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GTS v1.0: a macrophysics scheme for climate models based on a probability density function

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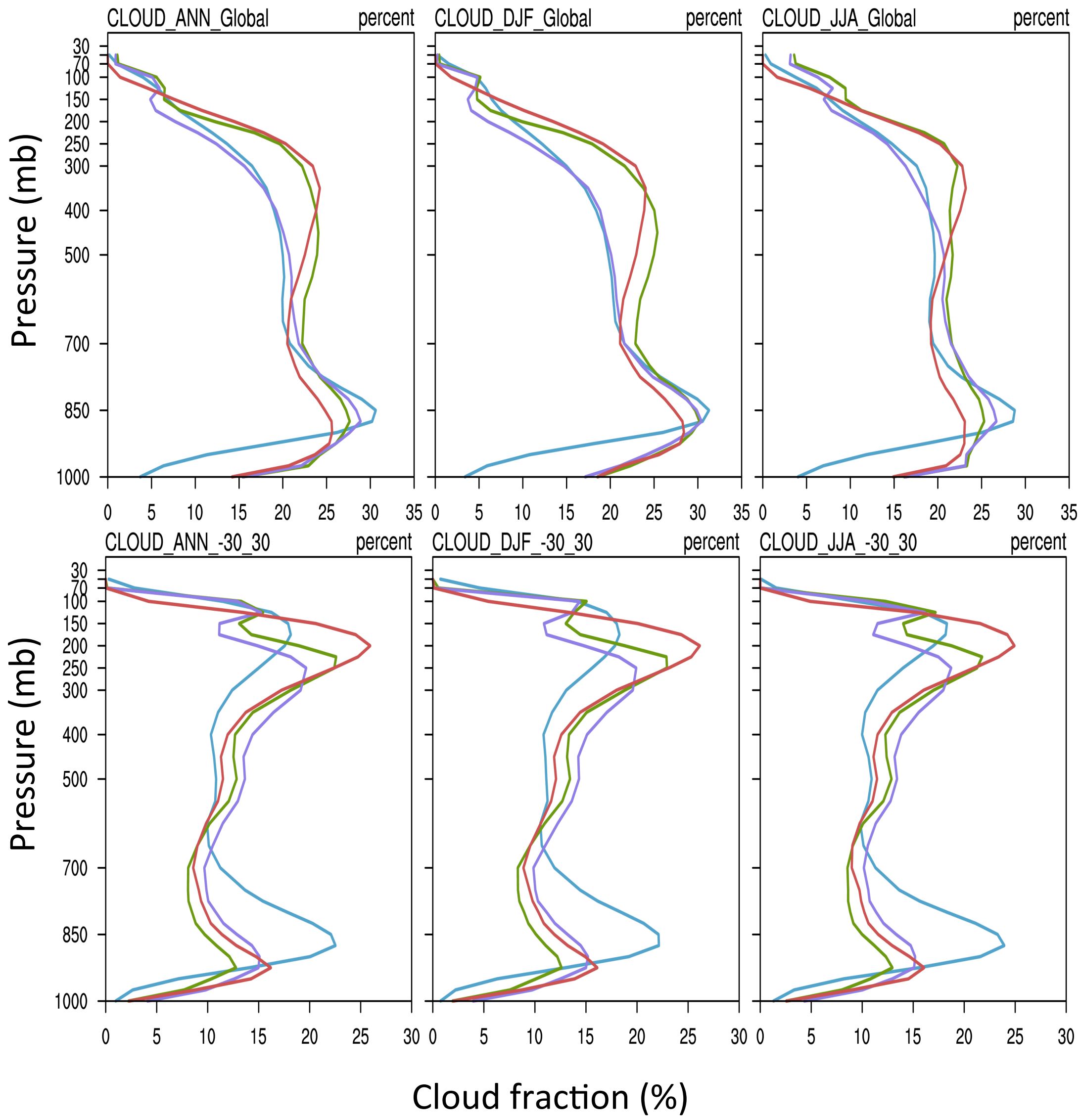

Figure S1. Vertical CF profiles averaged globally (upper) and for 30°N–30°S (lower), and for three periods (left: annual; central: DJF; right: JJA). Colored lines represent observational data from CloudSat/CALIPSO (blue) and the simulations by Park (red), U_pdf (purple), and T_pdf (green).

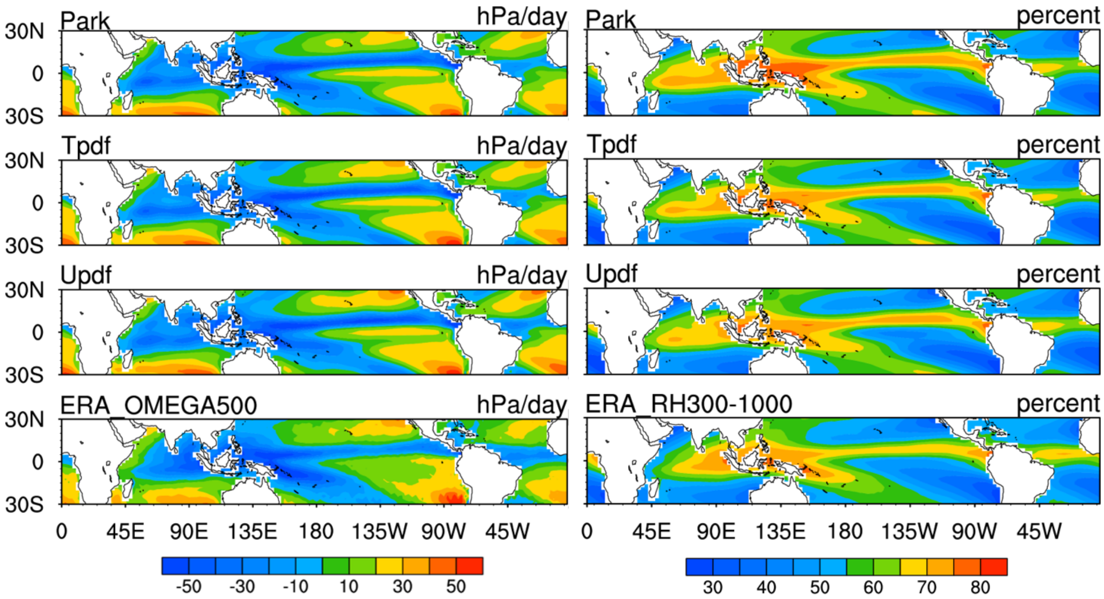

Figure S2. Latitude-longitude distribution of two large-scale parameters: vertical velocity at 500 mb (ω500, upper eight panels) and relative humidity averaged between 300 and 1000 mb (RH300–1000, lower eight panels) for the latitudinal range 30° N–30° S corresponding to Figure 8 in the paper.

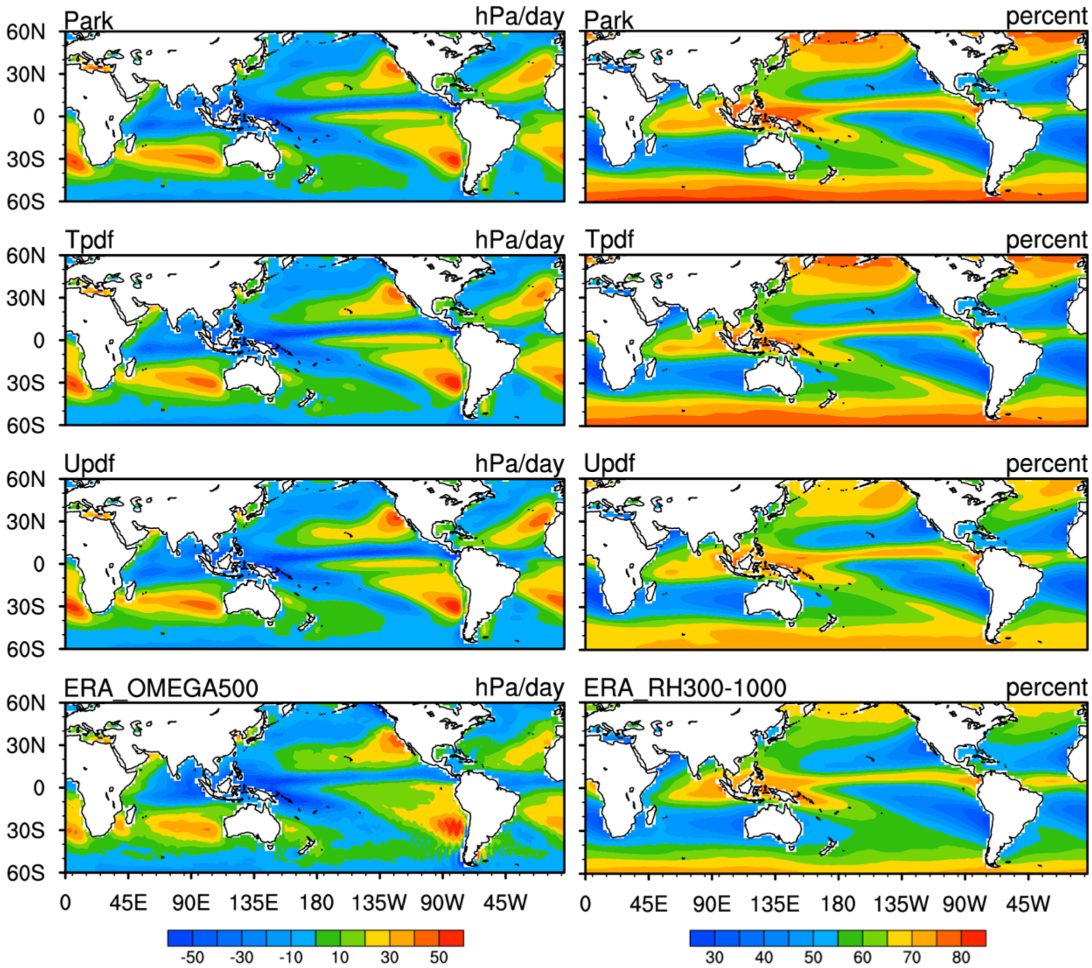

Figure S3. Latitude-longitude distribution of two large-scale parameters: ω500 (upper eight panels) and RH300–1000 (lower eight panels) for the latitudinal range 60° N–60° S corresponding to Figure 9 in the paper.

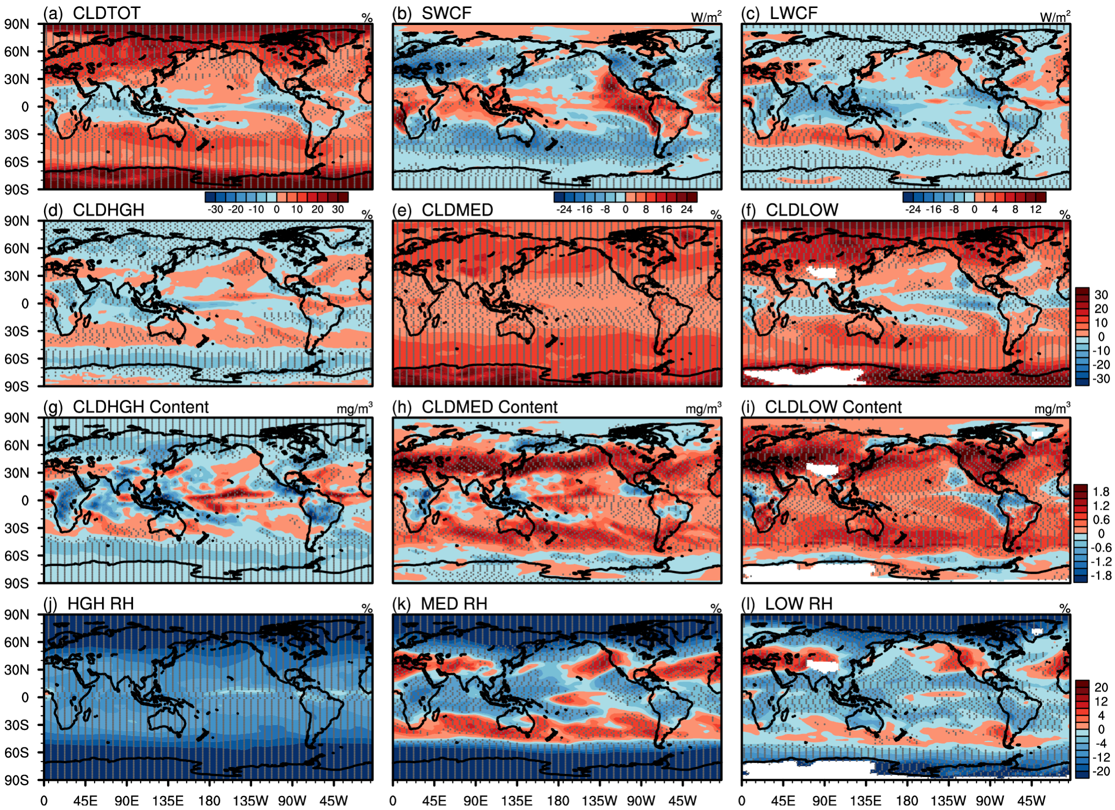

Figure S4. Similar as Figure 17 in the paper but for U_pdf of GTS scheme.

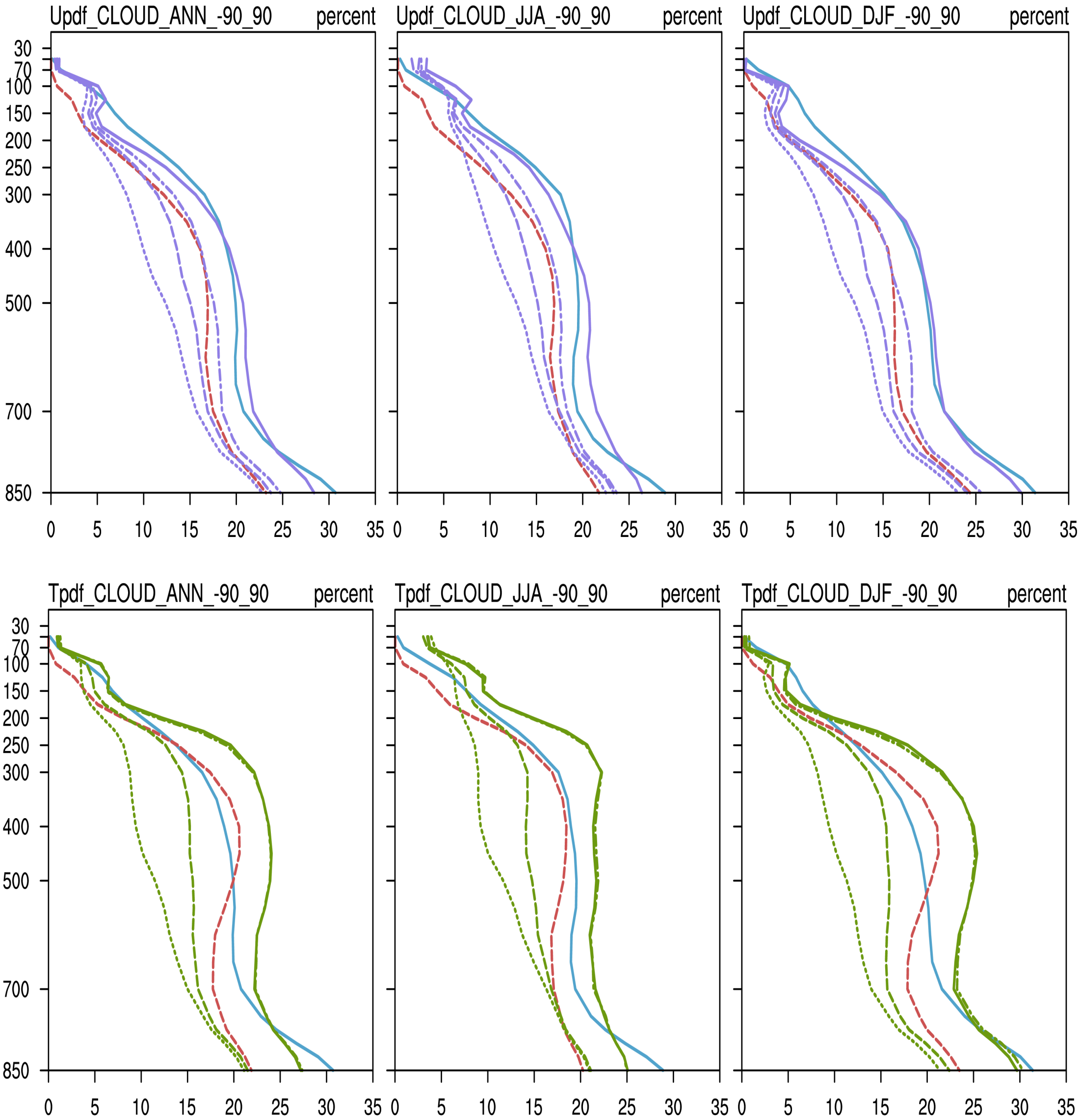

Figure S5. Sensitivity of vertical CF profile to the super-saturation ratio value (sup) for U_pdf (upper row) and T_pdf (lower row), with respect to annual (left), DJF (central), and JJA (right) global means. Colored lines represent observational data from CloudSat/CALIPSO (solid blue) or simulations by U_pdf (purple) or T_pdf (green) with sup = 1.0 (solid), sup = 1.0005 (dash-dot), sup = 1.005 (dashed), or sup = 1.05 (dotted) as well as by the U_pdf and T_pdf with Slingo ice CF parameterizations (dashed Red).

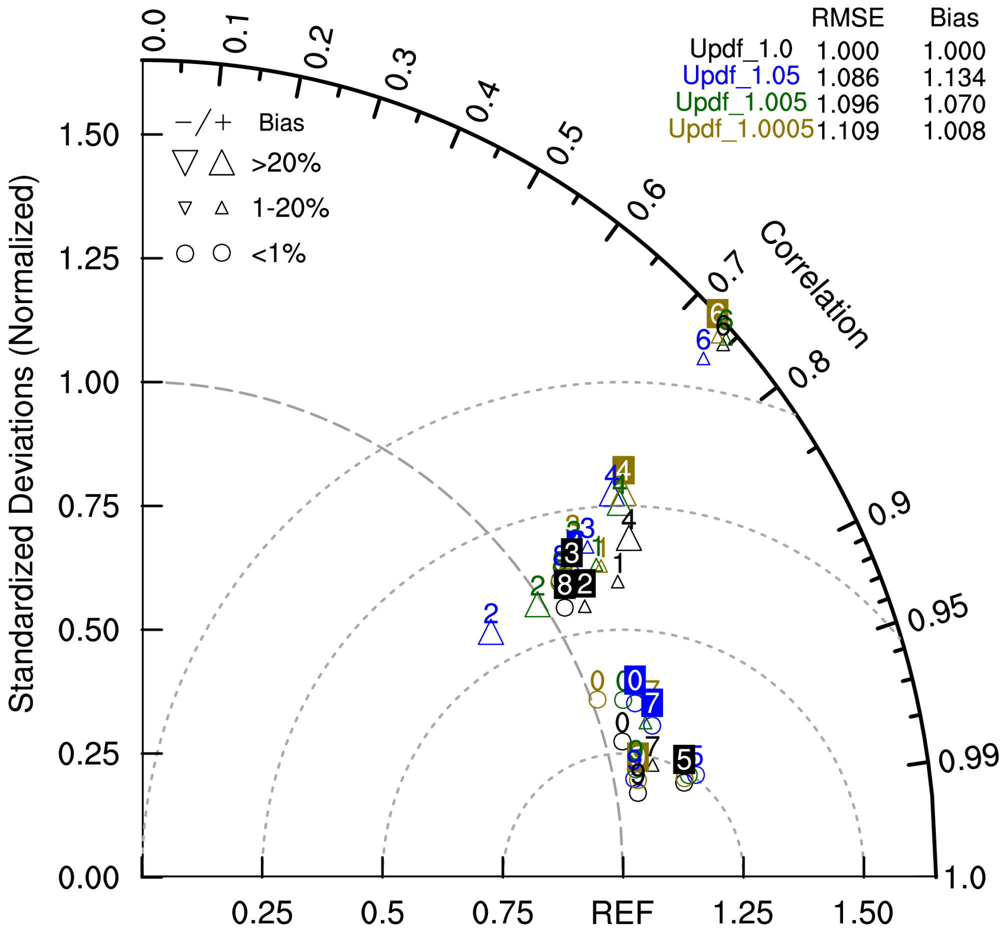

Figure S6. Space–time Taylor diagram for the ten climatic parameters simulated by the U_pdf with different super-saturation ratio value (sup) in the ice CF parameterization (sup = 1.0: black symbols; sup = 1.05: blue; sup = 1.005: green; sup = 1.0005: brown) and comparisons of these with the corresponding observational data provided by the atmospheric diagnostic package from the NCAR CESM group. The ten climatic parameters are marked from 0 to 9 where 0 denotes sea level pressure; 1 is SW cloud forcing, 2 is LW cloud forcing, 3 is land rainfall, 4 is ocean rainfall, 5 is land 2-m temperature, 6 is Pacific surface stress, 7 is zonal wind at 300 mb, 8 is relative humidity, and 9 is temperature.

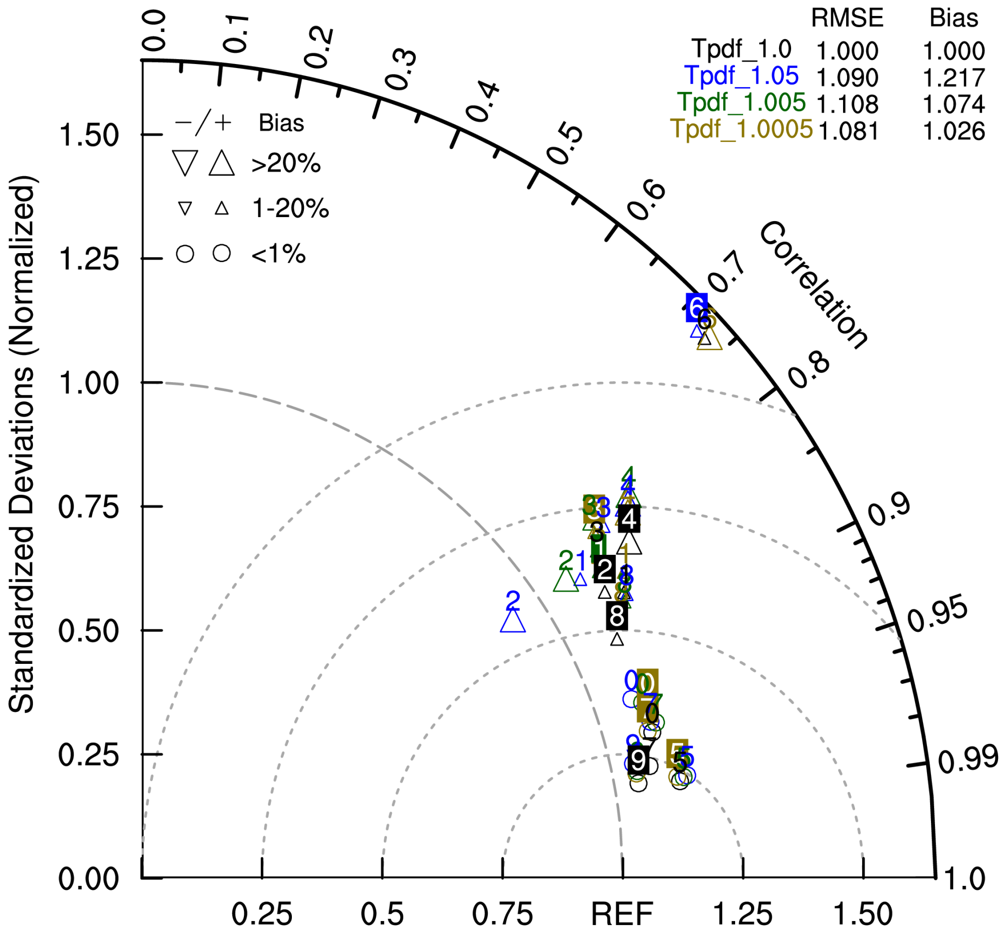

Figure S7. Space–time Taylor diagram for the ten climatic parameters simulated by the T_pdf with different super-saturation ratio value (sup) in the ice CF parameterization (sup = 1.0: black symbols; sup = 1.05: blue; sup = 1.005: green; sup = 1.0005: brown) and comparisons of these with the corresponding observational data provided by the atmospheric diagnostic package from the NCAR CESM group. The ten climatic parameters are marked from 0 to 9 where 0 denotes sea level pressure; 1 is SW cloud forcing, 2 is LW cloud forcing, 3 is land rainfall, 4 is ocean rainfall, 5 is land 2-m temperature, 6 is Pacific surface stress, 7 is zonal wind at 300 mb, 8 is relative humidity, and 9 is temperature.

Table S1. Correlation coefficients (R) for comparisons between the CF pressure-time distribution simulated by the five macrophysical schemes (Park, T_pdf, and U_pdf as well as U_pdf and T_pdf with Slingo ice CF schemes) and observational data from the TWP-ICE 2006 experiment (upper subtable). The lower subtable is similar as the upper but for relative humidity (RH).

CLOUD	All time	Time Period 1	Time Period 2	Time Period 3
Updf_Slingo	0.428	0.469	0.083	0.235
Updf	0.384	0.446	0.049	0.255
Park	0.471	0.468	0.125	0.275
Tpdf_Slingo	0.436	0.475	0.059	0.214
Tpdf	0.388	0.456	0.054	0.224

RH	All time	Time Period 1	Time Period 2	Time Period 3
Updf_Slingo	0.477	0.66	0.48	0.362
Updf	0.486	0.635	0.469	0.413
Park	0.405	0.609	0.498	0.199
Tpdf_Slingo	0.457	0.595	0.492	0.335
Tpdf	0.448	0.582	0.481	0.321

Table S2. RMSEs and correlation coefficients (R, in brackets) for comparisons between the vertical CF profiles simulated by the three macrophysical schemes (Park, T_pdf, U_pdf) and observational data from CloudSat/CALIPSO (Figure S1). Comparisons are made for three periods (JJA: June, July, August; DJF: December, January, February) and two latitudinal ranges. The smallest RMSE value of the three schemes in each case is bolded and underlined.

		Global			**30°N~30°S**		
		Park	**T_pdf**	**U_pdf**	**Park**	**T_pdf**	**U_pdf**
Including low levels	**Annual**	8.03 (0.83)	9.51 (0.86)	<u>**7.92**</u> (0.87)	6.15 (0.60)	6.03 (0.53)	<u>**5.38**</u> (0.59)
	JJA	<u>**8.58**</u> (0.81)	11.52 (0.85)	9.66 (0.85)	6.61 (0.61)	6.06 (0.54)	<u>**5.87**</u> (0.62)
	DJF	9.14 (0.81)	10.20 (0.85)	<u>**7.92**</u> (0.86)	6.31 (0.59)	6.65 (0.52)	<u>**5.60**</u> (0.57)
Excluding low levels	**Annual**	5.97 (0.91)	6.51 (0.96)	<u>**5.32**</u> (0.99)	5.89 (0.63)	5.75 (0.51)	<u>**5.13**</u> (0.55)
	JJA	<u>**6.60**</u> (0.92)	9.39 (0.97)	7.72 (0.98)	6.13 (0.63)	6.22 (0.49)	<u>**5.55**</u> (0.58)
	DJF	6.05 (0.92)	6.76 (0.95)	<u>**4.85**</u> (0.99)	6.20 (0.60)	5.93 (0.49)	<u>**5.45**</u> (0.52)

Table S3. Correlation, variance, and bias corresponding to the space-time Taylor diagram for the 10 climatic parameters shown in Figure 10 of the paper.

Space-Time	Park			U_pdf			T_pdf		
	cor	var	bias	cor	var	bias	cor	var	bias
Sea Level Pressure (ERA)	0.961	1.11	0.0177	0.964	1.04	0.0137	0.963	1.1	0.0125
SW Cloud Forcing (CERES-EBAF)	0.832	1.19	10.7	0.856	1.16	16	0.867	1.16	6.55
LW Cloud Forcing (CERES-EBAF)	0.844	1.25	7.76	0.859	1.07	14.6	0.858	1.12	16.6
Land Rainfall (30N-30S GPCP)	0.8	1.03	2.33	0.826	1.08	11.5	0.82	1.15	12.6
Ocean Rainfall (30N-30S GPCP)	0.834	1.19	29.8	0.828	1.22	34.8	0.831	1.22	29.6
Land 2m Temperature (Willmott)	0.985	1.13	0.0368	0.986	1.14	0.302	0.985	1.14	0.114
Pacific Surface Stress (5N-5S ERS)	0.751	1.57	13.7	0.746	1.62	18.9	0.731	1.6	19.2
Zonal Wind (300mb ERAI)	0.974	0.935	0.301	0.978	0.922	1.84	0.978	0.927	0.342
Relative Humidity (ERAI)	0.884	0.888	13.4	0.85	0.996	2.23	0.899	0.927	6.56
Temperature (ERAI)	0.973	1.06	0.632	0.987	1.04	0.652	0.983	1.05	0.682

Table S4. RMSEs for comparisons between the latitude–height cross-sections of RH simulated by the three macrophysical schemes (Park, T_pdf, and U_pdf) and ERA-Interim (Figure 11). The comparisons are made for three periods (JJA: June, July, August; DJF: December, January, February) and two latitudinal ranges. The smallest RMSE value of the three schemes in each case is bolded and underlined.

RH	Park	T_pdf	U_pdf
Annual	11.2	**6.4**	9.4
JJA	11.2	**7.3**	10.1
DJF	11.8	**6.9**	9.7

Table S5. RMSEs for comparisons between the latitude–height cross-sections of (a) specific humidity q and (b) air temperature T simulated by the three macrophysical schemes (Park, T_pdf, and U_pdf) and ERA-Interim (Figure 12). The comparisons are made for three periods (JJA: June, July, August; DJF: December, January, February) and two latitudinal ranges. The smallest RMSE value of the three schemes in each case is bolded and underlined.

(a)

q	Park	T_pdf	U_pdf
Annual	0.29	0.25	**0.23**
JJA	0.32	**0.26**	0.27
DJF	0.29	0.27	**0.25**

(b)

T	Park	T_pdf	U_pdf
Annual	2.62	2.49	**2.05**
JJA	2.65	2.43	**2.24**
DJF	2.94	2.86	**2.60**

Table S6. RMSEs for comparisons between the annual cycles of zonal mean total precipitable water (TMQ) and annual cycles of zonal wind at 200 mb (U200) simulated by the three macrophysical schemes (Park, T_pdf, and U_pdf) and ERA-Interim (Figures 13 and 14).

	Park	**T_pdf**	**U_pdf**
TMQ	1.44	0.86	**<u>0.82</u>**
U200	1.97	1.74	**<u>1.49</u>**

Table S7. RMSEs for comparisons between the global mean annual cycles of several parameters simulated by the three macrophysical schemes (Park, T_pdf, and U_pdf) and corresponding observational data (Figure 15). The smallest RMSE value of the three schemes in each case is bolded and underlined.

	Park	**T_pdf**	**U_pdf**
TMQ	2.08	**<u>1.70</u>**	1.74
FLUT	8.15	6.71	**<u>6.31</u>**
LWCF	6.18	6.32	**<u>6.06</u>**
SWCF	14.00	**<u>11.80</u>**	14.00
U_200	2.34	2.04	**<u>1.70</u>**
T_200	5.57	4.50	**<u>2.55</u>**

Table S8. Global annual means of the climatic parameters i.e. net radiation flux at the top of model (RESTOM), long-wave cloud forcing (LWCF), and shortwave cloud forcing (SWCF) simulated by the U_pdf (upper subtable) and T_pdf (lower subtable) of GTS cloud macrophysical schemes with different values of sup used in Figure S5.

U_pdf					
	sup = 1.0	sup = 1.0005	sup = 1.005	sup = 1.05	Slingo
RESTOM	-3.13	-2.71	-2.75	-2.45	-0.19
LWCF	22.31	21.19	19.89	17.88	19.86
SWCF	-54.66	-53.02	-52.22	-50.20	-48.98

T_pdf					
	sup = 1.0	sup = 1.0005	sup = 1.005	sup = 1.05	Slingo
RESTOM	1.18	1.19	1.75	1.82	3.37
LWCF	21.77	21.75	19.64	17.18	20.33
SWCF	-50.22	-50.31	-47.98	-45.83	-46.47

Table S9. Bias corresponding to the space-time Taylor diagram for the 10 climatic parameters shown in Figures S6 (upper subtable) and S7 (lower subtable).

U_pdf					
Bias (%): Space-Time	sup = 1.0	sup = 1.0005	sup = 1.005	sup = 1.05	Slingo
Sea level pressure (ERAI)	0.014	0.014	0.013	0.012	0.013
SW cloud forcing (CERES-EBAF)	15.834	12.379	10.658	6.559	3.845
LW cloud forcing (CERES-EBAF)	14.423	18.7	23.7	32.482	23.935
Land rainfall (30N-30S, GPCP)	11.413	13.015	12.314	15.282	18.494
Ocean rainfall (30N-30S, GPCP)	34.779	34.786	35.763	36.494	34.041
Land 2-m temperature (Willmott)	0.306	0.305	0.391	0.464	0.297
Pacific suface stress (5N-5S, ERS)	30.561	27.917	32.778	28.267	30.148
Zonal wind (300mb, ERAI)	3.89	5.059	4.425	5.514	5.115
Relative humidity (ERAI)	2.348	2.903	3.709	4.242	2.548
Temperature (ERAI)	0.85	0.836	0.909	0.969	0.814

T_pdf					
Bias (%): Space-Time	sup = 1.0	sup = 1.0005	sup = 1.005	sup = 1.05	Slingo
Sea level pressure (ERAI)	0.012	0.012	0.014	0.014	0.013
SW cloud forcing (CERES-EBAF)	6.429	6.628	1.677	2.88	1.438
LW cloud forcing (CERES-EBAF)	16.477	16.565	24.641	34.083	21.988
Land rainfall (30N-30S, GPCP)	12.655	10.844	13.454	14.193	18.854
Ocean rainfall (30N-30S, GPCP)	29.684	30.303	30.294	31.811	28.77
Land 2-m temperature (Willmott)	0.123	0.106	0.176	0.294	0.113
Pacific suface stress (5N-5S, ERS)	30.988	33.329	33.621	27.975	32.959
Zonal wind (300mb, ERAI)	5.511	5.842	6.03	6.493	6.597
Relative humidity (ERAI)	9.964	10.087	11.396	12.122	10.501
Temperature (ERAI)	0.84	0.843	0.871	0.957	0.811