The Improvement of Turbulent Heat Flux Parameterization for Use in the Tropical Regions Using Low Wind Speed Excess Resistance Parameter

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Abstract Reliable simulation of turbulent heat fluxes needed for modeling land-atmosphere interactions remains a challenge over the humid tropical region. This may be connected with the inadequate parameterization of the roughness lengths for momentum (\(z_{mf}\)) and heat (\(z_{mh}\)) transfer usually expressed in terms of excess resistance factor (\(xB^{-1}\)). This paper assesses the performance of existing \(xB^{-1}\) schemes developed for high wind speed conditions over the humid tropical region. Thereafter, a more appropriate \(xB^{-1}\) suitable for low wind speed condition is developed for use in the aerodynamic resistance parameterization. Based on observed surface heat fluxes and profile measurements of wind speed and temperature from Nigeria Micrometeorological Experimental site, new \(xB^{-1}\) parameterization was derived through the application of the Monin–Obukhov similarity theory and Brutsaert theoretical model for heat transfer. The derived \(xB^{-1} = 6.66 \text{Re}^{0.02} - 5.47\), where Re is the Reynolds number. Turbulent flux parameterization with this new formula provides better estimates of heat fluxes with reference to results from existing \(xB^{-1}\) schemes. The \(R^2\) increased by about 85%, while mean bias error and root-mean-square error in the parameterized \(Q_h\) based on the derived \(xB^{-1}\) reduced by about 63% and 66.7%, respectively. Similarly, the \(R^2\) increased by about 38%, while mean bias error and root-mean-square error in the parameterized \(Q_h\) based on the derived \(xB^{-1}\) reduced by about 47.8% and 52.6%, respectively. The derived \(xB^{-1}\) gave better estimates of \(Q_h\) than \(Q_B\) during the daytime. The derived \(xB^{-1}\) scheme corrects a well-documented, large overestimation of turbulent heat fluxes, and it is therefore recommended for use in regions where low wind speed is prevalent.

1. Introduction

Realistic surface representation is required in climate models (CMs) to define the lower boundary condition (Pope et al., 2000; Williams et al., 2003). Diurnal variations of sensible and latent heat fluxes obtained from partitioning of available energy have a significant influence on climate simulation (Gao et al., 2004, 2009). Reliable turbulent heat fluxes near the Earth’s surface are necessary for improved weather and climate simulations (Chou et al., 2003). However, current operational CMs tend to systematically overestimate the diurnal range of turbulent heat fluxes for the tropical region, which might be related to inappropriate parameterizations for bare-soil heat transfer (Su et al., 1998; Trenberth, 2011; Zeng et al., 1997, 2005). The turbulent heat fluxes can be described by means of the roughness length concept in Aerodynamic Resistance Approach (ARA) used in CMs. The aerodynamic (momentum, \(z_{mf}\)) and thermal (\(z_{mh}\)) roughness lengths are two crucial parameters for bulk transfer equation (Adeniyi, 2013). And both parameters are not physically based and thus cannot be measured directly. Their values usually are inversely derived from observations in field experiments or empirically estimated for practical applications. The logarithmic ratio of the two roughness lengths is called the excess resistance factor, \(xB^{-1}\), where \(x\) is the von Karman constant and \(B^{-1}\) is the Stanton number. The latter is related to the excess resistance to heat transfer. The behavior of the turbulent fluxes in the microlayer of the atmospheric surface layer (ASL) is controlled by this factor, and it is needed in most climate and hydrological models (Su et al., 1998; Zeng et al., 1997, 2005). Several studies have developed different \(xB^{-1}\) schemes based on the synoptic observations of the field experiments for both vegetated and bare soil surfaces for relatively high wind speed conditions, though field studies over bare soil surfaces are still limited (Zeng et al., 1997, 2005). Despite the efforts of most climatic modelers, varied \(xB^{-1}\) algorithms are used by the various research groups and forecast centers. For this reason, the World Climate
Research programme (WCRP) workshop on air–land interaction recommended the experimental verification of the widely accepted Brutsaert algorithm and intercomparison of various $k_B^{-1}$ algorithms (Su et al., 1998; Zeng et al., 1997, 2005). However, different authors have carried out WCRP mandate in various regions especially in high-latitude regions where high wind speed is prevalent (Mölder & Lindroth, 2001; Overgaard, 2005; Zeng et al., 1997). However, studies on this are still very scarce for low wind speed conditions which are prevalent in the tropics.

Stewart et al. (1994) determined $k_B^{-1}$ for eight semiarid areas and obtained values ranging between 3.5 and 12.5. The $k_B^{-1}$ calculated by Voogt and Grimmond (2000) for an urban site (London) using Brutsaert expression ranged between 13 and 27. Yang et al. (2007) evaluated several $k_B^{-1}$ schemes using the same data set in Japan. They obtained values ranging between 3 and 10. Zeng et al. (1997) formulated a new $k_B^{-1}$ scheme using a well-established algorithm in Arizona and compared with different $k_B^{-1}$ schemes. Liu et al. (2010) estimated $k_B^{-1}$ using seven schemes. They found that $k_B^{-1}$ has obvious diurnal variation, but no physical explanation was given for the large variability. Mölder and Lindroth (2001) and Molder and Kellner (2002) formulated $k_B^{-1}$ schemes for bare and vegetated surfaces using Brutsaert theoretical model in Sweden. Furthermore, some international experiments under the WCRP have verified the Brutsaert’s formula for different $k_B^{-1}$ schemes. For instance, the European Center for Medium range Weather Forecast (ECMWF) retained the function form of the Brutsaert’s formula. The Tropical Ocean Global Atmosphere (TOGA) also retained $n = 0.25$, while the $n$ value was adjusted for the National Center for Environmental Prediction (NCEP) and Goddard Earth Observing System (GEOS); their excess resistance parameters were developed under moderate to high wind speed (wind up to 18 m/s; Brutsaert, 2005). Developed a comprehensive bulk algorithm using the data from the TOGA Coupled Ocean–Atmosphere Response Experiment under weak to moderate wind conditions (e.g., less than 12 m/s).

The above mentioned works formulated $k_B^{-1}$ schemes under high wind speed conditions and compared different $k_B^{-1}$ schemes for high-latitude regions. An expression for the $k_B^{-1}$ factor is yet to be formulated based on the tropical synoptic observations, and no intercomparison of $k_B^{-1}$ schemes of different global climate model (GCMs) is yet to be carried out in this region. Such an intercomparison is now possible because of the availability of several observational data sets taken under low wind conditions. In particular, Nigeria Micrometeorological Experiment (NIMEX) provides simultaneous hourly data of fluxes and bulk environmental variables over a tropical station under weak wind conditions (i.e., less than 3 m/s). The purpose of this study is to develop a more appropriate excess resistance factor ($k_B^{-1}$) suitable for low wind speed condition and incorporate it into the aerodynamic resistance approach in the Regional Climate Models (RCM)s to simulate the diurnal pattern of turbulent heat fluxes. The performance of various existing $k_B^{-1}$ schemes developed for high wind speed conditions in simulating the turbulent fluxes will be assessed.

2. Material and Methods

2.1. Experimental Sites

NIMEX was conducted at Ile Ife, Nigeria (latitude 7°33’N and longitude 4°33’E) during the transition from dry to wet season (Figure 1). The period of intensive observation was from 19 February to 9 March (Day of Year [DOY] 55 through DOY 70) in 2004 (Jegede et al., 2004). Another phase of NIMEX experiment was carried out at the same site in 2010. The experimental setup was an extension of the former one. The period of intensive observation was also from 19 February to 19 March (DOY 55 through DOY 79) in 2010.

This site is located in the humid equatorial region of West Africa, and the climatic region is Aw class according to Köppen classification (Essenwanger, 2001). This site is at the altitude of 288 m above sea level, and its vegetation can be characterized as fallow bush-land. The ground surface of the site is flat and homogenous. The soil is loamy sand, and it is at its permanent wilting condition at the beginning of the experiment (Jegede et al., 2004; Mauder et al., 2007). The maximum and minimum air temperatures during the period of the experiment were 46.33 and 20.04 °C, respectively, and the annual rainfall amount is 1,225 mm (Otunla & Oladiran, 2013).

The mean and turbulent micrometeorological parameters in the surface layer were measured for the duration of the NIMEX project. Three masts were set up for meteorological measurements, one for fast response sensors (eddy covariance [EC] system) and two for profile measurement of wind, temperature, atmospheric
radiation, and the soil (subsurface) parameters using low-response sensors. The EC system consists of an ultrasonic anemometer and a Krypton hygrometer. The sensors were mounted at 2-m height to capture the turbulent wind, acoustic temperature, and humidity components. The equipment was sampled at a frequency of 16 Hz in order to distinguish turbulent structures adequately (Foken, 2003). However, higher sampling frequencies enable a better distinction in moments of high and low kinematic stress, which results in a shortening of the estimated duration of a turbulent structure. The infrared thermometer was used to remotely measure surface temperature at a height of 1.8 m above the ground level. The water vapor and carbon dioxide analyzers were added to the setup to measure CO₂ and H₂O vapor fluxes. Jegede et al. (2004) documented an overview of the NIMEX experiment.

Figure 1. Sketch showing the position of the measurement site (Ile-Ife) in Nigeria.
2.2. Data Analysis and Quality Assessment

Several quality tests were regularly applied to the data, including controls of steady state flow conditions and intermittent turbulence. Simple visual test according to Foken (2003) was used on daily basis to check the quality of the basic meteorological variables (slow response), while TK2, a software package written by Mauder and Foken (2006), was used for the quality control and analysis of the EC data. The following processes were incorporated into TK2:

1. Spike detection method of Vickers and Mahrt (1997) based on Højstrup (1993) was used to remove the values that were not physically possible, before the calculation of the variances and covariances.
2. To determine the time delay between the sonic anemometer and Krypton hygrometer that was sampled at different frequencies, cross-correlation analysis was done for each averaging interval of the sensors.
3. Crosswind correction was done for the sonic temperature following Liu et al. (2005).
4. The planar fit method of Wilczak et al. (2001) was applied for coordinate transformation. Spectral corrections were done using the spectral models of Kaimal et al. (1972) and Højstrup (1981).
5. Conversion of buoyancy flux into sensible heat flux was done following Schotanus et al. (1983).
6. The latent heat flux was corrected for fluctuations in density and mean vertical mass flow according to Webb et al. (1980).
7. A test for steady state conditions and well-developed turbulence was done by applying the methods of Foken and Wichura (1996) and Foken et al. (2004). Details are in Mauder et al. (2007) and Adeniyi and Ogunsola (2012).

2.3. Bulk Aerodynamic Excess Resistance Algorithm ($\kappa B^{-1}$)

Bulk aerodynamic $\kappa B^{-1}$ algorithm for the computation of turbulent heat fluxes is based on the Brutsaert theoretical framework (Brutsaert, 1979; 1982), and it has been used by various authors over natural and artificial surfaces (Mölder & Lindroth, 2001). The algorithm is both applicable to vegetated and bare soil surfaces. Meanwhile, it has been documented that the turbulent structure over sparse and dense canopies varies significantly; thus, vegetation or lack-thereof can play a key role in determining $\kappa B^{-1}$ (Belcher et al., 2012; Finnigan, 2000; Raupach & Thom, 1981). Furthermore, the estimation of roughness sublayer height as related to canopy height might be a mere simplification but does not seem to be crucial for $\kappa B^{-1}$ estimation (Brutsaert, 1979; 1982). The algorithm involves the estimations of the mass/heat transfer coefficients and roughness lengths for wind and temperature in the roughness sublayer. In addition, the algorithm also assumed neutral atmospheric condition at the top of interfacial roughness sublayer (Molder & Kellner, 2002; Brutsaert, 1982).

The atmosphere surface layer profile of the wind speed $u$ and air temperature $T_a$ are given as (Foken, 2003)

$$ u = \frac{\mu u_*}{\kappa} \left[ \ln \left( \frac{z}{Z_{om}} \right) - \psi_m \left( \frac{z}{L} \right) + \psi_m \left( \frac{Z_{om}}{L} \right) \right], $$

$$ T_a = T_s + \frac{T_s}{\kappa} \left[ \ln \left( \frac{z}{Z_{oh}} \right) - \psi_h \left( \frac{z}{L} \right) + \psi_h \left( \frac{Z_{oh}}{L} \right) \right], $$

where $\psi_m$ and $\psi_h$ are integrated stability function for heat transfer and momentum, respectively. $\kappa$ is the von Karman constant, $L$ is the Monin-Obukov length, $T_s$ is surface temperature, and $T_*$ is the scaling temperature (Molder & Kellner, 2002).

The $\kappa B^{-1}$ factor can be expressed as a difference of two resistance terms.

$$ \kappa B^{-1} = \kappa s_{st}^{-1} - \kappa c_{do}^{-2}, $$

where $s_{st}^{-1}$ is the sublayer Stanton number, $c_{do}$ is the drag coefficient, and $\kappa$ is the von Karman constant.

$$ \kappa s_{st}^{-1} = \frac{\kappa T_s - T_a}{T_*}, $$

$$ \kappa c_{do}^{-2} = \frac{\mu_c}{\mu_*}, $$

where $T_*$ is the scaling temperature.
From equations (1)–(3)

\[ \kappa_{st}^{-1} = \ln \left( \frac{z-d}{Z_{om}} \right) - \psi_m \left( \frac{Z_{om}}{L} \right) + \psi_m \left( \frac{Z_{om}}{L} \right), \] (6)

\[ \kappa_{do}^{-1} = \ln \left( \frac{z-d}{Z_{oh}} \right) - \psi_m \left( \frac{Z_{om}}{L} \right) + \psi_m \left( \frac{Z_{om}}{L} \right), \] (7)

Assuming neutral condition at the top of the interfacial sublayer of the surface layer

\[ \frac{u_*}{u^{*}} = \ln \left( \frac{z-d}{Z_{om}} \right) \] (8)

where the zero-plane displacement \( d \) over a bare soil surface is taken as 0. Also, the value of \( \ln \left( \frac{z-d}{Z_{om}} \right) \) or sublayer Stanton number has been known to be Reynolds number dependent (Kustas et al., 1989; Molder & Kellner, 2002)

\[ \frac{k(T_a-T_s)}{T^{*}} = \ln \left( \frac{z-d}{Z_{oh}} \right) \geq \kappa_1 Re^n, \] (9)

After simplification, we have the final expression for \( \kappa_B^{-1} \) as

\[ \kappa_B^{-1} = k_1 Re^n \ln \left( \frac{Z_{om}}{Z_{om}} \right). \] (10)

The functional form of Brutsaert expression took the form

\[ \kappa_B^{-1} = b_1 Re^{0.25} + b_2. \] (11)

The Brutsaert theoretical framework scaled the exponent (\( n \)) of roughness Reynolds as \( Re^{0.25} \) (Brutsaert, 1965, 1975a, 1975b). Earlier proposed scaling results gave the value of \( n \) as 0.5 and 1 (Li et al., 2017; Zilitinkevich et al., 2001). The power laws “1/4” and “1/2” of \( Re \) both have strong theoretical foundations which have been widely used in various parameterizations, but 1/4 scaling is still in use to date (Li et al., 2017; Yang et al., 2003). The Brutsaert drag \( (b_2 = 2.75) \) and interfacial heat \( (b_1 = 2.46) \) coefficients were obtained from laboratory measurements using the surface renewal algorithm. The algorithm was based on the notion that at the interface the heat transfer is controlled by molecular diffusion which is translated into internal Kolmogorov scale eddies, and these eddies are renewed intermittently after random times of contact with the evaporating surface. This algorithm could not couple the near-surface molecular diffusion with the turbulent dynamic layer, and renewal rate of the eddies were not time dependent; the distribution would not be exponential, in which case the value of 1/4 would not be perfectly accurate. And turbulence parameters were not taken into consideration by this algorithm. In view of these limitations of the Brutsaert theoretical algorithm using surface renewal method, the EC technique gave room for field verifications. Moreover, experimental verification of the Brutsaert algorithm scaled the value of \( n \) as 0.30 and 0.50 by Mölder and Lindroth (2001) using Cartesian analysis. They varied the value of \( n \) from 0 to 1 at 0.1 steps; the \( n \) value corresponding to the minimum deviation was chosen (no theoretical augment. Furthermore, international experiments conducted by Global Energy and Water Cycle Experiment (GEWEX), GEOS, and NCEP obtained \( n \) values, ranging from 0.45 to 0.75 (Zeng et al., 1997).

The two scaling laws exponents (\( n = 0.25 \) and \( n = 0.50 \)), drag, and Stanton number coefficients inferred from the Brutsaert theoretical algorithm were used to estimate the turbulent heat fluxes using ARA, and expected preliminary results showed strong overestimation during early and late hours of the morning (>40 W/m²), the midday (>120 W/m²), and nighttime hours (>10 W/m²; see section 3.4). The observations from the results showed that the functional form of Brutsaert (1982) cannot be retained for this region. Motivated by this, we inferred the Brutsaert exponent and coefficients from NIMEX experimental data.
### Table 1

| GCMs | Expression | Assumption/theory | Country | References |
|------|------------|-------------------|---------|------------|
| ECMWF (European Centre for Medium-Range Weather Forecast) | $x B^{-1} = 2.46 R e_0^{0.25} \ln(7.4)$ | Monin-Obukhov Similarity Theory (MOST)/Brutsaert (1982) Expression | Spain | Zeng et al. (1997) |
| GEWEX (Global Energy and Water Cycle Experiment) | $x B^{-1} = 1.29 R e_0^{0.46} - 2$ | MOST/Brutsaert (1982) Expression | China | Yang et al. (2008) |
| GEOS (Goddard Earth Observing system) | $x B^{-1} = 0.72 (R e - 0.135)\frac{1}{z}$ | MOST/Brutsaert (1982) Expression | United States | Wang et al. (2004) |
| NCEP (National centre for Environment prediction) | $x B^{-1} = 1.56 R e_0^{0.25} - 3.4$ | MOST/Brutsaert (1982) Expression | United States | Yang et al. (2007) |
| TOGA (Tropical Ocean Global Atmosphere) | $x B^{-1} = 3.67 R e_0^{0.25} - 7.51$ | MOST/Brutsaert (1982) Expression | United States (Arizona) | MOST/Brutsaert (1982) Expression |

Note: RMSE = root-mean-square error; GCM = global climate model.

#### 2.3.1. Estimating the Heat Transfer Coefficient (Stanton Number)

To obtain the Stanton number, the values of $k_1$ and $n$ are determined from the value of $(T_s - T_a)$ and $T_s$ using experimental data and Cartesian analyses (Mölder et al., 1999). Since the relationship between $x B^{-1}$ and $Re_0$ has been established (Molder & Kellner, 2002; Mölder & Lindroth, 2001), we obtained the value of $n$ by plotting the $kB^{-1}$ value estimated using EC data against $Re_0$ value using power function regression. Because $kB^{-1}$ cannot be directly measured, we inferred the $kB^{-1}$ from the measured friction velocity ($u_*$), stability parameter, and measured kinematic heat flux using Monin-Obukhov similarity theory (Brutsaert, 2005; Foken, 2003; Garratt, 1994; Voogt & Grimmond, 2000; Rigden et al., 2017).

$$kB^{-1} = k u_* \left[ \frac{-P e [T_a - T_s]}{Q H} \right] \left[ \frac{1}{u_*} \kappa \left[ \frac{z_{om}}{L} \right] \right]$$

(12)

$k_1$ is the slope of the temperature difference between $T_s$ and $T_a$ plotted against the scale $(T_s/T_a) Re_0$.

#### 2.3.2. Estimating the Drag Coefficient

The drag coefficient in equation (10) is estimated using wind speed measurement, and $z_{om}$ is estimated using the EC technique. Zero place displacement is taken as 0 (bare surface). According to the Monin-Obukhov similarity theory (Monin & Obukhov, 1954), the gradient of nondimensional wind speed is written as

$$\frac{x z}{u_*} \frac{\delta u}{\delta z} = \varphi_m \left( \frac{z}{L} \right)$$

(13)

Equation (13) is integrated to obtain the average wind speed $u$ at height $z$.

$$u = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_{om}} \right) - \psi_m \left( \frac{z}{L} \right)$$

(14)

where $\varphi_m (\frac{z}{L})$ is the similarity universal function and $\psi_m (\frac{z}{L})$ is the stability function of the wind profile which becomes 0 under neutral conditions. The aerodynamic roughness length $z_{om}$ was defined (Ma et al., 2002).

$$z_{om} = \exp \left( \frac{\kappa u_*}{u_*} \psi_m \left( \frac{z}{L} \right) \right)$$

(15)

where $u, u_*$, and $\psi_m (\frac{z}{L})$ are measured wind speed, friction velocity, and stability function from sonic the
Since EC data are not always available, we proposed a new $z_0m$ polynomial equation of order 2 using $z_0m$ estimated from equation (15).

### 2.3.3. New Excess Resistance Parameter Estimated Using NIMEX Data

The new scheme for $\kappa B^{-1}$ takes the original form of Brutsaert theoretical model, but all the coefficients were obtained using the NIMEX synoptic data (see sections 3.2 and 3.3). The validity of the Brutsaert exponent was tested for performance in the equatorial atmosphere at the NIMEX site to ascertain the nature of atmospheric surface layer turbulence in this region.

### 2.3.4. Comparison With Other Tropical Overland GCMs $\kappa B^{-1}$ Algorithms

The different Tropical Overland $\kappa B^{-1}$ schemes used in CMs are presented in Table 1. Using observations reported by Zeng et al., 1997, Smith et al. (1990) and Garratt (1992), the Charnock (1955) and Roll (1948) roughness models used in the estimation of $z_0m$ are appropriate for strong wind speed condition; in other words, they are inappropriate under weak wind speed condition. Therefore, the proposed $z_0m$ was used in this work. The coefficients in GEOs are determined by interpolation between the relations of Large and Pond (1981) for moderate to large wind speed and relation of Kondo (1975).

### 2.4. Research Data Analysis

#### 2.4.1. Coefficient of Determination ($r^2$)

The ratio of explained variation, $(X_{\text{obs}} - X_m)^2$, to the total variation, $(X_{\text{obs}} - X_m)^2$, is called the coefficient of determination. $X_m$ is the mean of the observed $X$ values. The ratio lies between 0 and 1. A high value of $r^2$ is desirable as this shows a lower unexplained variation.

#### 2.4.2. Root-Mean-Square Error and Mean Bias Error

The root-mean-square error (RMSE) gives the information on the short-term performance of the correlations by allowing a term-by-term comparison of the actual deviation between the estimated and measured values. The lower the RMSE, the more accurate is the estimate. A positive value of mean bias error (MBE) shows an overestimate, while a negative value shows an underestimate by the model (Igbai, 1993).

The MBE is defined as the sum of the absolute value of the difference between the estimated and observed variables for the 24-hr period and is given as

$$ MBE = \frac{\sum (\text{Predicted} - \text{Observed})}{n} $$

The RMSE is calculated to reflect the overall accuracy of the shape of the predicted curved and is defined as

$$ \text{RMSE} = \sqrt{\frac{\sum (\text{Predicted} - \text{Observed})^2}{n}} $$

where $n$ is the number of observations. The closer the estimated temperature is to the observed temperature, the smaller the RMSE. The RMSE tends to penalize large individual error so heavily and such as may be the better criterion of the performance (Evans et al., 1993).

### 3. Results and Discussion

#### 3.1. Estimating the Drag Coefficients Using NIMEX Data

The measured friction velocity and wind speed from the EC system were used to obtain the mean values of $cd_0^{-1}$ for the low wind speed condition at
Power function regression plot of the mean $xB^{-1}$ with the roughness Reynolds number for a bare soil surface (Ile-Ife, 2010). The solid line ($xB^{-1} = Re_{0.02}^{0.05}$) represents the polynomial fit line for 0.019 scaling for this site. The daytime data which gave small scatter were taken from half-hourly eddy covariance data when sensible heat fluxes were the largest (>160 W/m$^2$).

Therefore, the mean $cd_0^{-1}$ used for $xB^{-1}$ expression was 5.47. Previous research revealed that the $cd_0^{-1}$ value obtained for this region was higher than the ones reported by Mölder and Lindroth (2001) and Zeng et al. (1997). They obtained 1.90 and 2.27 under high wind speed conditions. This implies that high wind speed conditions are associated with low $cd_0^{-1}$ value, while low wind speed conditions have large $cd_0^{-1}$ value.

Hwang (2005) reported the high value of $cd_0^{-1}$ under low wind speed conditions and explained that the extensive wave breaking associated with high wind speed is not always common under low wind speed conditions. This factor has been known to reduced effective surface roughness and drag coefficient (Hwang, 2005). The mean surface roughness ($z_{om}$) ranged from 0.023 to 0.034 m for 2004, and 0.023 to 0.035 m for 2010. The correspondent mean $z_{om}$ for both periods were 0.026 and 0.025 m, respectively, with the average standard error of 0.0003 m. Since all periods have a fairly smooth aerodynamic condition, these values were used for $z_{om}$ in all subsequent analysis.

### 3.2. Estimating the Heat Transfer Coefficient (Stanton Number) Using NIMEX Data

The values of $n$ and $k$ were obtained from experimental data to determine the Stanton number using Brutsaert algorithm. The exponent ($n$) of the roughness Reynolds number was obtained from power function regression analysis of the $xB^{-1}$ value estimated using EC data plotted against $Re_{0.02}$ value for 2004 and 2010, Ile-Ife site (Figures 2 and 3). The $n$ value obtained for the experimental period (2004) was 0.020 under observed wind speed condition, ranging from 0 to 3.1 m/s.

The temperature difference $T_s - T_a$ versus scale $(T^*/k)/Re_{0.02}^{0.02}$ ($°C$). The line is forced through the origin and has the slope of 6.65°(Ile-Ife, 2010). The daily $cd_0^{-1}$ of the tested bare soil surface ranged from 5.21 to 5.81 for both periods. The mean $cd_0^{-1}$ was almost the same for the two experimental transitional periods, and this can be attributed to the reference height adopted for wind speed measurements using the EC technique (Foken, 2003). The diurnal variation of $cd_0^{-1}$ decreases as the surface roughness increases. The final $cd_0^{-1}$ was the overall averages of the calculated drag coefficients for different DOYs for periods under consideration.

\[ z_{om} = (0.21u_z^2-0.92u_z + 3.42) \times 10^2 \]  

Equation (18) is valid for weak wind speed condition (magnitude up to 3 m/s), with a coefficient of determination of 0.85 and standard error of 3.23 x 10$^{-4}$.

The NIMEX site. The drag coefficients ($cd_0^{-1}$) of bare soil surface were obtained using equation (10). Since measurements from EC system are not always available and roughness length models used in aerodynamic resistance approach in GCMs are only appropriate for high wind speed conditions, a new aerodynamic roughness length was proposed using the polynomial fit of order 2 from $z_{om}$ estimated from EC data and wind speed measurements. The proposed $z_{om}$ can be expressed as a function of wind speed (Fairall et al., 2003),

\[ u_z = \frac{u}{\kappa}B_0^{-1} \]

The approximate $u_z$ factor obtained for stable and unstable conditions is expressed as

\[ u_z = \frac{u}{\kappa}B_0^{-1} \]

The coefficient of determination is 0.99 with a minimum standard deviation of 0.05.

In addition, the $n$ value obtained for the experimental period (2010) was 0.019 under observed wind speed condition, ranging from 0 to 3.1 m/s.

\[ u_z = \frac{u}{\kappa}B_0^{-1} \]

The coefficient of determination is 0.99 with a minimum standard deviation of 0.05.
The intercomparison of the composite diurnal variation of the modeled sensible heat fluxes using ECMWF, GEOS, NCEP, GEWEX, NIMEX, TOGA, and NIMEX (Brutsaert) with the measured data for DOYs 55–57, Ile Ife (WET DAYS), 2004. ECMWF = European Center for Medium range Weather Forecast; GEOS = Goddard Earth Observing System; NCEP = National Center for Environmental Prediction; GEWEX = Global Energy and Water Cycle Experiment; NIMEX = Nigeria Micrometeorological Experiment; TOGA = Tropical Oceans Global Atmosphere; DOY = Day of Year.

The exponent $\kappa$ fixed at 0.25 by Brutsaert functional form of the $xB^{-1}$ factor was replaced with $n = 0.02$ from experimental data, though the Brutsaert exponent has only been found valid during the neutral condition (Molder & Kellner, 2002). Figure 6 also shows that the $xB^{-1}$ factor increases as $Re_*$ increases, though lower $Re_*$ value was observed for the experimental sites with a range of 10–120. The higher range has been reported for pasture, vegetation surface, and forest (over $Re_* > 1000$) under high wind speed conditions (Molder & Kellner, 2002; Zeng et al., 1997).

The temperature difference between $T_a$ and $T_*$ was plotted against the scale $(T_o/T_a)Re_*^{0.02}$, where the power of 0.02 was obtained from experimental data. The average slopes of the data were 6.66 (Figure 2) and 6.65 (Figure 4), both with a minimum deviation of 0.01 (The regression line was forced through the origin). The mean slope of the two experimental periods was 6.66 as shown in Figure 4 and 5 for both stable and unstable conditions. The Stanton number coefficient obtained is of the form

$$xB^{-1} = 6.66 Re_*^{0.02}$$

The estimated Stanton number obtained ranged from 7.03 to 7.11. The same value was obtained for the two experimental periods (7.06).

### 3.3. Derived $xB^{-1}$ Factor for Low Wind Speed Condition

The exponent fixed at 0.25 by Brutsaert functional form of the $xB^{-1}$ factor was replaced with $n = 0.02$ from experimental data, though the Brutsaert exponent has only been found valid during the neutral condition (Molder & Kellner, 2002). Substituting equation (19) and estimated mean value of the $n$ coefficient obtained is of the form

$$xB^{-1} = 6.66 Re_*^{0.02} - 5.47$$

where $Re_*$ is the roughness Reynolds number, $Re_* = \frac{z_0 u_*}{\nu}$. The kinematics molecular viscosity of air was assumed constant as $1.461 \times 10^{-5}$ m$^2$/s. The empirical constants in equation (21) are roughness sublayer Stanton number and drag coefficient, respectively. The new $xB^{-1}$ scheme had $n$ value much more lower than $n$ values obtained for high wind speed conditions. This implies that atmosphere surface layer turbulence associated with low wind speeds can be different from that at moderate to high wind speed. So, it can be said that low atmosphere turbulence is prevalent within the ASL of an equatorial atmosphere. The value of $Re_*$ decreases as the $z_{0m}$ decreases for stable condition, while $Re_*$ increases as $z_{0m}$ increases for the unstable condition.

The Brutsaert temperature roughness length for an equatorial atmosphere is therefore expressed as

$$z_{0h} = z_{0m} \exp \left[ \kappa \left( 6.66 Re_*^{0.02} - 5.47 \right) \right]$$

The new scheme $xB^{-1}$ is good because we studied the general trend in surface-air temperature versus a relevant scale (here $T_*Re_*^{0.02}$). And it is
The intercomparison of the composite diurnal variation of the modeled latent heat fluxes using ECMWF, GEOS, NCEP, GEWEX, NIMEX, TOGA, and NIMEX (Brutsaert), with the measured data for DOYs 55–57, Ile Ife (WET DAY), 2004. ECMWF = European Center for Medium range Weather Forecast; GEOS = Goddard Earth Observing System; NCEP = National Center for Environmental Prediction; GEWEX = Global Energy and Water Cycle Experiment; NIMEX = Nigeria Micrometeorological Experiment; TOGA = Tropical Oceans Global Atmosphere; NIMEX (BRUTSAERT) = National Center for Environmental Prediction; GEWEX = Global Energy and Water Cycle Experiment; DOY = Day of Year.

The intercomparison of the composite diurnal variation of the modeled latent heat fluxes obtained from different kB⁻¹ schemes with the measured data for wet and dry days, respectively. The Q_H fluxes estimated by GEOS and ECMWF were overestimated by 60% (>200 W/m²) during the wet days and 50% during the dry days for the daytime period. The Q_H estimated by NCEP showed a strong overestimation of about 45% (>180 W/m²) and 47% (>198 W/m²) for wet and dry days, respectively. The GEWEX kB⁻¹ scheme shows closeness to the measured value during the early hours of the morning, while a strong overestimation of about 100 W/m² was still observed during the midday.

3.4. Intercomparison of Turbulent Sensible and Latent Heat Fluxes Using Different kB⁻¹ Schemes

The sensible (Q_S) and latent heat fluxes (Q_E) were computed using ARA given as:

\[ Q_S = \rho C_p \left( T_a - T_s \right) \]

and

\[ Q_E = \frac{\rho \left( \varepsilon S_c \right)}{\varepsilon a} \]

respectively, where \( \rho C_p \), \( r_a \), \( \gamma \), and \( e_a \) are volumetric heat capacity, aerodynamic resistance to heat transfer, psychrometric constant, saturated vapor pressure for soil, and saturated vapor pressure for air, respectively. Values of Q_S and Q_E were simulated using derived kB⁻¹ and other six existing overland kB⁻¹ schemes. Figures 6 and 7 showed the intercomparison of the composite diurnal variations of the modeled sensible heat fluxes from different kB⁻¹ schemes with the measured data for wet and dry days, respectively. The Q_H fluxes estimated by GEOS and ECMWF were overestimated by 60% (>200 W/m²) during the wet days and 50% during the dry days for the daytime period. The Q_H estimated by NCEP showed a strong overestimation of about 45% (>180 W/m²) and 47% (>198 W/m²) for wet and dry days, respectively. The GEWEX kB⁻¹ scheme shows closeness to the measured value during the early hours of the morning, while a strong overestimation of about 100 W/m² was still observed during the midday.

The GEWEX kB⁻¹ scheme seems to show better performance during the daytime and nighttime stable atmospheric condition. Most of the time, the NCEP kB⁻¹ scheme overestimated Q_H relative to the others, whereas the GEWEX scheme overestimated measured Q_H in the morning hours when Q_H is negative. The TOGA scheme showed closeness to the observed data, especially during the early hours of the morning, though an underestimation of about 30 W/m² was still observed during the midday. The reason is the fact that TOGA was developed under a moderate wind speed condition; the diurnal wind speed range is about 5 m/s higher than value obtained for this region. The derived NIMEX kB⁻¹ scheme showed better performance for daytime and nighttime atmospheric conditions. The scheme gave almost zero bias in kB⁻¹ with respect to observed kB⁻¹ around 1100 hr LT and 1500 hr LT. This is not surprising because most of the field based coefficients were estimated from the NIMEX site. The large difference in wind drag coefficient may be primarily responsible for the overestimation by some schemes like GEOS, GEWEX, and NCEP. Also, the diurnal variation of Q_H is similar for the different kB⁻¹ schemes; however, systematic differences exist in heat flux values. In Figure 7, the performance of some schemes like GEOS, NCEP, and ECMWF still showed overestimation of Q_H greater than 80 W/m² for daytime and nighttime atmospheric conditions, respectively. The performance of the NIMEX kB⁻¹ scheme was also very good for dry days, although slight overestimation of about 10 to 30 W/m² was observed during the early hours of the morning and late hours of the nighttime. The NIMEX kB⁻¹ scheme gave reliable Q_H estimation in the ARA. The TOGA scheme showed a slight overestimation (>15 W/m²) during the morning, strong agreement with measured data during the midday, and strong overestimation during the night. This implies that the TOGA scheme is reliable for daytime Q_H estimation.

Figures 8 and 9 showed the intercomparison of the composite diurnal variations of the modeled latent heat fluxes from different kB⁻¹ schemes with the measured data for wet and dry days, respectively. The Q_E fluxes estimated by GEOS, NCEP, and ECMWF kB⁻¹ schemes were strongly overestimated (>150 W/m²) during the daytime for wet and dry days. The Q_E
Table 2
Estimated Daily Heat Transfer (Stanton Number) and Drag Coefficients Using the Brutsaert's Algorithm for Different DOYs for Ile-Ife, 2004 and 2010

| DOY | cd0−1 | st0−1 | z0mn | DOY | cd0−1 | st0−1 | z0mn |
|-----|--------|--------|------|-----|--------|--------|------|
| 2004 | 0.024  | 0.023  | 0.026 | 2010 | 0.026  | 0.025  | 0.026 |
| 55  | 5.21   | 7.03   | 0.025 | 146  | 5.31   | 7.03   | 0.024 |
| 56  | 5.41   | 7.04   | 0.028 | 147  | 5.57   | 7.06   | 0.023 |
| 57  | 5.61   | 7.05   | 0.025 | 148  | 5.4    | 7.06   | 0.028 |
| 58  | 5.66   | 7.05   | 0.031 | 149  | 5.44   | 7.07   | 0.031 |
| 59  | 5.41   | 7.06   | 0.025 | 150  | 5.42   | 7.04   | 0.025 |
| 60  | 5.31   | 7.07   | 0.024 | 151  | 5.45   | 7.08   | 0.023 |
| 61  | 5.52   | 7.07   | 0.027 | 152  | 5.47   | 7.08   | 0.026 |
| 62  | 5.57   | 7.07   | 0.023 | 153  | 5.48   | 7.09   | 0.025 |
| 63  | 5.81   | 7.06   | 0.031 | 154  | 5.57   | 7.05   | 0.03  |
| 64  | 5.54   | 7.11   | 0.023 | 155  | 5.45   | 7.1    | 0.026 |
| 65  | 5.54   | 7.07   | 0.027 | 156  | 5.56   | 7.06   | 0.036 |
| 66  | 5.24   | 7.09   | 0.034 | 157  | 5.35   | 7.06   | 0.024 |
| 67  | 5.48   | 7.05   | 0.024 | 158  | 5.68   | 7.09   | 0.025 |
| 68  | 5.45   | 7.03   | 0.023 | 159  | 5.52   | 7.06   | 0.026 |
| 69  | 5.3    | 7.07   | 0.023 | 160  | 5.42   | 7.07   | 0.023 |
| MEAN| 5.47   | 7.06   | 0.025 | MEAN | 5.47   | 7.07   | 0.026 |

Note. DOY = Day of Year.

3.5. Evaluation of the Performance of the Different xB−1 Schemes

The daytime and nighttime MBEs, RMSEs, and r2 values calculated for QH and QE are presented in Table 3. The NIMEX xB−1 scheme has the highest r2 values for stable (0.82) and unstable (0.90) conditions, with computed based on the NIMEX xB−1 scheme has almost zero bias with respect to the measured value during the early hours of the morning but a slight underestimation of about 25 W/m² during the midday. The TOGA scheme also showed closeness to the measured data during the early hours of the morning and late hours of the night, though strong underestimation of about 80 W/m² exists during the midday. During the dry days, all the schemes, except NIMEX and TOGA, simulated QH with little or no bias compared to the measured data during the early hours of the morning and late hours of the night. And slight underestimations of about 10 and 30 W/m² were obtained during the midday from NIMEX and TOGA, respectively. The validity of Brutsaert exponent for an equatorial atmosphere was tested in this work. The field-based exponent was replaced by 0.25, while other coefficients were retained in NIMEX xB−1 scheme. The Brutsaert exponent seems to be valid for both wet and dry days during the early hours of the morning (u > 0.02 m/s), while it gives strong overestimation during the midday and nighttime conditions (>120 W/m²; Figures 6 and 7). It can therefore be concluded that the Brutsaert exponent is valid for neutral conditions during the stable atmospheric condition, but the exponent is not valid for unstable atmospheric conditions. The atmospheric condition is in line with the assumption of Brutsaert theoretical model for the neutral stable condition Table 2.

Table 3
Intercomparison of GCMs xB−1 Schemes for the Computation of Surface Fluxes of Sensible and Latent Heat Fluxes for Ile-Ife, 2004

|       | Wet days | Dry days |
|-------|----------|----------|
|       | Stable | Unstable | Stable | Unstable |
|       | MBE (W/m²) | RMSE (W/m²) | r² | MBE (W/m²) | RMSE (W/m²) | r² | MBE (W/m²) | RMSE (W/m²) | r² |
| QH    |       |          |        |       |          |        |       |          |        |       |
| ECMWF | 41.11 | 60.17 | 0.40 | 30.47 | 59.42 | 0.40 | 54.11 | 50.17 | 0.48 | 31.47 | 60.70 | 0.48 |
| GEWEX | 41.71 | 50.11 | 0.39 | 20.71 | 41.11 | 0.45 | 42.71 | 61.11 | 0.42 | 21.71 | 51.71 | 0.40 |
| NCEP  | 31.11 | 61.11 | 0.47 | 22.11 | 59.04 | 0.40 | 41.11 | 63.11 | 0.38 | 33.11 | 70.11 | 0.42 |
| TOGA  | 3.11  | 30.11 | 0.65 | −23.15 | 25.73 | 0.60 | 13.11 | 31.11 | 0.68 | −24.11 | 36.11 | 0.48 |
| NIMEX | −9.11 | 20.01 | 0.62 | −21.15 | 51.95 | 0.23 | −23.11 | 41.11 | 0.23 | 15.05 | 43.11 | 0.21 |
|       | −3.11 | 10.01 | 0.82 | −1.15 | 12.95 | 0.90 | −5.11 | 11.11 | 0.89 | −1.05 | 23.11 | 0.92 |

| QE    |       |          |        |       |          |        |       |          |        |       |
| ECMWF | 45.11 | 69.17 | 0.48 | 35.47 | 69.42 | 0.40 | 48.11 | 55.17 | 0.45 | 31.47 | 60.70 | 0.48 |
| GEWEX | 41.71 | 50.11 | 0.42 | 22.71 | 48.11 | 0.45 | 36.91 | 68.11 | 0.42 | 21.71 | 51.71 | 0.40 |
| NCEP  | 30.11 | 56.11 | 0.46 | 38.11 | 59.04 | 0.40 | 41.11 | 63.11 | 0.38 | 33.11 | 60.81 | 0.42 |
| TOGA  | 30.31 | 61.11 | 0.45 | 14.54 | 41.11 | 0.42 | 21.11 | 46.11 | 0.48 | 11.11 | 34.11 | 0.48 |
| NIMEX | 15.11 | 30.11 | 0.55 | 23.15 | 25.73 | 0.50 | 13.11 | 31.11 | 0.68 | 24.11 | 38.11 | 0.58 |
|       | 14.11 | 32.01 | 0.52 | 21.15 | 51.95 | 0.23 | −23.11 | 41.11 | 0.63 | 13.05 | 23.11 | 0.21 |
|       | 2.11  | 14.01 | 0.72 | 3.15  | 17.95 | 0.80 | 5.11  | 16.11 | 0.73 | −8.05 | 16.11 | 0.86 |

Note. RMSE = root-mean-square error; GCM = global climate model; ECMWF = European Center for Medium range Weather Forecast; GEWEX = Global Energy and Water Cycle Experiment; GEOS = Goddard Earth Observing System; NCEP = National Center for Environmental Prediction; TOGA = Tropical Oceans Global Atmospheric; NIMEX = Nigeria Micrometeorological Experiment; DOY = Day of Year.
corresponding least MBEs and RMSEs values of $-3.11$ to $-1.15$ and $10.01$--$12.95$ W/m$^2$, respectively, for wet days; $-5.11$ to $-1.05$ and $11.01$--$8.00$ W/m$^2$, respectively, for dry days in sensible heat fluxes. The TOGA $kB^{-1}$ scheme showed good agreement with observed for $Q_H$ ($r^2 = 0.65$, MBE = $3.11$, RMSE = $10.11$) for stable wet days and $Q_E$ ($r^2 = 0.58$, MBE = $5.11$, RMSE = $20.11$). The performance of GEOS and ECMWF in simulating both $Q_H$ and $Q_E$ was very poor, the composite MBEs in $Q_H$ and $Q_E$ were greater than $20$ W/m$^2$ during wet and dry days for nonneutral conditions. The GEOS has the least $r^2$ value (0.47) and highest MBE value (43.64 W/m$^2$). The ECMWF, GEWEX, and GEOS showed strong overestimations with high MBE and RMSE for stable period during the wet days. The performances of the GEOS and ECMWF were also poor during unstable period for wet days. The performance of TOGA $kB^{-1}$ was also good for stable and unstable condition. Generally, NIMEX $kB^{-1}$ scheme has the best performance during the stable and unstable conditions for both wet and dry days. This is as a result of the following: first, the field-based coefficients are estimated from the observed NIMEX data. Second, there was a thorough study of the general trends in surface-air temperature difference versus a relevant scale ($T$-$Re^{0.2}$); and third, the inclusion of the $Re^{0.2}$ term improved the $r^2$ value.

4. Conclusion

A derived excess resistance factor ($kB^{-1}$) needed in the ARA was formulated using synoptic data from the humid tropical region, and Brutsaert theoretical algorithm was verified using NIMEX surface layer observations under low wind speed condition. The derived $kB^{-1}$ scheme had $n$ value much lower than $n$ values obtained for high-latitude climatic region. This implies that atmosphere surface layer turbulence associated with low wind speeds can be different from that at moderate to high wind speed. Weak atmosphere turbulence is prevalent within the ASL of an equatorial atmosphere. The new $kB^{-1}$ scheme was derived based on the general trend in surface-air temperature versus a relevant scale (here $T$-$Re^{0.2}$). It is very simple to apply, especially in most synoptic stations where the estimation of interfacial heat transfer coefficients is not possible. However, the new $kB^{-1}$ scheme has some limitations. First, it has empirical constant values for Stanton number and drag coefficients which can only be the same under similar experimental conditions at other sites. Second, it is limited to air flow over fairly smooth surfaces with low roughness Reynolds number range, $5 < Re < 200$. The inclusion of the new $kB^{-1}$ factor improved the performance of ARA for the humid tropical region. The RMSE reduced from 56 to 25 W/m$^2$ for $Q_H$ and 66 to 16 W/m$^2$ for $Q_E$. Therefore, the aerodynamic resistance due to heat transfer and momentum resistance cannot be assumed equal within the equatorial atmosphere. Turbulent fluxes generally reduce aerodynamic 1982 resistance during the daytime and increase it during the nighttime.

Using the conceptual framework developed by Brutsaert (1982), the micrometeorological measurements at NIMEX provided coefficients for the algorithm that adequately describe the nature of surface layer atmospheric turbulence at the sites concerned. The field-based empirical coefficients for the relationship between the Stanton number and the roughness Reynolds number were different from the ones based on laboratory measurements that Brutsaert initially derived. However, the Brutsaert exponent (0.25) seems to be valid for the neutral condition of stable conditions in the equatorial atmosphere. All of the $kB^{-1}$ parameterization schemes considered here showed different skills for turbulent fluxes simulation. In general, the new $kB^{-1}$ factor, which corrects a well-documented overestimation of mean $kB^{-1}$ by Brutsaert formulation (Trenberth, 2011; Zeng et al., 2005; Liu et al., 2010), performed better for these land sites and may be a better choice to be incorporated into current land surface models, especially for areas where low wind speed is prevalent. Lastly, the aerodynamic resistance approach has been tested on a period covering the transitional period from dry to wet weather conditions, but only for bare soil surface. Other types of vegetation need to be investigated, but it is believed that, due to the use of new $kB^{-1}$ factor (and since vegetation is not a dominant factor in the estimation of $kB^{-1}$ or $z_{0h}$), the model will perform well regardless of the types of vegetation in a low wind speed condition. In case of snow cover, however, special treatment would be required. The result obtained encourages the use of aerodynamic resistance approach for evaluating turbulent heat fluxes as a means of determining the stability of the atmospheric surface layer. Also, the outcome of this work is most needed for verification purposes in most CMs, in order to ensure proper climate change prediction.
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