Supplemental Material

Supplementary material for manuscript: "Simulated Tropical Precipitation Assessed Across Three Major Phases of the Coupled Model Intercomparison Project (CMIP)"

Fiedler et al., submitted to Monthly Weather Review

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1 Content

We include the following supplementary information:

- an analysis of the observational uncertainty across the four data sets (Section 2), shown in Fig. S1.
- an assessment of large-scale precipitation differences in tandem with SST differences (Section 3), illustrated in Fig. S2 and S3.
- the contributions from land and ocean to our assessment of wet and dry frequency in the tropics (Fig. S4–S5)
- frequency distributions of tropical precipitation to illustrate the CMIP model spread (Fig. S6)
- maps with the regional masks applied for calculating the monsoon metrics (Fig. S7)
- data tables detailing the models used in this study (Tab. 1-5)
- definition of the SPI classes (Tab. 6)

2 Observational uncertainty

We illustrate the uncertainty in precipitation observations used as reference for our CMIP intercomparison. For the four observational datasets, this uncertainty is due to regional differences in the rain gauge density [72], interpolation methods, satellite retrieval algorithms, and spatio-temporal resolution [122]. For each gridbox, we define the observational uncertainty for the period 2000–2014 as the range between the mean precipitation for the observational dataset with the highest value subtracted by the dataset with the lowest value (see Fig. S1). The observational differences are given relative to the mean of the four datasets. We find the largest ranges over islands, luv of mountain ranges, and coastal areas (Fig S1a).

Overall, the strongest uncertainty rarely exceeds 5 mm day^{-1}. During DJF, we find strongest disagreement in Central Africa with up to 6 mm day^{-1} (CMORPH high bias), over the Pacific Warm pool (CMORPH dry bias) as well as the Caribbean (CRU wet bias; Fig. S1b). During JJA, we find a remarkably higher uncertainty compared to DJF of 10 mm day^{-1} and more. Strongest disagreement among the datasets we find at the West coasts of India and Malay Peninsula during Monsoon (CMORPH dry bias; Fig. S1c). Somewhat smaller ranges are found in the Sahel (CMORPH wet bias), over the Amazon rain forest (CMORPH dry bias), and in the Pacific Warm pool region. This means, CMORPH disagrees the most with the other three datasets, driving the observational uncertainty with dry biases over India [89,98,123], South East Asia [75,125] and the area from Caribbean to Central America, and a wet bias over Central Africa [14,42].

Without CMORPH, the mean observational uncertainty would reduce from 0.85 to 0.46 mm day^{-1} (land: 0.96 to 0.38 mm day^{-1}). CRU for which less comparison studies exist agrees fairly well with the gauge-based dataset of the Global Precipitation Climatology Centre (GPCC) [109] over West Africa [3] and elsewhere [53]. However, patches of strong differences over individual islands vanish when only considering satellite data (Fig. S1d). These signals should not be given too much attention as these island measurements in CRU are based on few gauges that are not representative for larger areas [72]. Over land, TRMM and IMERG are almost identical, while over ocean, they differ by up to 1 mm day^{-1}, averaged over the study period. In general, the range of the four observational datasets remains below 2 mm day^{-1} in most tropical regions, while a markedly higher range mainly occurs during summer in the Monsoon regions.

3 SST pattern versus precipitation

The large scale precipitation biases can be caused dynamically through changes in the Walker circulation and can be driven by SSTs. Here, we test the hypothesis that the reduction in precipitation biases occurs in tandem with a reduction in large scale SST biases. The tropical mean SST is known to be biased low in most and high in some models, which has been attributed to a bias in cloud cover [77]. We find that both, the precipitation (Section 3.a.1) and SSTs in the tropical mean show a tighter range in CMIP6 than in CMIP5 and CMIP3. While the mean bias across all models does reduce somewhat in CMIP5 and CMIP6 compared to CMIP3, CMIP6 shows fewer models with strong positive and negative biases in precipitation and SSTs. However, there is no indication that the tropical mean in the two quantities are related in an obvious way (Fig. S2a).

The second large scale bias in tropical SSTs is the "cold tongue" in the Pacific Ocean [140], which is caused by the erroneous representation of the thermocline depth. The "cold tongue" region is indicated in Fig. S3. Fig. S2 shows that most models have a too cool cold tongue and a too wet tropical Pacific. While the cold tongue bias is substantially reduced in CMIP6 compared to CMIP3, the precipitation bias over the Tropical Pacific does not (Fig. S2b).

A Data Tables

Table 1: Model data used from CMIP3. All data is available as monthly means for 1900–2000. Temporally higher resolved data is marked with ([1]) for 3-hourly precipitation data in 1991–2000, ([2]) for daily precipitation data in 1961–2000, and ([3]) for daily outgoing longwave radiation data, the latter two both in 1961–2000. Note that availability for other variables may differ. See Tab. 5 for institution acronyms.

Model	Institution	Spatial resolution	References
bccr_bcm2_0[2,3]	BCCR/UIB NERSC/GFI	128×64	[101]
cccma_cgcm3_1[2,3]	CCCma	96×48	[101]
cccma_cgcm3_1_t63[2,3]	CCCma	128×64	[101]
cnrm_cm3[1,2,3]	CNRS	128×64	[107]
csiro_mk3_0[2,3]	CSIRO	192×96	[49]
csiro_mk3_5[2,3]	CSIRO	192×96	[49]
gfdl_cm2_0[1,2,3]	GFDL	144×90	[25]
gfdl_cm2_1[1,2,3]	GFDL	144×90	[25]
giss_aom[2]	GISS	90×60	[101]
giss_model_e_h	GISS	72×46	[101]
giss_model_e_r	GISS	72×46	[101]
iap_fgoals1_0_g[2,3]	IAP	128×60	[146, 147]
ingv_echam4[2,3]	INGV	320×160	[101]
inmcm3_0[1,2]	INM	72×45	[27]
ipsl_cm4[2,3]	IPSL	96×72	[84]
miroc_3_2_medres[1,2,3]	CCSR/NIES FRCGC	128×64	[71]
miroc3_2_hires[1,2,3]	CCSR/NIES FRCGC	320×160	[71]
miub_echo_g[2,3]	MIUB	96×48	[104] [76] [88]
mpi_echam5[2,3]	MPI-M	192×96	[105]
mri_cgcm2_3_2a[1,2,3]	MRI	128×64	[152]
ncar_ccsm3_0	NCAR	256×128	[22]
ncar_pcm1	NCAR	128×64	[137]
ukmo_hadcm3[2]	UKMO	96×73	[48, 66] [38]
ukmo_hadgem1	UKMO	192×145	[67, 85]

Table 2: Model data used from CMIP5. Monthly means are available for 1900–2000 from all models except MIROC4h and CanCM4. The availability of temporally higher-resolved data is indicated as in Tab. 1. See Tab. 5 for institution acronyms.

Model	Institution	Spatial resolution	References
ACCESS1-0[1,2,3]	CSIRO-BOM	192×144	[10, 11]
ACCESS1-3[1,2,3]	CSIRO-BOM	192×144	[10, 12]
BNU-ESM[2,3]	BNU	128×64	[64, 65]
CCSM4[1,2]	NCAR	288×192	[43, 87]
CESM1-BGC[2]	NCAR	288×192	[79, 80]
CESM1-CAM5[2]	NCAR	288×192	[40, 94]
CESM1-CAM5-1-FV2	NCAR	144×96	[40, 95]
CESM1-WACCM	NCAR	144×96	[82, 83]
CESM1-FASTCHEM[2]	NCAR	288×192	[40, 74]
CMCC-CESM[2,3]	CMCC	96×48	[19, 131]
CMCC-CM[1,2,3]	CMCC	480×240	[111] [110]
CMCC-CMS[2,3]	CMCC	192×96	[20, 40]
CNRM-CM5[1,2,3]	CNRM-CERFACS	256×128	[133] [116]
CNRM-CM5-2	CNRM-CERFACS	256×128	[133] [117]
CSIRO-Mk3-6-0[2,3]	CSIRO-QCCCE	192×96	[62, 63]
CanCM4[2]	CCCma	128×64	[16, 40]
CanESM2[2,3]	CCCma	128×64	[17, 40]
EC-EARTH[1,2,3]	EC-Earth	320×160	[54] [37]
FGOALS-g2[1,2,3]	IAP	128×60	[59, 78]
FGOALS-s2	IAP	128×108	[6]
FIO-ESM	FIO	128×64	[100] [99]

Table 3: Tab. 2 for CMIP5 data continued.

Model	Institution	Spatial resolution	References
GFDL-CM2p1	GFDL	144×90	[25] [33]
GFDL-CM3[1,2,3]	GFDL	144×90	[28, 50] [57]
GFDL-ESM2G[1,2,3]	GFDL	144×90	[32, 34] [30]
GFDL-ESM2M[1,2,3]	GFDL	144×90	[32, 34] [31]
GISS-E2-H-CC	GISS	144×90	[40, 90]
GISS-E2-R-CC	GISS	144×90	[40, 91]
HadCM3[2]	MOHC	96×73	[21] [118–120]
HadGEM2-CC[2,3]	MOHC	192×145	[52, 68]
HadGEM2-ES[1,2,3]	MOHC	192×145	[68, 69]
IPSL-CM5A-LR[1,2,3]	IPSL	96×96	[29] [26]
IPSL-CM5A-MR[1,2,3]	IPSL	144×143	[29] [41]
IPSL-CM5B-LR[2,3]	IPSL	96×96	[29] [39]
MIROC-ESM[1,2,3]	JAMSTEC, AORI, NIES	128×64	[139] [61]
MIROC-ESM-CHEM[1,2,3]	JAMSTEC, AORI, NIES	128×64	[139] [60]
MIROC4h[1,2,3]	AORI, NIES, JAMSTEC	640×320	[106] [4]
MIROC5[1,2,3]	AORI, NIES, JAMSTEC	256×128	[138] [5]
MPI-ESM-LR[2,3]	MPI-M	192×96	[45, 47]
MPI-ESM-MR[2,3]	MPI-M	192×96	[46, 47]
MPI-ESM-P[2,3]	MPI-M	192×96	[47, 70]
MRI-CGCM3[1,2,3]	MRI	320×160	[148, 149]
MRI-ESM1[1,2,3]	MRI	320×160	[1, 2]
NorESM1-M[1,2,3]	NCC	144×96	[9, 81]
NorESM1-ME	NCC	144×96	[129, 130]
bcc-csm1-1[1,2,3]	BCC	128×64	[143, 145]
bcc-csm1-1-m[1,2,3]	BCC	320×160	[143, 144]
inmcm4[1,2,3]	INM	180×120	[135] [136]

Table 4: Model data used from CMIP6. Precipitation data is available as monthly means for the time period 1900–2014 for all models except AWI-CM-1-1-MR, EC-Earth3-Veg and NESM3. Temporally higher-resolved data is not available for all models and availability is indicated as in Tab. 1. See Tab. 5 for institution acronyms.

Model	Institution	Spatial resolution	References
AWI-CM-1-1-MR[1]	AWI	384×192	[115]
BCC-CSM2-MR[1,2,3]	BCC	320×160	[7, 141]
BCC-ESM1[2,3]	BCC	128×64	[8, 142]
CanESM5[2,3]	CCCma	128×64	[18, 124]
CESM2	NCAR	288×192	[44] [24]
CESM2-WACCM[2,3]	NCAR	288×192	[23]
CNRM-CM-6-1[1,2,3]	CNRM-CERFACS	256×128	[132, 134]
CNRM-ESM2-1[1,2,3]	CNRM-CERFACS	256×128	[112, 113]
EC-Earth3-Veg[1,2,3]	EC-Earth	512×256	[36]
EC-Earth3[1,2,3]	EC-Earth	512×256	[35]
GFDL-CM4[1,2,3]	GFDL	360×180	[51, 55]
GISS-E2-1-G[1,3]	GISS	144×90	[92, 108]
GISS-E2-1-H	GISS	144×90	[93, 108]
HadGEM3-GC31-LL[2,3]	MOHC	192×144	[73, 103]
IPSL-CM6A-LR[1,2,3]	IPSL	144×143	[13]
MIROC6	JAMSTEC, AORI, NIES, R-CCS	256×128	[127] [128]
MPI-ESM-LR[1,2,3]	MPI-M	192×96	[86]
MRI-ESM2-0[1,2,3]	MRI	320×160	[150] [151]
NESM3[1]	NUIST	192×96	[15, 96]
SAM0-UNICON[1,2,3]	SNU	288×192	[97, 121]
UKESM1-0-LL	MOHC	192×96	[114, 126]

Table 5: Acronyms of modeling centers providing the datasets listed in Tab. 1 - 4.

Acronym	Modeling Center
AORI	Atmosphere and Ocean Research Institute, The University of Tokyo, Japan
AWI	Alfred Wegener Institute, Germany
BCC	Beijing Climate Center, China
BCCR	Bjerknes Center for Climate Research, Norway
BNU	Beijing Normal University, China
CCCma	Canadian Center for Climate Modeling and Analysis, Canada
CCSR	Center for Climate System Research, Tokyo, Japan
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy
CNRM	Centre National de Recherches Meteorologiques, France
CNRM-CERFACS	CNRM and Centre Europeen de Recherches et de Formation Avancee en Calcul Scientifique, France
CSIRO	Commonwealth Scientific and Industrial Research Organisation Atmospheric Research, Australia
CSIRO-BOM	CSIRO and Bureau of Meteorology, Australia
CSIRO-QCCCE	CSIRO and Queensland Climate Change Centre of Excellence, Australia
EC-Earth	EC-Earth Consortium
FIO	First Institute of Oceanography, China
FRCGC	Frontier Research Center for Global Change, Kanagawa, Japan
GFDL	Geophysical Fluid Dynamics Laboratory, USA
GFI	Geophysical Institute, University of Bergen, Norway
GISS	NASA/Goddard Institute for Space Studies, USA
IAP	Institute for Atmospheric Physics, China
INGV	National Institute of Geophysics and Volcanology, Italy
INM	Institute of Numerical Mathematics, Russia
IPSL	Institute Pierre Simon Laplace, France
JAMSTEC	Japan Agency for Marine-Earth Science and Technology, Japan
MIUB	University of Bonn, Germany
MOHC	Met Office Hadley Centre, UK
MPI-M	Max Planck Institute for Meteorology, Germany
MRI	Meteorological Research Institute, Japan
NCAR	National Center for Atmospheric Research, USA
NCC	Norwegian Climate Center, Norway
NERSC	Nansen Environmental and Remote Sensing Center, Norway
NIES	National Institute for Environmental Studies, Ibaraki, Japan
NIES	National Institute for Environmental Studies, Japan
NUIST	Nanjing University of Information Science and Technology, China
R-CCS	RIKEN Center for Computational Science, Japan
SNU	Seoul National University, Republic of Korea
UIB	University of Bergen, Norway
UKMO	Met Office, United Kingdom

Table 6: Mathematical definition of the occurrence probabilities (P), criteria, and classification for the Standardized Precipitation Index (SPI).

Criterion	SPI class	P [%]
SPI $\geq$ 2	W3: extremely wet	2.3
2 > SPI $\geq$ 1.5	W2: severely wet	4.4
1.5 > SPI $\geq$ 1	W1: moderately wet	9.2
1 > SPI > -1	N0: normal	68.2
-1 $\geq$ SPI > -1.5	D1: moderately dry	9.2
-1.5 $\geq$ SPI > -2	D2: severely dry	4.4
SPI $\leq$ -2	D3: extremely dry	2.3

B Figure gallery

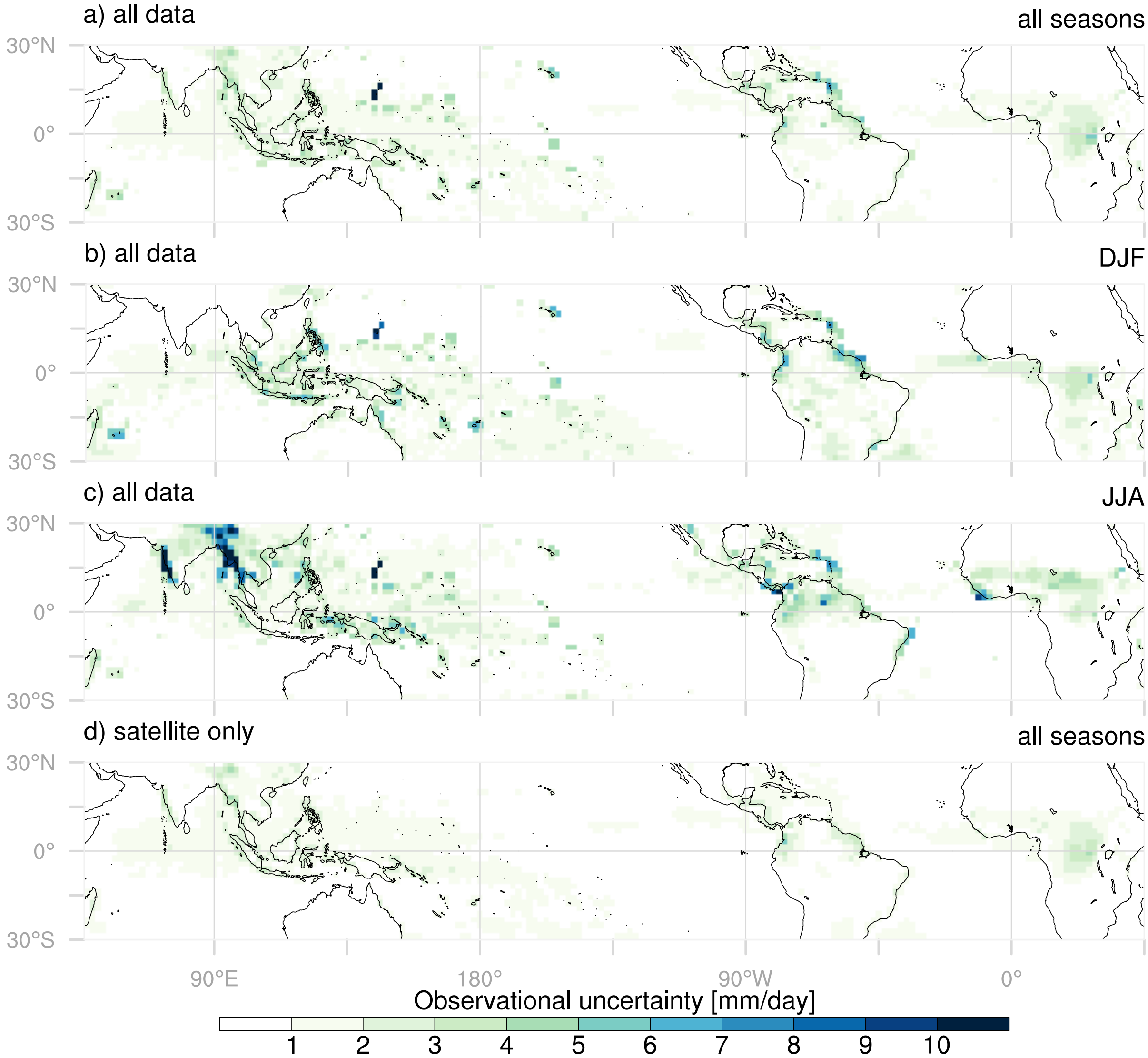

Figure S1: The observational uncertainty is shown as the range in long-term mean precipitation of (a-c) TRMM 3B42, CMORPH, IMERG and CRU and for (d) TRMM 3B42, CMORPH and IMERG for every grid box (T63). The calculation is based on monthly precipitation rates for 2000−2014 over (a,d) all seasons, (b) DJF and (c) JJA. The tropical mean range for a) is 0.85 (land: 0.95; ocean: 0.82) mm day^{-1}.

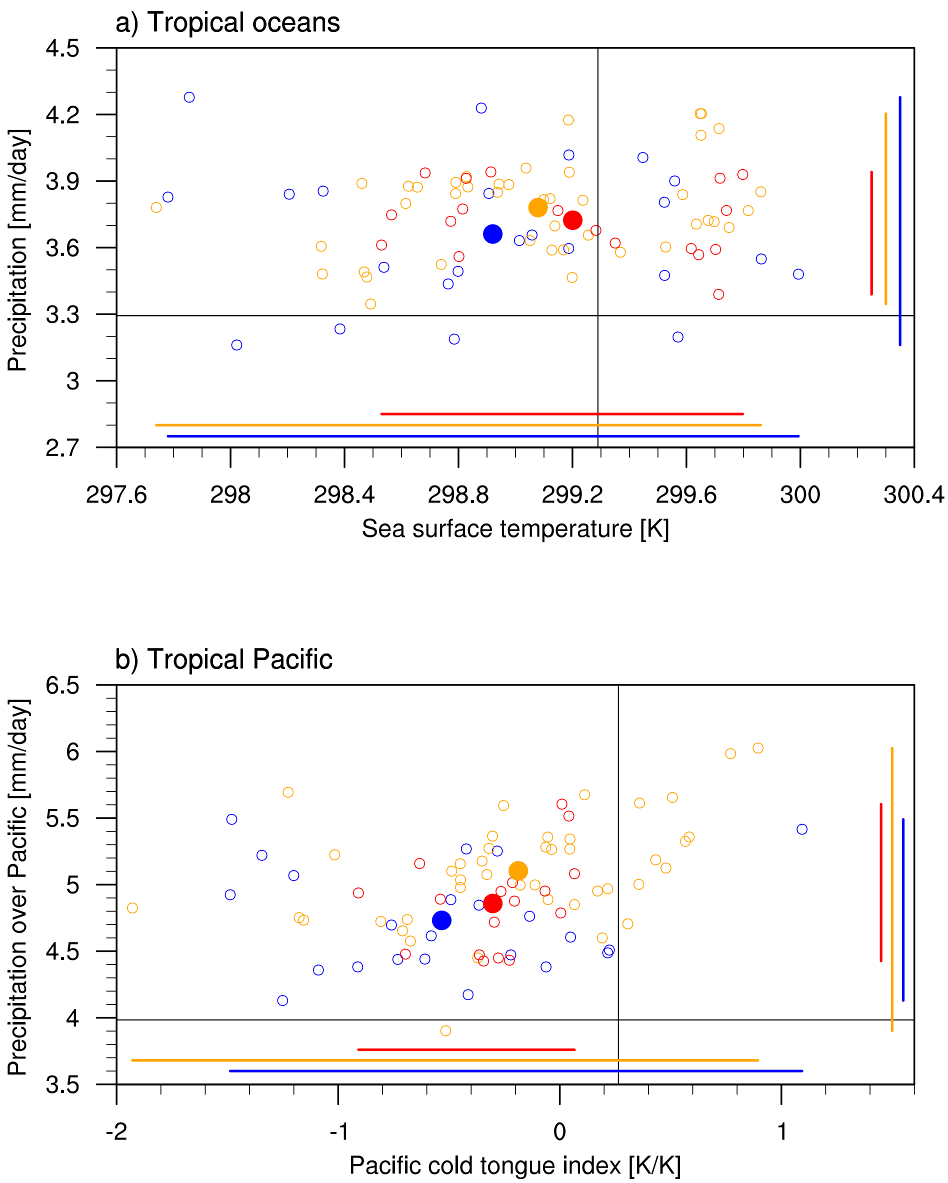

Figure S2: Precipitation versus SST differences. Shown are the (a) precipitation over the tropical oceans against sea surface temperatures, and (b) precipitation over the tropical Pacific against the Pacific cold tongue index following [140], using surface temperature averages for 180°W−140°W and 3°S−3°N minus 150°E−110°W and 20°S−20°N, depicted in Figure S3. Open circles mark 23 CMIP3 (blue), 43 CMIP5 (orange), 18 CMIP6 (red) model ensemble averages for 1980−1999, with their range depicted as colored lines. The black lines are the observed SST mean for 1980−1999 in HadISST [102], and the observed precipitation mean for 2000−2014 in TRMM. We show 1980−1999 because this is the period with the largest overlap of HadISST and the CMIP generations. The precipitation of CMIP6 2000–2014 is close to that time frame so we do not show it here.

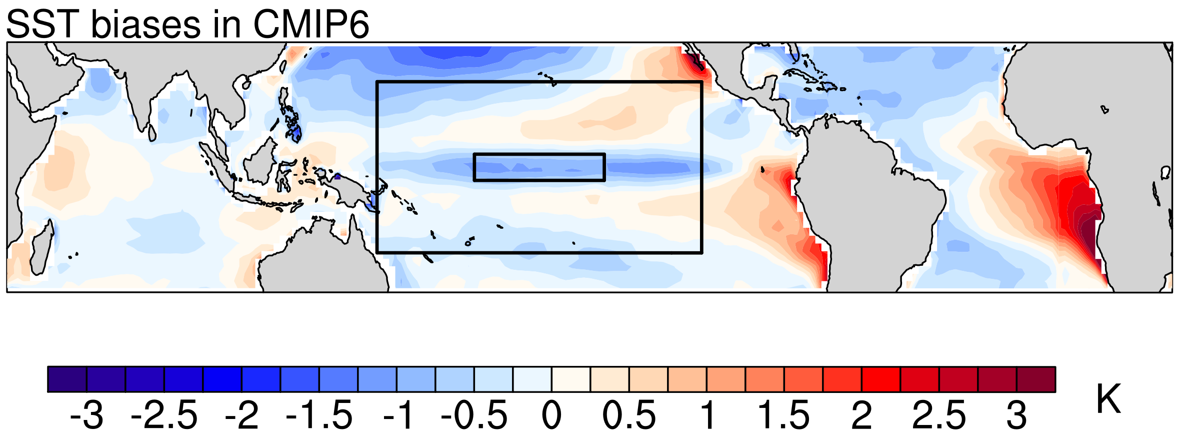

Figure S3: SST bias in CMIP6 models computed as the difference between the multimodel mean (equivalent to red dot in Fig. S2a) minus the observational product HadISST (equivalent to vertical line in Fig. S2a), both averaged over 1980−1999, again as in Fig. S2. The boxes used to define the cold-tongue index in Fig. S2b are indicated in black. Note that there is observational uncertainty for the SSTs at the order of 0.02 K in the tropical mean among the datasets HadISST [102] (used here), COBE SST2 [56], and ERSSTv5 [58] (not shown).

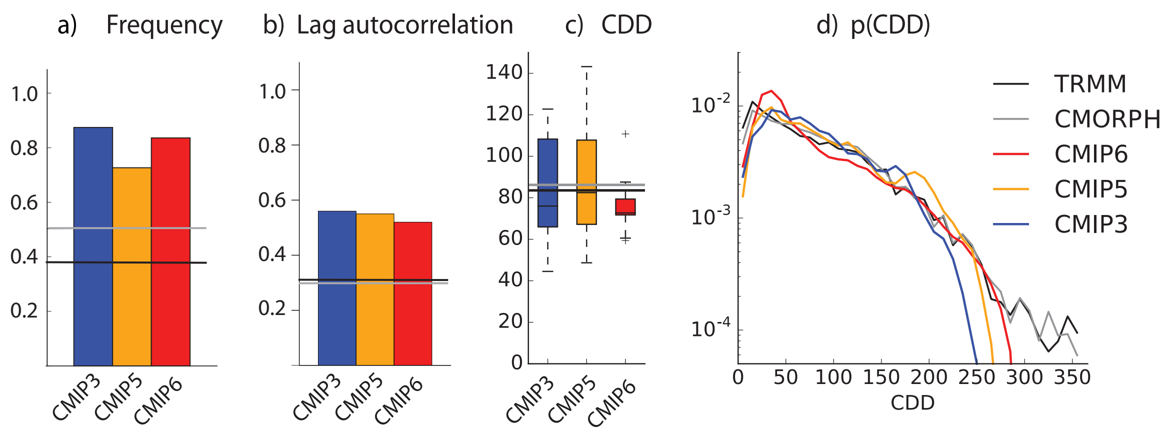

Figure S4: Wet and dry periods over land. Shown are: (a) The frequency of wet hours calculated by flattening three-hourly CMIP data and observations in time and space into a single dimension and counting the number of precipitation events; (b) the 1-day lag auto-correlation of total daily precipitation, temporally and spatially averaged for CMIP and observations, (c-d) the number of consecutive dry days (CDD) as (c) box plot for the time and spatial average from CMIP and observations plotted as horizontal lines, and (d) the probability of occurrence across time and space. All values are for the tropics (30°N–30°S) and from 1961–2000 for the models and from 2000–2014 for the observations.

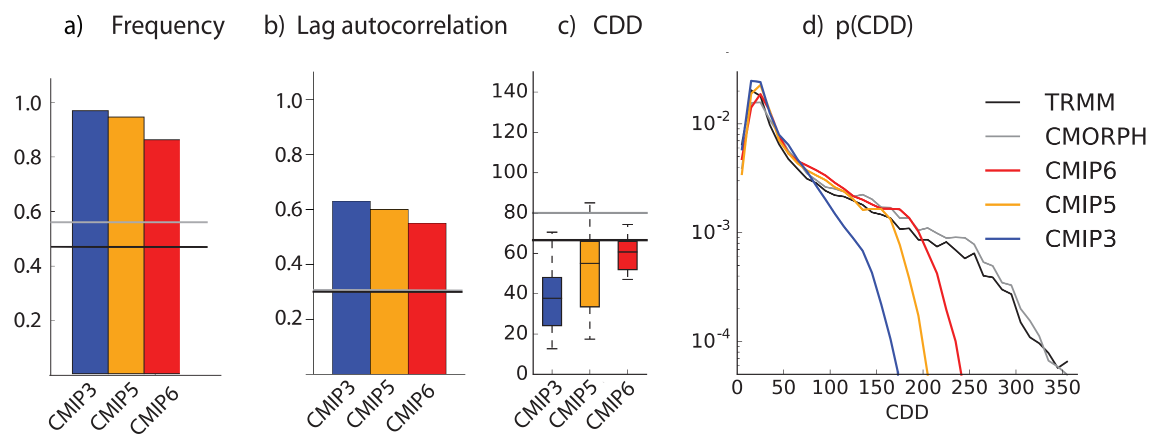

Figure S5: as Figure S4, but for ocean.

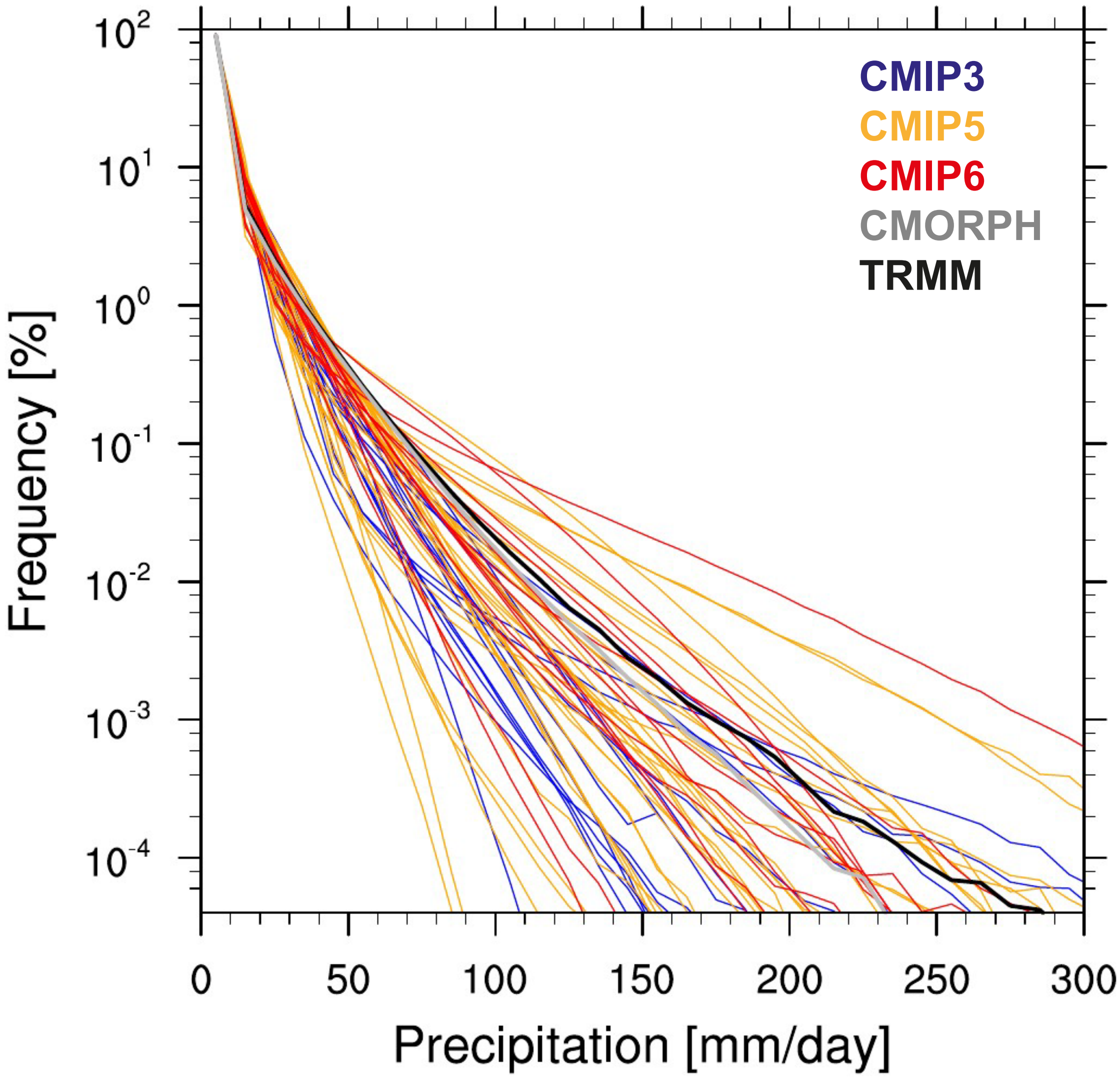

Figure S6: Probability density functions for individual models, TRMM, and CMORPH, of daily precipitation amounts. Most models in CMIP5 and CMIP6, and almost all in CMIP3 underestimate the frequency of the largest observed precipitation amounts with up to 290 mm day^{-1}. Only few models overestimate the frequency of the largest precipitation amounts and produce too large precipitation amounts.

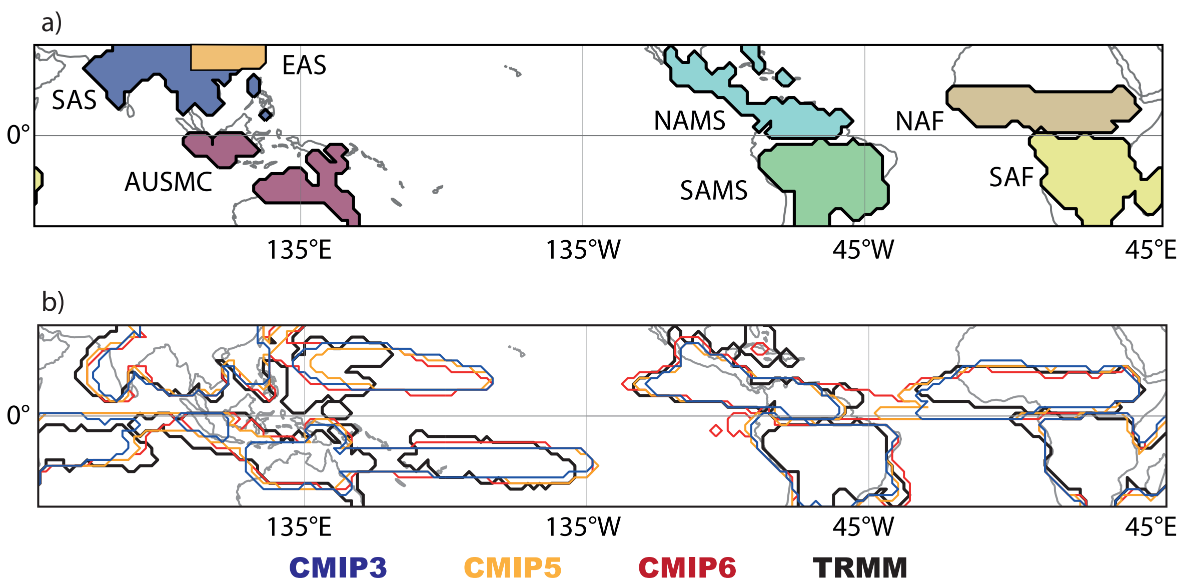

Figure S7: Monsoon precipitation domains. Shown are (a) the land-only monsoon domains calculated from TRMM data, and (b) the mean monsoon areas calculated from CMIP3 (blue), CMIP5 (orange) and CMIP6 (red) for 1900–1999) and TRMM (black) for 2000–2014. In (a) the equator separates the northern monsoon domains (North America Monsoon System (NAMS), North Africa (NAF), Southern Asia (SAS) and East Asian summer (EAS)) from the southern monsoon domains (South America Monsoon System (SAMS), South Africa (SAF), and Australian-Maritime Continent (AUSMC)), 60°E separates NAF from SAS, and 20°N and 100°E separates SAS from EAS.

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