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Open Access Earth System Science Data

*Supplement of*

# Bowen ratio-constrained global dataset of bulk air–sea turbulent heat 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 | Northen 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 | Northen Atlantic | -22 | 33 | 1993-01-01 | 1993-06-14 |
| SUBSW | UOP | Northen Atlantic | -34 | 18 | 1993-01-01 | 1993-06-20 |
| SUBCENT | UOP | Northen 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 | Northen Atlantic | -22 | 18 | 1993-01-01 | 1993-06-18 |
| SUBNW | UOP | Northen Atlantic | -34 | 33 | 1993-01-01 | 1993-05-31 |
| ASREX93 | UOP | Northen 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 | Northen Atlantic | -38 | 24.58 | 2012-09-16 | 2013-09-29 |
| WHOTS | UOP | Northen Pacific | -157.9 | 22.77 | 2004-08-13 | 2017-12-31 |
| SPURS2 | UOP | Northen 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 | Northen Atlantic | -51 | 14.83 | 2001-03-31 | 2017-12-31 |
| 2n155w | TRITON | Northen 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 | Northen Pacific | 156 | 0 | 1993-02-09 | 2017-12-31 |
| 0n110w | TRITON | Northen Pacific | -110 | 0 | 1993-05-09 | 2017-06-17 |
| 0n125w | TRITON | Northen Pacific | -125 | 0 | 1993-01-02 | 2017-09-21 |
| 0n140w | TRITON | Northen Pacific | -140 | 0 | 1993-04-28 | 2017-12-28 |
| 0n147e | TRITON | Northen Pacific | 147 | 0 | 1994-04-29 | 2015-07-20 |
| 0n155w | TRITON | Northen Pacific | -155 | 0 | 1994-10-23 | 2017-03-29 |
| 5s110w | TRITON | Southern Pacific | -110 | -5 | 1993-03-14 | 2017-12-29 |
| 5n95w | TRITON | Northen Pacific | -95 | 5 | 1996-05-10 | 2017-10-18 |
| 5n156e | TRITON | Northen Pacific | 156 | 5 | 1994-12-18 | 2014-07-22 |
| 5n170w | TRITON | Northen Pacific | -170 | 5 | 1993-04-06 | 2017-12-30 |
| 2s165e | TRITON | Southern Pacific | 165 | -2 | 1994-04-19 | 2017-09-22 |
| 5n140w | TRITON | Northen 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 | Northen Pacific | -110 | 5 | 1993-03-15 | 2017-12-30 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 5n125w | TRITON | Northen Pacific | -125 | 5 | 1993-10-03 | 2017-03-21 |
| 5n137e | TRITON | Northen Pacific | 137 | 5 | 2001-09-30 | 2015-06-25 |
| 0n165e | TRITON | Northen Pacific | 165 | 0 | 1993-01-01 | 2017-12-31 |
| 5n147e | TRITON | Northen Pacific | 147 | 5 | 1993-02-06 | 2013-11-30 |
| 5n155w | TRITON | Northen Pacific | -155 | 5 | 1994-10-24 | 2017-11-09 |
| 2s125w | TRITON | Southern Pacific | -125 | -2 | 1994-09-10 | 2017-09-15 |
| 5n165e | TRITON | Northen Pacific | 165 | 5 | 1993-12-31 | 2017-07-03 |
| 5n180w | TRITON | Northen Pacific | -179.5 | 5 | 1996-06-29 | 2017-11-28 |
| 0n170w | TRITON | Northen Pacific | -170 | 0 | 1995-04-17 | 2017-11-24 |
| 0n95w | TRITON | Northen 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 | Northen Pacific | -179.5 | 0 | 1994-11-18 | 2017-10-14 |
| 8s110w | TRITON | Southern Pacific | -110 | -8 | 1993-03-12 | 2017-12-31 |
| 8n95w | TRITON | Northen Pacific | -95 | 8 | 1995-08-23 | 2017-12-31 |
| 8n180w | TRITON | Northen 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 | Northen Pacific | 137 | 8 | 2002-07-03 | 2017-12-31 |
| 8n110w | TRITON | Northen Pacific | -110 | 8 | 1997-08-25 | 2017-07-15 |
| 8n125w | TRITON | Northen Pacific | -125 | 8 | 1996-09-19 | 2017-12-31 |
| 5s95w | TRITON | Southern Pacific | -95 | -5 | 1996-05-13 | 2017-12-31 |
| 8n155w | TRITON | Northen Pacific | -155 | 8 | 1995-04-09 | 2016-10-23 |
| 8n156e | TRITON | Northen Pacific | 156 | 8 | 1997-02-10 | 2014-03-11 |
| 8n165e | TRITON | Northen 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 | Northen Pacific | -170 | 8 | 1993-01-01 | 2017-12-01 |
| 2n95w | TRITON | Northen Pacific | -95 | 2 | 1993-01-01 | 2017-08-14 |
| 9n140w | TRITON | Northen Pacific | -140 | 9 | 1994-10-10 | 2017-12-31 |
| 2n125w | TRITON | Northen Pacific | -125 | 2 | 1993-05-04 | 2017-02-15 |
| 2n137e | TRITON | Northen Pacific | 137 | 2 | 1993-05-01 | 2015-04-19 |
| 2n140w | TRITON | Northen Pacific | -140 | 2 | 1998-10-02 | 2017-12-31 |
| 2n147e | TRITON | Northen Pacific | 147 | 2 | 1993-01-01 | 2015-07-09 |
| 2n110w | TRITON | Northen Pacific | -110 | 2 | 1993-09-13 | 2015-07-20 |
| 5s170w | TRITON | Southern Pacific | -170 | -5 | 1993-11-14 | 2017-10-17 |
| 2n165e | TRITON | Northen Pacific | 165 | 2 | 1993-01-02 | 2017-12-01 |
| 2n180w | TRITON | Northen Pacific | -179.5 | 2 | 1993-03-28 | 2017-11-25 |
| 5s165e | TRITON | Southern Pacific | 165 | -5 | 1994-04-20 | 2017-09-04 |
| 2n170w | TRITON | Northen Pacific | -170 | 2 | 1995-12-13 | 2017-12-31 |
| 5s180w | TRITON | Southern Pacific | -179.5 | -5 | 1993-03-25 | 2017-10-26 |
| 2n156e | TRITON | Northen Pacific | 156 | 2 | 1993-02-23 | 2015-03-02 |
| Heimdal | TAC | Northen Atlantic | 2 | 59 | 2014-03-01 | 2017-12-30 |
| 6200086 | TAC | Northen Atlantic | 6 | 55 | 2016-09-02 | 2016-10-09 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Visundfeltet | TAC | Arctic Ocean | 2 | 61 | 2014-04-30 | 2017-12-31 |
| Ekofisk | TAC | Northen Atlantic | 3 | 56 | 2017-01-01 | 2017-12-31 |
| Norne | TAC | Arctic Ocean | 8 | 66 | 2014-02-07 | 2015-10-23 |
| 6200095 | TAC | Northen 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 | Northen Atlantic | -23 | 0 | 1999-03-08 | 2017-11-30 |
| 0n0e | PIRATA | Northen Atlantic | 0 | 0 | 1998-11-10 | 2017-12-31 |
| 0n10w | PIRATA | Northen Atlantic | -10 | 0 | 1999-11-04 | 2017-12-31 |
| 10s10w | PIRATA | Southern Atlantic | -10 | -10 | 1997-09-12 | 2017-09-17 |
| 12n23w | PIRATA | Northen Atlantic | -23 | 12 | 2006-06-09 | 2017-12-31 |
| 12n38w | PIRATA | Northen Atlantic | -38 | 12 | 1999-02-06 | 2017-12-31 |
| 0n35w | PIRATA | Northen 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 | Northen Atlantic | -38 | 4 | 2001-04-23 | 2017-12-31 |
| 4n23w | PIRATA | Northen Atlantic | -23 | 4 | 2008-10-16 | 2017-07-03 |
| 8n38w | PIRATA | Northen Atlantic | -38 | 8 | 1998-02-01 | 2017-12-31 |
| 19s34w | PIRATA | Southern Atlantic | -34 | -19 | 2006-11-06 | 2017-12-31 |
| 20n38w | PIRATA | Northen Atlantic | -38 | 20 | 2007-05-23 | 2017-12-31 |
| 21n23w | PIRATA | Northen Atlantic | -23 | 21 | 2007-05-20 | 2017-12-31 |
| 15n38w | PIRATA | Northen Atlantic | -38 | 15 | 1998-01-29 | 2017-12-31 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 103969 | OOI | Northen 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 | Northen Atlantic | -39.57 | 59.94 | 2014-09-11 | 2017-10-11 |
| Coastal Pioneer | OOI | Northen 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 | Northen Atlantic | -70.89 | 40.36 | 2015-05-15 | 2017-12-31 |
| KEO | OCS | Northen 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 | Northen Pacific | -144.9 | 50.1 | 2007-06-09 | 2017-12-31 |
| 42019 | NDBC | Northen Atlantic | -95.34 | 27.91 | 1993-05-05 | 2017-12-31 |
| 42003 | NDBC | Northen Atlantic | -85.62 | 25.92 | 2000-06-17 | 2017-03-28 |
| 42002 | NDBC | Northen Atlantic | -93.65 | 26.06 | 1993-06-05 | 2017-10-03 |
| 42001 | NDBC | Northen Atlantic | -89.66 | 25.93 | 1999-05-20 | 2017-12-31 |
| 41046 | NDBC | Northen Atlantic | -68.39 | 23.82 | 2007-09-23 | 2017-12-30 |
| 41049 | NDBC | Northen Atlantic | -63.01 | 27.54 | 2009-05-15 | 2017-12-31 |
| 44066 | NDBC | Northen Atlantic | -72.64 | 39.62 | 2009-06-21 | 2017-12-31 |
| 42036 | NDBC | Northen Atlantic | -84.51 | 28.5 | 1998-11-19 | 2017-11-23 |
| 41048 | NDBC | Northen Atlantic | -69.57 | 31.83 | 2007-09-19 | 2017-12-31 |
| 41044 | NDBC | Northen Atlantic | -58.63 | 21.58 | 2009-05-12 | 2017-04-03 |
| 41047 | NDBC | Northen Atlantic | -71.45 | 27.46 | 2007-09-22 | 2017-09-22 |
| 42040 | NDBC | Northen Atlantic | -88.24 | 29.21 | 1995-12-07 | 2017-12-31 |
| 44008 | NDBC | Northen Atlantic | -69.25 | 40.5 | 1999-07-13 | 2017-05-21 |
| 42046 | NDBC | Northen Atlantic | -94.04 | 27.89 | 2008-04-10 | 2013-06-09 |
| 44011 | NDBC | Northen Atlantic | -66.56 | 41.09 | 2002-02-23 | 2016-01-15 |
| 42047 | NDBC | Northen Atlantic | -93.6 | 27.9 | 2008-07-15 | 2013-05-29 |
| 42055 | NDBC | Northen Atlantic | -94.11 | 22.14 | 2005-05-13 | 2017-12-31 |
| 42056 | NDBC | Northen Atlantic | -84.94 | 19.82 | 2005-05-05 | 2017-12-31 |
| 42057 | NDBC | Northen Atlantic | -81.58 | 16.97 | 2005-06-07 | 2017-12-31 |
| 42058 | NDBC | Northen Atlantic | -75.06 | 14.84 | 2006-04-19 | 2017-04-15 |
| 42045 | NDBC | Northen Atlantic | -96.5 | 26.22 | 2009-01-01 | 2017-05-27 |
| 42059 | NDBC | Northen Atlantic | -67.48 | 15.3 | 2007-04-18 | 2017-12-31 |
| 42089 | NDBC | Northen Atlantic | -80.06 | 19.7 | 2014-09-24 | 2016-11-17 |
| 42060 | NDBC | Northen Atlantic | -63.33 | 16.43 | 2009-04-28 | 2017-09-05 |
| 42039 | NDBC | Northen Atlantic | -86.01 | 28.79 | 1997-05-08 | 2017-12-31 |
| 46080 | NDBC | Northen Pacific | -150.13 | 57.92 | 2002-08-10 | 2017-10-01 |
| 44004 | NDBC | Northen Atlantic | -70.43 | 38.48 | 2004-08-25 | 2008-03-07 |
| 51000 | NDBC | Northen Pacific | -153.79 | 23.53 | 2009-04-25 | 2011-07-17 |
| 41043 | NDBC | Northen Atlantic | -64.79 | 21.03 | 2007-04-12 | 2017-09-09 |
| 46005 | NDBC | Northen Pacific | -131.08 | 46.13 | 2017-06-02 | 2017-11-23 |
| 46006 | NDBC | Northen Pacific | -137.38 | 40.76 | 2016-06-19 | 2017-12-30 |
| 46035 | NDBC | Northen Pacific | -177.7 | 57.02 | 2001-10-28 | 2007-01-23 |
| 46047 | NDBC | Northen Pacific | -119.52 | 32.39 | 1999-05-27 | 2001-08-07 |
| 46059 | NDBC | Northen Pacific | -129.98 | 38.07 | 2015-10-08 | 2017-12-31 |
| 46070 | NDBC | Northen Pacific | 175.27 | 55.06 | 2006-09-19 | 2017-03-19 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 46072 | NDBC | Northen Pacific | -172.11 | 51.67 | 2003-09-29 | 2016-12-17 |
| 46073 | NDBC | Northen Pacific | -172.01 | 55.01 | 2005-05-17 | 2015-01-28 |
| 46078 | NDBC | Northen Pacific | -152.6 | 55.56 | 2004-05-20 | 2016-09-20 |
| 46085 | NDBC | Northen Pacific | -142.88 | 55.88 | 2007-05-05 | 2016-03-07 |
| 46002 | NDBC | Northen Pacific | -130.51 | 42.66 | 2017-06-01 | 2017-07-06 |
| 46075 | NDBC | Northen Pacific | -160.79 | 53.97 | 2004-05-09 | 2016-11-25 |
| 51001 | NDBC | Northen Pacific | -162.01 | 24.45 | 2015-08-25 | 2017-12-31 |
| 41010 | NDBC | Northen Atlantic | -78.48 | 28.88 | 2002-09-19 | 2017-09-09 |
| 41002 | NDBC | Northen Atlantic | -74.94 | 31.76 | 2002-09-20 | 2017-01-15 |
| lciy2 | NDBC | Northen Atlantic | -80.06 | 19.7 | 2009-07-31 | 2012-10-23 |
| 46089 | NDBC | Northen Pacific | -125.79 | 45.94 | 2004-11-11 | 2017-06-25 |
| 41001 | NDBC | Northen Atlantic | -72.24 | 34.7 | 2002-09-19 | 2017-08-08 |
| 41040 | NDBC | Northen Atlantic | -53.14 | 14.54 | 2005-05-31 | 2017-06-25 |
| 41041 | NDBC | Northen Atlantic | -46.33 | 14.45 | 2005-05-29 | 2017-07-28 |
| 51100 | NDBC | Northen Pacific | -153.9 | 23.56 | 2009-04-25 | 2012-12-09 |
| 51004 | NDBC | Northen Pacific | -152.23 | 17.54 | 2009-09-12 | 2017-12-31 |
| 51002 | NDBC | Northen Pacific | -157.75 | 17.04 | 2016-10-18 | 2017-12-31 |
| 51101 | NDBC | Northen Pacific | -162.08 | 24.36 | 2009-04-23 | 2014-08-14 |
| 46001 | NDBC | Northen Pacific | -148.02 | 56.3 | 2017-08-23 | 2017-12-03 |
| 21229 | KOREA | Northen Pacific | 131.11 | 37.46 | 2011-12-28 | 2017-12-31 |
| JKEO | JKEO | Northen 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-metocean-buoy | AOOS | Arctic Ocean | -166.07 | 70.03 | 2011-07-03 | 2011-10-03 |
| hanna-shoal-metocean-buoy | AOOS | Arctic Ocean | -161.52 | 72.16 | 2011-08-30 | 2011-10-03 |

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

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

**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 ($\beta$, 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 $\beta$ ($\beta$ < -5 or $\beta$ > 5 in the physics-free NN and seven widely used products) that deviates from the range of $\beta$ observations collected from the 197 buoys.**

| | | All Samples (463585) | | | Samples (459293) excluding $\beta$ < -5 or $\beta$ > 5 | | |
|---|---|---|---|---|---|---|---|
| | | **SHF** | **LHF** | **$\beta$** | **SHF** | **LHF** | **$\beta$** |
| **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 |
| **IFREMER** | **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 |

**Table S4. Statistical metrics of the targeted cross-validation of estimated daily SHF, LHF and $\beta$ from the BrTHF model, physics-free NN models and seven widely used products, with and without removing estimated $\beta$ ($\beta$ < -5 or $\beta$ > 5 in the physics-free NN and seven widely used products) that deviates from the range of $\beta$ observations collected from the Southern Ocean Flux Station (SOFS) buoy.**

| | | All Samples (1466) | | | Samples (1400) excluding $\beta$ < -5 or $\beta$ > 5 | | |
|---|---|---|---|---|---|---|---|
| | | **SHF** | **LHF** | **$\beta$** | **SHF** | **LHF** | **$\beta$** |
| **JOFURO 3** | **BIAS (W/m²)** | 11.35 | -2.78 | 0.17 | 11.4 | -2.43 | 0.1 |
| | **RMSE (W/m²)** | 16.73 | 25.73 | 7.61 | 16.86 | 25.87 | 0.63 |
| | **r** | 0.87 | 0.88 | 0.1 | 0.86 | 0.87 | 0.39 |
| **IFREMER** | **BIAS (W/m²)** | -10.19 | 3.99 | -0.08 | -10.49 | 4.55 | -0.23 |
| | **RMSE (W/m²)** | 16.02 | 20.42 | 5.56 | 16.25 | 20.55 | 0.59 |
| | **r** | 0.9 | 0.93 | -0.07 | 0.9 | 0.93 | 0.49 |
| **SeaFlux** | **BIAS (W/m²)** | 0.91 | 9.25 | -0.01 | 1.21 | 10.06 | -0.06 |
| | **RMSE (W/m²)** | 10.73 | 21.6 | 1.13 | 10.77 | 21.84 | 0.56 |
| | **r** | 0.91 | 0.94 | 0.21 | 0.9 | 0.93 | 0.46 |
| **ERA5** | **BIAS (W/m²)** | 2.57 | -6.91 | 0.07 | 2.41 | -6.99 | 0 |
| | **RMSE (W/m²)** | 8.78 | 16.7 | 3.78 | 8.72 | 16.87 | 0.55 |
| | **r** | 0.94 | 0.96 | -0.08 | 0.94 | 0.96 | 0.56 |
| **MERRA2** | **BIAS (W/m²)** | 0.01 | 0.7 | -0.04 | 0.06 | 0.97 | -0.06 |
| | **RMSE (W/m²)** | 10.03 | 17.13 | 3.7 | 10.13 | 17.29 | 0.54 |
| | **r** | 0.92 | 0.95 | 0.18 | 0.91 | 0.94 | 0.56 |
| **OAFlux** | **BIAS (W/m²)** | 4.02 | 6.35 | 0.13 | 4 | 7.4 | -0.01 |
| | **RMSE (W/m²)** | 11.54 | 25.02 | 3.38 | 11.65 | 25.18 | 0.57 |
| | **r** | 0.9 | 0.9 | -0.1 | 0.89 | 0.89 | 0.42 |
| **OHF** | **BIAS (W/m²)** | 12.56 | 13.63 | 0.2 | 13.32 | 14.86 | 0.14 |
| | **RMSE (W/m²)** | 20.14 | 33.67 | 1.1 | 20.44 | 34.17 | 0.63 |
| | **r** | 0.8 | 0.82 | 0.15 | 0.79 | 0.81 | 0.36 |
| **Physical-free NN models** | **BIAS (W/m²)** | 0.17 | 6.24 | -0.01 | 0.37 | 6.66 | -0.06 |
| | **RMSE (W/m²)** | 9.43 | 16.46 | 1.61 | 9.5 | 16.65 | 0.56 |
| | **r** | 0.93 | 0.96 | 0.09 | 0.92 | 0.96 | 0.47 |
| **BrTHF** | **BIAS (W/m²)** | -0.97 | -1.57 | -0.06 | -0.68 | -0.95 | -0.09 |
| | **RMSE (W/m²)** | 9.63 | 15.6 | 0.73 | 9.63 | 15.45 | 0.52 |
| | **r** | 0.93 | 0.96 | 0.34 | 0.92 | 0.96 | 0.56 |

**Table S5. Statistical metrics of the targeted cross-validation of estimated daily SHF, LHF and $\beta$ from the BrTHF model, physics-free NN models and seven widely used products, with and without removing estimated $\beta$ ($\beta$ < -5 or $\beta$ > 5 in the physics-free NN and seven widely used products) that deviates from the range of $\beta$ observations collected from the Global Southern Ocean Station (GSOS) buoy.**

| | | All Samples (900) | | | Samples (795) excluding $\beta$ < -5 or $\beta$ > 5 | | |
|---|---|---|---|---|---|---|---|
| | | SHF | LHF | $\beta$ | SHF | LHF | $\beta$ |
| JOFURO 3 | BIAS (W/m$^2$) | 13.63 | -11.03 | 0 | 13.19 | -11.72 | 0.28 |
| | RMSE (W/m$^2$) | 16.65 | 21.83 | 7.67 | 16.4 | 22.1 | 0.65 |
| | r | 0.88 | 0.9 | -0.07 | 0.86 | 0.9 | 0.38 |
| IFREMER | BIAS (W/m$^2$) | -7.6 | -0.39 | -0.23 | -9.14 | -0.17 | -0.21 |
| | RMSE (W/m$^2$) | 13.76 | 12.45 | 8.21 | 13.74 | 12.07 | 0.46 |
| | r | 0.91 | 0.93 | 0.01 | 0.92 | 0.92 | 0.53 |
| SeaFlux | BIAS (W/m$^2$) | 0.41 | 2.23 | 0.2 | -0.03 | 2.26 | 0.02 |
| | RMSE (W/m$^2$) | 7.27 | 9.85 | 3.54 | 7 | 9.84 | 0.54 |
| | r | 0.93 | 0.96 | 0.1 | 0.93 | 0.96 | 0.4 |
| ERA5 | BIAS (W/m$^2$) | 4.47 | -8.18 | 0.44 | 3.74 | -9.05 | 0.15 |
| | RMSE (W/m$^2$) | 7.5 | 13.34 | 5.53 | 6.82 | 13.93 | 0.46 |
| | r | 0.97 | 0.98 | 0.02 | 0.97 | 0.97 | 0.62 |
| MERRA2 | BIAS (W/m$^2$) | -0.98 | -5.35 | 0 | -1.4 | -5.64 | -0.02 |
| | RMSE (W/m$^2$) | 6.87 | 10.43 | 1.73 | 6.83 | 10.65 | 0.4 |
| | r | 0.94 | 0.97 | 0.23 | 0.94 | 0.96 | 0.55 |
| OAFlux | BIAS (W/m$^2$) | 9.99 | 7.62 | -0.21 | 9.48 | 8.26 | 0.24 |
| | RMSE (W/m$^2$) | 12.43 | 15.81 | 15.65 | 11.9 | 16.26 | 0.64 |
| | r | 0.92 | 0.91 | 0.09 | 0.93 | 0.9 | 0.59 |
| OHF | BIAS (W/m$^2$) | 15.87 | 3.74 | -1.36 | 16.32 | 3.67 | 0.36 |
| | RMSE (W/m$^2$) | 20.07 | 16.79 | 39.08 | 20.6 | 17.06 | 0.87 |
| | r | 0.77 | 0.87 | -0.01 | 0.76 | 0.85 | 0.24 |
| Physical-free NN models | BIAS (W/m$^2$) | -2.09 | 3.38 | -0.17 | -2.11 | 3.33 | -0.08 |
| | RMSE (W/m$^2$) | 6.64 | 9.71 | 2.81 | 6.55 | 9.73 | 0.41 |
| | r | 0.95 | 0.96 | 0.05 | 0.95 | 0.96 | 0.53 |
| BrTHF | BIAS (W/m$^2$) | 2.12 | -1.43 | 0.1 | 2.28 | -0.51 | 0.04 |
| | RMSE (W/m$^2$) | 6.38 | 9.92 | 0.74 | 6.35 | 9.91 | 0.38 |
| | r | 0.95 | 0.96 | 0.16 | 0.95 | 0.96 | 0.51 |

**Table S6. Statistical metrics of the spatial ten-fold cross-validation of estimated daily SHF, LHF and $\beta$ from the BrTHF model, with and without removing estimated $\beta$ ($\beta$ < -5 or $\beta$ > 5 in the physics-free NN and seven widely used products) that deviates from the range of $\beta$ observations collected from the SOFS buoy.**

| | | All Samples (1466) | | | Samples (1400) excluding $\beta$ < -5 or $\beta$ > 5 | | |
|---|---|---|---|---|---|---|---|
| | | SHF | LHF | $\beta$ | SHF | LHF | $\beta$ |
| SOFS | BIAS (W/m$^2$) | -1.04 | -3.46 | -0.08 | -0.65 | -2.85 | -0.01 |
| | RMSE (W/m$^2$) | 9.43 | 15.36 | 0.73 | 9.36 | 15.12 | 0.52 |
| | r | 0.93 | 0.97 | 0.35 | 0.93 | 0.97 | 0.54 |

**Table S7. Statistical metrics of the spatial ten-fold cross-validation of estimated daily SHF, LHF and $\beta$ from the BrTHF model, with and without removing estimated $\beta$ ($\beta$ < -5 or $\beta$ > 5 in the physics-free NN and seven widely used products) that deviates from the range of $\beta$ observations collected from the GSOS buoy.**

| | | All Samples (900) | | | Samples (795) excluding $\beta$ < -5 or $\beta$ > 5 | | |
|---|---|---|---|---|---|---|---|
| | | SHF | LHF | $\beta$ | SHF | LHF | $\beta$ |
| GSOS | BIAS (W/m$^2$) | 1.1 | -0.78 | 0.07 | 1.14 | 0.04 | 0.01 |
| | RMSE (W/m$^2$) | 6.14 | 10.51 | 0.73 | 6.01 | 9.98 | 0.40 |
| | r | 0.95 | 0.95 | 0.19 | 0.95 | 0.95 | 0.54 |

**Table S8. Metrics of data coverage of observations across the six basins, based on the ocean boundaries shown in Figure 2. The Nearest Neighbor Distance (NND) is defined as the minimum distance from each buoy to its closest neighboring buoy.**

| | Area ($\times 10^4$ km$^2$) | Number of Buoys | Buoy density | Number of samples | Samples density | Nearest Neighbor Distance (km) | STD of NND (km) |
|---|---|---|---|---|---|---|---|
| Arctic Ocean | 1557 | 5 | 0.0003 | 1357 | 0.087 | 670.1 | 261.4 |
| Southern Pacific Ocean | 9014 | 28 | 0.0031 | 181604 | 20.147 | 515.9 | 632.1 |
| Northern Pacific Ocean | 8394 | 69 | 0.0082 | 110406 | 13.153 | 408.2 | 396.8 |
| Southern Atlantic Ocean | 4281 | 7 | 0.0016 | 127310 | 29.738 | 792.8 | 825.7 |
| Northern Atlantic Ocean | 4174 | 62 | 0.0148 | 16748 | 4.012 | 397.1 | 353.1 |
| Indian Ocean | 7816 | 26 | 0.0033 | 26160 | 3.347 | 803.2 | 1278.2 |

**Table S9. Sensitivity of BrTHF-derived SHF and LHF performance metrics to different ranges of $\beta$ constraint.**

| $\beta$ | SHF | | | LHF | | |
|---|---|---|---|---|---|---|
| | BIAS ($W/m^2$) | RMSE ($W/m^2$) | r | BIAS ($W/m^2$) | RMSE ($W/m^2$) | r |
| [-1,1] | -0.12 | 6.1 | 0.9 | -0.36 | 23.97 | 0.91 |
| [-5,5] | 0.09 | 6.05 | 0.9 | 0.14 | 23.67 | 0.91 |
| [-10,10] | -0.17 | 6.11 | 0.9 | -0.15 | 23.78 | 0.91 |
| [-20,20] | -0.14 | 6.16 | 0.9 | -0.76 | 24.27 | 0.91 |
| [-50,50] | 0.07 | 6.13 | 0.9 | 0.24 | 24.4 | 0.91 |

**Table S10. Sensitivity of the BrTHF model to different environmental inputs. RMSEs of SHF, LHE, and $\beta$ under different control scenarios are evaluated against daily observations from 197 buoys, with relative changes compared to the baseline scenario (SHF = 6.05 W/m$^2$, LHE = 23.67 W/m$^2$, $\beta$ = 0.22) shown in parentheses.**

| Input | | SHF (W/m$^2$) | LHF (W/m$^2$) | $\beta$ | Input | | SHF (W/m$^2$) | LHF (W/m$^2$) | $\beta$ |
|---|---|---|---|---|---|---|---|---|---|
| ***SLP*** | **+5%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) | ***WS*** | **+5%** | 6.1 (+0.83%) | 23.77 (+0.42%) | 0.22 (+0.0%) |
| | **-5%** | 6.05 (+0.0%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **-5%** | 6.04 (-0.17%) | 23.7 (+0.13%) | 0.22 (+0.0%) |
| | **+10%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **+10%** | 6.17 (+1.98%) | 24.01 (+1.44%) | 0.22 (+0.0%) |
| | **-10%** | 6.05 (+0.0%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **-10%** | 6.05 (+0.0%) | 23.87 (+0.84%) | 0.22 (+0.0%) |
| | **+20%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **+20%** | 6.4 (+5.79%) | 24.88 (+5.11%) | 0.23 (+4.55%) |
| | **-20%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **-20%** | 6.15 (+1.65%) | 24.61 (+3.97%) | 0.22 (+0.0%) |
| ***SW*** | **+5%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) | ***SWH*** | **+5%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) |
| | **-5%** | 6.05 (+0.0%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **-5%** | 6.06 (+0.17%) | 23.66 (-0.04%) | 0.22 (+0.0%) |
| | **+10%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **+10%** | 6.06 (+0.17%) | 23.68 (+0.04%) | 0.22 (+0.0%) |
| | **-10%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **-10%** | 6.06 (+0.17%) | 23.66 (-0.04%) | 0.22 (+0.0%) |
| | **+20%** | 6.08 (+0.5%) | 23.68 (+0.04%) | 0.22 (+0.0%) | | **+20%** | 6.06 (+0.17%) | 23.71 (+0.17%) | 0.22 (+0.0%) |
| | **-20%** | 6.07 (+0.33%) | 23.68 (+0.04%) | 0.22 (+0.0%) | | **-20%** | 6.07 (+0.33%) | 23.68 (+0.04%) | 0.22 (+0.0%) |
| ***LW*** | **+5%** | 6.05 (+0.0%) | 23.67 (+0.0%) | 0.22 (+0.0%) | ***$T_p$*** | **+5%** | 6.05 (+0.0%) | 23.67 (+0.0%) | 0.22 (+0.0%) |
| | **-5%** | 6.06 (+0.17%) | 23.66 (-0.04%) | 0.22 (+0.0%) | | **-5%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) |
| | **+10%** | 6.05 (+0.0%) | 23.69 (+0.08%) | 0.22 (+0.0%) | | **+10%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) |
| | **-10%** | 6.07 (+0.33%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **-10%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) |
| | **+20%** | 6.06 (+0.17%) | 23.72 (+0.21%) | 0.22 (+0.0%) | | **+20%** | 6.06 (+0.17%) | 23.68 (+0.04%) | 0.23 (+4.55%) |
| | **-20%** | 6.09 (+0.66%) | 23.69 (+0.08%) | 0.23 (+4.55%) | | **-20%** | 6.06 (+0.17%) | 23.68 (+0.04%) | 0.22 (+0.0%) |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ***SSS*** | **+5%** | 6.05 (+0.0%) | 23.67 (+0.0%) | 0.22 (+0.0%) | ***diff$_T$*** | **+5%** | 6.15 (+1.65%) | 23.68 (+0.04%) | 0.23 (+4.55%) |
| | **-5%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **-5%** | 6.05 (+0.0%) | 23.66 (-0.04%) | 0.22 (+0.0%) |
| | **+10%** | 6.05 (+0.0%) | 23.68 (+0.04%) | 0.22 (+0.0%) | | **+10%** | 6.33 (+4.63%) | 23.7 (+0.13%) | 0.23 (+4.55%) |
| | **-10%** | 6.06 (+0.17%) | 23.68 (+0.04%) | 0.22 (+0.0%) | | **-10%** | 6.14 (+1.49%) | 23.65 (-0.08%) | 0.22 (+0.0%) |
| | **+20%** | 6.06 (+0.17%) | 23.72 (+0.21%) | 0.22 (+0.0%) | | **+20%** | 6.94 (+14.71%) | 23.75 (+0.34%) | 0.23 (+4.55%) |
| | **-20%** | 6.08 (+0.5%) | 23.71 (+0.17%) | 0.22 (+0.0%) | | **-20%** | 6.56 (+8.43%) | 23.65 (-0.08%) | 0.22 (+0.0%) |
| ***ADT*** | **+5%** | 6.06 (+0.17%) | 23.68 (+0.04%) | 0.22 (+0.0%) | ***diff$_Q$*** | **+5%** | 6.07 (+0.33%) | 23.75 (+0.34%) | 1.84 (+736.36%) |
| | **-5%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | **-5%** | 6.04 (-0.17%) | 23.77 (+0.42%) | 0.23 (+4.55%) |
| | **+10%** | 6.06 (+0.17%) | 23.7 (+0.13%) | 0.23 (+4.55%) | | **+10%** | 6.1 (+0.83%) | 24 (+1.39%) | 0.28 (+27.27%) |
| | **-10%** | 6.07 (+0.33%) | 23.7 (+0.13%) | 0.22 (+0.0%) | | **-10%** | 6.04 (-0.17%) | 24.08 (+1.73%) | 0.23 (+4.55%) |
| | **+20%** | 6.09 (+0.66%) | 23.8 (+0.55%) | 0.23 (+4.55%) | | **+20%** | 6.17 (+1.98%) | 24.93 (+5.32%) | 2.09 (+850.0%) |
| | **-20%** | 6.11 (+0.99%) | 23.78 (+0.46%) | 0.22 (+0.0%) | | **-20%** | 6.05 (+0.0%) | 25.31 (+6.93%) | 0.23 (+4.55%) |
| ***CS*** | **+5%** | 6.06 (+0.17%) | 23.67 (+0.0%) | 0.22 (+0.0%) | | | | | |
| | **-5%** | 6.05 (+0.0%) | 23.66 (-0.04%) | 0.22 (+0.0%) | | | | | |
| | **+10%** | 6.06 (+0.17%) | 23.68 (+0.04%) | 0.22 (+0.0%) | | | | | |
| | **-10%** | 6.05 (+0.0%) | 23.66 (-0.04%) | 0.22 (+0.0%) | | | | | |
| | **+20%** | 6.06 (+0.17%) | 23.69 (+0.08%) | 0.22 (+0.0%) | | | | | |
| | **-20%** | 6.05 (+0.0%) | 23.66 (-0.04%) | 0.22 (+0.0%) | | | | | |

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**Table S11. Statistical metrics of the spatial ten-fold cross-validation of estimated daily SHF, LHF and $\beta$ from the BrTHF model and seven widely used products, with and without removing estimated $\beta$ ($\beta$ < -5 or $\beta$ > 5 in the seven widely used products) that deviates from the range of $\beta$ observations collected from the 197 buoys. The observations of SHF, LHF and $\beta$ were calculated from the high-frequency meteorological variables at sites.**

| | | All Samples (462082) | | | Samples (458233) excluding $\beta$ < -5 or $\beta$ > 5 | | |
|---|---|---|---|---|---|---|---|
| | | SHF | LHF | $\beta$ | SHF | LHF | $\beta$ |
| JOFURO 3 | BIAS (W/m$^2$) | 2.06 | -0.61 | 0.04 | 2.01 | -0.59 | 0.03 |
| | RMSE (W/m$^2$) | 9.02 | 30.32 | 9.97 | 8.94 | 30.36 | 0.23 |
| | r | 0.87 | 0.86 | 0.0 | 0.86 | 0.85 | 0.28 |
| IFREMER | BIAS (W/m$^2$) | -4.49 | 4.74 | -0.04 | -4.5 | 4.79 | -0.04 |
| | RMSE (W/m$^2$) | 9.8 | 28.92 | 5.36 | 9.76 | 28.91 | 0.18 |
| | r | 0.91 | 0.86 | 0.03 | 0.91 | 0.86 | 0.45 |
| SeaFlux | BIAS (W/m$^2$) | 0.48 | -2.88 | 0.01 | 0.48 | -2.87 | 0.01 |
| | RMSE (W/m$^2$) | 6.92 | 27.56 | 0.87 | 6.88 | 27.62 | 0.18 |
| | r | 0.9 | 0.88 | 0.08 | 0.9 | 0.87 | 0.34 |
| ERA5 | BIAS (W/m$^2$) | -2.62 | -10.72 | -0.01 | -2.69 | -10.78 | -0.01 |
| | RMSE (W/m$^2$) | 7.15 | 28.86 | 2.29 | 7.11 | 28.95 | 0.17 |
| | r | 0.91 | 0.89 | 0.03 | 0.91 | 0.89 | 0.4 |
| MERRA2 | BIAS (W/m$^2$) | 0.01 | -15.5 | -0.00 | -0.0 | -15.6 | 0.01 |
| | RMSE (W/m$^2$) | 6.53 | 35.9 | 8.02 | 6.5 | 36.02 | 0.17 |
| | r | 0.92 | 0.84 | 0.01 | 0.91 | 0.84 | 0.4 |
| OAFlux | BIAS (W/m$^2$) | -0.02 | 3.72 | 0.01 | -0.06 | 3.79 | 0.01 |
| | RMSE (W/m$^2$) | 7.86 | 32.09 | 1.78 | 7.81 | 32.16 | 0.19 |
| | r | 0.9 | 0.83 | 0.02 | 0.9 | 0.83 | 0.35 |
| OHF | BIAS (W/m$^2$) | 3.02 | 7.74 | 0.01 | 2.95 | 7.81 | 0.03 |
| | RMSE (W/m$^2$) | 12.11 | 34.81 | 23.11 | 11.74 | 34.81 | 0.26 |
| | r | 0.69 | 0.81 | 0.0 | 0.71 | 0.8 | 0.13 |
| BrTHF | BIAS (W/m$^2$) | -0.15 | -0.75 | 0.01 | -0.13 | -0.65 | 0.0 |
| | RMSE (W/m$^2$) | 6.07 | 23.61 | 0.21 | 6.02 | 23.62 | 0.15 |
| | r | 0.93 | 0.91 | 0.26 | 0.93 | 0.91 | 0.42 |

**Table S12. Statistical metrics of the spatial ten-fold cross-validation of estimated daily SHF, LHF and $\beta$ from the BrTHF model and COARE3.5 model, with and without removing estimated $\beta$ ($\beta$ < -5 or $\beta$ > 5 in the COARE3.5 model) that deviates from the range of $\beta$ observations collected from the 197 buoys.**

| | | All Samples (463585) | | | Samples (463127) excluding $\beta$ < -5 or $\beta$ > 5 | | |
|---|---|---|---|---|---|---|---|
| | | **SHF** | **LHF** | **$\beta$** | **SHF** | **LHF** | **$\beta$** |
| **BrTHF** | **BIAS (W/m$^2$)** | 0.09 | 0.14 | -0.01 | 0.13 | 0.08 | 0.00 |
| | **RMSE (W/m$^2$)** | 6.05 | 23.67 | 0.22 | 6.02 | 23.7 | 0.21 |
| | **r** | 0.93 | 0.91 | 0.25 | 0.93 | 0.91 | 0.31 |
| **COARE3.5** | **BIAS (W/m$^2$)** | -6.48 | -21.32 | -0.03 | -6.49 | -21.34 | -0.03 |
| | **RMSE (W/m$^2$)** | 10.3 | 34.44 | 6.35 | 10.3 | 34.45 | 0.23 |
| | **r** | 0.9 | 0.9 | 0.01 | 0.9 | 0.9 | 0.28 |

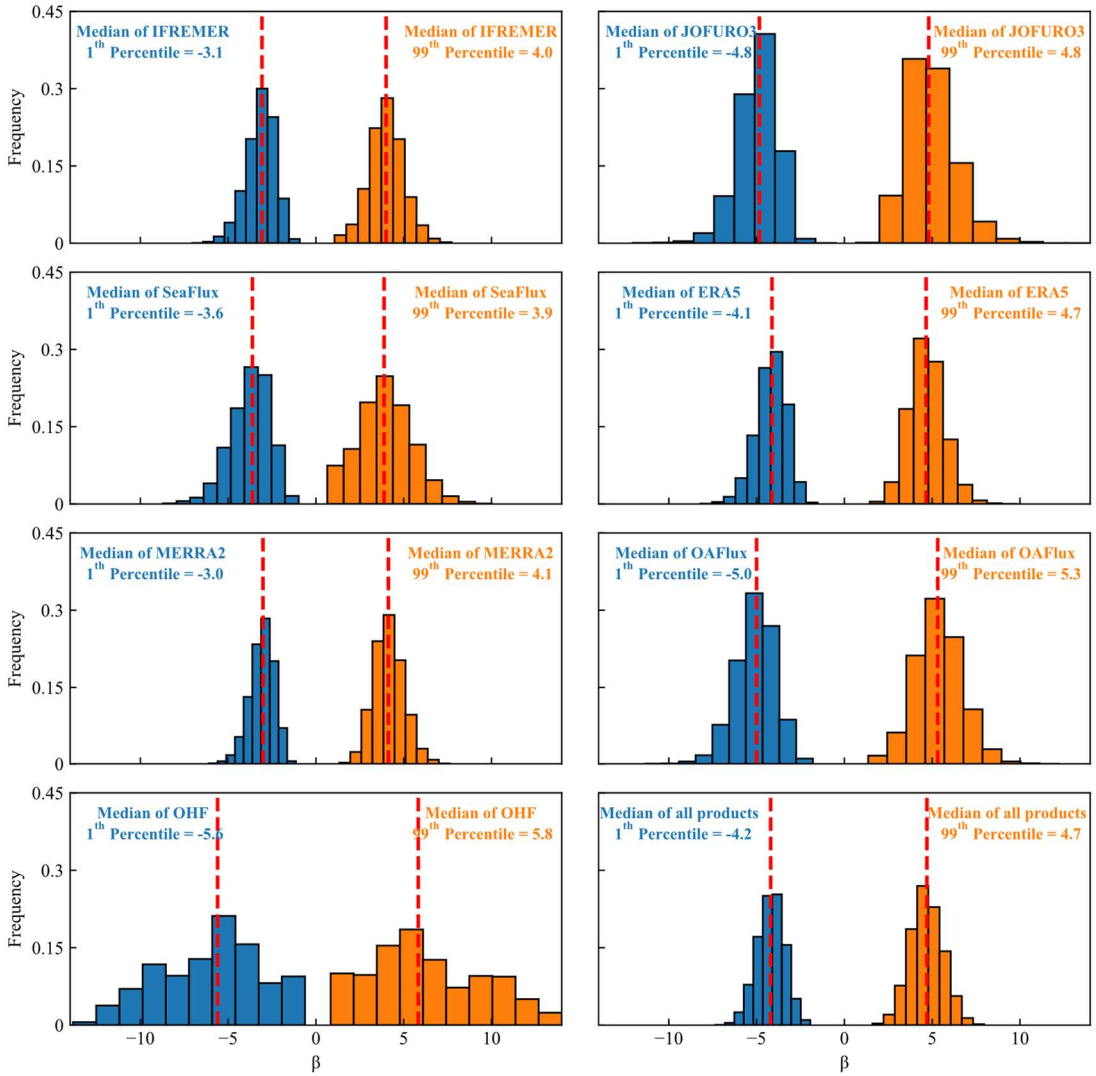


**Figure S1. The cumulative distributions of daily 1st and 99th percentiles of $\beta$ calculated from seven products and their union ensembles. The red dashed lines in each sub-figures represent the medians of the 1st and 99th percentiles, respectively.**

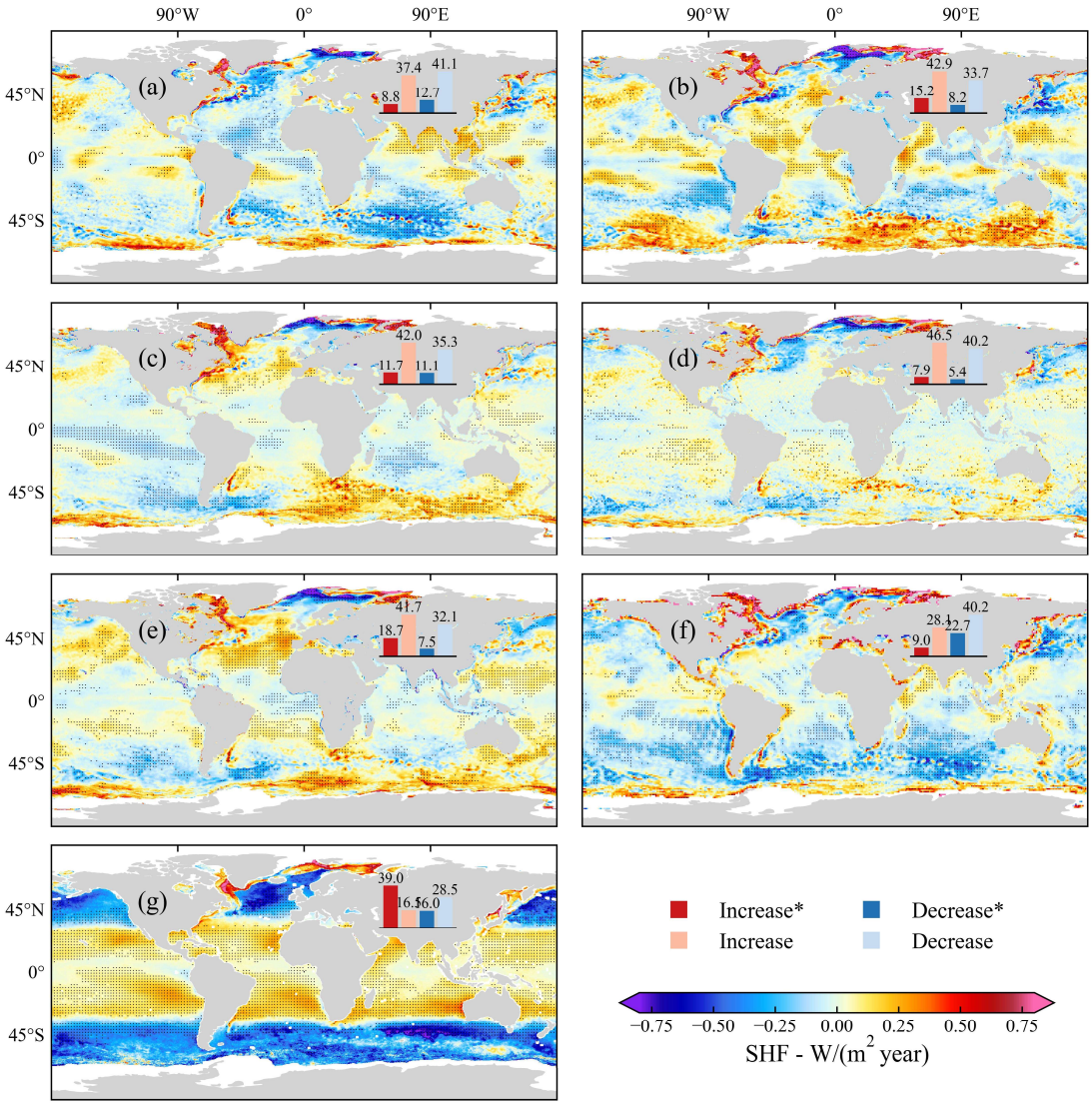


**Figure S2. Spatial maps of inter-annual trends for SHF from JOFURO3 (a), IFREMER (b), SeaFlux (c), ERA5 (d), MERRA2 (e), OAFlux (f), OHF (g) for the period 1993 to 2017. The trends were calculated using the Sen's slope method. Dotted areas indicate oceans where the p-value of the Mann-Kendall significance test is less than 0.05.**

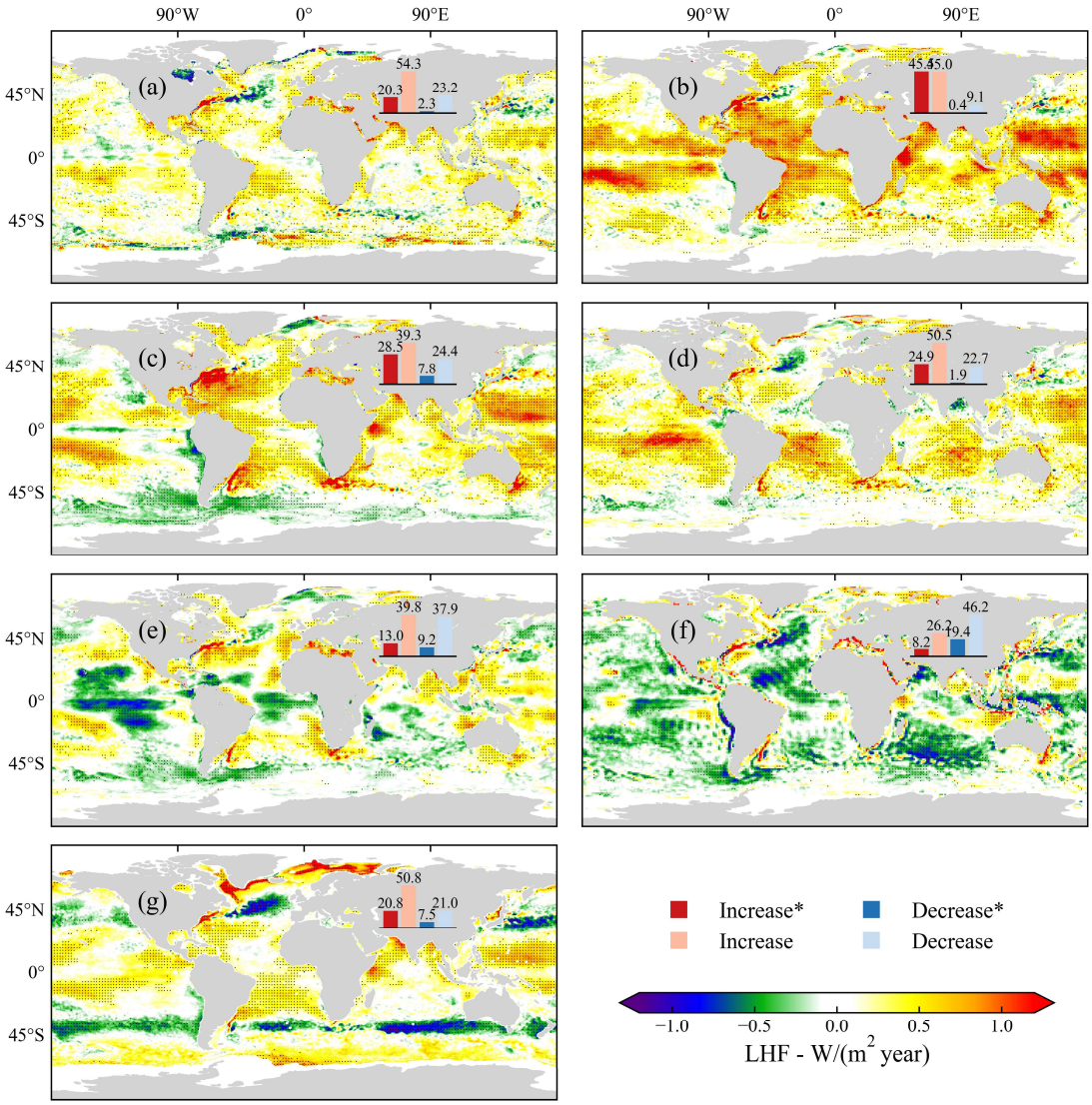


**Figure S3. Spatial maps of inter-annual trends for LHF from JOFURO3 (a), IFREMER (b), SeaFlux (c), ERA5 (d), MERRA2 (e), OAFlux (f), OHF (g) for the period 1993 to 2017. The trends were calculated using the Sen's slope method. Dotted areas indicate oceans where the p-value of the Mann-Kendall significance test is less than 0.05.**

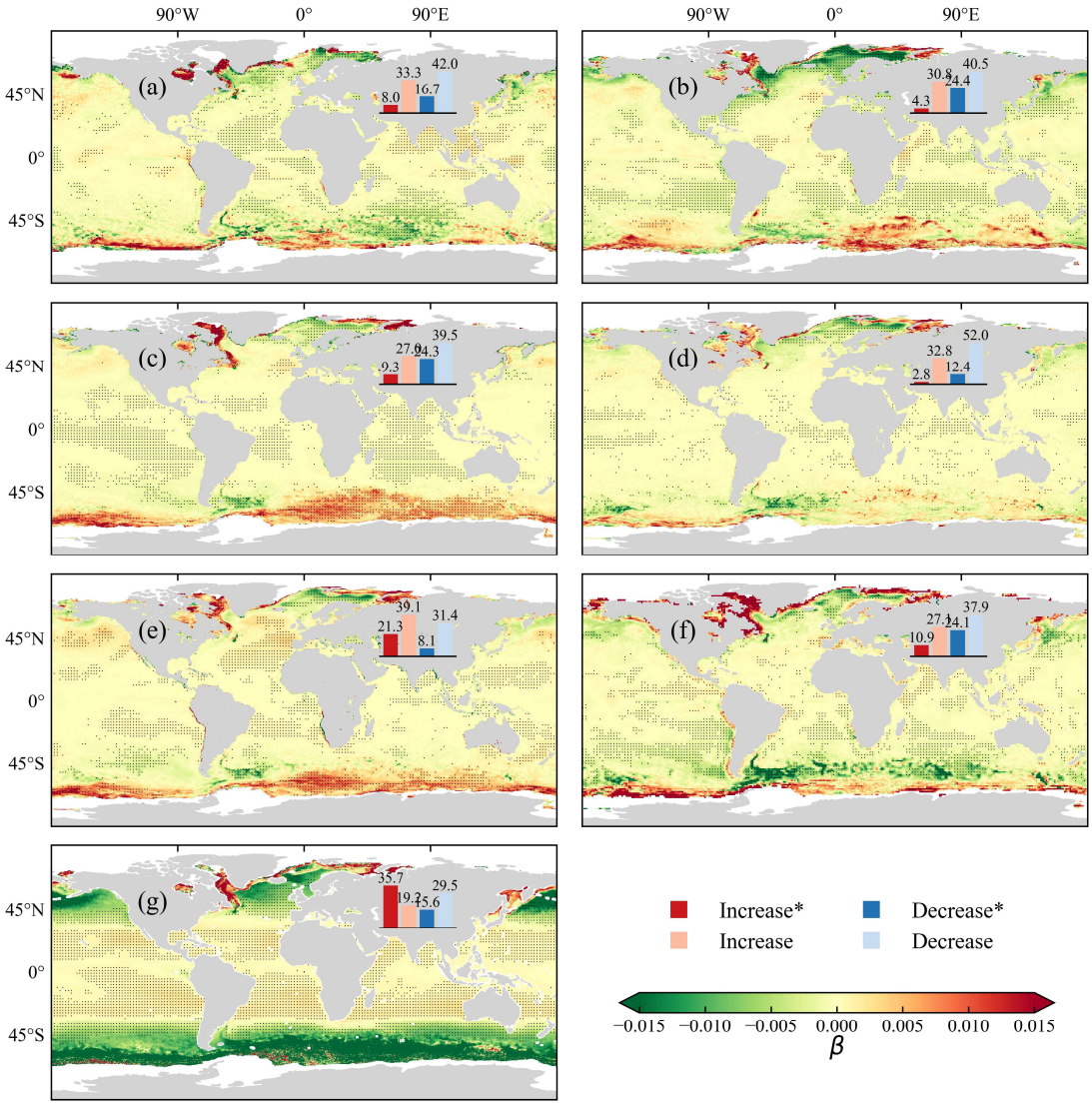


**Figure S4. Spatial maps of inter-annual trends for $\beta$ from JOFURO3 (a), IFREMER (b), SeaFlux (c), ERA5 (d), MERRA2 (e), OAFlux (f), OHF (g) for the period 1993 to 2017. The trends were calculated using the Sen's slope method. Dotted areas indicate oceans where the p-value of the Mann-Kendall significance test is less than 0.05.**