A COMPARISON OF SURFACE FRICTION VELOCITIES ESTIMATED BY DISSIPATION AND ITERATIVE BULK AERODYNAMIC METHODS DURING GALE

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Abstract. Energy dissipation method and an Iterative Bulk Aerodynamic Method (IBAM) are used to estimate friction velocity (u_*) for a wide wind speed range (5.66 to 21.6 ms^{-1}) with convective atmospheric conditions over the ocean during the Genesis of Atlantic Lows Experiment (GALE). Values of u_* obtained by the IBAM are in reasonably good agreement with those from the dissipation method. The iterative bulk method appears to do well for wind speeds up to about 21 ms^{-1}.

Introduction

Estimation of surface turbulent fluxes of momentum and heat over the ocean or large bodies of water using routine observations such as mean wind speed, air temperature and Sea Surface Temperature (SST) and specific humidity with the bulk aerodynamic method has always been a challenge given a variety of empirical relationships for the exchange coefficients [see for example, Garatt, 1977]. A more direct method of estimating surface flux of momentum is by the energy dissipation method in which energy dissipation rate is obtained from the inertial subrange of the spectrum and the friction velocity, u_* is computed using a simplified Turbulent Kinetic Energy (TKE) budget. Best and the most direct method of estimating surface turbulent fluxes will be to use the eddy correlation method which involves simultaneous measurements of high frequency longitudinal and vertical velocity fluctuations and then computing the covariances. Comparisons have been made in the past between the dissipation method and the bulk aerodynamic method for fair weather and moderate wind speed (4 to 20 ms^{-1}) conditions [Large and Pond, 1981 and Guymer et al., 1983]. But the problem has been to decide as to which empirical relationship to use for the bulk method and to account for the diabatic effects during the non-neutral atmospheric conditions.

An Iterative Bulk Aerodynamic Method (IBAM) of Liu et al., [1979] has the advantage that u_* is estimated by successive iterations to satisfy similarity relations for the surface layer and the viscous sublayer over the ocean. Similar iterations are carried out to compute temperature (θ_*) and humidity (q_*) scalings from which surface fluxes of sensible and latent heat can be estimated. One of the limitations of this method is that at high wind speeds, ratio of roughness length (z_o) to the thickness of the viscous sublayer (δ_v) could become large with the surface becoming aerodynamically rough.

The objective of this paper is to investigate the applicability of this IBAM for large wind speeds (~22 ms^{-1}) and highly convective conditions that were prevalent during GALE over the Atlantic ocean in the vicinity of the Gulf Stream. Maximum air-sea temperature difference of about -21.6° C was observed during this experiment. GALE was conducted from 15 January to 15 March of 1986 to study the east coast winter cyclones [Dirks et al., 1988]. Several observational platforms such as research vessels, buoys and research aircraft were used to study the air-sea interaction processes in the atmospheric boundary layer [Raman and Riordan, 1988]. Moored buoys and ship-board sounding systems were used to study the ocean-atmosphere interaction processes during GALE [Blanton et al., 1987]. Motivation for this comparative study is to identify the best method for estimating surface turbulent fluxes from ship and buoy observations during GALE.

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Observations

Observations for the periods of 18 to 20 January at 33° 50' N and 76° W and 25 to 29 January of 1986 at 33° 25' N and 76° 55'W discussed in this paper were obtained aboard RV Cape Hatteras with the ship facing the wind. Prevailing surface synoptic weather conditions during this period consisted of two cold air outbreaks, two cold fronts, and two offshore cyclogeneses.

A hot-wire anemometer was used at a height of 16 m above the sea surface (z) to measure the high frequency (~10 Hz) longitudinal velocity fluctuations (u') at a rate of 10 per second for a sampling time interval of 15 minutes and the conventional meteorological instruments aboard the research vessel were used with Seadata ASCII Interface Loop (SAIL) to obtain mean surface parameters such as the wind speed, air temperature, SST, and specific humidity. SAIL is a shipboard data acquisition system. The u' measurements were corrected for the relative motion of the ship and the mean values of u' were compared with the wind speeds corrected for the ship course vector through the SAIL system. Details of the instrumentation, data acquisition system such as SAIL and the data quality control are given by Raman and Riordan [1988] and Akkarappuram [1988].

Methods of Analysis

Dissipation Method.

The u' measurements were used to estimate the spectral density $S(\kappa)$ as a function of the wave number (κ). Energy dissipation rate (ε) was estimated from the inertial subrange of the spectrum using Kolmogorov's relationship of the form

$$S(\kappa) = \alpha \ \varepsilon^{2/3} \kappa^{-5/3}, \qquad (1)$$

TABLE 1. C_{dn} Values of Kondo (1975) used in the IBAM

u (ms^{-1})	10^3 C_d
0.3 - 2.2	$1.08 u^{-0.15}$
2.2 - 5.0	0.771 + 0.0858 u
5.0 - 8.0	0.867 + 0.0667 u
8.0 - 25.0	1.2 + 0.025 u
25.0 - 50.0	0.073 u

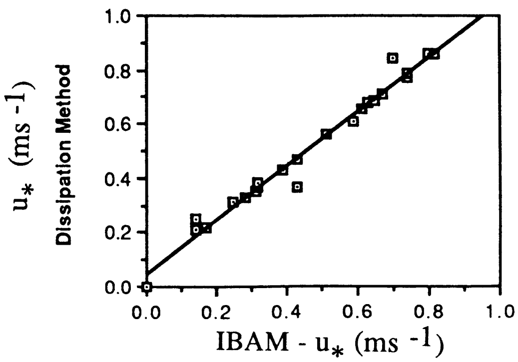

Fig. 1 Comparison between the friction velocities (ms^{-1}) obtained by the energy dissipation - and iterative bulk aerodynamic method.

where Kolmogorov's constant α is generally assumed to be 0.5. From the considerations of the TKE budget for steady neutral flow over homogeneous surface, energy dissipation rate, ε can be related to the u∗ as

$$\varepsilon = \frac{u_*^3}{kz}, \tag{2}$$

where k is von Karman's constant (= 0.4). Correcting for the stability effects with a function similar to the one used by Champagne et al., [1977], ε can be written as

$$\varepsilon = \frac{u_*^3}{kz}\left[1 + 0.5(z/L)^{\frac{2}{3}}\right]^{3/2}, \tag{3}$$

where the Obukhov length, L and the stability parameter, z/L are determined by the IBAM. Antonia et al., [1978] used Eq. (3) to correct the momentum flux in Bass Strait and found that the directly measured values of momentum flux were in reasonable agreement with the dissipation method. The maximum stability correction for u∗ was about 0.03 ms^{-1}. Mean wind speed was about 5.66 ms^{-1} and z/L - 1.34 for this case with an air-sea temperature difference of -5.5 ^oC.

<u>Iterative Bulk Aerodynamic Method</u> (IBAM).

This method involves matching the similarity profiles in the marine surface layer with the ones in the viscous sublayer and iteratively solve for the u∗, θ∗, and q∗. IBAM is described by Liu et al., [1979] who have shown it to work for low wind speeds when sea surface is aerodynamically smooth and the thickness of the viscous sublayer δ_v is larger than the roughness parameter z_0. They speculated that at large wind speeds, with $z_0 >> \delta_v$, the method could fail. As indicated before, the purpose of this paper is to test the validity of this method at large wind speeds in the presence of convective conditions.

Iterative method was tested for its sensitivity to various initial drag coefficient values and was found to be fairly insensitive. For the comparisons made in this study, neutral drag coefficients (C_{dn}) suggested by Kondo (1975) were used for initial values and are given in Table 1.

Discussion of Results

Friction values estimated using the energy dissipation method are compared with the values computed by the iterative bulk method using a scatter diagram [Figure 1]. Mean wind speeds for these data varied from 5 to 21.1 ms^{-1} and z/L values from - 2.71 to - 0.028 with a range of air sea temperature difference between - 17 and - 1.7 ^oC. Values of u∗ estimated by IBAM are in reasonable agreement with those obtained by a more direct energy dissipation method up to a wind speed of 21.6 ms^{-1}. A comparison between the u∗ values estimated by the IBAM and those obtained using eddy correlation method at a research pier at Duck, North Carolina during the SUPERDUCK experiment conducted in September and October 1986 is shown in Figure 2 [Kang, 1988]. Observations are for onshore flows with over water conditions and wind speed ranged from 3.3 to 12 ms^{-1} with neutral, stable and unstable conditions.

Assuming δ_v to be approximately equal to 10ν/u∗ where ν is the kinematic viscosity of air, a value of about 0.0002 m is obtained for the maximum wind of speed 21.6 ms^{-1}. Value of z_o using the iteration method is 0.00065 m which is in reasonable agreement with the corresponding roughness length estimated using Charnock's relation of the form,

$$z_o = 0.016\frac{u_*^2}{g},$$

where g is the gravitational acceleration.

Ratio between δ_v and z_o for the highest wind speed of this study is thus 0.256. Corresponding roughness Reynold's number, $u_* z_o/\nu$ would be 37.5. Although breaking waves continuously destroy the viscous sublayer, there are obviously regimes where it is continuously forming which could be the reason for the iterative method to work at high wind speeds. Another possibility is that the method is not sensitive to the similarity relations in the viscous sublayer, but is governed mainly by the marine surface layer processes.

Temporal Variations of Surface Turbulent Fluxes of Momentum and Heat

One of the GALE objectives is to study the spatial and temporal variations of energy exchanges at the air-sea

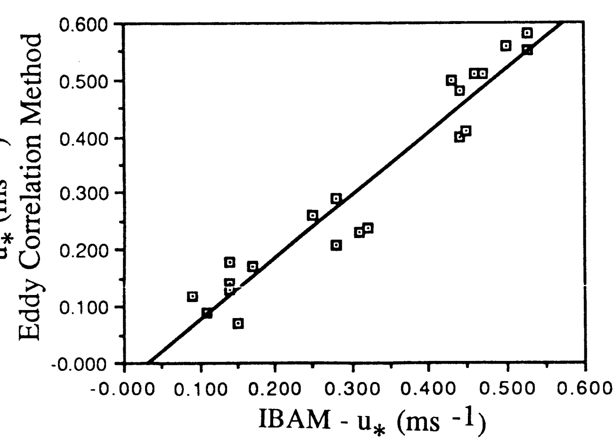

Fig. 2 Comparison between the friction velocities (ms^{-1}) obtained by the eddy correlation - and iterative bulk aerodynamic method.

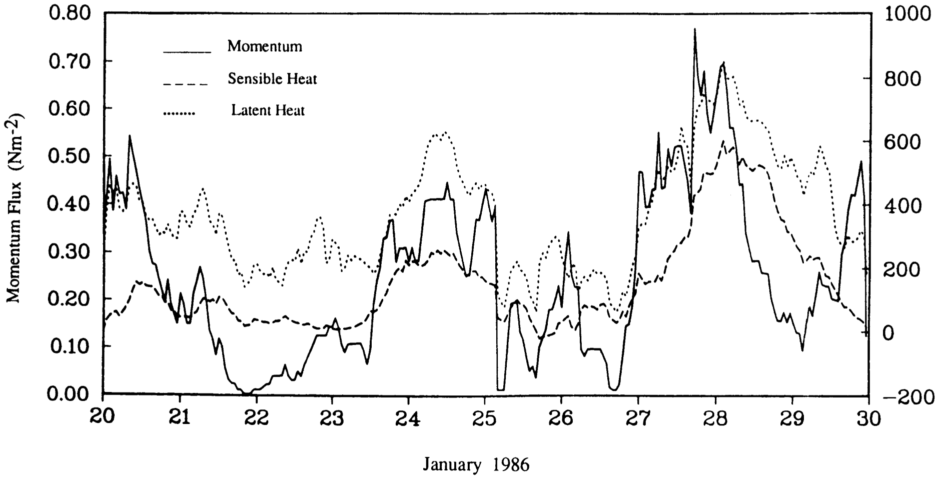

Fig. 3 Variations of surface fluxes of momentum (Nm^{-2}) and heat (Wm^{-2}) at buoy # 5 (33^o N and 78^o 24' W - depth of mooring 36 m).

interface in relation to the occurrence of various synoptic and mesoscale weather events such as coastal frontogenesis, cold front passage, offshore cyclogenesis, and cold air outbreak. Typical temporal variations of the fluxes of momentum and heat for buoy # 5 located at 33^o N and 78^o 24'W are shown in Figure 3. Spatial and temporal variations of the surface fluxes at different buoy and ship locations are discussed elsewhere [Akkarappuram, 1988].

Out of the six buoys deployed by North Carolina State University during GALE, the area surrounding the buoy # 5 registered the maximum surface momentum flux of 0.7 Nm^{-2}, sensible heat flux of 602 Wm^{-2}, and latent heat flux of 856 Wm^{-2} during the offshore cyclogenesis followed by a massive cold air outbreak with a wind speed of about 16 ms^{-1} and air-sea temperature difference of -20.8 ^oC on January 28/0200 UTC. The other significant synoptic event was the coastal frontogenesis on January 24 with a profound southwestward wind stress over the continental shelf in the alongshore direction [Blanton et al., 1987]. A maximum momentum flux of 0.45 Nm^{-2}; sensible heat flux of 260 Wm^{-2}, and latent heat flux of 632 Wm^{-2} were associated with this event around buoy # 5. These fluxes were computed using the iterative bulk method, as discussed above. Sensible and latent heat flux values compare favorably with those obtained using research aircraft [Wayland and Raman, 1988].

Conclusions

Values of surface friction velocity estimated by an iterative bulk method [Liu et al., 1979] agree reasonably well with that by the energy dissipation method for high winds (~ 21 ms^{-1}) with strong convective conditions. The method is based on matching the similarity profiles in the marine surface layer and the viscous sublayer. Although at these high wind speeds, the sea surface becomes aerodynamically rough and wave breaking occurs, the method is probably working because of two reasons. One is the possibility of the continuously forming viscous sublayer and the other is the fact that the method may not be very sensitive to the similarity relations in the viscous sublayer.

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