frontiers

Supplementary Material

1 THE COARE BULK TRANSFER MODEL

1.1 History

The international TOGA-COARE field program took place in the western Pacific warm pool over 4 months from November 1992 to February 1993. Development of a bulk air-sea flux algorithm for use by the COARE community began almost immediately. Based on the model of Liu et al. (1979)(LKB hereafter), 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 et al. (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 et al., 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 et al., 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 ms^{-1}. 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.

1.2 Latest Revision

This supplement documents the release of version 3.6. There are three components of the new version:

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

2) *Gas fluxes* – coareg36vn_xxx. The notation xxx specifies the gas species. Current gases are CO_2, DMS, CO, O_3, SF_6, and He. The gas flux versions also return return met fluxes and means at user-specified reference heights.

3) *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.

1.3 Significant Differences Between Versions

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 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_0, and whitecap fraction, f_{wh}, on wave parameters.

$$\frac{z_0}{H_s} = a(u_*/C_p)^b \tag{S1}$$

$$f_{wh1} = 0.00125\, U_{10}^{1.1}/\sqrt{W_a} \tag{S2}$$

$$f_{wh2} = 5.0e^{-8}\, (u_* H_s/\nu_w)^{0.9} \tag{S3}$$

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 ν_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., 2017) 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 (S2) is from the wave model and (S3) from a direct fit to HiWinGS data. The whitecap fraction result is critical to capture the bubble enhancement effects in gas transfer. Version 3.6 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. If we normalize the waterside k_w by water-side Schmidt number of 660 (equivalent to CO_2 at 20°C), then k_{660} is approximately the sum of turbulent-molecular diffusivity and bubble-mediated components

$$k_{w\ 660} \simeq k_{0\ 660} + k_{b\ 660} = 37.5\ Au_{*\nu} + \frac{B\ V_0\ f_{wh}}{\alpha(20)}\ \gamma(T)\ G(T) \tag{S4}$$

Here $u_{*\nu}$ is friction velocity characterizing the viscous part of the surface stress, $V_0 = 2450$ is the bubble volume flux per unit f_{wh} (Woolf, 1997), $\alpha(20)$ 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 (S4) 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 CO_2 to that for DMS is 5 to 6 (depending on temperature). So, given a specified function for f_{wh}, we use measurements of k for DMS and CO_2 to determine B as a function of wind speed. The value of B is sensitive to f_{wh} but the value of A is not. Previous versions of COAREG (Hare et al., 2004; Fairall et al., 2011) used a f_{wh} specification proportional to $U^{3.4}$. The forms given above (Eqs (S2) and (S3)) yield much lower whitecap fractions at high wind speeds. In COAREG 3.1 $A = 1.6$ and $B = 1.8$ in COAREG 3.6 we are currently using f_{wh2} with $A = 1.25$ and $B = 2.3$.

1.4 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/

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