Latent Heating Algorithm

Wei-Kuo Tao, Yukari N. Takayabu, Steve Lang and Taka Iguchi

- What is Latent Heating (LH)?
- How important is LH?
- How can LH be estimated and retrieved?
- Goddard CSH Algorithm for GPM - high latitude / winter season (**cold season)** and tropics (**warm season**); and its retrieved LH structures (July, August and September 2014)

CSH: Convective/Stratiform Latent
SLH: Spectral Latent Heating (Japan)

Recent LH (4) papers

- **Tao, W.-K.,** Y. N.Takayabu, et al., 2016: TRMM Latent Heating Retrieval and Comparison with Field Campaigns and Large-Scale Analyses, *Amer. Meteor. Soc. Meteorological Monographs - Multi-scale Convection-Coupled Systems in the Tropics, Chapter 2*, doi:10.1175/AMSMONOGRAPHS-D-15-0013.1

- Lang, S. E., and **W.-K. Tao**, 2018: The Next-generation Goddard Convective-Stratiform Heating Algorithm: New Tropical and Warm Season Retrievals for GPM. *J. Climate*, 31, 5997-6026, doi: 10.1175/JCLI-D-17-0224.1.

- **Tao, W.-K.,** T. Iguchi, and S. Lang, 2019: Expanding the Goddard CSH Algorithm for GPM: New Extratropical Retrievals. *J. Appl. Meteor. Climatol.*, (early release)

- Takayabu, Y. N., and **W.-K. Tao**, 2019: Latent heating retrievals from satellite observations. Chapter 5.12 in *Satellite Precipitation Measurement*, Springer (submitted).

Heating (LH, Q_1, Eddy Transport, Q_1-Q_R)

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

No Direct Measurements

Can be calculated through cloud resolving models

Good agreement between observed and simulated Q_1

Eddy — LH (Cloud Microphysics)

$$Q_1 - Q_R = \bar{\pi}\left[-\frac{1}{\bar{\rho}}\frac{\partial \bar{\rho}\overline{w'\theta'}}{\partial z}\right] + \frac{L_v}{C_p}(\bar{c} - \bar{e}_c - \bar{e}_r) + \frac{L_f}{C_p}(\bar{f} - \bar{m}) + \frac{L_s}{C_p}(\bar{d} - \bar{s})$$

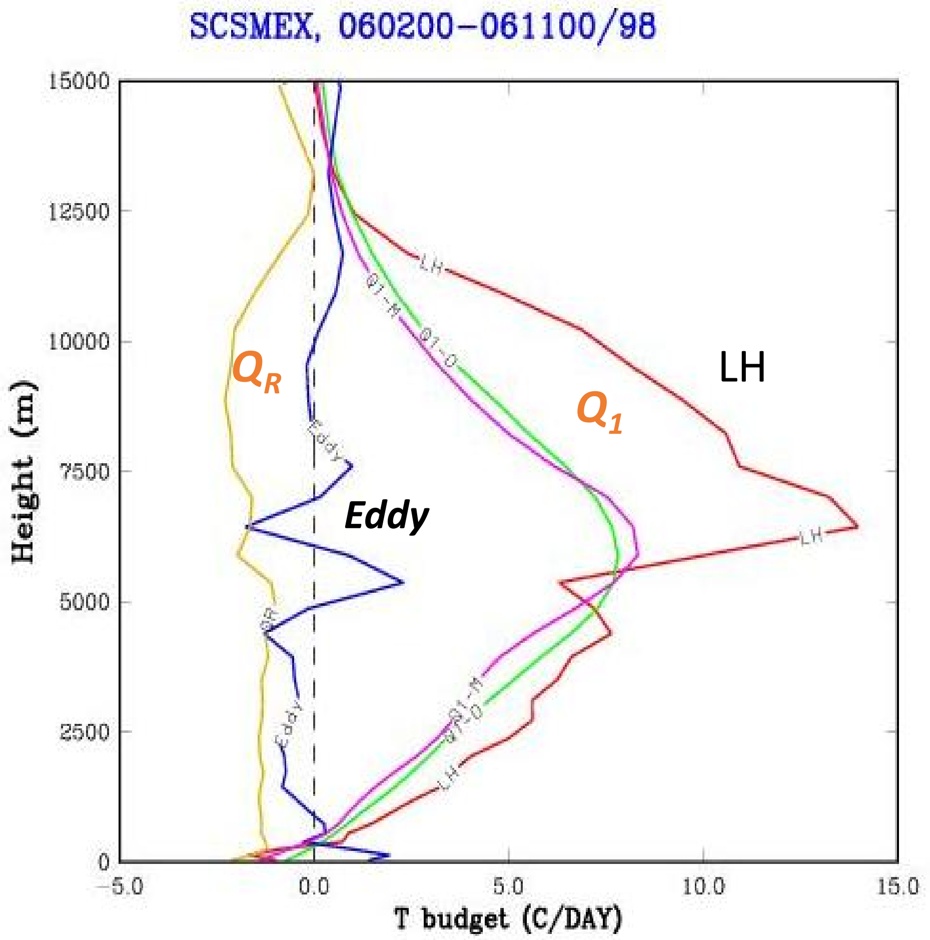
Or **as a residual from diagnostic budget study**

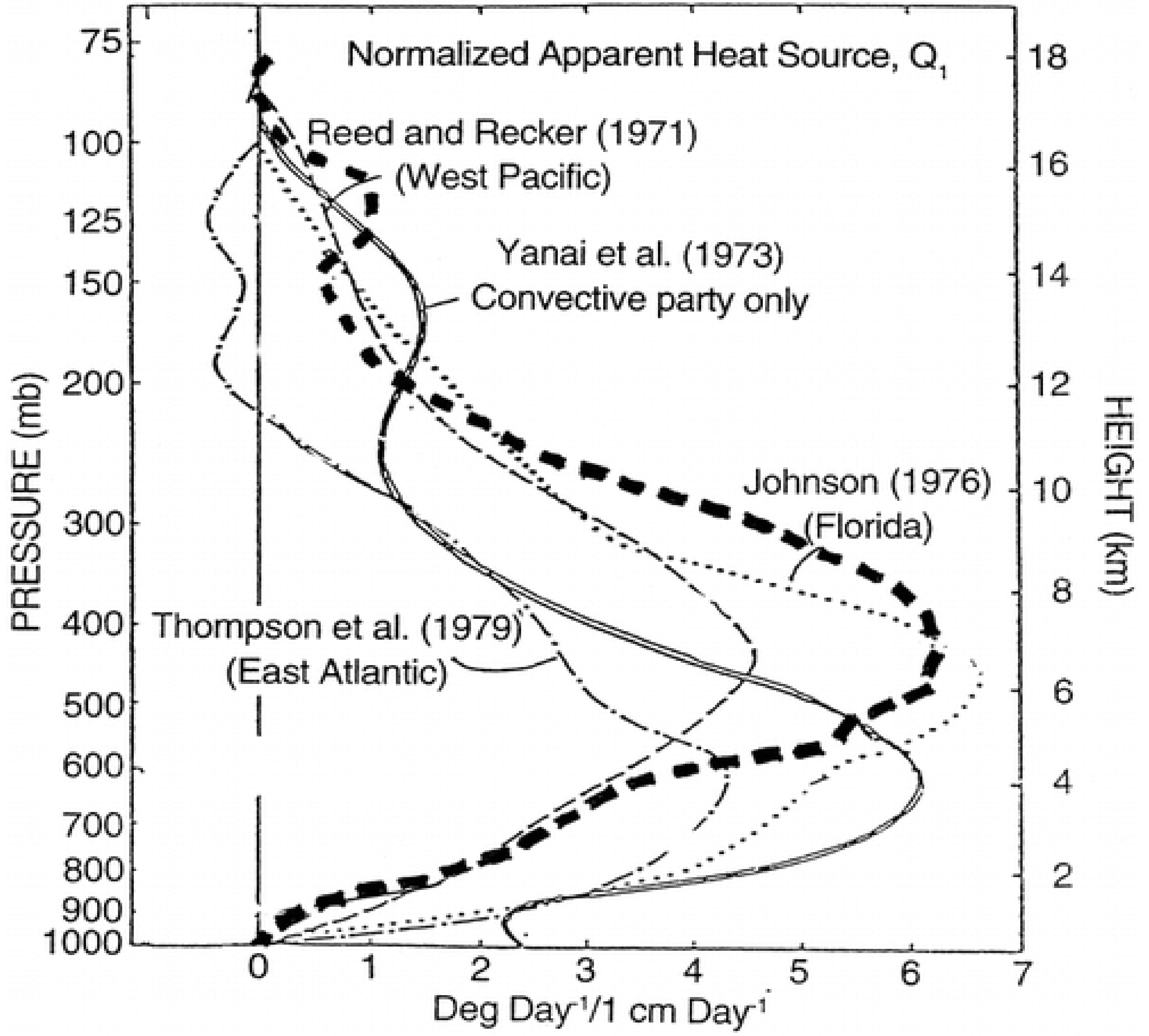
Through indirect measurement using sounding-networks (TRMM Field Campaigns)

Forcing Term

$$Q_1 - Q_R = \bar{\pi}\left[\frac{\partial \bar{\theta}}{\partial t} + \vec{V}\cdot\nabla\bar{\theta} + \bar{w}\frac{\partial \bar{\theta}}{\partial z}\right]$$

Yanai (1973)





Q_1 (apparent heat source): Estimated from sounding Network
(West Pacific,
East Atlantic,
Florida)

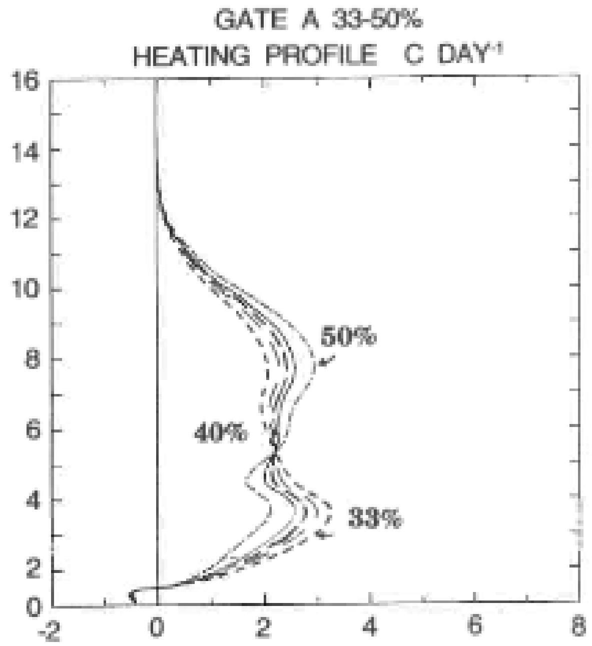


Fig. 12. The latent heating profiles derived by using 33 %, 37 %, 40 %, 43 % and 50 % of stratiform rain for a GATE squall system.

35% Stratiform for GATE

50% stratiform for EMEX

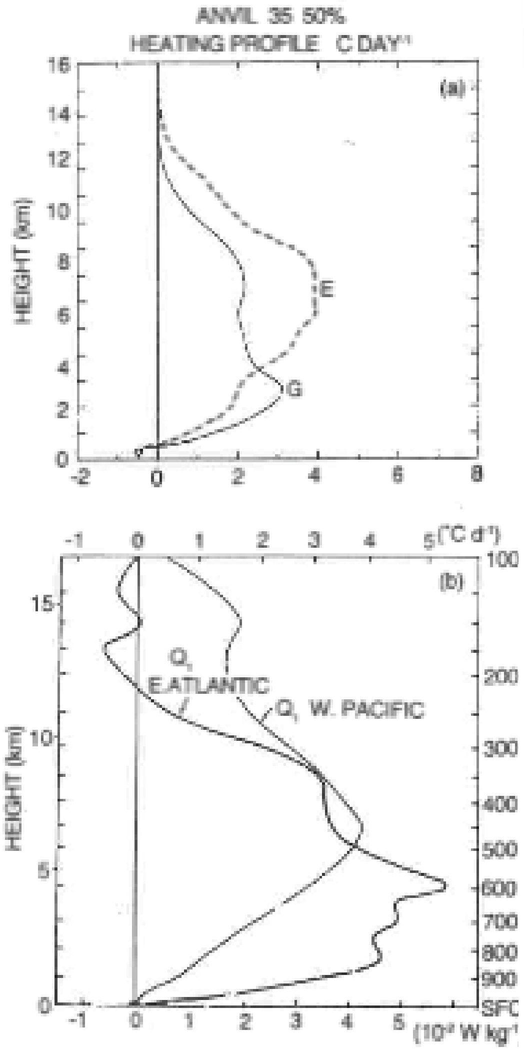


Fig. 13. (a) As Fig. 12 except by using 35 % and 50 % of stratiform rain for GATE and EMEX squall systems, respectively. (b) The Q_1 for the west Pacific and eastern Atlantic regions (From Thompson et al., 1979).

Top: 20% Stratiform

Bottom: 60% stratiform

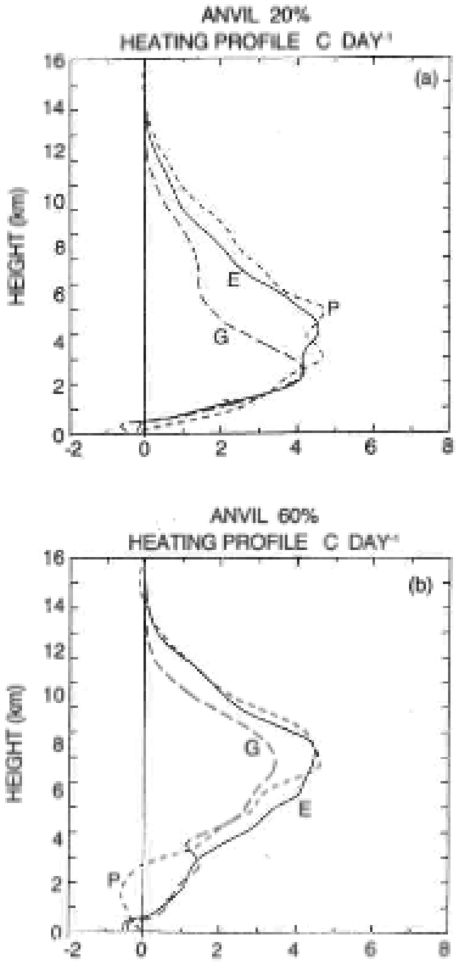
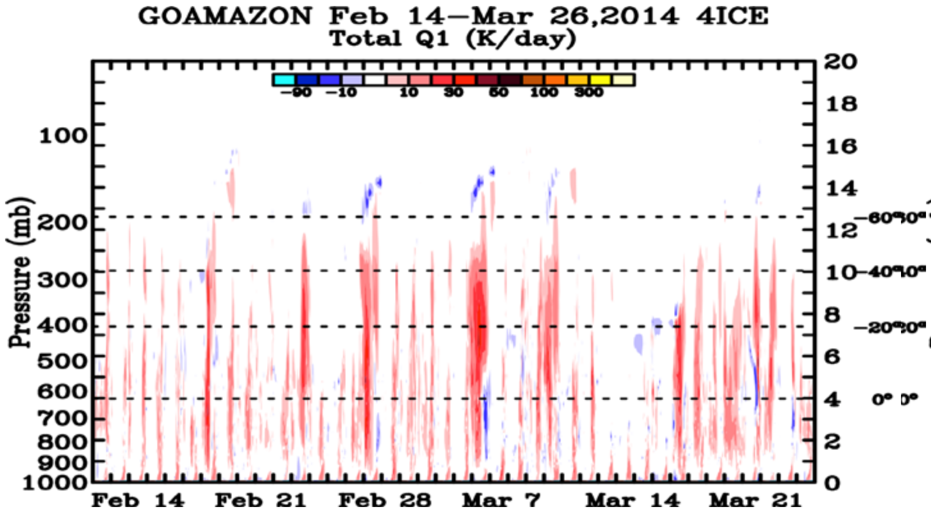


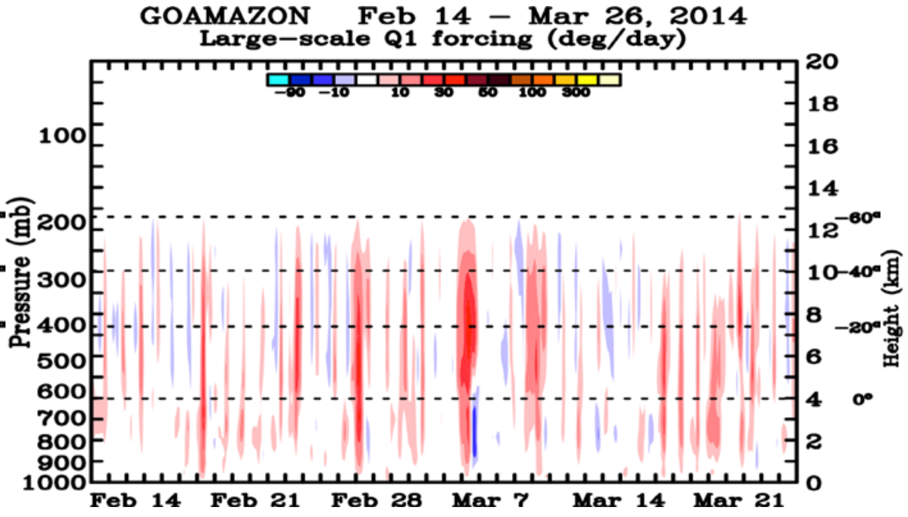
Fig. 10. The latent heating profiles derived by using (a) 20 % and (b) 60 % of stratiform rain associated with three different squall systems, GATE, PRE-STORM and EMEX. Letters, P, G, and E denote PRE-STORM, GATE and EMEX, respectively.

Tao et al. (1993)

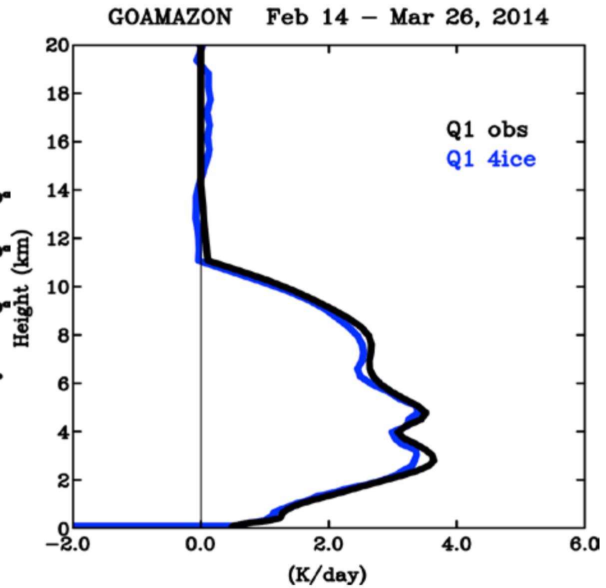
LH structure (profile) is very sensitive on the stratiform rainfall amount (or %)



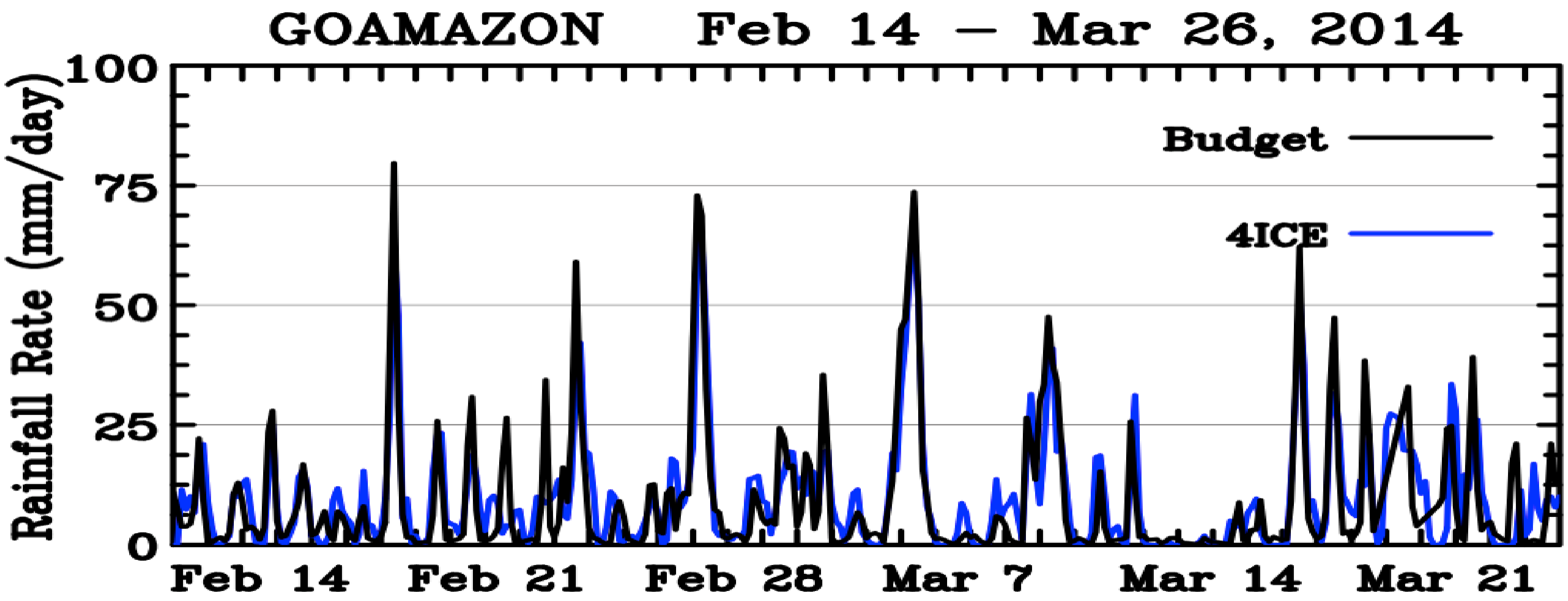
GCE Simulated Q_1



Sounding Derived Q_1



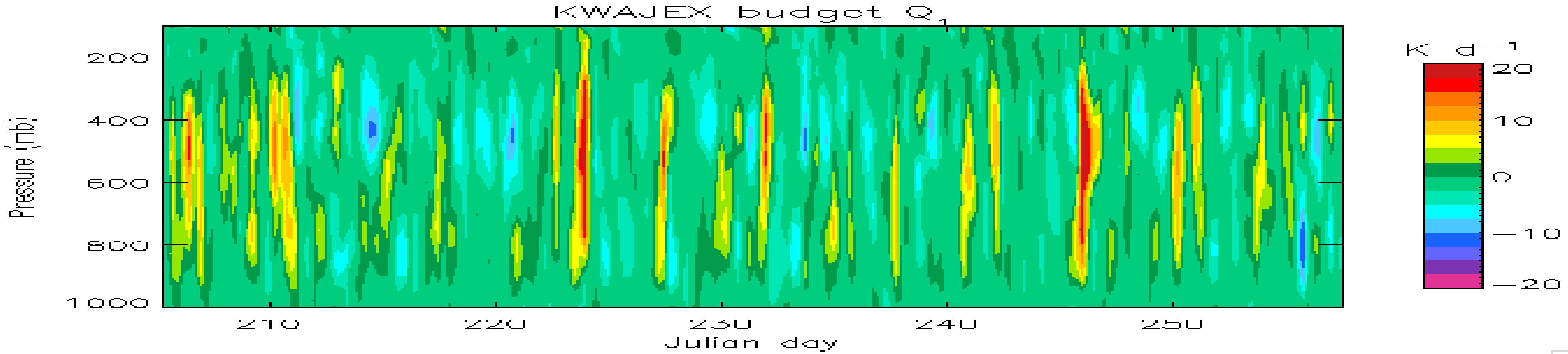
S. America



Time series of domain averaged surface rainfall (40 days)

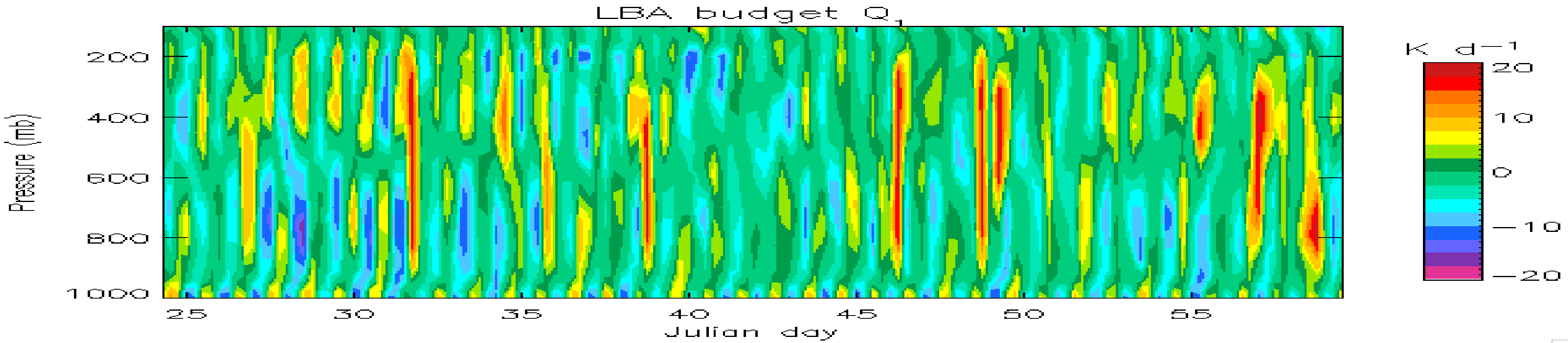
KWAJEX

July 24 - September 14



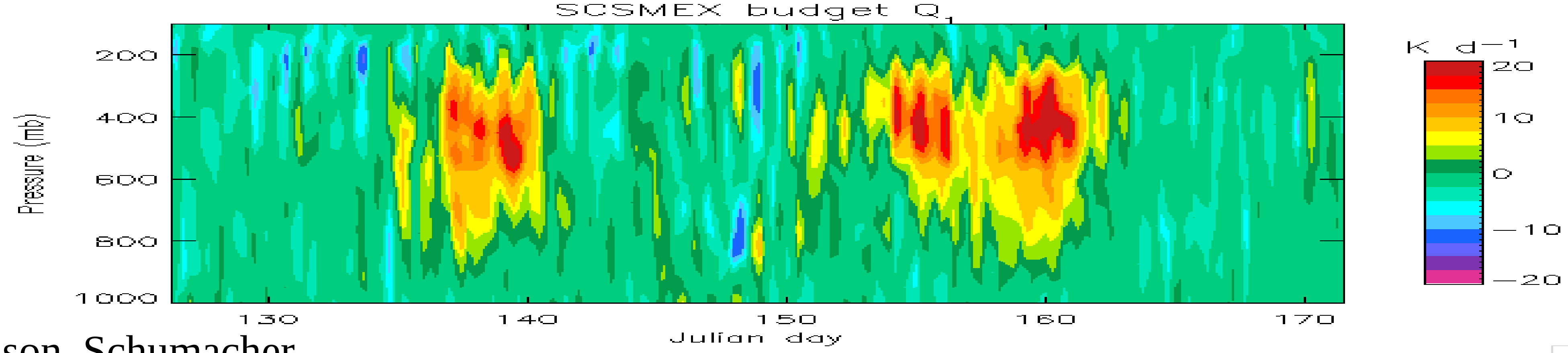
LBA

January 24 - February 24



SCSMEX

May 1 - June 30



Zhang, Johnson, Schumacher

Highlights	Reference
First paper to use a CRM to develop a LH algorithm - LH structure estimated from vertical hydrometeor profiles	Tao *et al.* (1990)
First paper on the CSH algorithm - composite both sounding estimated and CRM modeled convective and stratiform heating profiles into a simple look-up table (LUT)	Tao *et al.* (1993)
Examined the performance of the CSH algorithm using CRM simulated (consistency check), SSMI and ship borne estimated rainfall and stratiform percentages. Retrieved LH sensitive to surface rainfall amount and stratiform percentage.	Tao *et al.* (2000)
First paper to retrieve LH based on one-month of TRMM-estimated rainfall products.	Tao *et al.* (2001)
Improved CSH by using several CRM-simulations to build the LUTs, individual heating components retrieved separately, LUTs separated into many surface rain rate intensity bins and stratiform fractions	Tao *et al.* (2010)
Improved CSH by using even more CRM simulations with better microphysics to build the LUTs and added new metrics for echo top heights and low-level dBZ gradients to the LUTs	Lang and Tao (2018)
Expanded the retrieval of LH to higher latitudes and the cold season using NU-WRF simulations of synoptic storms to build separate LUTs	Tao *et al.* (2019)
Review papers on LH algorithms, applications and evaluations	Tao *et al.* (2006, 2016)

Tao *et al.* (2019)

Highlights	Reference
First paper on the SLH algorithm – index the LUTs according to vertical rain profile information: precipitation top height (PTH) for convective and shallow stratiform rain and melting-level rain intensity for anvil (deep stratiform with a PTH higher than the melting level).	Shige *et al.* (2004)
Improved SLH by separating convective heating retrieval into upper-level heating due to ice processes and lower-level heating due to liquid water processes, and shifted up or down the stratiform heating profile by matching the melting level in the LUT with the observed one. Good agreement between SLH estimates and diagnostic calculations for SCSMEX.	Shige *et al.* (2007)
Expanded SLH to the retrieval of Q_2. Good agreement between SLH estimates and diagnostic calculations for SCSMEX. Differences of SLH Q_2 estimates between the western Pacific Ocean and the Atlantic Ocean consistent with the results from the budget study.	Shige *et al.* (2008)
Comparisons of the LUTs from two- and three-dimensional CRM simulations. Less agreement between SLH estimates using the LUTs from three-dimensional CRM simulations and diagnostic calculations for SCSMEX supports using the LUTs from two-dimensional CRM simulations.	Shige *et al.* (2009)

GCE cases used for the CSH V6 Tropical / Warm Season LUTs

Field Campaign	Geographic Location	Dates	Modeling Days	Reference(s)
ARM-SGP-97	Land (Southern Great Plains)	June - July, 1997	29	Tao et al. (2004); Zeng et al. (2009)
ARM-SGP-02		May - June, 2002	20	Zeng et al. (2007, 2009)
SCSMEX/NESA	Ocean (South China Sea)	May – June, 1998	45	Tao et al. (2003b), Zeng et al. (2008)
TOGA-COARE	Ocean (Equatorial West Pacific)	November, 1992 – February, 1993	61	Das et al. (1999);; Johnson et al. (2002); Zeng et al. (2009)
GATE	Ocean (Tropical Atlantic)	August – September, 1974	20	Tao et al. (2004); Zeng et al. (2009)
KWAJEX	Ocean (Marshall Islands)	July – September, 1999	52	Zeng et al. (2008)
TWP-ICE	Ocean (Darwin, Australian)	January – February, 2006	24	Zeng et al. (2013)
MC3E	Land (Southern Great Plains)	April – March, 2011	33	Zeng et al. (2007)
DYNAMO	Ocean (Equatorial Indian Ocean)	November – December, 2011	31	Li et al. (2018)
GoAMAZON	Land (Amazon Basin)	February – March, 2014	40	Lang and Tao (2018)

In all, the GCE model CSH V6 database contains about **355 days (122 continental, 233 oceanic)** of model integration.

Cold-Season Algorithm and NU-WRF Model Database

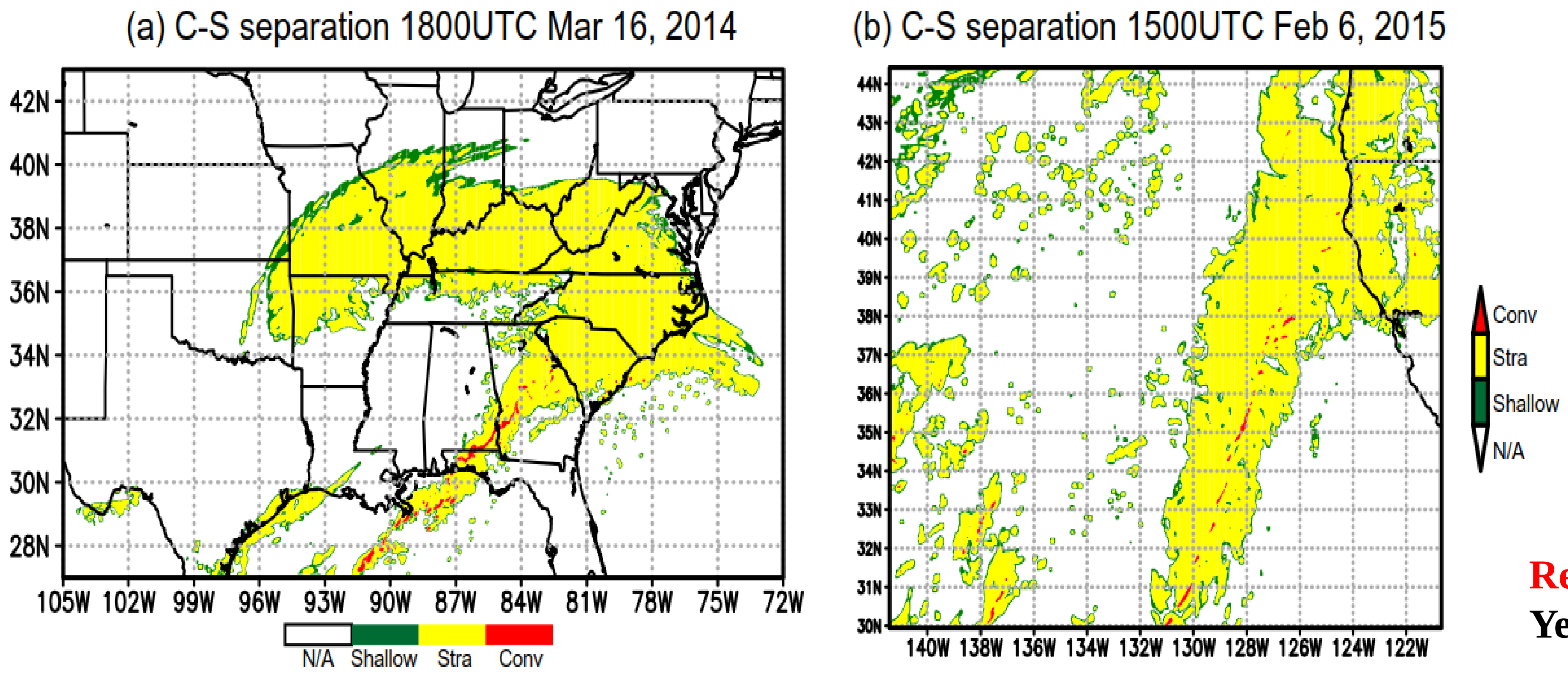
- NU-WRF simulations of winter storms
- Simulation descriptions and results (6 cases)
- Design of new CSH cold season look-up table (LUT)
- Qualitative validation (self-consistency checks)

Tao, W.-K., T. Iguchi, and S. Lang, 2019: Expanding the Goddard CSH Algorithm for GPM: New Extratropical Retrievals. *J. Appl. Meteor. Climatol.*, (early release)

Mid-Latitude Winter Cases differ from Tropical Convective Systems

Steiner-type Convective/Stratiform Separation applied to high-latitude, winter synoptic events

East Coast US



Calwater 2015

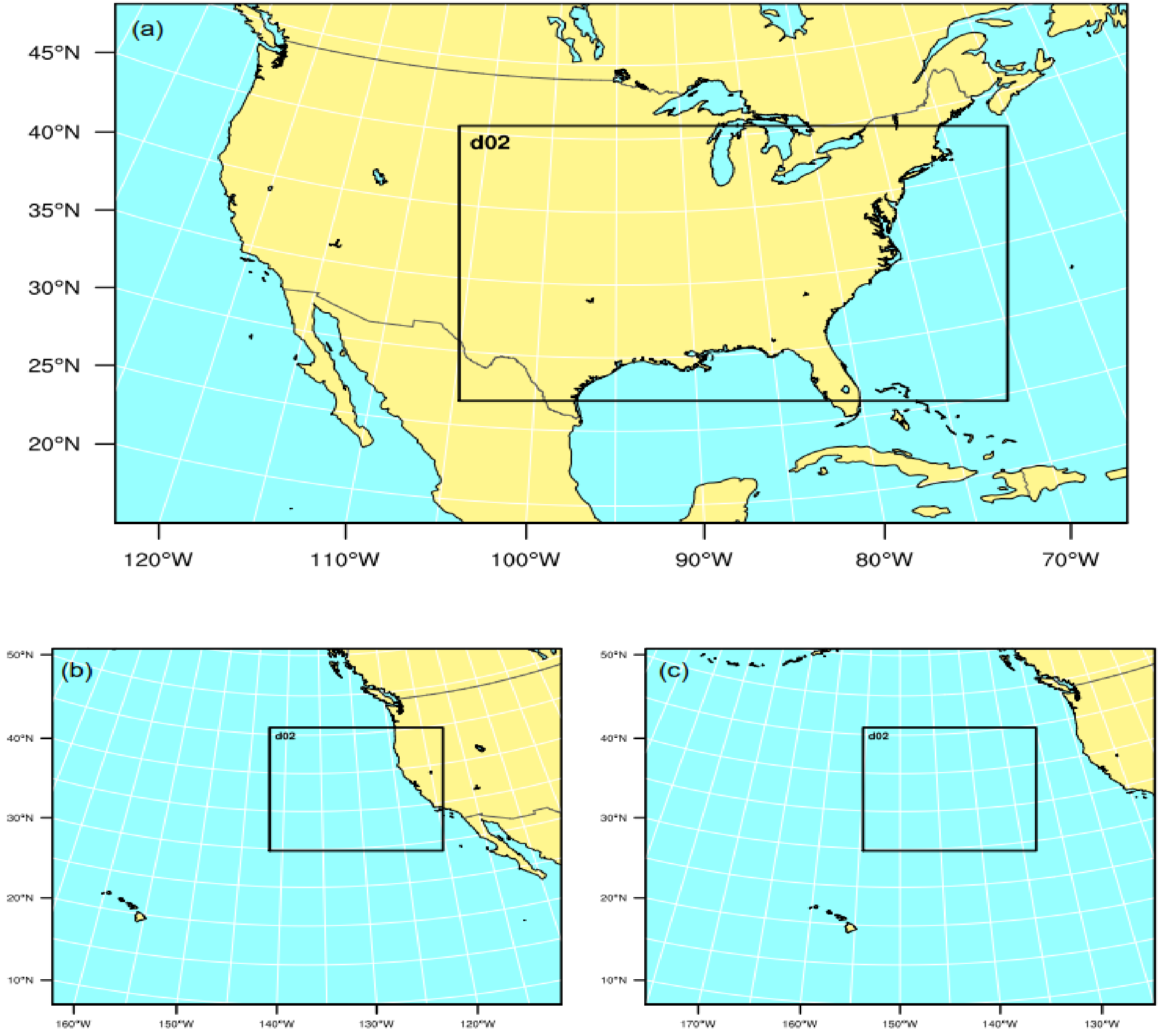
Red: Convective
Yellow: Stratiform

Convective regions have high surface precipitation rates but only ***cover a tiny fraction***, while stratiform regions cover nearly the entire surface precipitation area, making a tropical mesoscale convective system (MCS) convective-stratiform separation approach less suitable.

NASA Unified WRF (NU-WRF) CSH V6 Simulation Configurations

East Coast Synoptic Winter storms

CalWater 2015

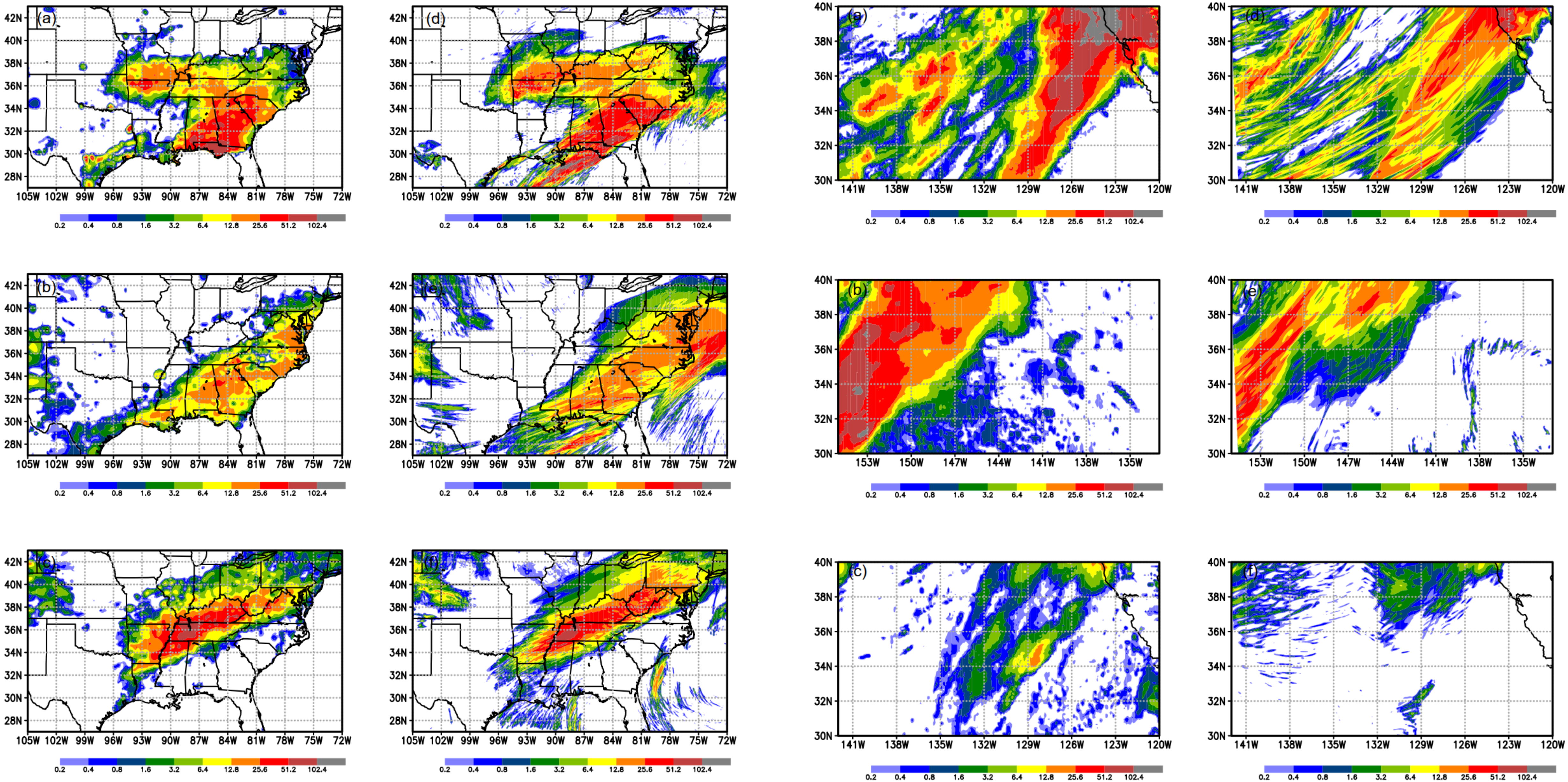


- Two nested domains with 9 km (outer) and 3 km (inner) resolution
- Initialized with NCEP FNL Re-Analyses
- **Goddard 4ICE microphysics scheme** (Lang *et al*. 2014; Tao *et al.* 2016)
- **Goddard long- and short-wave radiation** (Chou and Suarez 1999, 2001; Matsui and Jacob 2014)

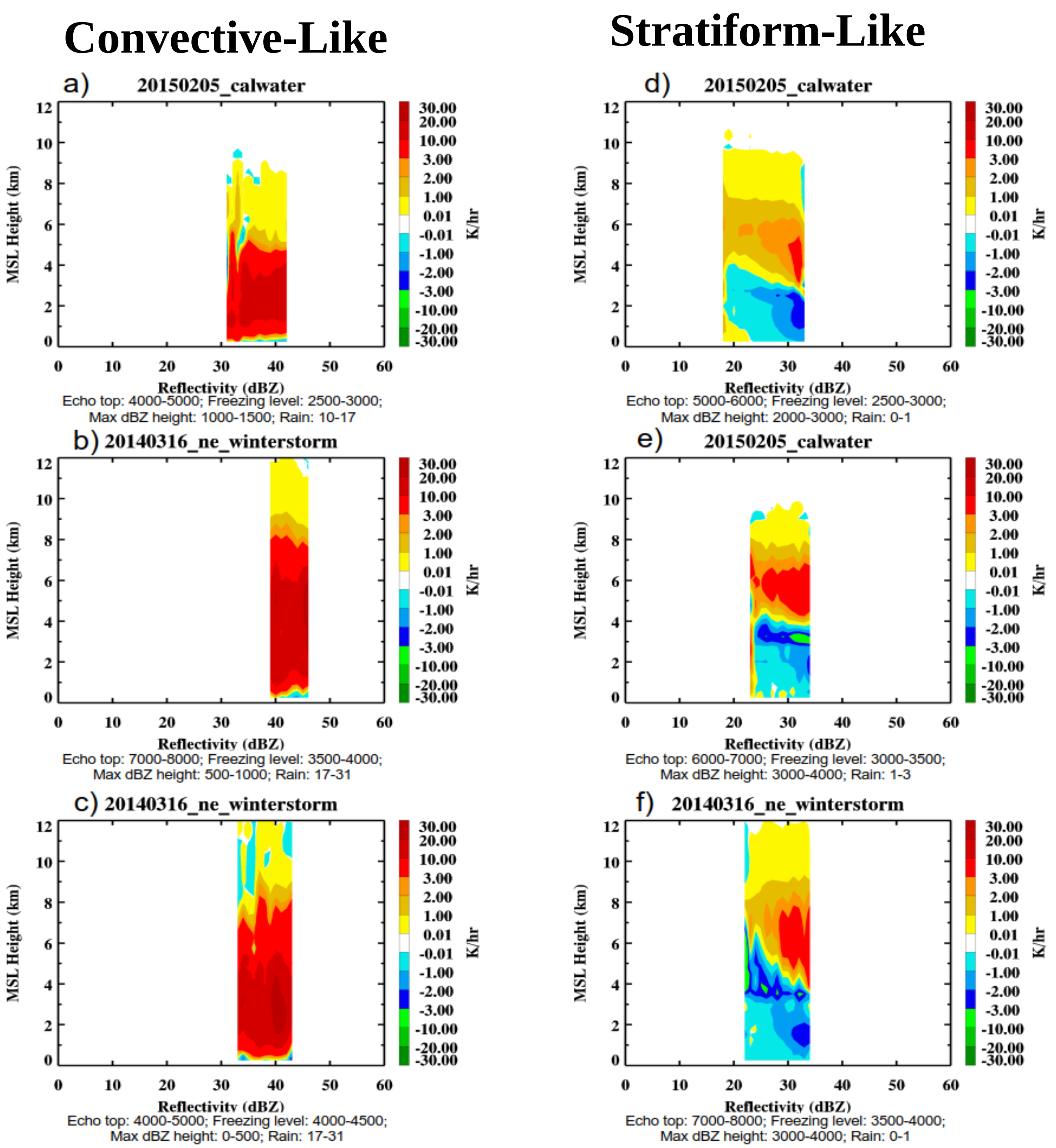
Both Goddard 4ICE $ Radiation: NCAR WRF (Spring 2019)

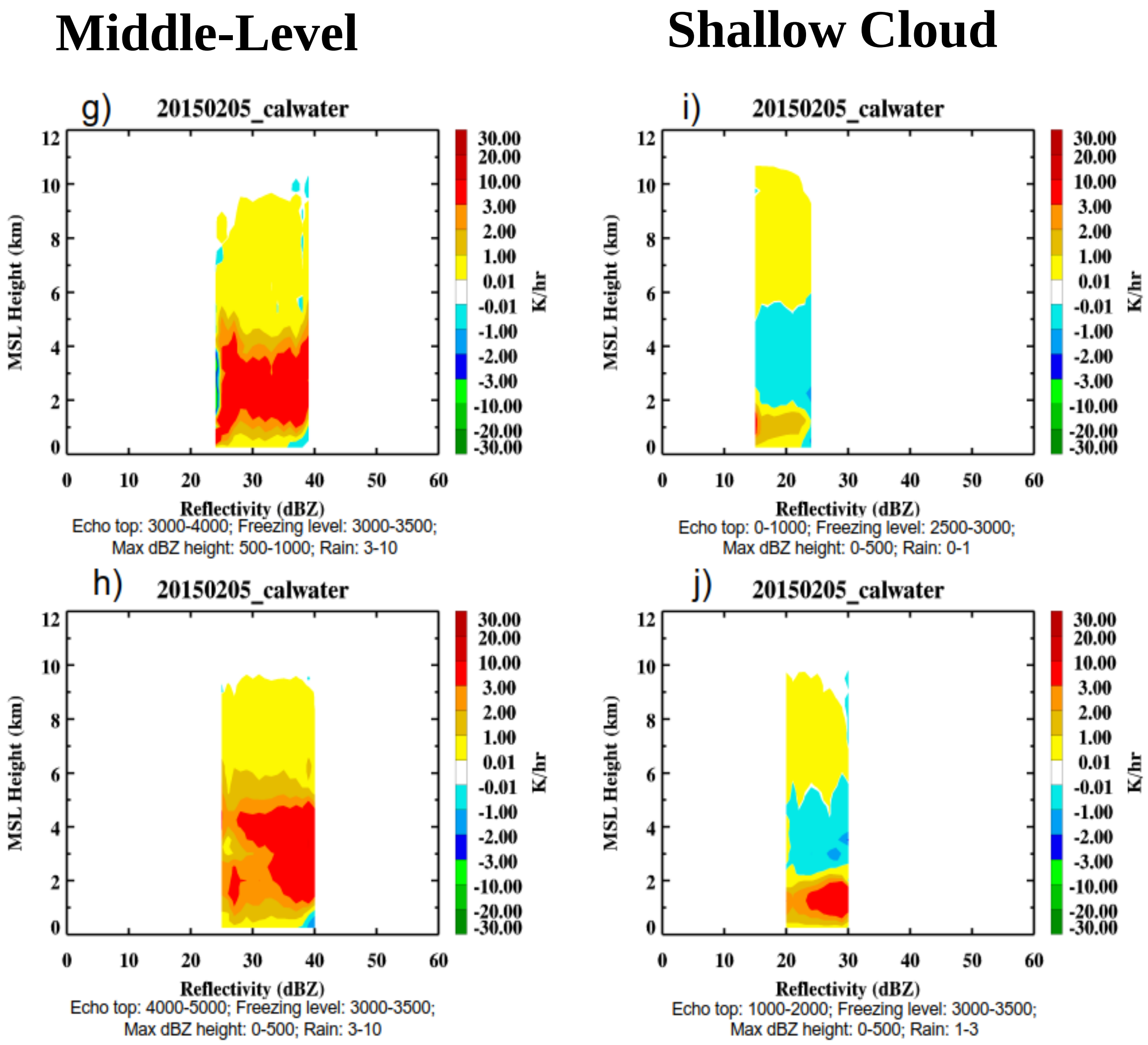
NU-WRF versus NLDAS-2 / IMERG surface rainfall – 6 Cases

NLDAS-2 | NU-WRF | *IMERG* | NU-WRF



Examples of latent heating profiles in the new cold season look-up table





Different surface precipitation rate, composite radar reflectivity, echo-top height, freezing level height, and maximum radar reflectivity height. → ***Different LH profiles***

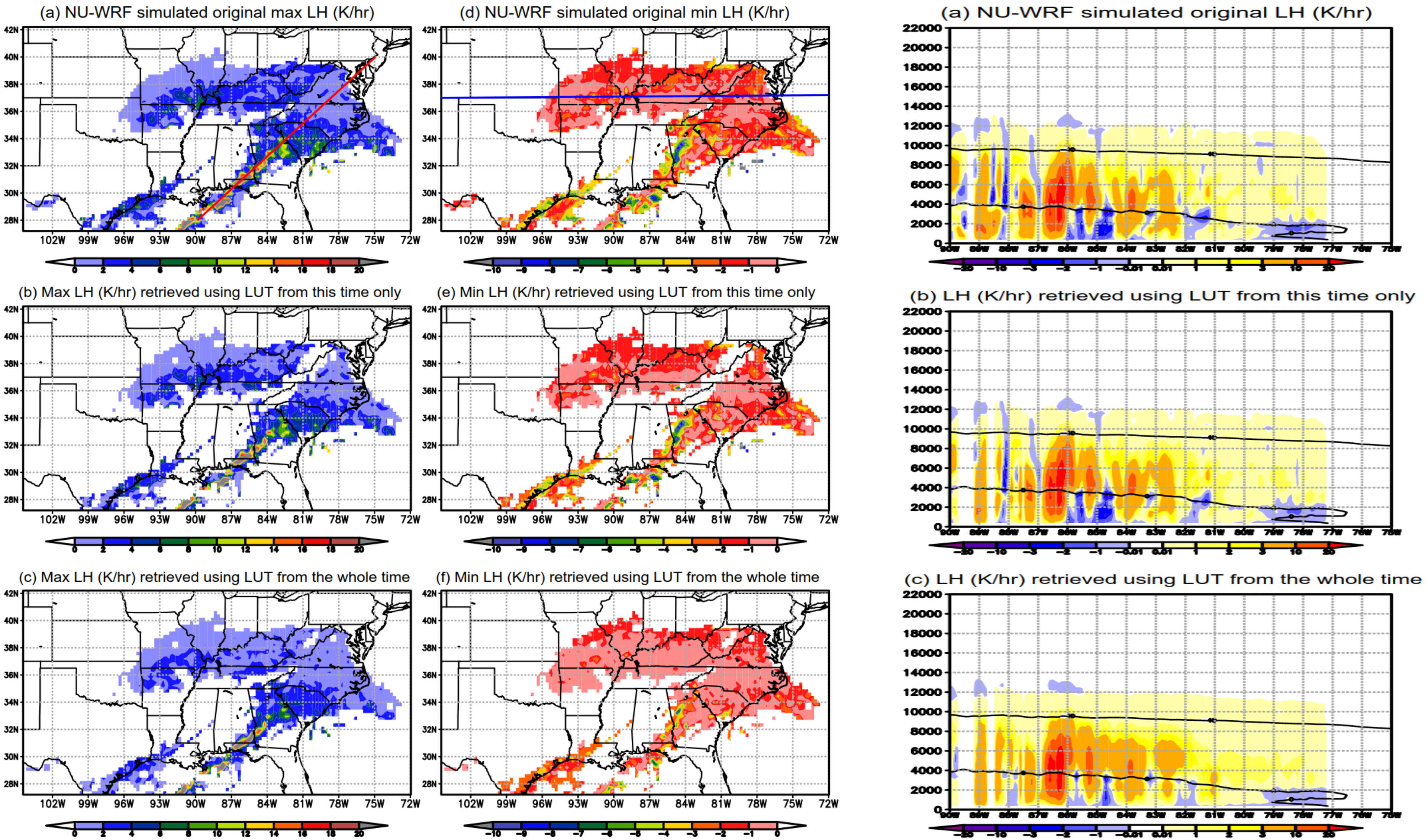
Self-consistency check results (horizontal and vertical snapshots)

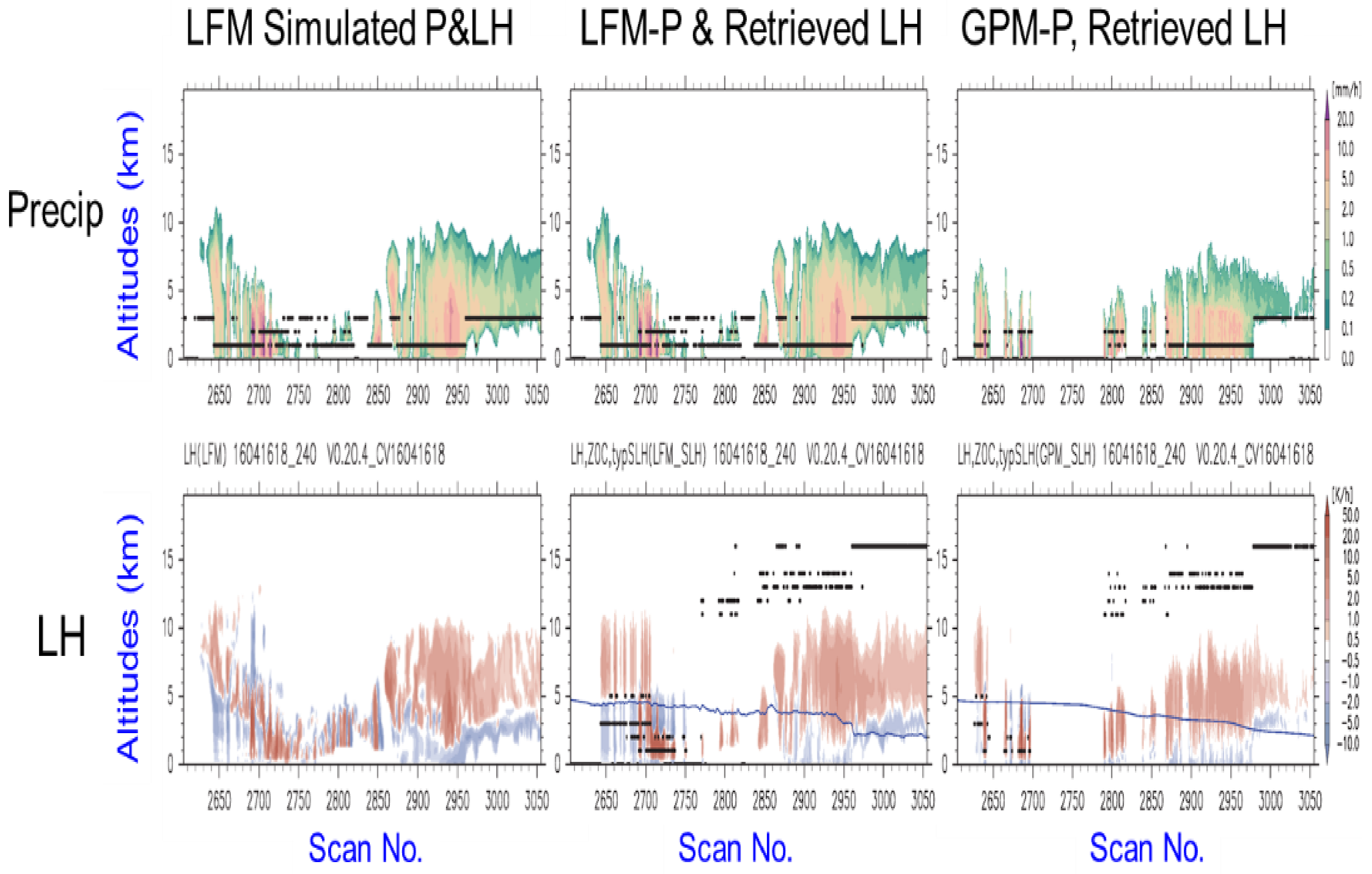
Maximum LH | Minimum LH | Vertical cross-section along red-line

NU-WRF **Simulated** LH

Retrieved LH 1st type

Retrieved LH 2nd type




LFM Simulated P&LH
LFM-P & Retrieved LH
GPM-P, Retrieved LH
Precip
LH
Altitudes (km)
Scan No.
LH(LFM) 16041618_240 V0.20.4_CV16041618
LH,Z0C,typSLH(LFM_SLH) 16041618_240 V0.20.4_CV16041618
LH,Z0C,typSLH(GPM_SLH) 16041618_240 V0.20.4_CV16041618
[mm/h]
[K/h]

Major Characteristics of CSH and SLH Algorithm

	SLH	CSH
Key References	Shige et al. (2003, 2007, 2008, 2009)	Tao et al. (1993, 2000, 2001, 2010), Lang and Tao (2018)
Cases	**Tropics: TOGA COARE** **Winter: 6 oceanic events**	**Tropics: 9 field campaigns (land and ocean)** **Winter: 6 events (land and ocean)**
Input	PR/DPR	Combined GMI/DPR
Products	LH, Q1R, Q2	Tropics: LH, QR, Q2 and , Eddy Heating and Moistening High latitudes: LH only
Look-up Tables	No horizontal eddy Based on CRM domain and **time (5min)** averaged (no subset): Consistent with surface rainfall	Combined horizontal and vertical eddy Samples 32 (64) km model subdomains for GPM (TRMM) 0.25^o x0.25^o (0.5^o x 0.5^o) gridded products

CSH V6 Results for July, August and September 2014

3-month averaged LH for 4 products

V5: GCE conv-strat separation (at 1 km resolution) + 1 km GCE simulations

V6.0: 2A23-like separation (at 4 km resolution) + 200 m GCE simulations

V6: V6.0 algorithm without Bob's new c-s classification + > 20 mm/h = convective

SLH: V6 Spectral Latent Heating Algorithm

Similarities and Differences between CSH V5 and V6

Warm Season

	V5	V6
Cases	6 Ocean + 4 Land	same
Microphysics	4ICE	same
GCE grid size	**1000 m**	**200 m**
GCE domain size	**512 km**	**1024 km**
Echo top Height bins	0-2, 2-4, 4-6, 6-8, >8 km	same
Low-level (0-2 km) vertical DBZ gradient*	Increasing or decreasing dBZs toward the surface	same
Look-Up Tables	20 stratiform bins 36 conditional intensity bins Land vs ocean Rainy, near rain, far from rain	same
Vertical Levels	80	same
Horizontal Resolution	0.25 degree	same
Conv-Strat Separation	**GCE method at model (1 km) resolution**	**2A23-like method at 4-km resolution**

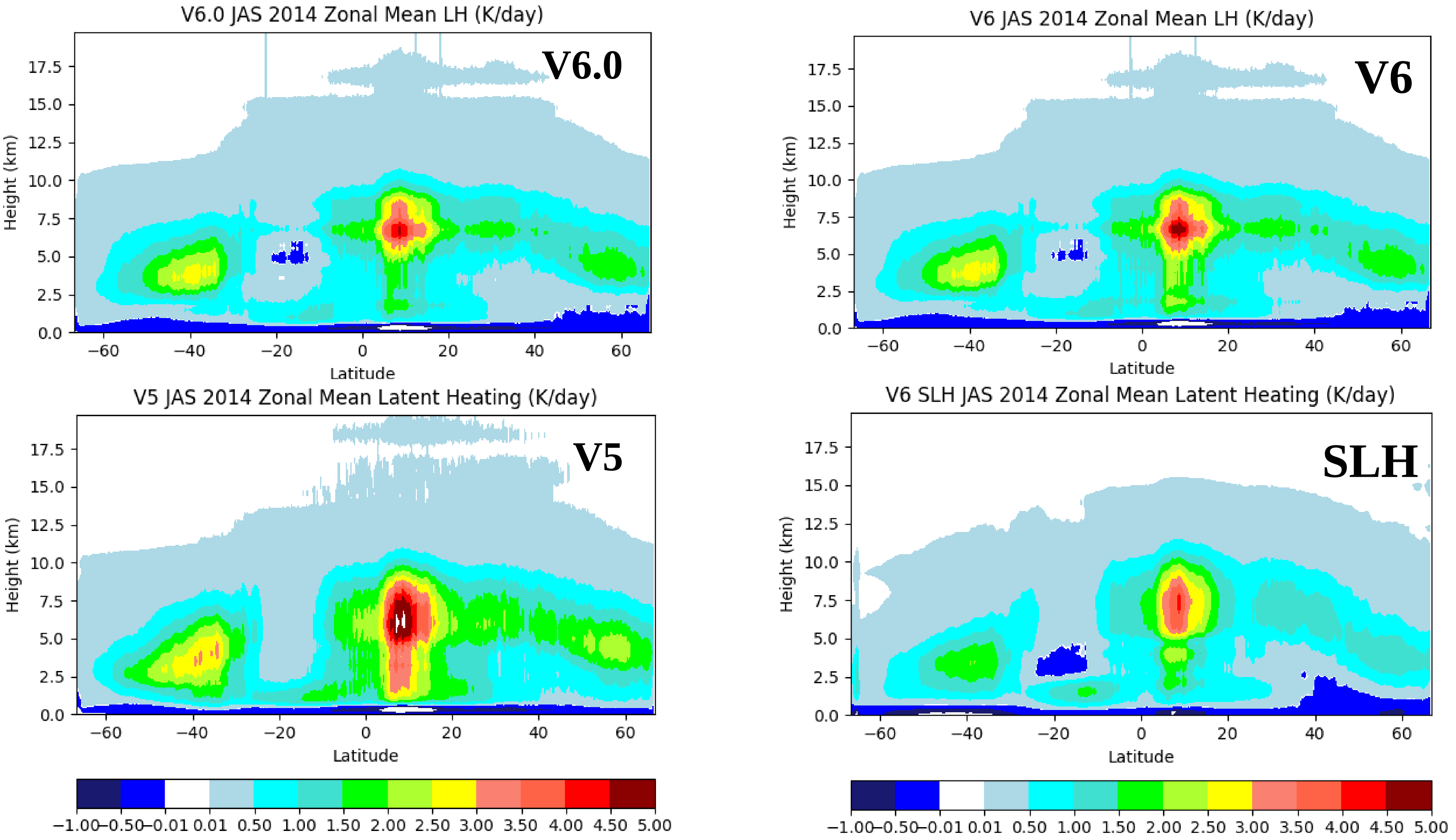
* Differentiate between stronger (drier) / weaker (moister) low level evaporative cooling

Cold Season

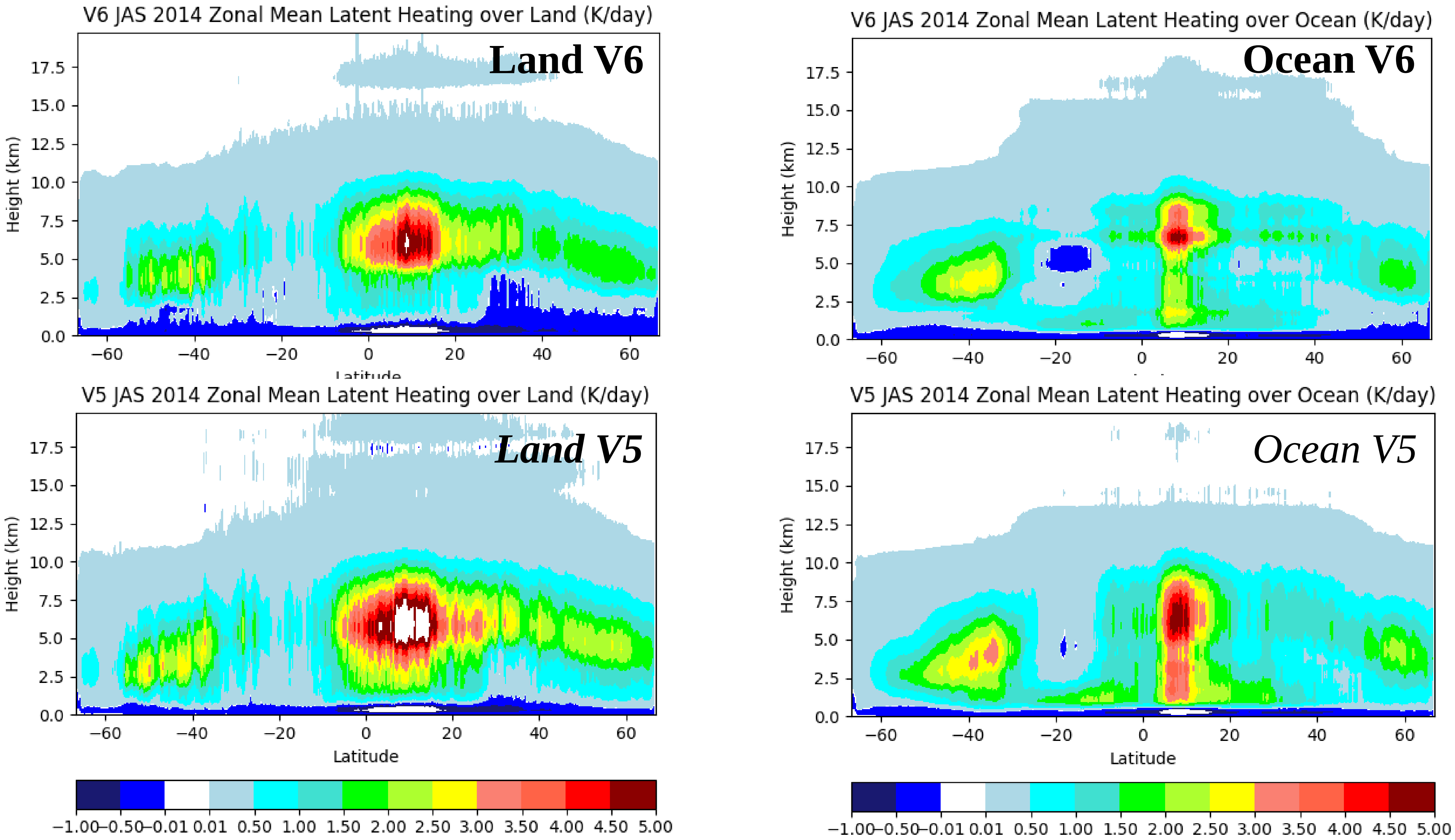
	V5	V6
Cases	3 East Coast + 3 West Coast	same
Microphysics	4ICE	same
NU-WRF grid size	3 km	same
Echo top Height bins	**6 bins, every 2 km**	**11 bins, every 1km**
Vertical DBZ gradient*	Decreasing / Not Decreasing	same
Freezing Level	13 bins	same
Max dBZ Height	**6 bins**	**8 bins**
Surface Rain Rate	**Not Used**	**17 bins**
Vertical Levels	80	same
Horizontal Resolution	0.25 degree	same

* By at least 10 dBZ towards the surface from the maximum dBZ height & value

ZONAL LH (V5, V6.0, V6, SLH)



ZONAL LH (V6 vs V5)



Vertically-Integrated Heating and Precipitation

$$\frac{1}{g}\int_{Lx}\int_{Ptop}^{P_{base}}(Q_1 - Q_R)\Delta p \Delta x = LP_o + S_o$$

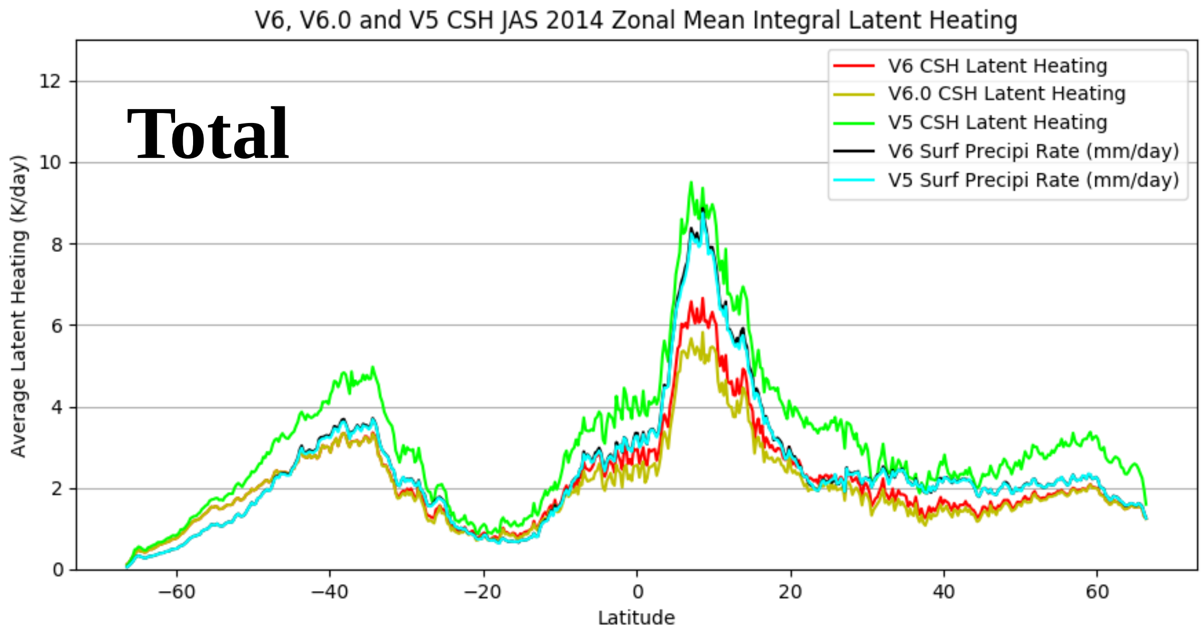
- Comparisons between V5 and V6 (V6.0 and V6)

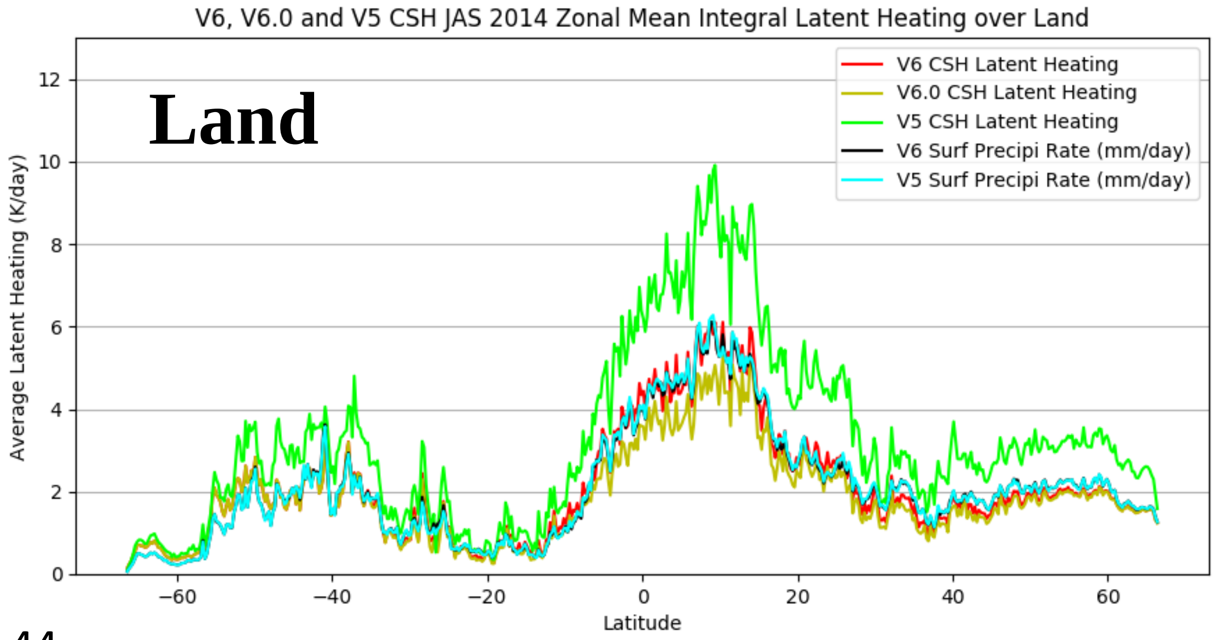
- Comparisons to SLH

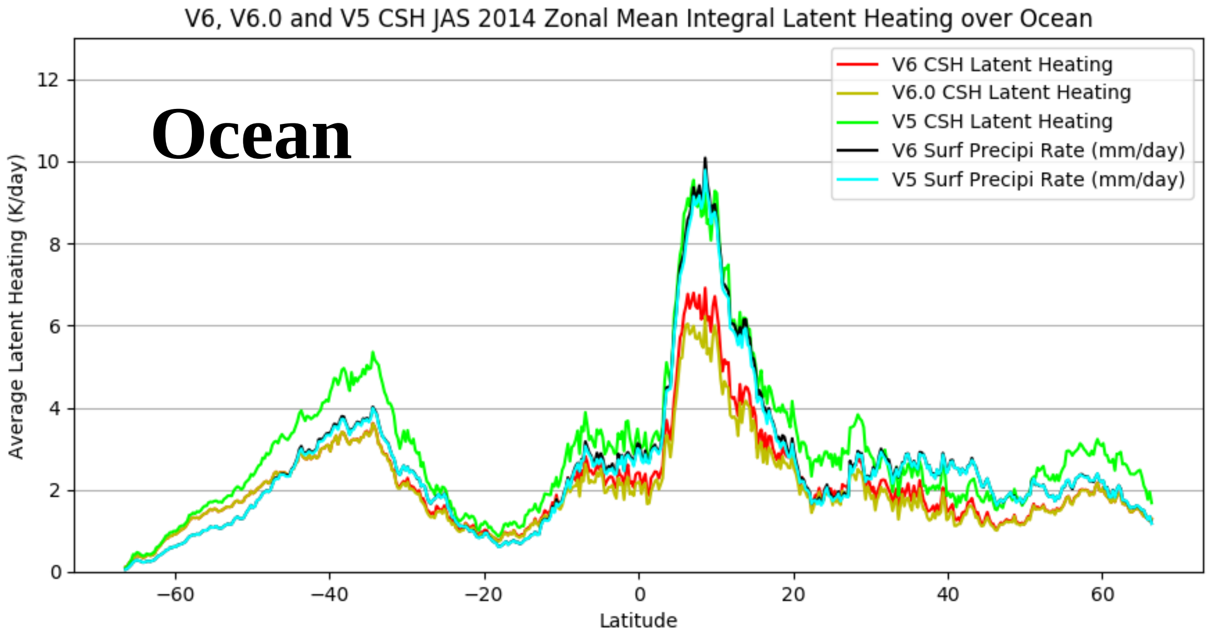
Vertically-integrated LH (rain equivalent) vs **Combined estimated surface rain**

CSH: V6 (Red), V6.0 (gold), and V5 (Green)

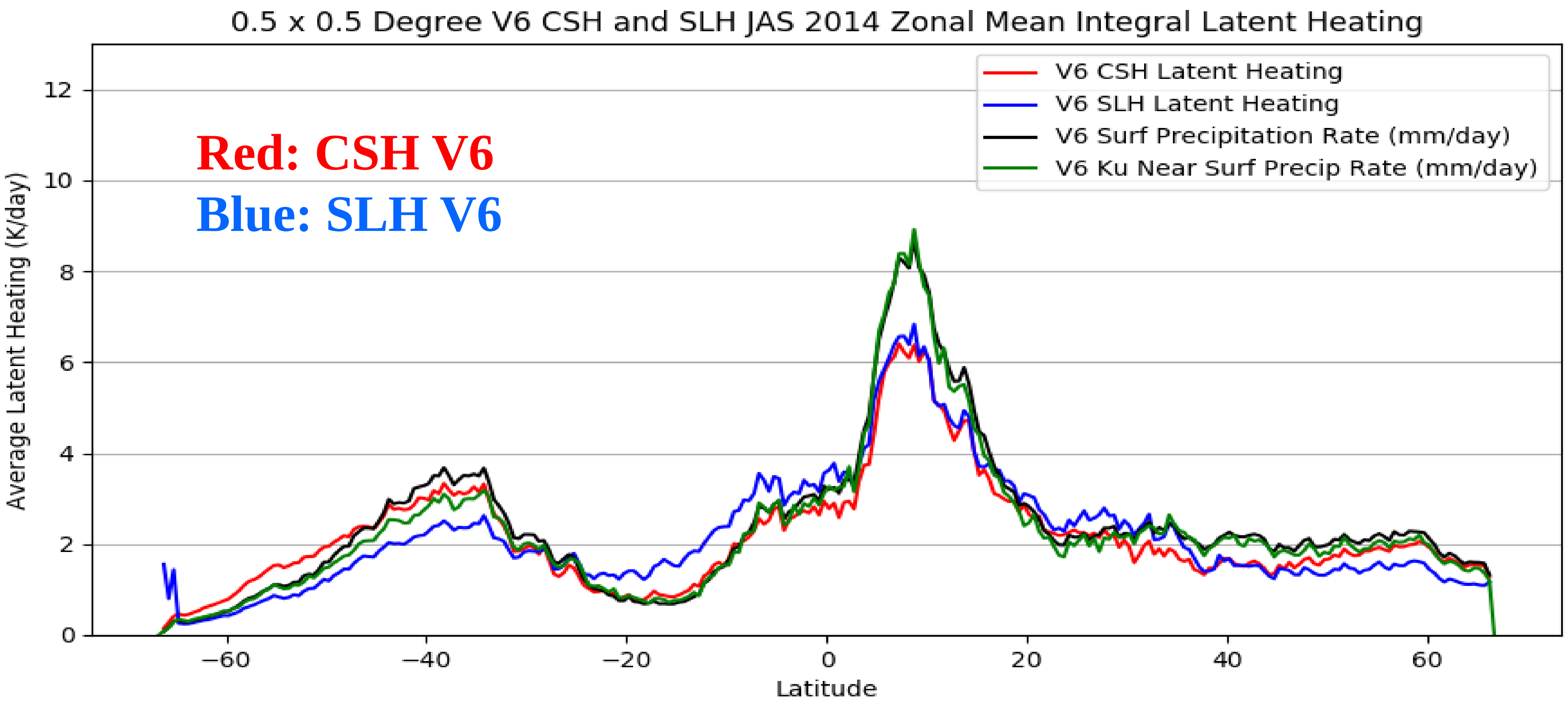
Overall, V6 is better than V6.0;
V6 is much better than V5



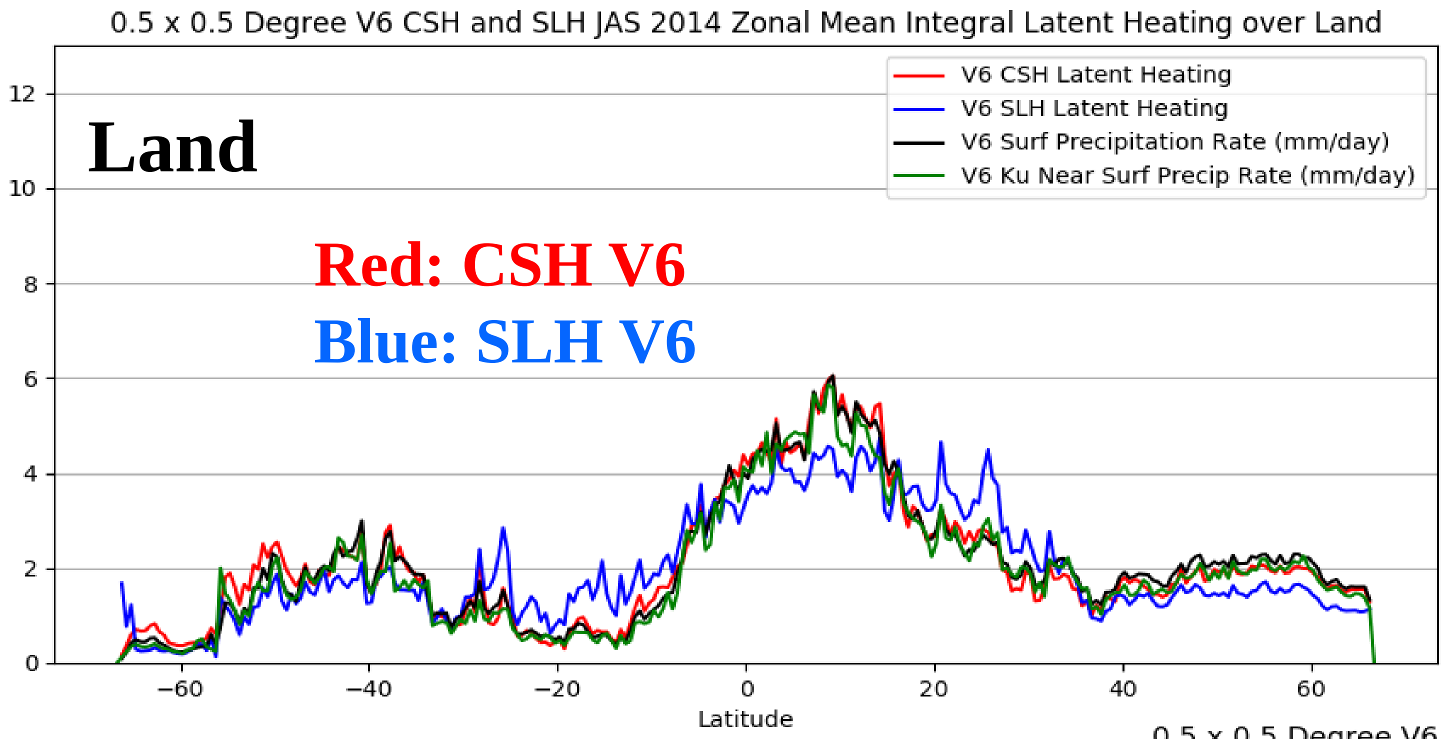




CSH/SLH Vertically-integrated LH vs Combined/Ku Surface Rain

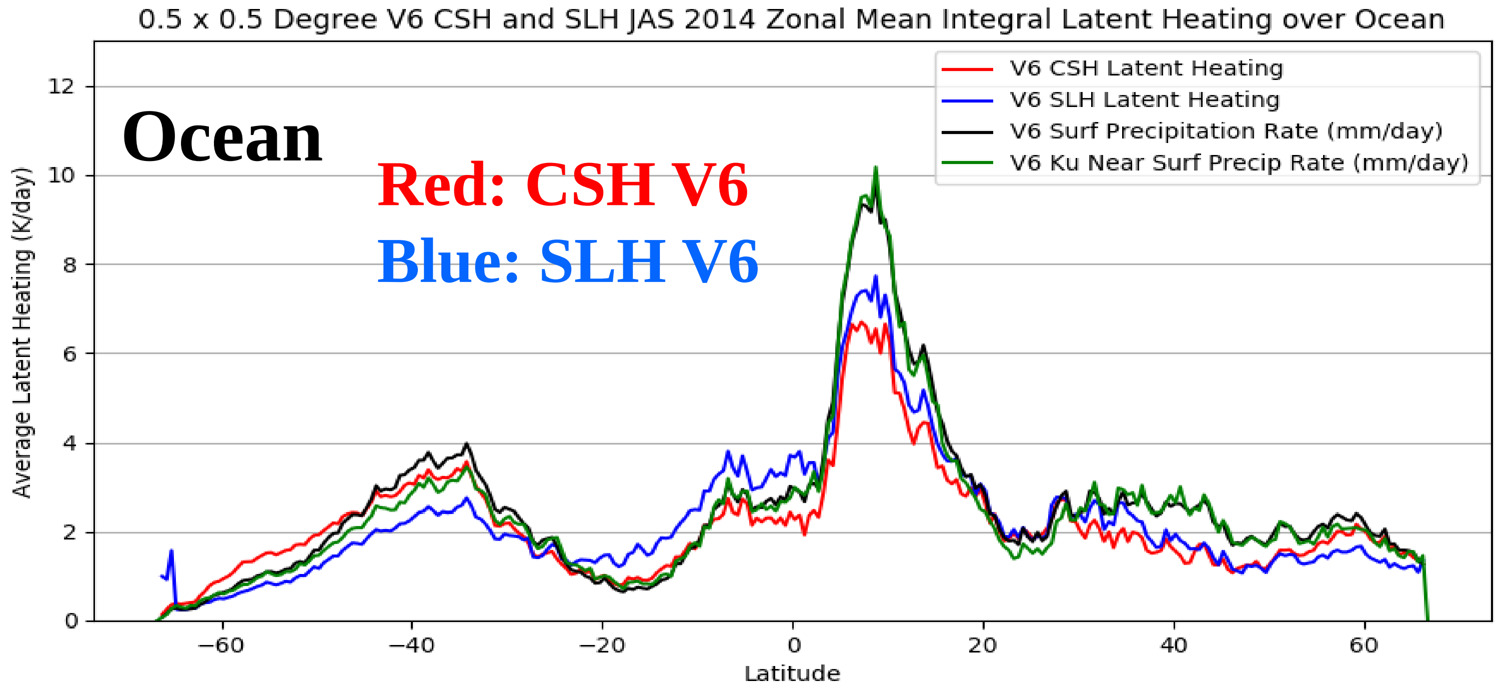


CSH V6 vs SLH V6



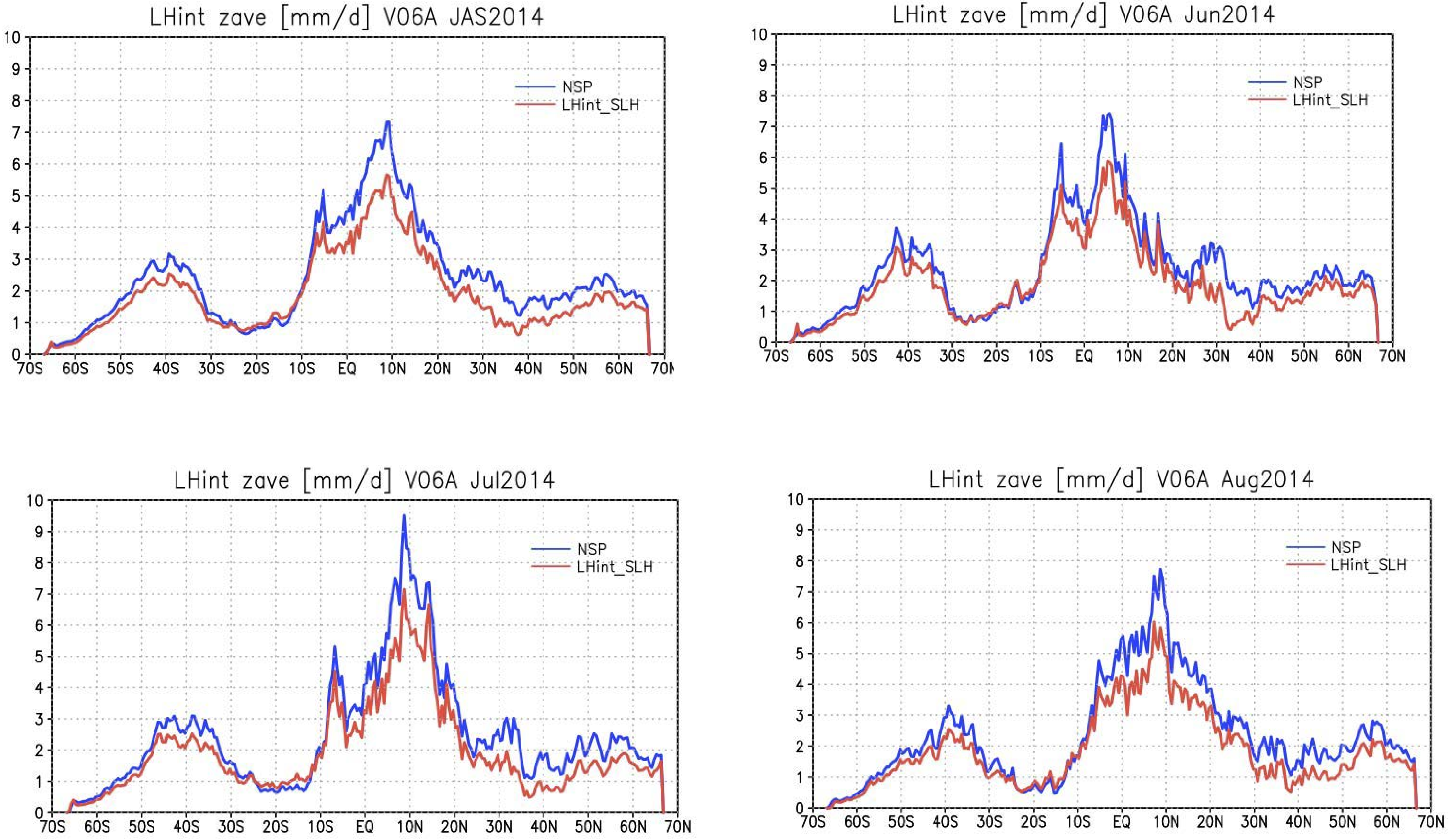
Integrated LH over Land

- CSH has more equivalent rain and is closer to the input surface precipitation



Integrated LH over Ocean

- SLH has more equivalent rain and is closer to the input surface precipitation in the deep Tropics
- CSH closer in Southern Hemisphere


LHint zave [mm/d] V06A JAS2014
NSP
LHint_SLH
0 1 2 3 4 5 6 7 8 9 10
70S 60S 50S 40S 30S 20S 10S EQ 10N 20N 30N 40N 50N 60N 70N
LHint zave [mm/d] V06A Jun2014
NSP
LHint_SLH
0 1 2 3 4 5 6 7 8 9 10
70S 60S 50S 40S 30S 20S 10S EQ 10N 20N 30N 40N 50N 60N 70N
LHint zave [mm/d] V06A Jul2014
NSP
LHint_SLH
0 1 2 3 4 5 6 7 8 9 10
70S 60S 50S 40S 30S 20S 10S EQ 10N 20N 30N 40N 50N 60N 70N
LHint zave [mm/d] V06A Aug2014
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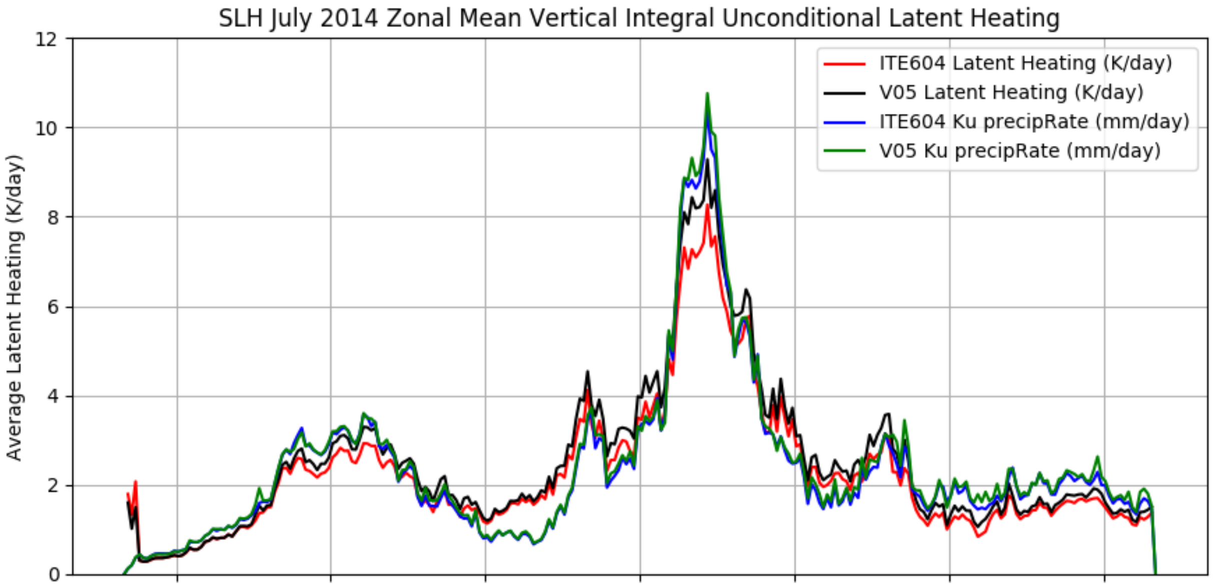
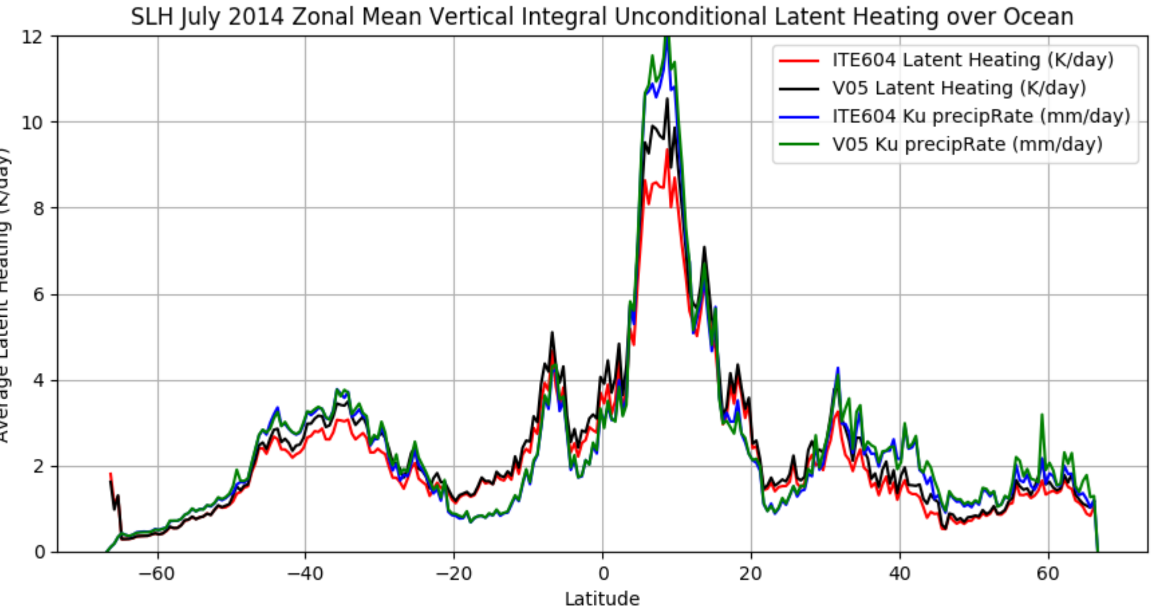
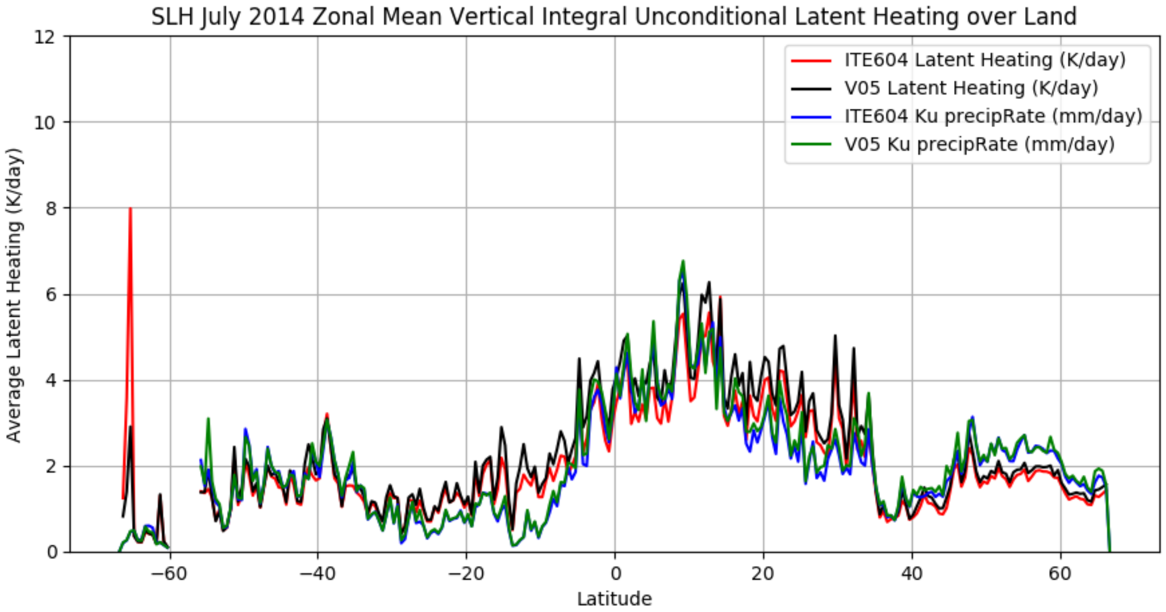

SLH July 2014 Zonal Mean Vertical Integral Unconditional Latent Heating
Average Latent Heating (K/day)
0
2
4
6
8
10
12
ITE604 Latent Heating (K/day)
V05 Latent Heating (K/day)
ITE604 Ku precipRate (mm/day)
V05 Ku precipRate (mm/day)


SLH July 2014 Zonal Mean Vertical Integral Unconditional Latent Heating over Ocean
Average Latent Heating (K/day)
0
2
4
6
8
10
12
−60
−40
−20
0
20
40
60
Latitude
ITE604 Latent Heating (K/day)
V05 Latent Heating (K/day)
ITE604 Ku precipRate (mm/day)
V05 Ku precipRate (mm/day)


SLH July 2014 Zonal Mean Vertical Integral Unconditional Latent Heating over Land
Average Latent Heating (K/day)
0
2
4
6
8
10
12
−60
−40
−20
0
20
40
60
Latitude
ITE604 Latent Heating (K/day)
V05 Latent Heating (K/day)
ITE604 Ku precipRate (mm/day)
V05 Ku precipRate (mm/day)

Zonal mean CSH LH (July 2014) ITE604 vs V05