



Supplement of

A performance-based multivariable weighting framework for WRF parameterization-scheme selection

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Table S1 Conceptual comparison of the variable weighting methods used in this study

Method	Weighting basis	Main information emphasized	Explicit term for error magnitude	Response term reflecting scheme dependence	Conflict term among variables	Interpretation in WRF parameterization screening
Equal weighting	Fixed identical weights for all variables	No variable differentiation	No	No	No	Baseline assumption that all evaluated variables contribute equally to the integrated score.
Entropy weighting	Entropy of normalized scheme-level error distributions	Discriminating information among candidate schemes	Indirect	No	No	Variables with stronger error dispersion among candidate schemes receive greater influence.
Coefficient-of-variation weighting	Ratio of standard deviation to mean error across candidate schemes	Relative error dispersion	Indirect	No	No	Variables with larger relative variation among candidate schemes receive greater influence.
CRITIC	Contrast intensity multiplied by conflict/non-redundancy among variables	Contrast and non-redundant information	Indirect	No	Yes	Variables receive higher weights when they vary strongly among schemes and are less redundant with other variables.
Proposed $MRE \times CV$ weighting	Product of the Softmax-transformed mean relative error and the Softmax-transformed absolute-error coefficient of variation, followed by normalization	Simulation difficulty and scheme-dependent response	Yes	Yes	No	Variables that are both difficult to simulate and responsive to alternative schemes within the evaluated physical-process group retain greater influence in the multivariable score.

Table S2 The comparison results of daily meteorological elements in the arid region of Northwest each year with the 30-year average climate values

Year	cRMSE	R	Standard Deviation Ratio	cMIEI
1991	0.50	0.88	1.05	0.58
1992	0.32	0.96	1.12	0.37
1993	0.59	0.85	1.09	0.62
1994	0.42	0.92	1.07	0.44
1995	0.51	0.91	1.22	0.51
1996	0.44	0.91	1.05	0.50
1997	0.34	0.94	1.02	0.37
1998	0.42	0.94	1.17	0.41
1999	0.26	0.98	1.14	0.24
2000	0.40	0.94	1.16	0.40
2001	0.61	0.85	1.17	0.63
2002	0.24	0.97	0.93	0.29
2003	0.49	0.92	1.21	0.54
2004	0.38	0.93	1.06	0.42
2005	0.50	0.90	1.16	0.54
2006	0.37	0.93	0.98	0.39
2007	0.20	0.98	1.08	0.23
2008	0.38	0.93	0.91	0.43
2009	0.46	0.90	1.06	0.50
2010	0.49	0.88	1.00	0.51
2011	0.46	0.92	1.17	0.46
2012	0.30	0.95	0.98	0.35
2013	0.43	0.90	0.97	0.53
2014	0.39	0.92	0.92	0.46
2015	0.54	0.88	1.11	0.59
2016	0.42	0.91	0.95	0.48
2017	0.46	0.91	1.09	0.54
2018	0.45	0.89	0.90	0.54
2019	0.69	0.84	1.29	0.76
2020	0.49	0.88	0.99	0.60

Table S3 The comparison results of daily meteorological elements in the coastal region of Southeast each year with the 30-year average climate values

Year	cRMSE	R	Standard Deviation Ratio	cMIEI
1991	0.42	0.91	0.97	0.77
1992	0.65	0.85	1.24	0.80
1993	0.41	0.94	1.19	0.56
1994	0.59	0.88	1.24	0.86
1995	0.50	0.90	1.17	0.55
1996	0.43	0.92	1.12	0.89
1997	0.54	0.86	1.03	0.65
1998	0.58	0.89	1.23	0.70
1999	0.54	0.87	1.08	0.77
2000	0.60	0.84	1.08	0.76
2001	0.44	0.94	1.20	0.53
2002	0.58	0.83	1.00	0.74
2003	0.43	0.92	1.10	0.62
2004	0.49	0.88	0.98	0.53
2005	0.51	0.94	1.31	0.50
2006	0.43	0.93	1.17	0.61
2007	0.53	0.88	1.12	0.62
2008	0.61	0.89	1.31	0.60
2009	0.38	0.93	0.99	0.49
2010	0.67	0.86	1.30	0.84
2011	0.48	0.89	1.05	0.70
2012	0.48	0.90	1.10	0.57
2013	0.51	0.89	1.10	0.57
2014	0.51	0.92	1.25	0.66
2015	0.75	0.74	1.08	0.78
2016	0.60	0.83	1.05	0.61
2017	0.47	0.92	1.16	0.61
2018	0.56	0.84	0.99	0.68
2019	0.58	0.89	1.26	0.69
2020	0.50	0.87	0.99	0.75

Figure S1 Multivariable assessment used to identify the representative year in the arid region of Northwest China

METRICS		1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
cRMSD	evp	0.407	0.306	0.220	0.290	0.194	0.348	0.270	0.298	0.262	0.368	0.359	0.381	0.430	0.295	0.278	0.175	0.209	0.313	0.342	0.299	0.313	0.246	0.527	0.351	0.812	0.597	0.489	0.674	0.727	0.908
	gst	0.109	0.135	0.150	0.112	0.088	0.154	0.120	0.143	0.182	0.212	0.151	0.141	0.163	0.123	0.097	0.148	0.104	0.199	0.116	0.173	0.241	0.126	0.182	0.070	0.151	0.206	0.100	0.278	0.181	0.181
	pre	0.988	0.528	1.215	0.836	1.062	0.830	0.607	0.798	0.354	0.639	1.210	0.207	0.906	0.740	1.050	0.739	0.300	0.649	0.922	0.981	0.824	0.557	0.716	0.745	0.862	0.590	0.826	0.546	1.315	0.531
	prs	0.219	0.354	0.654	0.539	0.276	0.392	0.523	0.329	0.579	0.151	0.366	0.581	0.155	0.331	0.493	0.405	0.452	0.135	0.310	0.599	0.894	0.147	0.155	0.297	0.314	0.163	0.313	0.627	0.361	0.311
	rhu	0.632	0.628	0.633	0.448	0.674	0.423	0.679	0.450	0.296	0.528	0.827	0.316	0.552	0.450	0.371	0.308	0.187	0.458	0.543	0.239	0.358	0.409	0.361	0.543	0.540	0.197	0.753	0.243	0.550	0.356
	ssd	0.448	0.626	0.786	0.842	0.418	0.620	0.701	0.920	0.377	0.982	1.154	0.812	0.771	0.571	0.564	0.149	0.295	0.471	0.553	0.398	0.361	0.285	0.217	0.615	0.454	0.756	0.832	0.323	0.773	0.955
	tem	0.135	0.178	0.177	0.132	0.119	0.201	0.125	0.173	0.235	0.246	0.168	0.182	0.215	0.143	0.112	0.179	0.158	0.257	0.150	0.233	0.361	0.139	0.281	0.073	0.181	0.288	0.145	0.380	0.225	0.227
	win	0.302	0.367	0.181	0.260	0.350	0.218	0.313	0.152	0.252	0.372	0.539	0.295	0.365	0.182	0.164	0.211	0.290	0.262	0.194	0.372	0.102	0.109	0.094	0.293	0.367	0.276	0.330	0.120	0.384	0.605
cRMSVD		0.501	0.325	0.587	0.425	0.512	0.435	0.341	0.418	0.261	0.397	0.615	0.244	0.487	0.382	0.503	0.370	0.201	0.377	0.464	0.494	0.463	0.298	0.431	0.389	0.536	0.417	0.461	0.446	0.694	0.488
SD_std		0.290	0.155	0.223	0.138	0.228	0.261	0.131	0.163	0.090	0.155	0.220	0.160	0.352	0.177	0.288	0.112	0.137	0.186	0.228	0.134	0.176	0.180	0.276	0.226	0.317	0.222	0.313	0.280	0.508	0.336
cMIEI		0.579	0.369	0.618	0.444	0.514	0.500	0.365	0.414	0.243	0.403	0.626	0.294	0.536	0.420	0.541	0.389	0.235	0.427	0.504	0.514	0.457	0.350	0.525	0.457	0.590	0.479	0.540	0.543	0.755	0.596
SD	evp	1.353	1.274	1.063	1.255	1.186	1.241	1.252	1.170	1.227	1.353	1.273	0.714	0.607	0.879	0.795	0.835	0.804	0.925	0.748	0.726	0.818	0.886	0.538	0.673	0.549	0.544	0.542	0.413	0.507	0.103
	gst	1.076	1.011	0.898	1.090	1.037	1.072	0.984	1.020	1.122	1.173	1.059	0.929	1.038	1.029	0.971	0.974	1.047	0.975	0.922	0.990	1.156	1.104	0.820	0.967	0.970	0.975	1.084	0.786	0.933	1.051
	pre	0.392	1.234	1.506	0.839	1.588	0.659	0.980	1.452	1.084	0.978	1.347	1.093	1.851	1.264	1.756	1.041	1.265	0.719	1.523	1.018	1.316	0.569	1.548	0.803	1.706	1.084	1.312	1.392	2.267	1.149
	prs	1.186	1.200	1.383	1.324	1.021	0.752	1.228	0.948	0.978	1.034	0.821	0.987	1.047	1.184	1.373	0.832	1.192	1.110	1.001	1.129	1.331	1.019	0.930	1.011	1.095	0.977	0.901	1.006	0.984	1.218
	rhu	1.274	1.339	1.005	1.051	1.507	1.016	0.864	0.994	0.995	1.244	1.528	0.740	0.781	0.962	0.988	1.055	1.155	1.393	1.239	1.203	1.143	1.103	0.800	1.477	1.052	1.037	1.015	0.862	0.932	1.119
	ssd	1.336	1.387	1.383	1.129	0.897	1.563	1.051	1.332	1.177	1.383	1.444	1.210	0.846	1.462	1.014	1.080	0.972	0.994	0.984	1.105	1.211	1.169	0.869	1.123	1.008	1.416	1.701	1.157	0.545	1.109
	tem	1.094	1.033	0.889	1.083	1.065	1.114	0.943	1.078	1.177	1.169	1.023	0.890	1.062	1.009	0.969	0.985	1.092	0.913	0.904	1.086	1.273	1.097	0.726	0.975	0.962	0.976	1.136	0.698	0.937	1.057
	win	1.226	0.930	1.108	1.202	1.250	1.049	1.152	1.135	0.997	0.940	1.235	1.054	1.254	1.035	0.988	1.181	0.981	0.865	0.894	1.065	0.905	0.959	1.008	1.145	0.705	0.932	0.954	1.029	1.001	0.913
cRMSL		1.049	1.121	1.089	1.074	1.220	1.049	1.023	1.168	1.141	1.162	1.173	0.929	1.211	1.059	1.156	0.983	1.075	0.911	1.055	0.999	1.174	0.976	0.968	0.923	1.109	0.952	1.090	0.898	1.286	0.988
CORR	evp	0.985	0.993	0.979	0.992	0.999	0.975	0.996	0.974	0.993	0.996	0.979	0.956	0.975	0.959	0.978	0.998	0.997	0.950	0.964	0.990	0.960	0.973	0.941	0.988	0.585	0.864	0.972	0.868	0.719	0.903
	gst	0.997	0.991	0.993	0.998	0.997	0.991	0.993	0.990	0.992	0.994	0.991	0.992	0.988	0.993	0.996	0.989	0.996	0.980	0.996	0.985	0.985	0.998	0.999	0.998	0.989	0.979	0.999	0.980	0.985	0.986
	pre	0.226	0.909	0.595	0.599	0.754	0.565	0.813	0.851	0.945	0.791	0.502	0.984	0.974	0.811	0.849	0.739	0.992	0.762	0.811	0.527	0.780	0.891	0.931	0.678	0.928	0.842	0.777	0.948	0.973	0.887
	prs	0.994	0.964	0.898	0.930	0.963	0.939	0.910	0.944	0.829	0.990	0.938	0.829	0.990	0.968	0.962	0.918	0.930	0.997	0.952	0.848	0.741	0.990	0.990	0.956	0.959	0.987	0.951	0.805	0.934	0.980
	rhu	0.873	0.896	0.801	0.906	0.934	0.912	0.744	0.898	0.956	0.912	0.867	0.978	0.836	0.896	0.930	0.957	0.995	0.980	0.904	0.993	0.953	0.929	0.943	0.977	0.863	0.982	0.721	0.977	0.840	0.950
	ssd	0.967	0.912	0.830	0.693	0.909	0.978	0.767	0.724	0.953	0.704	0.607	0.745	0.663	0.961	0.844	0.993	0.956	0.889	0.845	0.933	0.965	0.977	0.983	0.838	0.898	0.859	0.941	0.966	0.642	0.594
	tem	0.996	0.985	0.989	0.995	0.995	0.988	0.993	0.989	0.990	0.986	0.986	0.988	0.980	0.990	0.994	0.984	0.992	0.968	0.993	0.978	0.978	0.996	0.998	0.998	0.984	0.958	0.999	0.962	0.975	0.977
	win	0.984	0.930	0.991	0.989	0.976	0.979	0.967	0.998	0.968	0.928	0.904	0.960	0.973	0.985	0.986	0.995	0.957	0.971	0.985	0.937	0.999	0.995	0.996	0.972	0.966	0.961	0.944	0.993	0.926	0.803
cVSC		0.882	0.959	0.845	0.918	0.912	0.911	0.944	0.937	0.979	0.943	0.852	0.971	0.920	0.933	0.901	0.931	0.984	0.926	0.899	0.878	0.922	0.955	0.905	0.921	0.876	0.910	0.906	0.895	0.844	0.879

Figure S1. Multivariable assessment of each candidate year from 1991 to 2020 against the 30-year climatological mean in the arid region of Northwest China using centered MVIE statistics. Lower cMIEI indicates closer agreement with the 30-year climatological reference. The year 2007 had the lowest cMIEI and did not show strong anomalous deviations in the variable-level metrics; it was therefore selected as the representative screening year for this region. This climatological comparison was used for representative-year selection and was not the temporal aggregation used for WRF scheme-evaluation metrics.

Figure S2 Multivariable assessment used to identify the representative year in the coastal region of Southeast China

METRICS		1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
cRMSD	gst	0.096	0.185	0.097	0.191	0.103	0.190	0.179	0.166	0.175	0.140	0.123	0.217	0.158	0.089	0.165	0.119	0.192	0.204	0.260	0.195	0.233	0.145	0.181	0.170	0.135	0.143	0.151	0.184	0.150	0.206
	pre	0.467	0.800	0.489	0.688	0.631	0.501	0.562	0.681	0.605	0.725	0.529	0.657	0.448	0.605	0.641	0.535	0.590	0.779	0.370	0.778	0.532	0.540	0.621	0.534	0.924	0.715	0.496	0.586	0.586	0.546
	prs	0.139	0.222	0.120	0.243	0.142	0.197	0.198	0.185	0.263	0.129	0.186	0.145	0.138	0.168	0.215	0.212	0.236	0.195	0.263	0.318	0.269	0.186	0.097	0.149	0.110	0.287	0.128	0.194	0.138	0.218
	rhu	1.103	1.500	0.705	1.064	1.114	0.798	0.960	0.985	1.530	0.996	0.965	1.052	0.931	0.755	1.062	0.362	1.069	0.968	1.098	1.051	1.221	1.082	1.000	1.255	1.284	1.240	1.024	1.497	1.478	0.953
	ssd	0.543	0.716	0.503	0.697	0.533	0.427	0.860	0.746	0.742	0.677	0.500	0.739	0.680	0.548	0.518	0.374	0.749	0.542	0.530	0.856	0.590	0.680	0.561	0.809	0.884	0.776	0.710	0.858	0.988	0.663
	tem	0.085	0.181	0.106	0.188	0.087	0.176	0.144	0.140	0.143	0.132	0.114	0.175	0.123	0.098	0.174	0.121	0.186	0.219	0.261	0.169	0.244	0.140	0.162	0.143	0.107	0.139	0.139	0.146	0.088	0.201
	win	2.237	1.740	1.612	2.353	1.194	2.601	1.735	1.425	1.801	2.080	1.397	2.353	1.550	0.898	1.057	2.009	1.567	1.651	1.515	2.048	2.089	1.134	1.249	1.441	1.428	1.231	1.893	1.804	1.043	2.323
cRMSVD		0.420	0.653	0.414	0.587	0.504	0.433	0.542	0.579	0.542	0.596	0.438	0.578	0.435	0.486	0.513	0.426	0.533	0.612	0.382	0.665	0.482	0.481	0.509	0.514	0.751	0.604	0.472	0.559	0.582	0.500
SD_std		0.562	0.412	0.340	0.611	0.233	0.689	0.353	0.387	0.491	0.455	0.314	0.457	0.355	0.187	0.186	0.429	0.279	0.258	0.248	0.531	0.418	0.282	0.243	0.352	0.262	0.131	0.353	0.350	0.394	0.503
cMIEI		0.769	0.799	0.561	0.856	0.549	0.894	0.647	0.705	0.773	0.758	0.531	0.742	0.619	0.535	0.499	0.614	0.615	0.600	0.485	0.838	0.696	0.572	0.566	0.659	0.775	0.615	0.607	0.682	0.692	0.750
SD	gst	1.013	1.051	1.016	0.951	1.063	1.041	0.878	1.045	0.922	1.023	0.970	0.901	1.061	1.001	1.112	0.980	0.999	1.087	1.042	1.002	1.135	1.099	1.009	1.082	0.937	1.047	0.978	0.994	0.948	0.943
	pre	0.743	1.247	1.315	1.401	1.212	1.149	1.163	1.257	1.208	1.033	1.364	1.112	1.018	0.935	1.423	1.294	1.158	1.503	0.918	1.403	0.921	0.939	1.102	1.299	1.175	1.010	1.245	0.962	1.323	0.991
	prs	1.025	1.056	1.052	1.049	1.049	0.963	0.989	0.890	1.077	0.973	1.021	1.030	1.022	0.999	1.076	1.009	1.023	1.083	1.008	0.801	1.102	1.032	0.993	1.041	1.024	1.067	0.960	1.074	1.057	0.987
	rhu	1.410	2.180	1.563	1.152	1.767	1.551	0.996	1.626	2.035	0.842	1.374	0.719	1.630	1.216	1.612	1.111	1.702	1.425	1.411	1.508	1.328	1.050	1.733	1.929	1.084	1.137	1.536	1.081	2.153	1.346
	ssd	1.377	1.537	1.085	1.185	1.211	1.079	0.778	1.484	0.826	1.311	1.060	0.749	1.389	1.075	1.326	1.076	1.264	1.024	1.063	1.489	1.205	1.477	1.243	1.401	1.061	1.189	1.217	1.015	1.560	0.998
	tem	0.998	1.027	1.028	0.964	1.059	1.058	0.914	1.014	0.947	1.012	0.978	0.901	1.036	0.982	1.122	0.975	0.972	1.113	1.039	0.972	1.146	1.099	1.004	1.064	0.941	1.040	0.974	1.014	0.960	0.966
	win	2.579	1.798	1.992	2.814	1.246	3.043	1.913	2.079	2.073	2.279	1.898	2.156	1.995	1.511	1.405	2.266	1.625	1.754	1.657	2.519	2.290	1.785	1.212	1.886	1.752	1.418	1.999	2.018	1.290	2.425
cRMSL		0.970	1.239	1.191	1.239	1.165	1.117	1.027	1.229	1.075	1.081	1.200	0.997	1.100	0.980	1.312	1.165	1.125	1.310	0.990	1.297	1.055	1.097	1.097	1.249	1.084	1.053	1.160	0.990	1.257	0.985
CORR	gst	0.996	0.985	0.996	0.982	0.997	0.983	0.990	0.988	0.987	0.991	0.993	0.979	0.990	0.996	0.993	0.993	0.982	0.984	0.968	0.981	0.984	0.995	0.984	0.990	0.992	0.991	0.989	0.983	0.990	0.975
	pre	0.898	0.768	0.947	0.889	0.855	0.900	0.876	0.842	0.867	0.746	0.946	0.811	0.902	0.807	0.918	0.923	0.861	0.882	0.929	0.842	0.850	0.847	0.830	0.925	0.650	0.747	0.925	0.822	0.910	0.850
	prs	0.991	0.978	0.994	0.973	0.992	0.981	0.980	0.988	0.971	0.992	0.983	0.990	0.991	0.986	0.981	0.978	0.973	0.986	0.966	0.961	0.972	0.984	0.995	0.990	0.994	0.964	0.992	0.985	0.993	0.976
	rhu	0.628	0.803	0.943	0.519	0.815	0.893	0.538	0.822	0.688	0.426	0.712	0.285	0.856	0.784	0.767	0.946	0.809	0.734	0.633	0.719	0.480	0.444	0.867	0.816	0.243	0.331	0.752	0.034	0.802	0.707
	ssd	0.944	0.927	0.887	0.809	0.901	0.918	0.556	0.891	0.685	0.862	0.884	0.677	0.888	0.863	0.939	0.938	0.806	0.857	0.870	0.834	0.873	0.921	0.897	0.824	0.633	0.762	0.812	0.638	0.788	0.780
	tem	0.996	0.984	0.995	0.982	0.998	0.987	0.993	0.990	0.991	0.992	0.994	0.988	0.993	0.995	0.993	0.993	0.983	0.984	0.968	0.986	0.983	0.995	0.987	0.992	0.996	0.992	0.990	0.990	0.997	0.980
	win	0.513	0.335	0.595	0.601	0.452	0.574	0.431	0.792	0.496	0.410	0.699	0.026	0.646	0.820	0.661	0.463	0.365	0.385	0.438	0.625	0.410	0.812	0.375	0.658	0.579	0.528	0.353	0.450	0.611	0.305
cVSC		0.910	0.851	0.943	0.884	0.903	0.922	0.857	0.885	0.866	0.839	0.937	0.833	0.919	0.880	0.937	0.934	0.881	0.894	0.926	0.864	0.891	0.899	0.886	0.919	0.743	0.828	0.915	0.842	0.892	0.874

Figure S2. Multivariable assessment of each candidate year from 1991 to 2020 against the 30-year climatological mean in the coastal region of Southeast China using centered MVIE statistics. Lower cMIEI indicates closer agreement with the 30-year climatological reference. The year 2009 had the lowest cMIEI and did not show strong anomalous deviations in the variable-level metrics; it was therefore selected as the representative screening year for this region. This climatological comparison was used for representative-year selection and was not the temporal aggregation used for WRF scheme-evaluation metrics.

Table S4 Summary of simulation experiment on the proposed $MRE \times CV$ weighted combination of parameterization schemes in the arid region of Northwest China

	mp_physics	bl_pbl_physics	cu_physics	ra_physics	sf_surface_physics
1	8 Thompson	2 MYJ + 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
2	1 Kessler	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
3	2 Lin	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
4	3 WSM3	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
5	4 WSM5	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
6	5 Eta/Ferrier	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
7	6 WSM6	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
8	9 Milbrandt	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
9	10 Morrison	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
10	11 CAM	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
11	13 Lin-SBU	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
12	14 WDM5	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
13	16 WDM6	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
14	17 NSSL 2-17	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
15	18 NSSL 2-18	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
16	19 NSSL 1-19	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
17	21 NSSL 1-21	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
18	24 WSM7	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
19	26 WDM7	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
20	28 Thompson aerosol-aware	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
21	50 P3	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
22	50 P3	1 YSU + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
23	50 P3	4 QNSE +4 QNSE	6 Tiedtke	4 RRTMG	2 Noah LSM

24	50 P3	5 MYNN2.5 + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
25	50 P3	5 MYNN2.5 + 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
26	50 P3	5 MYNN2.5 + 5 MYNN	6 Tiedtke	4 RRTMG	2 Noah LSM
27	50 P3	7 ACM2 + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
28	50 P3	7 ACM2 + 7 Pleim- Xiu	6 Tiedtke	4 RRTMG	2 Noah LSM
29	50 P3	1 YSU + 1 MM5	2 BMJ	4 RRTMG	2 Noah LSM
30	50 P3	1 YSU + 1 MM5	3 GF	4 RRTMG	2 Noah LSM
31	50 P3	1 YSU + 1 MM5	5 Grell 3	4 RRTMG	2 Noah LSM
32	50 P3	1 YSU + 1 MM5	14 NSAS	4 RRTMG	2 Noah LSM
33	50 P3	1 YSU + 1 MM5	16 New Tiedtke	4 RRTMG	2 Noah LSM
34	50 P3	1 YSU + 1 MM5	93 GD	4 RRTMG	2 Noah LSM
35	50 P3	1 YSU + 1 MM5	99 Old KF	4 RRTMG	2 Noah LSM
36	50 P3	1 YSU + 1 MM5	6 Tiedtke	1 RRTM	2 Noah LSM
37	50 P3	1 YSU + 1 MM5	6 Tiedtke	3 CAM	2 Noah LSM
38	50 P3	1 YSU + 1 MM5	6 Tiedtke	5 New Goddard	2 Noah LSM
39	50 P3	1 YSU + 1 MM5	6 Tiedtke	99 GFDL	2 Noah LSM
40	50 P3	1 YSU + 1 MM5	6 Tiedtke	99 GFDL	1 SLAB
41	50 P3	1 YSU + 1 MM5	6 Tiedtke	99 GFDL	4 NoahMP
42	50 P3	1 YSU + 1 MM5	6 Tiedtke	99 GFDL	5 CLM4

Table S5 Summary of simulation experiment on equally weighted combination of parameterization schemes in the arid region of Northwest

	mp_physics	bl_pbl_physics	cu_physics	ra_physics	sf_surface_physics
1	8 Thompson	2 MYJ + 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
2	1 Kessler	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
3	2 Lin	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
4	3 WSM3	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
5	4 WSM5	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
6	5 Eta/Ferrier	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
7	6 WSM6	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
8	9 Milbrandt	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
9	10 Morrison	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
10	11 CAM	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
11	13 Lin-SBU	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
12	14 WDM5	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
13	16 WDM6	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
14	17 NSSL 2-17	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
15	18 NSSL 2-18	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
16	19 NSSL 1-19	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
17	21 NSSL 1-21	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
18	24 WSM7	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
19	26 WDM7	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
20	28 Thompson aerosol-aware	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
21	50 P3	2 MYJ+ 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
22	50 P3	1 YSU + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
23	50 P3	4 QNSE +4 QNSE	6 Tiedtke	4 RRTMG	2 Noah LSM

24	50 P3	5 MYNN2.5 + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
25	50 P3	5 MYNN2.5 + 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
26	50 P3	5 MYNN2.5 + 5 MYNN	6 Tiedtke	4 RRTMG	2 Noah LSM
27	50 P3	7 ACM2 + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
28	50 P3	7 ACM2 + 7 Pleim- Xiu	6 Tiedtke	4 RRTMG	2 Noah LSM
29	50 P3	2 MYJ+ 2 MYJ	2 BMJ	4 RRTMG	2 Noah LSM
30	50 P3	2 MYJ+ 2 MYJ	3 GF	4 RRTMG	2 Noah LSM
31	50 P3	2 MYJ+ 2 MYJ	5 Grell 3	4 RRTMG	2 Noah LSM
32	50 P3	2 MYJ+ 2 MYJ	7 ZM	4 RRTMG	2 Noah LSM
33	50 P3	2 MYJ+ 2 MYJ	14 NSAS	4 RRTMG	2 Noah LSM
34	50 P3	2 MYJ+ 2 MYJ	16 New Tiedtke	4 RRTMG	2 Noah LSM
35	50 P3	2 MYJ+ 2 MYJ	93 GD	4 RRTMG	2 Noah LSM
36	50 P3	2 MYJ+ 2 MYJ	99 Old KF	4 RRTMG	2 Noah LSM
37	50 P3	2 MYJ+ 2 MYJ	6 Tiedtke	1 RRTM	2 Noah LSM
38	50 P3	2 MYJ+ 2 MYJ	6 Tiedtke	3 CAM	2 Noah LSM
39	50 P3	2 MYJ+ 2 MYJ	6 Tiedtke	5 New Goddard	2 Noah LSM
40	50 P3	2 MYJ+ 2 MYJ	6 Tiedtke	99 GFDL	2 Noah LSM
41	50 P3	2 MYJ+ 2 MYJ	6 Tiedtke	99 GFDL	1 SLAB
42	50 P3	2 MYJ+ 2 MYJ	6 Tiedtke	99 GFDL	4 NoahMP
43	50 P3	2 MYJ+ 2 MYJ	6 Tiedtke	99 GFDL	5 CLM4

Table S6 Summary of simulation experiment on the proposed $MRE \times CV$ weighted combination of parameterization schemes in the coastal region of Southeast China

	mp_physics	bl_pbl_physics	cu_physics	ra_physics	sf_surface_physics
1	8 Thompson	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
2	1 Kessler	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
3	2 Lin	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
4	3 WSM3	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
5	4 WSM5	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
6	5 Eta/Ferrier	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
7	6 WSM6	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
8	9 Milbrandt	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
9	10 Morrison	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
10	11 CAM	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
11	13 Lin-SBU	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
12	14 WDM5	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
13	16 WDM6	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
14	17 NSSL 2-17	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
15	18 NSSL 2-18	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
16	19 NSSL 1-19	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
17	21 NSSL 1-21	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
18	24 WSM7	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
19	26 WDM7	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
20	28 Thompson aerosol-aware	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
21	50 P3	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
22	16 WDM6	1 YSU + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
23	16 WDM6	3 GFS + 3 GFS	6 Tiedtke	4 RRTMG	2 Noah LSM
24	16 WDM6	4 QNSE + 4 QNSE	6 Tiedtke	4 RRTMG	2 Noah LSM
25	16 WDM6	5 MYNN2.5 + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
26	16 WDM6	5 MYNN2.5 + 2	6 Tiedtke	4 RRTMG	2 Noah LSM

		MYJ			
27	16 WDM6	5 MYNN2.5 + 5 MYNN	6 Tiedtke	4 RRTMG	2 Noah LSM
28	16 WDM6	6 MYNN3+ 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
29	16 WDM6	6 MYNN3 + 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
30	16 WDM6	6 MYNN3 + 5 MYNN	6 Tiedtke	4 RRTMG	2 Noah LSM
31	16 WDM6	7 ACM2 + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
32	16 WDM6	7 ACM2 + 7 Pleim-Xiu	6 Tiedtke	4 RRTMG	2 Noah LSM
33	16 WDM6	8 BouLac + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
34	16 WDM6	8 BouLac + 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
35	16 WDM6	9 UW + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
36	16 WDM6	9 UW + 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
37	16 WDM6	11 Shin-Hong + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
38	16 WDM6	12 GBM + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
39	16 WDM6	99 MRF + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
40	16 WDM6	11 Shin-Hong + 1 MM5	1 KF	4 RRTMG	2 Noah LSM
41	16 WDM6	11 Shin-Hong + 1 MM5	2 BMJ	4 RRTMG	2 Noah LSM
42	16 WDM6	11 Shin-Hong + 1 MM5	5 Grell 3	4 RRTMG	2 Noah LSM
43	16 WDM6	11 Shin-Hong + 1 MM5	11 MsKF	4 RRTMG	2 Noah LSM
44	16 WDM6	11 Shin-Hong + 1 MM5	14 NSAS	4 RRTMG	2 Noah LSM
45	16 WDM6	11 Shin-Hong +	16 New	4 RRTMG	2 Noah LSM

		1 MM5	Tiedtke		
46	16 WDM6	11 Shin-Hong + 1 MM5	93 GD	4 RRTMG	2 Noah LSM
47	16 WDM6	11 Shin-Hong + 1 MM5	99 Old KF	4 RRTMG	2 Noah LSM
48	16 WDM6	11 Shin-Hong + 1 MM5	5 Grell 3	1 RRTM	2 Noah LSM
49	16 WDM6	11 Shin-Hong + 1 MM5	5 Grell 3	3 CAM	2 Noah LSM
50	16 WDM6	11 Shin-Hong + 1 MM5	5 Grell 3	5 New Goddard	2 Noah LSM
51	16 WDM6	11 Shin-Hong + 1 MM5	5 Grell 3	99 GFDL	2 Noah LSM
52	16 WDM6	11 Shin-Hong + 1 MM5	5 Grell 3	99 GFDL	1 SLAB
53	16 WDM6	11 Shin-Hong + 1 MM5	5 Grell 3	99 GFDL	4 NoahMP
54	16 WDM6	11 Shin-Hong + 1 MM5	5 Grell 3	99 GFDL	5 CLM4

Table S7 Summary of simulation experiment on equally weighted combination of parameterization schemes in the coastal region of Southeast

	mp_physics	bl_pbl_physics	cu_physics	ra_physics	sf_surface_physics
1	8 Thompson	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
2	1 Kessler	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
3	2 Lin	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
4	3 WSM3	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
5	4 WSM5	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
6	5 Eta/Ferrier	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
7	6 WSM6	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
8	9 Milbrandt	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
9	10 Morrison	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
10	11 CAM	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
11	13 Lin-SBU	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
12	14 WDM5	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
13	16 WDM6	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
14	17 NSSL 2-17	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
15	18 NSSL 2-18	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
16	19 NSSL 1-19	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
17	21 NSSL 1-21	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
18	24 WSM7	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
19	26 WDM7	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
20	28 Thompson aerosol-aware	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
21	50 P3	2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
22	16 WDM6	1 YSU + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
23	16 WDM6	3 GFS + 3 GFS	6 Tiedtke	4 RRTMG	2 Noah LSM
24	16 WDM6	4 QNSE + 4 QNSE	6 Tiedtke	4 RRTMG	2 Noah LSM
25	16 WDM6	5 MYNN2.5 + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
26	16 WDM6	5 MYNN2.5 + 2	6 Tiedtke	4 RRTMG	2 Noah LSM

		MYJ			
27	16 WDM6	5 MYNN2.5 + 5 MYNN	6 Tiedtke	4 RRTMG	2 Noah LSM
28	16 WDM6	6 MYNN3+ 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
29	16 WDM6	6 MYNN3 + 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
30	16 WDM6	6 MYNN3 + 5 MYNN	6 Tiedtke	4 RRTMG	2 Noah LSM
31	16 WDM6	7 ACM2 + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
32	16 WDM6	7 ACM2 + 7 Pleim-Xiu	6 Tiedtke	4 RRTMG	2 Noah LSM
33	16 WDM6	8 BouLac + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
34	16 WDM6	8 BouLac + 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
35	16 WDM6	9 UW + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
36	16 WDM6	9 UW + 2 MYJ	6 Tiedtke	4 RRTMG	2 Noah LSM
37	16 WDM6	11 Shin-Hong + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
38	16 WDM6	12 GBM + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
39	16 WDM6	99 MRF + 1 MM5	6 Tiedtke	4 RRTMG	2 Noah LSM
40	16 WDM6	11 Shin-Hong + 1 MM5	1 KF	4 RRTMG	2 Noah LSM
41	16 WDM6	11 Shin-Hong + 1 MM5	2 BMJ	4 RRTMG	2 Noah LSM
42	16 WDM6	11 Shin-Hong + 1 MM5	5 Grell 3	4 RRTMG	2 Noah LSM
43	16 WDM6	11 Shin-Hong + 1 MM5	11 MsKF	4 RRTMG	2 Noah LSM
44	16 WDM6	11 Shin-Hong + 1 MM5	14 NSAS	4 RRTMG	2 Noah LSM
45	16 WDM6	11 Shin-Hong +	16 New	4 RRTMG	2 Noah LSM

		1 MM5	Tiedtke		
46	16 WDM6	11 Shin-Hong + 1 MM5	93 GD	4 RRTMG	2 Noah LSM
47	16 WDM6	11 Shin-Hong + 1 MM5	99 Old KF	4 RRTMG	2 Noah LSM
48	16 WDM6	11 Shin-Hong + 1 MM5	16 New Tiedtke	1 RRTM	2 Noah LSM
49	16 WDM6	11 Shin-Hong + 1 MM5	16 New Tiedtke	3 CAM	2 Noah LSM
50	16 WDM6	11 Shin-Hong + 1 MM5	16 New Tiedtke	5 New Goddard	2 Noah LSM
51	16 WDM6	11 Shin-Hong + 1 MM5	16 New Tiedtke	99 GFDL	2 Noah LSM
52	16 WDM6	11 Shin-Hong + 1 MM5	16 New Tiedtke	99 GFDL	1 SLAB
53	16 WDM6	11 Shin-Hong + 1 MM5	16 New Tiedtke	99 GFDL	5 CLM4

Figure S3 Complete process-level variable weights derived from the five weighting methods in the arid region of Northwest China

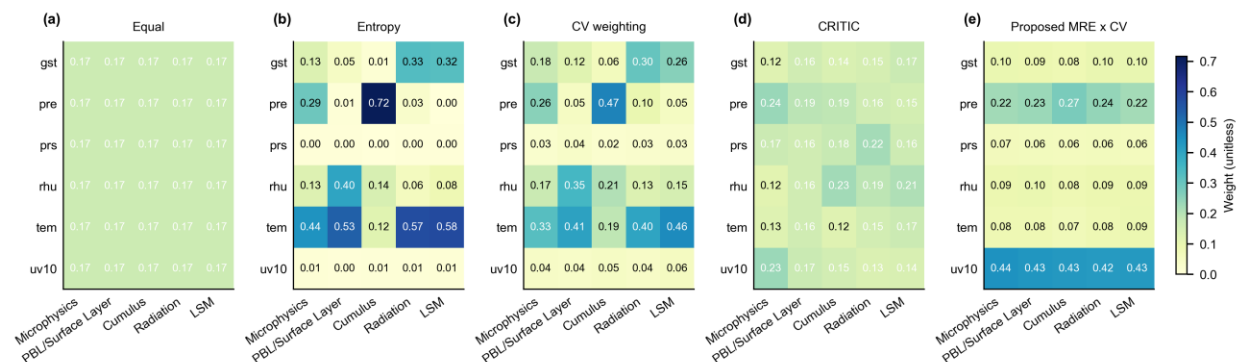


Figure S3. Complete process-level variable weights derived from equal weighting, entropy weighting, coefficient-of-variation weighting, CRITIC weighting, and the proposed $MRE \times CV$ weighting in the arid region of Northwest China. Weights are unitless and were calculated for each physical-process evaluation stage.

Figure S4 Complete process-level variable weights derived from the five weighting methods in the coastal region of Southeast China

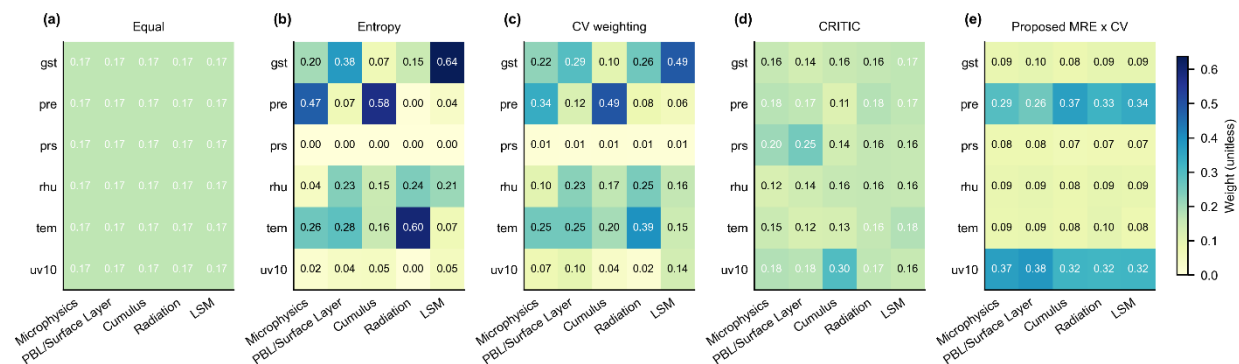


Figure S4. Complete process-level variable weights derived from equal weighting, entropy weighting, coefficient-of-variation weighting, CRITIC weighting, and the proposed $MRE \times CV$ weighting in the coastal region of Southeast China. Weights are unitless and were calculated for each physical-process evaluation stage.

Figure S5 Sensitivity of the proposed variable weights to the normalization function

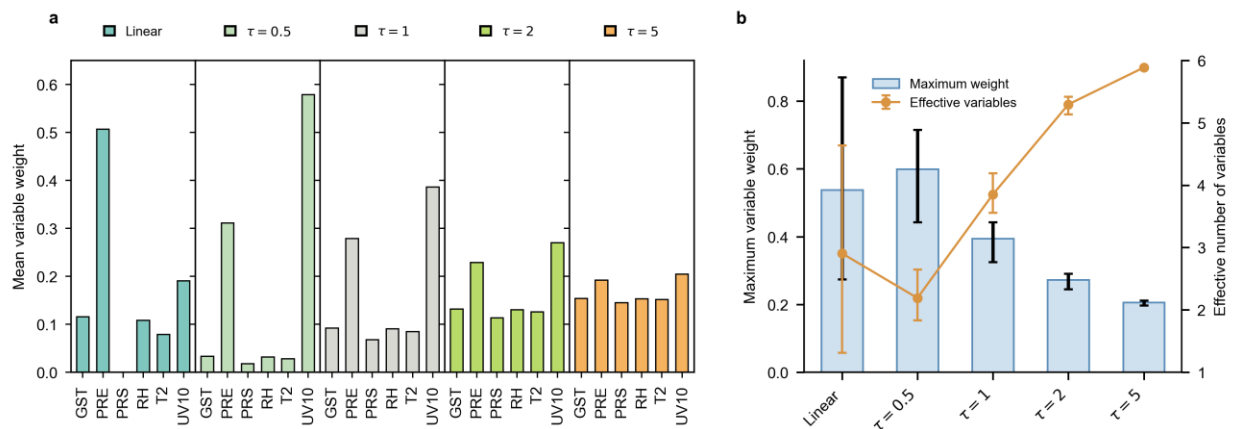


Figure S5. Sensitivity of the proposed variable weights to the normalization function. (a) Mean variable weights under linear normalization and temperature-scaled Softmax transformations. The original Softmax setting corresponds to $\tau = 1$. (b) Weight-concentration diagnostics, including the maximum variable weight and the effective number of variables. Error bars indicate the range across the two study regions and five physical processes.

Figure S6 Sampling stability of the proposed $\text{MRE} \times \text{CV}$ variable weights

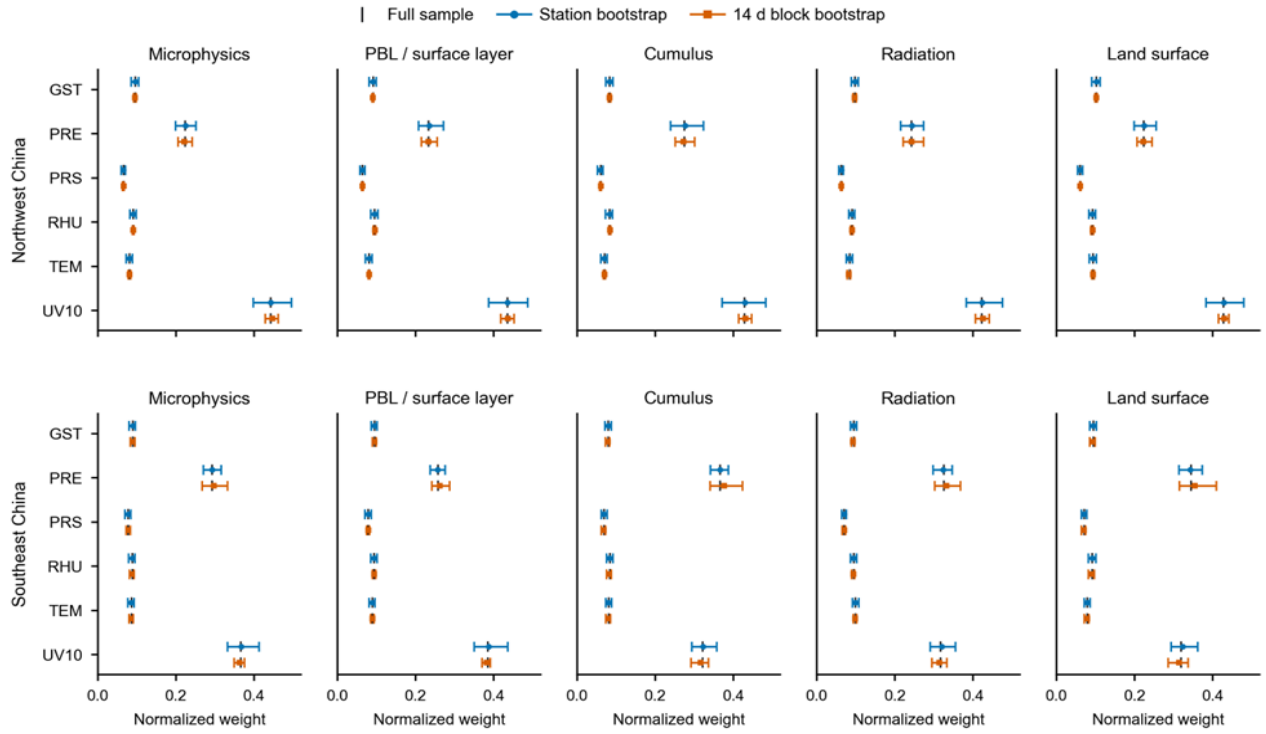


Figure S6. Sampling stability of the normalized variable weights derived using the proposed $\text{MRE} \times \text{CV}$ method. Rows represent the arid region of Northwest China and the coastal region of Southeast China, and columns represent the five physical-process evaluation stages. Blue circles and orange squares show the mean weights from 500 station-bootstrap and 500 14 d moving-block-bootstrap samples, respectively; horizontal error bars indicate the 2.5th–97.5th percentile intervals. Black vertical markers, repeated on the corresponding station- and time-bootstrap rows, show the full-sample weights. All weights are dimensionless.

Weight-stability analysis of the proposed $\text{MRE} \times \text{CV}$ weights

The stability of the derived variable weights was evaluated separately for station sampling and intra-seasonal temporal sampling. For each study region and each of the five physical-process evaluation stages, a station bootstrap sample was formed by drawing the original number of stations with replacement while retaining all 92 summer days. This procedure was repeated 500 times. Temporal dependence was retained through a moving-block bootstrap: starting days of contiguous 14 d blocks were sampled with replacement, the blocks were concatenated, and the

resulting sequence was truncated to the original 92 d summer length. This procedure was also repeated 500 times. In addition, the weights were recalculated separately for June, July, and August to test fixed within-summer time windows. The MRE component, absolute-error CV component, and final normalized weights were recalculated for every resample or monthly subset.

For resample b , the rank similarity between the resampled and full-sample weight vectors was quantified using the Spearman correlation ρ_b . The largest change in weight magnitude was calculated as

$$\Delta_{max,b} = \max_m \left| \omega_m^{(b)} - \omega_m^{(full)} \right|.$$

We also calculated the retention rate of the full-sample highest-weight variable and the retention rate of the unordered set containing the two highest-weight variables. The point-interval estimates in Fig. S6 show the bootstrap mean and the 2.5th–97.5th percentile interval for each normalized weight. Table S8 reports the complete region- and process-level summaries.

Table S8 Exact summary of variable-weight stability under station and temporal sampling

Perturbation	Region	Evaluation stage	n	Mean Spearman ρ	min ρ	Mean Δ_{max}	max Δ_{max}	Top-1 retention	Top-2 retention
Station bootstrap	Northwest China	Microphysics	500	1.000	1.000	0.021	0.056	1.000	1.000
		PBL / surface layer	500	0.999	1.000	0.023	0.057	1.000	1.000
		Cumulus	500	0.975	0.943	0.026	0.066	1.000	1.000
		Radiation	500	1.000	1.000	0.021	0.054	1.000	1.000
		Land surface	500	0.984	0.943	0.022	0.056	1.000	1.000
	Southeast China	Microphysics	500	0.996	0.943	0.018	0.048	0.998	1.000
		PBL / surface layer	500	0.986	0.943	0.019	0.052	1.000	1.000
		Cumulus	500	0.986	0.943	0.016	0.037	0.942	1.000
		Radiation	500	0.947	0.886	0.017	0.039	0.542	1.000
		Land surface	500	0.979	0.943	0.018	0.043	0.754	1.000
14 d block bootstrap	Northwest China	Microphysics	500	1.000	1.000	0.010	0.021	1.000	1.000
		PBL / surface layer	500	1.000	1.000	0.010	0.022	1.000	1.000
		Cumulus	500	0.957	0.943	0.011	0.029	1.000	1.000
		Radiation	500	1.000	1.000	0.012	0.030	1.000	1.000
		Land surface	500	0.992	0.943	0.009	0.022	1.000	1.000
	Southeast China	Microphysics	500	0.999	1.000	0.015	0.040	0.994	1.000
		PBL / surface layer	500	0.992	0.943	0.010	0.030	1.000	1.000
		Cumulus	500	0.997	0.943	0.018	0.057	0.988	1.000
		Radiation	500	0.944	0.886	0.014	0.043	0.760	1.000
		Land surface	500	0.987	0.943	0.019	0.065	0.902	1.000
Monthly subsets	Northwest China	Microphysics	3	1.000	1.000	0.019	0.033	1.000	1.000
		PBL / surface layer	3	1.000	1.000	0.024	0.039	1.000	1.000
		Cumulus	3	0.981	0.943	0.024	0.039	1.000	1.000
		Radiation	3	1.000	1.000	0.023	0.041	1.000	1.000
		Land surface	3	0.981	0.943	0.018	0.037	1.000	1.000

Perturbation	Region	Evaluation stage	n	Mean Spearman ρ	min ρ	Mean Δ_{max}	max Δ_{max}	Top-1 retention	Top-2 retention
		Microphysics	3	1.000	1.000	0.017	0.023	1.000	1.000
		PBL / surface layer	3	0.981	0.943	0.006	0.009	1.000	1.000
	Southeast China	Cumulus	3	0.962	0.943	0.019	0.028	1.000	1.000
		Radiation	3	0.943	0.886	0.013	0.018	0.667	1.000
		Land surface	3	0.962	0.886	0.018	0.031	0.667	1.000

Table S9 Numerical verification of variable-set subcomposition stability

Omitted variable	Region-stage cases	Maximum absolute residual	Minimum rho	Ordering preserved
GST	10	1.110e-16	1.000	10/10
PRE	10	2.220e-16	1.000	10/10
PRS	10	1.665e-16	1.000	10/10
RHU	10	1.665e-16	1.000	10/10
TEM	10	1.110e-16	1.000	10/10
UV10	10	2.220e-16	1.000	10/10

The maximum absolute residual is $\max_m \left| \omega_m^{(-k)} - \omega_m / (1 - \omega_k) \right|$ across both regions, all five physical-process evaluation stages, and all retained variables. The residuals are at floating-point precision. The minimum ρ is the minimum Spearman correlation between the recomputed and theoretically renormalized retained-variable weights across the ten region-stage cases.

Variable-set subcomposition stability

The effect of deleting one variable can be derived directly from the normalization structure of the proposed method. Because the MRE and absolute-error CV scores are calculated independently for each variable from the same candidate-scheme errors, omitting another variable does not change the unnormalized final scores of the retained variables. Substituting Eqs. (13)–(15) shows that the normalization denominators in the two Softmax components cancel during the final product normalization. The unnormalized final score of variable m can therefore be denoted as a_m , and the final weight can be written as

$$\omega_m = \frac{a_m}{\sum_{j=1}^M a_j}$$

After variable k is omitted, the weight of each retained variable $m \neq k$ becomes

$$\omega_m^{(-k)} = \frac{a_m}{\sum_{j \neq k} a_j} = \frac{\omega_m}{1 - \omega_k}$$

Consequently, for any two retained variables m and l ,

$$\frac{\omega_m^{(-k)}}{\omega_l^{(-k)}} = \frac{\omega_m}{\omega_l}$$

Thus, deleting one variable necessarily changes the absolute normalized shares because the retained weights must again sum to one, but it preserves the ratios and ordering among all retained variables. This is a structural subcomposition property of the weighting formula rather than an empirical consequence of a particular sample.

Table S10 Sensitivity of selected schemes to an equally weighted additive combination rule**(a) Stage-level screening outcomes**

Region	Physical-process stage	Proposed MRE $\times$ CV scheme	Proposed stage cMIEI	Additive $\alpha=0.5$ scheme	Additive stage cMIEI	Selection outcome
Northwest China	Microphysics	P3	1.185947	P3	1.170784	Unchanged
	PBL / surface layer	YSU + MM5	1.178968	YSU + MM5	1.164481	Unchanged
	Cumulus	Tiedtke	1.180181	New Tiedtke	1.165333	Changed
	Radiation	GFDL	1.166701	GFDL	1.157822	Unchanged
	Land surface	Noah LSM	1.164356	Noah LSM	1.156549	Unchanged
Southeast China	Microphysics	WDM6	1.036659	WDM6	1.041232	Unchanged
	PBL / surface layer	Shin-Hong + MM5	1.025430	Shin-Hong + MM5	1.032803	Unchanged
	Cumulus	Grell 3	1.031720	Grell 3	1.030902	Unchanged
	Radiation	GFDL	1.011017	GFDL	1.012825	Unchanged
	Land surface	Noah LSM	1.012347	Noah LSM	1.014569	Unchanged

(b) Independent 2010 validation of the additive-rule final configuration

Region	Configuration source	cMIEI	cVSC	cRMSL
Northwest China	Proposed MRE $\times$ CV	1.308193	0.183733	1.152229
	Additive $\alpha=0.5$	1.311540	0.196013	1.249443
Southeast China	Proposed MRE $\times$ CV	1.005176	0.511203	1.074488
	Additive $\alpha=0.5$	1.005176	0.511203	1.074488

Table S11 Absolute changes in variable weights and schemes selected under MRE-only and MRE
× CV weighting

Region	Stage	Scheme selected under both rules	GST	PRE	PRS	RHU	TEM	UV10
Northwest	Microphysics	P3	0.0011	0.0073	0.0019	0.0009	0.0042	0.0116
	PBL/Surface Layer	YSU + MM5	0.0004	0.0039	0.0013	0.0066	0.0069	0.0087
	Cumulus	Tiedtke	0.0021	0.0158	0.0020	0.0004	0.0001	0.0122
	Radiation	GFDL+ GFDL	0.0081	0.0007	0.0024	0.0015	0.0099	0.0164
	LSM	Noah LSM	0.0146	0.0130	0.0041	0.0043	0.0200	0.0218
Southeast	Microphysics	WDM6	0.0007	0.0084	0.0024	0.0012	0.0012	0.0066
	PBL/Surface Layer	Shin-Hong + MM5	0.0042	0.0015	0.0032	0.0024	0.0030	0.0048
	Cumulus	Grell 3	0.0051	0.0480	0.0080	0.0024	0.0010	0.0315
	Radiation	GFDL	0.0089	0.0006	0.0066	0.0069	0.0172	0.0269
	LSM	Noah LSM	0.0098	0.0022	0.0046	0.0064	0.0004	0.0091

Figure S7 Correlation structure among the evaluated variables

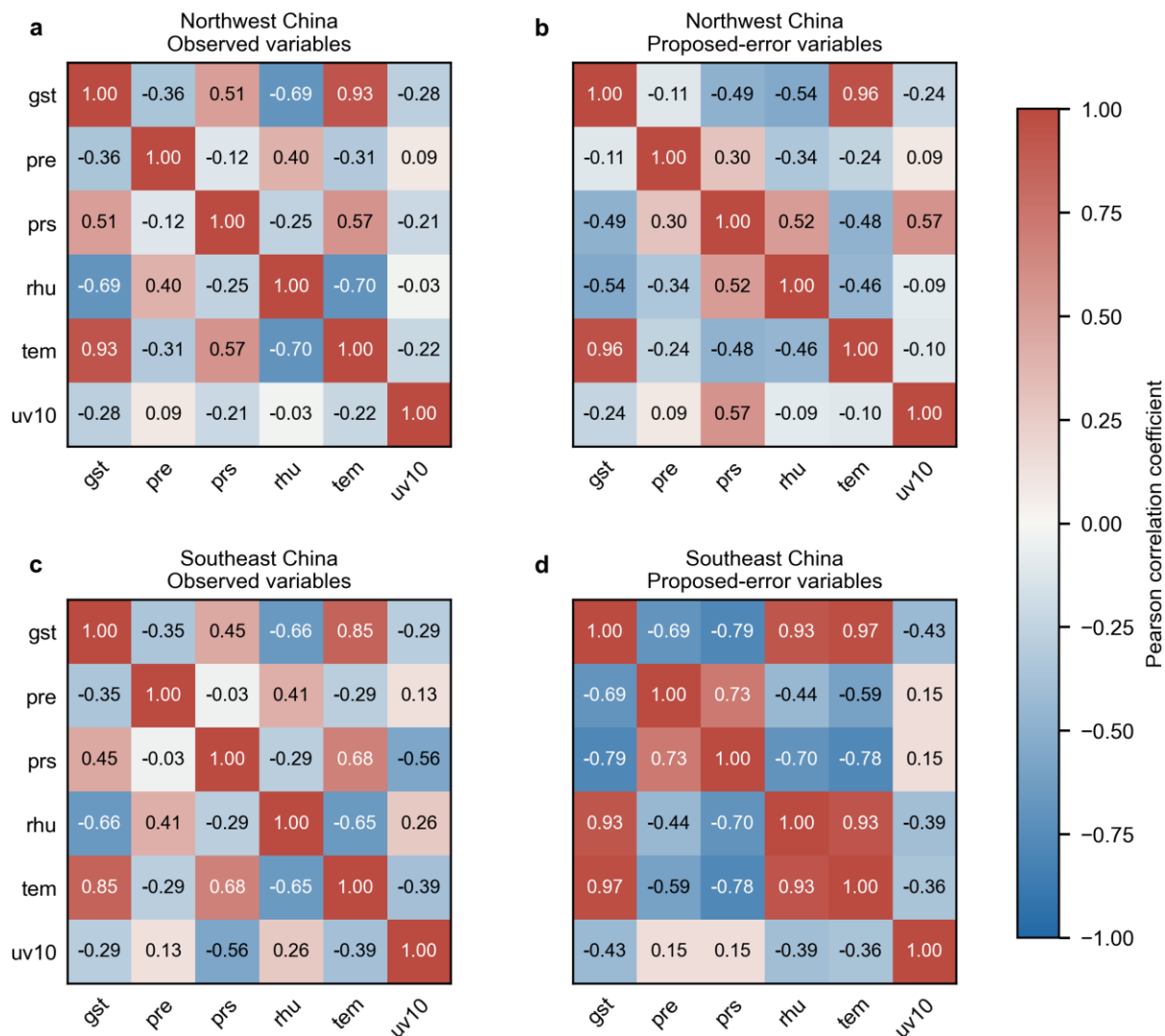


Figure S7. Correlation structure among the evaluated variables. Panels show Pearson correlation matrices calculated from observed daily station series and from the proposed $\text{MRE} \times \text{CV}$ scheme-level standardized-error matrices for Northwest China and Southeast China. Correlation coefficients are unitless. The figure documents both the physical co-variation among observed variables and the redundancy structure in the error information used for multivariable parameterization-scheme evaluation.

Table S12 Sensitivity of selected stage-level schemes to removing GST

Region and year	Physical-process stage	Original best scheme	No-GST best scheme	Stable after removing GST
Northwest China	Cumulus	Tiedtke	Tiedtke	Yes
	Microphysics	P3	P3	Yes
	PBL / surface layer	YSU + MM5	YSU + MM5	Yes
	Radiation	GFDL	GFDL	Yes
	Land surface	Noah LSM	Noah LSM	Yes
Southeast China	Cumulus	Grell 3	Grell 3	Yes
	Microphysics	WDM6	WDM6	Yes
	PBL / surface layer	Shin-Hong + MM5	9 UW + 2 MYJ	No
	Radiation	GFDL	GFDL	Yes
	Land surface	Noah LSM	NoahMP	No

Table S13. Pathway linking MRE $\times$ CV variable weights, rank reversals, and final parameterization-scheme selection**Panel A. Stage-by-stage pathway from variable weights to selected schemes**

Region	Physical-process stage	Highest-weight variables	Equal-weight Top-1 scheme	MRE $\times$ CV-weight Top-1 scheme	Top-1 changed
Northwest China	Microphysics	UV10 (0.443) PRE (0.224)	P3	P3	No
	PBL/surface layer	UV10 (0.435) PRE (0.233)	MYJ + MYJ	YSU + MM5	Yes
	Cumulus	UV10 (0.428) PRE (0.275)	Tiedtke	Tiedtke	No
	Radiation	UV10 (0.422) PRE (0.243)	RRTMG	GFDL	Yes
	Land surface	UV10 (0.428) PRE (0.224)	Noah LSM	Noah LSM	No
Southeast China	Microphysics	UV10 (0.366) PRE (0.293)	WDM6	WDM6	No
	PBL/surface layer	UV10 (0.385) PRE (0.257)	Shin-Hong + MM5	Shin-Hong + MM5	No
	Cumulus	PRE (0.366) UV10 (0.321)	New Tiedtke	Grell 3	Yes
	Radiation	PRE (0.325) UV10 (0.317)	GFDL	GFDL	No
	Land surface	PRE (0.345) UV10 (0.319)	Noah LSM	Noah LSM	No

Panel B. Pairwise score-difference decomposition for rank-reversal cases

Case ID	Region	Physical-process stage	A: equal-weight winner	B: MRE × CV-weight winner	$\Delta I_{eq} = I_{eq}(B) - I_{eq}(A)$	$D_{dyn} = MIEI_{dyn}(B) - MIEI_{dyn}(A)$	Total reweighting effect = $\Delta I_{MRE \times CV} - \Delta I_{eq}$	Main variables promoting the MRE × CV-weight winner after reweighting	Main variables opposing the MRE × CV-weight winner after reweighting
B1	Northwest China, 2007	PBL/surface layer	MYJ + MYJ	YSU + MM5	0.0047	-0.0056	-0.0103	UV10 (-0.0097) GST (-0.0015)	PRE (0.0021)
B2	Northwest China, 2007	Radiation	RRTMG	GFDL	0.0074	-0.0119	-0.0192	UV10 (-0.0188) RHU (-0.0027)	PRE (0.0047); GST (0.0008)
B3	Southeast China, 2009	Cumulus	New Tiedtke	Grell 3	0.0013	-0.0059	-0.0073	PRE (-0.0043) RHU (-0.0017)	PRS (0.0011)

Panel C. Variable-level contribution terms for rank-reversal cases

Case ID	Variable	w_m^{eq}	$w_m^{MRE \times CV}$	$z_{A,m}$	$z_{B,m}$	$\Delta z_m = z_{B,m} - z_{A,m}$	$w_m^{eq} \Delta z_m$	$w_m^{MRE \times CV} \Delta z_m$	$E_m = (w_m^{MRE \times CV} - w_m^{eq}) \Delta z_m$	Effect on MRE × CV-weight winner
B1	GST	0.1667	0.0912	0.8630	0.8825	0.0196	0.0033	0.0018	-0.0015	promotes
	PRE	0.1667	0.2335	1.0900	1.1220	0.0320	0.0053	0.0075	0.0021	opposes
	PRS	0.1667	0.0643	0.1982	0.2074	0.0092	0.0015	0.0006	-0.0009	promotes
	RHU	0.1667	0.0951	0.7529	0.7546	0.0017	0.0003	0.0002	-0.0001	promotes
	TEM	0.1667	0.0814	0.5332	0.5350	0.0019	0.0003	0.0002	-0.0002	promotes
	UV10	0.1667	0.4347	1.2065	1.1703	-0.0362	-0.0060	-0.0157	-0.0097	promotes
B2	GST	0.1667	0.0983	0.8630	0.8506	-0.0124	-0.0021	-0.0012	0.0008	opposes

Case ID	Variable	w_m^{eq}	$w_m^{\text{MRE} \times \text{CV}}$	$z_{A,m}$	$z_{B,m}$	Δz_m $= z_{B,m} - z_{A,m}$	$w_m^{\text{eq}} \Delta z_m$	$w_m^{\text{MRE} \times \text{CV}} \Delta z_m$	E_m $= (w_m^{\text{MRE} \times \text{CV}} - w_m^{\text{eq}}) \Delta z_m$	Effect on MRE $\times$ CV- weight winner
	PRE	0.1667	0.2428	1.0900	1.1517	0.0617	0.0103	0.0150	0.0047	opposes
	PRS	0.1667	0.0630	0.1982	0.2223	0.0241	0.0040	0.0015	-0.0025	promotes
	RHU	0.1667	0.0900	0.7529	0.7879	0.0350	0.0058	0.0032	-0.0027	promotes
	TEM	0.1667	0.0837	0.5332	0.5425	0.0094	0.0016	0.0008	-0.0008	promotes
	UV10	0.1667	0.4222	1.2065	1.1329	-0.0736	-0.0123	-0.0311	-0.0188	promotes
B3	GST	0.1667	0.0797	0.9395	0.9549	0.0154	0.0026	0.0012	-0.0013	promotes
	PRE	0.1667	0.3664	1.0679	1.0465	-0.0214	-0.0036	-0.0078	-0.0043	promotes
	PRS	0.1667	0.0688	0.7300	0.7183	-0.0116	-0.0019	-0.0008	0.0011	opposes
	RHU	0.1667	0.0837	1.0185	1.0389	0.0204	0.0034	0.0017	-0.0017	promotes
	TEM	0.1667	0.0805	0.7939	0.8018	0.0079	0.0013	0.0006	-0.0007	promotes
	UV10	0.1667	0.3209	0.9914	0.9887	-0.0028	-0.0005	-0.0009	-0.0004	promotes

Figure S8 Scheme-ranking uncertainty of the selected stage-level parameterization schemes

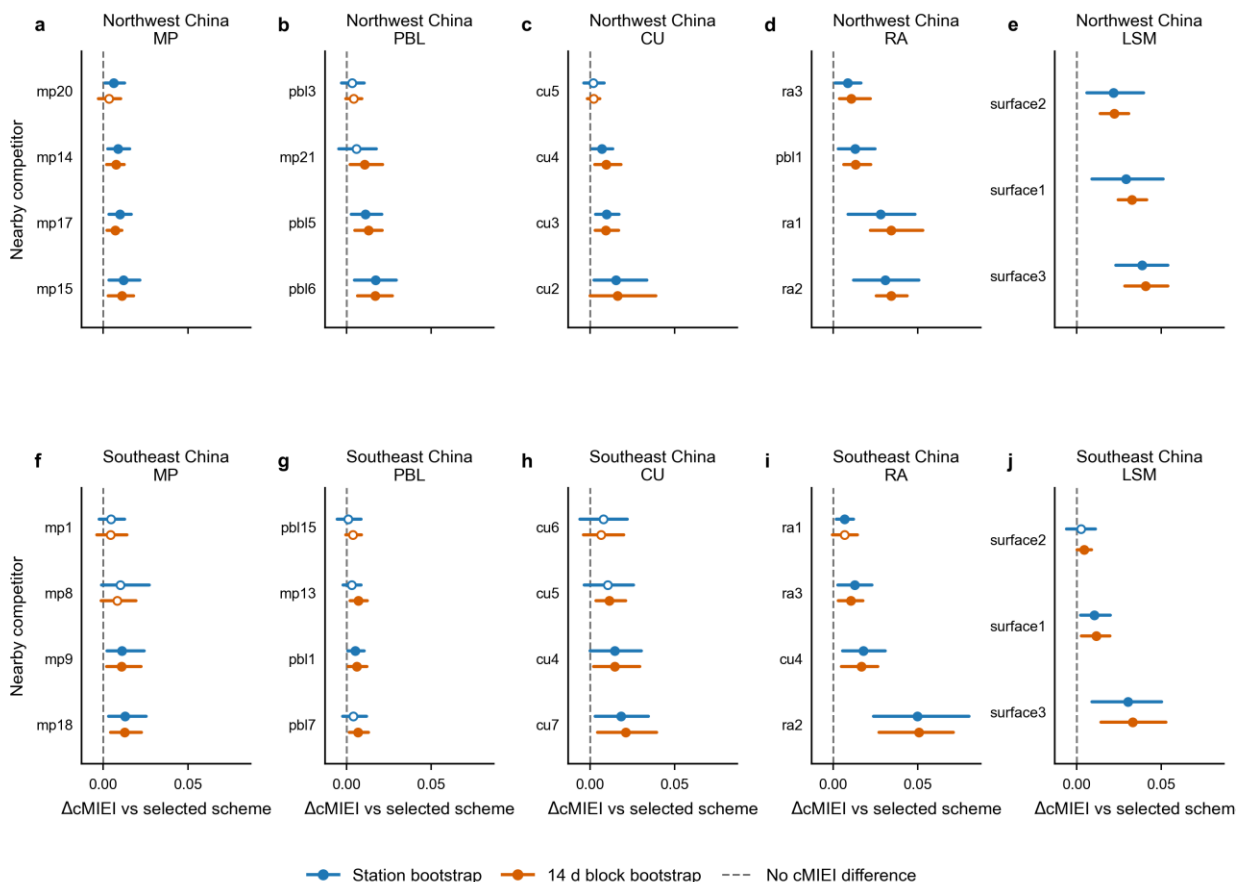


Figure S8. Bootstrap uncertainty in the cMIEI advantage of the full-sample selected stage-level schemes over nearby competitors. Blue circles indicate station-bootstrap samples, and orange squares indicate 14 d moving-block-bootstrap samples. Horizontal bars show 95% bootstrap intervals of $\Delta cMIEI$. Positive values indicate that the selected scheme had a lower cMIEI than the competing scheme. Intervals entirely to the right of zero indicate stable separation under the corresponding resampling analysis.

Table S14 Rank retention of the full-sample selected stage-level schemes under station and temporal resampling

Region	Evaluation stage	Full-sample selected scheme	Perturbation	Top-1 retention	Top-2 retention	Top-3 retention
Northwest China	Cumulus	Tiedtke	Station bootstrap	0.418	0.768	0.918
			14 d block bootstrap	0.518	0.818	0.942
	Land surface	Noah LSM	Station bootstrap	0.938	1.000	1.000
			14 d block bootstrap	1.000	1.000	1.000
	Microphysics	P3	Station bootstrap	0.678	0.906	0.974
			14 d block bootstrap	0.536	0.822	0.870
	PBL / surface layer	YSU + MM5	Station bootstrap	0.432	0.750	0.896
			14 d block bootstrap	0.666	0.892	0.984
	Radiation	GFDL + GFDL	Station bootstrap	0.792	0.926	0.994
			14 d block bootstrap	0.998	1.000	1.000

Region	Evaluation stage	Full-sample selected scheme	Perturbation	Top-1 retention	Top-2 retention	Top-3 retention
Southeast China	Cumulus	Grell 3	Station bootstrap	0.500	0.694	0.822
			14 d block bootstrap	0.504	0.804	0.944
	Land surface	Noah LSM	Station bootstrap	0.406	0.896	0.998
			14 d block bootstrap	0.712	0.992	0.998
	Microphysics	WDM6	Station bootstrap	0.444	0.658	0.800
			14 d block bootstrap	0.436	0.660	0.808
	PBL / surface layer	Shin-Hong + MM5	Station bootstrap	0.196	0.404	0.564
			14 d block bootstrap	0.384	0.644	0.840
	Radiation	GFDL + GFDL	Station bootstrap	0.736	0.934	0.990
			14 d block bootstrap	0.718	0.976	1.000

Table S15 Unweighted daily station-level performance of the five final configurations**(a) Northwest China, 2007**

Variable	Unit	Method	RMSE	MAE	Mean Bias	r
GST	°C	Equal	11.053	9.893	-9.740	0.647
		MRE $\times$ CV	8.588	7.386	-6.791	0.653
		Entropy	7.791	6.713	-6.002	0.693
		CV	9.281	8.221	-7.930	0.705
		CRITIC	11.053	9.893	-9.740	0.647
PRE	mm d ⁻¹	Equal	3.522	1.165	0.021	0.438
		MRE $\times$ CV	3.657	1.176	0.002	0.355
		Entropy	3.660	1.258	0.107	0.381
		CV	3.571	1.277	0.178	0.436
		CRITIC	3.522	1.165	0.021	0.438
PRS	hPa	Equal	13.298	7.078	-5.719	0.983
		MRE $\times$ CV	13.303	7.100	-5.731	0.983
		Entropy	13.502	7.451	-6.452	0.983
		CV	13.533	7.503	-6.539	0.983
		CRITIC	13.298	7.078	-5.719	0.983
RHU	%	Equal	16.011	12.899	-10.379	0.717
		MRE $\times$ CV	19.165	15.859	-14.555	0.696
		Entropy	16.697	13.619	-11.509	0.749
		CV	15.063	12.072	-9.013	0.760
		CRITIC	16.011	12.899	-10.379	0.717
TEM	°C	Equal	3.686	3.040	-2.529	0.858
		MRE $\times$ CV	2.704	2.173	-0.495	0.874
		Entropy	2.587	2.071	-0.427	0.886
		CV	2.915	2.370	-1.527	0.886
		CRITIC	3.686	3.040	-2.529	0.858
U10	m s ⁻¹	Equal	2.784	2.166	-0.257	0.371
		MRE $\times$ CV	2.820	2.214	-0.577	0.459
		Entropy	3.117	2.399	-0.258	0.456
		CV	3.115	2.393	-0.181	0.433
		CRITIC	2.784	2.166	-0.257	0.371
V10	m s ⁻¹	Equal	2.616	1.991	-0.222	0.211
		MRE $\times$ CV	2.677	1.988	-0.236	0.248
		Entropy	2.980	2.215	-0.540	0.247
		CV	3.086	2.299	-0.471	0.238
		CRITIC	2.616	1.991	-0.222	0.211

(b) Southeast China, 2009

Variable	Unit	Method	RMSE	MAE	Mean Bias	r
GST	°C	Equal	3.526	2.843	-0.156	0.607
		MRE × CV	3.627	2.894	-0.755	0.600
		Entropy	3.551	2.865	-0.156	0.616
		CV	4.273	3.437	-2.154	0.578
		CRITIC	3.526	2.843	-0.156	0.607
PRE	mm d ⁻¹	Equal	18.027	8.358	1.450	0.486
		MRE × CV	20.238	11.482	6.136	0.469
		Entropy	18.905	8.091	0.735	0.449
		CV	18.047	9.983	4.219	0.496
		CRITIC	18.027	8.358	1.450	0.486
PRS	hPa	Equal	20.577	10.958	-0.868	0.789
		MRE × CV	20.581	10.948	-0.851	0.789
		Entropy	20.588	11.006	-0.956	0.789
		CV	20.569	10.935	-0.863	0.790
		CRITIC	20.577	10.958	-0.868	0.789
RHU	%	Equal	9.693	7.740	3.084	0.525
		MRE × CV	11.206	9.068	5.632	0.487
		Entropy	9.225	7.311	-0.596	0.551
		CV	11.650	9.433	5.467	0.398
		CRITIC	9.693	7.740	3.084	0.525
TEM	°C	Equal	1.882	1.420	-0.277	0.744
		MRE × CV	2.020	1.589	-0.675	0.732
		Entropy	1.846	1.370	0.043	0.753
		CV	2.360	1.922	-1.221	0.703
		CRITIC	1.882	1.420	-0.277	0.744
U10	m s ⁻¹	Equal	1.701	1.264	0.164	0.505
		MRE × CV	1.670	1.223	0.039	0.491
		Entropy	1.719	1.268	0.209	0.493
		CV	1.658	1.201	0.004	0.480
		CRITIC	1.701	1.264	0.164	0.505
V10	m s ⁻¹	Equal	2.261	1.741	0.547	0.558
		MRE × CV	2.143	1.636	0.430	0.566
		Entropy	2.241	1.736	0.587	0.562
		CV	2.104	1.604	0.202	0.552
		CRITIC	2.261	1.741	0.547	0.558

(c) Northwest China, 2010

Variable	Unit	Method	RMSE	MAE	Mean Bias	r
GST	°C	Equal	8.403	7.331	-6.501	0.630
		MRE × CV	10.779	9.722	-9.442	0.636
		Entropy	7.628	6.610	-5.760	0.678
		CV	9.139	8.141	-7.727	0.685
		CRITIC	8.403	7.331	-6.501	0.630
PRE	mm d ⁻¹	Equal	3.927	1.269	0.084	0.063
		MRE × CV	3.838	1.242	0.037	0.064
		Entropy	3.879	1.306	0.156	0.078
		CV	3.938	1.324	0.166	0.083
		CRITIC	3.927	1.269	0.084	0.063
PRS	hPa	Equal	13.588	7.680	-5.926	0.982
		MRE × CV	13.578	7.660	-5.897	0.982
		Entropy	13.820	7.963	-6.637	0.983
		CV	13.844	8.008	-6.734	0.983
		CRITIC	13.588	7.680	-5.926	0.982
RHU	%	Equal	20.635	16.685	-13.821	0.518
		MRE × CV	18.060	14.338	-9.672	0.541
		Entropy	18.251	14.838	-10.924	0.608
		CV	17.276	13.895	-8.568	0.611
		CRITIC	20.635	16.685	-13.821	0.518
TEM	°C	Equal	3.352	2.674	-0.461	0.804
		MRE × CV	4.129	3.458	-2.483	0.787
		Entropy	3.178	2.545	-0.414	0.825
		CV	3.478	2.855	-1.523	0.819
		CRITIC	3.352	2.674	-0.461	0.804
U10	m s ⁻¹	Equal	3.292	2.563	-0.429	0.297
		MRE × CV	3.070	2.397	-0.058	0.277
		Entropy	3.589	2.730	-0.042	0.331
		CV	3.517	2.685	0.004	0.320
		CRITIC	3.292	2.563	-0.429	0.297
V10	m s ⁻¹	Equal	2.952	2.176	-0.457	0.112
		MRE × CV	2.825	2.123	-0.409	0.118
		Entropy	3.188	2.358	-0.713	0.155
		CV	3.210	2.387	-0.672	0.160
		CRITIC	2.952	2.176	-0.457	0.112

(d) Southeast China, 2010

Variable	Unit	Method	RMSE	MAE	Mean Bias	r
GST	°C	Equal	3.699	2.948	-0.732	0.696
		MRE × CV	3.875	3.043	-1.225	0.685
		Entropy	3.621	2.898	-0.715	0.713
		CV	4.655	3.702	-2.636	0.654
		CRITIC	3.699	2.948	-0.732	0.696
PRE	mm d ⁻¹	Equal	19.264	8.958	1.125	0.454
		MRE × CV	20.671	11.484	5.065	0.452
		Entropy	19.312	8.557	0.129	0.451
		CV	19.368	10.732	3.725	0.430
		CRITIC	19.264	8.958	1.125	0.454
PRS	hPa	Equal	20.691	10.994	-0.862	0.789
		MRE × CV	20.693	10.972	-0.821	0.789
		Entropy	20.700	11.042	-0.950	0.789
		CV	20.678	10.964	-0.854	0.790
		CRITIC	20.691	10.994	-0.862	0.789
RHU	%	Equal	9.714	7.871	3.420	0.539
		MRE × CV	11.299	8.996	6.007	0.497
		Entropy	8.931	7.254	0.044	0.577
		CV	11.681	9.394	5.697	0.419
		CRITIC	9.714	7.871	3.420	0.539
TEM	°C	Equal	1.976	1.541	-0.413	0.805
		MRE × CV	2.124	1.673	-0.763	0.793
		Entropy	1.905	1.467	-0.132	0.813
		CV	2.487	2.036	-1.324	0.767
		CRITIC	1.976	1.541	-0.413	0.805
U10	m s ⁻¹	Equal	1.747	1.293	0.029	0.517
		MRE × CV	1.696	1.246	-0.107	0.527
		Entropy	1.787	1.330	0.125	0.504
		CV	1.697	1.250	-0.138	0.505
		CRITIC	1.747	1.293	0.029	0.517
V10	m s ⁻¹	Equal	2.173	1.706	0.548	0.571
		MRE × CV	2.069	1.619	0.425	0.575
		Entropy	2.163	1.703	0.603	0.572
		CV	2.060	1.601	0.195	0.559
		CRITIC	2.173	1.706	0.548	0.571

Table S16 Cross-evaluation of the five final configurations under common weighting objectives**(a) Northwest China, 2007**

Configuration	Equal	MRE $\times$ CV	Entropy	CV	CRITIC
Equal	1.1242	1.1863	0.8099	1.0191	1.1060
MRE $\times$ CV	1.1300	1.1663	0.7914	1.0064	1.1109
Entropy	1.1367	1.1982	0.7841	1.0129	1.1162
CV	1.1306	1.2069	0.7918	1.0188	1.1108
CRITIC	1.1242	1.1863	0.8099	1.0191	1.1060

(b) Southeast China, 2009

Configuration	Equal	MRE $\times$ CV	Entropy	CV	CRITIC
Equal	1.0148	1.0094	1.0252	1.0245	1.0032
MRE $\times$ CV	1.0160	1.0061	1.0378	1.0361	1.0007
Entropy	1.0236	1.0175	1.0538	1.0505	1.0054
CV	1.0133	1.0079	1.0131	1.0130	1.0065
CRITIC	1.0148	1.0094	1.0252	1.0245	1.0032

(c) Northwest China, 2010

Configuration	Equal	MRE × CV	Entropy	CV	CRITIC
Equal	1.2821	1.3123	0.9361	1.1342	1.2452
MRE × CV	1.2815	1.3082	0.9347	1.1309	1.2405
Entropy	1.2725	1.3249	0.9116	1.1202	1.2294
CV	1.2727	1.3220	0.9163	1.1236	1.2293
CRITIC	1.2821	1.3123	0.9361	1.1342	1.2452

(d) Southeast China, 2010

Configuration	Equal	MRE × CV	Entropy	CV	CRITIC
Equal	1.0254	1.0142	1.0569	1.0537	1.0074
MRE × CV	1.0204	1.0052	1.0587	1.0549	0.9994
Entropy	1.0213	1.0137	1.0504	1.0468	1.0056
CV	1.0414	1.0298	1.0795	1.0754	1.0204
CRITIC	1.0254	1.0142	1.0569	1.0537	1.0074

Note. Rows identify the configuration-selection method; columns identify the evaluation weighting rule. For each region-year, all five weight vectors were derived from the same five method-labelled final configurations. Methods selecting the same configuration retain their separate labels. Each column applies one common vector to all configurations using common daily June–August station samples. Values are dimensionless cMIEI; bold marks the column minimum. Compare configurations within each column.

Table S17 Complete stepwise selection pathways for Entropy, CV and CRITIC weighting**(a) Northwest China, 2007**

Stage	Entropy Selected scheme	cMIEI	CV Selected scheme	cMIEI	CRITIC Selected scheme	cMIEI
Microphysics	P3	1.0143	P3	1.0276	P3	1.1501
PBL/surface layer	YSU + MM5	0.6666	YSU + MM5	0.7670	MYJ + MYJ	1.1264
Cumulus	New Tiedtke	1.1010	New Tiedtke	1.0887	Tiedtke	1.0986
Radiation	GFDL + GFDL	0.6574	RRTMG + RRTMG	0.8729	RRTMG + RRTMG	1.0986
Land surface	NoahMP	0.5777	NoahMP	0.7857	Noah LSM	1.0863

(b) Southeast China, 2009

Stage	Entropy Selected scheme	cMIEI	CV Selected scheme	cMIEI	CRITIC Selected scheme	cMIEI
Microphysics	WDM6	1.0968	WDM6	1.0909	WDM6	1.0504
PBL/surface layer	ACM2 + MM5	1.0106	Shin-Hong + MM5	1.0444	Shin-Hong + MM5	1.0492
Cumulus	New Tiedtke	1.0914	NSAS	1.0527	New Tiedtke	1.0054
Radiation	GFDL	0.9349	New Goddard	0.9981	GFDL	1.0165
Land surface	Noah LSM	0.9618	Noah LSM	1.0093	Noah LSM	1.0156