

Comparison of WRF local and nonlocal boundary layer Physics in Greater Kuala Lumpur, Malaysia

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Abstract. The urban boundary layer (UBL) is the internal advection layer of atmosphere above urban region which determines the exchanges of momentum, water and other atmospheric constituents between the urban land surface and the free troposphere. This paper tested the performance of three planetary boundary layer (PBL) physics schemes of Weather Research and Forecast (WRF) software to ensure the appropriate representation of vertical structure of UBL in Greater Kuala Lumpur (GKL). Comparison was conducted on the performance of respective PBL schemes to generate vertical and near-surface weather profile and rainfall. Mellor-Yamada-Janjic (MYJ) local PBL scheme coupled with Eta MM5 surface layer scheme was found to predict the near-surface temperature and wind profile and mixing height better than the nonlocal schemes during the intermonsoonal period with least influences of the synoptic background weather.

1. Introduction

Urban boundary layer (UBL) is the vertical atmospheric structure formed due to urban land use that contribute to the dryness, turbulent instability and increment of mixing height [1]. The urban-induced vertical air movements essentially determine the development and the structure of the boundary layer where fluxes of heat, moisture and component exchange between land surface and atmosphere. However, such eddies are unable to be resolved using conventional mesoscale numerical model and have to be parameterized through the planetary boundary layer (PBL) model. In Weather and Research Forecast (WRF) software, the PBL physics resolve the subgrid-scale vertical interaction of surface heat, moisture and air constituent flux such as nonlocal transport, entrainment near PBL top, transitions between stable (SBL) and convective boundary layer (CBL) [2]. The PBL scheme determines the lapse rate, vertical turbulence fluxes and radiation admittance of the vertical layer under the free atmosphere layer (500 - 3000 m from Earth surface). Hence, it can potentially affect the heat exchanges fluxes between the surface layer and the boundary layer to determine the urban-induced heating. The boundary layer turbulence problem is assumed with the gradient transport theory (K-theory) and is generally closed with two methods. They are (a) the local closure approach that estimates the turbulent fluxes at



each point from the mean properties of its adjacent points and (b) the nonlocal treatment which determines the fluxes from the depth of boundary layer.

Comparative studies in the south-central USA have confirmed that local schemes produce closer agreement of vertical profile and near-surface variables under stable condition [3,4]. Nevertheless, it is prone to overestimation of the moisture content during summer. Nonlocal schemes excel in reconstructing the PBL height and estimating the lower boundary lapse rate which is pertinent to the prediction of pollution distribution [5]. Notwithstanding the inconsistent and site-specific performance of each boundary layer scheme, the PBL schemes were widely tested in the midlatitude region [6,7], but little information is available for applicability in tropical regions. This has therefore rendered the site-specific investigation necessary to adopt more appropriate scheme for detailed UBL study within the region.

This paper tested the performance of the boundary layer physics to ensure the applicability and weakness of the schemes to represent the transportation and dynamics of boundary layer structure in Greater Kuala Lumpur (GKL), Malaysia. From which, the comparison result can be referenced for future UBL study in GKL or region with similar background weather and urbanization conditions. Section 2 first discussed the parameterization method of the selected PBL schemes as well as the experiment design. In Section 3, each PBL physics was evaluated before settling on the better performing scheme to reproduce the turbulent transportation and mixing within the UBL.

2. Experiment design

Table 1. WRF domain and physics settings

Parameter	Value/ Option	Parameter	Value/ Option
Analyzed period (1-day spin up)	19 days (2 nd April/Oct 2003 0800 MYT – 20 th April/Oct 2003 0800 MYT)	Boundary layer schemes	MYJ: MYJ PBL with Eta MM5 SUR scheme; YSU: YSU PBL with MM5 SUR scheme; ACM2: ACM2 PBL with MM5 SUR scheme
Domains setting	4 domains (27km, 9km, 3km, 1km)		
Vertical levels	37 vertical eta levels. 15 level for bottom 12 km		
Lateral boundary data	ERA-interim 6-hourly reanalysis model level data		
Land use map	Updated with 3 urbanization level (Low and high density residential and commercial/industrial) [8]	Microphysics scheme	Lin: Purdue Lin single moment scheme
Land surface model (LSM)	Noah LSM coupled with single-layer urban canopy model (UCM) with calibrated urban parameters [8]	Cumulus scheme	BMJ: Betts-Miller-Janjić scheme for 1 st and 2 nd domains only

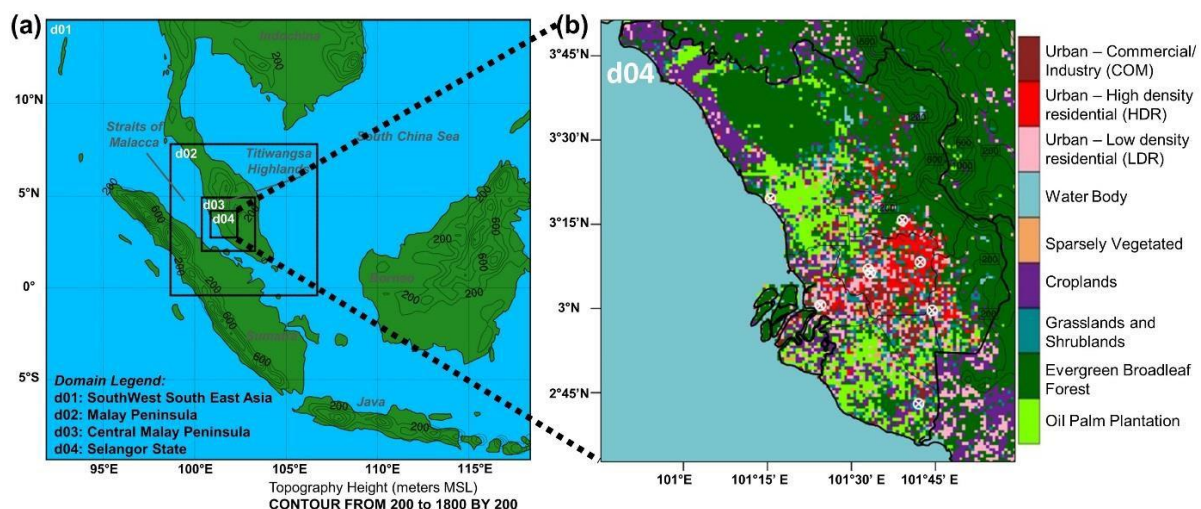


Figure 1. (a) WRF domains settings, (b) Updated land use map of 4th domain (d04) with 8 weather stations (ST), 1 rain gauge (ST6-Sepang) and 1 sounding station (ST6).

Three widely applied PBL schemes, namely the local scheme, Mellor-Yamada-Janjić (MYJ) and two nonlocal schemes, Yonsei University scheme (YSU) and Asymmetric Convective Model (ACM2) were chosen for comparison. Firstly, MYJ is an implementation of Mellor-Yamada PBL parameterization into numerical weather prediction field [9]. Additional prognostic equation for TKE is introduced to predict its generation, transportation and dissipation and the entrainment near PBL top [2]. This scheme is suitable for stable and slightly unstable flows because it is able to ensure the conservation of boundary layer [3]. The YSU scheme [10], on the other hand, is an improved version of the nonlocal parameterization Middle Range Forecast. It combines specified profile for diffusivity and counter-gradient term in the same equation. The explicit treatment of entrainment process is also included at the top of PBL. The scheme is therefore suitable to predict unstable flows by addressing the nonlocal fluxes when rigorous eddies circulation approaches the depth of the boundary layer [3,4]. The ACM2 scheme [11] is a hybrid scheme combining both local eddy diffusion and nonlocal transport scheme from ACM1. The ratio of nonlocal fluxes to total fluxes near-surface is introduced as a stability indicator for the smooth transition between SBL and CBL [2,5]. In WRF, each PBL scheme is bonded to associated surface layer (SUR) scheme.

The intermonsoonal periods, April and October with weaker synoptic forcing were studied to emphasize on the local climate, especially urban heating and its influence on topographic flow [12]. Due to the variability of atmospheric boundary layer to the background weather condition, this paper tested the PBL scheme performance in 2003 with least influence of rainfall anomaly [8]. The domain information for the simulation was given in Figure 1a with other input data and physics settings in Table 1. Simulation cases adopting MYJ, YSU and ACM2 PBL schemes were respectively run for the two mentioned intermonsoonal periods (April and October). Abilities to predict the vertical profile and boundary layer height were tested with measured data (marked in Figure 1b) to ensure the schemes reproduce the vertical flux dynamics and later the near-surface profile and distribution of precipitation. The performance of each PBL scheme was evaluated with statistical error indices, including mean absolute error (MAE), root mean square error (RMSE) and fractional absolute error (FAE).

3. Result and discussion

3.1 Vertical profile

The performances of each PBL schemes in October and April were evaluated with sounding data (ST6 marked in Figure 1b) during the morning (0800 MYT) and evening (2000 MYT) transitional hours in Figure 2. The temperature and humidity profiles were similar for all schemes with less than ± 0.4 K and ± 0.6 g/kg bias respectively with the largest deviation observed around the typical mixing layer height of UBL (1-1.5 km) [12]. The positive bias between the schemes at 0800 MYT was significantly greater in October (1.2 ± 0.8 ms⁻¹) than in April (0.6 ± 0.3 ms⁻¹). The boundary layer was relatively calm and invariant in April compared to October. It was therefore arrived that the performance of the schemes deviated greatly under influence of strong synoptic flow. The lower modeled wind speed suggested that the vertical mixing was suppressed within the boundary layer in Figure 2c,f. The insufficient mixing hence explained the negative bias of the modeled temperature and mixing ratio around the mixing height. The tabulated error statistics in Table 2 showed that October was better estimated with the nonlocal schemes while the weak wind condition during April was better estimated with MYJ. This clearly revealed the respective strength of PBL schemes. ACM2 with the physical representation of local and nonlocal eddy diffusion movement returned the best compliance among the nonlocal schemes under convective synoptic condition [11]. The MYJ is known to estimate vertical quantities through prognostic eddy diffusivity of adjacent grids and hence simulated cases under calm condition better [9]. Although MYJ has induced insufficient mixing under large-scale boundary condition in October [3], it showed an edge in solving cases of stable and localized boundary conditions well in the calm April.

3.2 Planetary boundary height

The vertical tendency of variables is principally dependent on the boundary layer height (PBLH), especially for the nonlocal schemes [10,11]. It was noticeable that the modeled PBLH was less than 1000 m and well below the level derived for the SEA region ($\text{PBLH} = 1250 \pm 670 \text{ m}$ [13]). The lapse rate method ($\Delta\theta/\Delta z \leq 0.002 \text{ Km}^{-1}$) was adopted to standardize the PBLH of each schemes [3,14]. In Figure 2g,h, the unified derivation approach increased the modeled PBLH and associated well among the schemes ($< \pm 100 \text{ m}$) for the daytime PBLH (0900 – 1900 MYT). The PBLH of each scheme was evaluated against the measured PBLH extracted from sounding (ST6) with hit rate and MAE (hit rate threshold $< 100 \text{ m}$), lower value was desirable. All the schemes predicted the PBLH reasonably well during the transition period (0800 and 2000 MYT). In Table 2, the adjusted PBLH demonstrated that MYJ was able to capture the entrainment of the free atmosphere into the boundary layer. Among the nonlocal schemes, the ACM2 produced a better mixed UBL with the highest modeled PBLH peak during the day. It was also noticeable that the hotter month (April) produces a generally higher mixing layer height during the day due to enhance convective activities nearing summer.

3.3 Near-surface profile

The ability to reproduce the near-surface condition depends on the accompanying SUR scheme of each PBL scheme [4,5], hence, diurnal data from the 8 ground weather stations (marked in Figure 1b) were analyzed for respective SUR schemes. The near-surface condition predicted by each scheme has smaller bias between each other compared to the vertical profile. The bias level recorded $0.4 \pm 0.2 \text{ }^{\circ}\text{C}$ T2, $2.1 \pm 1.2\%$ RH2 and $0.5 \pm 0.2 \text{ ms}^{-1}$ wspd10. YSU and ACM2 cases delayed the response of peak temperature and relative humidity up to two hours. MYJ case, nevertheless produced closer diurnal profile especially in October. All schemes overestimated the wind strength in the day [7] as shown in Figure 2k, with MYJ case produced more reasonable agreement. In Table 2, MYJ recorded overall the lowest statistical error for near-surface condition. This indicated that Eta similarity theory SUR of MYJ scheme predicted T2 and RH2 better. The good performance was attributed to the determination of heat transfer coefficient according to the roughness length of the surfaces [15]. The large deviation of T2 during the peak hour was attributed to the application of MYJ that generate insufficient mixing in daytime (Section 3.2). Due to the incompetency of the nonlocal scheme, the MYJ remained as the optimum choice to model the near-surface condition. A large bias for T2 and RH2 around 1700 – 2000 MYT during both intermonsoon seasons was potentially related to the concurrent precipitation events.

3.4 Rainfall amount

The precipitation amount simulated by full grid microphysics (RAINNC) and subgrid cumulus (RAINCL) drivers were summed for total precipitation to evaluate against the rain gauge data at Sepang (ST6). All schemes, notably MYJ has successfully captured the initiation time of the rain at 1500 - 1600 MYT in both months and 0500 MYT in October in Figure 2m,n. A good agreement of rainfall amount was also produced by MYJ model. This could be explained as the heterogeneous land sea mask in MC shelters the GKL region from large scale turbulence movement and created a relatively calm weather condition compared to the rest of the Malay Peninsula [16]. The nonlocal scheme was considered less suitable for application unless critical Richardson number that determines the regime SBL and CBL is re-iterated for further adaptation. Conclusively, MYJ remained a more suitable candidate of scheme for the current study under relative stable weather condition, resonating with previous findings [4].

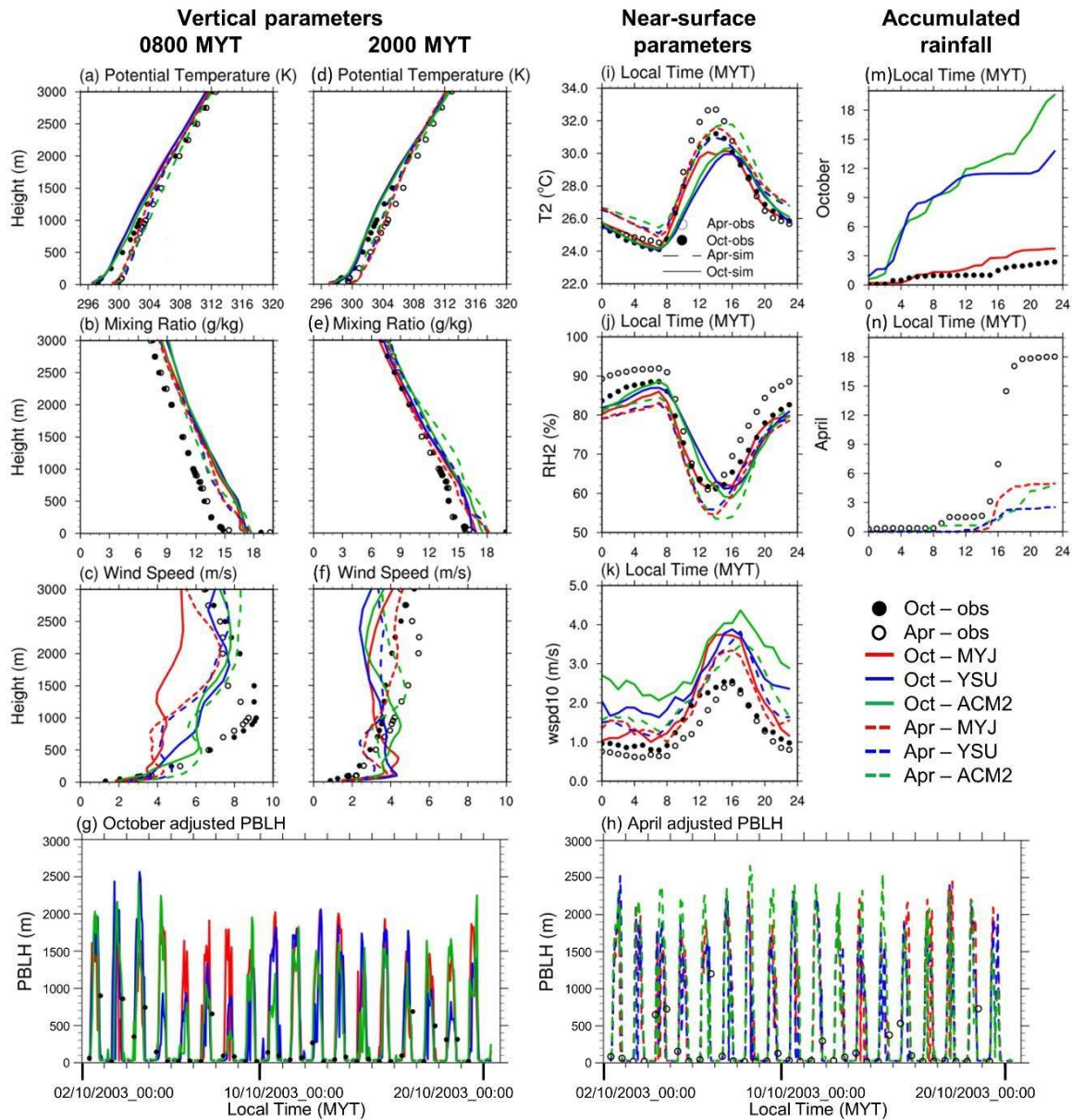


Figure 2. Evaluation of (a)(d) potential temperature, (b)(e) mixing ratio, (c)(f) wind speed, (g)(h) PBLH against sounding data at 0800 MYT (Column 1) and 2000 MYT (Column 2). Evaluation of hourly averaged of (i) T2, (j) RH2, (k) wspd10, (m)(n) accumulated rainfall with ground weather stations. Marker for observation while lines for simulation result.

Table 2. Error indices deviation of PBL schemes for vertical variables, PBLH and near-surface variables. (†) FAE are dimensionless, (*) multiplication of 100 for vertical potential temperature, T2 and RH2.

Schemes	MYJ		YSU		ACM2		MYJ		YSU		ACM2		MYJ		YSU		ACM2	
Vertical parameters																		
Time	Vertical potential temperature (K)						Vertical mixing ratio (kg/kg)						Vertical wind speed (ms ⁻¹)					
	8am	8pm	8am	8pm	8am	8pm	8am	8pm	8am	8pm	8am	8pm	8am	8pm	8am	8pm	8am	8pm
Error indices	October																	
MAE	0.64	0.66	0.63	0.45	0.42	0.29	1.58	1.41	2.05	1.40	2.02	1.54	2.39	1.66	1.16	1.47	1.00	1.45
RMSE	0.74	0.73	0.73	0.54	0.46	0.34	1.83	1.61	2.18	1.56	2.13	1.73	2.81	2.22	1.49	1.99	1.45	1.65
FAE*†	0.21	0.21	0.21	0.15	0.14	0.09	0.13	0.12	0.18	0.12	0.18	0.14	0.41	0.29	0.20	0.24	0.15	0.23
April																		
MAE	0.35	0.69	0.43	0.75	0.31	0.65	0.73	0.85	0.81	1.07	1.22	1.39	0.89	0.73	1.16	0.90	1.14	0.79
RMSE	0.43	0.77	0.48	0.83	0.37	0.71	1.03	1.12	1.07	1.37	1.34	1.77	1.06	0.83	1.42	1.01	1.23	0.91
FAE†	0.12	0.22	0.14	0.24	0.10	0.21	0.06	0.07	0.07	0.08	0.11	0.10	0.26	0.20	0.35	0.23	0.33	0.21
Near-surface parameters																		
PBLH																		
Schemes	MYJ		YSU		ACM2		MYJ		YSU		ACM2		MYJ		YSU		ACM2	
Month	2-meter temperature, T2 (°C)						2-meter relative humidity, RH2 (%)			10-meter wind speed, wspd10 (ms ⁻¹)			Adjusted PBLH (m)					
	October																	
Average	27.09						77.08			1.47			Hit					
MAE	1.43	1.72	1.67	7.35	8.18	8.45	1.05	1.39	1.77	Hit Rate%			66.7	73.0	72.2			
RMSE	1.82	2.19	2.13	9.27	10.50	10.65	1.45	1.86	2.25	MAE			15.50	16.97	21.95			
FAE*†	5.30	6.37	6.16	9.93	10.99	11.57	6.56	7.41	8.23									
April																		
Average	27.49						81.12			1.22			Hit					
MAE	1.76	1.77	1.83	10.73	10.22	10.36	1.02	1.16	1.26	Hit Rate%			72.2	72.2	77.8			
RMSE	2.24	2.20	2.33	13.19	12.46	13.20	1.38	1.55	1.64	MAE			11.36	12.34	18.06			
FAE*†	6.36	6.42	6.61	14.35	13.57	14.19	7.12	7.56	7.99									

4. Conclusion

In general, all schemes in prediction of vertical profile, near-surface profile and precipitation amount were more uncertain in the October which experienced a stronger synoptic forcing. The PBL schemes also gave larger variation for the vertical profile and rainfall amount during the convective period. This was attributed to the relatively significant influence of the synoptic condition on these PBL processes. It was also notable that the nonlocal scheme, namely ACM2 gave a closer agreement to the vertical profile in October. However, the remaining model evaluations of vertical and precipitation profile clearly inclined toward the MYJ local scheme. Similarly, the local scheme simulated shallower PBLH but closer agreement with measured data after normalization. The allocation of thermal roughness length to respective land use also improved the near-surface condition prediction for Eta MM5 SUR scheme. Therefore, the strong coupling of the MYJ PBL scheme and Eta MM5 SUR scheme prompted the future analysis on the effect of urbanization to be conducted with the combination.

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