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On the parameterization of turbulent fluxes over the tropical Eastern Pacific

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Abstract

We present estimates of turbulent fluxes of heat and momentum derived from low level (∼30 m) aircraft measurements over the tropical Eastern Pacific and provide empirical relationships that are valid under high wind speed conditions (up to 25 ms^{-1}). The estimates of total momentum flux and turbulent kinetic energy can be represented very accurately (r^2=0.99, when data are binned every 1 ms^{-1}) by empirical fits with a linear and a cubic terms of the average horizontal wind speed. The latent heat flux shows a strong quadratic dependence on the horizontal wind speed and a linear relationship with the difference between the air specific humidity and the saturated specific humidity at the sea surface, explaining 96% of the variance. The estimated values were used to evaluate the performance of three currently used parameterizations of turbulence fluxes, varying in complexity and computational requirements. The comparisons with the two more complex parameterizations show good agreement between the observed and parameterized latent heat fluxes, with less agreement in the sensible heat fluxes, and one of them largely overestimating the momentum fluxes. A third, very simple parameterization shows a surprisingly good agreement of the sensible heat flux, while momentum fluxes are again overestimated and a poor agreement was observed for the latent heat flux (r^2=0.62). The performance of all three parameterizations deteriorates significantly in the high wind speed regime (above 10–15 ms^{-1}). The dataset obtained over the tropical Eastern Pacific allows us to derive empirical functions for the turbulent fluxes that are applicable from 1 to 25 ms^{-1}, which can be introduced in meteorological models under high wind conditions.

1 Introduction

The atmosphere and oceans interact and are coupled through very small-scale processes that are related to the surface turbulent fluxes of momentum and heat (latent and sensible), as well as to trace gas and particle fluxes. Momentum and heat fluxes are important to the atmospheric and oceanic dynamics, while trace gas and particle fluxes constitute sinks and/or sources for their global budgets. Surface entropy fluxes have been found to relate linearly with the intensification of convection in the tropical Eastern Pacific (Raymond et al., 2003). This correlation was more important than that with the local convective available potential energy (CAPE) or with the convective inhibition (CIN). An accurate representation of all these fluxes in large-scale weather and climate models is needed, but the theory is sometimes not adequate and observations are scarce in many regions of the globe.

In this study we utilize high-resolution measurements obtained close to the surface (between 25 and 50 m a.s.l.) to derive turbulent fluxes of heat and momentum under conditions of high horizontal winds, which are not typically sampled. Furthermore, those observations are use to test the validity of 3 parameterizations currently used in numerical models.

2 Measurements and methodology

The data presented in this study were obtained during two field campaigns in which the C-130 instrumented aircraft (operated by the National Center for Atmospheric Research, NCAR) made low-level flights close to the surface of the ocean. Data were obtained from eight flights during the East Pacific Investigation of Climate (EPIC2001), in September and October 2001 (Raymond et al., 2004). The flight patterns alternated between near the surface (25–50 m) for 10 min and then at 1600 m where another level run was made for ~7 min, heading south along the 95° W meridian from 14° N to 2° S. During February 2004, the same aircraft participated in research flights during the Gulf of Tehuantepec Experiment (GOTEX), again making low-level runs, but the patterns were more variable than those during EPIC2001. The low-level segments from eight flights from GOTEX were utilized for this study.

The high frequency wind measurements were obtained from the five-hole gust probe system located on the radome of the aircraft. The air temperature was determined from one of the Rosemount thermometers and the specific humidity was derived from one of the Lyman-alpha sensors. A detailed description of the sensors and their performance (resolution, precision and errors) can be found in the web page of the Research Aviation Facility at NCAR (http://raf.atd.ucar.edu/Bulletins/bulletin3.html).

Turbulent fluxes of the different variables were obtained as the covariance of the turbulent fluctuations from the mean values averaged over segments of 100 s (which corresponds roughly to 10 km). The mean values were determined over the same segment. Tests were performed to determine the sensitivity to the averaging period, utilizing averages of 1, 5, 10, 15 and 20 km. The results indicate that the mean value of the fluxes was independent of the averaging period, but the variance was largest when 1 km was used. The choice of 10 km is consistent with other studies (Khelif et al., 2005). Data segments were inspected for outliers that were identified and excluded from the analysis. In some cases these outliers were linked to large directional shear close to the ocean (perhaps as a result of gust fronts associated with precipitation in the northern regions of the 95° W flights during EPIC2001). In other cases, outliers were related to segments that included precipitation (as determined by the presence of water drops in the 2D-C probe).

3 Results and discussion

3.1 Determination of turbulent fluxes

The tendency equation for the turbulent kinetic energy (TKE) per unit mass [$\bar{e}=0.5\overline{(u_i'^2)}$] can be written as follows (Stull, 1994):

$$\frac{\partial \bar{e}}{\partial t} + \overline{u_j}\frac{\partial \bar{e}}{\partial x_j} = -\overline{(u_i'u_j')}\frac{\partial \overline{u_i}}{\partial x_j} + \delta_{i3}\frac{\overline{(u_i'\theta_v')}}{\overline{\theta_v}}g - \frac{\partial \overline{(u_j'e')}}{\partial x_j} - \frac{1}{\bar{\rho}}\frac{\partial \overline{(p'u_i')}}{\partial x_i} - \varepsilon \tag{1}$$

where, $\overline{u_j}$ correspond to the mean wind velocities in the 3 dimensions (j=1,3); u_j' , to the turbulent fluctuations of the wind; θ'_v, to the turbulent fluctuation of the virtual potential temperature; p', to the turbulent fluctuation of the pressure; ρ and θ_v, to the mean air density and mean virtual potential temperature, respectively; and ε, to the turbulent dissipation rate. The terms on the left-hand side of this equation correspond to the local tendency and the advection by the mean wind. The terms on the right-hand side of the equation correspond to the production/destruction of turbulent kinetic energy by shear of the mean wind, the production/destruction by buoyancy, the transport term due to turbulent eddies, the redistribution of turbulent kinetic energy by pressure perturbations and the viscous dissipation.

An equivalent expression can be written for the horizontal momentum flux (TMF):

$$\begin{aligned}\frac{\partial\left(\overline{u'_i w'}\right)}{\partial t} + \overline{u_j}\frac{\partial\left(\overline{u'_i w'}\right)}{\partial x_j} = &-\left(\overline{u'_i u'_j}\right)\frac{\partial \overline{w}}{\partial x_j} - \left(\overline{w' u'_j}\right)\frac{\partial \overline{u_i}}{\partial x_j} + \frac{g}{\overline{\theta_v}}\left(\overline{u'_i \theta'_v} + \delta_{i3}\overline{w'\theta'_v}\right)\\ &- \frac{\partial\left(\overline{u'_i u'_j w'}\right)}{\partial x_j} - \frac{1}{\overline{\rho}}\left(\frac{\partial \overline{p' w'}}{\partial x_i} + \frac{\partial \overline{p' u'_i}}{\partial z}\right) + \frac{p'}{\overline{\rho}}\left(\frac{\overline{\partial u'_i}}{\partial z} + \frac{\overline{\partial w'}}{\partial x_i}\right) - 2\varepsilon_{wu_i}\end{aligned} \qquad (2)$$

where i and j=1,2. The terms in this equation (from left to right) correspond to the local tendency of the TMF, the advection by the mean wind, the production/destruction by shear of the mean wind, the production/destruction by buoyancy, the transport term due to turbulent eddies and the redistribution of TMF due to pressure correlations (which are small and usually neglected) and due to the return-to-isotropy term and finally, the viscous dissipation term. The Coriolis and molecular diffusion termas have been neglected.

Inspection and scale analysis of Eqs. (1) and (2) indicate that the dominant terms are: the advection and production by shear terms, which are proportional to the cubic power of the velocity scale, and the buoyancy and transport by pressure perturbations terms, which are a linear function of the velocity scale.

We examined the dependence of the empirically determined fluxes on the mean variables that are predicted in large scale meteorological models: horizontal wind speed, difference between air and sea surface temperature and difference between air specific humidity and saturated specific humidity at the sea surface. The total horizontal

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momentum flux and the turbulent kinetic energy present a strong non-linear relationship with the mean horizontal wind, as shown in Figs. 1a and b. The individual data points were binned in intervals of horizontal wind speeds of 1 $\mathrm{ms^{-1}}$ before determining the best-fit curves. The non-linear regression yields a cubic and a linear term in each case:

$$\mathrm{TMF}=aV + bV^3 \tag{3}$$

$$\mathrm{TKE}=cV + dV^3 \tag{4}$$

where V corresponds to the magnitude of the horizontal wind (in $\mathrm{ms^{-1}}$) and a=3.395E-03 $\mathrm{N\,s\,m^{-3}}$, b=7.72E−05 $\mathrm{N\,s^3\,m^{-5}}$, c=30107E−02 $\mathrm{ms^{-1}}$ and d=2.66E−04 $\mathrm{s\,m^{-1}}$. These fits give correlation coefficients of 0.99 for both the TMF and the TKE.

The relevant budget equation for the turbulent specific humidity flux is given by:

$$\frac{\partial\overline{(q'u'_i)}}{\partial t} + \overline{u_j}\frac{\partial\overline{(q'u'_i)}}{\partial x_j} = -\overline{(q'u'_j)}\frac{\partial\overline{u_i}}{\partial x_j} - \overline{(u'_iu'_j)}\frac{\partial\overline{q}}{\partial x_j} - \frac{\partial\overline{(q'u'_iu'_j)}}{\partial x_j} + \delta_{i3}\frac{\overline{(q'\theta'_v)}}{\overline{\theta_v}}g + \frac{1}{\overline{\rho}}\frac{\overline{(p'\partial q')}}{\partial x_j} - 2\varepsilon_q \tag{5}$$

where $\overline{q}$ and q' correspond to the mean and the turbulent perturbation of the specific humidity, respectively, and the other variables were introduced when discussing Eqs. (1) and (2). Scale analysis of Eq. (5) indicates that the terms range in magnitude from 10^{-4} and 10^{-11}, with the production term due to the gradient of the mean specific humidity being the dominant one and proportional to V^2. The vertical latent heat flux ($\mathrm{LHF}=\rho_{\mathrm{air}}L_v\overline{w'q'}$) has a strong (quadratic) dependence on the horizontal wind speed, while only a linear relationship with the difference of air specific humidity and saturated specific humidity at the sea surface, consistent with the scale analysis of the corresponding budget equation. The LHF estimated as the eddy covariance was stratified in terms of the horizontal wind speed in bins of 1 $\mathrm{ms^{-1}}$, and the following empirical relationship was derived:

$$\mathrm{LHF}=a + bV^2 + c\Delta q \tag{6}$$

where $\Delta q=[q_{air}-qs_{ss}]$ and $a=-100\,W\,m^{-2}$, $b=0.772\,Ws^2\ m^{-4}$ and $c=34216\,W\,m^{-2}$. This relationship explains 96% of the variance for a horizontal wind range between 1 and 20 m s^{-1}. Figure 2 shows the dispersion diagram between observed and predicted latent heat fluxes. It is rather remarkable that such a simple function can reproduce quite accurately the latent heat fluxes covering a wide range of wind speeds, given that the magnitude of the flux also varies over a large range.

In contrast, the vertical sensible heat flux ($SHF=\rho_{air}c_p\overline{w'\theta'}$) exhibited very little dependence on the horizontal wind speed, and only a linear relationship with the air-sea surface temperature difference, as expected. The following empirical relationship, derived as described above, has a correlation coefficient of 0.99,

$$SHF=a+b\Delta T \qquad (7)$$

where $\Delta T=[T_{ss}-T_{air}]$ in Kelvin and $a=1.4\,W\,m^{-2}$ and $b=9.1\,W\,m^{-2}K^{-1}$.

These results provide simple and accurate formulae for the turbulent fluxes of latent and sensible heat, momentum and TKE over the ocean that can be introduced in mesoscale and large scale weather and climate models, to test their sensitivity over a wide range of observed horizontal wind speeds.

3.2 Comparison with parameterizations

The turbulent fluxes derived from the observations (using the covariance method) were compared against the resulting fluxes from three different parameterizations currently utilized, which vary widely in level of complexity and computational requirements. The parameterization presented in Fairall et al. (1996) was derived from the TOGA-COARE field project (herein denoted as F96). The calculation of the turbulent fluxes is based on concepts of Monin-Obhukov similarity, involves an iterative method and is the most computationally expensive of the three parameterizations evaluated. The comparison is fairly good, especially for momentum fluxes. The latent heat fluxes also compared favorably (Fig. 3c), but note that there is a systematic over-estimate for low wind speeds and a systematic under-estimate for wind speeds above 15 m s^{-1}, with also much larger variability. The comparison of the sensible heat fluxes is the poorest of the three, as the parameterization is clearly over-estimating the observations for wind speeds above 15 m s^{-1}. This bias may be due to the fact that the fluxes depend strongly on the temperature difference rather than on the horizontal wind speed. There is no clear explanation for this transition in the behavior of the parameterized values at a particular horizontal wind speed, but it may be because the parameterization may have been derived from observations at lower wind speeds than those sampled in this study.

The parameterization presented by Kara et al. (2000), including the corrections introduced by Kara et al. (2002, herein denoted as K02), are only in moderate agreement with the observations. In particular, the latent heat fluxes derived using the parameterization K02 are more variable than the observations derived by eddy covariance. The correlation coefficient is only 0.62 (compared to 0.87 for the F96 parameterization), with a difference in the mean of the population about 34% from the observations. The sensible heat fluxes are systematically over-estimated, exhibiting the largest variability of the three parameterizations evaluated. The inclusion of the corrections presented by Kara et al. (2002) led to a slight improvement in the representation of all fluxes, particularly of the momentum flux. Figure 3a illustrates the latent heat flux as a function of the horizontal wind showing a clear difference in the performance of the parameterization for winds below and above 10 m s^{-1}. Fluxes are under-estimated for low wind speeds and grossly over-estimated for higher wind speeds. This parameterization represents the poorest comparison with the observed latent heat fluxes.

Mendoza et al. (1997, herein denoted M97) includes a simple parameterization of the air-sea turbulent fluxes to predict sea surface temperature anomalies in the Gulf of Mexico, based on parameterizations from the literature (Isemer and Hasse, 1987, for the wind stress and Adem et al., 1994, for the sensible and latent heat fluxes). The parameterization does not require iterative calculations and the drag coefficients are described in terms of the Richardson number. The evaluation of the performance of this parameterization against the fluxes derived by eddy covariance in the tropical

Eastern Pacific suggests that the parameterization is fairly good given its simplicity. It performs better than K02 for latent and sensible heat fluxes, but over-estimates the turbulent momentum fluxes in the same manner as K02. The correlation coefficient of 0.88 for the latent heat flux is similar to that obtained with F96 and much better than the 0.62 obtained from the K02 parameterization. Fig. 3b shows the performance of the latent heat flux as a function of horizontal wind speed. There is again a difference in performance for low vs. high wind speeds, with fluxes under-estimated for wind speed less than 10 m s^{-1} and over-estimated for higher winds.

Figure 4 presents the observed and parameterized turbulent sensible heat fluxes (SHF) as a function of wind speed. Note that, in contrast with the latent heat fluxes and TKE shown above, the sensible heat fluxes obtained from the observations show no monotonic response as a function of wind speed. There is an increase in the SHF with horizontal wind speeds up to 10 ms^{-1} and no distinguishable trend for higher wind values. For the strongest wind observed (above 15 ms^{-1}), the observations show very small or even negative SFH at 30 m. The reason for this is possibly that these stronger winds were associated with some upwelling of colder seawater, so that the sensible heat was transferred from the ocean to the atmosphere. The three parameterizations perform reasonably well for low wind speeds (below 10 ms^{-1}), with performance becoming increasingly worse as wind speed increases. The correlation coefficients are shown in Table 1, between 0.76 and 0.79 for each parameterization, with significant mean root square errors.

The turbulent horizontal momentum fluxes are presented in Fig. 5 again for observations and the three parameterization, with some statistical parameters shown in Table 2. In this case, there is a monotonic increase with increasing wind speed, behavior reproduced by all three parameterizations. Nevertheless, only F96 is able to reproduce the magnitude of the fluxes, slightly overestimating the observations for winds speeds below 10 ms^{-1} and underestimating them for higher winds speeds. The parameterizations of K02 and M97 systematically overestimate the magnitude of the fluxes, by up to 90%. Such large overestimates would lead to an erroneous momentum transfer in numerical models where these parameterizations were included.

4 Final remarks

Empirical relationships have been determined for the latent and sensible heat fluxes as well as the total horizontal momentum flux and turbulent kinetic energy in a wind speed range from 1 to 25 m s^{-1} (for 10 km averages), applicable over the tropical Eastern Pacific. This range in velocity is larger than previous studies have explored, and, in addition, the Eastern Pacific is a region that has been largely neglected in observational studies. Moreover, because the sea surface temperature in the Eastern Pacific rapidly changes through the sea surface temperature front (observed between 1–2° N), the range of sensible heat fluxes sampled was also large.

The comparison with three currently used parameterizations has shown that the performance of each parameterization as a function of horizontal wind speed is different. F96, derived for TOGA-COARE provides the best results, when applied to the tropical Eastern Pacific. The parameterization presented by M97 and currently used at our research center in Mexico gives a surprisingly good agreement given its simplicity. In fact it performs better than K02 for latent and sensible heat fluxes.

The Working Group on Ocean Model Development of the Climate Variability and Predictability Program (http://www.eprints.soton.ac.uk/91979; WCRP Informal Report 14/2002) is recommending the use of K02 in coupled climate models. Our results indicate that the latent and sensible heat fluxes derived from the K02 parameterization have a different behavior under low and high wind conditions and may not adequately represent those fluxes in our region of study. Moreover, the momentum fluxes may also be mis-represented, potentially leading to erroneous predictions. We recommend that further testing of the parameterization similar to the one presented in this study, be carried out before it is implemented in more climate models.

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Table 1. Statistical parameters for the different methods of estimating the turbulent sensible heat flux (COV: covariance method, K02: Kara et al., 2002; M97: Mendoza et al., 1997; F96: Fairall et al., 1996).

SHF	COV	K02	M97	F96
Average [W/m^2]	10.93	22.11	16.77	11.48
RMSE [W/m^2]		32.18	19.45	12.65
Correlation coefficient		0.79	0.78	0.76

Table 2. Statistical parameters for the different methods of estimating the turbulent horizontal momentum flux (COV: covariance method, K02: Kara et al., 2002; M97: Mendoza et al., 1997; F96: Fairall et al., 1996).

TMF	COV	K02	M97	F96
Average [W/m^2]	0.27	0.44	0.51	0.27
RMSE [W/m^2]		0.25	0.32	0.09
Overestimation (%)		93	87	57

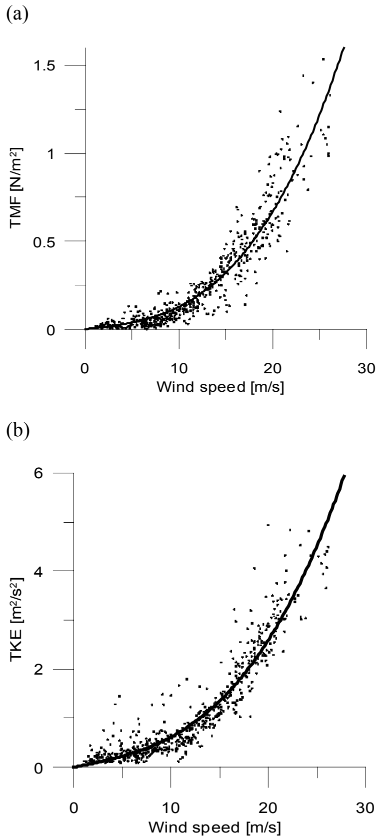

Fig. 1. **(a)** Turbulent horizontal momentum flux (TMF) and **(b)** Turbulent kinetic energy (TKE), as a function of the horizontal wind speed. The datapoints (~600) correspond to eddy covariances averaged over 100 s. The solid lines correspond to best fits determined when the data were binned in intervals of 1 ms^{-1} (see text and Eqs. 3 and 4).

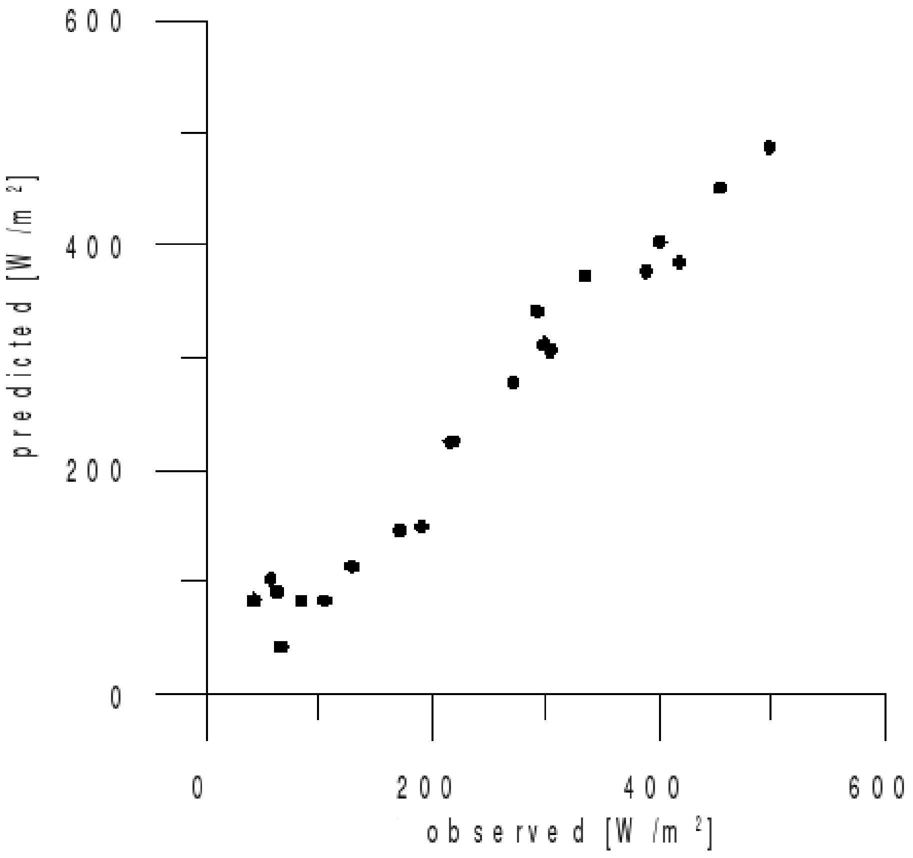

Fig. 2. Dispersion diagram of predicted (y-axis) versus observed values of the latent heat fluxes, utilizing the empirical fit: LHF=a+b V^2+c Δq (see text).

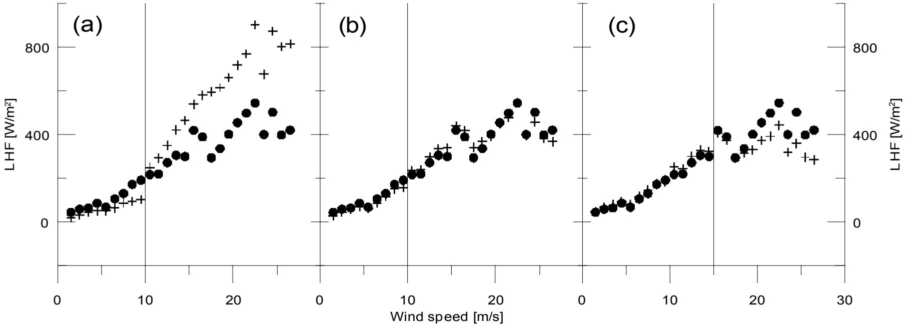

Fig. 3. Turbulent latent heat fluxes from observations (dots) and derived from the three parameterizations (crosses) as a function of horizontal wind speed (binned in 1 ms^{-1} intervals), for **(a)** K02, **(b)** M97 and **(c)** F96. Note that there is a change in performance of the parameterizations at 10 ms^{-1} (K02 and M97) and at 15 ms^{-1} (F96), indicated by the vertical lines.

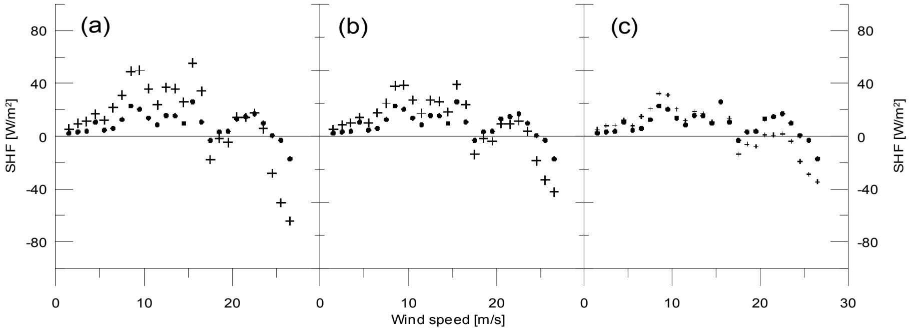

Fig. 4. Turbulent sensible heat fluxes from observations (dots) and derived from the three parameterizations (crosses) as a function of horizontal wind speed (binned in 1 ms^{-1} intervals), for **(a)** K02, **(b)** M97 and **(c)** F96.

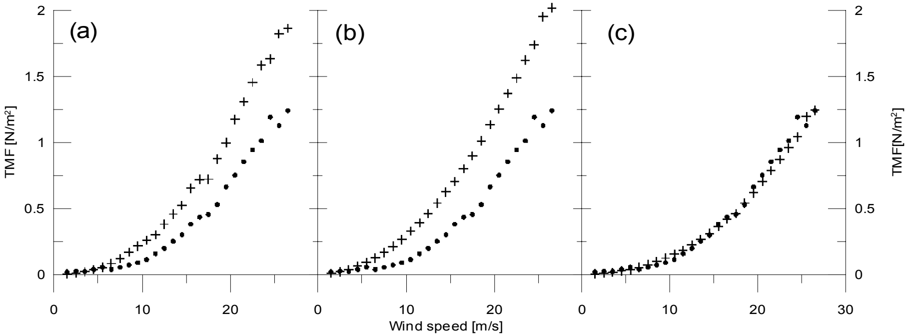

Fig. 5. Turbulent horizontal momentum fluxes from observations (dots) and derived from the three parameterizations (crosses) as a function of horizontal wind speed (binned in 1 ms^{-1} intervals), for **(a)** K02, **(b)** M97 and **(c)** F96.