Objectively Determined Fair-Weather CBL Depths in the ARW-WRF Model and Their Comparison to CASES-97 Observations

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ABSTRACT

High-resolution 24-h runs of the Advanced Research version of the Weather Research and Forecasting Model are used to test eight objective methods for estimating convective boundary layer (CBL) depth $h$, using four planetary boundary layer schemes: Yonsei University (YSU), Mellor–Yamada–Janjic (MYJ), Bougeault–LaCarrere (BouLac), and quasi-normal scale elimination (QNSE). The methods use thresholds of virtual potential temperature $\theta_v$, turbulence kinetic energy (TKE), $\theta_v$, $z$, or Richardson number. Those that identify $h$ consistent with values found subjectively from modeled $\theta_v$ profiles are used for comparisons to fair-weather observations from the 1997 Cooperative Atmosphere–Surface Exchange Study (CASES-97).

The best method defines $h$ as the lowest level at which $\theta_v(z) = 2$ K km$^{-1}$, working for all four schemes, with little sensitivity to horizontal grid spacing. For BouLac, MYJ, and QNSE, TKE thresholds did poorly for runs with 1- and 3-km grid spacing, producing irregular $h$ growth not consistent with $\theta_v$-profile evolution. This resulted from the vertical velocity $W$ associated with resolved CBL eddies: for $W > 0$, TKE profiles were deeper and $\theta_v$ profiles more unstable than for $W < 0$. For the 1-km runs, 25-point spatial averaging was needed for reliable TKE-based $h$ estimates, but thresholds greater than free-atmosphere values were sensitive to horizontal grid spacing. Matching $\theta_v(h)$ to $\theta_v(0.05h)$ or $\theta_v$ at the first model level were often successful, but the absence of eddies for 9-km grids led to more unstable $\theta_v$ profiles and often deeper $h$.

Values of $h$ for BouLac, MYJ, and QNSE, are mostly smaller than observed, with YSU values close to slightly high, consistent with earlier results.

1. Introduction

This paper evaluates the ability of four planetary boundary layer (PBL) schemes to replicate observed clear-air convective boundary layer (CBL) depth $h$ in the Advanced Research version of the Weather Research and Forecasting Model (ARW-WRF), through developing a suite of objective criteria, evaluating them using model virtual potential temperature $\theta_v$ profiles, and finally comparing them to observations, for four days in the 1997 Cooperative Atmosphere–Surface Exchange Study (CASES-97; LeMone et al. 2000). The CBL depth is an important tool in evaluating model representation of PBL evolution. Similarly, CBL depth determines the amount of dilution expected for trace gases emitted from the surface or entrained into the CBL top (e.g., Tucker et al. 2009), and is thus a vital parameter for idealized air pollution models. CBL growth destroys the convective “cap,” fixing the time at which the lower-CBL temperature becomes warm enough to overcome negative buoyancy to form deep convective clouds, making $h$ a significant factor in convective initiation (e.g., Trier et al. 2011). Finally, $h$ is an important parameter within the PBL schemes themselves.

The CBL depth results from the interplay of surface virtual temperature flux, shear-generated turbulence, and subsidence, making its counterpart in WRF reflect more than just the PBL scheme. The roles of surface and CBL processes are embodied in the focus on both surface and CBL schemes in the local land–atmosphere coupling studies recently described by Santanello et al. (2009, 2011). Others (e.g., Hu et al. 2010; LeMone et al. 2010a; Shin and Hong 2011; Svensson et al. 2012) have factored in the virtual potential temperature flux bias as

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well as the PBL scheme(s) in question. Shear-generated turbulence is handled by PBL schemes, but surface momentum flux (friction velocity \( u_\kappa \)) is used as input. However, the effect of its bias is likely relatively small for the buoyancy-driven CBLs considered here; moreover, comparisons with observations are difficult, because \( u_\kappa \) is a function of scale (e.g., Kustas et al. 2005; Strassberg et al. 2008). Uncertainty in both modeled and measured subsidence makes it difficult to evaluate its role.

Previous evaluations show that PBL schemes that parameterize vertical turbulent fluxes as proportional to the corresponding local vertical gradient tend to underestimate CBL depth; while those allowing for “non-local” transport, which account for fluxes by eddies stretching through the CBL, yield deeper (and sometimes too deep) values. Weisman et al. (2008) and Kain et al. (2005) note that the Yonsei University (YSU; Hong et al. 2006) nonlocal PBL scheme grows the CBL more aggressively than the Mellor–Yamada–Janjic (MYJ) local scheme (Janjic 2001) over the central United States, leading to too much drying out in the former case. Trier et al. (2011) show a similar result, but note that altering the surface fluxes can lead to almost as large differences. These studies focus on vertical profiles. As pointed out by Shin and Hong (2011), comparisons using default model \( h \) values are made difficult by different definitions for different PBL schemes. Selection of a universal \( h \) criterion provides a better basis for comparison. Indeed, the \( h \) criterion used by Hu et al. (2010) actually improved agreement with observations for both MYJ and YSU, although \( h \) from MYJ remained too low. Our comparisons use model results on a 1-km horizontal grid, with the ultimate goals of looking at the impacts of local changes in land surface characteristics on CBL growth and resolving mesoscale (∼10 km) motions. Such runs produce realistic-looking CBL circulations (e.g., LeMone et al. 2010b) that, along with the small grid spacing, violate the “horizontal homogeneity” assumptions implicit in the schemes themselves. In addition, the circulations as well as the PBL schemes produce fluxes, leading to a “competition” that only approximately represents reality. These issues are consistent with such finescale runs inhabiting Wyngaard’s (2004) “terra incognita.” However, WRF runs with grid spacing of 4 km or less are commonly done because of their success in replicating hurricanes (e.g., Davis et al. 2008), precipitating convection (Trier et al. 2008, 2010; Weiss et al. 2008; Weisman et al. 2008), urban air pollution (Bao et al. 2008), the impact of the land surface on mesoscale circulations (e.g., Case et al. 2008), and convective initiation (Trier et al. 2004).

Our definitions of CBL depth \( h \) follow the illustration in Fig. 1. In the figure, \( h_1 \) is the top of the “mixed,” near-constant virtual potential temperature \( \Theta_e \) layer, and \( h_2 \) is the base of the free atmosphere, rarely penetrated by boundary layer air over a region at a given time. In the transition or entrainment layer, between \( h_1 \) and \( h_2 \), lies the boundary layer top \( z_i \), where the normalized virtual temperature flux, \( w'\Theta_v \) reaches a minimum. In the expression, \( w \) and \( T_v \) are vertical velocity and virtual temperature, respectively, the primes indicate a departure from the mean (denoted by an overbar), and the subscript “0” applies to the surface. The ratio of the transition-layer depth to \( h_1 \) or \( z_i \) varies; several representations are summarized in Traumner et al. (2011).

The bottom-left frame shows the (large eddy simulation) LES-based turbulence kinetic energy (TKE) or

\[
e = 0.5(u'^2 + v'^2 + w'^2),
\]

where \( (u', v', w') \) are the components of turbulent motion, and the overbar is a horizontal average over time, for Moeng and Sullivan’s (1994, their Fig. 9) buoyancy-driven [(\( u'_{\kappa}, w'_{\kappa} \) = (0.56, 2.02 m s\(^{-1}\))] and shear-driven [(\( u'_{\kappa}, w'_{\kappa} \) = (0.50, 0 m s\(^{-1}\))] cases, with the buoyancy velocity \( w_{\kappa} = \left( w_{mean}/T_{mean} \right)^{1/3}, \) where \( g \) is the acceleration of gravity, \( u_{\kappa} = \left( \frac{\overline{w^2}}{\overline{w^2}} \right)^{1/4} \) is the friction velocity, and \( \overline{u'w'} \) are the vertical fluxes of the horizontal wind components \( u \) and \( v \) at the surface, respectively. The TKE profiles in the figure closely resemble those based on aircraft measurements in a similar environment by Stull (1988, his Fig. 2.9).

The profiles represent data averaged over time and space for LES or observations; with statistical uniformity and a sufficient sample, they approach the ideal “ensemble average” that the PBL schemes are designed to replicate. At any instant, \( h \) varies in time and space, as illustrated by the schematic in the lower right frame. The scale of these variations can be up to several kilometers in the presence of CBL structures like Benard-like cells or horizontal convective rolls (for illustrations showing time–space variability in convective CBLs see Weckwerth et al. 1997; Cohn et al. 1998; Cohn and Angevine 2000; Weckwerth et al. 2004; Miao et al. 2006; Bennett et al. 2010; Traumner et al. 2011). Such structures, mimicked in WRF (e.g., Trier et al. 2004; Miao and Chen 2008; LeMone et al. 2010b), also vary in time and space, so it is necessary either to allow for these irregularities in interpretation, or more ideally, use averaged data for comparisons.

Armed with these definitions, we evaluate and select the best criteria for \( h \) diagnosis, apply them, and compare the results to observations in the following sections. Observations and methods of analysis are described in section 2; model runs, PBL schemes, and analysis of model results are described in section 3. We evaluate several \( h \) criteria, describe the impact of the resolved...
CBL eddies, and describe horizontal averaging in section 4. After discussing factors other than CBL schemes that influence $h$ in WRF, we compare modeled $h$ values to observations and assess the impact of horizontal averaging and grid spacing in section 5. We discuss and summarize the conclusions in section 6.

2. Observations

Figure 2 shows locations of the CASES-97 instrumentation, which provide an excellent dataset for evaluating the ability of the ARW-WRF to replicate the fair-weather diurnal cycle. OXF (Oxford), BEA (Beaumont), and WHI (Whitewater) denote 915-MHz radar wind profilers (RWP), operated by Argonne National Laboratory (wind and signal-to-noise ratio data are available online at http://gonzalo.er.anl.gov/ABLE/data_archive/). On five different fair-weather days, radiosondes were released every 90 min over the diurnal cycle, from the RWP sites, affording estimates of PBL depth (data are available online at http://www.eol.ucar.edu/projects/cases97). Aircraft sampled boundary layer fluxes
along the three tracks shown in the figure. Surface fluxes were sampled at 10 different locations with winter-wheat, grassland, or bare-ground cover (numbered from 1–10 in the figure; we use 30-min data available online at http://www.eol.ucar.edu/isf/projects/cases97/asciiDownload30min.jsp). The S-band dual-polarization Doppler radar (S-Pol) and Weather Surveillance Radar-1988 Doppler (WSR-88D) radars, located around 37.55°N, 97.5°W, documented the clear-air convective structure. More details on the observations can be found in LeMone et al. (2000, 2002), and Yates et al. (2001).

Soundings at Beaumont, Kansas, are the focus of this paper because of the uniformity of nearby vegetation (grassland), the distance from any major urban area, and the quality of the dataset. Surface fluxes for this study are based on sites 1 and 2, since they are grassland sites near Beaumont. Because virtual temperature flux so strongly influences $h$, it is important to note that the surface sensible and latent heat fluxes $H$ and $LE$ based on eddy correlation might be underestimated (e.g., Twine et al. 2000). Assuming that the other two terms in the budget—net radiation and flux into the soil—were accurate, Chen et al. (2003) used data for the whole experiment to find the $H + LE$ for sites 1 and 2 are equal to an average of 77% of what would be required for balancing the surface energy budget; and LeMone et al. (2002) combined the data from sites 1–8 for individual days, finding that $H + LE$ were 91%, 94%, and 85% of the values required to close the budget on 29 April, 10 May, and 20 May, respectively.

Table 1 summarizes conditions for the four days analyzed. Thin high clouds were observed on two of the days and the PBL was too dry (mixing ratio $Q < 5$ g kg$^{-1}$) for appreciable low cloudiness, so the net radiation had a sinusoidal “clear sky” evolution on all four days. Winds ranged from light to moderate (Table 1), and inversions varied in strength (Fig. 3). Sonic temperature fluxes, a close approximation to virtual temperature fluxes, were similar for the four days and in the buoyancy-driven range associated with Moeng and Sullivan’s (1994) TKE profile in Fig. 1.

The determination of CBL depth exploits the strength of the sensors used.

- For RWP, CBL depth $h_{RWP}$ is set equal to the height of the center of the gate (60 m for BEA) just below the maximum signal-to-noise ratio dropoff with height (Coulter and Holdridge 1998), suggesting that the values thus obtained lie within the lower transition layer. The $h_{RWP}$ (wind) values are based on 10 total 1-min (5 min) samples over 50 min. The time stamp

### Table 1. CASES-97 weather conditions around Beaumont, Kansas. Numbers apply to 1830 UTC (solar noon). Winds based on RWP and radiosonde profiles; surface values based on averages of sites 1 and 2 for 1815 and 1845 UTC.

<table>
<thead>
<tr>
<th>Date</th>
<th>PBL wind (m s$^{-1}$)</th>
<th>$z_i$ (m)</th>
<th>$(wT_{a0})$ (K m s$^{-1}$)</th>
<th>$T_a$ (K)</th>
<th>$u_*$ (m s$^{-1}$)</th>
<th>$w_*$ (m s$^{-1}$)</th>
<th>$-L$ (m)</th>
<th>Cloudiness</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 Apr</td>
<td>SSW 11</td>
<td>1022</td>
<td>0.20</td>
<td>298.09</td>
<td>0.47</td>
<td>1.89</td>
<td>39</td>
<td>Broken cirrus but $R_{net}$ smooth</td>
<td></td>
</tr>
<tr>
<td>4–5 May</td>
<td>S–SSE 13</td>
<td>1217</td>
<td>0.18</td>
<td>296.48</td>
<td>0.55</td>
<td>1.93</td>
<td>69</td>
<td>Clear</td>
<td></td>
</tr>
<tr>
<td>10–11 May</td>
<td>SSW 6</td>
<td>1389</td>
<td>0.17</td>
<td>293.39</td>
<td>0.31</td>
<td>1.97</td>
<td>14</td>
<td>Clear</td>
<td></td>
</tr>
<tr>
<td>20–21 May</td>
<td>E-ENE 7–8</td>
<td>950</td>
<td>0.16</td>
<td>293.31</td>
<td>0.41</td>
<td>1.72</td>
<td>33</td>
<td>Scattered cirrus</td>
<td></td>
</tr>
</tbody>
</table>

* Could be underestimated by up to 15%–23% (see text).
Fig. 3. Observed $\Theta_v$ profiles (red) at Beaumont 1830 UTC (near solar noon) for the four days used in this study, along with profiles based on BouLac (green), MYJ (turquoise), QNSE (blue), and YSU (purple). CBL depth based on radar wind profiler ($h_{RWP}$) included.
Table 2. PBL schemes used in this study. \( K \) = eddy exchange coefficient, \( L_{\text{mix}} \) = length scale, and \( e \) = dissipation. All are fed \( u_s \) surface sensible and latent heat fluxes HFX and QFX from the Noah LSM.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Basic physics</th>
<th>WRF CBL depth</th>
<th>Primary references</th>
</tr>
</thead>
<tbody>
<tr>
<td>BouLac</td>
<td>Level-1.5 scheme</td>
<td>( \Theta_{\text{(mix)}} = \Theta_{\text{(z)}} + 0.5 ) K (interpolated)</td>
<td>Bougeault and LaCarrere (1989)</td>
</tr>
<tr>
<td></td>
<td>(a) Solve for ( e ) using (1)</td>
<td></td>
<td>Therry and LaCarrere (1983)</td>
</tr>
<tr>
<td></td>
<td>(b) Fluxes from ( K ) and vertical gradients</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(c) ( K = 0.4L_{\text{mix}}^{0.5} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(d) ( L_{\text{mix}} ) based on how far parcel can travel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MYJ</td>
<td>Level-2.5 scheme</td>
<td>( q(z_k) = 0.1 ) m s(^{-1} )</td>
<td>Janjic (2001)</td>
</tr>
<tr>
<td></td>
<td>(a) solves for ( \theta^* ) ( (\theta^* ) equation not prognostic ( \rightarrow 2.5) )</td>
<td></td>
<td>Mellor and Yamada (2002)</td>
</tr>
<tr>
<td></td>
<td>(b) ( K_{\text{M.H}} = L_{\text{mix}}^{0.5} \left[ L_{\text{mix}}, e, \left( \frac{\partial U}{\partial z} \right)^2, \left( \frac{\partial V}{\partial z} \right)^2, \left( \frac{\partial \Theta}{\partial z} \right)^2 \right] )</td>
<td></td>
<td>Mellor and Yamada (1974)</td>
</tr>
<tr>
<td></td>
<td>(c) Master length scale ( L_{\text{mix}} ) Preliminary ( L_{\text{mix}} = L_{\text{mix},0} = L_{\text{mix},b}(kz + L_{\text{mix},0}) ) ( L_{\text{mix},0} = a \left( q dz \right) \left( qdz \right) \left( qdz \right) ) ( q = (2e)^{0.5} ) ( L_{\text{mix}} ) found iteratively from equation for ( L_{\text{mix}}/q )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QNSE</td>
<td>Similar to MYJ except</td>
<td>( q(z_{k+1}) ) drops to 0.01 m s(^{-1} )</td>
<td>Sukoriansky et al. (2005)</td>
</tr>
<tr>
<td></td>
<td>(a) ( L_{\text{mix}} ) determined differently for stable PBL</td>
<td></td>
<td>Sukoriansky and Galperin (2008)</td>
</tr>
<tr>
<td></td>
<td>(b) ( K_{\text{M.H}} = 0.55\alpha_{\text{M.H}}(Ri)L_{\text{mix}}^{0.5} ), where ( \alpha_{\text{M.H}}(Ri) ) based on spectral model</td>
<td></td>
<td>Detering and Etling (1985)</td>
</tr>
<tr>
<td>YSU</td>
<td>(a) ( k = k_{\text{M.H}}Pr, k_{\text{M.H}} ) from (6) in mixed layer</td>
<td>( \text{Ri}(z_1 - h_{\text{YSU}}) = 0 ) for unstable PBL, equivalent to ( \text{Ri}(h_{\text{YSU}}) = \Theta_{\text{(mix)}}(z_1) + \Theta_{\text{(mix)}}(z_1) )</td>
<td>Hong et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>(b) Flux from (3), including terms to produce nonlocal flux</td>
<td></td>
<td>Noh et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>(c) Mix of Louis (1979) scheme and entrainment flux used between top of mixed layer ( h_{\text{YSU}} ) and height where flux = 0.01 value at ( h_{\text{YSU}} )</td>
<td></td>
<td>Louis (1979)</td>
</tr>
<tr>
<td></td>
<td>(d) ( \Theta_T = C(w_sT_v)_b/w_s ), where ( C ) a constant, ( w_s ) a scaling velocity defined in text</td>
<td></td>
<td>Betts et al. (1996)</td>
</tr>
</tbody>
</table>

for the wind data is 10 min past the hour (the first 10 min being used for the Radio Acoustic Sounding System profiles); the average time for the wind data is 35 min past the hour.

- For radiosondes, \( h_1 \) and \( h_2 \) were determined subjectively from \( \Theta \) profiles, and from the height range across which the radiosonde vertical velocity (wsonde), a function of environmental turbulence, drops from about 5 to 3 m s\(^{-1} \) (Johansson and Bergstrom 2005). The apparent transition layer in the \( \Theta \) profiles probably reflects the impact of the history of mixing along the balloon’s trajectory. The influence of larger-scale vertical air velocity fluctuations (associated with terrain or larger CBL eddies) can lead to scatter in wsonde-based \( h \) estimates.

Clearly the time-averaged \( h_{\text{RWP}} \) values are statistically more representative of CBL height than the instantaneous samples from soundings. Instantaneous \( h_1 \) values can vary significantly, as implied in Fig. 1; while \( h_2 \) based on temperature from the radiosonde soundings probably reflects previous CBL intrusion events. Because of the various uncertainties, we include all \( h \) estimates when comparing to model results.

3. ARW-WRF runs

a. The simulations

ARW-WRF version 3.2 simulations were run for the four days in Table 1, using the PBL schemes described in Table 2. Each simulation was run for 24 h, starting at 1200 UTC (0600 LST), using four two-way interacting nested grids with spacing of 27, 9, 3, and 1 km, respectively (Fig. 4). The vertical grid has 44 sigma levels, with the lowest half model level just below 5 m, 15 levels below 1 km, 22 levels at or below 2 km, and the top level at about 16 km. The 1-km inner grid was selected to include significant local land surface variability and to resolve mesoscale eddies (10 km or larger). Initial and boundary conditions for WRF are based on the 3-h North American Regional Reanalysis (NARR, see online at http://dss.ucar.edu/pub/narr/) data on a 32-km grid.

In addition to the four PBL schemes, the physical parameterizations used include the Noah land surface model (Chen and Dudhia 2001a,b; Ek et al. 2003), the Rapid Radiative Transfer Model (RRTM) longwave parameterization scheme (Mlawer et al. 1997), the Dudhia (1989) shortwave radiation scheme, and the Lin et al.
(1983) bulk microphysics scheme. Surface characteristics are based on the Moderate Resolution Imaging Spectroradiometer (MODIS) VEGPARM Table version 3.1.1, with surface roughness values $z_0$ modified as shown in Table 3. Land-use types for the inner grid (Fig. 4) show that the Beaumont site is surrounded by grassland, consistent with the land cover at nearby surface flux sites 1 and 2.

Additional model runs were done to assess the impact of grid spacing; and one run was conducted to evaluate the impact of recent changes in YSU, as described in Shin et al. (2012). The YSU run uses WRF/YSU version 3.3.1 with the same settings as the primary runs. The impact of horizontal grid spacing was tested using sets of runs for 10 May with the outer three grids (27-, 9-, and 3-km spacing) but with no feedback from finer to coarser

### Table 3. Changes from Default MODIS VEGPARM 3.1.1.

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>Default $z_0$ min</th>
<th>Default $z_0$ max</th>
<th>NEW $z_0$ min</th>
<th>NEW $z_0$ max</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Evergreen needleleaf forest</td>
<td>0.5</td>
<td>0.5</td>
<td>1.09</td>
<td>1.09</td>
</tr>
<tr>
<td>2 Evergreen broadleaf forest</td>
<td>0.5</td>
<td>0.5</td>
<td>2.65</td>
<td>2.65</td>
</tr>
<tr>
<td>3 Deciduous needleleaf forest</td>
<td>0.5</td>
<td>0.5</td>
<td>0.85</td>
<td>1.09</td>
</tr>
<tr>
<td>4 Deciduous broadleaf forest</td>
<td>0.5</td>
<td>0.5</td>
<td>0.8</td>
<td>1.7</td>
</tr>
<tr>
<td>5 Mixed forests</td>
<td>0.2</td>
<td>0.5</td>
<td>0.8</td>
<td>1.4</td>
</tr>
<tr>
<td>6 Closed shrublands</td>
<td>0.01</td>
<td>0.05</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>7 Open shrublands</td>
<td>0.01</td>
<td>0.06</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>8 Woody savannas</td>
<td>0.01</td>
<td>0.05</td>
<td>0.83</td>
<td>0.83</td>
</tr>
<tr>
<td>9 Savannas</td>
<td>0.15</td>
<td>0.15</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>10 Grasslands</td>
<td>0.1</td>
<td>0.12</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>11 Permanent wetlands</td>
<td>0.3</td>
<td>0.3</td>
<td>0.045</td>
<td>0.045</td>
</tr>
<tr>
<td>12 Croplands</td>
<td>0.05</td>
<td>0.15</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>13 Urban and built-up</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>14 Cropland/natural vegetation mosaic</td>
<td>0.05</td>
<td>0.14</td>
<td>0.023</td>
<td>0.06</td>
</tr>
<tr>
<td>15 Snow and ice</td>
<td>0.001</td>
<td>0.001</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>16 Barren or sparsely vegetated</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>17 Evergreen needleleaf forest</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>18 Evergreen broadleaf forest</td>
<td>0.3</td>
<td>0.3</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>19 Deciduous needleleaf forest</td>
<td>0.15</td>
<td>0.15</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>20 Deciduous broadleaf forest</td>
<td>0.05</td>
<td>0.1</td>
<td>0.02</td>
<td>0.03</td>
</tr>
</tbody>
</table>
The impact of vertical grid spacing was explored with one run using the MYJ scheme for 4–5 May with everything the same but 28 vertical levels.

b. The PBL schemes (for references see Table 2)

To facilitate later comparisons of the four PBL schemes used, we outline their basic characteristics. We selected the YSU scheme because it is a simple, unique, and widely used scheme that allows nonlocal vertical transport. The three other schemes, MYJ, Bourgeaût–LaCarrere (BouLac), and quasi-normal scale elimination (QNSE) allow only local transport. We selected MYJ because it is widely used. The other two schemes, BouLac and QNSE, are different from MYJ in interesting ways summarized below; however, like MYJ, they solve for TKE (represented here by $e$), from

$$\frac{\partial (e)}{\partial t} = \frac{1}{p} \frac{\partial}{\partial z} \left( u^' w^' e + u^' w^' \frac{\partial U}{\partial z} - v^' w^' \frac{\partial V}{\partial z} + \frac{g}{u^*} w^' T^*_v - e \right). \quad (1)$$

In (1), the wind components ($u$, $v$, $w$) are in a right-handed coordinate system with $u$ positive east; each component is the sum of the resolved (upper case) and unresolved/parameterized (primed) component. For virtual temperature $T^*_v$, the resolved portion is indicated with an overbar, and the unresolved with a prime. The first term on the right-hand side is the vertical divergence of the vertical transport of TKE by $w^'$, the second and third terms are shear production, the fourth term is buoyancy production, and the fifth term is dissipation. Note that (1) allows for interaction with CBL structure through $U$, $V$, and $\Theta^*_v$, but not resolved vertical velocity $W$. Moreover, horizontal gradients and horizontal advection are neglected.

For convenience, we will refer to the three PBL schemes that use (1) as “TKE schemes.”

The time tendency for a resolved variable $S$ due to $w^' S^'$, the flux associated with unresolved eddies, is given by

$$\left( \frac{\partial S}{\partial t} \right)_{\text{flux}} = -\frac{\partial}{\partial z} (w^' S^'), \quad (2)$$

where $w^' S^'$ is found from

$$w^' S^' = -K_s \left( \frac{\partial S}{\partial z} - \gamma_s \right) + E. \quad (3)$$

The terms $\gamma_s$ and $E$ are added to allow nonlocal vertical fluxes. Both are set to zero for the three TKE schemes used here.

The eddy-exchange coefficients for momentum $M$ and heat $H$ for the three TKE schemes is given by

$$K_{M,H} = F_{M,H} L_{\text{mix}} e^{0.5}, \quad (4)$$

where $L_{\text{mix}}$ is a mixing length or master length scale. For BouLac, $F_{M,H} = 0.4$, and $K_M = K_H$. In MYJ, $F_{M,H}$ is a complex function that incorporates $L_{\text{mix}} e^\theta$, the vertical shear, and $\Theta^*_v z$ (Table 2). For QNSE, $F_{M,H} = 0.55 a_{M,H}(\text{Ri})$, where the Richardson number $\text{Ri}$ is given by

$$\text{Ri} = \frac{g \Delta \Theta^*_v \Delta z}{\Theta^*_v \left( (\Delta U)^2 + (\Delta V)^2 \right)}. \quad (5)$$

where differences (top minus bottom, denoted by $\Delta$) are taken between grid points separated by $\Delta z$ and a small value is substituted for the denominator for non-zero values. For neutral conditions ($\text{Ri} = 0$), $a_M = 1$ and $a_H = 1.4$. For unstable conditions ($\text{Ri} < 0$), $a_{M,H}$ increases with $|\text{Ri}|$.

From Table 2, the scale $L_{\text{mix}}$ for BouLac is determined from the $\Theta^*_v$ profile using a parcel technique, while $L_{\text{mix}}$ for QNSE and MYJ is intimately tied to $e$ and CBL depth.

The fourth scheme, YSU, finds $K_H$ from the following expression:

$$K_M = k w_s z \left( 1 - \frac{z}{h_{\text{YSU}}} \right)^2, \quad z \leq h_{\text{YSU}}, \quad (6)$$

where $h_{\text{YSU}}$ is the CBL depth as determined in YSU (Table 2), $k = 0.4$ is the von Kármán constant, and the velocity scaling factor $w_s = (u_s + 3 k w_s) / h_{\text{YSU}}^{1/3}$ owes its origins to the surface-layer expression from Businger et al. (1971), so that (6) is a close match to surface-layer $K_M$ at small $z$. A Prandtl number $Pr$ based on surface conditions, $h_{\text{YSU}}$, an assumed surface-layer depth (0.1$h_{\text{YSU}}$), and $z$, is used to find $K_M = K_M / Pr$. The nonlocal terms $\gamma_s$ and $E$ are both included in (3), with the first allowing fluxes independent of $\partial S / \partial z$, and the second accounting for entrainment. The fluxes in the entrainment zone are treated separately, and are a function of vertical gradients and surface virtual temperature flux.

Each of the schemes is provided surface energy fluxes and $u_s$ from the Noah land surface model.

c. Analysis of model results

Hourly surface sensible and latent heat fluxes ($H$ and $LE$) and vertical profiles of the wind components, temperature, mixing ratio, pressure, and the turbulence variables associated with the TKE schemes (TKE, $L_{\text{mix}}$, and $K_H$) were extracted from the WRF runs for the grid square corresponding to Beaumont. Also, maps of $W$ just above the PBL were extracted to assess impacts of subsidence.
The CBL profiles were objectively analyzed to determine \( h \) using the criteria in Table 4, moving upward from the lowest model level to the first height at which each criterion is met. There are three types: (i) those matching the \( \Theta_v \) at \( h \) to some near-surface level (criteria 1–3), (ii) those based on vertical gradients, including one (criterion 4) inspired by a method commonly used to subjectively identify the top of the well-mixed layer, and two based on Ri (criteria 4–7), and (iii) those based on a TKE threshold (criterion 8). Criterion 5 identifies the inflection point in the inversion layer \([i.e., \text{the lowest height at which } \Theta_{v,z} \text{ reaches a maximum (} \Theta_{v,z} \text{) is } 0] \),

We use (5) to evaluate Ri. Based on Vogelezang and Holtslag (1996), a correction of \( u_*^2 \) is often added to the bracketed term in the denominator to allow for light-wind situations (e.g., Zeng et al. 2004); the wind is sufficiently strong (Table 1) that this is not necessary for the cases considered here. Adjacent layers are used to calculate Ri loc, which is assumed to apply to midway between; this is also true for vertical gradients. CBL height \( h \) is found by interpolating between the heights associated with the appropriate variables.

To filter out the effect of resolved CBL eddies on CBL profiles and hence \( h \), 9- (25) point average profiles and surface data were computed from the 9 (25) grid squares forming a 3- (5) km square centered at Beaumont.

![Image](image-url)
4. Evaluation of CBL criteria using modeled profiles

a. Evaluation of CBL depth criteria at a point

To evaluate the $h$ criteria, we plotted the objectively determined CBL depths on the corresponding model $\Theta_v$ profiles, as illustrated in Fig. 5. Then, using the definitions of Fig. 1, we sorted the objective estimates into categories ($<h_1$ or “too low,” $\sim h_1$, $\sim z_n$, $\sim h_2$, $>h_2$ or “too high,” or “erratic”), the last applying to a lack of consistency with the $\Theta_v$ profiles. For example, a criterion that corresponds to $h_1$ at one time, too low, at another

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**Fig. 6.** Evaluation of CBL-depth criteria based on one-point data.

**Fig. 7.** For the four days, simulated growth of the CBL for $h_1$ equal to the height at which $\Theta_{v,z} = 2$ K km$^{-1}$, for 1-km grid square corresponding to Beaumont.
Evaluations were done for all the 1-km data (all four schemes, all four days), and then checked by asking volunteers experienced in boundary layer meteorology to select the criteria that seemed to identify $h$ most successfully. A second check was done by repeating the evaluation using the series of profiles for the 3- and 9-km grid runs. Since the model $\Theta_c$ profiles often only had an unambiguous change in static stability at the top of the mixed layer, $h_1$ was far easier to identify than $h_2$ or $z_i$. Plots of TKE profiles were included to understand the behavior of the TKE criterion.

The results, shown in Fig. 6, show that the most consistent and successful criteria are based on the $\Theta_c$ profile. The most successful criterion, which defines $h$ as the height at which $\Theta_{v,z} = 2 \text{ K km}^{-1}$ (criterion 4) is consistent with mixed layer top $h_1$ for all four schemes and all four days. This is not surprising: using the base of the inversion to estimate $h$ is a common practice, as illustrated by the references in Table 4. Matching $\Theta_c$ at $h$ to level 1 (criterion 1) provides $h$ values that vary between $z_i$ and $h_2$, for QNSE and YSU, making it difficult to use as a universal estimate, with too high estimates based on this criterion for two days for MYJ. However, this criterion yields consistent estimates of $h_2$ for all four days for BouLac. Unfortunately, this criterion is dependent on the height of the first grid level and therefore the vertical grid spacing. This problem is addressed by using $\Theta_v$ at 0.05 h (criterion 3), but the $h$ values, which vary between $h_1$ and $z_i$, are a function of PBL scheme and day. Moreover, the iterative process required to obtain $h$ does not always converge, and $h$ based on this criterion is too low on two days for the YSU scheme.

The maximum-$\Theta_{v,z}$ criterion 5 shows up as “high” primarily because of what appear to be too-high values in the afternoon; often (but not always) the morning values look like good estimates of $z_i$. Figure 5 shows such behavior. Using MYJ with 28 vertical levels reveals $h$ estimates that are uniformly too high (not shown). The layer Richardson number criterion 6 varied from around $z_i$ to too high, depending on the day and the PBL scheme, even though the threshold selected is lower than the 0.3 value used in the Community Climate System Model version 2 (Zeng et al. 2004).

There are two criteria labeled erratic: those based on thresholds of $R_i_{loc}$ and TKE. The $R_i_{loc} = 0.5$ criterion 7...
identified reliable $h$ values for only two of the 16 cases. Figure 5 illustrates this erratic behavior. For much of the day, the $h$ estimates based on this criterion look good; but the diagnosed CBL is far too shallow at 2000 and 2200 UTC. This follows from small vertical shear (not shown) and slightly stable stratification in the middle to upper CBL at 2000 and 2200 UTC. Similarly, the table shows mostly erratic behavior for the TKE criterion 8. In Fig. 5, TKE = 0.2 m$^2$ s$^{-2}$ does a reasonable job until 1900 UTC, after which $h$ appears to be underestimated at 2000 UTC (exaggerating the reduction in CBL depth at this time), and overestimated at 2100 UTC.

b. The impact of resolved CBL eddies

The PBL schemes, representing ensemble averages, assume negligible horizontal variation and hence should produce smooth CBL growth in fair-weather conditions. Instead, even the “successful” criteria can produce irregular growth at a given point. If we apply the 2 K km$^{-1}$ criterion, one of the smoothest-varying of the eight criteria in Fig. 5, to other days and schemes, we find in Fig. 7 that “smooth” growth is rarely simulated. This to some degree mimics observations: our Fig. 1 and Fig. 5 in LeMone et al. (2002) suggest that departures of about 20%–25% from a smooth curve might be expected at a point, with larger fractional deviations relative to the mean CBL depth during the midmorning, when the CBL is growing rapidly (see also Bennett et al. 2010; Traumner et al. 2011). However, the hour-to-hour variability in $h$ based on TKE and Ri remains often tends to be much larger and thus looks unrealistic.

The irregular growth of the CBL in Fig. 7 and the qualitative association of shallow TKE profiles with shallow and more stable CBL $\Theta_{\text{mix}}$ profiles in Fig. 5 suggest the influence of resolved CBL structures, which have repeatedly been documented in fine-grid WRF runs (e.g., Trier et al. 2004; Miao and Chen 2008; LeMone et al. 2010b). Their presence is confirmed in Fig. 8, which shows resolved vertical velocity $W$ on the scale of a few kilometers in the mid-PBL not only for 4 May, but the other three days as well. Rampanelli et al. (2004) attribute
them to the model responding to the unstable CBL, much as described in classic linear convection theory (e.g., Asai 1970).

Figure 9 shows the impact of $W$ for the three TKE schemes, keeping in mind that the effects described reflect past time steps as well as the present.

For BouLac, $W$ fortuitously switches from negative at 1800 UTC to positive at 1900 UTC, a half hour before and after solar noon, allowing us to compare two times with roughly equal surface virtual temperature flux. The large change in $L_{mix}$ is related to a change in CBL depth (reflected in $\Theta_{e,z}$), because the air parcel energy approach (Table 2) typically makes $L_{mix}$ equal to the vertical distance from the closer edge (top or bottom) of the CBL as defined by the $\Theta_e$ profile. It follows from (1), (3), (4), and the $\Theta_e$ profile, that TKE and $K$ would be shallow as well. Here, we neglect the impact of shear, noting that its effect on the TKE budget is relatively small (e.g., Moeng and Sullivan 1994) for these buoyancy-driven CBLs (Table 1). From (4), the TKE and $L_{mix}$ profiles reinforce one another to produce larger $K$ for $W > 0$.

For MYJ, the winds are lighter than for the BouLac case (cf. 4 and 10 May in Table 1). Thus, TKE is even more strongly related to buoyancy production via (1), and hence, via (3), to $\Theta_{e,z}$, which is negative to 1200 m for $W > 0$ but positive above about 200 m for $W < 0$. The master length scale $L_{mix}$ is related to both TKE and $h$ (Table 2), both of which are suppressed for $W < 0$, leading [from (4)] to an extremely stunted $K_H$ profile.

For QNSE, there are again opposite $W$ for the hours straddling solar noon in a buoyancy-driven CBL (Table 1). In this case, smaller $W$ changes produce smaller but perceptible differences in TKE, $L_{mix}$, and $K_H$. At 1800 UTC, $W < 0$ compresses and stabilizes the CBL, but only leads to slightly less TKE production than for $W > 0$.

The degree of $W$ influence varies with the scheme. For MYJ, the complex relationship among TKE, $L_{mix}$ and $h$ makes $K_H$ extremely sensitive to static stability, and hence, to vertical velocity, which can result in wild fluctuations. Fortunately, these average out; for example, a large single-point $K_H$ value at 2100 UTC of $\sim 2500$ m$^2$ s$^{-1}$ on 10 May is hardly reflected in the corresponding 9-point horizontal average ($335$ m$^2$ s$^{-1}$) centered at Beaumont. Smaller sensitivity for QNSE is likely related to the smoothly varying functions of Ri used to obtain $K_{M,H}$ from their neutral values.

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![Vertical Velocity Level 11 (~540m) 21UTC 10 May 1997](image)

**Fig. 10.** As in Fig. 8, but for all four PBL schemes on 10 May.
For YSU, the impact of resolved CBL eddies is relatively weak, since hourly $W$ magnitudes do not exceed 20 cm s$^{-1}$ at Beaumont. Moreover, $K_B$ is related to surface fluxes, the lowest model level, and $h_{YSU}$ via (6). For $W < 0$, the impacts on the $\Theta_v$ profile are restricted to reducing $h$, slightly stabilizing the entrainment zone, and whatever feedback the compression of the superadiabatic layer has on the lowest model level and its interaction with the surface, with the reverse for $W > 0$.

c. Horizontal averaging to filter out CBL eddy impact

To mitigate the impact of resolved CBL eddies on $h$, we averaged the vertical profiles for the nine 1-km grid squares centered on Beaumont for all four days, and the 25 1-km grid squares centered on Beaumont for 10 May, the day that appeared to have the most irregular behavior. As seen in LeMone et al. (2010b), the $W$ field for 10 May, illustrated in Fig. 10 and Fig. 8, is the most cellular of the four days, consistent with the weak winds (Table 1). Note the previously mentioned comparatively small $W$ for YSU. This results from a more near-neutral CBL, which in turn reflects nonlocal fluxes; and, in the YSU version 3.2 used here, also an increase in heat flux out of the surface layer related to an adjustment of the Prandtl number.

Nine-point averaging smooths CBL growth as defined by the top of the mixed layer (or where $\Theta_{w,z} = 2$ K km$^{-1}$), as illustrated for MYJ in Fig. 11; however, noticeable temporal changes in stratification are not eliminated without 25-point averaging. Similarly, the TKE profiles require 25-point averaging to show reasonably smooth growth, particularly in the afternoon. Note that, after horizontal averaging, the TKE profiles above 100 m AGL more closely resemble their counterparts in Fig. 1 in

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FIG. 11. For 1-km inner grid, comparison of 25-point (solid line) and 9-point (dotted line) averaged profiles of $\Theta_v$, TKE, and $W$, centered at Beaumont to point values at Beaumont (dashed line), for MYJ 10 May. In the figure, $\Theta_v$, TKE, and $W$ are incremented by an additional 3 K, 1 m$^2$ s$^{-2}$, and 1 m s$^{-1}$, respectively, for each hour after 1500 UTC.
both shape and depth, with TKE falling to free-atmosphere values above $h_1$. BouLac and QNSE respond similarly to horizontal averaging. For all three PBL schemes, 25-point averaging reduces $W$ to $0.1 \, \text{m s}^{-1}$ or less.

Evaluations of objective $h$ estimates based on 9-point-averaged TKE profiles appear in Fig. 12, along with a comparison of evaluations for 1-, 9-, and 25-point averages for 10 May. From Fig. 6, TKE-based $h$ values are mostly erratic for single-point values; Fig. 12 shows only BouLac producing consistent $h$ values on all four days with 9-point averaging. With 25-point averaging, however, diagnosed $h$ values are more consistent with the $\Theta_e$ profiles (i.e., fewer erratic judgments) for all three schemes. The 0.2 m$^2$ s$^{-2}$ threshold produces good $h_1$ values for MYJ, while 0.101 m$^2$ s$^{-2}$ produces good $h_1$ values for BouLac, and good $z_i$ values for QNSE. A lower threshold for BouLac (0.001 m$^2$ s$^{-2}$) also yielded $z_i$ estimates. In the table, it should be noted that too high reflects values that are just a bit over $h_2$ at times.

5. Comparison to observations

a. Impact of confounding factors

In comparing model to observed CBL heights, factors other than the PBL schemes need to be considered. Among these are surface buoyancy fluxes, subsidence, horizontal advection, and $\Theta_e$ stratification above the CBL. We discuss the first three here and consider the last factor in evaluation of the daily comparisons.

From LeMone et al. (2010a), a bias in surface buoyancy flux produces an $h$ bias approximately equal to the square root of the ratio of the total modeled to total observed buoyancy flux since sunrise. The averages of the square roots of the ratios for the present cases (Table 5) range from 1.09 on 29 April to 1.11 for 10 May to 1.15 and 1.18 for 4 and 20 May, respectively. From the foregoing, these model overestimates of surface buoyancy flux could be artificial, offset by a likely underestimate in observed values. Moreover, allowing for hour-to-hour variability in the observations, the observed and modeled buoyancy flux curves have similar shapes. Thus, the modeled and observed fluxes are sufficiently close that we need not adjust for model surface-flux magnitude or phase differences.

Synoptic-scale subsidence $W_{\text{syn}}$ at the CBL top suppresses the growth rate $\frac{dh}{dt}$ via

$$\frac{dh}{dt} = w - W_{\text{syn}},$$

\[\text{(7)}\]

### Table 5. Comparison of observed and modeled surface virtual temperature flux integrated from 1200 to 1850 UTC, $\left(\Delta T_y \Delta t\right)_0$ (K m). [For comparison, $\left(\Delta T_y \Delta t\right)_0 = 0.1 \, \text{K m s}^{-1}$ for $6.5 \, \text{h} = 2340 \, \text{K m}$.]

<table>
<thead>
<tr>
<th>Date/scheme</th>
<th>Observed*</th>
<th>Model</th>
<th>(Model/obs)$^{0.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 Apr</td>
<td>BouLac 2528</td>
<td>2930</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>MYJ 2528</td>
<td>3017</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>QNSE 2528</td>
<td>3104</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>YSU 2528</td>
<td>2871</td>
<td>1.07</td>
</tr>
<tr>
<td>4 May</td>
<td>BouLac 2262</td>
<td>3039</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>MYJ 2262</td>
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<tr>
<td>20 May</td>
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<td>3398</td>
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<tr>
<td></td>
<td>YSU 2490</td>
<td>3220</td>
<td>1.14</td>
</tr>
</tbody>
</table>

* Probably too low by 10%–25% (see section 2).
where \( w_e \), the entrainment velocity or the rate at which "free atmosphere" air is engulfed into the boundary layer, should be taken care of by the surface and PBL schemes. From (7), an error of 0.01 m s\(^{-1}\) in \( W_{\text{syn}} \) would lead to an error in \( h \) that would accumulate at the rate of 36 m each hour assuming no effect on \( w_e \).

The potential effect of \( W_{\text{syn}} \) was evaluated by estimating its magnitude a number of ways using data for 10 May. We examined time series of four gridpoint vertical averages of \( W \) just above CBL top (1.5–2.1 km AGL), for the four PBL schemes, using the 1-km-grid 9-point averages, and the 3- and 9-km single-point values at Beaumont for the runs with no feedback from smaller scales. These showed all four schemes converging toward the same time series with the same time-averaged value (\( \sim 1 \) cm s\(^{-1}\) as the influence of the resolved CBL eddies decreased. This result, though not surprising, confirms that differences between modeled CBL depth resulting from use of different PBL schemes are not caused by differences in \( W_{\text{syn}} \). This value was confirmed by plotting maps of vertical velocity just above maximum CBL top, at level 22 (\( \sim 1900 \) m).

It is beyond our capability, however, to estimate impact of \( W_{\text{syn}} \) on comparisons of modeled to observed \( h \), because rigorous estimates of \( W_{\text{syn}} \) to the needed accuracy (<0.01 m s\(^{-1}\)) are not available for WRF, and it is difficult to estimate subsidence from observations. For 10 May, above-CBL temperature budgets, sink rates for above-CBL features in the 90-min soundings during the day, and sink rates of the top of the RWP high signal-to-noise ratio field in the late afternoon, revealed \( W_{\text{syn}} \) \( 0.02–0.03 \) m s\(^{-1}\) at around 2 km AGL, consistent with NARR, but slightly greater over Beaumont than for the WRF simulations. Perhaps because of stronger winds and the associated impact of horizontal advection on sounding features, budgets and feature sink rates did not yield consistent \( W_{\text{syn}} \) estimates at Beaumont for the other days.

The impact of horizontal advection is through resolved CBL eddies and larger-scale gradients. The impact of resolved CBL eddies is mitigated through time averaging (in the case of the RWP data) and spatial averaging (for model profiles). The impact of larger-scale gradients is likely small on these four fair-weather days. LeMone et al. (2000, their Fig. 13) shows small and fairly consistent \( h \) differences of the order of 100–200 m over 60 km for 4 May, 20 May, and 10 May; and LeMone et al. (2010a, their Fig. 9) shows a similar changes across the same region in 2002.

b. Comparisons for 1-km grid runs

For 4 May, Fig. 13 compares MYJ \( h \) based on the eight criteria to observations. From Fig. 6, the successful
criteria (i.e., those correctly identifying $h$ on model $\Theta_v$ profiles) are (3) $\Theta_v(h) = \Theta_v(0.05h)$ and (4) $\Theta_{v,z}(h) = 2Kk_m^2$; both reflect the $h$ underestimate associated with MYJ. Figure 6 shows that $h$ values based on criteria (1) [$\Theta_v(h) = \Theta_v(\text{Level 1})$] and (2) [$\Theta_v(h) = \Theta_v(\text{Level 1}) + 1K$] are too high for this day, so the apparent good matches in the figure through 2100 UTC are misleading. Similarly, the too-high max-$\Theta_{v,z}$ and Ri (Level 1 $- h$) criteria lead to apparent good agreement with observations through 2100 UTC for the wrong reasons. The nine-point mean smoothes out the CBL growth curves, but not completely. As in the case of 10 May (Fig. 11), the nine-point smoothed Ri$_{oc}$- and TKE-based $h$ curves are still quite irregular in the afternoon.

Figure 14 compares observed to model $h$ using $\Theta_{v,z}(h_1) = 2Kk_m^2$, based on average profiles for the nine 1-km grid squares centered at Beaumont. From Fig. 6, this criterion is a successful indicator of $h_1$ for all four PBL schemes on all four days. As expected, BouLac, MYJ, and QNSE mostly underestimate $h_1$, while YSU is closer to observed values on 29 April, 4 May, and 10 May. For 20 May, all the PBL schemes cross or intercept the observed $h_1$ line, with YSU showing a high bias from 1700–1900 UTC, all but BouLac high at 1800 UTC, and the TKE schemes low for other parts of the day. Despite the smoothing, CBL growth retains some of the irregularity seen in Figs. 5, 11, and 13 for the TKE schemes, with the impact of resolved CBL eddies most evident.
in the afternoon. The midafternoon decrease in $h_1$ for all four schemes on 4 May, when the sounding temperatures suggest a still-growing PBL, might result from errors in modeled subsidence. Alternatively, since wsonde-based $h_1$ values appear comparable or higher than those based on $\Theta$ (perhaps due to local eddies lofting the balloon), the drop of wsonde-based $h_1$ to below that from $\Theta$ at 2300 UTC could indicate that observed $\Theta$ profiles are starting to fail as a measure of CBL depth.

As a consistency check, modeled and observed $\Theta_v$ profiles at solar noon (1830 UTC) on the four days are compared in Fig. 3. There are clearly differences in $\Theta_v$ magnitudes and vertical gradients above the CBL that likely reflect model initial conditions different from what was actually observed, especially for 29 April and 20 May, when both differ. Taking time-averaged $h_{\text{RWP}}$ as more representative than the instantaneous $h_1$ based on the radiosonde $\Theta_v$ profile, the TKE schemes underestimate the CBL depth for the two better-reproduced profiles on 4 and 10 May, and on 29 April, but they overestimate $h_{\text{RWP}}$ for 20 May. The YSU scheme replicates the CBL depth on 4 May, is slightly lower than $h_{\text{RWP}}$ for 29 April and 10 May, and overestimates $h_{\text{RWP}}$ on 20 May.

Figure 15 compares objectively determined model $h$ to observations on all four days, for $h_{\text{RWP}}(h_1) = 2$ K km$^{-1}$. The data are combined for the four days by first normalizing the $h_1$ time series for each day by dividing the hourly model $h_1$ on that day by the corresponding $h_{\text{RWP}}$, then averaging the resulting time series, and finally multiplying the result by the corresponding 4-day-averaged hourly $h_{\text{RWP}}$ values. Though it includes data for 20 May, Fig. 15 shows that the TKE schemes produce too low a value, with YSU the closest to observations. As in Fig. 14, all PBL schemes appear too low starting at 2000 UTC.

With 25-point smoothing, TKE-based CBL depths increase more smoothly and become more reliable $h$ indicators. Figure 16 shows the impact of the 25-point averages on $h$ for the most successful TKE thresholds of Fig. 12 and compares them to $h$ based on $\Theta_{w,z} = 2$ K km$^{-1}$. The $h$ curves based on 25-point-averaged TKE mostly correspond to the maximum height estimates based on the less-smoothed profiles. Furthermore, the 25-point TKE-based $h$ curves are reasonably consistent with the three closely corresponding $h_1$ curves based on the $\Theta_{v,z}$ criterion.

c. Comparisons to results from coarser resolution

Figure 17 compares average $\Theta_v$, TKE, and $W$ profiles for the runs with 3-km grids, 9-km grids, and horizontally averaged 1-km grids (25-point averages for the TKE schemes, 9-point averages for YSU). The averages are constructed from the four profiles centered on solar noon (1700, 1800, 1900, and 2000 UTC), by normalizing the heights $z$ for each profile by its depth $h_1$ (based on $\Theta_{w,z} = 2$ K km$^{-1}$), interpolating the data to correspond to normalized heights at $0.02z/h_1$ intervals, averaging the four points at each normalized height, and then multiplying the heights by the corresponding time-averaged $h_1$ value.

The figure reveals interesting grid-scale-related similarities and differences in terms of stability, TKE, and the impact of resolved eddies. First, the 3-km grid still has resolved CBL eddies for all three TKE schemes, as revealed by the mean $W$ profiles, with YSU values remaining small; while such eddies at 9 km are quite weak. As in the case of Fig. 9 for single-point 1-km data, $W > 0$ at 3 km probably accounts for the $\Theta_v$ profiles being more unstable than for the 25-point averages of the 1-km grid data. Second, the 9-km grid $\Theta_v$ profiles are more unstable than their counterparts based on the 25-point averaged 1-km data, for all three TKE schemes. This likely follows from the near absence of resolved CBL eddies, which at 1-km grid spacing transport heat from the lower CBL and make the average profile more near neutral. Apparently the parameterized fluxes are not sufficient make up for the lack of resolved eddies, a likely result of the lack of nonlocal fluxes in (3). Finally, the YSU $\Theta_v$ profiles remain near neutral for all three grid spacings despite the lack of strong resolved CBL eddies, a result of including nonlocal fluxes in (3).

The behavior of the TKE profiles is consistent with the foregoing. At 3 km, larger TKE is consistent with $W > 0$ and more unstable $\Theta_v$ profiles, just as at 1 km (Fig. 9). At 9 km, the larger parameterized TKE is consistent with the more unstable $\Theta_v$ profiles, with the result being that
the TKE scheme creates more subgrid-scale turbulence to make up for the absence of the resolved eddies.

Based on the criteria deemed useful for this day, Fig. 18 and Tables 6 and 7 mostly show small impact of horizontal grid spacing on \( h \) for 10 May, particularly given other sources of differences: 1) The 9-km grid point has an elevation about 30 m lower than the other grids. This offset increases the height relative to the ground for \( \Theta_v \), features above the CBL. Near the ground, there should not be much difference, and at intermediate heights, the offset should be between 0 and 30 m. 2) There is a ~3-km horizontal offset in the center of the grid squares, with the 9-km grid square the outlier, which seems to have minor impact. 3) Assigning the vertical gradient to
midway between the \( \Theta_e \) grid points makes the exact position of \( h \) depend on the strength of the gradients above and below, which is typically less than the vertical grid spacing (of order 100 m at these heights, as shown in Fig. 3). 4) The \( h \) values in the tables are influenced by the method of finding average \( h \) (Tables 6 and 7). The 3-km grid values are not included in the tables because they are influenced by resolved eddies.

- PBL depths based on \( \Theta_{u,z} = 2 \) K km\(^{-1} \) are fairly consistent for the three TKE schemes in Fig. 18 and Table 6. There are slight differences for YSU and BouLac, but they are less than the vertical grid spacing (Fig. 3).
- TKE-based CBL depths are larger for the 9-km grid than the 1-km grid average for MYJ \( (h_1) \) and QNSE \( (z_i) \) in Fig. 18 and Table 7, but slightly smaller for BouLac. For the 3-km grid point, TKE-based CBL depth evolves more irregularly with time due to CBL eddies, especially for BouLac in the figure, with comparatively large depths between 1700 and 2000 UTC resulting from updrafts (vertical maxima 0.2–0.4 m s\(^{-1} \)), and an anomalously shallow depth at 2200 UTC associated with a downdraft (vertical maximum 0.4 m s\(^{-1} \)). It is encouraging, however, that the drop of TKE to background in Fig. 17 is not sensitive to grid spacing; and that the height at which this occurs is higher than \( h_1 \), consistent with LES (see Fig. 1).
- PBL depths based on level 1 \( \Theta_e \) values for the 9-km grid point have increases of the order of the elevation offset in Table 6. For YSU, \( z_i \) is slightly deeper at coarser resolution but still less than the vertical grid spacing.
- PBL depths based on 0.05-\( h \) \( \Theta_e \) values are larger for 9 km than for 1 km in Table 6. This follows from the greater CBL instability at 9 km, as illustrated by the vertical lines on the BouLac \( \Theta_e \) profiles in Fig. 17. This suggests that the level-1 criterion would be sensitive to horizontal grid spacing at coarser vertical grid spacing. We did not evaluate this criterion for YSU, since it was deemed too low for this day.

6. Discussion and conclusions

Several criteria for determining CBL depth in WRF were evaluated against modeled \( \Theta_e \) profiles and then used to compare WRF-derived \( h \) from the BouLac, MYJ, QNSE, and YSU PBL schemes to observations on four different fair-weather days in CASES-97. Comparisons of \( h \) based on successful criteria to observations are consistent the well-documented low \( h \) bias for the TKE schemes, with more accurate to too-high \( h \) from the YSU scheme (Kain et al. 2005; Weisman et al. 2008; Hu et al. 2010). For BouLac, MYJ, and QNSE, the presence of resolved CBL eddies led to unrealistically irregular growth of \( h \) during the day, rendering some of the criteria useless without smoothing; their absence led to more unstable CBLs at coarser resolution, thus deepening...
the CBL according to some criteria. Furthermore, several of the criteria used were sensitive to PBL scheme and grid spacing either in the horizontal or vertical, suggesting that testing of selected criteria using model profiles is important once a model setup has been defined. Readers should be cautioned that the $h$ metric should be used along with CBL profiles in PBL scheme evaluation, and that none of the comparisons discussed include low clouds or precipitation.

With these caveats in mind, we found the following for the present simulations. Depths are defined as in Fig. 1, with $h_1$ the top of the well-mixed layer as defined by $\Theta$ or $\Theta_y$, $h_2$ the top of the inversion layer, with $z_i$ somewhere in between.

- The criterion $\Theta_{v,z}(h) = 2$ K km$^{-1}$ is the most successful. The resulting CBL depth $h_1$ varies more smoothly with time than those involving $R_{h_{loc}}$ or TKE for the 1-km

![Fig. 18. As in Fig. 16, but for 9-km grid (1 point, thick solid line), 3-km grid (1 point, dotted line), and 1-point grid (25 points, dashed line), centered on Beaumont.](image)
data even without averaging, and produces a close match to modeled mixed layer top \( h_1 \) for all four schemes on all four days. Also, this criterion was relatively insensitive to grid spacing. For comparison, use of \( \Theta_{v,z} = 3 \text{ K km}^{-1} \) (as in Liu and Liang 2010) yielded plausible values of \( h_1 \) to \( z_i \), suggesting that \( \Theta_{v,z} = 4 \text{ K km}^{-1} \) (as in Zeng et al. 2004) would be closer to \( z_i \) for the present model runs.

- Use of TKE at 1-km horizontal grid spacing is successful only after averaging the TKE profiles over a 5 km \( \times \) 5 km square centered on Beaumont. Not surprisingly, different thresholds were required for different PBL schemes, with 0.2 m\(^2\) s\(^{-2}\) yielding good estimates of \( h_1 \) for MYJ, 0.101 m\(^2\) s\(^{-2}\) yielding good estimates of \( h_1 \) for BouLac, and 0.101 m\(^2\) s\(^{-2}\) yielding good \( z_i \) estimates for QNSE. The TKE-based \( h \) estimates changed for BouLac, MYJ, and QNSE with horizontal grid spacing; however, the drop in TKE to “background” was relatively insensitive. Moreover, this background height is greater than \( h_1 \), consistent with LES (Fig. 1).

Other criteria based on \( \Theta_{v} \), namely using \( \Theta_{v}(\text{level 1}) \) or \( \Theta_{v}(0.05h) \) had mixed success.

- The level-1 criteria suffer from a sensitivity to vertical grid spacing: with the dense vertical grid used here, the closeness of level 1 to the surface led to \( h \) estimates that ranged from \( z_i \) to “too high.” The \( \Theta_{v}(\text{level 1}) + 1 \) criterion always produced too-high \( h \) values.

- The 0.05\( h \)-criterion was designed to remove sensitivity to vertical grid spacing, but the iterative procedure used does not always converge, and the values thus obtained were “too low” for the YSU scheme on 2 days. Finally, \( h \) based on this criterion is larger at 9-km horizontal grid spacing than for the horizontally-averaged 1-km grid profiles using the TKE schemes, since the absence of CBL eddies for the larger grid spacing leads to a more superadiabatic lapse rate. It follows that a level-1 criterion with a coarse vertical grid (or a level-3 or -4 criterion with the grid used here) would run into the same problem.

For comparison, \( h \) as defined by Hu et al. (2010) leads to overestimates using the present dataset, although there is a reasonable match to \( h_2 \) during the afternoon. Hu et al. define \( h \) as the height at which \( \Theta_{v}(h) = \Theta_{v,\text{min}} + 1.5 \text{ K} \) holds, where \( \Theta_{v,\text{min}} \) is the minimum value of \( \Theta_{v} \) in the CBL. Joseph Olson (2011, NOAA/ESRL, personal communication) has found that adding 1 K rather than 1.5 K yielded a better estimate of \( h \), as expected, the resulting \( h \) values were even higher than the “too high” values using 0.2, suggesting a smaller threshold is appropriate. Given successful use of 0.3 in CCSM V2 (Zeng et al. 2004), our high bias probably reflects a sensitivity to vertical grid spacing.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Avg of four ( h ) values</th>
<th>( h ) from avg of four profiles</th>
<th>Avg of four ( h ) values</th>
<th>( h ) from avg of four profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>BouLac ( \Theta_{v}(h_1) = 2 \text{ K km}^{-1} )</td>
<td>1134</td>
<td>1149</td>
<td>1167</td>
<td>1184</td>
</tr>
<tr>
<td>( \Theta_{v}(h_2) = \Theta_{v}(\text{level 1}) )</td>
<td>1413</td>
<td></td>
<td>1376</td>
<td></td>
</tr>
<tr>
<td>( \Theta_{v}(z_i) = \Theta_{v}(0.05z_i) )</td>
<td>1290</td>
<td>1290</td>
<td>1232</td>
<td>1233</td>
</tr>
<tr>
<td>MYJ ( \Theta_{v}(h_1) = 2 \text{ K km}^{-1} )</td>
<td>1130</td>
<td>1145</td>
<td>1121</td>
<td>1141</td>
</tr>
<tr>
<td>( \Theta_{v}(h_2) = \Theta_{v}(\text{level 1}) )</td>
<td>1369</td>
<td></td>
<td>1332</td>
<td></td>
</tr>
<tr>
<td>( \Theta_{v}(z_i) = \Theta_{v}(0.05z_i) )</td>
<td>1238</td>
<td>1237</td>
<td>1174</td>
<td>1181</td>
</tr>
<tr>
<td>QNSE ( \Theta_{v}(h_1) = 2 \text{ K km}^{-1} )</td>
<td>141</td>
<td>1149</td>
<td>1160</td>
<td>1160</td>
</tr>
<tr>
<td>( \Theta_{v}(h_2) = \Theta_{v}(\text{level 1}) )</td>
<td>1313</td>
<td></td>
<td>1275</td>
<td></td>
</tr>
<tr>
<td>( \Theta_{v}(z_i) = \Theta_{v}(0.05z_i) )</td>
<td>1251</td>
<td>1249</td>
<td>1172</td>
<td>1184</td>
</tr>
<tr>
<td>YSU ( \Theta_{v}(h_1) = 2 \text{ K km}^{-1} )</td>
<td>1308</td>
<td>1308</td>
<td>1248</td>
<td>1269</td>
</tr>
<tr>
<td>( \Theta_{v}(z_i) = \Theta_{v}(\text{Level 1}) )</td>
<td>1426</td>
<td></td>
<td>1358</td>
<td></td>
</tr>
</tbody>
</table>

Table 7. For Beaumont, 10 May, average of PBL heights (m AGL) based on TKE profiles at 1700, 1800, 1900, and 2000 UTC.

<table>
<thead>
<tr>
<th>PBL scheme</th>
<th>TKE criterion (m(^2) s(^{-1}))</th>
<th>9-km grid (m AGL)</th>
<th>1-km grid (25-point avg) (m AGL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BouLac ( h_1 )</td>
<td>0.101</td>
<td>1157</td>
<td>1217</td>
</tr>
<tr>
<td>MYJ ( h_1 )</td>
<td>0.20</td>
<td>1295</td>
<td>1125</td>
</tr>
<tr>
<td>QNSE ( z_i )</td>
<td>0.101</td>
<td>1452</td>
<td>1347</td>
</tr>
</tbody>
</table>
• For the 1-km grid, the criterion $Ri_{loc}(h) = 0.5$ is strongly dependent on the PBL scheme. For example, the greater CBL static stability for YSU sometimes translated into too-shallow a CBL using this criterion, and changes in stratification associated with $W$ led to unreliable identification of depth for the TKE schemes; a larger threshold could help solve this problem. However, the increase in instability at coarser horizontal grids for the TKE schemes would also have an effect.

• The maximum $\Theta_{o,z}$ criterion did not work as well as hoped, often yielding $h$ estimates that were too high. We would anticipate more success at higher vertical resolution, since increasing the number of vertical grid points from 28 to 44 improved its behavior.

The presence of resolved CBL eddies in the high-resolution runs (1- and 3-km horizontal grids) greatly diminishes the success of TKE-based thresholds in determining $h$ without horizontal (or time) averaging, likely affecting those schemes that use these criteria (MYJ, QNSE) internally. Near elimination of such eddies and their associated upward heat transport at 9-km horizontal grid spacing leads to more unstable $\Theta_p$ profiles, larger TKE, and, as noted, the potential to affect $h$. The transition of the CBL from near-neutral with large heat transport by CBL eddies at 1 km to unstable with transport achieved through the PBL scheme at 9 km suggests model-system compensation that keeps the fluxes consistent with their surface values.

Though the resolved eddies can look quite realistic, with patterns changing from cellular to linear with increasing winds, as pointed out in LeMone et al. (2010b), other aspects are artificial. For example, the Prandtl number modification in YSU version 3.2 that increases heat transport out of the surface layer led to more near-neutral conditions, much weaker resolved CBL eddies, and more linear convection with weak winds, compared to the other schemes here and to YSU version 2.1.2 in LeMone et al. even though the boundary layers are buoyancy driven in all cases. Moreover, stronger (but still linear) resolved CBL eddies appeared in a test run for 10 May with YSU/WRF version 3.3.1, which has been modified to reduce excess mixing as described in Shin et al. (2012). Also, not only do the TKE schemes fail to represent nonlocal transport, but they do not allow vertical TKE transport by the resolved flow, as observed in nature (e.g., LeMone 1976); none of the schemes accounts for horizontal turbulence transport.

While $h$ is a useful metric for evaluating CBL schemes, profiles should also be considered. Comparing results from runs using WRF/YSU version 3.3.1 to the present runs indicated similar values of $h$ [nearly identical using the $\Theta_o$(level 1)-criterion]. However, as pointed out by Shin et al. (2012), less-aggressive vertical mixing leads to more realistic vertical profiles.

The lack of clouds limits the conclusions of this study. However, some of the criteria can be easily generalized. For example, TKE would drop abruptly at cloud top. Also, one could replace $\Theta_s$ in the $\Theta_{o,z}$ criterion with the liquid-water potential temperature $\Theta_L = \Theta - Q_L/c_p$, where $L$ is the latent heat of condensation, $Q_L$ is the liquid-water mixing ratio, and $c_p$ is the specific heat at constant pressure. However, smoothing could be problematic in the presence of clouds. Indeed, as pointed out in LeMone et al. (2010b), the resolved CBL structures produce cloud fields that resemble observations. This, plus a potential role for such structures in convective initiation (e.g., Trier et al. 2004) and propagation (Trier et al. 1991) makes one hesitant to smooth them out for such applications.

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