NOTES AND CORRESPONDENCE

Sensitivity of Numerical Simulations to Parameterizations of Roughness for Surface Heat Fluxes at High Winds over the Sea

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ABSTRACT

A few roughness length schemes for surface sensible and latent heat fluxes have been developed to fit observations under low and moderate wind (<20 m s^{-1}) conditions. It is not clear to what degree these schemes can be extrapolated to cases of high wind conditions (>25 m s^{-1}). In this study, numerical experiments are carried out to reveal the sensitivity of a simulated hurricane to the roughness length schemes for heat fluxes. It is shown that great disparity exists in the response of the model-simulated hurricane to the schemes. This suggests that further research involving both theory and observations is required in order to reduce the uncertainties in numerical simulation of air–sea fluxes under high wind conditions.

1. Introduction

Numerical weather prediction models commonly use the classic Monin–Obukhov (M–O) similarity theory to parameterize surface turbulent fluxes using the model-resolvable variables that drive and influence the fluxes. Although research activities for the refinement of the flux parameterization schemes have been carried out for a few decades, uncertainties still remain in the specification of the parameters used in the flux parameterization schemes. These uncertainties come from a variety of sources (e.g., Weidinger et al. 2000), but for fluxes over the sea there are two major ones. The first major source of uncertainty is the validity of the M–O similarity theory. For example, over the sea, the M–O similarity theory does not explicitly take into account the full physics of the surface wave field and its influence on the surface fluxes; thus, additional theory and empiricism must be applied for a physically sound delineation of the processes associated with the fluxes across the air–sea interface. The second major source of uncertainty is related to the fact that specification of the parameters in the flux parameterization scheme must be fit to observational data, which can also contain uncertainties. When applying the flux parameterization schemes based on the M–O similarity theory under high wind conditions, an additional uncertainty emerges because reliable observational data are only available for weak and moderate surface winds (<20 m s^{-1}). However, numerical weather prediction of extreme weather events is of great importance, and it is not clear to what degree these formulas can be extrapolated to cases of high wind conditions.

When a new flux parameterization scheme is proposed based on the most recent observations, testing it in numerical models is an important step toward its ultimate evaluation. One possible approach for testing a surface flux parameterization scheme is to implement the scheme in a numerical weather prediction model and to evaluate the model's sensitivity to the changes made by the new scheme. Then, results from the model's forecast are compared with observations of weather events that span a wide range of environmental conditions. The sensitivity evaluation and comparison with observations should be performed under two types of conditions. The

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first is similar to those from which the scheme is derived, and the second is one in which the use of the scheme is extrapolated. As an example of the sensitivity evaluation under the first type of conditions, Garratt and Pielke (1989) performed numerical experiments in which the sensitivity of a numerical model to a few parameters used in surface flux schemes, including the roughness lengths for heat fluxes, was examined. Their results indicated that the model's sensitivity to the parameters was generally less than that found in previously published comparisons related to turbulence closure schemes. It is with respect to the second type of condition that this study is conducted.

In this study, several roughness length schemes for sensible and latent heat fluxes will be applied over the sea in numerical simulations of a hurricane in which the maximum surface wind speed is much greater than the maximum wind speeds of the datasets from which these schemes were derived. Model results are compared to evaluate the sensitivity of the model to the different schemes. A hurricane was chosen because the skill of numerical forecasts of hurricane intensity is strongly dependent on how accurately hurricane forecast models simulate air–sea interaction; in particular, the intensification of hurricanes is sensitive to the ratio of the air–sea interfacial enthalpy and momentum fluxes (Emanuel 1995). Surface flux parameterization schemes that were derived based on observations at weak and moderate wind speeds are used in almost all the operational hurricane forecasting models. Errors are inevitable when extrapolating the use of these schemes to the extreme wind speed conditions associated with hurricanes. This paper is organized as follows. Section 2 provides a brief description of the roughness length schemes for sensible and latent heat fluxes that are applied in this study. The design of numerical simulations will be discussed in section 3, which is followed by a summary of the results from all the simulations (section 4). Finally, the implication of the numerical results and concluding remarks will be presented in section 5.

2. Roughness length schemes for heat fluxes used in the study

The atmospheric surface layer can be divided into two sublayers according to what processes are dominant. Immediately adjacent to the surface, there is a viscous sublayer in which molecular diffusive processes are dominant. Above the viscous sublayer the profiles of wind, temperature, and water vapor are logarithmic with distance from the surface. It is generally not feasible to measure surface heat fluxes within the viscous sublayer; instead they are measured in the logarithmic sublayer. The surface fluxes are statistically related to the temperature and moisture profile through specification of surface roughness lengths, which are the virtual origins of logarithmic temperature and moisture profiles (e.g., Donelan 1990; Fairall et al. 1996). It should be pointed out that the above layering of the atmospheric surface layer is ideal in that it is assumed that the surface is even and homogenous, and the roughness is due to the existence of a very thin viscous sublayer. In reality, the earth surface is covered with roughness elements of various sizes, and is always heterogeneous. Researchers of the atmospheric surface layer have more than one way to layer the atmospheric surface layer for the purpose of investigation. As pointed out in the review paper by Marht (2000), regardless of how the atmospheric surface layer is layered, the concept of roughness length as the origin of logarithmic temperature and moisture profiles is needed for using the bulk formula to estimate surface fluxes using mean variables. By nature, the origin of logarithmic temperature and moisture profiles varies with the characteristics of the underneath surface. Because there is no unique way of measuring surface fluxes, it is intrinsicly difficult to use a single approach to parameterizing roughness lengths for surface sensible and latent heat fluxes based on observations. Therefore, various parameterizations of roughness lengths for surface sensible and latent heat fluxes have been derived from observations, depending on where and under what conditions the observations were taken.

Parameterization schemes of the roughness lengths for surface sensible and latent heat fluxes, denoted as z_{0T} and z_{0q}, respectively, have been developed based on measurements taken both in laboratories (e.g., Kader and Yaglom 1972) and the natural environment (e.g., Brutsaert 1979, 1982; Brutsaert and Sugita 1996; Zilitinkevich et al. 2001). According to the approaches used in the parameterizations, these schemes can be categorized into four groups: (i) directly fitting to data with respect to a nondimensional parameter such as the roughness Reynolds number (R_{re}) (e.g., Fairall et al. 2001); (ii) assuming that the flow in the molecular sublayer is instantaneously smooth (e.g., Makin and Mastenbroek 1996); (iii) using the surface renewal model where the *ratio* of the temperature or the moisture roughness length to the momentum roughness length (z_0) is functionally dependent on the roughness Reynolds number (R_{re}) and the Prantdl number (P_r) (e.g., Liu et al. 1979; Donelan 1990; Garratt 1992; Zilitinkevich et al. 2001), that is,

$$\frac{z_{0T,q}}{z_0} = F(R_{re}, P_r);$$

and (iv) assuming that the heat or moist transfer coefficient at a reference height (z_r) above the surface is constant based on observations, such as Large and Pond (1982), Smith (1988), and DeCosmo et al. (1996). Therefore, great disparity exists in the expressions of z_{0T} and z_{0q}. Table 1 contains a representative sample of the schemes that are used in this sensitivity study.

It should be noted that among all the formulas in Table 1, only those of Fairall et al. (2001), Large and Pond (1982), and Zilitinkevich et al. (2001) were derived us-

TABLE 1. Summary of roughness length schemes for heat fluxes used in this study, where $R_{re} = u_* z_0/\upsilon$, u_* is the so-called friction velocity, υ is the molecular viscosity of surface air, and C_H is the transfer coefficient of sensible heat (assuming equal to that of water vapor) at the reference height (z_r).

Source of formula	Approach	Formula
Fairall et al. (2001)	i	$z_{0T} = z_{0q} = 5.5 \times 10^{-5} R_{re}^{-0.63}$
Makin and Mastenbroek (1996), hereafter MM96	ii	$z_{0T} = z_{0q} = 0.21 \dfrac{\upsilon}{u_*}$
Zilitinkevich et al. (2001)	iii	$\dfrac{z_{0T}}{z_0} = \exp[-\kappa(4.0R_{re}^{0.5} - 3.2)]$ $\dfrac{z_{0q}}{z_0} = \exp[-\kappa(4.0R_{re}^{0.5} - 4.2)]$
Large and Pond (1982) and DeCosmo et al. (1996), hereafter LP-D ($C_H = 1.0 \times 10^{-3}$)	iv	$z_{0T} = z_{0q} = \exp\left[\dfrac{-\kappa^2}{C_H \ln\left(\dfrac{z_r}{z_0}\right)}\right]$
Garratt [1992, Eq. (4.16)], hereafter GA	iii	$\dfrac{z_{0T}}{z_0} = \dfrac{z_{0q}}{z_0} = \exp(-2.0)$
Garratt [1992, Eqs. (4.27) and (4.28)], hereafter GB	iii	$\dfrac{z_{0T}}{z_0} = \dfrac{z_{0q}}{z_0} = \exp(-2.48R_{re}^{0.25} + 2.0)$

ing observations taken over the sea. The rest of the formulas were established based on observations taken over the land with different surface characteristics, or on observations taken in controlled laboratory experiments. The use of these formulas over the sea is based on the assumption that the heat and mass transfer for smooth flow and fully rough flow over the sea are similar, respectively, to the heat and mass transfer for the smooth surface and for the bluff-rough surface over the land (Garratt 1992). It is worth noting that this assumption has never been validated by observations.

We note that the roughness lengths for the surface heat fluxes are physically different from those for momentum flux. For the case of the sensible heat flux, z_{0T} and z_0 will be equal only if the surface skin temperature is the same as the temperature at the height z_0. Beljaars and Holtslag (1991) show that in reality the difference between these two temperatures depends on the characteristics of the surface, and can be as high as 6 K. Over the sea, many observations at low and moderate winds speeds (e.g., Fairall et al. 2001) indicate that the difference is also wind speed dependent and cannot be ignored. As noted by many authors (e.g., Zeng and Dickinson 1998), z_0 is in general greater than z_{0T} because both molecular transfer and pressure fluctuations can transfer momentum to the surface, while the heat flux is supported only by molecular transfer. Thus, the momentum roughness length can be considered as an upper bound to the value of the surface heat and moisture roughness lengths.

3. Numerical simulations

a. Numerical model

Numerical experiments are carried out using the National Atmospheric and Oceanic Administration/Environmental Technology Laboratory (NOAA/ETL) regional air–sea coupled modeling system (Bao et al. 2000), which consists of three well-tested components: the National Center for Atmospheric Research–Pennsylvania State University (NCAR–Penn State) fifth-generation Mesoscale Model (MM5; Grell et al. 1994), the Princeton Ocean Model (POM; Blumberg and Mellor 1987), and the ocean surface wave model developed by the Wave Model Development and Implementation Group (WAM; WAMDI Group 1988). MM5 is a regional, nonhydrostatic, sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulations. The model has a variety of grid-resolvable microphysics and subgrid-scale cumulus convection schemes for precipitation physics, along with several options for the parameterization of planetary boundary layer and surface-layer processes.

POM is a sigma-coordinate, free-surface, hydrostatic primitive equation ocean model, which includes a turbulence submodel. The version of POM used in the coupled modeling system incorporates an improved turbulence submodel to explicitly solve for turbulent mixing in the water column. It also has a data-ingesting module to assimilate in situ temperature and salinity observation data, satellite altimetric data, and surface temperatures inferred from multichannel infrared imagery. WAM is a third-generation wave model that solves the wave transport equation explicitly without any prior assumptions about the shape of the spectrum. It describes the evolution of the directional wave spectrum by solving the wave energy equation. Because the horizontal resolutions of both WAM and POM are no finer than that of MM5, each time step of either WAM or POM contains a few time steps of MM5. Variable passing required for the coupling takes place only when either WAM or POM advances one time step in the integration.

b. Experiment design

Because it is well known that the intensity of a hurricane is controlled by the sensible and latent heat fluxes across the air–sea interface for a given large-scale environment, we choose the scenario of a hurricane passing over an initially warm water surface for the sensitivity experiments. The choice of the hurricane case is motivated by previous studies using both uncoupled atmospheric models (e.g., Emanuel 1986, 1995; Rotunno and Emanuel 1987; Braun and Tao 2000) and coupled models (e.g., Bao et al. 2000), which indicate that the intensities of model-simulated hurricanes are highly sensitive to the sensible and latent heat fluxes from the sea. All the experiments are performed to reveal the sensitivity of the model-simulated hurricane intensity to the different schemes of roughness lengths for both sensible and latent heat fluxes. Atmospheric analyses from the National Centers for Environmental Prediction (NCEP) for the period surrounding the intensification and landfall of Hurricane Opal (1995) beginning at 1200 UTC 2 October 1995 are used to provide boundary conditions for MM5. The initial conditions are constructed by incorporating a Rankine vortex into the analysis at 1200 UTC 2 October 1995, with the center of the vortex at the center of Hurricane Opal (based on the NCEP best track information). All model simulations are carried out for 72 h. All the experiments use the same atmospheric boundary conditions and hurricane vortex initialization so that the atmospheric environmental conditions that predominantly control the hurricane track remain constant.

c. Model configuration

A nested grid system of two meshes is used in this study, with grid resolutions of 45 and 15 km. The finer mesh covers the entire Gulf of Mexico. Both meshes contain 25 sigma levels, with the lowest level 15 m above the surface. The model physics includes the Betts–Miller parameterization scheme (Betts and Miller 1986) for subgrid cumulus convection, an explicit scheme (Reisner et al. 1998) for grid-resolvable water vapor condensation (taking into account cloud water, rainwater, and ice), the Blackadar scheme (Blackadar 1979; Grell et al. 1994) for the planetary boundary layer mixing processes and for vertical diffusion, and an M–O scheme for the surface momentum and heat fluxes [including the parameterized sea spray effect by Fairall et al. (1994)]. In the M–O scheme, the surface sensible and latent heat fluxes at the height z above the surface are given, respectively, by

$$H_s = -\rho C_p \kappa u_* T_* \quad \text{and} \quad H_l = -\rho L_e \kappa u_* q_*,$$

where

$$T_* = \frac{\Delta T}{\ln(z/z_{0T}) - \Psi_h};$$

$$q_* = \frac{\Delta q}{\ln(\kappa u z/K_a + z/z_{0q}) - \Psi_q};$$

u is the wind speed at z; κ is the von Kármán constant; u_* is the friction velocity; ΔT and Δq are the air–sea temperature and moisture differences; z_{0T} and z_{0q} are the roughness lengths, respectively, for the surface sensible and latent heat fluxes (assuming equal over the water in MM5); Ψ_h and Ψ_q are stability correction factors for thermal fluxes (assuming equal in MM5); and K_a is a background diffusivity.

The grid of POM used in this study has a horizontal resolution of $\frac{1}{5}°$ in longitude (about 20 km) and $\frac{1}{25}°$–$\frac{1}{5}°$ in latitude (about 4–20 km with the higher resolution occurring near the coastline) and consists of 86 $\times$ 87 grid points. A total of 21 vertical sigma levels is used with corresponding physical depths of 0, 1, 2, 5, 10, 20, 40, 70, 100, 150, 250, 400, 600, 850, 1150, 1500, 2000, 2500, 3000, 3500, and 4000 m in a water column that is 4000 m deep. POM is initialized with the output of a 9-month spinup run (ending 0000 UTC 1 October 1995). The details of how POM is initialized can be found in Bao et al. (2000).

The horizontal resolution of WAM is 0.4° ($\sim$40 km). The wave spectrum is discretized into 25 frequency bands and 24 directional bands. The frequency bands are logarithmically spaced from 0.042 to 0.41 Hz at intervals of $\Delta f/f = 0.1$, while the directional bins are spaced evenly by 15°. WAM is initialized from a zero wave state because under high wind conditions; the wave state described by WAM adjusts rapidly to the input wind forcing.

Using this model configuration, simulations are performed using the various surface roughness formulas listed in Table 1. For comparison purposes, a control simulation is also run using the default scheme in MM5; that is over the sea the roughness lengths for the heat fluxes are set equal to those for momentum flux. This default scheme can be considered as giving the maximum possible transfer coefficients of heat and moisture and, thus, in theory, leading to the most intense hurricane (Emanuel 1995).

4. Summary of numerical results

For a hurricane, the dynamic link among the minimum sea level pressure at the center, the maximum wind, and convection near the eye-wall is so strong that the central sea level pressure is a very good indicator of the hurricane intensity. Figure 1 shows the difference in the intensity of the simulated hurricane in terms of the minimum sea level pressure (SLP) when different roughness length schemes for surface heat fluxes are used. It is seen that when the Zilitinkevich et al. (2001) roughness length scheme for heat fluxes is used, the simulated hurricane does not intensify at all. The other schemes do produce an intensified hurricane, but the rate of intensification varies significantly with different schemes. The difference in the minimum SLP at the peak of the intensification caused by different choices of the roughness length schemes for surface heat fluxes, excluding the extreme result with the scheme of Zilitinkevich et al. (2001), is as large as 17 mb. When comparing with the sensitivity of the simulated hurricane to other processes in air–sea interaction (e.g., Fig. 5 in Bao et al. 2000), it is interesting to note that the sensitivity to the roughness length schemes for heat fluxes is comparable in terms of the difference in the minimum SLP at the peak of the intensification to the sen-

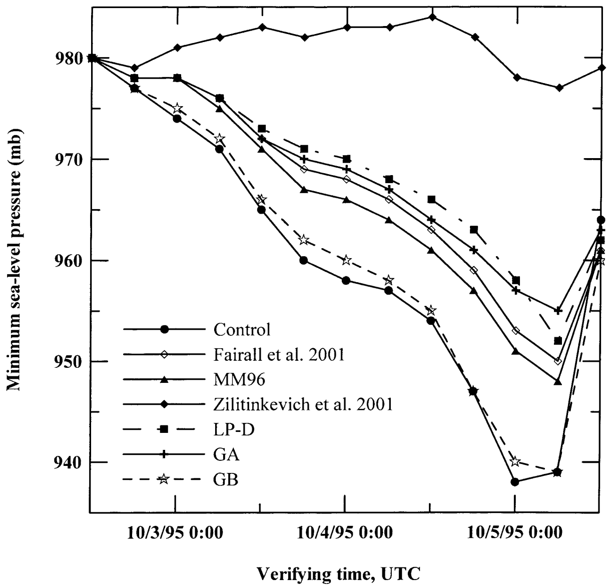

FIG. 1. The difference in the intensity of the simulated hurricane in terms of the minimum SLP when different roughness length schemes for surface heat fluxes are used.

sitivity to sea spray parameterizations. It should be mentioned that the simulated hurricane track does not vary with the choice of the roughness length scheme for heat fluxes although the moving speed of the simulated hurricane does change slightly (not shown).

The analytic model of the structure of mature tropical cyclones developed by Emanuel (1986) predicts that the intensity of a hurricane, measured by the maximum azimuthal wind speed, depends on the value C_k/C_d, where C_k is the exchange coefficient of sensible heat flux (assumed equal to that of latent heat flux) and C_d is the exchange coefficient of momentum flux. Results from numerical simulations using an axis-symmetric tropical cyclone model (Emanuel 1995) further showed that to make the intensity of simulated hurricanes realistic, the value C_k/C_d must lie in the range 0.75–1.5 for that model. Figure 2 shows the values of C_k and C_d as a function of wind speed (panels a and b), and the sensitivity of the value of C_k/C_d (as a function of wind speed) to different schemes of the roughness lengths for surface heat fluxes that are used in this study (panel c). The values of C_k, C_d, and C_k/C_d shown are calculated at 10 m above the sea surface by assuming the following: 1) the roughness length for momentum flux is described by the Charnock relation with $\alpha = 0.011$, 2) the air–sea temperature difference is 4 K, 3) the exchange coefficients for sensible and latent heat fluxes are equal, and 4) the stability of the surface layer is neutral. It is seen that the value C_k/C_d is below 0.75 (i.e., the lower bound of Emanuel's range for realistic hurricanes) for 10-m wind greater than 30 m s^{-1} in all the schemes except for the GB scheme (see the definition in Table 1), which produces similar intensification in this study as does the default scheme used in MM5 (see Fig. 1). For 10-m wind speeds exceeding 30 m s^{-1}, the results shown in Fig. 2 correspond well to those shown in Fig. 1; that is, the lower the value of C_k/C_d, the less intense the simulated hurricane is.

It should be noted that in the control experiment, the value of C_k/C_d would be 1 if the exchange coefficient of sensible heat flux were equal to that of latent heat flux. In reality, the actual exchange coefficient of latent heat flux in the Blackadar scheme is, instead of being equal, smaller than that of sensible heat flux (see the discussion in Braun and Tao 2000), rendering the value of C_k/C_d slightly smaller than 1. Since the effect of sea spray is not significant during the first 12 h into the simulation because the surface maximum wind speed is below 35 m s^{-1} (see Fig. 5b in Bao et al. 2000), the correspondence between Fig. 1 and Fig. 2 qualitatively explains why some of the roughness length schemes for heat fluxes produce a less intense simulated hurricane than the other; that is, the values of C_k/C_d in some of the schemes are smaller than the others during the initial spinup of the simulated hurricane, resulting in less air–sea enthalpy flux to further intensify the hurricane.

5. Discussion and concluding remarks

It has been shown that great disparity exists in both the formulas of the roughness length schemes for surface sensible and latent heat fluxes and their behavior in a weather prediction model. The results of the numerical simulations performed in this study suggest that the disparity in their behavior is great with high wind events over the sea. The sensitivity of the simulated hurricane to the roughness length schemes for heat fluxes is comparable with the sensitivity to the parameterization of sea spray. As a consequence, the sea state and the surface temperature of the Gulf of Mexico as described by the coupled modeling system are sensitive to the variation in the formulas of the roughness length schemes (not shown).

One of the factors that contributes to this disparity is that the parameterizations are based on different observational datasets, taken at different places under various conditions and analyzed by different groups. All the schemes are formulated and fit differently to observations. Because of this and because all the observations were taken at weak and moderate wind speeds, the extrapolated and asymptotic behavior of individual schemes for high winds varies greatly. Additional complexity is added for high wind speeds because sea spray is believed to play an important role in heat transfer across the air–sea interface. There has been a lack of observations on the contribution of sea spray to sensible and latent heat fluxes. Theoretically, the whole issue can be summarized as the need to determine the difference between the skin temperature (or water vapor-mixing ratio) and the temperature at the height of the roughness length for momentum. Unfortunately, a direct measure-

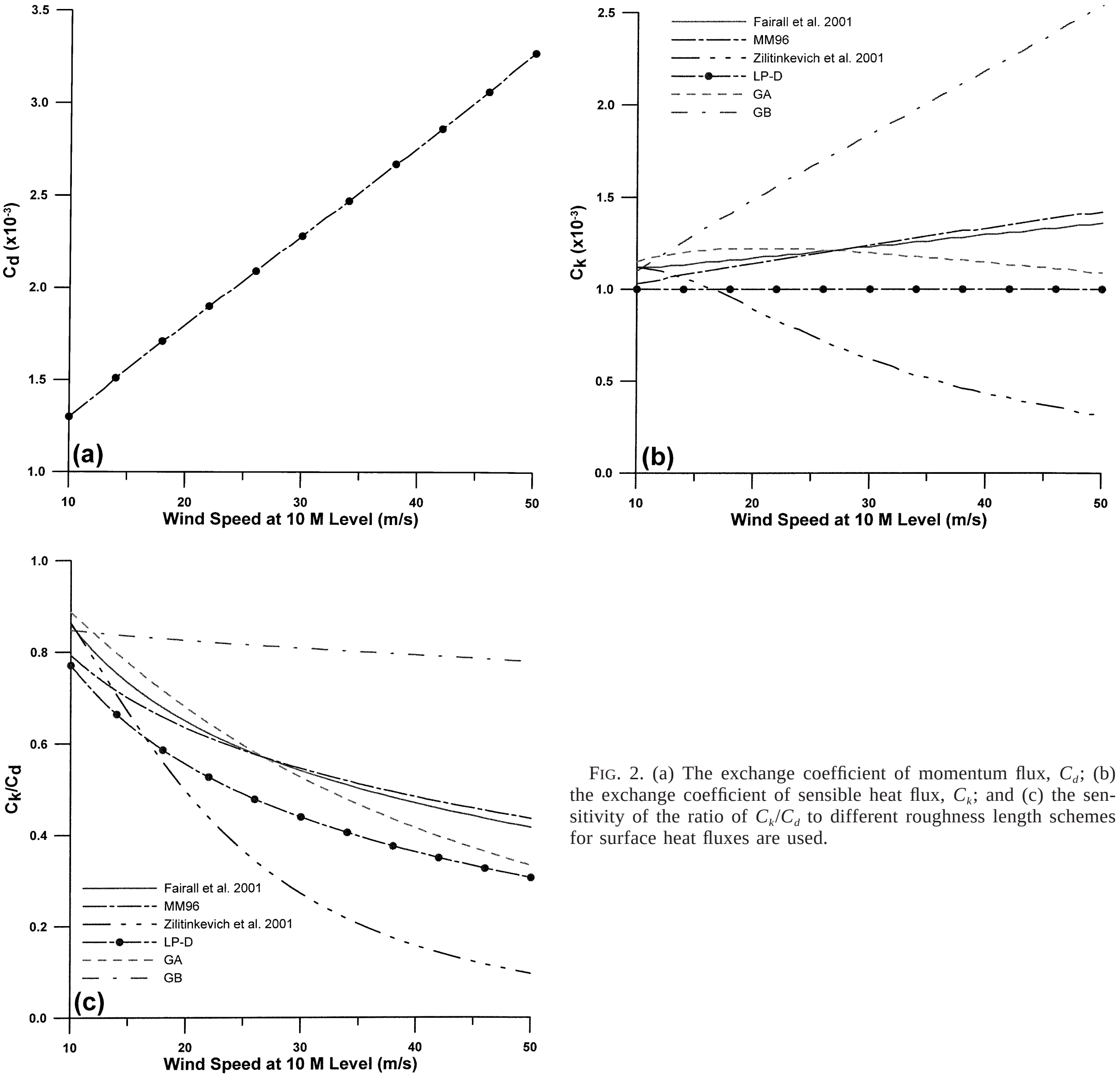

FIG. 2. (a) The exchange coefficient of momentum flux, C_d; (b) the exchange coefficient of sensible heat flux, C_k; and (c) the sensitivity of the ratio of C_k/C_d to different roughness length schemes for surface heat fluxes are used.

ment of these differences even at low wind speeds is extremely difficult. Such information is often inferred from measurements of wind, temperature, and humidity at a few meters above the surface. Therefore, great uncertainties in the parameterizations still exist due to the difference in the conditions under which the measurements are made, how the measurements are taken, and how they are analyzed.

It is important to emphasize here that the choice of the parameterization schemes of the roughness lengths for surface heat fluxes over the sea at high winds is highly uncertain. There are still theoretical and practical problems of how to formulate the schemes for high wind speeds, and caution should be exercised in using a particular formula in a model under high wind conditions where the application of the formula is extrapolated. Finally, this sensitivity study suggests that further research involving both theory and observations is required in order to reduce the uncertainties in numerical simulation of air–sea fluxes under high wind conditions.

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