3.2 THE PERFORMANCE OF SEA SURFACE TURBULENT FLUX ALGORITHMS OVER THE GLOBAL OCEANS

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1. INTRODUCTION

Knowledge of the sea surface turbulent fluxes, *i.e.*, latent and sensible heat fluxes as well as momentum flux or wind stress, is important for understanding air-sea interactions, forcing ocean models, evaluating numerical weather prediction and coupled atmosphere-ocean models, understanding the ocean heat and freshwater budget, and the partitioning of the global pole-to-equator transport between the atmosphere and ocean. Bulk aerodynamic algorithms are used to calculate these fluxes in weather forecasting and climate models and to produce data sets such as the Hamburg Ocean Atmosphere Parameters from Satellite Data (HOAPS) (http://www.mpimet.mpg.de/Depts/Physik/HOAPS), the Goddard Satellite-Based Surface Turbulent Fluxes (GSSTF) (Chou et al. 2001, 2002; http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/hydrology/hd_main.html), and the Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations (J-OFURO) (Kubota et al. 2002; http://dtsv.scc.u-tokai.ac.jp). These algorithms utilize Monin-Obukhov similarity theory to relate the turbulent fluxes to the bulk aerodynamic variables such that:

$$\tau = \rho_a C_D S U \,, \qquad (1)$$

$$\mathrm{LH} = \rho_a L_v C_E S(q_s - q_a) \,, \qquad (2)$$

and

$$\mathrm{SH} = \rho_a C_p C_H S(\theta_s - \theta_a) \qquad (3)$$

momentum (or drag coefficient), C_E is the exchange coefficient for moisture, C_H is the exchange coefficient for heat, U is the near-surface wind speed, S is the near-surface wind speed with convective gustiness if it is considered ($S = U$ otherwise), q_s and q_a are the surface and near-surface atmospheric specific humidities respectively, and θ_s and θ_a are the surface and near-surface potential temperatures respectively.

Presented here is an evaluation of the performance of 12 such algorithms based upon an extensive data set of inertial-dissipation and covariance flux measurements. The algorithms, listed in Table 1, are commonly used by the community, in modeling and data assimilation, and in the generation of satellite-based data sets. These algorithms differ in terms of what waves they explicitly consider and whether or not they consider convective gustiness, the effect of salinity in depressing the sea surface saturated humidity, and the cool skin/warm layer effect on sea surface temperature. These differences are also listed in Table 1.

The flux measurements and surface observations which are used as input into the algorithms are from 12 experiments performed by the Environmental Technology Laboratory (ETL) and Centre d'Etude des Environments Terrestre et Planétaires (CETP) from 5°S to 60°N. These experiments are listed in Table 2 along with when and where these experiments took place. The surface saturated humidity, q_s, is calculated by each of the algorithms from SST according to their respective formulae, and bulk SST is adjusted for the warm layer/cool skin effect in those algorithms that include this formulation (see Table 1).

2. RESULTS

The computed fluxes by the algorithms are compared with the observed inertial-dissipation wind stress, covariance latent heat (LH) flux, and covariance sensible heat (SH) flux when available. For CATCH, only the inertial-dissipation fluxes were available for latent and sensible heat fluxes. Thus, these were used to compare with the computed fluxes during this cruise.

The results of this comparison have shown that the algorithms have significantly high biases

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TABLE 1. The algorithms used in this study. Also listed are the differences in how the algorithms consider waves, convective gustiness, the salinity effect on surface saturated humidity, and the cool skin/warm layer effect.

Algorithm	Acronym	Waves	Conv. gust.	Salinity effect	Cool skin/ warm layer
Dupuis et al. (1997)/Yelland & Taylor (1996) coeffs.					
with convective gustiness	BDY-C	gravity	yes	yes	no
without convective gustiness	BDY-NC	gravity	no	yes	no
Bourassa-Vincent-Wood (Bourassa et al. 1999)	BVW	gravity, capillary	yes	yes	no
Community Climate Model version 3 (Large and Pond 1981, 1982)	CCM3	gravity	no	yes	no
Clayson-Fairall-Curry (Clayson et al. 1996)	CFC	gravity, capillary	no	yes	yes
Coupled Ocean-Atmosphere Response Experiment version 3 (Fairall et al. 1996; 2001, paper submitted to *J. Climate*)	COARE 3.0	gravity	yes	yes	yes
European Centre for Medium-Range Weather Forecasting (Beljaars 1995a,b)	ECMWF	gravity	yes	no	no
Goddard Earth Observing System reanalysis version 1 (Large and Pond 1981; Kondo 1975)	GEOS-1	gravity	no	no	no
Goddard Satellite-Based Surface Turbulent Fluxes version 2 (Chou 1993)	GSSTF-2	gravity	no	yes	no
Hamburg Ocean Atmosphere Parameters from Satellite Data (Smith 1988)	HOAPS	gravity	no	yes	no
Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations (Kondo 1975; Large and Pond 1982; Kubota and Mitsumori 1997)	J-OFURO	gravity	no	no	no
The University of Arizona (Zeng et al. 1998)	UA	gravity	yes	yes	no

for certain cruises. In particular, the wind stress and sensible heat flux biases for CATCH are considerably higher than from the other cruises. These high biases might be contributed by strong pitching and rolling of the ship due to the sea state for wind stress (Eymard et al. 1999) and to the use of inertial-dissipation sensible heat fluxes instead of covariance fluxes. Also, some algorithms consistently have the highest biases. For wind stress the highest biases are from both versions of BDY, BVW, CFC, and J-OFURO, and for LH and SH flux the highest biases are from both versions

TABLE 2. The experiments used in this study as well as when and where they were.

Experiment	Acronym	Institution	Time period	Lat.	Lon.
Atlantic Stratocumulus Transition Experiment	ASTEX	ETL	6/92	30°N	25°W
Couplage avec l'Atmosphère en Conditions Hivernales	CATCH	CETP	1/97-2/97	47°N	40°W
Coupled Ocean-Atmosphere Response Experiment	COARE	ETL	11/91-2/92	2°S	156°E
Fronts and Atlantic Storm Track Experiment	FASTEX	ETL	12/96-1/97	45°N	35°W
Flux, État de la Mer et Télédétection en Condition de Fetch Variable	FETCH	CETP	3/98-4/98	43°N	4.33°E
Joint Air-Sea Monsoon Experiment	JASMINE	ETL	5/99	8°N	89°E
Kwajalein Experiment	KWAJEX	ETL	7/99-9/99	8°N	167.5°E
	Moorings[a]	ETL	9/99-10/99	52°N	140°W
	Nauru '99	ETL	6/99-7/99	0.5°N	167°E
	PACS Flux '99[b]	ETL	11/99-12/99	±10°	100°W
San Clemente Ocean Probing Experiment	SCOPE	ETL	9/93	33°N	118°W
Tropical Instability Wave Experiment	TIWE	ETL	11/91-12/91	0°	140°W

[a] A cruise to service buoys in the North Pacific.

[b] Part of the Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC).

of BDY. The standard deviation of the differences (SDDs) between computed and measured wind stresses, LH fluxes, and SH fluxes do not differ much among algorithms. The SDDs from some cruises, though, are higher (*e.g.*, CATCH) than those from the other cruises. These higher SDDs are probably due to sampling variability in the measured fluxes which is found to vary greatly with wind speed.

In order to evaluate the performance of these 12 algorithms and to determine the least and most problematic algorithms, a scoring system is developed based upon the biases and SDDs. For a particular turbulent flux, a score $s^{i}_{\text{bias}_F}$ (where i = 1 to 12 for each of the cruises and $F = \tau$, LH, or SH) is assigned to each algorithm for each of the 12 cruises based upon the magnitude of its bias. This score can range from 1 for the algorithm with the lowest bias to 12 for the algorithm with the highest bias. Similarly, a score $s^{i}_{\text{SDD}_F}$ is assigned to each algorithm for each cruise based upon its SDD. Then, for each algorithm, the bias and SDD scores are averaged to obtain a mean bias score, $\overline{s_{\text{bias}_F}}$, and a mean SDD score, $\overline{s_{\text{SDD}_F}}$. This method, however, assigns the same weighting to each cruise regardless of the number of data points in each cruise. An alternate method is to score each algorithm based upon the magnitude of its biases, S_{bias_F}, and SDDs, S_{SDD_F}, determined using all of the data from the 12 cruises combined. Thus, a flux score is obtained,

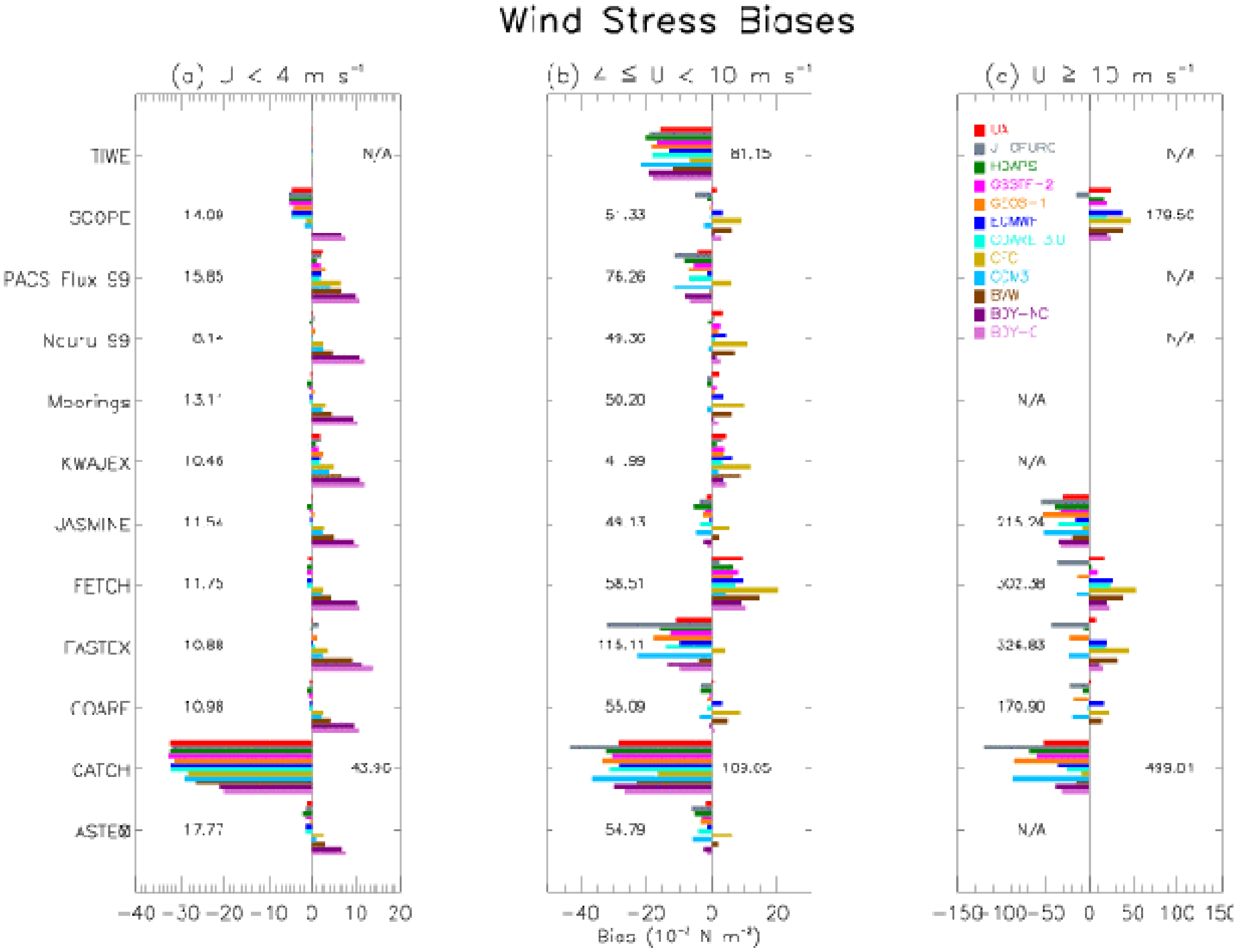

FIG. 1. The wind stress biases multiplied by 10^3 for each of the 12 cruises for three wind speed ranges: (a) $U < 4$ m s^{-1}, (b) $4 \leq U < 10$ m s^{-1}, and (c) $U \geq 10$ m s^{-1}. Each bar represents the bias of each of the 12 algorithms used. N/A means that no acceptable stresses were taken in that range of wind speeds.

$$S_F = \frac{1}{4}\left(\overline{S_{\text{bias}_F}} + \overline{S_{\text{SDD}_F}} + S_{\text{bias}_F} + S_{\text{SDD}_F}\right), \qquad (4)$$

and an overall flux score is obtained by averaging the three flux scores. Then, the algorithms are divided into three categories: A for the four least problematic with the lowest scores, C for the four most problematic with the highest scores, and B for those in between. In alphabetical order, the Category A algorithms are COARE 3.0, ECMWF, GEOS-1, and UA, and the Category C algorithms are BDY-C, BDY-NC, CFC, and J-OFURO. This ranking scheme is found to be rather robust when taking into consideration the effects of the choice of direct fluxes used in the comparison and of measurement uncertainty. Even so, considering all of the uncertainties that go into creating such a ranking scheme, only the differences between Categories A and C are significant.

To understand these rankings, the algorithms are compared over various meteorological conditions. Fig. 1 shows the wind stress biases for three wind speed ranges: (a) light winds ($U < 4$ m s^{-1}), (b) moderate winds ($4 \leq U < 10$ m s^{-1}), and (c) high winds ($U \geq 10$ m s^{-1}). At low wind speeds, the highest biases are usually from both versions of BDY whereas at higher wind speeds the highest biases are usually from BVW and CFC. Fig. 2 is the same as Fig. 1 except for LH flux. Again, BDY has the highest biases and continues to have high biases for higher wind speeds along with ECMWF and CCM3. However, for some cruises J-OFURO's overestimation is much greater than these three algorithms. Similarly, for SH flux the highest biases are produced by both versions of BDY at low wind speeds and continues to do so at higher wind speeds for most cruises with J-OFURO

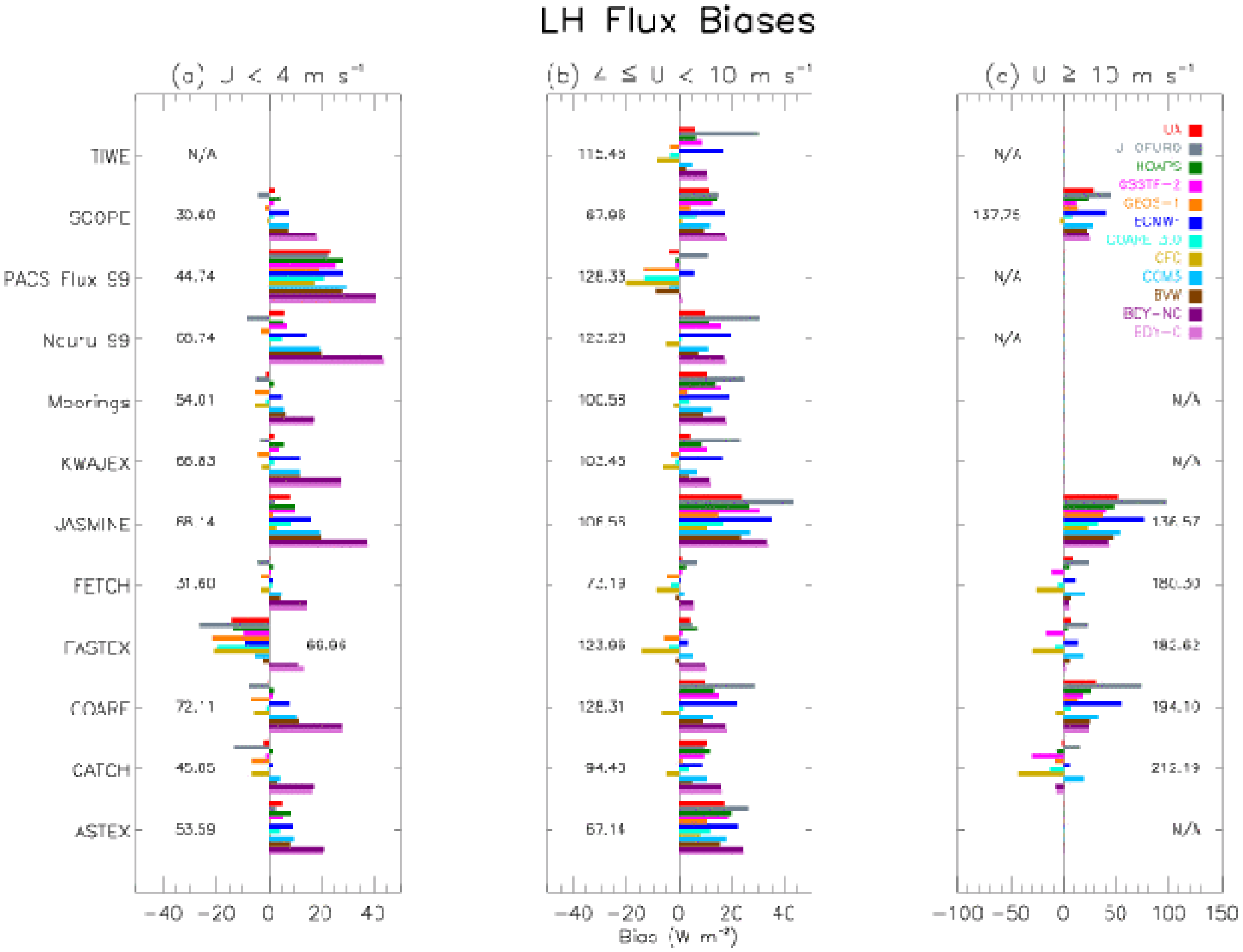

FIG. 2. The same as in Fig. 1 except for latent heat (LH) flux.

surpassing BDY for some cruises.

Across sea surface temperature (SST), both versions of BDY have the highest biases for wind stress, LH flux, and SH flux for warm tropical SSTs (SST > 30°C). For cooler SSTs (SST < 18°C), the highest wind stress biases are from BVW and CFC.

3. DISCUSSION AND CONCLUSIONS

So, of the twelve algorithms compared here, the least problematic based upon the overall Category A rankings are those commonly used in weather forecasting and data assimilation models as well as by the community: COARE 2.6, ECMWF, GEOS-1, and UA. Of the most problematic based upon the overall Category C rankings are BDY with and without convective gustiness, CFC, and J-OFURO. Some explanation of these results will be presented at the Conference. However, some issues still need to be resolved. For instance, all algorithms have exceptionally high biases during some cruises (*e.g.*, CATCH). Also, most algorithms have positive biases for LH flux during certain conditions (moderate wind speeds and tropical SSTs in particular) (Fig. 2). Furthermore, there are the issues of how to parameterize convective gustiness and the exchange coefficients.

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