

1 **Bowen ratio-constrained global dataset of air-sea turbulent heat**
2 **fluxes from 1993 to 2017**

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Table S1. Summary of buoys involved in this study.

ID	source	Ocean basin	Lon	Lat	Date start	Date end
COARE	UOP	Southern Pacific	155.99	-1.76	1993-01-01	1993-03-03
CMOCENT	UOP	Northern Atlantic	-70.5	40.49	1996-07-31	1997-06-13
Bengal	UOP	Indian Ocean	89.45	18.01	2014-12-09	2016-01-28
SUBNE	UOP	Northern Atlantic	-22	33	1993-01-01	1993-06-14
SUBSW	UOP	Northern Atlantic	-34	18	1993-01-01	1993-06-20
SUBCENT	UOP	Northern Atlantic	-29	25.5	1993-01-01	1993-06-16
arabian	UOP	Indian Ocean	61.5	15.5	1994-10-17	1995-10-19
SUBSE	UOP	Northern Atlantic	-22	18	1993-01-01	1993-06-18
SUBNW	UOP	Northern Atlantic	-34	33	1993-01-01	1993-05-31
ASREX93	UOP	Northern Atlantic	-69.7	33.9	1993-12-16	1994-03-24
STARTUS	UOP	Southern Pacific	-85.15	-20.16	2000-10-08	2017-05-13
SPURS1	UOP	Northern Atlantic	-38	24.58	2012-09-16	2013-09-29
WHOTS	UOP	Northern Pacific	-157.9	22.77	2004-08-13	2017-12-31
SPURS2	UOP	Northern Pacific	-125.03	10.05	2016-08-24	2017-11-05
SOFS	UOP	Indian Ocean	141.96	-46.69	2010-03-18	2017-11-07
NTAS	UOP	Northern Atlantic	-51	14.83	2001-03-31	2017-12-31
2n155w	TRITON	Northern Pacific	-155	2	1993-03-03	2017-12-08
5s125w	TRITON	Southern Pacific	-125	-5	1993-10-07	2017-08-24
5s140w	TRITON	Southern Pacific	-140	-5	1996-09-08	2017-12-31
5s155w	TRITON	Southern Pacific	-155	-5	1995-12-28	2017-12-31
5s156e	TRITON	Southern Pacific	156	-5	1993-01-04	2014-12-24
2s140w	TRITON	Southern Pacific	-140	-2	1994-10-14	2017-12-31
2s110w	TRITON	Southern Pacific	-110	-2	1996-05-21	2017-06-18
0n156e	TRITON	Northern Pacific	156	0	1993-02-09	2017-12-31
0n110w	TRITON	Northern Pacific	-110	0	1993-05-09	2017-06-17
0n125w	TRITON	Northern Pacific	-125	0	1993-01-02	2017-09-21
0n140w	TRITON	Northern Pacific	-140	0	1993-04-28	2017-12-28
0n147e	TRITON	Northern Pacific	147	0	1994-04-29	2015-07-20
0n155w	TRITON	Northern Pacific	-155	0	1994-10-23	2017-03-29
5s110w	TRITON	Southern Pacific	-110	-5	1993-03-14	2017-12-29
5n95w	TRITON	Northern Pacific	-95	5	1996-05-10	2017-10-18
5n156e	TRITON	Northern Pacific	156	5	1994-12-18	2014-07-22
5n170w	TRITON	Northern Pacific	-170	5	1993-04-06	2017-12-30
2s165e	TRITON	Southern Pacific	165	-2	1994-04-19	2017-09-22
5n140w	TRITON	Northern Pacific	-140	5	1993-10-17	2017-12-31
2s156e	TRITON	Southern Pacific	156	-2	1996-07-29	2016-10-10
2s155w	TRITON	Southern Pacific	-155	-2	1994-05-25	2017-10-04
2s170w	TRITON	Southern Pacific	-170	-2	1993-11-13	2017-11-06
2s180w	TRITON	Southern Pacific	-179.5	-2	1994-06-09	2017-12-10
2s95w	TRITON	Southern Pacific	-95	-2	1993-01-01	2017-08-16
5n110w	TRITON	Northern Pacific	-110	5	1993-03-15	2017-12-30
5n125w	TRITON	Northern Pacific	-125	5	1993-10-03	2017-03-21

5n137e	TRITON	Northern Pacific	137	5	2001-09-30	2015-06-25
0n165e	TRITON	Northern Pacific	165	0	1993-01-01	2017-12-31
5n147e	TRITON	Northern Pacific	147	5	1993-02-06	2013-11-30
5n155w	TRITON	Northern Pacific	-155	5	1994-10-24	2017-11-09
2s125w	TRITON	Southern Pacific	-125	-2	1994-09-10	2017-09-15
5n165e	TRITON	Northern Pacific	165	5	1993-12-31	2017-07-03
5n180w	TRITON	Northern Pacific	-179.5	5	1996-06-29	2017-11-28
0n170w	TRITON	Northern Pacific	-170	0	1995-04-17	2017-11-24
0n95w	TRITON	Northern Pacific	-95	0	1997-08-10	2017-06-28
8s170w	TRITON	Southern Pacific	-170	-8	1993-01-06	2017-09-15
8s155w	TRITON	Southern Pacific	-155	-8	1993-03-07	2017-09-20
0n180w	TRITON	Northern Pacific	-179.5	0	1994-11-18	2017-10-14
8s110w	TRITON	Southern Pacific	-110	-8	1993-03-12	2017-12-31
8n95w	TRITON	Northern Pacific	-95	8	1995-08-23	2017-12-31
8n180w	TRITON	Northern Pacific	-179.5	8	1993-12-06	2017-08-29
8s180w	TRITON	Southern Pacific	-179.5	-8	1993-11-23	2017-12-31
8s165e	TRITON	Southern Pacific	165	-8	1993-01-04	2017-12-31
8n137e	TRITON	Northern Pacific	137	8	2002-07-03	2017-12-31
8n110w	TRITON	Northern Pacific	-110	8	1997-08-25	2017-07-15
8n125w	TRITON	Northern Pacific	-125	8	1996-09-19	2017-12-31
5s95w	TRITON	Southern Pacific	-95	-5	1996-05-13	2017-12-31
8n155w	TRITON	Northern Pacific	-155	8	1995-04-09	2016-10-23
8n156e	TRITON	Northern Pacific	156	8	1997-02-10	2014-03-11
8n165e	TRITON	Northern Pacific	165	8	1993-01-01	2017-12-31
8s95w	TRITON	Southern Pacific	-95	-8	1996-10-20	2017-12-31
8s125w	TRITON	Southern Pacific	-125	-8	1996-09-14	2017-12-31
8n170w	TRITON	Northern Pacific	-170	8	1993-01-01	2017-12-01
2n95w	TRITON	Northern Pacific	-95	2	1993-01-01	2017-08-14
9n140w	TRITON	Northern Pacific	-140	9	1994-10-10	2017-12-31
2n125w	TRITON	Northern Pacific	-125	2	1993-05-04	2017-02-15
2n137e	TRITON	Northern Pacific	137	2	1993-05-01	2015-04-19
2n140w	TRITON	Northern Pacific	-140	2	1998-10-02	2017-12-31
2n147e	TRITON	Northern Pacific	147	2	1993-01-01	2015-07-09
2n110w	TRITON	Northern Pacific	-110	2	1993-09-13	2015-07-20
5s170w	TRITON	Southern Pacific	-170	-5	1993-11-14	2017-10-17
2n165e	TRITON	Northern Pacific	165	2	1993-01-02	2017-12-01
2n180w	TRITON	Northern Pacific	-179.5	2	1993-03-28	2017-11-25
5s165e	TRITON	Southern Pacific	165	-5	1994-04-20	2017-09-04
2n170w	TRITON	Northern Pacific	-170	2	1995-12-13	2017-12-31
5s180w	TRITON	Southern Pacific	-179.5	-5	1993-03-25	2017-10-26
2n156e	TRITON	Northern Pacific	156	2	1993-02-23	2015-03-02
Heimdal	TAC	Northern Atlantic	2	59	2014-03-01	2017-12-30
6200086	TAC	Northern Atlantic	6	55	2016-09-02	2016-10-09
Visundfeltet	TAC	Arctic Ocean	2	61	2014-04-30	2017-12-31

Ekofisk	TAC	Northern Atlantic	3	56	2017-01-01	2017-12-31
Norne	TAC	Arctic Ocean	8	66	2014-02-07	2015-10-23
6200095	TAC	Northern Atlantic	-15	53	2017-02-27	2017-12-31
5s95e	RAMA	Indian Ocean	95	-5	2001-10-27	2017-12-31
0n67e	RAMA	Indian Ocean	67	0	2014-08-08	2017-12-30
0n80.5e	RAMA	Indian Ocean	80.5	0	1993-07-25	2017-10-31
0n90e	RAMA	Indian Ocean	90	0	2009-08-01	2017-06-11
12n90e	RAMA	Indian Ocean	90	12	2009-11-07	2017-12-31
12s55e	RAMA	Indian Ocean	55	-12	2012-03-07	2013-04-26
15n90e	RAMA	Indian Ocean	90	15	2008-10-21	2017-12-31
12s67e	RAMA	Indian Ocean	67	-12	2012-06-29	2017-12-31
8s80.5e	RAMA	Indian Ocean	80.5	-8	2008-08-24	2017-12-31
4n90e	RAMA	Indian Ocean	90	4	2006-11-17	2015-11-26
8s67e	RAMA	Indian Ocean	67	-8	2007-01-15	2017-12-31
8s55e	RAMA	Indian Ocean	55	-8	2010-10-19	2017-12-31
12s93e	RAMA	Indian Ocean	93	-12	2011-03-23	2017-02-24
8s95e	RAMA	Indian Ocean	95	-8	2009-11-15	2017-12-31
4s57e	RAMA	Indian Ocean	57	-4	2015-11-18	2016-11-24
4s67e	RAMA	Indian Ocean	67	-4	2013-07-25	2017-12-31
4s80.5e	RAMA	Indian Ocean	80.5	-4	2008-08-21	2017-12-31
8n90e	RAMA	Indian Ocean	90	8	2006-11-15	2017-03-22
12s80.5e	RAMA	Indian Ocean	80.5	-12	2010-05-18	2017-12-31
1.5n67e	RAMA	Indian Ocean	67	1.5	2016-09-06	2017-12-31
1.5s67e	RAMA	Indian Ocean	67	-1.5	2013-07-26	2017-12-31
1.5s80.5e	RAMA	Indian Ocean	80.5	-1.5	2012-08-23	2016-12-31
0n23w	PIRATA	Northern Atlantic	-23	0	1999-03-08	2017-11-30
0n0e	PIRATA	Northern Atlantic	0	0	1998-11-10	2017-12-31
0n10w	PIRATA	Northern Atlantic	-10	0	1999-11-04	2017-12-31
10s10w	PIRATA	Southern Atlantic	-10	-10	1997-09-12	2017-09-17
12n23w	PIRATA	Northern Atlantic	-23	12	2006-06-09	2017-12-31
12n38w	PIRATA	Northern Atlantic	-38	12	1999-02-06	2017-12-31
0n35w	PIRATA	Northern Atlantic	-35	0	1998-01-24	2017-12-31
14s32w	PIRATA	Southern Atlantic	-32	-14	2006-11-08	2016-01-24
8s30w	PIRATA	Southern Atlantic	-30	-8	2005-08-22	2017-12-31
6s10w	PIRATA	Southern Atlantic	-10	-6	2000-03-16	2017-06-11
5s10w	PIRATA	Southern Atlantic	-10	-5	1999-01-28	2000-03-13
4n38w	PIRATA	Northern Atlantic	-38	4	2001-04-23	2017-12-31
4n23w	PIRATA	Northern Atlantic	-23	4	2008-10-16	2017-07-03
8n38w	PIRATA	Northern Atlantic	-38	8	1998-02-01	2017-12-31
19s34w	PIRATA	Southern Atlantic	-34	-19	2006-11-06	2017-12-31
20n38w	PIRATA	Northern Atlantic	-38	20	2007-05-23	2017-12-31
21n23w	PIRATA	Northern Atlantic	-23	21	2007-05-20	2017-12-31
15n38w	PIRATA	Northern Atlantic	-38	15	1998-01-29	2017-12-31
103969	OOI	Northern Atlantic	-70.89	39.94	2015-10-24	2017-12-31

Global Southern Ocean	OOI	Southern Pacific	-89.21	-54.41	2015-02-20	2017-12-30
Global Irminger Sea	OOI	Northern Atlantic	-39.57	59.94	2014-09-11	2017-10-11
Coastal Pioneer	OOI	Northern Atlantic	-70.78	40.13	2013-11-22	2017-12-31
Global Argentine Basin	OOI	Southern Atlantic	-42.44	-42.92	2015-11-16	2017-03-24
103941	OOI	Northern Atlantic	-70.89	40.36	2015-05-15	2017-12-31
KEO	OCS	Northern Pacific	144.6	32.3	2007-09-27	2017-12-31
ARC	OCS	Indian Ocean	30	-38.5	2010-12-02	2011-01-15
PAPA	OCS	Northern Pacific	-144.9	50.1	2007-06-09	2017-12-31
42019	NDBC	Northern Atlantic	-95.34	27.91	1993-05-05	2017-12-31
42003	NDBC	Northern Atlantic	-85.62	25.92	2000-06-17	2017-03-28
42002	NDBC	Northern Atlantic	-93.65	26.06	1993-06-05	2017-10-03
42001	NDBC	Northern Atlantic	-89.66	25.93	1999-05-20	2017-12-31
41046	NDBC	Northern Atlantic	-68.39	23.82	2007-09-23	2017-12-30
41049	NDBC	Northern Atlantic	-63.01	27.54	2009-05-15	2017-12-31
44066	NDBC	Northern Atlantic	-72.64	39.62	2009-06-21	2017-12-31
42036	NDBC	Northern Atlantic	-84.51	28.5	1998-11-19	2017-11-23
41048	NDBC	Northern Atlantic	-69.57	31.83	2007-09-19	2017-12-31
41044	NDBC	Northern Atlantic	-58.63	21.58	2009-05-12	2017-04-03
41047	NDBC	Northern Atlantic	-71.45	27.46	2007-09-22	2017-09-22
42040	NDBC	Northern Atlantic	-88.24	29.21	1995-12-07	2017-12-31
44008	NDBC	Northern Atlantic	-69.25	40.5	1999-07-13	2017-05-21
42046	NDBC	Northern Atlantic	-94.04	27.89	2008-04-10	2013-06-09
44011	NDBC	Northern Atlantic	-66.56	41.09	2002-02-23	2016-01-15
42047	NDBC	Northern Atlantic	-93.6	27.9	2008-07-15	2013-05-29
42055	NDBC	Northern Atlantic	-94.11	22.14	2005-05-13	2017-12-31
42056	NDBC	Northern Atlantic	-84.94	19.82	2005-05-05	2017-12-31
42057	NDBC	Northern Atlantic	-81.58	16.97	2005-06-07	2017-12-31
42058	NDBC	Northern Atlantic	-75.06	14.84	2006-04-19	2017-04-15
42045	NDBC	Northern Atlantic	-96.5	26.22	2009-01-01	2017-05-27
42059	NDBC	Northern Atlantic	-67.48	15.3	2007-04-18	2017-12-31
42089	NDBC	Northern Atlantic	-80.06	19.7	2014-09-24	2016-11-17
42060	NDBC	Northern Atlantic	-63.33	16.43	2009-04-28	2017-09-05
42039	NDBC	Northern Atlantic	-86.01	28.79	1997-05-08	2017-12-31
46080	NDBC	Northern Pacific	-150.13	57.92	2002-08-10	2017-10-01
44004	NDBC	Northern Atlantic	-70.43	38.48	2004-08-25	2008-03-07
51000	NDBC	Northern Pacific	-153.79	23.53	2009-04-25	2011-07-17
41043	NDBC	Northern Atlantic	-64.79	21.03	2007-04-12	2017-09-09
46005	NDBC	Northern Pacific	-131.08	46.13	2017-06-02	2017-11-23
46006	NDBC	Northern Pacific	-137.38	40.76	2016-06-19	2017-12-30
46035	NDBC	Northern Pacific	-177.7	57.02	2001-10-28	2007-01-23
46047	NDBC	Northern Pacific	-119.52	32.39	1999-05-27	2001-08-07
46059	NDBC	Northern Pacific	-129.98	38.07	2015-10-08	2017-12-31
46070	NDBC	Northern Pacific	175.27	55.06	2006-09-19	2017-03-19
46072	NDBC	Northern Pacific	-172.11	51.67	2003-09-29	2016-12-17

46073	NDBC	Northern Pacific	-172.01	55.01	2005-05-17	2015-01-28
46078	NDBC	Northern Pacific	-152.6	55.56	2004-05-20	2016-09-20
46085	NDBC	Northern Pacific	-142.88	55.88	2007-05-05	2016-03-07
46002	NDBC	Northern Pacific	-130.51	42.66	2017-06-01	2017-07-06
46075	NDBC	Northern Pacific	-160.79	53.97	2004-05-09	2016-11-25
51001	NDBC	Northern Pacific	-162.01	24.45	2015-08-25	2017-12-31
41010	NDBC	Northern Atlantic	-78.48	28.88	2002-09-19	2017-09-09
41002	NDBC	Northern Atlantic	-74.94	31.76	2002-09-20	2017-01-15
lciy2	NDBC	Northern Atlantic	-80.06	19.7	2009-07-31	2012-10-23
46089	NDBC	Northern Pacific	-125.79	45.94	2004-11-11	2017-06-25
41001	NDBC	Northern Atlantic	-72.24	34.7	2002-09-19	2017-08-08
41040	NDBC	Northern Atlantic	-53.14	14.54	2005-05-31	2017-06-25
41041	NDBC	Northern Atlantic	-46.33	14.45	2005-05-29	2017-07-28
51100	NDBC	Northern Pacific	-153.9	23.56	2009-04-25	2012-12-09
51004	NDBC	Northern Pacific	-152.23	17.54	2009-09-12	2017-12-31
51002	NDBC	Northern Pacific	-157.75	17.04	2016-10-18	2017-12-31
51101	NDBC	Northern Pacific	-162.08	24.36	2009-04-23	2014-08-14
46001	NDBC	Northern Pacific	-148.02	56.3	2017-08-23	2017-12-03
21229	KOREA	Northern Pacific	131.11	37.46	2011-12-28	2017-12-31
JKEO	JKEO	Northern Pacific	146.42	38.09	2008-03-03	2010-06-14
64071	Iceland	Arctic Ocean	-9.26	68.47	2007-11-28	2009-04-12
point-lay-metoocean-buoy	AOOS	Arctic Ocean	-166.07	70.03	2011-07-03	2011-10-03
hanna-shoal-metoocean-buoy	AOOS	Arctic Ocean	-161.52	72.16	2011-08-30	2011-10-03

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18 **Table S2. Evaluation of the importance scores of 17 features for modeling air-sea turbulent**
19 **heat fluxes**

Forcing variables	Importance scores - %	
	SHF	LHF
<i>ADT</i>	1.08	1.42
<i>SLA</i>	0.81	1.18
<i>T_a</i>	0.46	1.03
<i>Q_a</i>	6.66	0.87
<i>SLP</i>	0.72	2.06
<i>SW</i>	2.51	1.14
<i>LW</i>	0.82	1.23
<i>diff_Q</i>	0.85	49.93
<i>SSS</i>	0.85	1.13
<i>SSD</i>	0.75	1.1
<i>T_s</i>	0.25	0.41
<i>Q_s</i>	0.29	0.43
<i>CS</i>	0.82	1.25
<i>WS</i>	10.19	27.59
<i>SWH</i>	0.7	1.15
<i>T_p</i>	0.68	1.43
<i>diff_T</i>	71.56	6.66
Total	100	100

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Table S3. Statistical metrics of the spatial ten-fold cross-validation of estimated daily sensible heat flux (SHF), latent heat flux (LHF) and Bowen ratio (β , SHF/LHF) from the Bowen ratio-constrained air-sea turbulent heat fluxes (BrTHF) model, physics-free Neural Network (NN) models and seven widely used products, with and without removing estimated β ($\beta < -5$ or $\beta > 5$ in the physics-free NN and seven widely used products) that deviates from the range of β observations collected from the 197 buoys.

		All Samples (463585)			Samples (459293) excluding $\beta < -5$ or $\beta > 5$		
		SHF	LHF	β	SHF	LHF	β
JOFURO 3	BIAS (W/m²)	-2.54	-1.61	-0.04	-2.49	-1.64	-0.03
	RMSE (W/m²)	9.18	30.41	10.02	9.45	30.46	0.23
	r	0.87	0.86	0.0	0.91	0.86	0.28
IFREME R	BIAS (W/m²)	4.05	-7.3	0.04	4.06	-7.38	0.04
	RMSE (W/m²)	9.49	29.81	5.3	9.45	29.81	0.18
	r	0.91	0.87	0.03	0.91	0.86	0.46
SeaFlux	BIAS (W/m²)	-0.88	0.49	-0.01	-0.88	0.46	-0.01
	RMSE (W/m²)	6.93	27.9	0.87	6.89	27.97	0.18
	r	0.91	0.88	0.06	0.91	0.87	0.34
ERA5	BIAS (W/m²)	2.16	8.35	0.01	2.24	8.41	0.01
	RMSE (W/m²)	7.05	28.29	2.3	6.99	28.38	0.17
	r	0.91	0.89	0.03	0.91	0.89	0.4
MERRA2	BIAS (W/m²)	-0.43	13.48	-0.01	-0.41	13.58	-0.01
	RMSE (W/m²)	6.56	35.54	6.42	6.53	35.67	-0.17
	r	0.92	0.84	0.0	0.92	0.84	0.39
OaFlux	BIAS (W/m²)	-0.41	-6.2	-0.01	-0.37	-6.29	-0.01
	RMSE (W/m²)	7.85	32.87	1.84	7.8	32.96	0.19
	r	0.9	0.83	0.03	0.9	0.83	0.35
OHF	BIAS (W/m²)	-3.44	-10.19	0.01	-3.38	-10.3	-0.03
	RMSE (W/m²)	12.34	36.05	23.08	11.97	36.07	0.26
	r	0.69	0.81	0.0	0.71	0.8	0.13
Physical- free NN models	BIAS (W/m²)	0.42	-2.0	-0.03	0.43	-2.04	0.01
	RMSE (W/m²)	6.29	25.72	39.21	6.24	25.79	0.17
	r	0.93	0.9	0.01	0.93	0.89	0.40
BrTHF	BIAS (W/m²)	0.09	0.14	-0.01	0.06	0.05	-0.0
	RMSE (W/m²)	6.05	23.67	0.22	6.0	23.69	0.15
	r	0.93	0.91	0.25	0.93	0.91	0.43

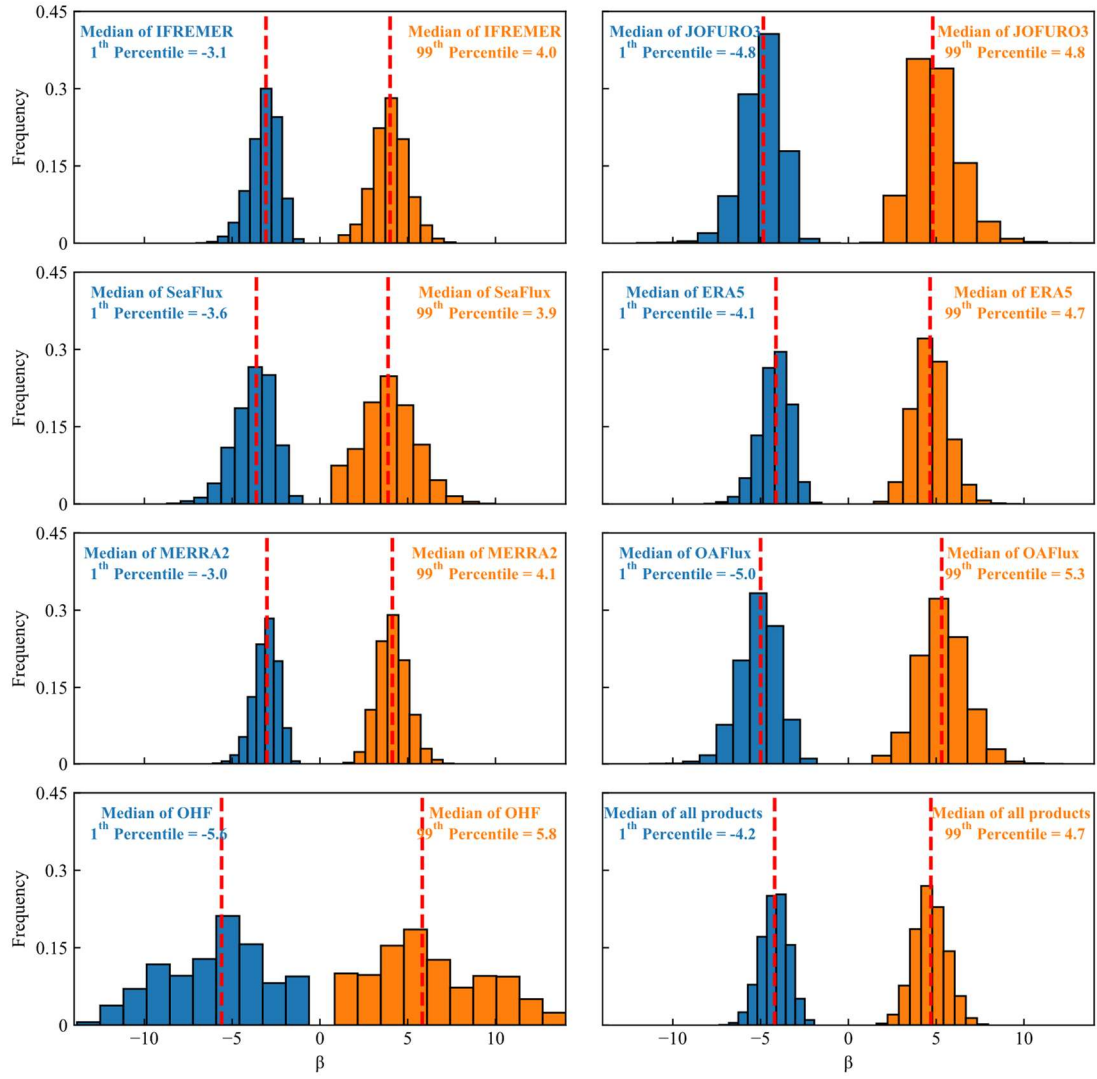


Figure S1. The cumulative distributions of daily 1st and 99th percentiles of β calculated from seven products and their union ensembles. The red dashed lines in each sub-figures represent the medians of the 1st and 99th percentiles, respectively.