Evaluating impact of simulated mixed-phase clouds on the Antarctic energy budget during the AWARE field campaign

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Motivation

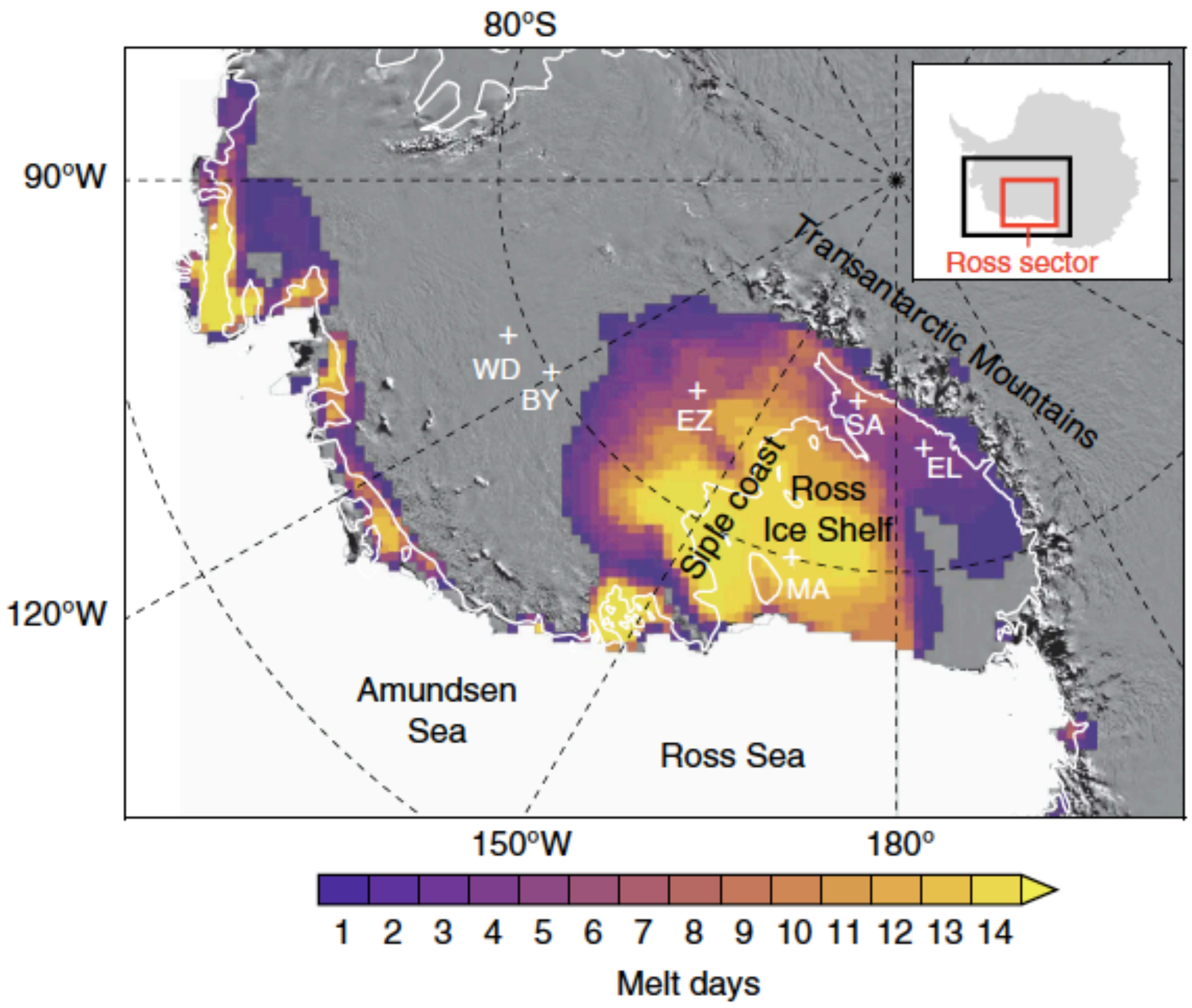
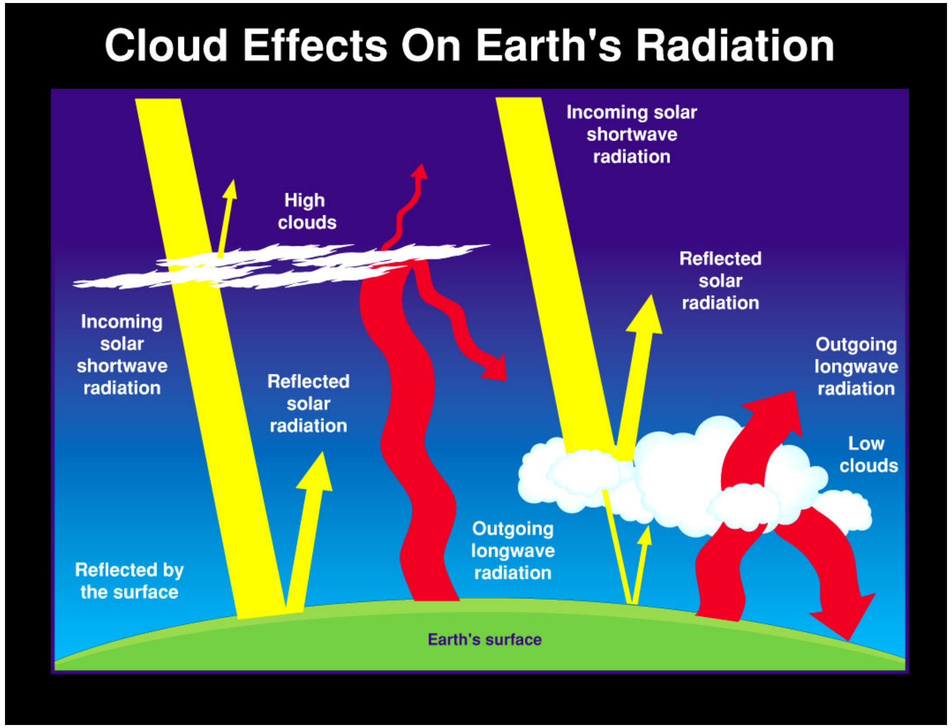


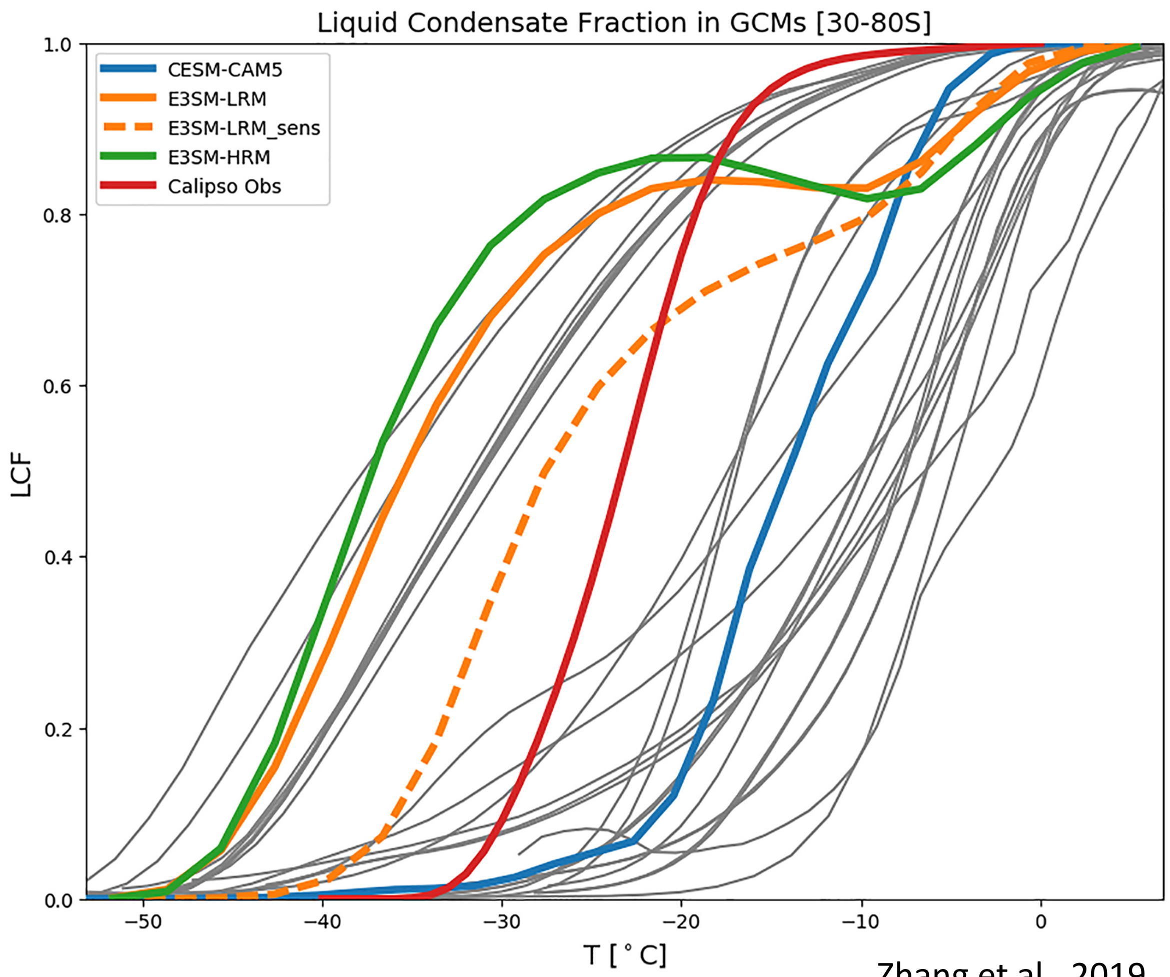
Figure 1a in Nicolas et al., 2017



Credit: CERES Instrument Team, NASA Langley Research Center

- Extensive melting event was observed at the West Antarctic Ice Sheet (WAIS) during January 2016;
- High-latitude mixed-phase clouds are believed to play a key role in modulating surface energy budget and impacting the surface melt.

Motivation



Zhang et al., 2019

- Large uncertainties remain in the simulated mixed-phase clouds over the Southern Hemisphere from GCMs.
- Source of model uncertainties:
  - The Wegner-Bergeron-Findeisen (WBF) process (Xie et al., 2008);
  - Ice nucleation (DeMott et al., 2015);
  - Interaction between shallow convection and cloud microphysics (Kay et al., 2016).

Science questions:

- ❑ How is the E3SM model performance on the high-latitude mixed-phase clouds during the AWARE field campaign?
- ❑ How do cloud parameterizations affect simulated mixed-phase clouds?

Single column model test in cloud physics

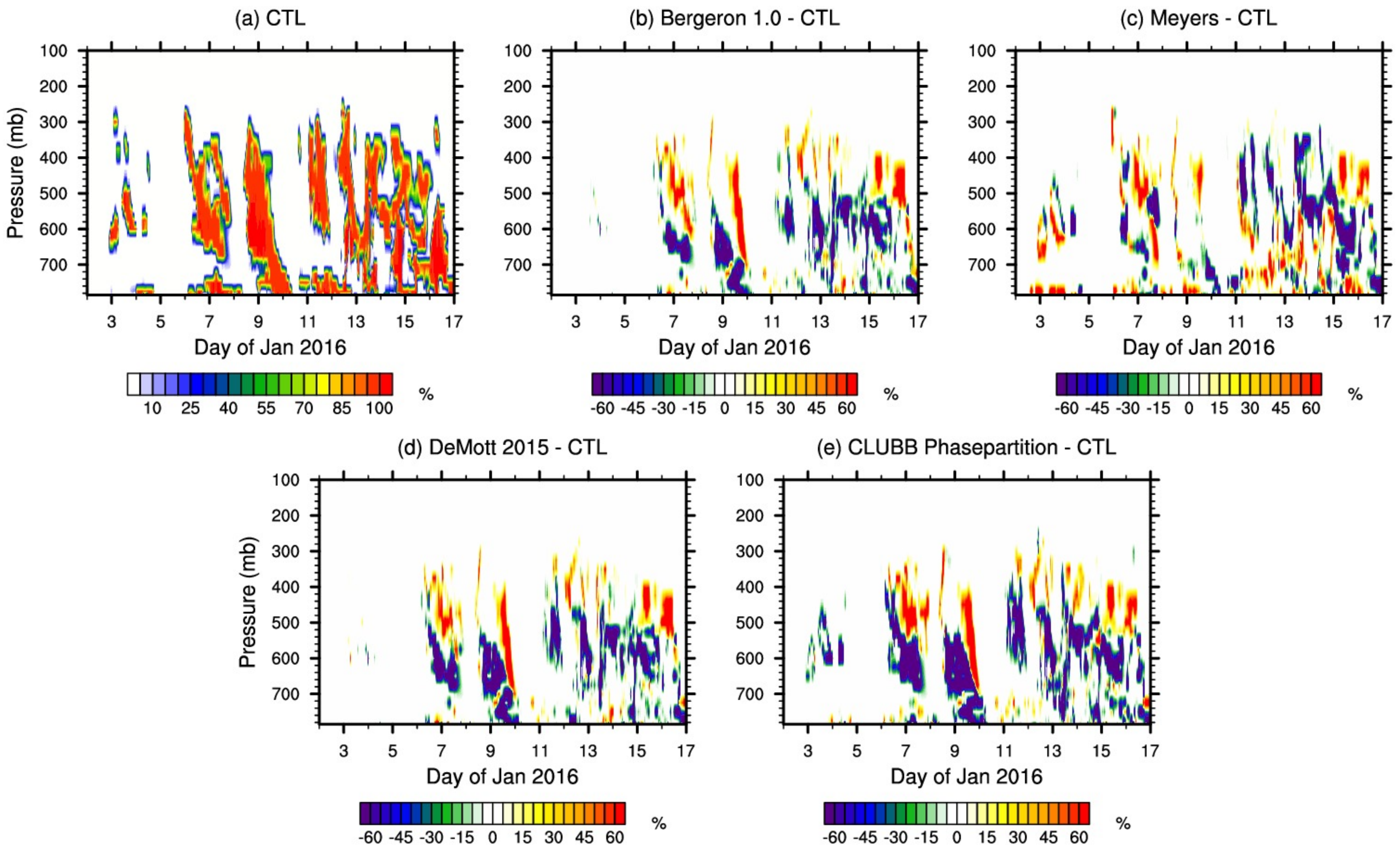
Experiment	Description
CTL	Default EAMv1 model configuration
Bergeron 1.0	Same as the EAMv1, but restore the parameter "berg_eff_factor" back to 1.0. WBF rate reduces by 10 times.
Meyers	Replace CNT ice nucleation scheme (Wang et al., 2014) with Meyers et al (1992), which nucleates more ice than CNT.
DeMott 2015	Replace CNT ice nucleation scheme (Wang et al., 2014) with DeMott et al (2015).
CLUBB Phase partition	Partition CLUBB produced cloud condensate into liquid and ice based on temperature, similar to Park and Bretherton (2009)

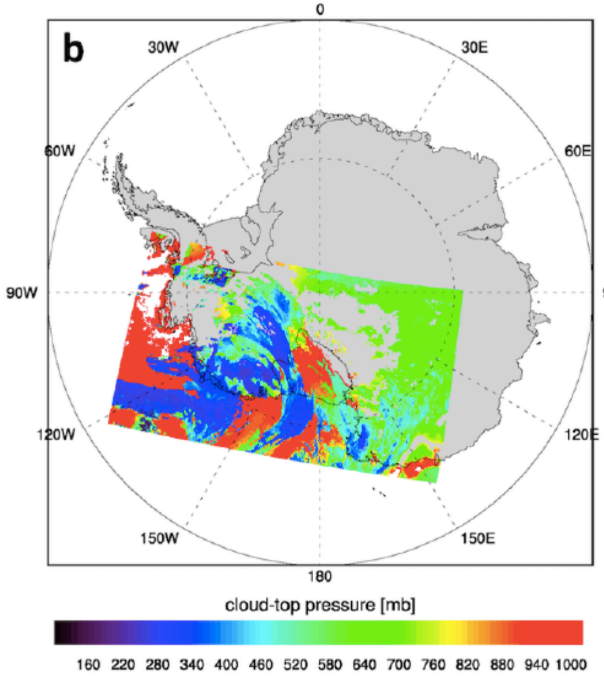
- Forcing data of SCM: ECMWF reanalysis data
- Simulation period: 01-31 January 2016
- Location: West Antarctic Ice Sheet (WAIS) Divide

$$
\begin{aligned}
f &= 0; && \text{for } T > 268.15\text{ K},\\
f &= (T_{ice} - T)/30; && \text{for } 238.15\text{ K} < T < 268.15\text{ K},\\
f &= 1; && \text{for } T < 238.15\text{ K}
\end{aligned}
$$

where f is the fraction of ice over total detrained cloud condensate.

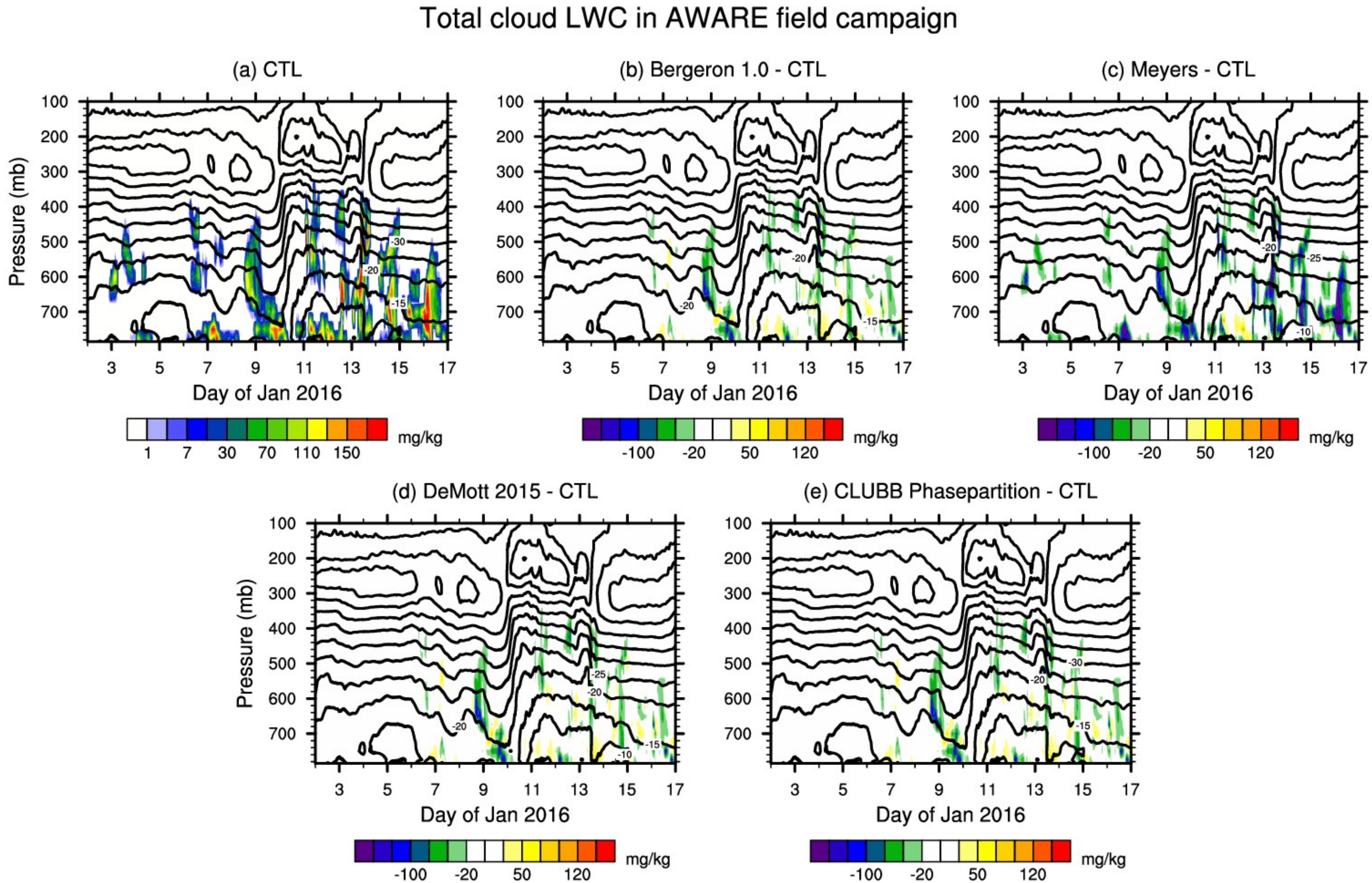
Cloud fraction at WAIS Divide



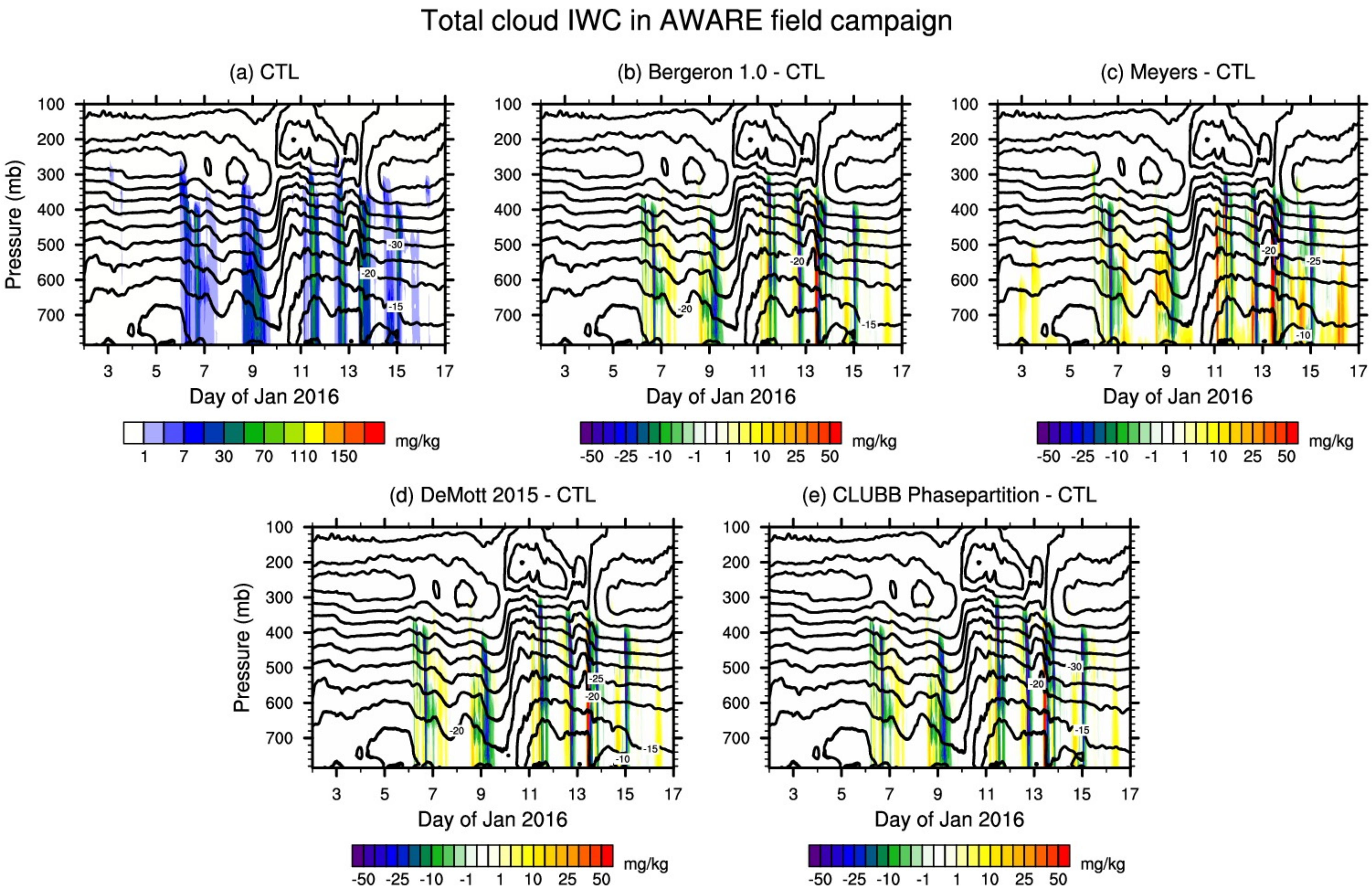


Estimates of cloud-top pressure from MODIS/Aqua for 06:50–06:55 UTC on 11 January 2016. (Supplementary Figure 4 in Nicolas et al., 2017)

- Multi-layer clouds are frequently simulated in the SCM;
- Low-level clouds with cloud top at 600-700 mb on 11 January are reasonably captured by CTL;
- Clouds are sensitive to changes in the cloud physics.

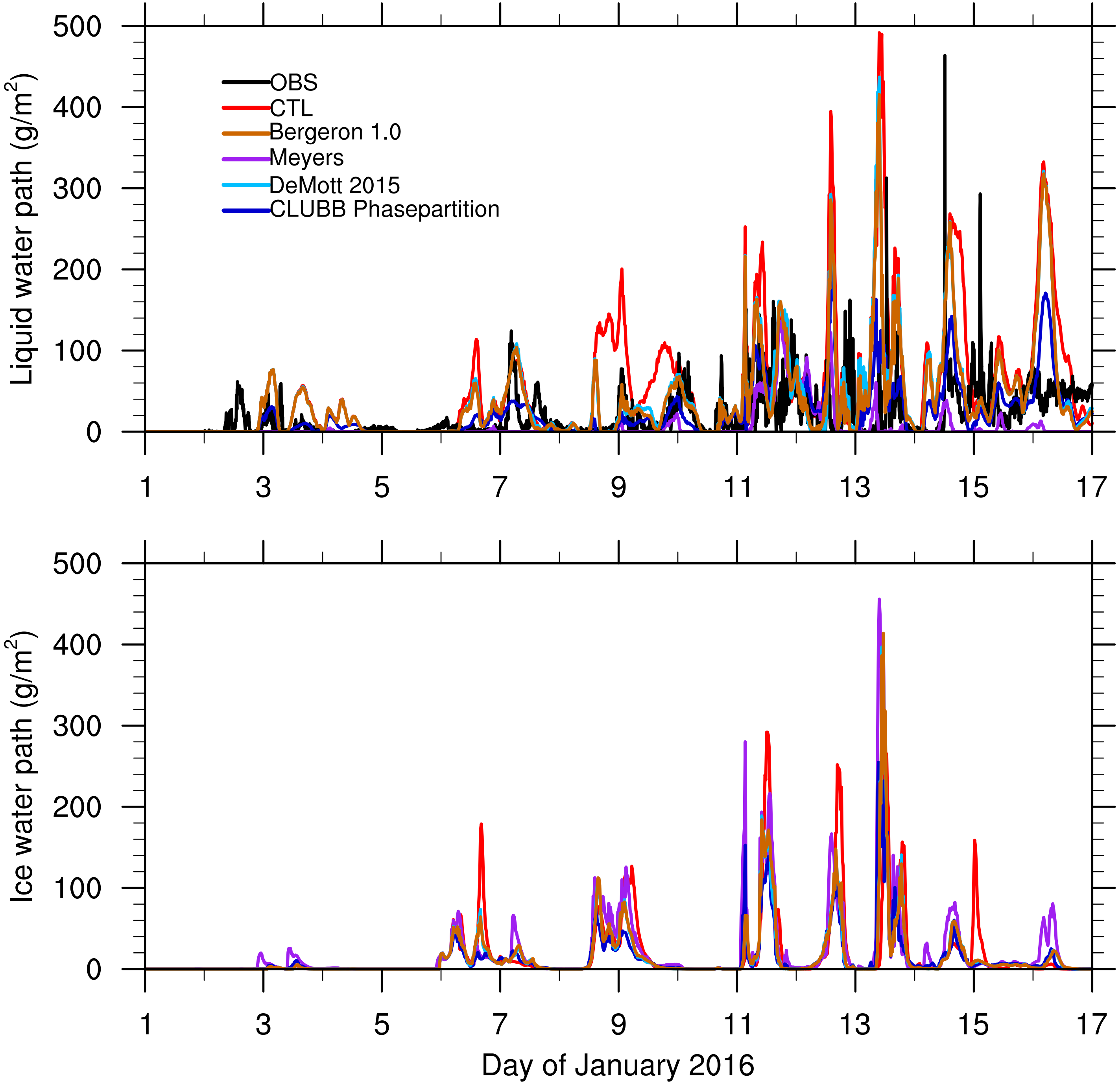


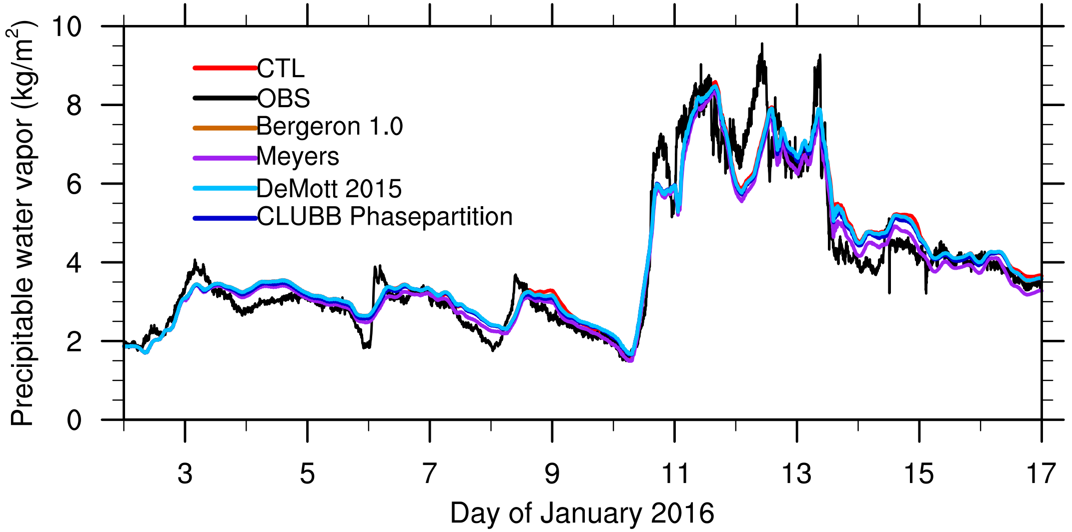
Total cloud LWC in AWARE field campaign
(a) CTL
(b) Bergeron 1.0 - CTL
(c) Meyers - CTL
(d) DeMott 2015 - CTL
(e) CLUBB Phasepartition - CTL
Pressure (mb)
Day of Jan 2016
mg/kg
1 7 30 70 110 150
-100 -20 50 120



Total cloud IWC in AWARE field campaign
(a) CTL
(b) Bergeron 1.0 - CTL
(c) Meyers - CTL
(d) DeMott 2015 - CTL
(e) CLUBB Phasepartition - CTL
Pressure (mb)
Day of Jan 2016
mg/kg
1 7 30 70 110 150
-50 -25 -10 -1 1 10 25 50

LWP and PWV at WAIS Divide





- Although precipitable water vapor in SCM is constrained by the forcing, the response of simulated LWP and IWP to cloud physics is significant.
- CTL simulation overestimates the cloud liquid. Bergeron & DeMott improve.

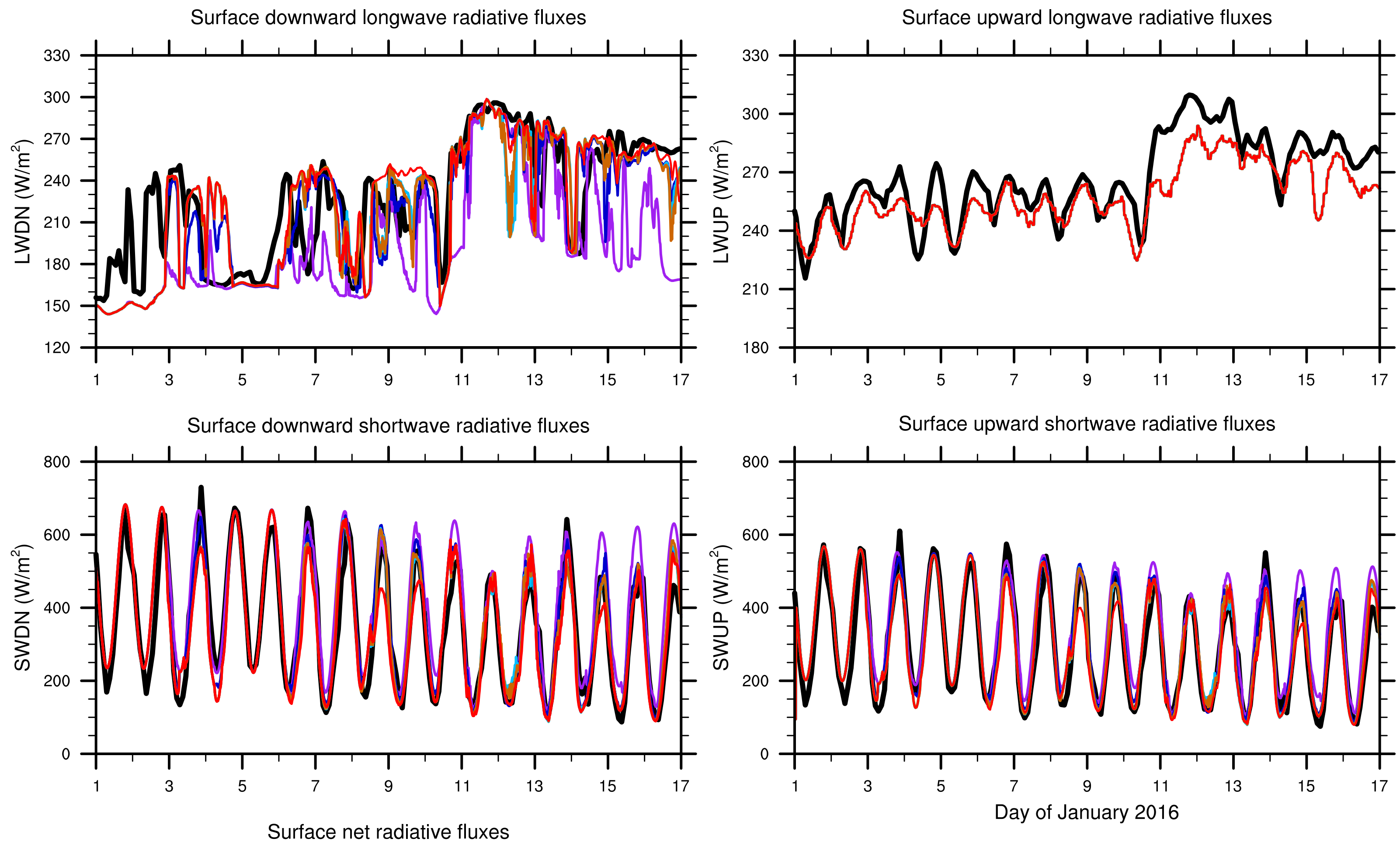
- Bennartz et al. (2013) pointed out that liquid-bearing clouds with **10–40 g/m^2 LWP** are responsible for the **cloud radiative enhancement effect.**
  - ✓ opaque enough to enhance downwelling LW radiation but thin enough to allow SW radiation to penetrate cloud

- LW radiation is similar to blackbody radiation and SW is attenuated when LWP > 40 g/m^2.

Fraction over the whole period (10 to 14 Jan., 2016) that modeled clouds have cloud radiative enhancement effect

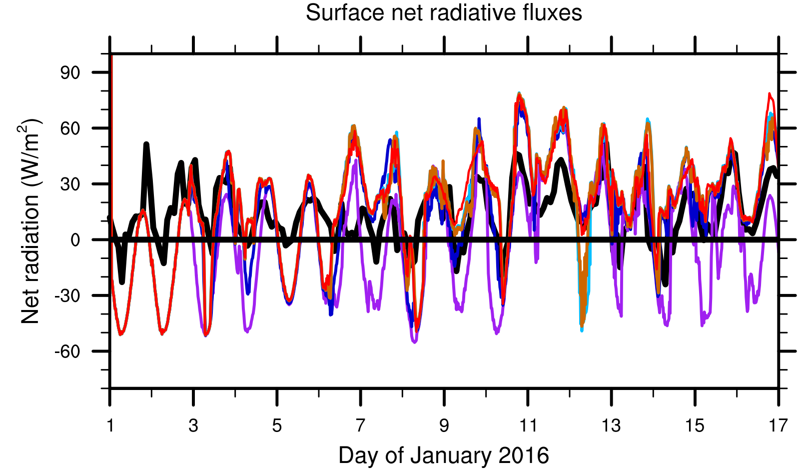
	OBS	**CTL**	**Bergeron 1.0**	**Meyers**	**DeMott 2015**	**CLUBB Phasepartition**
10 LWP 40 g/m^2	29.0%	22.9%	33.3%	11.1%	27.8%	30.9%
LWP 40 g/m^2	32.1%	60.8%	47.2%	27.4%	51.7%	44.8%

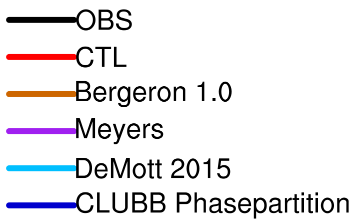
Values are sampled between 10 and 14 January 2016, when extensive melting event were observed over the West Antarctica.



Radiative fluxes at WAIS Divide

- The **overestimated** occurrence of frequency of liquid-bearing clouds with LWP > 40 g/m^2 results in **underestimation** in SW downwelling radiation in CTL;
- The modifications of ice nucleation and WBF process and CLUBB all reduce the simulated LWP, producing stronger cloud radiative effects.

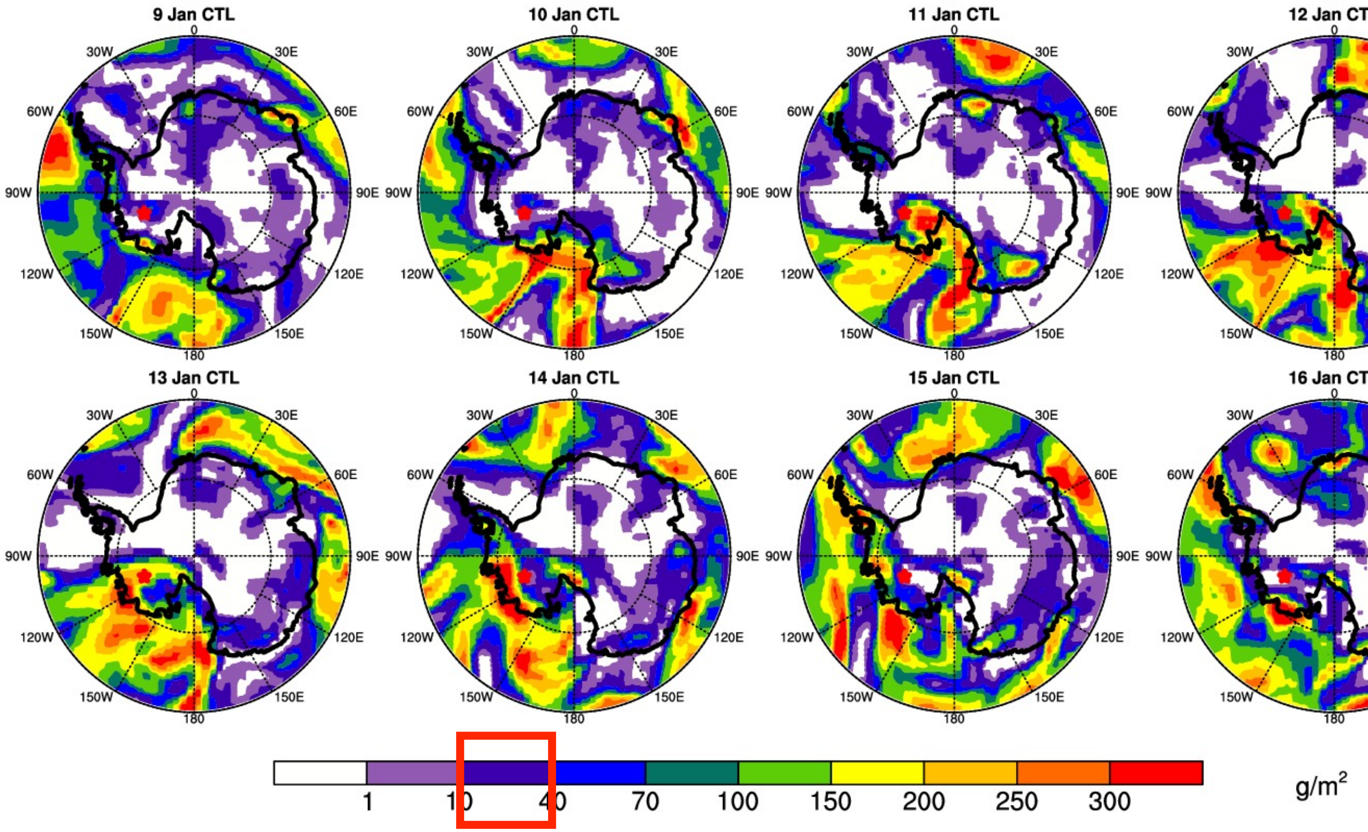


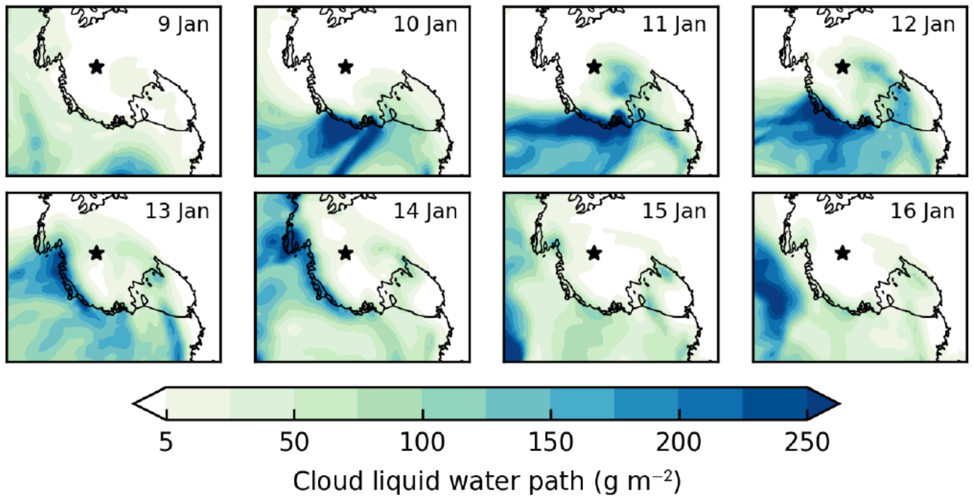


Averaged downwelling radiative fluxes at surface for 10–14 January 2016

	OBS	CTL	Bergeron 1.0	Meyers	DeMott 2015	CLUBB Phasepartition
LWDN (W/m^2)	261.9	259.6	258.0	233.2	255.4	257.4
SWDN (W/m^2)	312.7	304.3	314.7	354.6	324.0	312.0

Examination in E3SM CAPT simulation





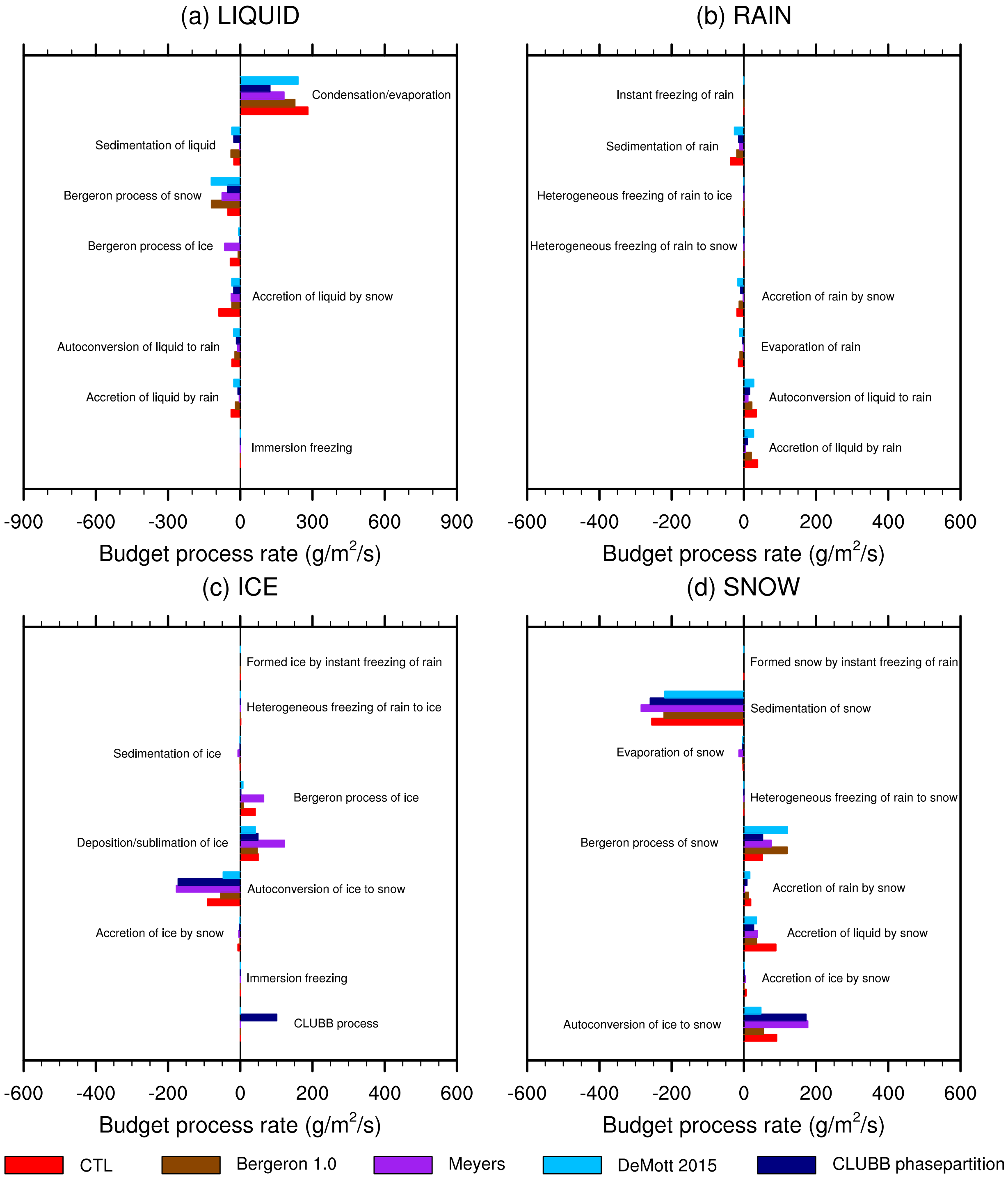
Daily mean cloud LWP by ERA-Interim (Supplementary Figure 2 in Nicolas et al., 2017)

- E3SM CTL captures the temporal evolution and spatial distribution of cloud LWP, but overestimates LWP during the melting period over the WAIS;
- Cloud radiative enhancement effect is less effective in the E3SM CTL simulation.

Summary

- The response of simulated high-latitude mixed-phase clouds to cloud physics parameterizations is evaluated against the ARM observation at the WAIS Divide during AWARE campaign.
- Overestimated LWP is simulated in the default E3SM, resulting in an underestimation of SWDN. Consistent conclusion is shown in global simulation.
- WBF process, ice nucleation, and the interaction between CLUBB and cloud microphysics can impact the cloud radiative enhancement through altering the simulated mixed-phase cloud phase partition.

SCM budget analysis



- Process tendencies are averaged between 12 and 13 January 2016.
- The source of liquid phase is dominant by condensation from CLUBB;
- Snow contributes to large portions of cloud ice phase, and the majority of ice phase is converted from liquid water;
- Slower WBF process and more efficient ice nucleation result in higher ice production;
- Interaction between shallow convection and cloud microphysics can also modulate simulated cloud phase.

Part 2 results

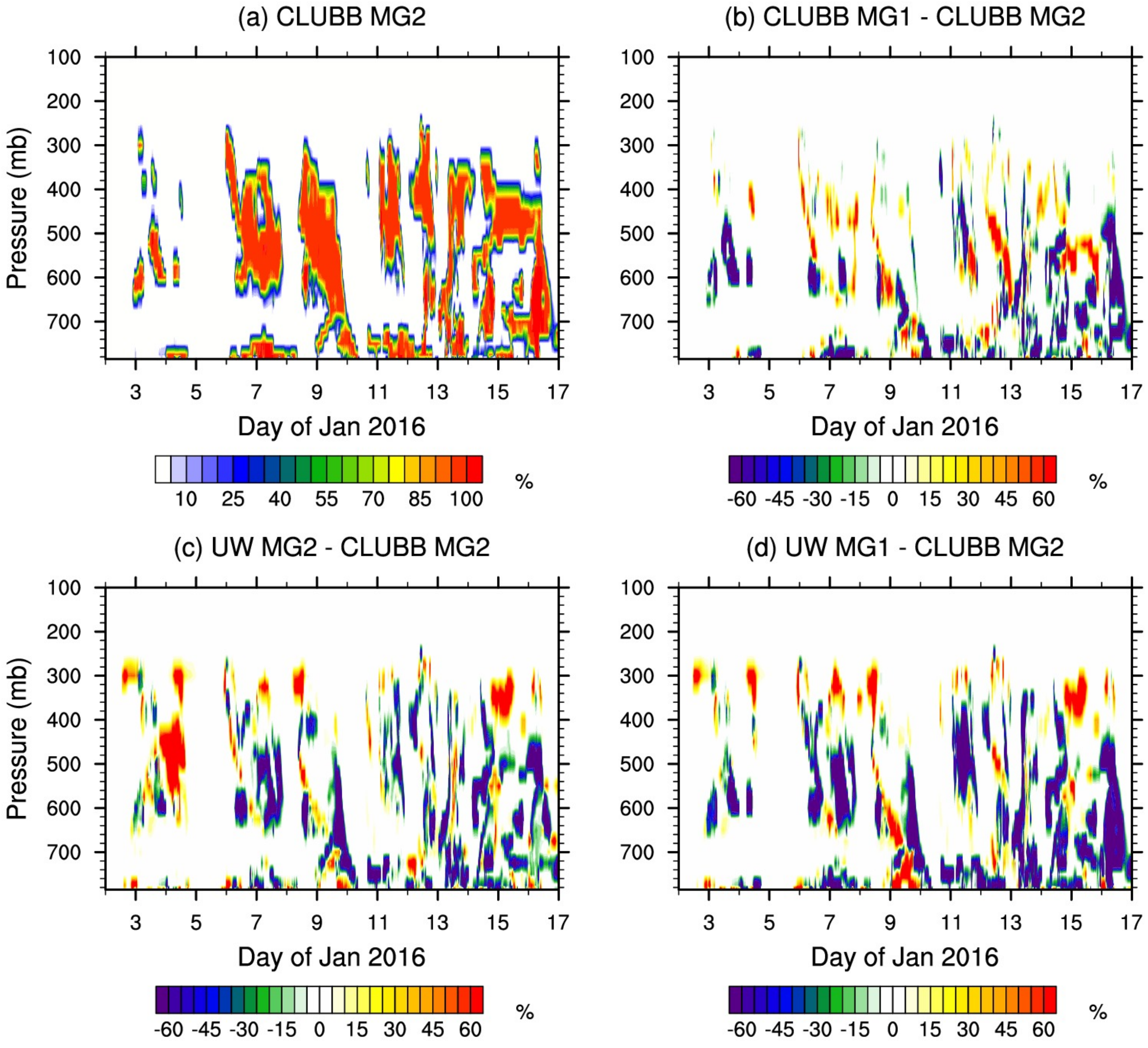
Comparison between CLUBB-MG2, CLUBB-MG1, UW-MG2 and UW-MG1

Test in SCM EAMv1

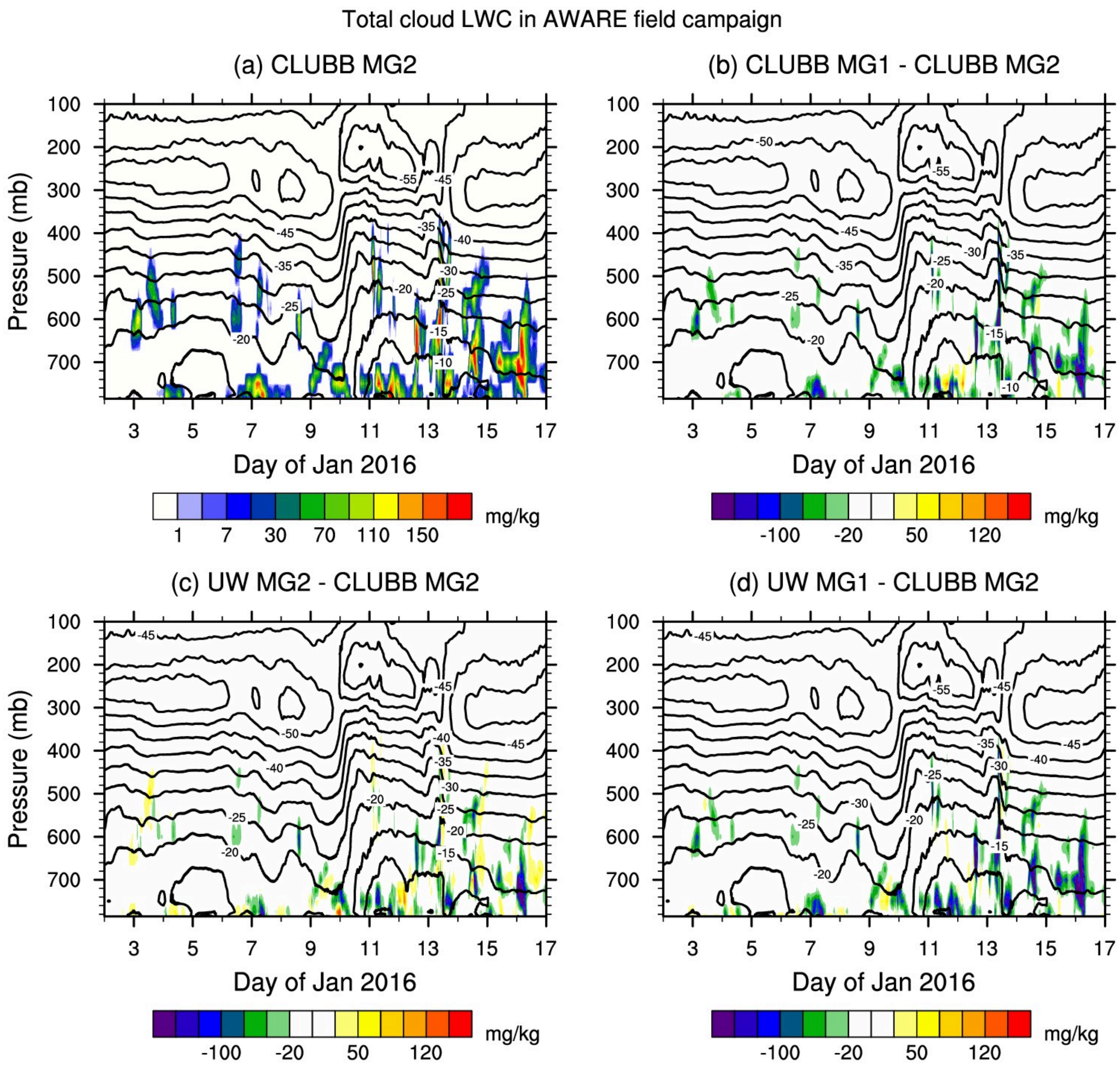
Physics	CLUBB MG2	CLUBB MG1	UW MG2	UW MG1
Deep convection	Zhang-McFarlane (ZM) scheme (Zhang & McFarlane, 1995)	ZM	ZM	ZM
Shallow convection	CLUBB (Golaz et al., 2002)	CLUBB	Park and Bretherton (UW) scheme (Park & Bretherton, 2009)	UW scheme
PBL scheme	CLUBB	CLUBB	Bretherton and Park (2009)	Bretherton and Park
Cloud macrophysics	CLUBB	CLUBB	Park et al. (2014)	Park et al.
Stratiform cloud microphysics	MG2 scheme (Gettelman& Morrison, 2015)	MG1 scheme (Morrison & Gettelman, 2008)	MG2 scheme	MG1 scheme

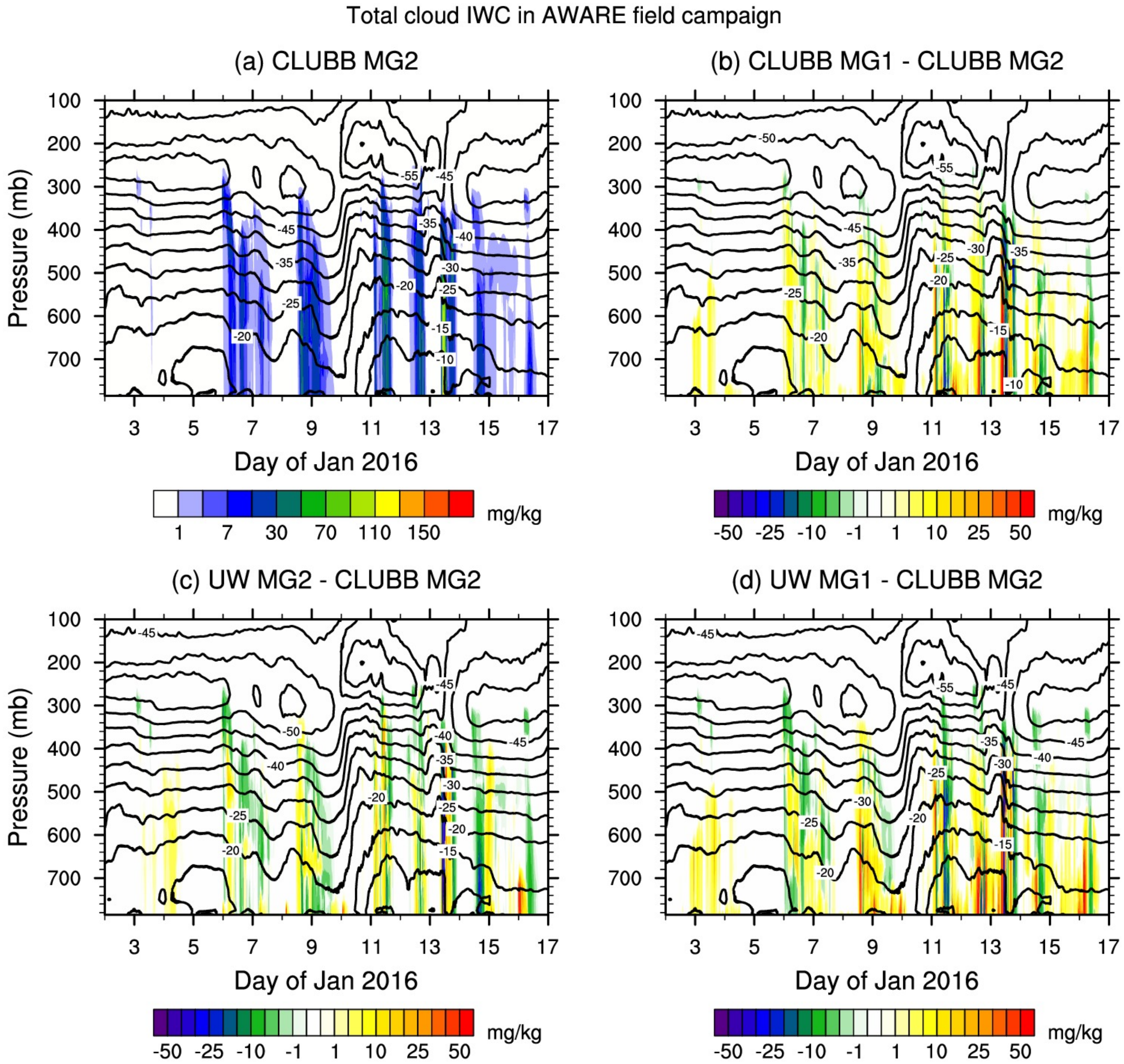
Note: We restore the ice deposition growth rate tuning parameter "berg_eff_factor" back to 1.0 in all simulations.

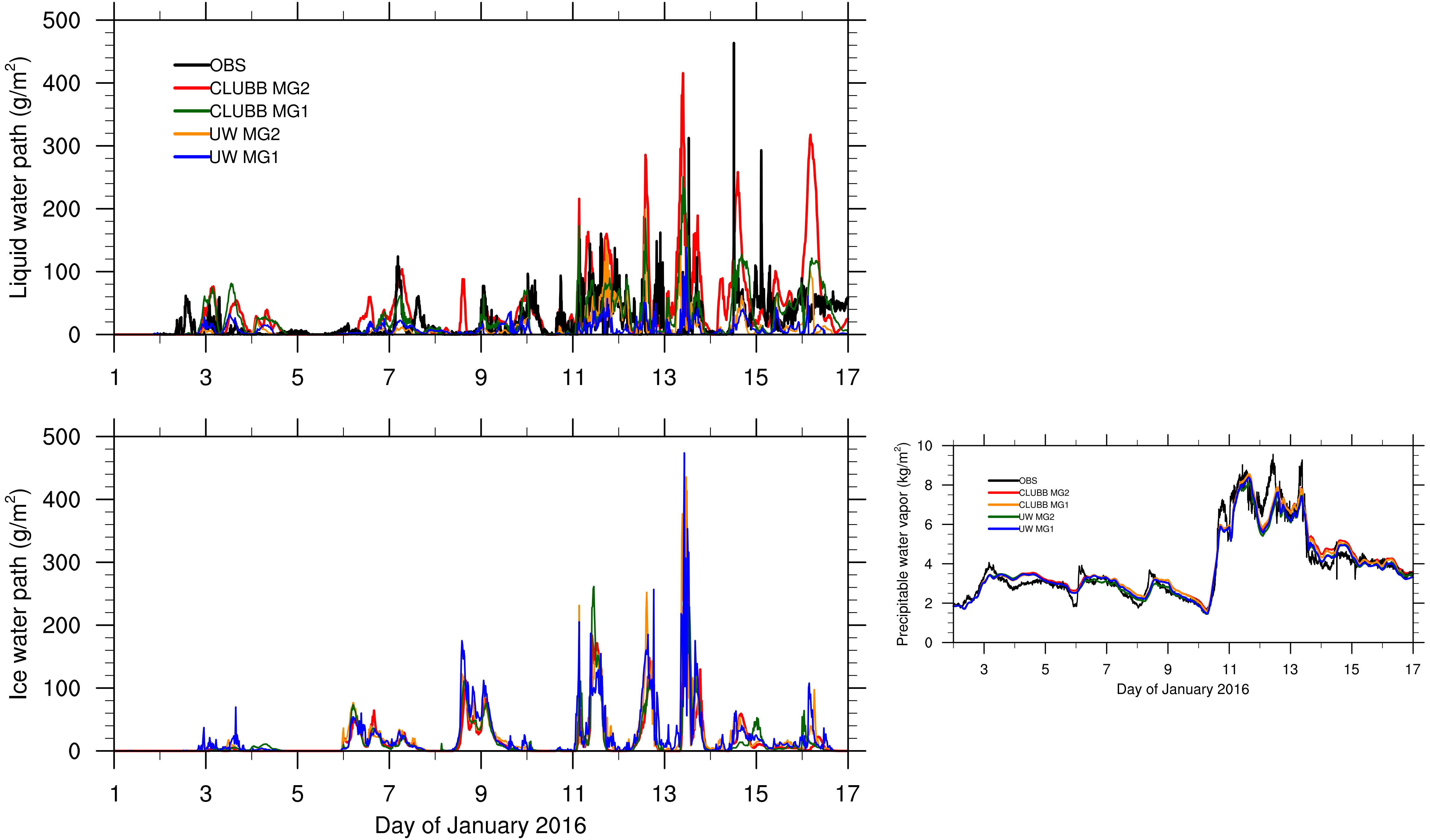
- SCM has run for the January 2016, at the WAIS station.

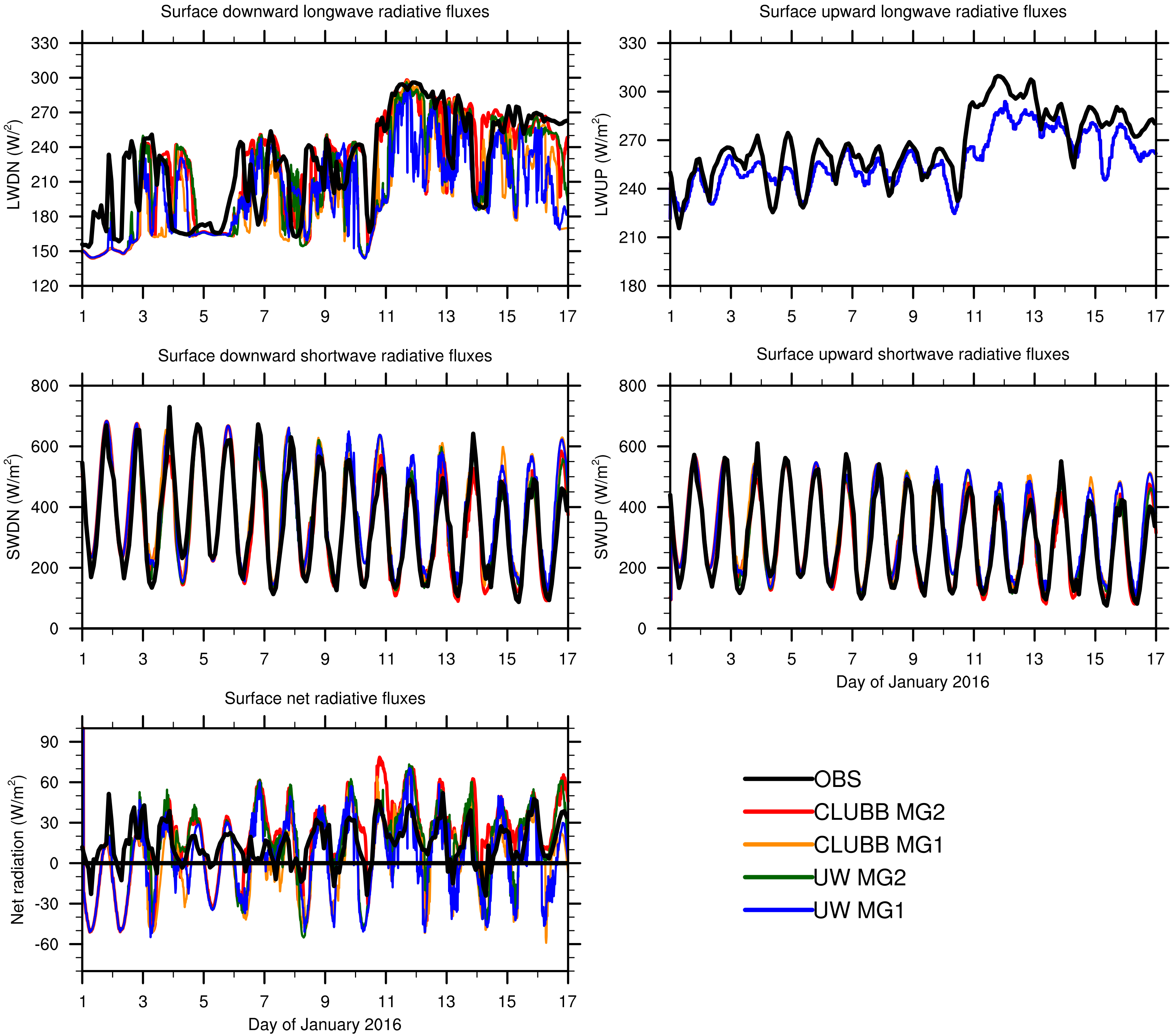


(a) CLUBB MG2
(b) CLUBB MG1 - CLUBB MG2
(c) UW MG2 - CLUBB MG2
(d) UW MG1 - CLUBB MG2
Pressure (mb)
100
200
300
400
500
600
700
3
5
7
9
11
13
15
17
Day of Jan 2016
10 25 40 55 70 85 100
-60 -45 -30 -15 0 15 30 45 60
%

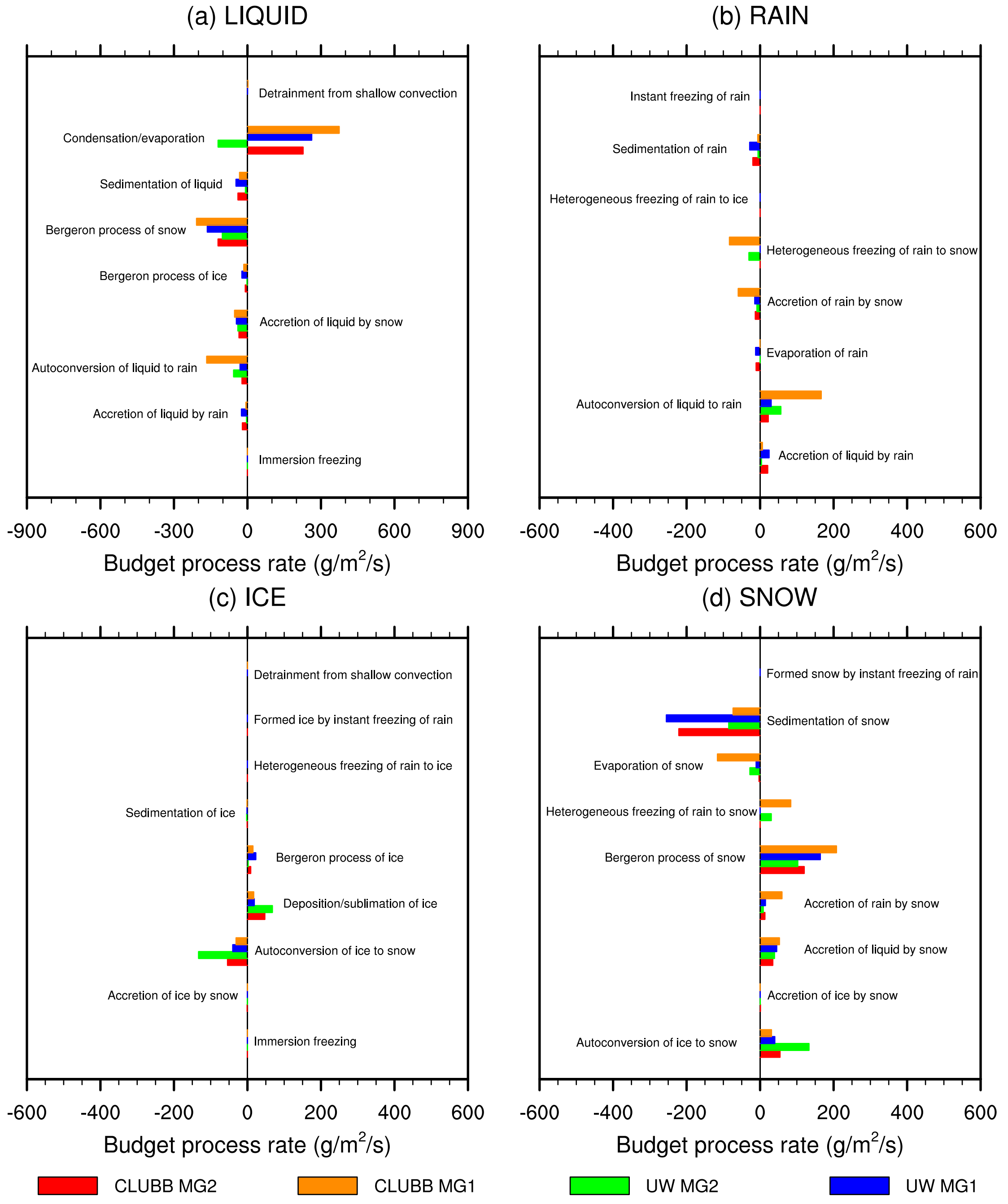

Total cloud LWC in AWARE field campaign
(a) CLUBB MG2
(b) CLUBB MG1 - CLUBB MG2
(c) UW MG2 - CLUBB MG2
(d) UW MG1 - CLUBB MG2
Pressure (mb)
Day of Jan 2016
mg/kg
1 7 30 70 110 150
-100 -20 50 120


Total cloud IWC in AWARE field campaign
(a) CLUBB MG2
(b) CLUBB MG1 - CLUBB MG2
(c) UW MG2 - CLUBB MG2
(d) UW MG1 - CLUBB MG2
Pressure (mb)
Day of Jan 2016
mg/kg


OBS
CLUBB MG2
CLUBB MG1
UW MG2
UW MG1
Liquid water path (g/m^2)
0
100
200
300
400
500
1
3
5
7
9
11
13
15
17
Ice water path (g/m^2)
Day of January 2016
Precipitable water vapor (kg/m^2)
0
2
4
6
8
10
OBS
CLUBB MG2
CLUBB MG1
UW MG2
UW MG1
Day of January 2016



Surface downward longwave radiative fluxes
LWDN (W/^{2})
Surface upward longwave radiative fluxes
LWUP (W/m^2)
Surface downward shortwave radiative fluxes
SWDN (W/m^2)
Surface upward shortwave radiative fluxes
SWUP (W/m^2)
Day of January 2016
Surface net radiative fluxes
Net radiation (W/m^2)
Day of January 2016
OBS
CLUBB MG2
CLUBB MG1
UW MG2
UW MG1


(a) LIQUID
Detrainment from shallow convection
Condensation/evaporation
Sedimentation of liquid
Bergeron process of snow
Bergeron process of ice
Accretion of liquid by snow
Autoconversion of liquid to rain
Accretion of liquid by rain
Immersion freezing
-900 -600 -300 0 300 600 900
Budget process rate (g/m²/s)
(b) RAIN
Instant freezing of rain
Sedimentation of rain
Heterogeneous freezing of rain to ice
Heterogeneous freezing of rain to snow
Accretion of rain by snow
Evaporation of rain
Autoconversion of liquid to rain
Accretion of liquid by rain
-600 -400 -200 0 200 400 600
Budget process rate (g/m²/s)
(c) ICE
Detrainment from shallow convection
Formed ice by instant freezing of rain
Heterogeneous freezing of rain to ice
Sedimentation of ice
Bergeron process of ice
Deposition/sublimation of ice
Autoconversion of ice to snow
Accretion of ice by snow
Immersion freezing
-600 -400 -200 0 200 400 600
Budget process rate (g/m²/s)
(d) SNOW
Formed snow by instant freezing of rain
Sedimentation of snow
Evaporation of snow
Heterogeneous freezing of rain to snow
Bergeron process of snow
Accretion of rain by snow
Accretion of liquid by snow
Accretion of ice by snow
Autoconversion of ice to snow
-600 -400 -200 0 200 400 600
Budget process rate (g/m²/s)
CLUBB MG2
CLUBB MG1
UW MG2
UW MG1