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# Sensitivity of Planetary Boundary Layer Scheme in WRF-Chem Model for Predicting $PM_{10}$ Concentration (Case study: Jakarta)

# Sensitivity of Planetary Boundary Layer Scheme in WRF-Chem Model for Predicting $PM_{10}$ Concentration (Case study: Jakarta)

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**Abstract**. Weather Forecasting-Chemistry (WRF-Chem) is an air pollution model that combines meteorological factors and atmospheric chemistry simultaneously (online coupled). Many schemes selected on WRF-Chem according to boundary layer conditions of the study area. The objectives of this study were to evaluate WRF-Chem model and analyze the sensitivity of Yonsei University (YSU) scheme and Mellor Yamada Janjic (MYJ) scheme as physical boundary layer parameters, especially for Jakarta region. Particulate matter 10 micrometers or less in diameter (PM10) selected as the air pollutant parameter. The model outputs compared to observational data in five locations in Jakarta. The regression analysis between air temperature data shows that the values of R2 are 0.5 - 0.6 in February and 0.5 - 0.9 in August. Another result, the wind velocity from WRF-Chem overestimates but the hourly averages have a similar diurnal pattern with the observation. The PM10 concentration model output is underestimated which is caused by local emissions that are not accommodated in the model. The sensitivity analysis shows a higher sensitivity index for MYJ than YSU scheme, especially in August, so the model outcome of the MYJ scheme has a good response to the observations in Jakarta. It is seen that the extreme concentration of PM10 produced through the WRF-Chem with both schemes in February and August have the same time in morning. The model output of WRF-Chem through both schemes also demonstrate the minimum concentration of PM10 that follows during afternoon. The Planetary Boundary Layer (PBL) height analysis shows that in morning until noon, the PBL height with MYJ scheme is lower than YSU. It is different for other hours, that from the afternoon through the night until next morning, the height of PBL with MYJ scheme is thicker than YSU. At the point when the PBL is high, the pollutants assorted in a more volume so the estimation of the pollutant concentration estimated on the surface will be reduced.

Keywords : planetary boundary layer, WRF, PM10, wind

## 1. Introduction

Air pollution and its impact have become a concern in several countries including Indonesia. In general, air pollution occurs in large cities due to high transportation and industrial activities. However, pollutants transported to other areas in the vicinity, thus affecting the air quality of the area.

Air quality data becomes important for use in indicating public health around the measurement site. However, continuous and even measurable air quality measurements throughout the region require considerable cost. Limitations of air quality data become one of the problems that often encountered in conducting research. Modelling on air pollution can be an alternative to predict air quality and pollutant distribution in different regions. Air pollution models have built from simple to complex. Due to the large influence of meteorological factors on the dispersion of pollutants, a combined model involving meteorological factors with atmospheric chemistry expected to be closer to the actual conditions on the surface. The current model of air pollution sufficiently developed to model numerical weather predictions combined with atmospheric chemistry models, one of which is Weather Research Forecasting-Chemistry (WRF-Chem) model.

WRF-Chem is a model that combines atmospheric meteorological and chemical factors simultaneously (online coupled). Based on the research that has been done, WRF-Chem has been widely used to estimate the concentration of pollutants in sub-tropical regions [1,2,3,4]. While research on WRF-Chem for the tropics is still little done. The WRF-Chem model uses several parameterization schemes that can selected according to the location conditions that modelled or analyzed for the quality of the air. Selection of the parameterization scheme will affect the model output, so the choice of the parameterization scheme is essential to obtain the closest scheme in a model. The use of parameterization schemes in sub-tropical regions will be different from tropical regions. Therefore, it is necessary to understand the most appropriate scheme for use in a particular area, and this can be done through the comparison of the outputs of different schemes, so the sensitivity can be known.

Misenis and Zhang [5] in Texas and Cuchiara *et al.* [6] in Texas and Zhong *et al.* [3] in East Asia have done research on the sensitivity of the WRF-Chem model among others. Because there is not many uses the WRF-Chem model in Indonesia, therefore this research is the first step to know the parameter scheme that is good enough for the Indonesia region by taking case study of Jakarta and its surroundings. Jakarta is chosen to be a study area because it has a continuous ambient air quality monitoring station (SPKU) that makes it easy to validate or compare the outcome of the model.

In this research, the parameterization scheme analyzed by the sensitivity is the Planetary Boundary Layer (PBL) physical parameter with Yonsei University (YSU) and Mellor Yamada Janjic (MYJ) scheme. Types of pollutants to study are the Particulate matter 10 micrometers or less in diameter ($PM_{10}$). This study aims to evaluate the use of WRF-Chem model as well as to test the sensitivity of the physical parameterization scheme of PBL for $PM_{10}$ in Jakarta area.

## 2. Data and Methods

The following is the data used in this study. The model initial and boundary condition are driven from the Global Data Forecasting System (GFS) with a spatial resolution of 0.5° x 0.5°. The global EDGAR-HTAP emissions data for 2010 are used for initial pollutants of WRF-Chem. The ambient air quality data is obtained from SPKU observation (Fig. 1) in Jakarta area 2010 (DKI 1), 2011 (DKI 2) and 2013 (DKI 3, DKI 4 and DKI 5).

Simulations were conducted on February 9, 2010, and August 7, 2010, taken at 00:00 UTC. The data collection on the land represents the highest rainfall in the rainy season and the lowest rainfall in the dry season. The grid used during the simulation of 4 km x 4 km with longitude and latitude points is located at coordinates 105.2 ° east to 107.8 ° E -5.4 ° LS to -7.6 ° LS. The study uses only one domain with focus Jakarta area (Fig. 1). The simulation was for 7 days and ends at 12.00 UTC.

Several studies have used the YSU and MYJ schemes with the same pollutant or region. Kumar *et al.* [7], Ge *et al*. [8], Nuryanto and Nuraini [9], Heriyanto and Nuraini [10] have used the YSU scheme. While the MYJ scheme has been used by Turyanti [11], Beck *et al.* [12], Amnuaylojaroen *et al.* [13]. The difference between the YSU and MYJ schemes is not only visible in terms of their turbulence flux, but also in the surface clay parameter (sf_sfclay_physics) for the YSU scheme is one (1), while the MYJ scheme is two (2). The choice of the schemes used in the research shows in Table 1.

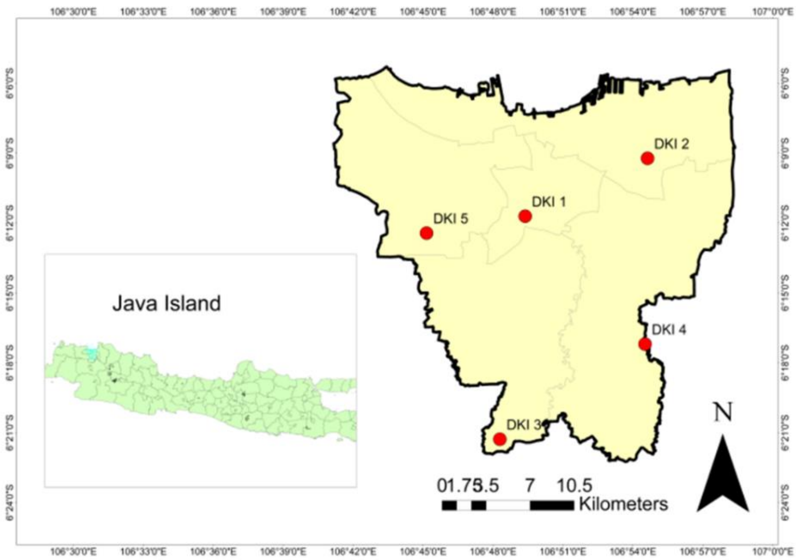


**Figure 1.** The study area.

**Table 1.** The schemes used in the study.

| Parameters | Scheme | Remarks |
|---|---|---|
| Microphysics | Lin et al. | The single moment scheme includes several modifications such as saturation adjustment and is associated with minor crystal ice sedimentation [1] |
| Cumulus | Grell 3D | An increase of the Grell D scheme that can be used at high resolution [15] |
| PBL | YSU | Nonlocal schemes with explicit entertainment layers and parabolic K-profiles in unstable mix layers [16] |
| | MYJ | Local scheme with vertical mixing and 1.5 TKE prognostic [16] |
| Long wave radiation | RRTMG | A scheme that can handle the direct and indirect effects of aerosols in WRF simulations [17] |
| Short wave radiation | RRTMG | A scheme that can handle the direct and indirect effects of aerosols in WRF simulations [17] |
| Chem option | RADM2 Chemistry and GOCART aerosols | There are 158 chemical reactions among 26 species [17] |

The sensitivity test of the PBL schemes of the model results refers to Pianosi et al. [14]. Sensitivity analysis performed using the Standardized Regression Coefficients (SRC) method [14]. SRC is one of the easiest methods used in analyzing sensitivity by using linear regression [14]. The results obtained from SRC are values between -1 and 1. Sensitivity values that are close to 1 indicate that the model has a good response with observation, whereas the sensitivity value approaching -1 indicates that the model does not respond well to observation. Sensitivity is calculated using equation (1).

$$Si = b_i \frac{SD(x_i)}{SD(y)} \qquad (1)$$

Si = sensitivity index
bi = slope
SD(xi) = standard deviation of model i
SD(y) = standard deviation of observation

Sensitivity analysis of parameter scheme were tested based on surface layer thickness (level 1). The thickness of this layer was calculated from the value of ph and phb output of the model, which is still in the form of geopotential perturbation data. The *pbl* value obtained through equation (2).

$$pbl = \frac{ph+phb}{gravity} \tag{2}$$

pbl = layer thickness on each of the outer layers of the model in this case the surface layer (m)
ph = *Perturbation geopotential* ($m^2/s^2$)
phb = *Base-state geopotential* ($m^2/s^2$)
gravity = 9.8 ($m/s^2$)

The stages of research can be seen in Figure 2.

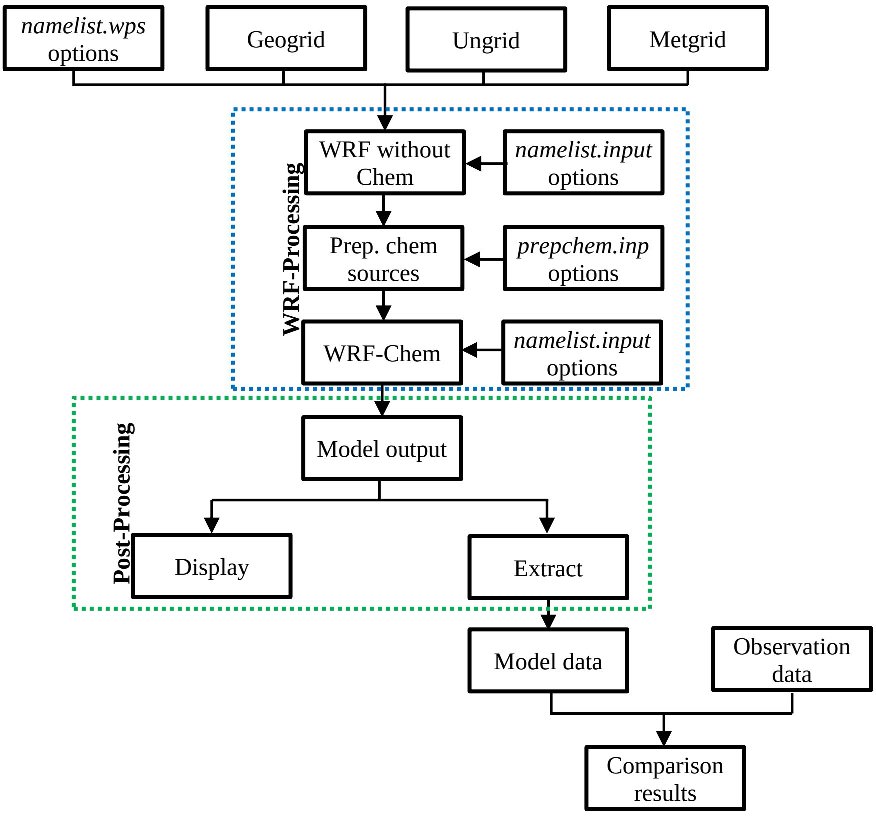


**Figure 2.** Process flow diagram.

## 3. Results and discussions

### *3.1. Spatial Distribution Pattern Concentration $PM_{10}$ Model*

Model simulations conducted in February and August, where February represents the rainy season and August represents the dry season. In February, the maximum concentration of $PM_{10}$ using the YSU scheme at 07:00 LT occurred in Pandeglang District at 9,599 µg / $m^3$. In contrast to night time at 7 pm, maximum concentration of $PM_{10}$ is in Lebak Regency with concentration value of 2,991 µg / $m^3$. $PM_{10}$ concentration using YSU scheme in August at 07:00 LT, result maximum concentration around Tangerang 17,023 µg / $m^3$. Serang Regency is also a region with high $PM_{10}$ concentration. At 19:00 LT, maximum concentration occurred in Bogor and Tangerang areas with a maximum concentration of 3,819 µg / $m^3$.

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Different patterns of $PM_{10}$ concentration distribution in the morning and evening also shown in Fig. 3. It might be caused by the influence of atmospheric stability. In the morning until noon, atmospheric conditions tend to be unstable resulting in the removal of air masses and pollutants located on the surface. While at night, atmospheric conditions tend to be stable and there is a decrease in air mass along with pollutants to the surface so that pollutants ($PM_{10}$) at night are more diffuse on the surface than in the morning and afternoon.

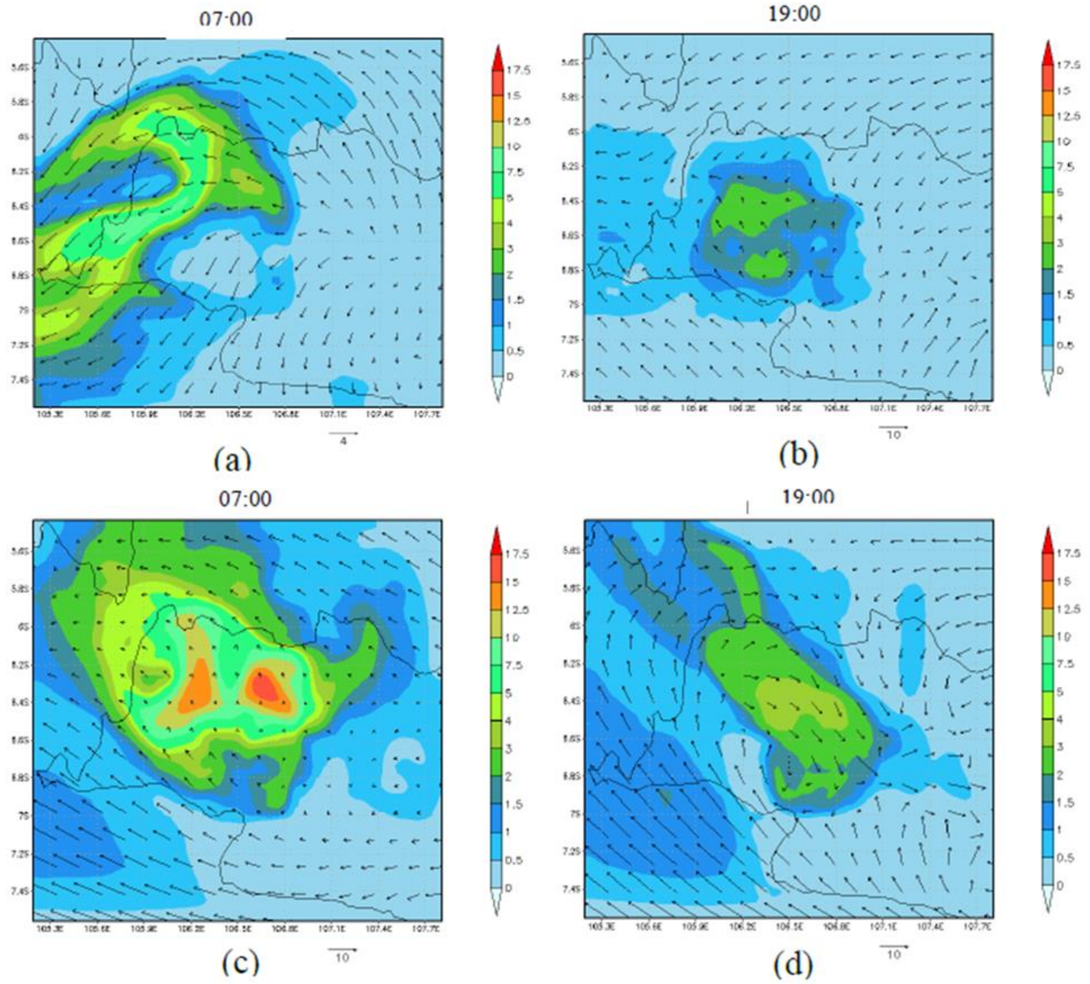


**Figure 3.** Concentration of PM10 on an average hourly basis using the YSU scheme in February (a) at 07:00 LT (b) at 19:00 LT (b) and August (c) at 07:00 LT (d) at 19:00 LT.

### *3.2. Comparison of $PM_{10}$ Spread Concentration between YSU and MYJ Schemes*

The concentration of $PM_{10}$ in February in the Jakarta area is relatively low compared to August. The $PM_{10}$ concentration values generated from the two different moons also look different; it can be due in February to be a wet season so pollutants will be carried away by rain. The concentration of $PM_{10}$ using the MYJ scheme shows more concentration higher than the YSU scheme, for the same location (Fig. 4). The YSU scheme with a non-local approach causes mixing to involve a wider scale of both vertical and horizontal than MYJ.

The maximum concentration of $PM_{10}$ in February is not in the study area but spread to the Tangerang region while the maximum value is $PM_{10}$. In August, using the maximum concentration the YSU scheme occurred around Tangerang and Depok areas, whereas for the MYJ scheme the maximum concentration of $PM_{10}$ occurred in Jakarta area.

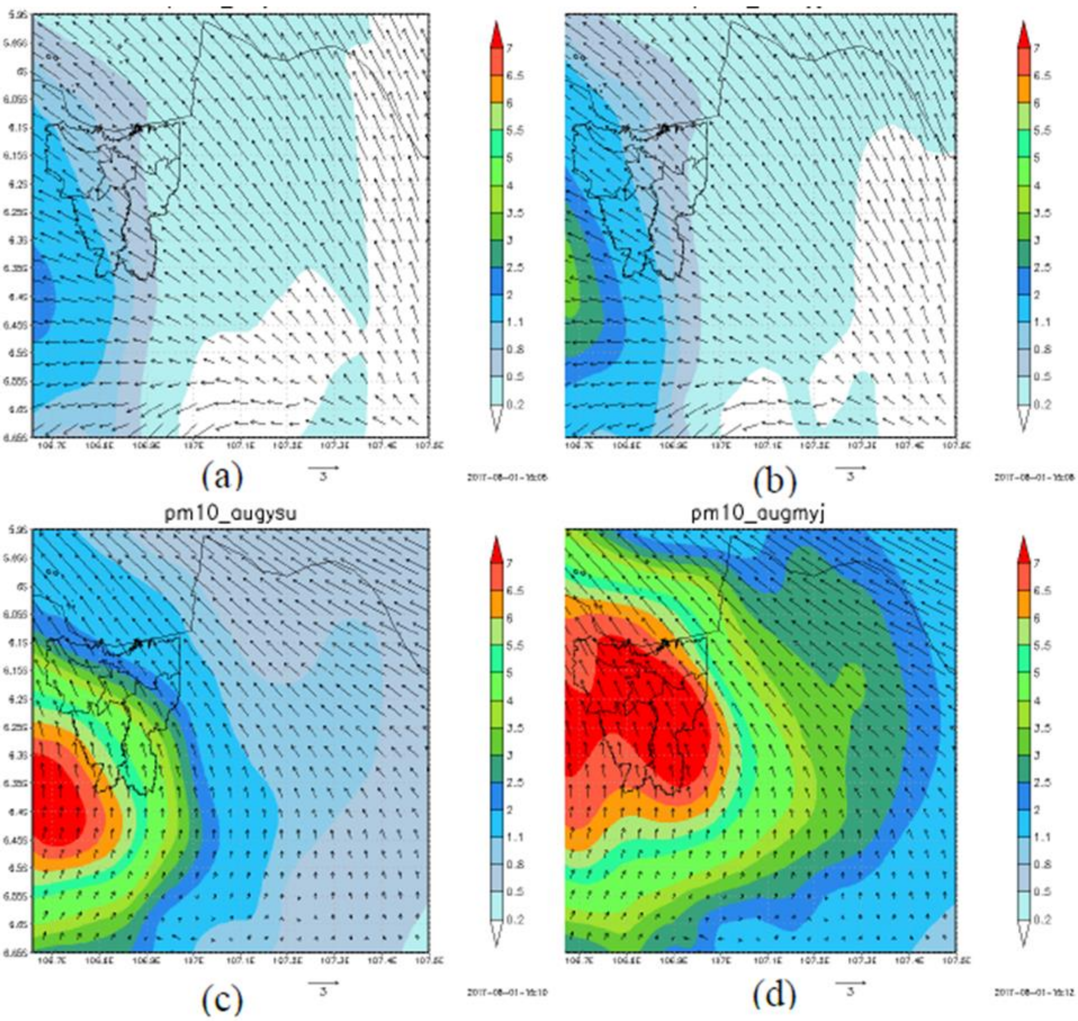


**Figure 4.** The February PM10 concentration distribution uses (a) the YSU scheme and (b) the MYJ scheme and in August it uses (c) the YSU scheme and (d) the MYJ scheme in Jakarta and surrounding areas

Figure 5 shows the average $PM_{10}$ concentration fluctuations per hour in DKI1. The model simulation results show that the average $PM_{10}$ concentration value of the MYJ scheme is greater than the YSU scheme, except at night there is a tendency of MYJ concentration value near or below YSU. This is expected from the influence of wind speed. At night, the wind speed of the MYJ scheme is higher than the YSU scheme, so the $PM_{10}$ concentration will be lower. The difference in means values of $PM_{10}$ concentration using the YSU and MYJ schemes obtained through the difference of the two schemes (YSU-MYJ). In August the difference from YSU with MYJ is negative, the $PM_{10}$ concentration using the MYJ scheme is always greater than the YSU scheme. In contrast to February, the difference between the two schemes is a positive value indicating that the average $PM_{10}$ concentration using the YSU scheme is larger than the MYJ scheme.

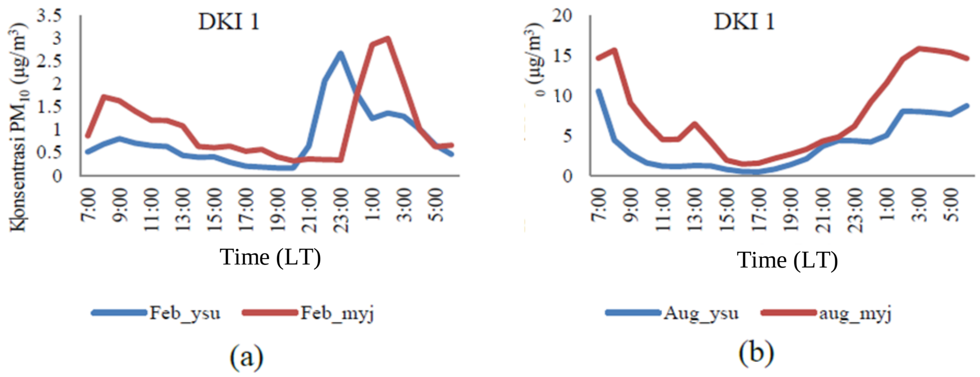


**Figure 5.** Hourly mean of $PM_{10}$ concentration during (a) February and (b) August.

### *3.3. Comparison for Meteorological Factor of Model and Observations*

Based on the results of data processing, both using the YSU and MYJ schemes in different months (February and August), showed that the largest wind speed occurred in the afternoon at around 15:00 LT (YSU) and at 16:00 - 17:00 LT (MYJ) which can be seen in Fig. 6. Diurnal fluctuations in observation data are closer to the output of the YSU scheme. Observation data in DKI 1 around Bundaran Hotel Indonesia showed that the maximum wind speed based on an hourly average occurs at around 15:00 LT. This could be caused by solar radiation that reaches a maximum during the day and there is a considerable pressure difference so that wind speed increases [18].

Model wind speed is higher than observation data. Similar results also occur in the study of Li *et al.* [19] that the output wind speed of the model with the scheme (YSU, MYJ) is greater than the observation results. This can be caused by the height of the model layer is different from the height of the observation that the model is at an altitude of 10 m while the observation is about 2 m, this is in accordance with the research of Turyanti [11] which uses the MYJ scheme. Surface wind speed in the February period has a lower range than August, according to observation data. The opposite is true for the wind speed at the upper layer (10 m) which has a larger range in February in the both scheme options. The wind speed of the YSU and MYJ schemes began to look different in size towards the afternoon until the middle of the night, that is, the value of the wind speed of the MYJ scheme was greater than YSU. This shows the influence of different approaches to turbulence kinetic energy used in both PBL schemes.

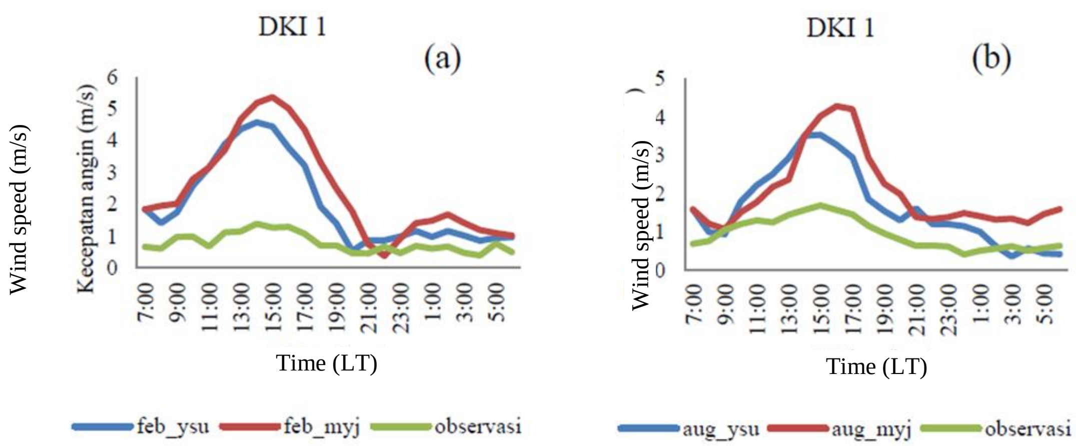


**Figure 6.** Hourly mean of wind speed during (a) February and (b) August.

Based on the WRF-Chem model simulation results for air temperature values at five points (5 SPKU) tend to approach the observed value. The results of the regression analysis show that the coefficient of determination ($R^2$) of the outputs of the two schemes has a value of 0.55-0.92 (Table 2). Model simulations in February resulted in a coefficient of determination between the models with observations ranging from 0.5 to 0.6. The output of the model in August for temperature has a coefficient of determination that varies from the two schemes, namely 0.5 to 0.9. Variations of the determination coefficient caused by the use of observation data used. Regarding the limitations of observation data, temperature data in 2010 only existed in Jakarta, while in 2011 for DKI 2, DKI 3, DKI 4 and 2013 for DKI 5.

**Table 2.** The value of coefficient of determination between the models with observations

| **Areas** | **Coefficient of determination** | | | |
|---|---|---|---|---|
| | **February** | | **August** | |
| | **YSU** | **MYJ** | **YSU** | **MYJ** |
| DKI1 | 0.5468 | 0.5818 | 0.7166 | 0.7406 |
| DKI2 | 0.5934 | 0.6293 | 0.8962 | 0.9155 |
| DKI3 | 0.5821 | 0.5695 | 0.8716 | 0.8894 |
| DKI4 | 0.5895 | 0.6010 | 0.9111 | 0.9083 |
| DKI5 | 0.6996 | 0.8996 | 0.6625 | 0.5687 |

### *3.4. $PM_{10}$ Concentration of Model and Observation*

The $PM_{10}$ concentration of the WRF-Chem model shows underestimated values using both the YSU scheme and the MYJ scheme for both months of modeling simulation (Fig. 7). The value issued by the model is very different from observations that is caused by local emissions that are not accommodated in the model. There are differences in $PM_{10}$ peak points from February and August. In February, the maximum $PM_{10}$ value using the YSU scheme occurs at night, which is around 23:00 LT, while the MYJ scheme shows the maximum $PM_{10}$ value occurs at around 00:00 LT. Observation data in February shows the maximum value of $PM_{10}$ occurs at night which is around 00:00 LT.

The maximum $PM_{10}$ value on the model using the YSU scheme in August occurs at 07:00 LT while the observation results show the maximum $PM_{10}$ value occurs in the morning around 10:00 LT. This is happening because of the observation data where an effect of local emissions from motor vehicles that is accumulated in. Likewise, with the MYJ scheme, the maximum concentration of $PM_{10}$ from the model output occurs in the morning around 8:00 LT. So that it has been seen that, the maximum concentration of $PM_{10}$ generated through the models of the two schemes has the same time. The model output also shows the minimum concentration of $PM_{10}$ that occurs during the daytime, using both the YSU scheme and the MYJ scheme. This is caused by the influence of vertical diffusion that change every hour during the day [19]. Vertical diffusion is affected by the presence of solar radiation that bounces to the surface, so that solar radiation is one of the factors of vertical diffusion.

The results of the correlation analysis of the output model and observation of pollutant concentration showed a small value. Therefore, a correlation analysis performed on the average hourly concentration values is shown in Table 3. Significant tests on the correlation value between concentrations the average model output and observation pollutants shown in Table 3 with a t table value of 1.711. The results of the YSU scheme show that DKI 1, DKI 3, DKI 4 and DKI 5 have insignificant correlation coefficients, while for the MYJ scheme; only DKI 4 has insignificant correlation. Overall, the correlation coefficient value in DKI 4 is not significant, so the possibility of the model has not been able to predict $PM_{10}$ concentration in the region.

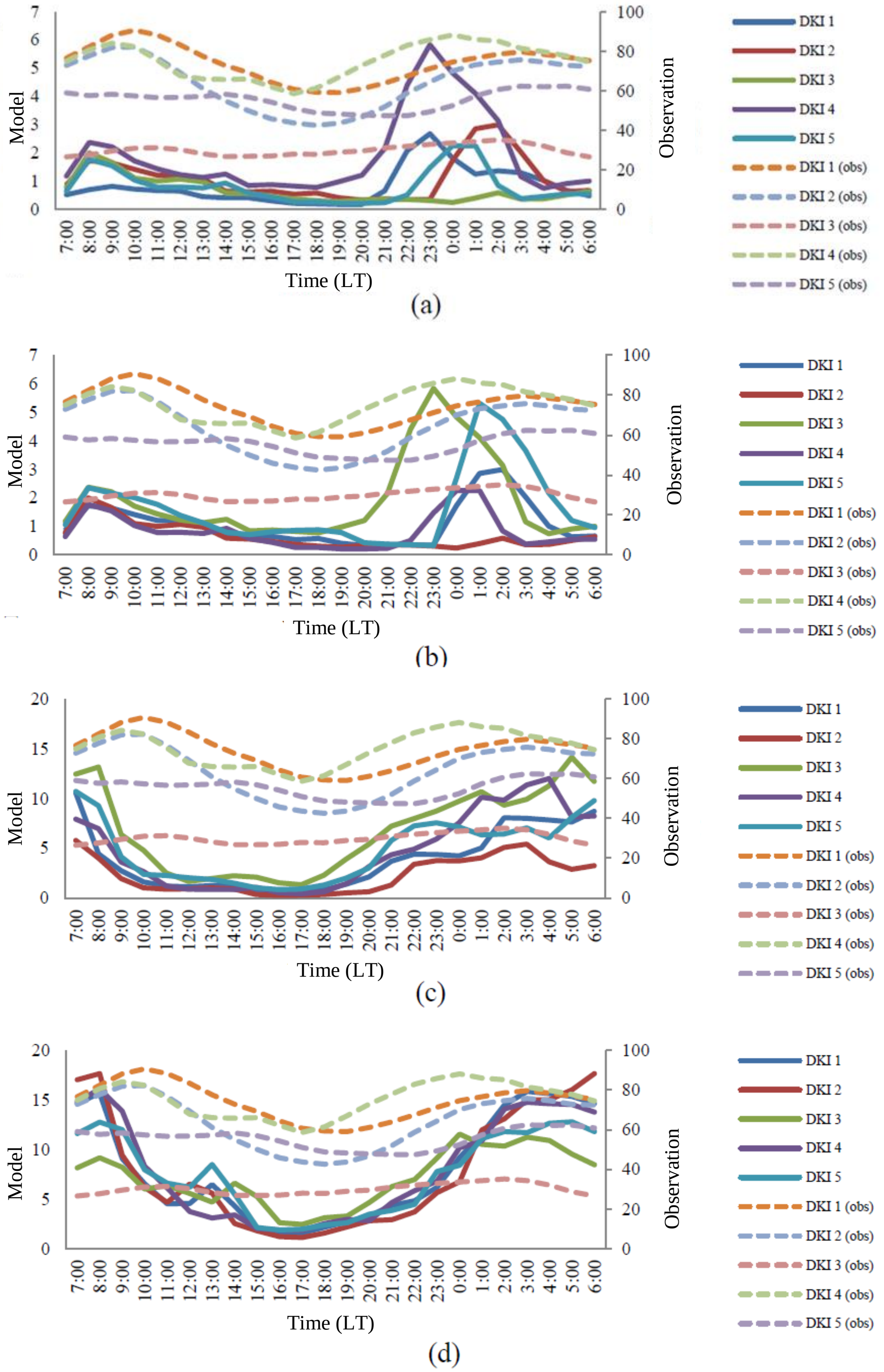


**Figure 7.** Diurnal patterns of $PM_{10}$ (µg / m$^3$) from observation and WRF-Chem model output in February using (a) YSU and (b) MYJ Schemes and in August using (c) YSU and (d) MYJ Schemes.

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**Table 3.** The value of coefficient of correlations between the models with observations

| Areas | Coefficient of determination | | | |
|---|---|---|---|---|
| | February | August | | |
| | YSU | MYJ | YSU | MYJ |
| DKI 1 | 0.21 | 0.58 | 0.26 | 0.53* |
| DKI 2 | 0.63* | 0.54* | 0.63* | 0.76* |
| DKI 3 | 0.42* | 0.63* | 0.30 | 0.60* |
| DKI 4 | -0.32 | 0.02 | -0.27 | 0.14 |
| DKI 5 | 0.15 | 0.43* | 0.47* | 0.86* |

* Significance values

### *3.5. The Sensitivity of the Parameterization Scheme to Observation*

The model output of each scheme or parameters are different. The difference in the output of the model shows the response of the parameter changes (sensitivity). Sensitivity analysis can determine the output variation of the model to changes in one or more parameters [20]. Figure 8 shows the sensitivity value in DKI 1 - DKI 5. Based on the results of the sensitivity analysis, in August the MYJ scheme consistently had a higher sensitivity value than the YSU scheme. In contrast to August, the YSU scheme has a higher sensitivity than the MYJ scheme for DKI 2 and DKI 3. In February, it is suspected by the influence of rain and the regional characteristics of DKI 2 and DKI 3.

### *3.6. Comparison of PBL Height at Surface Using the YSU and MYJ Schemes*

PBL height is one of the most important variables for air quality modelling. PBL height will have an impact on the intensity of vertical pollutants mixing so that it will affect the characteristics of pollutant dispersal [21]. The WRF-Chem model simulation results in a higher level of PBL with the MYJ scheme larger than the YSU scheme although the difference between the two schemes is not too large in both February and August. This result is the same as the research conducted by Banks *et al.* [16] that the PBL height of the YSU scheme is smaller than the MYJ scheme. However, in certain hours (morning to noon) the height of PBL YSU is higher than MYJ (Fig. 9). The PBL differences are seemed very small. According to Cuchiara *et al.* [6], the height of PBL using the YSU scheme produces greater value during the day and a smaller value at night. Based on PBL height data from the five SPKU points, it shows that in February the height of PBL with MYJ scheme was higher than YSU around 12:00 to 07:00 LT, while for August it was around at 14:00 to 21:00 LT at night.

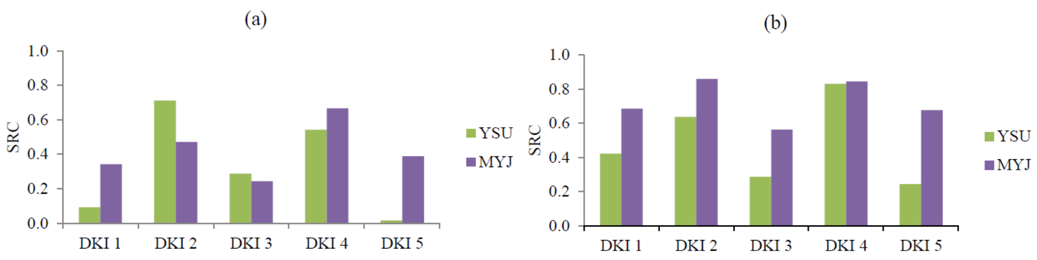


**Figure 8.** Sensitivity results from model output and observation of PM10 in (a) February and (b) August.

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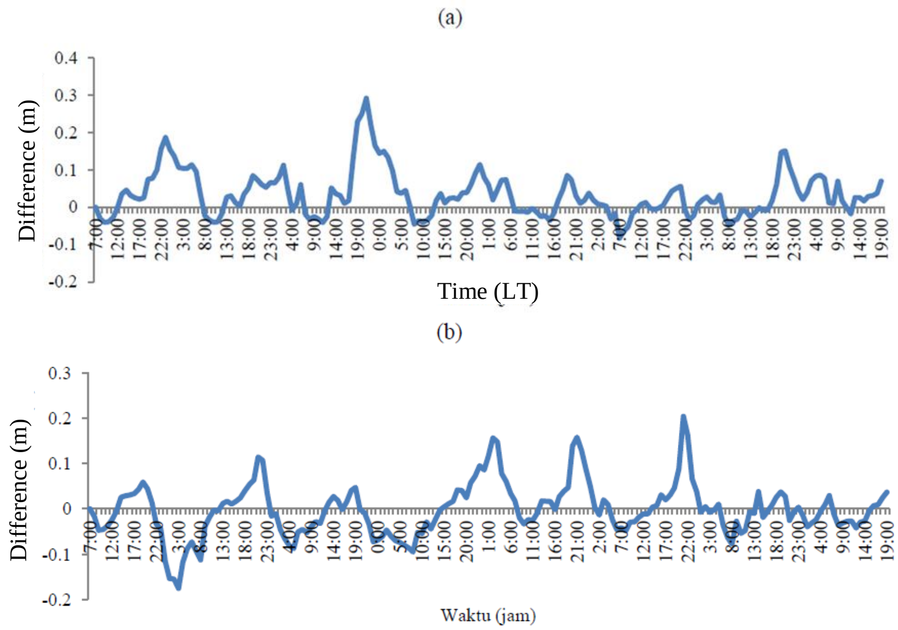


**Figure 9.** Difference of PBL height from MY schemes in (a) February and (b) August.

For the explanations delineated above, the concentration of simulated PM10 during daytime was lower than at night. In summary, in the model, the effects of vertical dispersion of the hourly change tendency of PM10 during daytime are much more essential compared with the effects of daily averaged PM10. The difference of PM10 concentration in YSU and MYJ schemes is still little in separate stations; meanwhile, the modelling results in different location contain certain differences.

Figure 10 shows that there is a relationship that is inversely proportional between the height of PBL and $PM_{10}$ concentration in DKI 1. The greater the height of PBL, the smaller the $PM_{10}$ concentration produced. The statement applies to the results of the model using the YSU scheme and MYJ scheme in February and August in the five SPKU points. The process of dispersing pollutants can cause inversely proportional relationships. When the height of the PBL is high, the pollutants mixed in a larger volume so the value of the pollutant concentration measured on the surface will be smaller.

It should be noted that the different representations of vertical dispersion in these PBL schemes might have different influences on $PM_{10}$ simulation under different conditions of atmospheric stability in different regions. It seems to be that the little difference of diffusivity calculation between haze and clean days by the PBL schemes calculation might lead to this interesting phenomenon, which is probably the main way to improve $PM_{10}$ forecasting in coastal city.

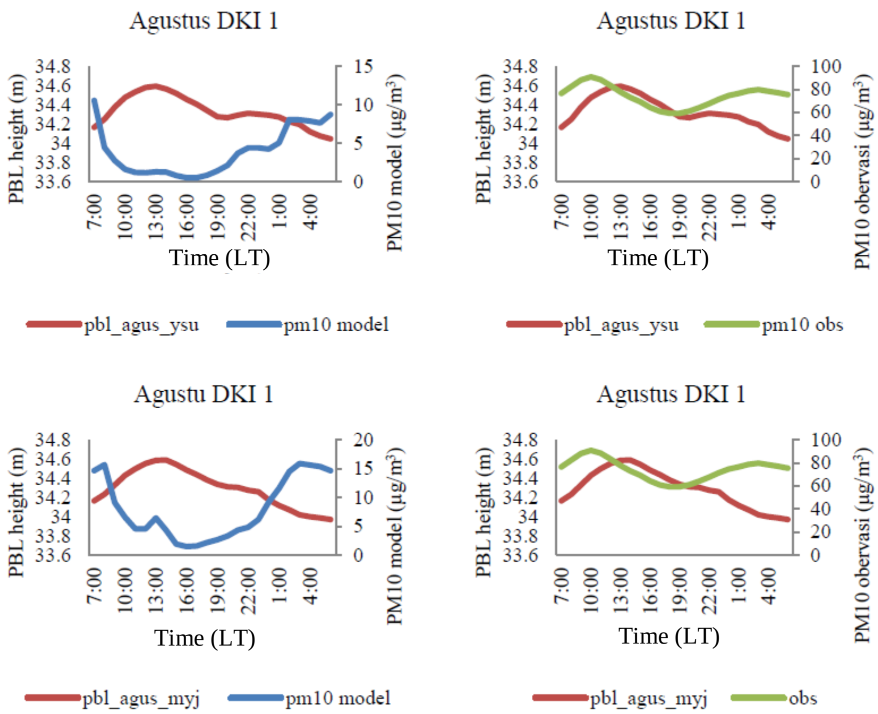


**Figure 10.** Comparison of PBL height and mean of PM10 at DKI1

## 4. Conclusions

The WRF-Chem model can produce a model output that is good for temperature because it has a coefficient of determination of 0.5-0.6 for February and 0.5-0.9 for August. The model output for the wind is still to overestimate and $PM_{10}$ is still underestimate that are affected by resident emissions that are not put up in the model. In this study, the PBL scheme has a small impact compared to difference in observation. The results of the $PM_{10}$ concentration model output with the MYJ scheme produce a greater concentration value compared to the YSU scheme. Sensitivity analysis of the two schemes against observation shows that the MYJ scheme has greater sensitivity than the YSU scheme. The height ratio of PBLs from the two schemes shows that in February the PBL height with the MYJ scheme was higher than YSU around 12:00 to 07:00 LT. It has been understood that the highest concentration of $PM_{10}$ created by the WRF-Chem with both schemes in the February and August has the equivalent time in the morning. The model output of WRF-Chem over both schemes also displays the smallest concentration of $PM_{10}$ that monitors during the afternoon. Whereas for August, it is around 14:00 to 21:00 LT. PBL height analysis also shows a relationship that is inversely proportional between the height of PBL and $PM_{10}$ concentration. Exactly when the PBL is high, the pollutants arranged in a more volume so the estimation of the pollutant concentration assessed on the surface will be decreased. The reasons for the reduced image of diurnal difference in the PBL schemes, resulting in $PM_{10}$ miscalculations in numerical models, need to be studied in detail and then modifications need to be done to improve results for different locations.

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