Sensitivity of High-Resolution Simulations of Hurricane Bob (1991) to Planetary Boundary Layer Parameterizations

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ABSTRACT

The fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model is used to simulate Hurricane Bob (1991) using grids nested to high resolution (4 km). Tests are conducted to determine the sensitivity of the simulation to the available planetary boundary layer parameterizations, including the bulk aerodynamic, Blackadar, Medium-Range Forecast (MRF) model, and Burk–Thompson boundary layer schemes. Significant sensitivity is seen, with minimum central pressures varying by up to 16 mb and maximum winds by 15 m s\(^{-1}\). The Burk–Thompson and bulk aerodynamic boundary layer schemes produced the strongest storms while the MRF scheme produced the weakest storm. Simulated horizontal precipitation structures varied substantially between the different PBL schemes, suggesting that accurate forecasts of precipitation in hurricanes can be just as sensitive to the formulation of the PBL as they are to the cloud microphysical parameterizations.

Each PBL scheme is different in its formulation of the vertical mixing within the PBL and the surface fluxes, with the exception of the MRF and Blackadar schemes, which share essentially the same surface flux parameterization. Detailed analyses of the PBL schemes describe the key differences in the surface fluxes and how they impact storm intensity. In order to isolate the effects of vertical mixing and surfaces fluxes, simulations were conducted in which each of the surface flux schemes was used in conjunction with the same vertical mixing scheme, and vice versa. These experiments indicate that simulated intensity is largely determined by the surface fluxes rather than by the vertical mixing, with the exception of the MRF PBL case, in which excessively deep vertical mixing acts to dry the lower PBL and reduce hurricane intensity. Simulations that vary only the surface fluxes suggest that the intensity of the simulated hurricane increases with increasing values of the ratio of the exchange coefficients for enthalpy and momentum, \(C_k/C_\theta\). However, even for identical values of \(C_k/C_\theta\), the simulated intensity varies depending on the wind speed dependence of the surface roughness parameter \(z_0\).

1. Introduction

Observations within the planetary boundary layer (PBL) in the inner-core region of hurricanes are rare, often available only from isolated dropsondes or buoys. This lack of data forces modelers to use boundary layer parameterizations that have largely been developed for lower wind speed conditions. Assumptions about boundary layer processes are particularly important to models attempting to simulate the convective-scale to mesoscale processes responsible for the evolution and maintenance of hurricanes. It is important to understand how assumptions regarding the character of surface fluxes and vertical mixing within the boundary layer impact simulations of hurricanes so that we understand the limitations of current assumptions and have some direction for future observational studies. This study describes high-resolution simulations of Hurricane Bob (1991) and their sensitivity to different formulations of boundary layer processes, and provides detailed analysis of the components of these boundary layer schemes that produce the sensitivity.

Surface fluxes of sensible and latent heat play a vital role in the development and maintenance of tropical cyclones (Byers 1944). Riehl (1954), Palmén and Riehl (1957), and Malkus and Riehl (1960) have noted that while the heat gained from the ocean is only a small fraction of that transported inward by the radial inflow or released by condensation in the updrafts, it is essential for growth of the hurricane. Malkus and Riehl (1960) showed that surface fluxes in the inner core of hurricanes are capable of increasing the equivalent potential temperature, \(\theta_e\), by more than 10 K, which contributes significantly to the deepening of hurricanes to pressures well below 1000 mb. Ooyama (1969) suggested that surface fluxes in the outer region of hurricanes are also necessary in order to maintain \(\theta_e\) against the effects of entrainment of subsiding dry air into the planetary boundary layer. Emanuel (1986) and Rotunno and
Emanuel (1987) further demonstrated the importance of surface fluxes by showing that hurricanes can develop and be maintained even in environments with no initial convective available potential energy as a result of energy derived from surface fluxes of sensible and latent heat.

The dependence of the maximum tangential winds on the surface exchange coefficients for heat and momentum was first suggested by Malkus and Riehl (1960), Ooyama (1969), Rosenthal (1971), and Emanuel (1986, 1995b, 1997), using numerical and mathematical models of hurricanes, confirmed that the potential intensity of hurricanes increases (decreases) with increases in the exchange coefficient for heat (momentum). In other words, hurricanes become stronger as the transfer of sensible and latent heat from the sea surface is increased and as the frictional dissipation is decreased. These models treated the PBL as a single layer and did not consider the impact of how the vertical mixing takes place.

Anthes and Chang (1978) conducted simulations of hurricanes using a model with high vertical resolution in the boundary layer, but relatively coarse resolution above the PBL and a coarse 60-km horizontal grid spacing. By comparing the model with high resolution in the PBL (a nine-level model) to one treating the PBL as a single layer (a five-level model), they found that the extra degrees of freedom allowed by resolving the boundary layer impacted the behavior of the simulated storms and their sensitivity to changes in surface properties, although their structures above the PBL were similar. Specifically, differences in the responses of the nine- and five-level models to changes in sea surface temperature (SST) included no initial adjustment of the winds, a stronger response to SST, a nonlinear variation of intensity with SST, weaker dynamic coupling, and a weaker change in evaporation in the five-level model.

The different behaviors of the nine- and five-level models raise questions about the sensitivity of more sophisticated, higher-resolution models to the parameterization of PBL processes. Furthermore, the dependence of potential hurricane intensity on surface exchange coefficients for heat and momentum suggests that, for PBL schemes that utilize different parameterizations of surface fluxes, some PBL schemes may be more predisposed toward developing strong hurricanes than others. As model resolution approaches the convective scale, how sensitive will simulations be to different formulations of the PBL physics? Will the sensitivity to the PBL physics be primarily a function of the surface flux parameterization, or will the parameterization of the vertical fluxes above the surface play an important role?

The Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) fifth-generation Mesoscale Model (MM5; Dudhia 1993; Grell et al. 1995) has already been shown to have some skill at simulating hurricanes (Karyampudi et al. 1998) including some at high resolution (6 km; Liu et al. 1997, 1999). The model contains several different representations of PBL processes including a simple bulk aerodynamic PBL (Deardorff 1972), the Blackadar PBL (Blackadar 1976, 1979; Zhang and Anthes 1982; Oncley and Dudhia 1995), a version of the Medium-Range Forecast (MRF) model PBL (Hong and Pan 1996), and a version of the PBL scheme of Burk and Thompson (1989). Evaluation of the model PBL physics can provide insight into the sensitivity of hurricane simulations to the representations of vertical mixing and surface fluxes. In this study, we perform such sensitivity tests in simulations of Hurricane Bob (1991). In section 2, the numerical experiments are described, including the derivation of initial conditions and modifications to some of the model physics. Section 3 provides a brief description of a coarse grid resolution simulation, while sections 4 and 5 describe the high-resolution simulations and the results of sensitivity tests. Brief descriptions of the PBL and surface flux parameterizations are given in appendixes A and B.

2. Simulation description

Version 2.5 of the MM5 model was used to conduct 72-h simulations of Hurricane Bob (0000 UTC 16 Aug–0000 UTC 19 Aug 1991) using a coarse grid consisting of 193×163 grid points in x, y with a grid spacing of 36 km (see Fig. 1). Higher-resolution simulations were performed using a one-way interactive nest between the coarse grid and two finer grids (12 and 4 km, indicated
in Fig. 1). The grid meshes included 27 vertical half-σ levels, where σ is defined as $\sigma = (p - p_{\text{top}})/(p_{\text{top}} - p_{\text{bot}})$, $p$ is pressure, and $p_{\text{bot}}$ and $p_{\text{top}}$ (25 mb) are the pressures at the surface and model top, respectively.

The coarse grid was centered at 33°N, 84°W. Initial and boundary conditions were obtained from 12-hourly global analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) archived at NCAR. Analysis fields, including temperature, relative humidity, geopotential height, and winds at mandatory pressure levels and with horizontal resolution of 2.5° × 2.5° were interpolated horizontally to model grid points. These interpolated analyses were refined by adding information from standard twice-daily rawinsondes and 3-hourly surface and buoy reports using a Barnes objective analysis technique (Manning and Haugen 1992). Final analyses were then interpolated to the model σ levels.

No special observations were available near the initial time and insertion of a bogus vortex was not performed since the storm was only in the tropical depression stage at the initial time. It is noted that use of analyses from the National Centers for Environmental Prediction (NCEP) for initial and boundary conditions produced only a weak vortex rather than a hurricane. The differences between the simulations with ECMWF and NCEP analyses have not been examined in detail, but we speculate that a potential factor may be the inclusion of winds, temperature, and relative humidity at the surface in the ECMWF analyses, while the lowest level of information in the NCEP analyses is at 1000 mb. Furthermore, a hurricane was only obtained when using the Betts–Miller cumulus parameterization. The Kain–Fritsch and Grell schemes produced less precipitation and only weak vortices.

Physics options for the coarse-grid simulation included the Betts–Miller cumulus parameterization, the Goddard Cumulus Ensemble (GCE) model cloud microphysics (Tao and Simpson 1993), the MRF PBL scheme (Hong and Pan 1996), and the cloud radiative scheme of Dudhia (1989). High-resolution simulations were conducted by using 1-h output from the 36-km grid to provide initial and boundary conditions for the 12- and 4-km grids (163 × 178 grid points) beginning at hour 48 of the 72-h control run (thus providing identical initial conditions for all experiments). The 4-km domain was moved with the storm in order to keep the storm nearly centered within the domain. Physics options for the 12- and 4-km simulations were similar to the coarse-grid simulation except that no cumulus parameterization was used on the 4-km grid and the PBL scheme was varied for the sensitivity tests. Although heating associated with the dissipation of turbulent kinetic energy near the surface has been shown to have an impact on hurricane intensity (Bister and Emanuel 1998; Zhang and Althusher 1999), this effect has not been included in this study.

The Goddard microphysical scheme was modified to allow for the option to use graupel or hail as a third class of ice. The modifications included changes to the particle distribution, density, and fall speed constants as well as to the transformation rates, which had previously been written explicitly in terms of the hail fall speed parameters. Other modifications were made to the microphysics that included the addition of subroutines that maintain total water balance while eliminating negative mixing ratios that arise after the calculation of advection terms, changing the slope and intercept parameters in the Fletcher equation (which specifies the number concentration of ice nuclei as a function of temperature) from 0.6 and $10^{-5} \text{L}^{-1}$ to 0.46 and $10^{-4} \text{L}^{-1}$, respectively, in order to provide a better fit to observed ice concentrations (Meyers et al. 1992), limiting the ice nuclei concentration to $\sim 1000 \text{L}^{-1}$, and adding a small fall velocity for cloud ice of 0.2 m s$^{-1}$. A new formulation of the conversion of cloud ice to snow by vapor deposition (to be described in a future paper) was incorporated to correct for a lack of a dependence of this process on relative humidity. The original GCE scheme used a saturation adjustment technique that involved both cloud water and cloud ice. In the modified GCE scheme, the saturation adjustment involves cloud water only. These changes to the microphysics scheme primarily impact the distributions of cloud ice and snow largely as a result of the new formulation of the ice-to-snow conversion process. Intercept parameters for rain, snow, and graupel were set to $22 \times 10^5 \text{m}^{-4}$, $100 \times 10^6 \text{m}^{-4}$, and $4 \times 10^6 \text{m}^{-4}$, respectively. The rain intercept is the same as that used by Lord et al. (1984) in simulations of hurricanes. For snow, the intercept parameter was based on simulations of convective systems by Ferrier et al. (1995). The graupel value is the standard value in the model and is based upon Rutledge and Hobbs (1984).

Nine high-resolution simulations were conducted to test the sensitivity to PBL physics (Table 1). The first four experiments in Table 1 simply use the PBL schemes available in the modeling system: the Burk–Thompson scheme, the bulk aerodynamic scheme, the Blackadar scheme, and the MRF PBL scheme. A brief review of each of the PBL schemes is given in the appendixes. The remaining experiments involve various combinations of vertical mixing and surface flux schemes and are intended to identify the separate impacts of vertical mixing and surface fluxes.

Simulation results from both the coarse and fine grids will be compared to available observations, which include time series of storm track; minimum central pressure and maximum wind speed; radar reflectivity fields.
maximum value of 46 m s$^{-2}$ and then intensified rapidly thereafter, reaching a max-
imum pressure of 957 mb by 72 h.

The evolution of the simulated central pressure and maximum winds during the initial 6–8 h of simulation is strongly affected by spinup of the vortex on the fine grid. This spinup phase involves an adjustment (con-
traction) of the vortex caused by the increase in reso-
volution from 36 to 4 km as well as spinup of the cloud physics as precipitation processes switch from be-
ing represented by the cumulus parameterization to a
bulk microphysical parameterization. Following the
spinup period, the rates of pressure fall and wind speed increase are more indicative of the sensitivity to the PBL parameterizations.

Considerable variation in final central pressures is evident (Fig. 3a), with 16 mb separating the extreme cases. The Burk–Thompson and bulk aerodynamic PBL schemes produce steady rates of pressure fall throughout most of the simulation period, with the Burk–Thompson
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Figure 2. Time series of (a) minimum sea level pressure and (b) maximum wind speed from observations and from the 36-km simulation. The observed winds are based upon flight-level data from reconnaissance aircraft while the model winds represent the maximum hurricane winds within the model domain.

Figure 3. Time series of (a) minimum sea level pressure and (b) maximum wind speed from observations and from the 4-km simulations using variable PBL physics. See Table 1 for a listing of the experiments.

PBL case generally producing slightly lower pressures. Following the initial spinup of the storm, the central pressures in the Burk–Thompson and bulk aerodynamic cases are usually within about 3 mb of the observed 6-hourly pressures. The Blackadar and MRF PBL cases tend to result in much higher central pressures, with final values that are about 12 and 16 mb higher, respectively, than in the Burk–Thompson case.

The time series of maximum wind speed (Fig. 3b) indicate that all of the 4-km simulations produce winds significantly greater than those observed by reconnaissance aircraft. Differences in the maximum winds follow those of the central pressure depression; that is, the lower the central pressure, the stronger the winds, with the MRF PBL scheme producing the weakest winds and the Burk–Thompson and bulk aerodynamic schemes the strongest winds. It is possible that the reconnaissance aircraft did not sample the strongest winds in Bob since flight legs were obtained either at the 850- or 700-mb levels (roughly the 1.25- and 2.8-km levels, respectively) during this period. Simulation results presented here and in Liu et al. (1999), as well as Doppler winds for Hurricane Norbert (1984) described in Marks et al. (1992), suggest that the strongest winds in hurricanes may lie below these levels, so it is possible that winds stronger than those indicated by the flight data may have occurred within Hurricane Bob. However, even when taking these potential errors into account, it is likely that the simulated winds are too strong.

Perhaps a better comparison of wind information is obtained by examining surface wind fields. A surface (10 m) wind analysis valid for 0300 UTC 19 August [provided courtesy of S. Houston, NOAA/HRD; see Houston and Powell (1993)] is shown in Fig. 4. The eye was located just east of Cape Hatteras, with maximum winds in excess of 50 m s$^{-1}$ analyzed to the east of the center. The region of winds exceeding 35 m s$^{-1}$

Figure 4. Surface wind analysis for Hurricane Bob at 0300 UTC 19 Aug (courtesy of S. Houston, NOAA/HRD). Contours are isotachs drawn every 5 m s$^{-1}$. Shaded region encloses winds exceeding 35 m s$^{-1}$.
extended about 2° of longitude to the east of the center. Flight-level data just prior to 0000 UTC 19 August extending from the center at 700 mb suggested that winds in excess of 35 m s⁻¹ extended outward only to a radius of about 80 km, while flight-level data near 0300 UTC indicated such strong winds out to almost 150-km radius, so the actual eastward extent of the strong winds is uncertain. To the west of the center, winds exceeding 35 m s⁻¹ extended outward only 0.5°–1° of longitude, indicative of the impacts of the land surface.

Figure 5 shows that the winds at the lowest model level (42 m) for the simulations are in reasonable agreement with observations in terms of maximum values (~45–55 m s⁻¹), but the distributions vary considerably. The Burk–Thompson case (Fig. 5a) yields localized areas of winds slightly greater than 55 m s⁻¹ in the southeast quadrant of the storm and winds greater than 35 m s⁻¹ extending outward from the center to the east and west about 75 km. The bulk aerodynamic case (Fig. 5b) shows a strong wavenumber 2 pattern with winds exceeding 55 m s⁻¹ in the southwestern and northeastern quadrants. The area of winds greater than 35 m s⁻¹ is largest in this case, extending eastward slightly more than 100 km. The Blackadar (Fig. 5c) and MRF (Fig. 5d) cases produce weaker winds with maximum values on the eastern side of the storm slightly exceeding 45 m s⁻¹ in both cases and the area of winds greater than 35 m s⁻¹ being smaller than in the Burk–Thompson case. In all of the simulations, the storm is too far to the southeast for coastal impacts to occur in the wind field.

Along with storm intensity, the PBL parameterizations also impact the simulated precipitation structure. The simulated radar reflectivity² fields at 72 h for the different PBL cases are displayed later (Fig. 7). These precipitation patterns can be compared to that seen from the Cape Hatteras NEXRAD radar shown in Fig. 6. The NEXRAD radar data indicate a partial eyewall, open to the south, at a radius of about 25 km. This partial eyewall structure was persistent throughout much of the time for which radar observations were available. Outer rainbands on the eastern side of the storm extended toward the northern side, where they merged with a region of heavy, mostly stratiform precipitation northwest of the eye. A convective band with reflectivities exceeding 50 dBZ extended from north of the center eastward at a radius of about 160–200 km, and another band of weaker precipitation extended from the southern end around to the northwestern side of the storm at a radius of about 80–100 km.

The simulated radar reflectivity fields at 72 h (Fig. 7), valid at 0000 UTC 19 August (about 1 h prior to the radar image), show a well-defined eyewall in each case. In the Burk–Thompson case (Fig. 7a), the eyewall contains high reflectivities encircling most of the eye, typical of much of the simulation period. The simulated eyewall radius is about 40–45 km, about twice as wide as observed. Precipitation outside of the eyewall consists of weakly organized cells rather than well-organized bands or wide stratiform rain areas. Although the simulated eyewall radius is larger than observed, the overall size of the precipitation area is smaller. Along the eastern side of the simulated storm, the eyewall rainbands protrude southward in a manner similar to the observed bands in this area. While the model produces a broader region of precipitation to the northwest of the center, similar to the observations, the coverage of stratiform precipitation appears to be less than observed. The strong convective band observed about 180 km to the north of the eye is not simulated at all, although we note that an experiment with a 1.3-km grid centered on the storm, to be reported on in a future paper, produced a well-defined convective band to the north and northeast of the center, suggesting that higher horizontal resolution was necessary to reproduce the weakly forced convection in some of the outer rainbands. The Burk–Thompson case generally results in the most compact rain area of the four experiments. In the bulk aerodynamic PBL case (Fig. 7b), heavy precipitation encloses only about one-half to three-fourths of the eye. This precipitation structure more closely resembles observed reflectivities (Fig. 6) from the Cape Hatteras radar at this time, but only develops within the final hours of the simulation. Convection in outer rainbands to the north and northeast of the center is located at radii of ~150–200 km, in reasonable agreement with the radar observations. The Blackadar PBL scheme (Fig. 7c) produces a precipitation pattern that is similar to the Burk–Thompson case, but the area of precipitation is somewhat broader and the outer convective band that extends southward along the eastern side of the storm is more fully developed. For the MRF PBL case (Fig. 7d), heavy rain surrounds the eye and convection outside of the eyewall is much more active. This case yields the largest areal coverage of precipitation, but also the weakest storm. In general, the variability in the horizontal precipitation structure seen between the different PBL cases is comparable to that obtained from a set of simulations using variable cloud microphysics (not shown, but involving variations of the GCE microphysics scheme and the Reisner microphysics option), which suggests that quantitative precipitation forecasting in hurricanes can be just as dependent on accurate representation of PBL processes as it is on accurate representation of cloud microphysics.

² The equivalent radar reflectivity factor for rain, Zₑ, is computed following Fovell and Ogura (1988) as $Zₑ = 720κNₑλ⁻³$, where $κ = 10^{14}$; $Nₑ$ is the intercept parameter of the raindrop size distribution; $λ$ is the slope of the raindrop size distribution; $λ = (πρₑNₑ/ρ₀qₑ)^{-1}$; $ρₑ$ and $ρ₀$ are the densities of water and air, respectively; and $qₑ$ is the rain mixing ratio. The reflectivity is expressed in decibels, or dBZ, where dBZ = 10 log₁₀(Zₑ).
**b. Vertical structure**

The vertical structures of the simulated hurricanes are compared by examining vertical cross sections of the temporally and azimuthally averaged fields for each case for the period 62–66 h using output every 15 min. Cross sections of vertical velocity are shown in Fig. 8 and indicate that vertical motions in the eyewall are strongest in the Burk–Thompson case (Fig. 8a) and weakest in the bulk aerodynamic and MRF cases (Figs. 8b,d). Each case shows the characteristic outward slope of the mean updraft with height (Malkus 1958; Jorgensen 1984; Marks and Houze 1987). In the Blackadar and Burk–Thompson PBL cases, the updrafts tilt outward very sharply in the lowest few kilometers, but have much smaller tilts at middle to upper levels. A similar structure of the vertical motions can be seen in the analyses of Black et al. (1994) in Hurricane Emily (1987) in the right- and left-front quadrants of the storm (the rear quadrants were characterized by weak or descending motion) and in the simulation of Hurricane Andrew (1992) in Liu et al. (1999). In all but the MRF PBL case, relatively strong downdrafts are adjacent to the eyewall at low levels.

The average tangential winds (Fig. 9) are generally maximum much closer to the surface than is usually seen in airborne Doppler radar data. The model winds tend to peak between 500 and 800 m for the Burk–Thompson, bulk aerodynamic, and Blackadar cases and
1–1.5 km for the MRF case. Doppler wind data described by Marks and Houze (1987) and Marks et al. (1992) suggest maximum azimuthally averaged tangential winds in the 1.5–2.5-km layer. The bulk aerodynamic and Burk–Thompson PBL cases have the strongest winds. Although the vertical motions in the bulk aerodynamic case are relatively weak like those of the MRF case, the tangential winds are as strong as in the Burk–Thompson case. The fact that a strong vortex developed from comparatively weak vertical motions in the eyewall suggests the potential importance of the parameterization of momentum dissipation near the surface.

Radial velocities in the MRF case (Fig. 10d) show relatively deeper, but weaker, radial inflow compared to the other cases (Figs. 10a–c), which are characterized by very shallow (<1.5 km) and strong inflow. Nearly coincident with the eyewall updraft and immediately above the low-level inflow is a region of outflow, which is strongest in the Burk–Thompson case, and weaker in the Blackadar and bulk aerodynamic cases. This outflow region is similar to that seen in the analysis of Hurricane Allen (1980) by Jorgensen (1984) and in the simulation of Hurricane Andrew by Liu et al. (1997, 1999). At upper levels (8–14-km altitude), there is considerable variation in the outflow structure. The outflow in the Burk–Thompson case is quite strong and is maximum within about 100 km from the center, apparently associated with the much stronger and more upright updraft in that case. The outflow is weaker in the other cases and is generally maximum at larger radii. Evident in the Burk–Thompson case, and to a lesser degree in the Blackadar and bulk aerodynamic PBL cases, is a secondary outflow layer near 10.5-km altitude associated with convection outside of the eyewall.

In working toward an understanding of the mechanisms that account for the variations in intensity between the different PBL cases, we start with an examination of the equivalent potential temperature ($\theta_e$) structure in each case. The maximum potential intensity of hurricanes has been related partly to the magnitude of the boundary layer $\theta_e$ (Riehl 1954; Malkus and Riehl 1960; Emanuel 1986; Holland 1997), which typically increases radially inward as inflowing air moves toward lower pressure and picks up heat and moisture from the sea surface (Malkus and Riehl 1960; Liu et al. 1999). The average low-level $\theta_e$ and cloud water structure for each case is depicted in Fig. 11. Outside of 100-km radius, $\theta_e$ in the boundary layer is comparable in the Burk–Thompson and Blackadar cases, slightly lower in the bulk aerodynamic case, and significantly lower in the MRF PBL case because of much drier air. At radii less than 100 km, $\theta_e$ increases rapidly toward the center with $\theta_e$ being highest in the Burk–Thompson case, about the same in the Blackadar and bulk aerodynamic cases, and lowest in the MRF case. Because of the dry PBL in the MRF case, the cloud base is high, with an average height of about 1 km outside of the eyewall and about 600–800 m in the eyewall. In contrast to the MRF case, each of the other cases (Figs. 11a–c) is characterized by relatively low cloud bases, typically about 500 m outside of the eyewall and 100–200 m in the eyewall. These lower cloud bases are in better agreement with observed and diagnosed cloud bases (Riehl 1954; Malkus and Riehl 1960; Hawkins and Imbembo 1976; Moss and Rosenthal 1975). Figure 11 clearly suggests that the weaker intensity of the MRF case is related to the drier conditions in the boundary layer, but does not adequately explain the differences in intensity between the other three cases.

c. PBL tendencies

To diagnose how the different PBL parameterizations contribute to or inhibit development of the simulated storm, the contributions by PBL processes to the local tendencies ($\partial/\partial t$), hereafter referred to as PBL tendencies, of the horizontal velocity components, temperature, and water vapor were outputted directly from the model at 2-h intervals. Azimuthally and temporally (62–66 h) averaged PBL tendencies for the tangential velocity, temperature, and water vapor for each case are shown in Figs. 12–14. Note that the vertical scale in the plots for the MRF case is 2.5 km compared to 1 km for the other cases. Also note the contour interval difference for the moisture tendencies between the bulk aerodynamic PBL case and the other cases. Qualitatively speaking, the tangential velocity tendencies (Fig. 12) in each case are similar, with each case showing the deceleration of the vortex circulation. However, the tendencies vary quantitatively in some significant ways. The MRF and Blackadar tangential velocity tendencies are weaker than in the Burk–Thompson case,
as should be expected given the weaker winds in these cases. The velocity tendencies in the bulk aerodynamic case are also much weaker than those in the Burk–Thompson case, despite the fact that the tangential velocities are comparable. This result suggests that, for a hurricane circulation of a given intensity, there is less spindown of the circulation by friction in the bulk aerodynamic case than in the Burk–Thompson case.

The temperature and water vapor tendencies in the Burk–Thompson (Figs. 13a and 14a) and Blackadar (Figs. 13c and 14c) cases are qualitatively similar. The temperature tendencies for both cases show maximum warming of about the same magnitude below 0.4 km in the eyewall region. The Burk–Thompson case produces some weak cooling above 0.4 km. The moisture tendencies for these cases show maximum moistening of the boundary layer in the eyewall region and weaker moistening, peaking near the middle of the boundary layer, in the region outside of the eyewall. Quantitatively, the key difference is in the magnitude of the moisture tendencies in the eyewall region, with the moistening being much stronger in the Burk–Thompson case. While some of this extra moistening comes from the larger wind speeds in the Burk–Thompson case, it
will be shown in section 5a that the surface flux parameterizations contribute significantly to this difference. The greater moistening of the PBL in the Burk–Thompson case is an important factor contributing to the higher $u_e$ in the PBL and the greater intensity of the hurricane in this case. Another factor is the frictional dissipation of momentum, which is not obvious in Fig. 12 because of the different wind speeds of these cases.

Temperature and moisture tendencies in the MRF and bulk aerodynamic PBL cases differ markedly from those in the Blackadar and Burk–Thompson cases. The MRF PBL scheme (Figs. 13d and 14d) produces strong warming and drying of the lowest 1 km and cooling and moistening between about 1 and 3 km. These strong and deep temperature and moisture tendencies are produced in association with large values of the eddy exchange coefficient that extend through a deeper layer (Fig. 15d) compared to the other cases (Figs. 15a–c). The drying of the lower PBL results mainly from the increase of the eddy exchange coefficient with height up to 0.7 km (Fig. 15a). The height of the PBL, $h$, in this case reaches about 3 km in the eyewall region and results from the equation defining the height of the PBL [Eq. (A1)]. In the case of the hurricane boundary layer, the static stability [the denominator in Eq. (A1)] tends to be relatively small while the winds are strong, resulting in a large value of $h$. This overestimate of $h$ can be reduced by applying the corrections of Vogelezang and Holtslag (1996), in which the shear is taken as the difference in wind speed between the top of the PBL and the top of the surface layer rather than assuming that the wind speed is zero at the bottom of the boundary layer. However, applying this correction in the model leads to little improvement of the simulation (not shown). Another problem is that the PBL scheme does not take into account the effects of clouds. For example, in the eyewall region, a typically diagnosed value of $h$ is about 3 km, whereas observed convective cloud bases are generally $\sim 500$ m or less. Hence, the diagnosed PBL top is well above the level at which cumulus transports start to dominate vertical mixing.

The bulk aerodynamic PBL scheme produces temperature (Fig. 13b) and moisture (Fig. 14b) tendencies that are concentrated near the surface and are, in the case of moisture, very strong compared to the other cases. To illustrate the cause of these tendencies, con-
consider the equation expressing the PBL moisture tendency at the first model level:

\[
\frac{\partial q_y}{\partial t}_{\text{PBL}} = \left[ K \frac{\partial q_y}{\partial z} + \frac{E_s}{\rho L_v} \right] / \Delta z_1,
\]

where \( q_y \) is the vapor mixing ratio, \( K \) the eddy diffusivity coefficient, \( E_s \) the surface moisture flux, [Eq. (B2)], \( L_v \) the latent heat of vaporization, \( \rho \) the density of air, and \( \Delta z_1 \) the vertical grid increment of the lowest layer. In the Blackadar, MRF, and Burk–Thompson cases, \( E_s \) is positive and \( \partial q_y / \partial z \) is negative so that the two terms in brackets partially cancel. However, in the bulk aerodynamic case, water vapor is well mixed so that \( \partial q_y / \partial z \) is zero, leading to a much larger tendency. Although the PBL water vapor tendencies (Fig. 14b) act to eliminate the well-mixed layer, the mixed layer is maintained by a dry convective adjustment scheme that is active only in conjunction with the bulk aerodynamic PBL scheme (see appendix A). A similar process leads to the large temperature tendencies near the surface in Fig. 13b. When the bulk aerodynamic simulation is repeated with the convective adjustment scheme turned off, the water vapor and temperature tendencies (not shown) resemble those in the Blackadar and Burk–Thompson cases.

5. The role of surface fluxes versus vertical mixing

a. Surface fluxes

Since theory and idealized modeling of hurricanes indicate a relationship between hurricane intensity and the exchange coefficients for heat and momentum, it is instructive to compare the exchange coefficients in each scheme. However, since the surface layer characteristics vary in each simulation, it can be difficult to fairly evaluate the PBL schemes unless identical winds, temperatures, and vapor mixing ratios are used in the calculations. Here, we use simulation results from the Burk–Thompson case at 62 h to evaluate surface fluxes \( (H_s, E_s, \text{ and } \tau_s) \) and exchange coefficients \( (C_u, C_q, \text{ and } C_D) \) for heat, moisture, and momentum, respectively. See appendix B for a summary of the surface flux algorithms.
for each PBL scheme. The MRF and Blackadar PBL schemes use nearly identical surface flux algorithms, so only the Blackadar case is discussed. An important factor to note from appendix B is the different treatment of the surface roughness parameter, \( z_0 \), in each scheme. In the bulk aerodynamic scheme, \( z_0 \) is independent of the surface wind speed, whereas in the Blackadar and Burk–Thompson schemes, \( z_0 \) varies linearly with the square of the friction velocity, \( u^* \). However, the rate at which \( z_0 \) increases with \( u^* \) in the Blackadar case is more than double that in the Burk–Thompson case.

Emanuel (1995b) has derived equations that suggest that the maximum wind and minimum central pressure in hurricanes are proportional to \( \left( \frac{C_k}{C_D} \right)^{1/2} \) and \( \frac{C_k}{C_D} \), respectively, where \( C_k \) is the exchange coefficient for enthalpy, \( k = c_r T + L_e q_e \), \( c_r \) is the specific heat of air at constant pressure, \( T \) temperature, and \( q_e \) the water vapor mixing ratio. In the bulk aerodynamic and Burk–Thompson PBL schemes \( C_k = C_{e0} = C_{eB} \), whereas in the MRF and Blackadar PBL schemes \( C_k \neq C_{eB} \), so in the latter cases we evaluate \( C_k \) from

\[
C_k = \frac{H_s + E_s}{\rho_s V_a (k_g - k_o)}
\]

where \( H_s \) and \( E_s \) are the surface heat and moisture fluxes (defined in appendix B); \( \rho_s \), \( V_a \), and \( k_g \) are the air density, wind speed, and enthalpy, respectively, at the lowest model level; and \( k_o \) is the enthalpy at the ocean surface. The horizontal distributions of \( C_k / C_D \) (not shown) are uniform so that \( C_k / C_D \) is effectively independent of wind speed.

Table 2 shows area-averaged, minimum, and maximum values of the surface heat, moisture, and momentum fluxes as well as exchange coefficients, obtained from a 280 \( \times \) 280 km\(^2\) area centered on the storm. The Burk–Thompson scheme produces the largest moisture fluxes, while the bulk aerodynamic and Blackadar schemes are comparable. While the average moisture fluxes differ by only 100 W m\(^{-2}\), the maximum values (from the eyewall region) differ by more than 600 W m\(^{-2}\). Heat fluxes are significantly less than the moisture fluxes, ranging from a factor of 3–4 smaller in the Blackadar scheme to almost an order of magnitude smaller in the Burk–Thompson case. The maximum value of the heat flux in the eyewall region in the Blackadar case

Fig. 12. Vertical cross sections of azimuthally and temporally averaged tangential velocity tendency averaged over hours 62–66, using output at 2-h intervals. Contours are drawn at 5 m s\(^{-1}\) h\(^{-1}\) intervals. Panels correspond to the following PBL schemes: (a) Burk–Thompson, (b) bulk aerodynamic, (c) Blackadar, and (d) MRF. Note that the vertical scale in (d) is 2.5 km compared to 1 km in the other panels.

Fig. 13. Same as in Fig. 12 but for temperature tendency. Contours are drawn at 1 K h\(^{-1}\) intervals.
is nearly twice those in the bulk aerodynamic and Burk–Thompson cases.

For the bulk aerodynamic and Burk–Thompson schemes, $C_u = C_q$. The exchange coefficient for heat in the bulk aerodynamic scheme is nearly uniform throughout the storm with a value of about $1.4 \times 10^{-3}$, while in the Burk–Thompson case $C_u$ varies with wind speed and ranges from 1 to $2.2 \times 10^{-3}$. For the Blackadar scheme, $C_q \neq C_u$. In fact, $C_q$ is fairly uniform and small whereas $C_u$ varies strongly with wind speed and is large. Values of $C_u$ range from 1 to $1.5 \times 10^{-3}$ while $C_q$ ranges from 1 to $2.9 \times 10^{-3}$. The differences between $C_q$ and $C_u$ in the Blackadar scheme are due to the term $ku_* x_a / K_a$ in the logarithm in Eq. (B9), which can be several orders of magnitude larger than $x_a / x_0$. The fact that $C_q$ is smaller in the Blackadar case than in the Burk–Thompson case.

### Table 2. Surface fluxes and exchange coefficients for moisture ($E_s$ and $C_q$), heat ($H_s$ and $C_0$), and momentum ($t_s$ and $C_D$) at $t = 62$ h (see appendix B for notation). In the last column, $C_j$ is the exchange coefficient for enthalpy. For each PBL scheme, the first number in the column is the average value over a $280 \times 280$ km$^2$ area centered on the storm, while the second and third numbers are the minimum and maximum values within that area.

<table>
<thead>
<tr>
<th>Case</th>
<th>$E_s$ (W m$^{-2}$)</th>
<th>$H_s$ (W m$^{-2}$)</th>
<th>$t_s$ (kg m$^{-1}$ s$^{-1}$)</th>
<th>$C_q$ ($\times 10^{-3}$)</th>
<th>$C_0$ ($\times 10^{-3}$)</th>
<th>$C_j$</th>
<th>$C_j/C_0$</th>
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<tbody>
<tr>
<td>Burk–Thompson</td>
<td>686</td>
<td>46</td>
<td>1.34</td>
<td>1.54</td>
<td>1.54</td>
<td>1.53</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>−23</td>
<td>0.01</td>
<td>1.02</td>
<td>1.02</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2031</td>
<td>280</td>
<td>6.61</td>
<td>2.25</td>
<td>2.25</td>
<td>2.23</td>
<td></td>
</tr>
<tr>
<td>Bulk</td>
<td>615</td>
<td>80</td>
<td>0.82</td>
<td>1.38</td>
<td>1.38</td>
<td>1.38</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>62</td>
<td>6</td>
<td>0.017</td>
<td>1.30</td>
<td>1.30</td>
<td>1.30</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>1322</td>
<td>263</td>
<td>3.12</td>
<td>1.74</td>
<td>1.74</td>
<td>1.74</td>
<td>1.27</td>
</tr>
<tr>
<td>Blackadar</td>
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<td>119</td>
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<td>8.60</td>
<td>1.49</td>
<td>1.49</td>
<td>1.49</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 14. Same as in Fig. 12 but for water vapor tendency. Contours are drawn at 0.5 g kg$^{-1}$ h$^{-1}$ intervals in (a), (c), and (d) and at 3 g kg$^{-1}$ h$^{-1}$ intervals in (b).

Fig. 15. Same as in Fig. 12 but for eddy diffusivity coefficient. Contours are drawn at 10 m$^2$ s$^{-1}$ in (a)–(c) and 50 m$^2$ s$^{-1}$ in (d).
Thompson case partially accounts for the weaker intensity of the hurricane in the Blackadar case.

Drag coefficients are listed in Table 2 and are plotted in Fig. 16 as a function of wind speed along with estimates of $C_D$ from Hawkins and Imbembo (1976). The values of $C_D$ from the Blackadar scheme agree fairly well with the Hawkins and Imbembo values up to a wind speed of 45 m s$^{-1}$, but are smaller at higher velocities. The Burk–Thompson values of $C_D$ roughly parallel the Blackadar values, but are about 20% less because of the weaker dependence of $z_0$ on wind speed (appendix B). The bulk aerodynamic drag coefficient is uniform because of the lack of a wind speed dependence of $z_0$.

The maximum surface stress, $\tau_s$, in the eyewall region in the bulk aerodynamic case is half that in the Burk–Thompson case and almost one-third of that in the Blackadar case. As mentioned previously, the weaker momentum dissipation in the bulk aerodynamic case enables it to produce a strong hurricane despite the relatively weaker vertical motions (Fig. 8). This result can be seen clearly if we relate the vertical motion in the eyewall to the upward mass flux, $M_u$, at the top of the PBL associated with Ekman pumping. From Emanuel (1995a,b), $M_u \propto C_D V_{\text{max}}$ and $V_{\text{max}} \propto (C_i/C_D)^{1/2}$, so that $M_u \propto (C_i C_D)^{1/2}$. The values of $(C_i C_D)^{1/2}$ for the Burk–Thompson, bulk aerodynamic, and Blackadar schemes are 2.2, 1.5, and 1.6, respectively, and are qualitatively consistent with the variations of vertical velocity in Fig. 8.

Representative values of $C_i/C_D$ are shown in the last column of Table 2. The MRF and Blackadar schemes are characterized by $C_i/C_D \sim 0.7$. The Burk–Thompson and bulk aerodynamic PBL schemes are associated with $C_i/C_D$ values of 1.0 and 1.3, respectively, which according to Emanuel (1995b) suggests that the Blackadar and MRF surface flux schemes should produce the weakest storms and the bulk aerodynamic scheme the strongest storm. However, this analysis does not completely account for the impacts of the surface fluxes in the simulations because the method of vertical mixing varies in each scheme. To evaluate these impacts, each of the surface flux schemes must be used in combination with the same method for vertical mixing in the PBL. Consequently, three additional simulations have been conducted in which the surface flux schemes from the bulk aerodynamic and Burk–Thompson PBL schemes have been used in combination with the vertical mixing in the Blackadar PBL scheme. These experiments are listed in Table 1 as BL/BT, BL/BU1, and BL/BU2. Two simulations using the bulk aerodynamic surface flux scheme are conducted, one which excludes the wind speed dependence of $z_0$ (BL/BU1), as in the original bulk scheme, and one that includes the wind speed dependence (BL/BU2) in Eq. (B12).

Figure 17 shows time series of the minimum central pressure (Fig. 17a) and maximum wind (Fig. 17b) for these experiments. The original Blackadar simulation produces the weakest storm, which is expected since $C_i/C_D$ is smallest in this case. Inclusion of the Burk–Thompson surface fluxes, which has a larger value of $C_i/C_D$, produces a much stronger storm in terms of both central pressure and maximum wind. The bulk aerodynamic surface flux scheme (case BL/BU1, without
the wind speed dependence of $z_o$) is characterized by the largest value of $C_i/C_D$, but produces an intensity only slightly larger than that in the Blackadar case, in apparent contradiction to Emanuel (1995b). However, if the wind speed dependence of $z_o$ is included in the bulk aerodynamic surface flux scheme (case BL/BU2), then the bulk scheme does result in the strongest storm. Cases BL/BU1 and BL/BU2 have identical values of $C_i/C_D$, but result in very different intensities, suggesting that the intensity is related not only to the magnitude of $C_i/C_D$, but also to the horizontal variations of $C_k$ and $C_D$, arising from their dependence on wind speed.

Since the maximum wind speed and minimum central pressure are expected to vary, respectively, as $(C_i/C_D)^{1/2}$ and $C_i/C_D$, we anticipate larger variations in central pressure than in maximum wind speed as $C_i/C_D$ changes. For cases including the wind speed dependence of $z_o$, the variation of central pressure (~20 mb; Fig. 17) represents about 40% of the total pressure fall (~50 mb), while the variation in maximum wind speed (~10 m s$^{-1}$) represents only 13% of the maximum wind (~75 m s$^{-1}$). The value of $C_i/C_D$ increases from 0.7 to 1.0 to 1.3 between the Blackadar, Burk–Thompson, and bulk aerodynamic schemes, but the minimum pressure does not decrease linearly with $C_i/C_D$, as suggested by Emanuel (1995b), likely because of the complex interactions between boundary layer processes, cloud microphysics, and storm dynamics. A similar argument can be made for the maximum wind speed.

The precipitation patterns are also modified by varying the surface fluxes (Fig. 18). For case BL/BT (Fig. 18b), the rainfall rate is more intense than in the original Blackadar simulation (Fig. 18a) and the area of precipitation is more compact, much like the original Burk–Thompson simulation (Fig. 7a). Similar to its intensity (Fig. 17), the precipitation pattern in case BL/BU1 (Fig. 18c) is approximately intermediate between the original Blackadar simulation and case BL/BT. When the wind speed dependence of $z_o$ is included (case BL/BU2, Fig. 18d), the rainfall rate increases and the precipitation pattern becomes slightly more compact like case BL/ BT.

**b. Vertical mixing**

The impacts of the vertical mixing schemes on storm structure and intensity can be determined by using the same surface flux scheme in combination with each of the vertical mixing schemes. Two experiments have already been completed: 1) the original Burk–Thompson simulation and 2) the Burk–Thompson surface fluxes with the Blackadar vertical mixing scheme (BL/BT, Table 1). Two additional experiments are conducted (Table 1) using the Burk–Thompson surface fluxes with the bulk aerodynamic (BU/HT) and MRF (MRF/HT) vertical mixing schemes.

Figure 19 shows time series of the minimum central pressure and maximum wind speed for these experiments. The original Burk–Thompson simulation and experiments BL/HT and BU/HT produce storms with comparable intensity in terms of both minimum pressure (Fig. 19a) and maximum winds (Fig. 19b), suggesting that the simulated intensity is determined primarily by the surface fluxes rather than by vertical mixing. However, the MRF vertical mixing scheme is clearly an exception. While the MRF/HT simulation results in a lower central pressure and stronger maximum winds than the original MRF simulation (Fig. 3) because of the increase in the exchange coefficient for enthalpy associated with the Burk–Thompson surface fluxes, the intensity is still substantially lower than with the other vertical mixing schemes. As suggested in section 4c, the weaker intensity is caused by excessively deep vertical mixing and the drying of the lower PBL in the MRF scheme.

The precipitation pattern in experiment MRF/HT (Fig. 20a) is comparable to that in the original MRF simulation. This result indicates that the vertical mixing in the PBL may be exerting a stronger control over the precipitation distribution than the surface fluxes in the MRF cases. The rainfall rates and precipitation pattern in case BU/HT (Fig. 20b) are comparable to the Burk–Thompson and BL/HT cases (Figs. 7a and 18b), suggesting that vertical mixing is producing little impact on the precipitation pattern in these cases. In other words, in the Burk–Thompson, Blackadar, and bulk aerodynamic cases, the differences in precipitation rates and patterns appear to be driven largely by the differences in the surface flux schemes and their impact on intensity.

**6. Conclusions**

The PSU–NCAR mesoscale model MM5 has been used to simulate Hurricane Bob (1991) at high resolution. The model was able to reproduce to varying degrees the track and intensity of the hurricane, but results exhibited strong sensitivity to the parameterization of boundary layer processes. The PBL parameterizations used in the simulations included the Burk–Thompson, MRF, Blackadar, and bulk–aerodynamic PBL schemes. Among the sensitivity tests, simulated minimum sea level pressures and maximum winds varied by about 16 mb and 15 m s$^{-1}$, respectively, with the Burk–Thompson and bulk aerodynamic schemes producing the strongest storms and the MRF PBL scheme producing the weakest storm.

Azimuthal mean vertical structures in the Burk–Thompson, Blackadar, and bulk aerodynamic PBL cases were generally quite similar except for stronger upward motion and upper-level outflow in the Burk–Thompson case. The MRF PBL simulation differed significantly in several ways: the low-level inflow was deeper and weaker, strong outflow from the eye above the PBL was absent, the PBL was significantly drier, and cloud base was significantly higher than in the other cases.
The mean structure of the PBL-induced changes (or tendencies) in temperature, moisture, and momentum suggest that the MRF scheme produces excessively deep mixing up to 2–3 km above the surface in the eyewall, which results in drying of the lower PBL. The bulk aerodynamic scheme produces very shallow and strong tendencies of moisture and temperature, but these tendencies result from the fact that a convective adjustment scheme (active only in connection with the bulk aerodynamic PBL scheme) maintains a well-mixed PBL in this case. The tendencies of temperature and moisture in the Burk–Thompson and Blackadar schemes are qualitatively similar, suggesting that the key difference between these schemes is in the surface flux algorithms.

Each PBL scheme is different in its formulation of the vertical mixing within the PBL and the surface fluxes, with the exception of the MRF and Blackadar schemes, which share essentially the same surface flux parameterization. Emanuel (1995a,b) suggested that the intensity of a hurricane increases as the ratio of the
exchange coefficients for enthalpy and momentum, $C_h/C_D$, increases. Vertical motion in the eyewall can be related to vertical motion associated with Ekman pumping at the top of the boundary layer, which scales as $(C_h/C_D)^{1/2}$. Analysis of the surface flux schemes under identical conditions indicates that the Blackadar and MRF schemes are associated with a low value of $C_h/C_D = 0.7$, while the Burk–Thompson and bulk aerodynamic schemes have larger values of 1.0 and 1.3, respectively. The low values of $C_h/C_D$, and hence weaker storms, in the Blackadar and MRF cases are due to the relative small value of the exchange coefficient for moisture compared to the Burk–Thompson and bulk aerodynamic cases. The bulk aerodynamic case has a large value of $C_h/C_D$, but a small value of $(C_h/C_D)^{1/2}$, which explains why it develops a strong vortex despite having the weakest mean eyewall vertical motions of all the cases.

Because both the surface fluxes and vertical mixing differ between each of the PBL schemes, the individual roles of these processes are difficult to ascertain from these experiments. In order to isolate the effects of vertical mixing and surfaces fluxes, additional simulations were conducted in which each of the surface flux schemes was used in conjunction with an identical vertical mixing scheme, and vice versa. Simulations that vary only the surface fluxes indicate that, as long as the surface roughness parameter increases with wind speed, the intensity of the simulated hurricane increases with increasing values of $C_h/C_D$. However, the variations of minimum pressure and maximum wind speed do not

![Fig. 19. Time series of (a) minimum sea level pressure and (b) maximum wind speed from observations and from the 4-km simulations using the Burk–Thompson surface flux scheme and varying vertical mixing schemes. See Table 1 for a listing of the experiments.](image)

![Fig. 20. Simulated radar reflectivity patterns at 1 km MSL and sea level pressure at $t = 72$ h (valid at 0000 UTC 19 Aug) for the high-resolution simulations using the Burk–Thompson surface flux scheme with (a) the MRF vertical mixing scheme and (b) bulk aerodynamic vertical mixing scheme. Sea level pressure contours are drawn every 4 mb. See Figs. 7a and 18b for comparison to the cases using the Burk–Thompson surface flux scheme with the Burk–Thompson vertical mixing scheme and the Blackadar vertical mixing scheme, respectively.](image)
vary exactly as expected from theory presumably because of complex interactions between PBL processes, cloud microphysical processes, and storm dynamics. Furthermore, even for identical values of $C_{u}/C_{p}$, the simulated intensity varies significantly depending on the wind speed dependence of the surface roughness parameter $z_{0}$. For simulations that use identical surface fluxes but different vertical mixing schemes, the results show that the Burk-Thompson, Blackadar, and bulk aerodynamic vertical mixing schemes produce storms of comparable intensity and structure, while the MRF vertical mixing scheme produces a weaker storm primarily because it diagnoses an excessively deep boundary layer and causes drying of the lower portion of the PBL.

Simulated horizontal precipitation structures varied substantially between the different PBL schemes, suggesting that accurate forecasts of precipitation in hurricanes can be just as sensitive to the formulation of the PBL as they are to the cloud microphysical parameterizations. The surface flux schemes account for much of this sensitivity, although in the MRF PBL case, vertical mixing is important. The deeper vertical mixing in the MRF PBL case led to more active convective precipitation in the area outside of the eyewall compared to the other vertical mixing schemes. Thus, it appears that the intensity and precipitation structure of the storm are primarily influenced by the surface fluxes while vertical mixing plays a secondary role.

This study highlights the need to obtain measurements of the exchange coefficients for heat, moisture, and momentum in the hurricane boundary layer and their dependence on wind speed. Accurate characterization of these coefficients is essential for improved forecasts of hurricane intensity. Doppler radars [particularly the Doppler on Wheels (Wurman and Winslow 1998)] and drop sondes can play a significant role in observing the depth and vertical structure of the PBL and characterizing the vertical fluxes within it. Although neglected here, the effects of dissipative heating, sea spray, and the ocean–atmosphere coupling are also likely to be important in determining the intensity and structure of hurricanes.

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APPENDIX A
Boundary Layer Parameterizations

a. The bulk aerodynamic scheme

The bulk aerodynamic PBL scheme in MM5 (Dardorff 1972; Grell et al. 1995) treats the first full-$\sigma$ model level (86 m in this case) as the top of the boundary layer and uses similarity theory to determine surface fluxes of momentum, heat, and moisture and tendencies of these variables at the first half-$\sigma$ model level (42 m). The bulk aerodynamic scheme in MM5 allows for mixing above the first model level by applying $K$ theory in the free atmosphere. Tendencies of the model variables associated with this vertical mixing are calculated from $\partial C/\partial z$($K_{\text{bulk}}\partial C/\partial z$), where $C=(u, v, \theta, q_{s})$. The eddy diffusivity coefficient, $K_{C}$, is specified as a function of the local Richardson number following Eqs. (28) and (29) in Zhang and Anthes (1982). In addition to the above calculations, when the bulk aerodynamic PBL option is used, MM5 applies a dry convective adjustment scheme (not included in the PBL scheme, but separate from it) to remove unstable layers (defined by $\partial \theta/\partial p > -0.003 \text{ K m}^{-1}$) in the boundary layer. The dry convective adjustment scheme is not used in conjunction with the other PBL schemes.

b. The Blackadar PBL scheme

The Blackadar PBL scheme (Blackadar 1976, 1979; Zhang and Anthes 1982; Oncley and Dudhia 1995) contains two different regimes of turbulent mixing: a stable, or nocturnal, regime and a free-convection regime. The stable regime is divided into three categories with the appropriate category being determined by the sign and magnitude of the bulk Richardson number, $R_{b}$. When $R_{b} > 0.2$, the surface is assumed to be very stable, while for $0 < R_{b} < 0.2$ the surface layer is assumed to be in a state of damped mechanical turbulence. When $R_{b} < 0$ and $|z_{a}/L| \leq 1.5$ ($z_{a}$ is the height of the first half-$\sigma$ level, $L$ is the Monin–Obukhov length scale), a state of forced convection is assumed. Tendencies of surface variables are determined from a local-$K$ approach. Above the surface layer, mixing in the free atmosphere is determined from $K$ theory in a manner similar to the bulk aerodynamic scheme.

In the free-convection regime, $R_{b} < 0$ and $|z_{a}/L| \geq 1.5$, the vertical transfers of heat, moisture, and momentum are not determined by local gradients, but by the thermal structure of the whole mixed layer and the surface heat flux. Prognostic variables within the mixed layer are modified by assuming that vertical exchanges take place between the lowest layer and each level of the mixed layer. See Zhang and Anthes (1982) for details of the free-convection mixing scheme. Above the mixed layer, mixing is determined from $K$ theory as before.

c. The MRF PBL scheme

The MRF scheme (Hong and Pan 1996) is a nonlocal scheme in which the tendencies are dependent on the bulk characteristics of the PBL and include countergradient transports of temperature and moisture that account for the contributions from large-scale eddies (the countergradient term for moisture is set to zero over the
ocean in the MM5 code). The eddy diffusivity coefficient for momentum, $K_n$, is a function of the friction velocity, $u_\text{f}$, and the PBL height, $h$, given by

$$h = \text{Rib}_s \frac{\theta_s V(h)^2}{g[\theta_s(h) - \theta_s]} \quad (A1)$$

where $g$ is gravity, $\text{Rib}_s$ is the critical bulk Richardson number ($\text{Rib}_s = 0.5$), $V(h)$ and $\theta_s(h)$ are the wind speed and virtual potential temperature at the top of the PBL, $\theta_s = \theta_{sw} + \theta_s$ is a near-surface potential temperature given in Eq. (9) of Hong and Pan (1996), $\theta_{sw}$ is the virtual potential temperature at the lowest half-σ level, and $\theta_s$ is a scaled virtual temperature excess near the surface that incorporates the effects of surface heat fluxes. The eddy diffusivity for temperature and moisture is computed from $K_n$ by using a Prandtl number relationship given in Eq. (10) of Hong and Pan (1996).

d. The Burk–Thompson scheme

The Burk–Thompson PBL scheme (Burk and Thompson 1989) is a Mellor–Yamada level-2.5 closure model that includes a prognostic equation for the turbulent kinetic energy. In contrast to the description of the level-3 equations in Burk and Thompson (1989), the scheme in MM5 neglects the effects of liquid water as well as the countergradient terms in the fluxes of heat and moisture. The eddy diffusivity for moisture is taken as $K_q = 1.0075K_u$ ($K_u$ being the eddy exchange coefficient for heat) rather than as a function of the vertical velocity variance. The fluxes are derived from a local-$K$ approach, but unlike the free-atmosphere formulations for eddy diffusivity in the Blackadar and bulk aerodynamic scheme, in which the eddy diffusivity is a function of the local Richardson number, the eddy diffusivity in the Burk–Thompson scheme is given by a complex algebraic function involving the predicted mean and turbulence variables.

APPENDIX B

Surface Flux Parameterizations

The parameterizations of the surface fluxes of heat, moisture, and momentum play a key role in the simulation of hurricanes, which gain energy at the surface through transfer of sensible and latent heat and lose energy at the surface to frictional dissipation. In the following sections, we briefly summarize the surface flux algorithms used in each PBL scheme. For this discussion, we use a generic framework in which the surface fluxes of heat ($H_s$), moisture ($E_s$), and momentum ($\tau_s$) are given by

$$H_s = \rho_s C_H V_s (\theta_s - \theta_a), \quad (B1)$$

$$E_s = \rho_s L_e C_q V_s [q_{sw}(T_s) - q_{sw}], \quad (B2)$$

$$\tau_s = \rho_s C_T V_s, \quad (B3)$$

where $\rho_s$, $q_{sw}$, and $V_s$ are the air density, vapor mixing ratio, and velocity at the lowest model level; $q_{sw}$ is the saturation vapor mixing ratio at the surface and is a function of the sea surface temperature $T_s$; $C_H$, $C_q$, and $C_T$ are exchange coefficients for heat, moisture, and momentum, respectively; $L_e$ is the latent heat of vaporization; and $M$ is the moisture availability ($M = 1$ over the ocean). The differences between the different PBL schemes is then contained in the three exchange coefficients $C_H$, $C_q$, and $C_T$. For this discussion, only exchange coefficients for unstable conditions are presented.

a. The bulk aerodynamic scheme

Exchange coefficients in the bulk aerodynamic scheme are defined following Deardorff (1972), with $C_H = C_T^2$ and $C_q = C_q = C_T C_a$. For unstable conditions ($\text{Rib} < 0$),

$$C_u = \left[ \frac{1}{C_u} - 25 \exp(0.26\psi - 0.03\psi^2) \right]^{-1} \quad (B4)$$

$$C_T = \left[ \frac{1}{C_T^N} + 1 - \frac{1}{C_u} \right]^{-1} \quad (B5)$$

where $\psi = \log_{10}(-\text{Rib}) - 3.5$, $\text{Rib} = (gh\theta_s)\theta_s - \theta_j)/V^2$, $h$ is the height of the first full-σ level, $\theta_j = 283.16$, $\theta_s$ and $\theta_j$ are the potential temperatures at the first half-σ level and the ground, and $V$ is a combination of the wind speed and a convective velocity (see Grell et al. 1995). The velocity $V$ is used in (B1)–(B3) instead of the actual wind speed $V_s$. The parameters $C_u$ and $C_T$ are the neutral values for $C_u$ and $C_T$ given by

$$C_u^N = \left[ \frac{1}{k} \ln \frac{z_a}{z_0} + 8.4 \right]^{-1} \quad (B6)$$

$$C_T^N = \left[ 0.74 \frac{1}{k} \ln \frac{z_a}{z_0} + 7.3 \right]^{-1}, \quad (B7)$$

where $z_a = 0.025h$, $z_0$ is the surface roughness parameter, and $k$ the von Kármán constant ($k = 0.4$). It is important to note that, unlike the other three PBL schemes, in the bulk aerodynamic PBL scheme, $z_a$ is independent of the wind speed over the ocean. Also, unlike the other schemes that take $z_a$ as the height of the first half-σ level, the bulk scheme assumes that the surface layer depth is a small fraction of the height of the first full-σ level.

b. The MRF and Blackadar PBL schemes

The MRF and Blackadar schemes use nearly identical representations of the surface fluxes. For these schemes, $C_H \neq C_T$, and the exchange coefficients can be expressed as follows:
\[ C_p = k^2 \left( \frac{\ln z_a}{z_0} - \psi_m \right)^{-1} \left( \frac{\ln z_a}{z_0} - \psi_0 \right)^{-1}, \]  
\[ C_q = k^2 \left( \frac{\ln z_a}{z_0} - \psi_m \right)^{-1} \left[ \ln \left( \frac{K_a z_a}{z_0} + \frac{z_a}{z_0} \right) - \psi_0 \right], \]  
where \( z_a \) is the height of the first half-\( \sigma \) level, \( u_{*0} \) is a small background value, and \( \psi_m \) and \( \psi_0 \) are nondimensional stability functions that depend on the PBL regime (i.e., stable, mechanical turbulence, forced, or free convection). In Eq. \( \text{(B9)} \), the first term in the second logarithm can be rewritten as \( z_a/z_0 \), with \( z_a = K_a u_{*0} \), and is included to add increased resistance to the transfer of water vapor from the surface (Onclay and Dudhia 1995). The maximum value of \( z_a \) is 0.06 cm, whereas \( z_0 \) can reach \( \sim \)5 cm. Consequently, \( z_a/z_0 > z_a/z_0 \) and the exchange coefficient for water vapor is smaller than that for heat. The surface roughness parameter, \( z_{wo} \), varies with wind speed over the ocean and is prescribed following Delsol et al. (1971),} \[ z_0 = 0.032u_{*0}^2 + z_{wo}, \]  
where \( z_{wo} \) is a background value of \( 10^{-4} \) m. As in the bulk aerodynamic scheme, the velocity scale \( V_s \) is used in \( \text{(B1)} \)–\( \text{(B3)} \) instead of the wind speed \( V_s \). The primary difference between the Blackadar and MRF PBL schemes is in the definition of the nondimensional stability functions for the free convection regime. For the purposes of this study, this difference is negligible.

c. The Burk–Thompson scheme

For the Burk–Thompson scheme, the surface fluxes are based on Louis (1979) and Louis et al. (1981), with \( C_a = C_q \) and the wind speed \( V_s \) used in \( \text{(B1)} \)–\( \text{(B3)} \). In the unstable case \( \text{Rib} < 0 \), where \( \text{Rib} = (g z_a/\theta_v)(\theta_{sw} - \theta_{so})/V_s^2 \), \( \theta_v = (\theta_{sw} + \theta_{so})/2 \), and \( \theta_{sw} \) and \( \theta_{so} \) are the virtual potential temperatures at the first model level and the ground], the exchange coefficients are

\[ C_a = C_q = C_N \left[ 1 - \frac{3b\text{Rib}}{1 + 3bcC_N(\sqrt{z_a/\text{Rib}/z_0})^{1/2}} \right] \]  
and
\[ C_D = C_N \left[ 1 - \frac{2\text{Rib}}{1 + 3bcC_N(\sqrt{z_a/\text{Rib}/z_0})^{1/2}} \right], \]  
where \( b \) and \( c \) are constants \((b = c = 5)\). The parameter \( C_N \) is the exchange coefficient for both heat and momentum under neutral conditions, \( C_{1/2} = k/\ln(z_a/z_0) \), where \( z_a \) is the height of the first half-\( \sigma \) level. As in the MRF and Blackadar schemes, \( z_0 \) is allowed to vary with the wind speed, but in the Burk–Thompson PBL scheme, the relationship follows Garratt (1977),

\[ z_0 = 0.0144u_{*0}^2 + z_{wo}. \]  
Thus, for the same \( u_{*0} \), the Burk–Thompson scheme yields a smaller \( z_0 \) than in the MRF and Blackadar schemes.

REFERENCES


