THE TOGA-COARE BULK AIR-SEA FLUX ALGORITHM
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History

The international TOGA-COARE field program took place in the western Pacific warm pool over 4 months from November 1992 to February1993. Development of a bulk air-sea flux algorithm for use by the COARE community began almost immediately. Based on the model of Liu, Katsaros and Businger (1979, LKB), it took account of the light wind, strongly convective conditions over tropical oceans. **Version 1.0** was released in November 1993, and included modifications to the basic LKB code for wind roughness length (Smith, 1988), Monin-Obukhov profile functions for strong convection, and low-wind "gustiness" (Godfrey and Beljaars, 1991). **Version 2.0** (August 1994) included code to model the ocean cool skin physics (Saunders, 1967), and also daytime near-surface warming based on a simplified version of the Price, Weller and Pinkel (1986) ocean mixing model (Fairall et al., 1996a). These optional features enabled conversion from bulk to true skin temperature for calculating the fluxes. Calculation of fluxes of momentum (Caldwell and Elliott, 1971) and sensible heat (Gosnell, Fairall and Webster, 1995) due to rainfall were incorporated in the code, as was the so-called Webb correction to latent heat flux which arises from the requirement that the net dry mass flux be zero (Webb et al., 1980). The formalism of this version of the algorithm was fully described in Fairall et al. (1996b).

A major modification to the algorithm was made at a COARE Air-Sea Interaction (Flux) Group Workshop (Bradley and Weller, 1995). Transfer coefficients were reduced by six percent to give better average agreement with covariance latent heat fluxes from several COARE ships. This **version 2.5**, was used successfully on ocean-atmosphere field campaigns by members of the Flux Group, at various locations and from a variety of platforms. At the following workshop (Bradley and Weller, 1997) it was agreed that, after minor faults were corrected, a **version 2.5b** COARE bulk algorithm "package", consisting of the Fortran source code, a test data set, and the corresponding computed flux results, would be made generally available. This was released at the final Flux Group workshop (Bradley, Moncrieff and Weller, 1997), and available from several archive sites. Shortly after, a Matlab version was posted on the NOAA web site.

Version 2.5b had been developed using COARE measurements exclusively, which were limited to wind speeds in the range 0-12 ms^{-1} and the tropical environment. Nevertheless, the algorithm was frequently applied beyond these limits, including by the authors. Between 1997 and 1999 the NOAA air-sea interaction database expanded with directly measured covariance and inertial dissipation fluxes from cruises at higher latitudes and in stronger winds. This enabled further development of the COARE algorithm (Bradley et al. 2000, Fairall et al. 2001). In January 2000 **version 2.6a** was posted in both Fortran and Matlab codes. It was updated in June 2001 with **version 2.6bw**, which included the option to calculate momentum roughness lengths using surface gravity wave information. At this stage, with little further modification to either physics or parameterizations, the formalism of the algorithm was published (Fairall et al. 2003), as version 3.0a at the suggestion of a reviewer who felt the advances over 2.5b warranted this. The

COARE model framework was adapted to the physics/chemistry of air-sea gas transfer and described by Hare et al. 2004 and later updated as the COAREG31 codes (Fairall et al. 2011).

Version 3.5 was released in 2013 following the publication of Edson et al. 2013, which made adjustments to the wind speed dependence of the Charnock parameter based on a large data base of direct covariance stress observations (principally from a buoy). This led to an increase in stress for wind speeds greater than about 18 m/s. The roughness Reynolds number formulation of the scalar roughness length was tuned slightly to give the same values of Ch and Ce as version 3.0. The diurnal warm layer model was structured as a separate routine instead of embedded in a driver program.

This document describes the new release of version 3.6. There are three components of the new versions:

Meteorological fluxes (stress, sensible, latent heat) – coare36vn_zrf. The notation is 36=version, vn means vectorized code, zrf means it returns values of wind speed, temperature and humidity at user-specified reference heights.

Gas fluxes – coareG36vn_xxx. The notation xxx specifies the gas. Current gases are co2, dms, co, ozone, sf6, and hel. It also returns also returns all met fluxes and means at user-specified reference heights

Hurricane fluxes. The hurricane model is not considered part of the COARE suite because it includes the effects of sea spray and will not be discussed here.

Significant differences between versions 3.5 and 3.6

COARE 2.5 versions were based on concepts and empirical relationships carried over from LKB, modified as described in Fairall et al. (1996b) on the basis of about 800 hours of quality controlled eddy-flux measurements on Moana Wave during the COARE IOP. These were mostly for wind speeds less than $10 ms^{-1}$. For versions 2.6 and 3.0, transfer coefficients were obtained using a dataset which combined COARE data with those from three other NOAA field experiments, and a reanalysis of the HEXMAX data (DeCosmo et al. 1996). This extended the range to around $20 ms^{-1}$. The algorithm thus formulated was then validated against a covariance flux database containing 7216 hours of data from all NOAA cruises to 1999, including about 800 hours with wind speeds exceeding $10 ms^{-1}$ and 2200 hours at high latitudes (Fairall et al. 2003). COARE 3.5 was based on Edson's buoy data (Edson et al. 2013) and was compared to a large data base (a total of 16,000 hours of observations) combining observations from NOAA, WHOI, and U. Miami (Fairall et al. 2011).

The principal advances in version 3.6 are built around improvements in the representation of the effects of waves on fluxes. This includes improved relationships of surface roughness, z_o, and whitecap fraction, W_f, on wave parameters.

$$\frac{z_0}{H_s} = a(u_* / C_p)^{\mathrm{b}} \tag{1a}$$

$$Wf_1 = 0.00125 * U_{10}^{1.1} / \sqrt{W_a} \tag{1b}$$

$$Wf_2 = 5.0E-8*(\mathrm{u}_* H_s / \nu_w)^{0.9} \quad (1c)$$

Here a and b are constants (0.15 and 2.2), H_s the significant wave height, C_p the phase speed of waves at the peak of the frequency spectrum, $W_a=C_p/U_{10}$ is the wave age, and υ_w the kinematic viscosity of seawater. The advances are due to better observations in the HIWINGS field program (Brumer et al. 2017a,b; Blomquist et al. 2018) and the use of a wave model (Banner and Morison 2010; Zappa et al. 2016) to allow us to span the phase space of wave parameters. Equation 1b is from the wave model and 1c from a direct fit to HIWINGS data (see Fig. 1). The whitecap fraction result is critical to capture the bubble enhancement effects in gas transfer. Version 36 also allows near-surface ocean salinity to be specified; Ss=0 is appropriate for lakes while Ss=35 is typical for the ocean.

The major change to the gas transfer algorithm is the adoption of a new specification of whitecap fraction. COAREG specifies the gas transfer velocity, k, as the combination of air-sea and ocean side transfer velocities. Details are provided in the companion writeup, but if we normalize the waterside k_w by water-side Schmidt number of 660 (equivalent to CO2 at 20 C), then k660 is approximately the sum of turbulent-molecular diffusivity and bubble-mediated components

$$k_{w660} \cong k_{0660} + k_{b660} = 37.5 A u_{*\nu} + \frac{B V_0 W_f}{\alpha(20)} \gamma(\mathrm{T})\,\mathrm{G}(\mathrm{T}) \quad (2)$$

Here $u_{*\upsilon}$ is friction velocity characterizing the viscous part of the surface stress, α(20) the solubility of the gas at 20 C, γ and G are temperature dependent functions of the gas solubility and Schmidt number, and A and B are constants. The first term on the RHS of (2) is the same for all gases; the second term scales with whitecap fraction and is larger for less soluble gases. For example, the ratio of the second term for CO2 to that for DMS is 5 to 6 (depending on temperature). So, given a specified function for Wf, we use measurements of k for DMS and CO2 to determine B as a function of wind speed. The value of B is sensitive to W_f but the value of A is not. Previous versions of COAREG (Hare et al. 2004; Fairall et al. 2011) used a Wf specification proportional to $U^{3.4}$. The forms given above (Eqs 1b and 1c) yield much lower whitecap fractions at high wind speeds. In COAREG31 A=1.6 and B=1.8; in COARE3.6 we are currently using W_{f2} with A=1.2 and B=2.5.

The bulk algorithm "package"

The "package" consists of the bulk algorithm programs as described above plus additional programs that exercise the algorithms by calling input data files and making some comparison plots. The programs and data files are found on

ftp://ftp1.esrl.noaa.gov/BLO/Air-Sea/bulkalg/cor3_6/

Programs

<u>Meteorology</u>:

coare36vn_zrf .m and *coare36vnWarm.m* (COARE matlab source code). *coare36vn_zrf .m* is a vectorized matlab code that takes a specified single line of data or a matrix and returns 42 different parameters. *coare36vnWarm.m* requires a time series of data because it computes the diurnally forced warm layer which depends on time integrals of the forcing. It is intended to allow a correction of an ocean temperature measurement made at depth (say a ship's TSG with an intake at 5 m). *coare36vn_zrf .m* is embedded in the warm layer code.

Exercise programs:

test_coare36.m. No datafile, specifies basic conditions and computes fluxes as a function of wind speed (2 -20 m/s). An example figure shows Cd and Ce as a function of wind speed (Fig. 2)

red_VP_bulk_36.m. Datafile **VP_test_data_1.txt**. Small dataset from a buoy with bogus values for variables the buoy does not measure. A sample graph shows the time series of latent heat flux (Fig. 3). This program compares versions 3.0 and 3.6.

WarmCoolLayer_check_36.m. Datafile **Revelle10minutesLeg3_r3.mat** taken from leg3 of the DYNAMO field program. This program exercises the vectorized version of the warm layer code using the Dynamo time series. Fig. 4 shows the time series of water temperature from the PSD seasnake (near surface), the shp's TSG at 5 m depth, and an estimate of SST computed from TSG and the model warm layer value.

<u>COAREG:</u>
coareG36vn_xxx.m. The notation xxx specifies the gas. Current gases are co2, dms, co, ozo, sf6, and hel.

Exercise programs:

read_vectorCO2_DMS_36.m. Datafiles **Avemet10new.mat, DeltaCO2.mat**, and **SO_GASEX_UH_DMS_Flux_Hourly_Ver2b_nohds2.txt.** This program reads data from the GASEX08 field program and graphs comparisons for CO2, DMS, SF6, and He (see Fig. 5).

Test_red_HIWINGS_v5_hr.m. Datafile **flux_HIWINGS.mat**. Reads the data from HIWINGS field program and compares mean values of algorithm with direct measurements as a function of wind speed. Mean values of k660 for DMS and CO2 are shown in Fig. 6.

Matlab programs

Meteorology
A=coare36vn_zrf(u,zu,t,zt,rh,zq,P,ts,Rs,Rl,lat,zi,rain,Ss,cp,sigH,zrf_u,zrf_t,zrf_q)

```
% Input:
%
%     u = water-relative wind vector magnitude (m/s) at height zu(m)
%     t = bulk air temperature (degC) at height zt(m)
%    rh = relative humidity (%) at height zq(m)
%     P = surface air pressure (mb) (default = 1015)
```

%   ts = water temperature (degC) see jcool below
%   Rs = downward shortwave radiation (W/m^2) (default = 150)
%   Rl = downward longwave radiation (W/m^2) (default = 370)
%   lat = latitude (default = +45 N)
%   zi = PBL height (m) (default = 600m)
% rain = rain rate (mm/hr)
%   Ss = sea surface salinity (PSU)
%   cp = phase speed of dominant waves (m/s)
% sigH = significant wave height (m)
% zu, zt, zq heights of the observations (m)
% zrf_u, zrf_t, zrf_q reference height for profile. Use this to compare observations at different heights
%
%

Warm Layer
B=coare36vnWarm(yday,Ur,zu,Tair,zt,RH,zq,Pair,Tsea,Solar,IR,Lat,Lon,zi,Rainrate,ts_depth,Ss,cp,sigH,zrf_u,zrf_t,zrf_q);

***********   input data **************
%   yday=   day-of-year
%   Ur=   wind speed (m/s) relative to water at height zu
%   zu=   height (m) of wind measurement
%   Tair=   air temp (degC)at height zt
%   zt=   height (m) of air temperature measurement
%   RH=   relative humidity (%) at height zq
%   zq=   height (m) of air humidity measurement
%   Pair=   air pressure (mb)
%   Tsea=   bulk surface sea temp (degC) at ts_depth
%   Solar=   downward solar flux (w/m^2) defined positive down
%   IR=   downward IR flux (w/m^2) defined positive down
%   Lat=   latitude (deg N=+)
%   Lon=   longitude (deg E=+)
%   zi=   inversion height (m)
%   Rainrate=   rain rate (mm/hr)
%   ts_depth   depth (m) of water temperature measurement
%   Ss =   sea surface salinity (PSU)
%   cp =   phase speed of dominant waves (m/s)
%   sigH =   significant wave height (m)
%   zu, zt, zq heights of the observations (m)
%   zrf_u, zrf_t, zrf_q reference height for profile. Use this to compare observations at different heights
%

Gas Transfer

```
[A,G]=coareG36vn_co2(u,zu,t,zt,rh,zq,P,ts,Rs,Rl,lat,zi,rain,Ss,cp,sigH,zrf_u,zrf_t,zrf_q,dCO2)
%

% Input:
%
%     u = water-relative wind vector magnitude (m/s) at height zu(m)
%     t = bulk air temperature (degC) at height zt(m)
%    rh = relative humidity (%) at height zq(m)
%     P = surface air pressure (mb) (default = 1015)
%    ts = water temperature (degC) see jcool below
%    Rs = downward shortwave radiation (W/m^2) (default = function of latitude)
%    Rl = downward longwave radiation (W/m^2) (default = function of latitude)
%   lat = latitude (default = +45 N)
%    zi = PBL height (m) (default = 600m)
%  rain = rain rate (mm/hr)
%    Ss = sea surface salinity (PSU)
%    cp = phase speed of dominant waves (m/s)
%  sigH =  significant wave height (m)
%  zu, zt, zq heights of the observations (m)
%  zrf_u, zrf_t, zrf_q  reference height for profile.  Use this to compare observations at different heights
%  dCO2 air-sea delta fCO2, micro-atmospheres
%
```

In this case, A is the same matrix as returned by *coare36vn_zrf* while G contains the gas transfer information. The output files are lengthy and described in the codes. If wave information is not available or wind speed formulation is preferred, set cp and sigH=NaN. The codes are configured to compute the cool skin correction to SST (assumes it is a bulk sensor). Cool skin requires To turn off cool skin correction set jcoolx=0. If the water temperature measurement is made at depth, you might consider using the warm layer code.

Example

The COARE routines (*coare36vn_zrf.m* and *coareG36vn_xxx.m*) can be executed with a single line of data or with multiple lines in a matrix. Here is a simple example of a single line execution to illustrate using it to compare measurements made from a buoy with those from a ship. The example is taken from Fairall and Bradley (2007), see Fig. 7 (Fig. A1 in their report). Measurements are made from the buoy: SST=25.22 C, ta=24.7 C (zt=2.88 m), u=5.0 m/s (zu=3.22 m), and RH=77 (zq=2.88 m). We use P=1010 mb and bogus values for Rl=320 W/m^2 and Rs=200, rain=0, and zi=600m. The ship sensors are at zrf_u=18 m, zrf_t=17.4 m, and zrf_q=17.4 m. We can execute the following line

```
u=5;At=coare36vn_zrf(u,3.22,24.7,2.88,77,2.88,1010,25.22,200,320,10,600,0,35,NaN,NaN,18,17.4,17.4);At(:,21:24) ;
```

and At will a line of data with 43 parameters – 21 through 24 will be the mean values at the ship heights.

		u	ta	qa	RH
At(21:24)	ans =	5.5595	24.5417	14.4682	75.2592
Buoy values		5.0	24.7		77.0

Thus, we expect the wind speed at the ship sensors to be about 0.5 m/s higher, the air temperature about 0.15 C lower, and the RH to be about 1.7 % lower. Notice that if we reverse the process

u=5.56;At=coare36vn_zrf(u,18,24.54,17.4,75.26,17.4,1010,25.22,200,320,10,600,0,35,NaN,NaN,3.22,2.88,2.88);

Then we will recover the original values.

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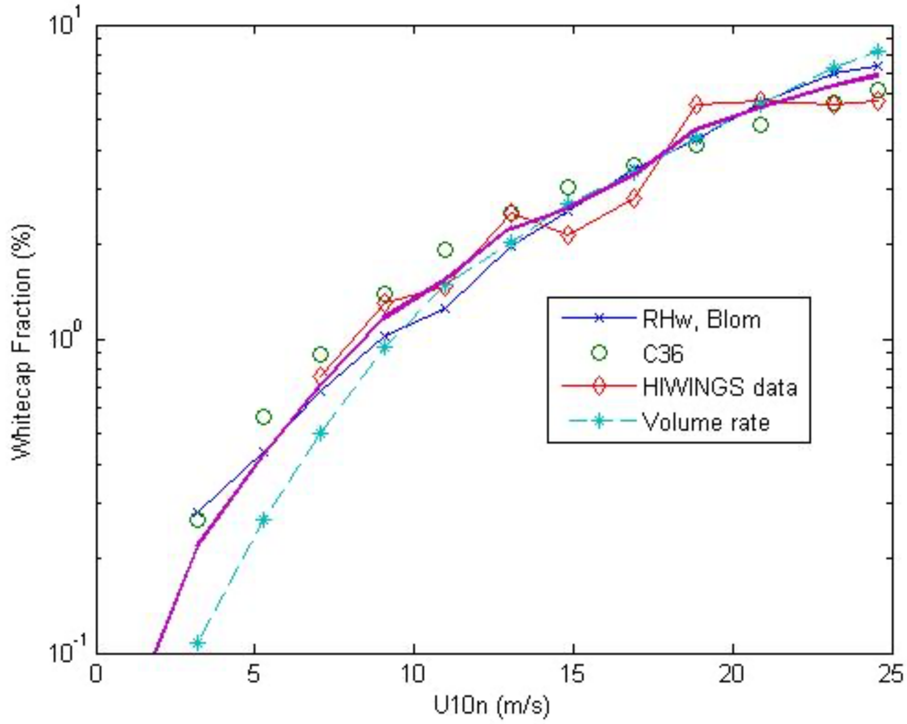

Figure 1. Mean whitecap fraction from HIWINGS.

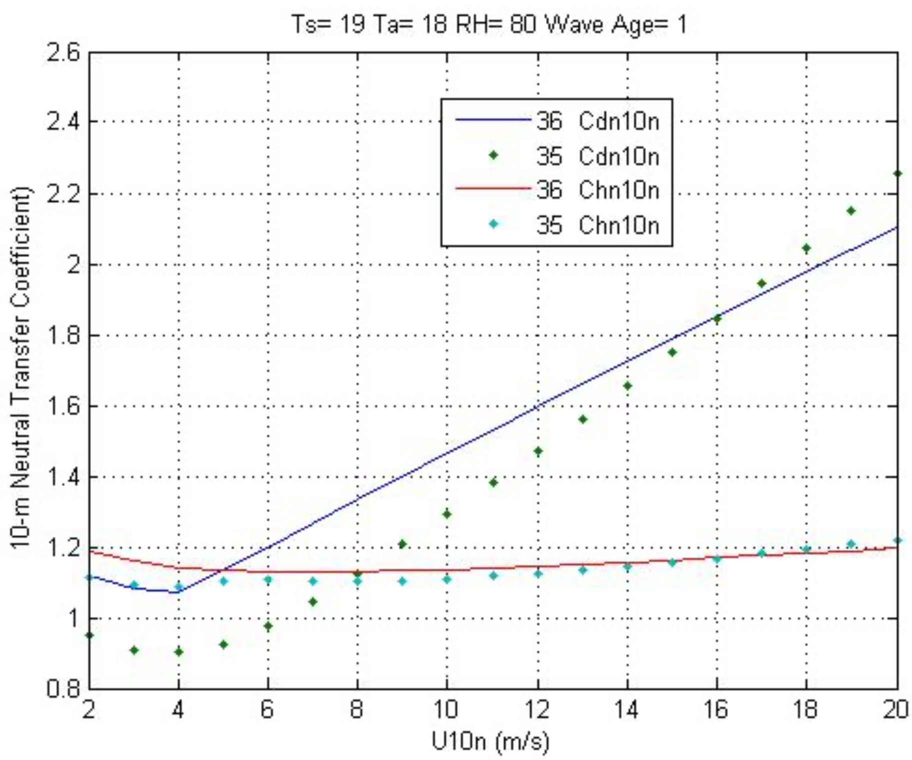

Figure 2. Cd10n and Ch10n from *testCoare36.m*.

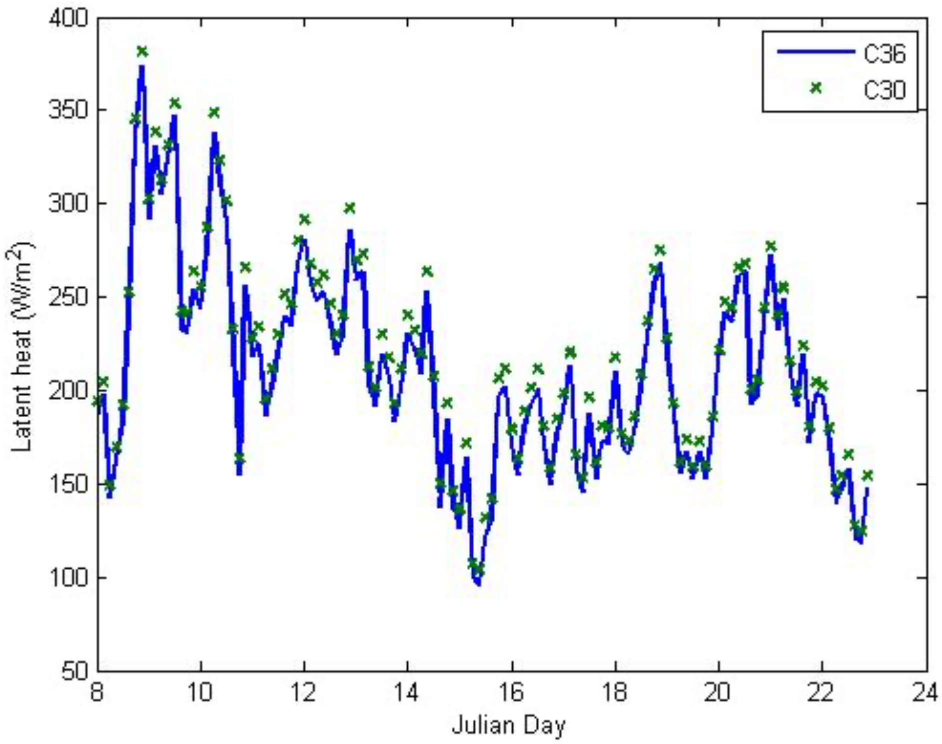

Figure 3. Latent heat flux time series from r*ed_VP_bulk_36.m.*

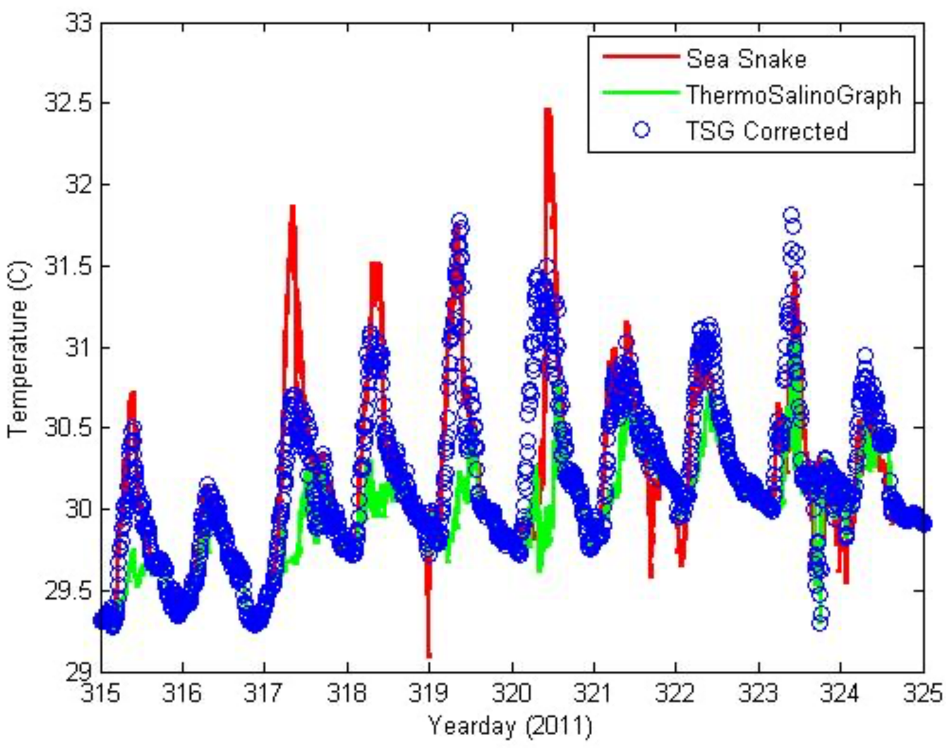

Figure 4. Time series of SST from DYNAMO using *WarmCoolLayer_check_36.m.*

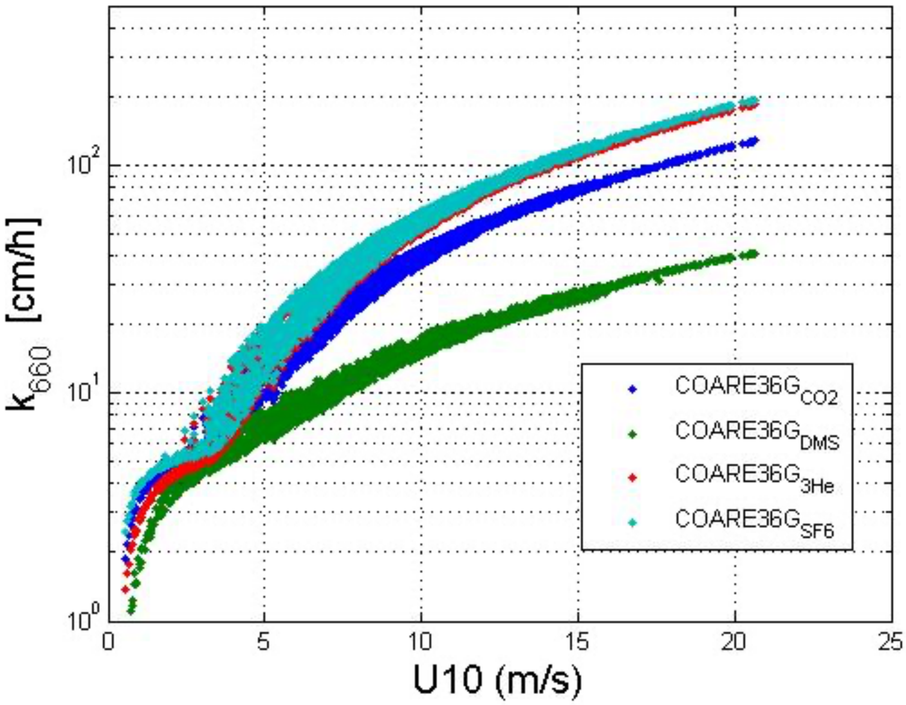

Figure 5. Schmidt-normalized gas transfer velocity vs wind speed from GASEX08 using *read_vectorCO2_DMS_36.m*.

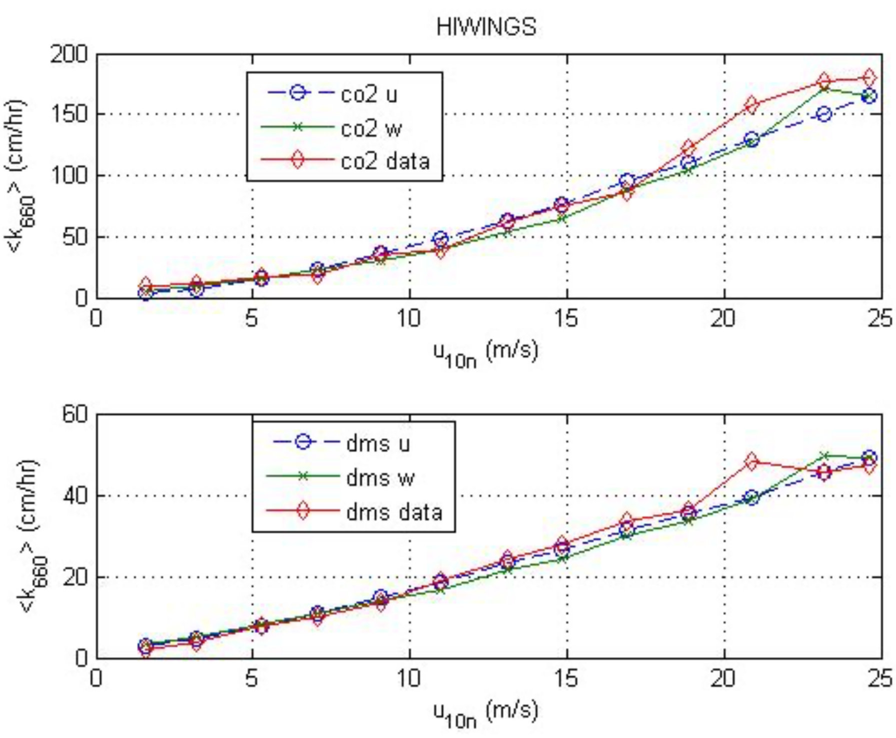

Figure 6. Mean k660 for CO2 and DMS from HIWINGS using *Test_red_HIWINGS_v5_hr.m*.

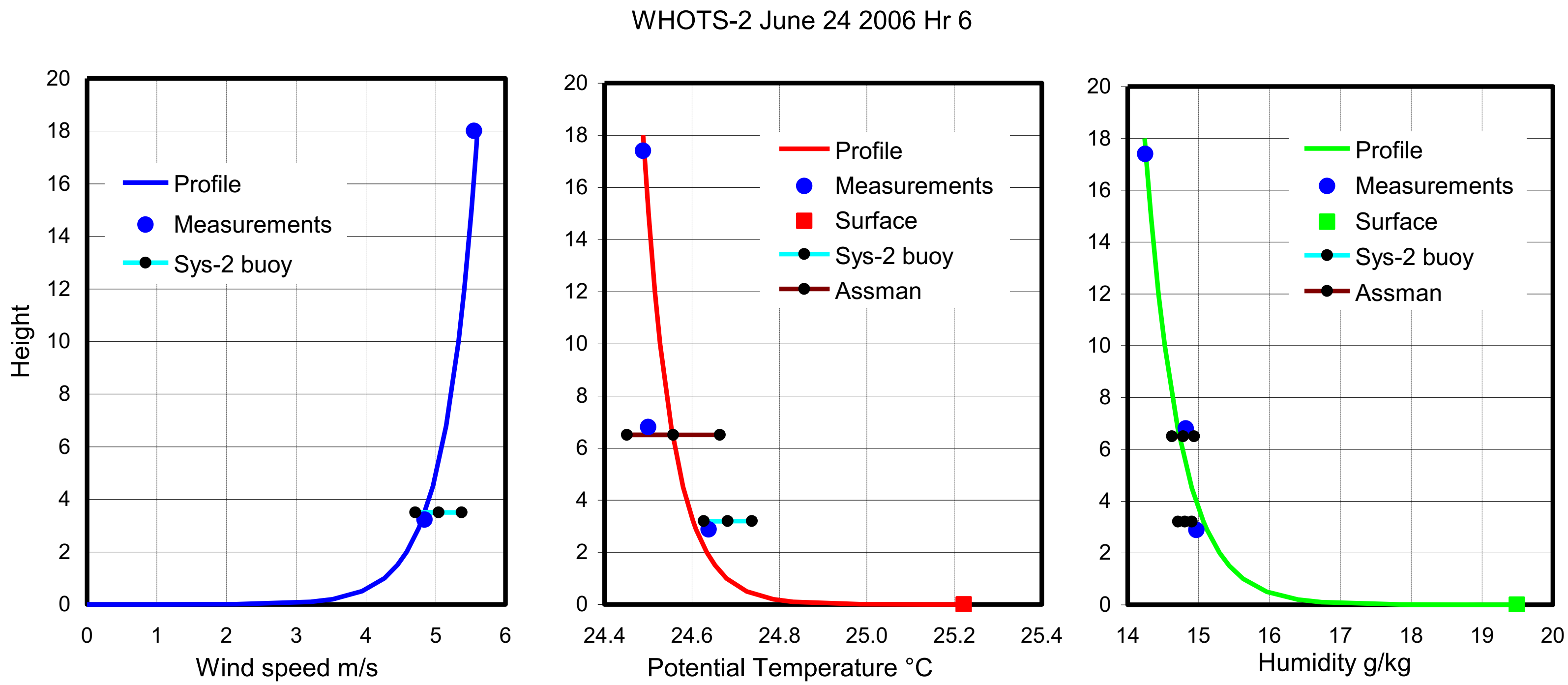

Figure 7. (Fig. A1 from Fairall and Bradley 2007). Example of need for height adjustment when comparing measured values at various levels above the sea surface. The ship's anemometer was at 18 m on the foremast, and the temperature/humidity sensor at 17.4 m. Temperature and humidity were measured with an Assman psychrometer through a forward chock at 6.8 m height. The ship was standing about 0.25 nm downwind of the WHOI buoy, which had two wind sensors at 3.22 m above the sea surface and two temperature/humidity sensors at 2.88 m. The ship and buoy data points are hourly averages; the Assman values are spot readings. The profiles were constructed from flux/gradient parameters calculated using Version 3.0 of the COARE bulk flux algorithm as follows;

Parameter	u_*	t_*	q_*	z_o	z_{ot} , z_{oq}	ψ_m	ψ_t , ψ_q	z/L
Units	ms^{-1}	C	$g\ kg^{-1}$	m	m			
Value	0.184	-0.026	-0.192	4.75e-5	7.74e-5	0.705	1.257	-0.427

Surface values (u_0, t_0 and q_0) were 0 ms^{-1}, 25.22 °C, and 19.57 $g\ kg^{-1}$ respectively; $\kappa = 0.4$.