5.5 UNCERTAINTIES IN THE PARAMETERIZATIONS OF AIR-SEA ENERGY FLUXES AND THEIR IMPACT ON AIR-SEA COUPLED MODELING

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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 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). However, numerical weather prediction of extreme weather events is of great importance, and it is not clear to what degree these formulae 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 condition. The 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.

2. ROUGHNESS LENGTH SCHEMES

The atmospheric surface layer can be divided into

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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 temperature and moisture profiles (e.g., Donelan 1990; Fairall et al. 1996).

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_e) and the Prantdl number (P_r) (e.g., Liu et al. 1979; Donelan 1990; Garratt 1992; Zilitinkevich et al. 2001), i.e.,

$$\frac{z_{0T,q}}{z_0} = F\left(R_{re}, P_r\right) \quad ; \tag{1}$$

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; 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 formulae in Table 1, only those of Fairall et al. 2001, Large and Pond (1982) and Zilitinkevich et al. (2001) were derived using observations taken over the sea. The rest of the formulae 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 formulae 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 EXPERIMENTS

3.1 Numerical model

Numerical experiments are carried out using the National Atmospheric and Oceanic Administration (NOAA)/Environmental Technology Laboratory (ETL) regional air-sea coupled modeling system (Bao et al. 2000), which consists of three well-tested components: the National Center for Atmospheric Research (NCAR)/Penn State atmospheric 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. The coupled modeling system passes information between the three individual model components at each possible time step.

3.2 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; Rotunno and Emanuel 1987; Emanuel 1995; 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 hours. 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.

3.2 Model configuration

A nested grid system of two meshes is used in this study, with grid resolutions of 45 km 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), and an M-O scheme for the surface momentum and heat fluxes (including the parameterized sea spray effect by Fairall et al. 1994). The Blackadar scheme (Blackadar 1979; Grell et al. 1994) was used for the planetary boundary-layer mixing processes and for vertical diffusion.

The grid of POM used in this study has a horizontal resolution of 1/5 degree in longitude (about 20 km) and 1/25-to-1/5 degree in latitude (about 4 to 20 km with the higher resolution occurring near the coastline) and consists of 86 x 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, 4000 m in a water column that is 4000 m deep. POM is initialized with the output of a nine-month spin-up 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 degrees (~40 km). The wave spectrum is discretized into 25 frequency bands and 24 directional bands. The frequency bands are logarithmically spaced from 0.042 Hz to 0.41 Hz at intervals of $\Delta f/f = 0.1$, while the directional bins are spaced evenly by 15 degrees. 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 formulae listed in Table 1. For comparison purposes, a control simulation is also run using the default scheme in MM5, i.e., 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. RESULTS

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 sensitivity 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).

5. DISCUSSIONS AND SUMMARY

It has been shown that great disparity exists in both the formulae 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.

One of the factors that contributes to this disparity is that the parameterizations are based on different observational datasets, taken at different places 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 measurement 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.

6. REFERENCES

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

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

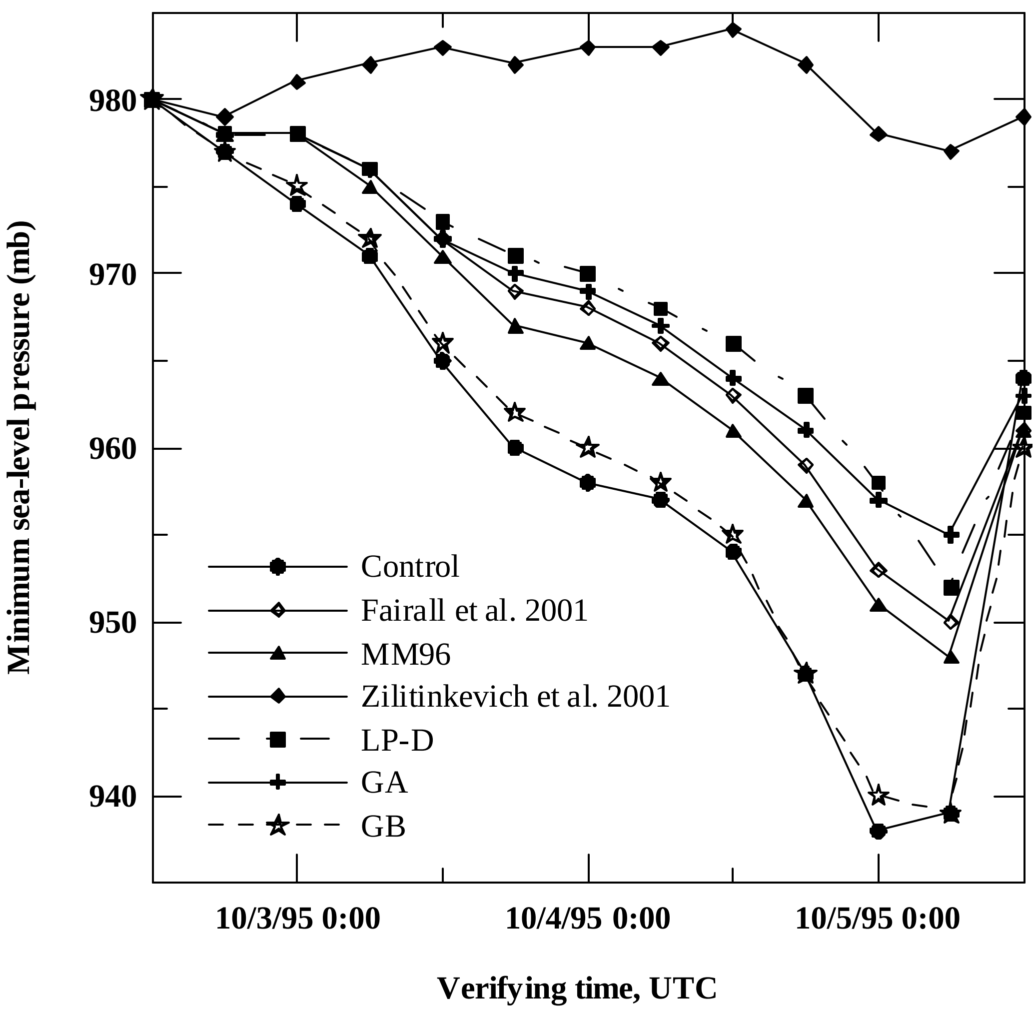

Figure 1 The difference in the intensity of the simulated hurricane in terms of the minimum sea level pressure (SLP) when different roughness length schemes for surface heat fluxes are used.