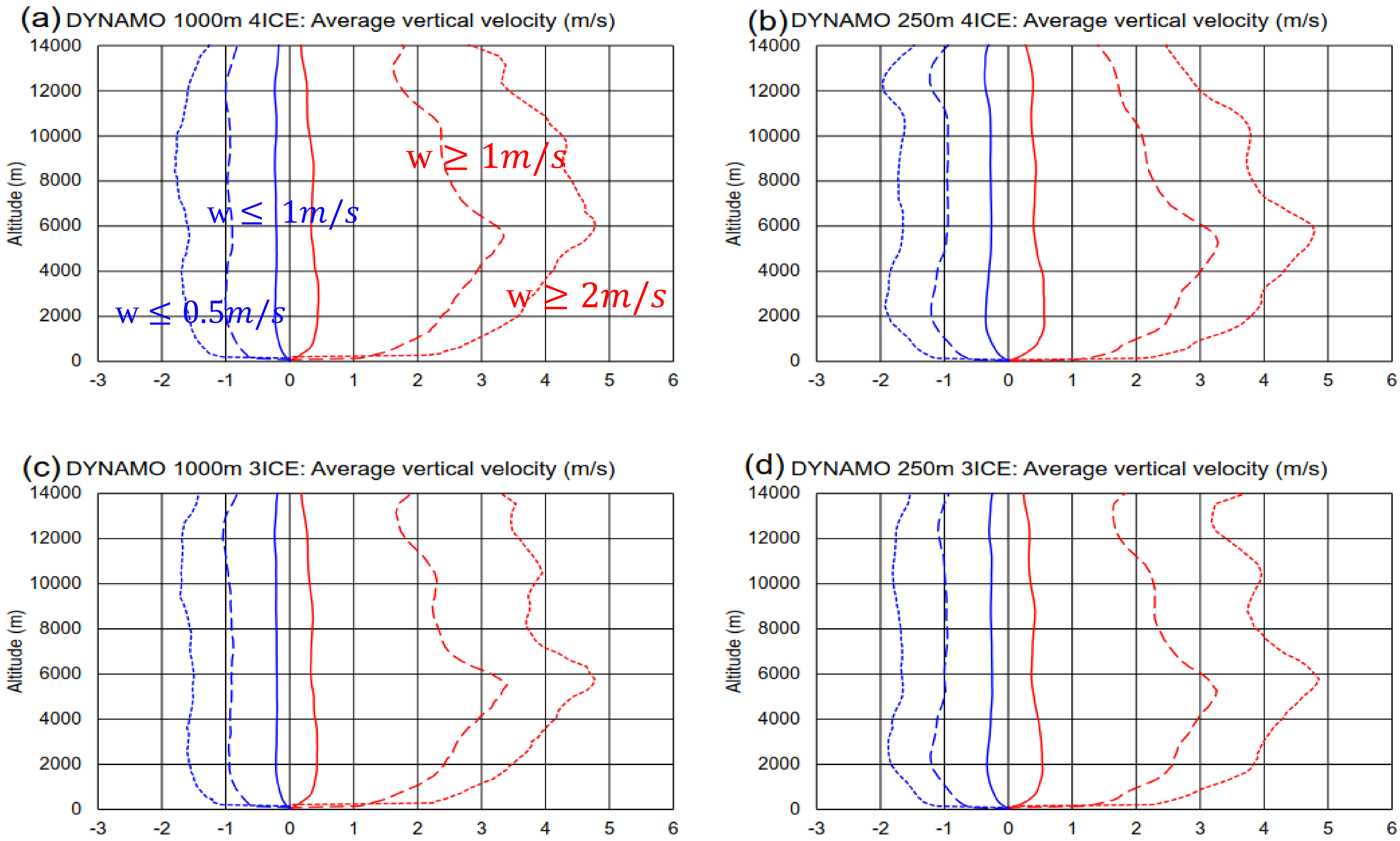


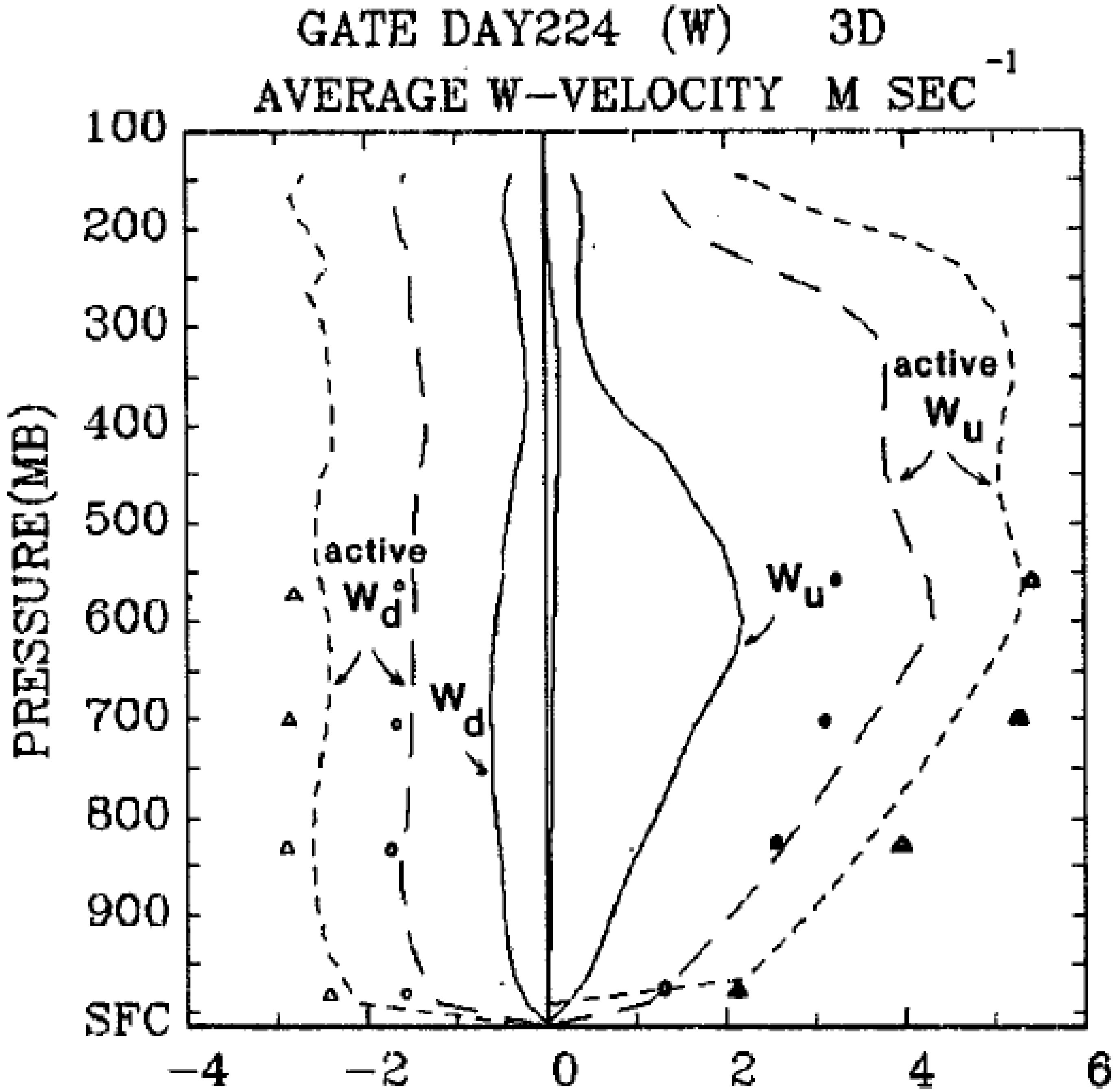
Areal coverage (%) of active updraft and downdraft of the modeling domain is generally less than 2%.

The downdraft area is about twice as much as the updraft area.



Mean vertical velocity profiles for DYANMO case for the four sensitivity tests



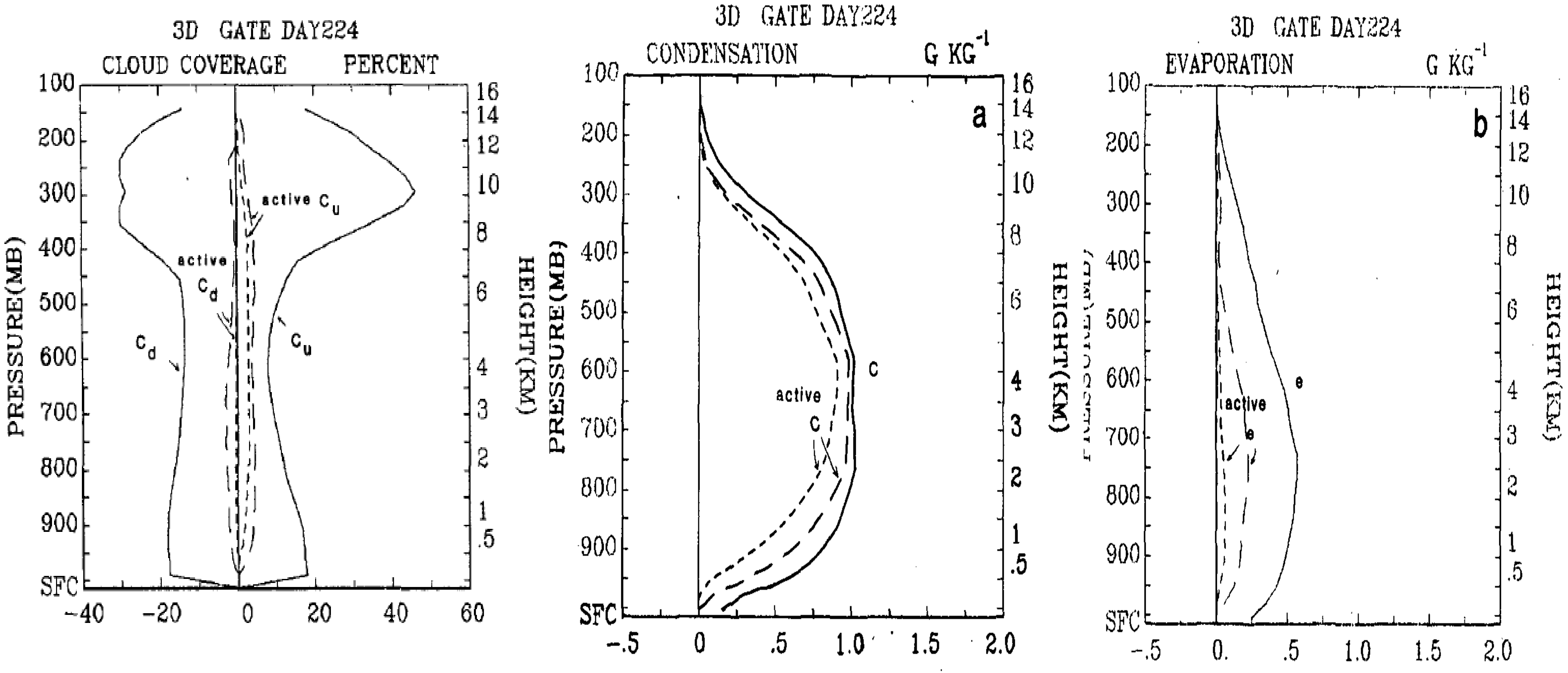


"Both numerical experiment and Zipser and LeMone's analyzed results show that the mean intensities of active updrafts are 2-4 m/s…"

Areal coverage (%) of active updraft and downdraft

Condensation rate

Evaporation rate



Altitude Range (m)	Zipser and LeMone		2D GCE			3D GCE		
	Draft	Core	Cloudy	Active 1ms^{-1}	Active 2ms^{-1}	Cloudy	Active 1ms^{-1}	Active 2ms^{-1}
9500			1.36 (34.6/25.4)	2.92 (2.98/1.02)	8.00 (1.60/0.20)	1.60 (45.9/26.8)	1.98 (2.67/1.35)	8.60 (1.54/0.18)
4300-6100	0.57 (16.9/29.9)	2.66 (4.6/1.8)	1.04 (11.3/10.9)	2.80 (4.2/1.5)	12.70 (2.8/0.22)	0.81 (11.7/14.4)	2.87 (4.3/1.5)	22.20 (2.89/0.13)
2600-4300	0.60 (18.3/30.3)	1.30 (2.1/1.1)	0.75 (8.4/11.2)	1.05 (4.1/3.9)	2.45 (2.7/1.1)	0.58 (8.3/14.3)	1.23 (3.6/3.1)	7.21 (2.61/0.39)
700-2500	0.65 (16.3/25.2)	1.91 (2.1/1.1)	1.07 (13.9/12.9)	1.37 (4.1/3.0)	2.63 (2.1/0.8)	0.76 (13.4/17.0)	1.72 (4.3/2.5)	4.90 (2.45/0.50)
300-700	0.86 (16.6/18.8)	1.88 (1.5/0.8)	1.13 (15.3/13.5)	1.24 (2.47/2.00)	2.03 (0.73/0.36)	0.95 (17.2/18.2)	1.68 (3.2/1.9)	3.40 (0.85/0.25)
0-300	1.01 (15.9/15.7)	1.60 (0.3/0.2)	1.11 (15.6/14.0)	1.36 (0.87/0.64)	1.78 (0.16/0.09)	0.99 (17.6/17.8)	1.38 (1.1/0.8)	1.20 (0.12/0.10)

Ratio of fractional cloud coverage (R=cloud updraft coverage/downdraft coverage). Fractional coverages occupied by cloud drafts and active cloud drafts] over the domain are also shown within the parentheses

LeMone, M. A., & Zipser, E. J. (1980). Cumulonimbus vertical velocity events in GATE. Part I: Diameter, intensity and mass flux. J. Atmos. Sci., 37(11), 2444–2457. https://doi.org/10.1175/1520-0469(1980)037<2444:CVVEIG>2.0.CO;2

Zipser, E. J., & LeMone, M. A. (1980). Cumulus vertical velocity events in GATE. Part II: Synthesis and model core structure. J. Atmos. Sci., 37(11), 2458–2469. https://doi.org/10.1175/1520-0469(1980)037<2458:CVVEIG>2.0.CO;2

Summary

- Cloud-resolving modeling study provides a reference framework for retrieval cloud and precipitation microphysical processes by linking the observables (vertical velocity and its structure of updraft/downdraft cores) with process rates.
- Fractional areal coverage of active updrafts is about 1% (0.5%) for the threshold of 1 m/s (2m/s) of the total domain area, but accounts for 83% (66%) of all condensation, with similar percentages for deposition and freezing. This indicates the importance of focusing on the observations of active updrafts.
- Processes associated with active downdrafts: evaporation, sublimation, and melting are more widely scattered spatially compared with the active updraft region.

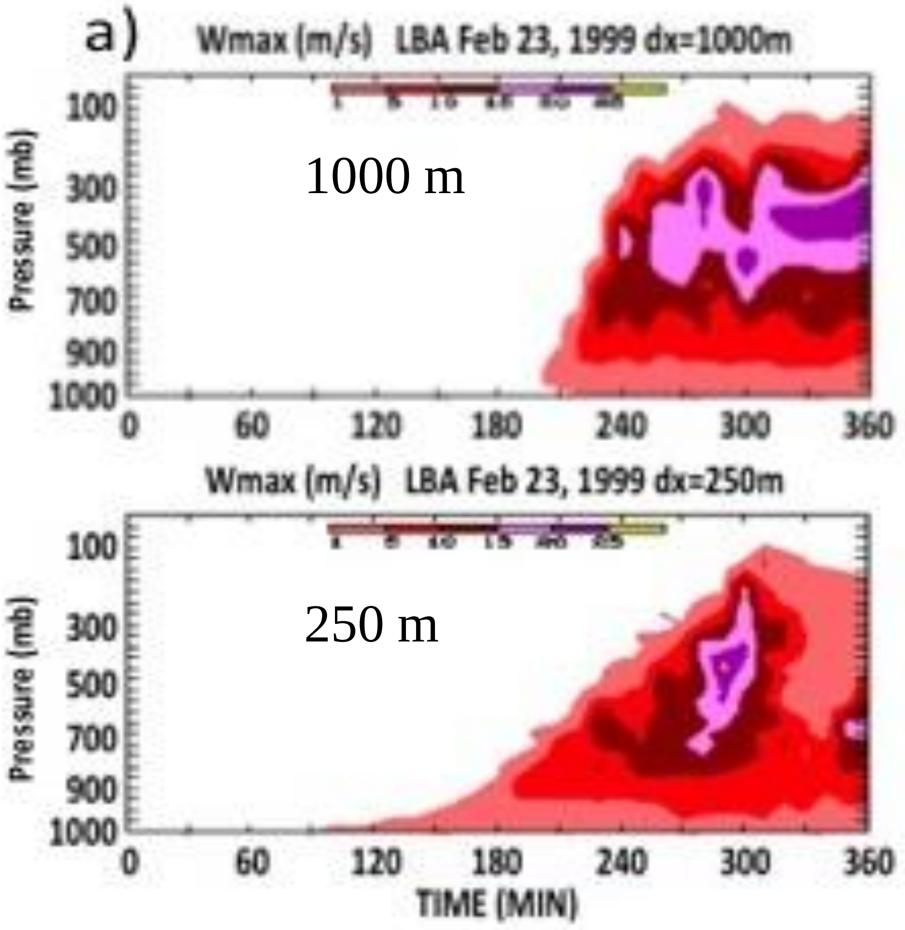
No measurement : Microphysics Processes!

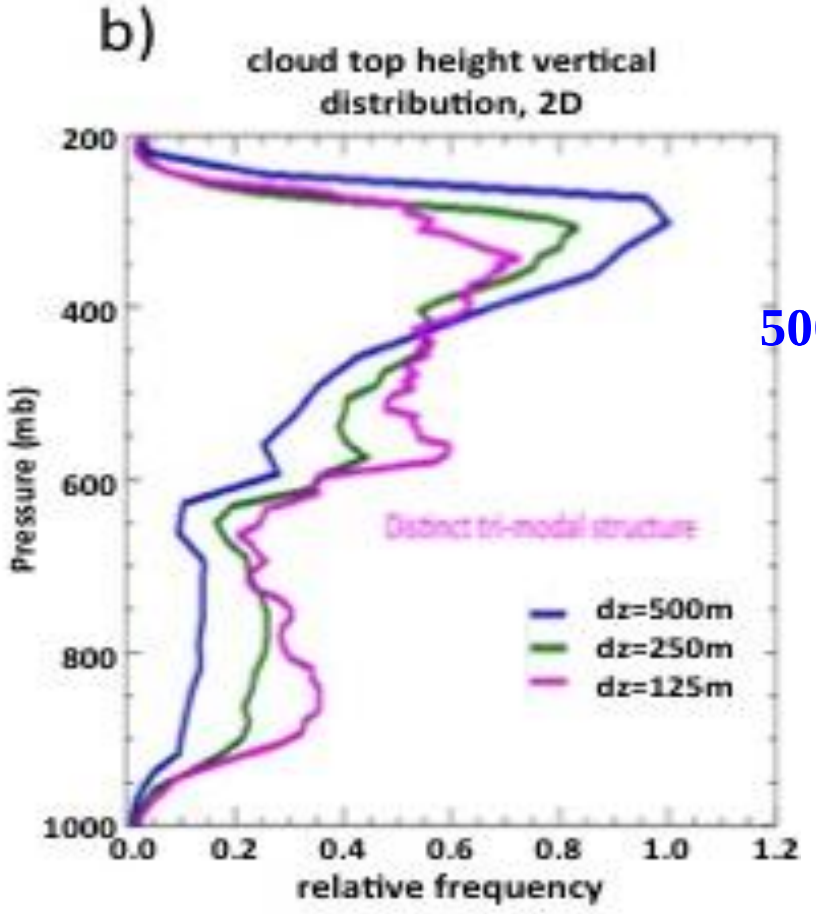
What are the uncertainties of cloud/microphysical processes?

The vertical profiles of the cloud/precipitation properties in convective and stratiform regions, ***mixed phase*** (melting, riming, ice processes), ***life cycle***

Need to have the following *measurements of cloud properties*

- 3D vertical velocity structures;
- **High temporal resolution aerosol/CCN measurements**;
- Vertical (ice, liquid) hydrometeor particles (droplet spectrum, condensation, size, density) measurements;
- Comprehensive polarmetric radar measurements (i.e., S/C-band ground-based for convective cores and air/space borne or vertically pointing X/K-band for anvil/stratiform characteristics)

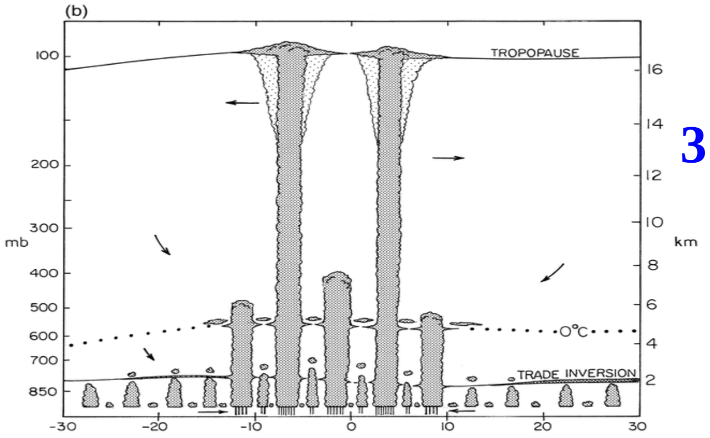




DZ:
500, 250 and 125 m

DX:
1000 and 250 m

Transition from
Shallow to Deep



Cumulus Congestus

3 cloud types in tropical convection

Johnson *et al.*, 1999