



Aerosol Radiative Forcing Estimation Using Moderate Resolution Imaging Spectroradiometer (MODIS) in Kuching, Sarawak

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ABSTRACT

High uncertainties in aerosol radiative forcing (ARF) arise from inaccurate estimation for aerosol optical depth (AOD) as an input parameter into Santa Barbara Discrete Ordinate Radiative Transfer (SBDART) model. Influence of AOD in ARF at the top of atmosphere (TOA) and surface over Kuching from 2011 until 2015 was investigated using Moderate Resolution Imaging Spectroradiometer (MODIS). Multi plane regression technique was used to retrieve AOD from MODIS (AOD_{MODIS}) by using different statistics (mean and standard deviation ($MODIS_{\mu\pm\sigma}$) and relative absolute error ($MODIS_{RAE}$) for accuracy assessment in spatial averaging and compared with Aerosol Robotic Network (AERONET). The relationship between AOD_{MODIS} and AOD from AERONET ($AOD_{AERONET}$) showed R^2 value for $MODIS_{\mu\pm\sigma}$ and $MODIS_{RAE}$ is 0.906 and 0.932, respectively. AOD_{MODIS} over Kuching tends to underestimate AOD during low variations and overestimate AOD when aerosol loading is higher. The retrieval of AOD_{MODIS} was used as an input parameter into SBDART for ARF estimation and compared with ARF from AERONET. When using AOD_{MODIS} from $MODIS_{\mu\pm\sigma}$, the ARF at TOA was between -5.95 Wm^{-2} and 0.89 Wm^{-2} and at the surface was from -389.7 Wm^{-2} and -31.4 Wm^{-2} while for $MODIS_{RAE}$, ARF value at the surface was from -392.3 Wm^{-2} and -27.3 Wm^{-2} while at TOA was between -5.89 Wm^{-2} and 0.98 Wm^{-2} . Average ARF value within the atmosphere for both $MODIS_{\mu\pm\sigma}$ and $MODIS_{RAE}$ were 151.6 Wm^{-2} and 130.4 Wm^{-2} , respectively. There is a poor relationship between the SBDART and AERONET for $MODIS_{\mu\pm\sigma}$, where R^2 is 0.33, while strong relationship is observed for $MODIS_{RAE}$ with R^2 value at 0.724.

Keywords: Aerosol optical depth, aerosol radiative forcing, AERONET, MODIS

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INTRODUCTION

Atmospheric aerosols are one of the largest sources of uncertainty in assessing climate change and cause the quantification of aerosol

effects to become very challenging for many researchers. There are two effects of aerosols as stated by Charlson et al. (1992): (1) direct effect leads to scattering; and (2) absorption mechanisms while indirect effects modify the properties of clouds. The effects of aerosol can be quantified through the estimation of aerosol radiative forcing (ARF) in unit Wm^{-2} by using radiative transfer models (RTM) with aerosol optical properties such as aerosol optical depth (AOD) and single scattering albedo (SSA) as an input parameter (Dhar et al., 2017). Unfortunately, high uncertainties in modelling ARF may arise from the input parameters for RTM (McComiskey et al., 2008). Santa Barbara Discrete Ordinate Atmospheric Radiative Transfer (SBDART) model is mostly used by researchers to estimate ARF. An example study was by Dhar et al. (2017) who observed good agreement with the slopes at 1.45 and 1.26, with and without aerosol respectively, and indicated that surface net shortwave fluxes estimated by SBDART model are slightly lower than obtained from CNR4 radiometer due to uncertainties in the input parameters such as AOD, SSA and asymmetry factor (ASY). The AOD was being measured as a unitless parameter and defined as extinction coefficients of aerosol loading that was measured in vertical column of the atmosphere (Alam, Trautmann, Blaschke, & Majid, 2012). Dhar et al. (2017) explained changes in AOD and surface ARF during the observation period in Tripura which showed surface ARF primarily governed by the magnitude of AOD values. Higher AOD value (0.71) causes the ARF value during winter and pre monsoon to have comparable values of 32 Wm^{-2} and 33.45 Wm^{-2} respectively, and ARF value decreased in the monsoon due to lower SSA value (0.94) as well as AOD value.

Satellite data monitors global aerosol budget and their radiative effects on climate such as Moderate Resolution Imaging Spectroradiometer (MODIS) which has spatial data at 10 km twice a day (Remer et al., 2005). Ground based data like Aerosol Robotic Network (AERONET) is useful in estimating continuous microphysical and optical properties for aerosol in real time monitoring and can be used to validate satellite data (Holben et al., 1998). Validation between satellite and ground based data is necessary to develop a long term database for climatological studies and to improve the accuracy and coverage achievable with a single sensor (Prasad & Singh, 2007). More, Pradeep Kumar, Gupta, Devara, and Aher (2013) studied the comparison of aerosol products retrieved from AERONET, MICROTOPS Sunphotometer and MODIS over a tropical urban city and found the result which showed R^2 values ranging from 0.62 to 0.93. For MODIS, it was inclined to predict smaller AOD value as compared to actual AOD value derived from AERONET especially during winter, possibly due to improper assumptions of surface reflectance and the incorrect selection of aerosol type.

The aim of this study is to retrieve AOD from MODIS ($\text{AOD}_{\text{MODIS}}$) by multiple plane regression technique using two different statistics which are mean and standard deviation ($\text{MODIS}_{\mu\pm\sigma}$) (Tripathi et al., 2005) and the usage of relative absolute error ($\text{MODIS}_{\text{RAE}}$) (Collopy & Armstrong, 2000), which is introduced for accuracy assessment in spatial averaging and compared with AERONET ($\text{AOD}_{\text{AERONET}}$). Collopy and Armstrong (2000) stated the relative absolute error (RAE) is a useful measure especially when making comparisons across a small set of time series data. However, RAE has not been used in retrieval of AOD study. Next, the impact of $\text{AOD}_{\text{MODIS}}$ using $\text{MODIS}_{\mu\pm\sigma}$ and $\text{MODIS}_{\text{RAE}}$ daily variations are evaluated for conducting quantitative estimation of ARF as an input parameter into SBDART model over Kuching area. To date, there is no documented study regarding ARF estimation in Malaysia

even though it is very much needed since Malaysia receives considerable amount of smoke aerosols almost every year during the haze phenomenon. Therefore, it is important to understand whether the radiative force due to biomass smoke burning and other aerosol types cause positive or negative climatic implications.

MATERIALS AND METHODS

The experimental site for this study is Kuching, Sarawak with tropical rainforest climate, which is moderately hot and humid. The average annual rainfall is approximately 4200 mm with an average of 247 rainy days per year. Two types of data used were MODIS and AERONET from 2011 until 2015. For AERONET, AOD at 500 nm Level 2 (quality assured) data with the uncertainty under cloud free conditions was $<\pm 0.01$ for $\lambda > 440$ nm and $<\pm 0.02$ for shorter wavelengths (Holben et al., 1998). MODIS data was capable of retrieving AOD under cloud free conditions with an accuracy of $\pm 0.05 \pm 0.20$ over land and $\pm 0.04 \pm 0.10$ over the ocean at mid-visible wavelength (Chu et al., 2002). AOD at 550 nm obtained from Terra MODIS Level 2 (MOD04) was categorised as processed data where the geophysical satellite derived information on both qualitative and quantitative analysis (Engel-cox, Holloman, Coutant, & Hoff, 2004) with spatial resolution of $10 \text{ km} \times 10 \text{ km}$.

Spatial and temporal averaging were conducted, with ± 20 min as the time window with respect to MODIS overpass, then compared with the time availability for AERONET. Minimum distance technique was performed for MODIS data to calculate the closest pixel of latitude and longitude to the AERONET site with evaluation of 11×11 window size. The spatial average for MODIS over the AERONET was collocated from pixels lying in $\pm(1/4^\circ)$ of latitude (1.491°) and longitude (110.349°) of AERONET station. The 53 points extracted from MODIS data were corresponding to latitude, longitude and AOD value using Matlab software.

Five nearest values of latitude and longitude data lying within the $\mu \pm \sigma$ and the lowest RAE were chosen to reduce error during ARF estimation using SBDART model. These two methods were compared. Then, multiple regression plane technique was analysed to predict AOD value based on the latitude and longitude to locate optimum value for AOD based on regression equation. The results were plotted in scatter plot with independent variables, latitude and longitude, on the X and Y axes and dependent variable, AOD, on the Z axis (Tripathi et al., 2005). Next, AOD data was interpolated by using power of law shown in Equation 1, as suggested by Prasad and Singh (2007), to convert AOD from different wavelength range for both data to the same wavelength range for easy comparison and validation.

$$AOD_{550nm} = AOD_{500nm} \left(\frac{550}{500} \right)^{-\alpha} \quad (1)$$

α is the angstrom exponent at wavelength 440/870 nm obtained from AERONET data. The AOD_{MODIS} was validated by using $AOD_{AERONET}$ to understand errors in retrieval of AOD, so that retrieval algorithm can be corrected (More et al., 2013). The statistics obtained in this analysis are correlation coefficient (R^2), root mean square error (RMSE) and mean absolute percentage error (MAPE). Finally, AOD derived from $MODIS_{\mu \pm \sigma}$ and $MODIS_{RAE}$ used as input parameter into SBDART for ARF estimation (Ricchiazzi, Yang, Gautier, & Soble, 1998). The net flux

at the top of atmosphere (TOA) and surface were computed separately, within the wavelength range from 0.2 to 4.0 μm over 24 h with one hour time interval. The outcome from SBDART model is the value of instantaneous irradiance which is downward and upward solar fluxes (Ricchiazzi, Yang, Gautier, & Soble, 1998) and calculated into ARF value. Calculation of ARF can be estimated by using Equation 2 with negative values of ARF which correspond to cooling effect while positive values of ARF correspond to warming effect, either at the surface or at TOA (Alam, Trautmann, Blaschke, & Majid, 2012).

$$\Delta F = (F_a \downarrow - F_a \uparrow) - (F_n \downarrow - F_n \uparrow) \tag{2}$$

Where $F_a \downarrow$ and $F_a \uparrow$ are downward and upward solar fluxes at the surface in the presence of aerosols and $F_n \downarrow$ and $F_n \uparrow$ are the same quantity but without aerosols and ΔF is the ARF value. The difference between the TOA and surface gives the atmospheric forcing (ΔF_{atm}) which represents the energy absorbed in the atmosphere.

RESULTS AND DISCUSSION

From the interpolation results, comparison between AOD_{MODIS} and $AOD_{AERONET}$ were made based on Julian Days. Figure 1 shows the daily average for AOD_{MODIS} and $AOD_{AERONET}$ over Kuching from 2011 until 2015 by using $MODIS_{\mu \pm \sigma}$.

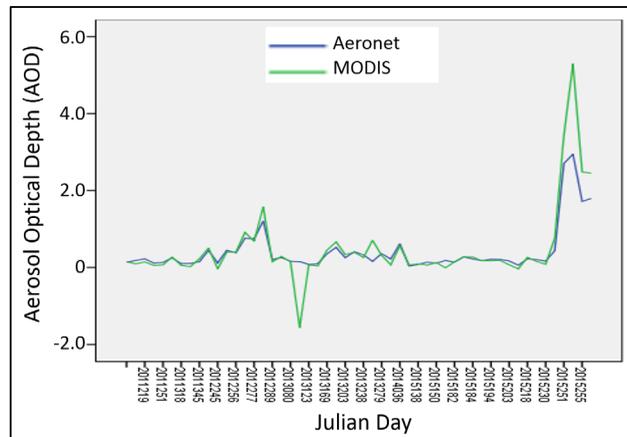


Figure 1. Daily average AOD at 550 nm wavelength retrieved from AOD_{MODIS} and $AOD_{AERONET}$ Using $MODIS_{\mu \pm \sigma}$

Based on Figure 1, the range value for AOD_{MODIS} was -1.56 to 5.3 while for $AOD_{AERONET}$ the minimum and maximum values were 0.04 and 2.95, respectively. The high AOD value on certain Julian Days was due to the high concentration of aerosol loading at Kuching area as a result of dry season which usually occurs from June to September every year, as well as due to the presence of haze. Overestimation of AOD_{MODIS} occurred at Julian Day 253 in 2015 when extremely high AOD_{MODIS} was observed, at 5.3, while $AOD_{AERONET}$ was only 2.9. During the dry season, the surface is dry and causes the surface reflectance to be high, which may cause the

overestimation of AOD. An error of ± 0.006 in measuring the surface reflectance yields an error of ± 0.06 in retrieval of AOD (Tripathi et al., 2005). Extremely low AOD value was obtained during the wettest seasons from November to March. There was a large underestimation for AOD_{MODIS} on Julian Day 245 in 2011 where predicted AOD_{MODIS} was -1.6 as compared with the actual value from $AOD_{AERONET}$ which was only 0.15. The inconsistency between aerosol microphysical and optical properties and surface reflectance used in the MODIS were possible reasons for the underestimation of AOD during the wet season (More et al., 2013). Figure 2 presents daily average for AOD_{MODIS} and $AOD_{AERONET}$ by using $MODIS_{RAE}$ from 2011 until 2015.

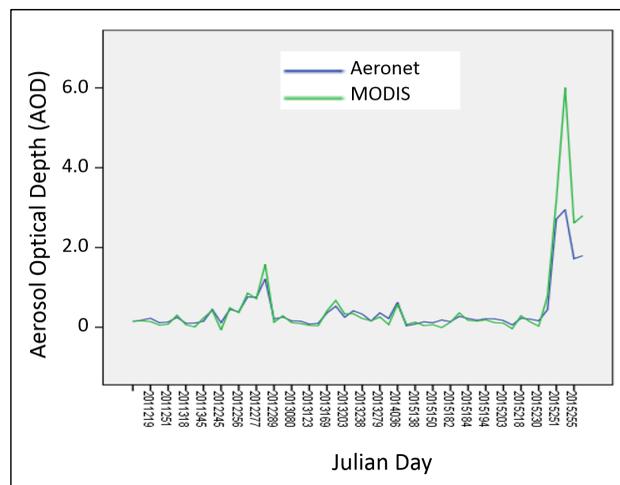


Figure 2. Daily average AOD at 550 nm wavelength retrieved from AOD_{MODIS} and $AOD_{AERONET}$ using $MODIS_{RAE}$

As presented in Figure 2, the range value for AOD_{MODIS} was -0.06 to 6.0 while for $AOD_{AERONET}$ the minimum and maximum values were 0.04 and 2.95 respectively. Overestimation of AOD_{MODIS} occurred on Julian Day 253 in 2015 when extremely high AOD_{MODIS} was observed with 6.0 and only 2.9 for $AOD_{AERONET}$. The variations of AOD at Kuching is the same where high concentration of AOD is observed during dry seasons (June to September). On the contrary, during wet seasons from November to March, the aerosol loading was monitored at low AOD. Therefore, it can be said that the spectral variations of AOD at Kuching are based on the seasonal distinctive features. Similar results were also obtained by Salinas, Chew, Mohamad, Mahmud and Liew (2013) at Kuching area but data was available only for 2011, where there was low aerosol loading for most of the period except for the months of August and September which examined high AOD values from regional episodes of biomass burning and fire activity during these particular months. Linear regression technique between AOD_{MODIS} and $AOD_{AERONET}$ are displayed in Figure 3.

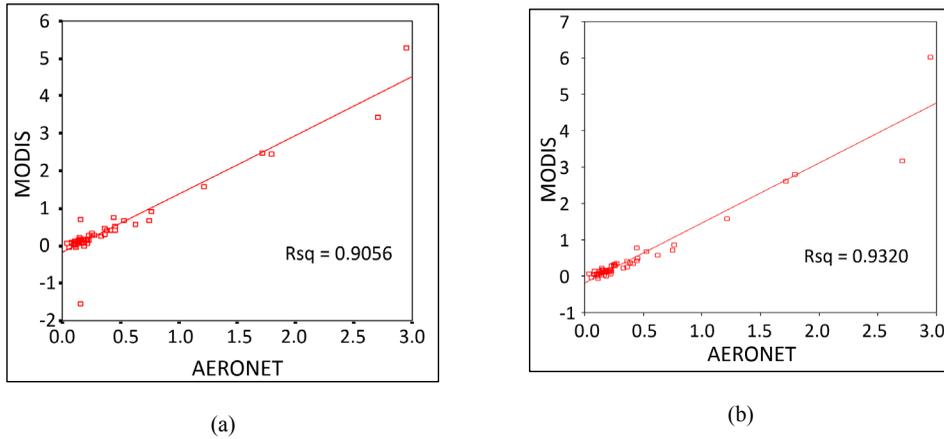


Figure 3. Linear regression for AOD_{MODIS} and $AOD_{AERONET}$ using: (a) $MODIS_{\mu \pm \sigma}$; and (b) $MODIS_{RAE}$

Based on Figure 3, the retrieval algorithm performance is validated from the resulting statistical parameters of the linear regression which are intercept (A), slope (B) and correlation coefficient (R^2).

$$AOD_{MODIS} = A + B * AOD_{AERONET} \quad (3)$$

Here non zero intercepts ($A = -0.1762$ and -0.1181) for $MODIS_{\mu \pm \sigma}$ and $MODIS_{RAE}$, respectively show that the retrieval algorithm is biased at low AOD value due to association with a sensor calibration error or incorrect assumption on ground surface reflectance (Zhao et al., 2002). Chu et al. (2002) stated large errors in surface reflection estimation could lead to larger intercept values. Lanzaco, Olcese, Palancar, and Toselli (2016) studied the comparison of AOD using MODIS and AERONET where the underestimation of AOD was probably due to incorrect characterisation of the local aerosols and the predominantly low AOD values observed. A slope that is different from unity indicates inconsistency between aerosol microphysical and optical properties used in the retrieval algorithm (Zhao et al., 2002) and represents systematic biases in the MODIS retrievals (More et al., 2013). Slope higher than unity at 1.5609 for $MODIS_{\mu \pm \sigma}$ and for $MODIS_{RAE}$ at 1.6469, indicates an overestimation of AOD by MODIS with respect to AERONET retrieval. The R^2 obtained for $MODIS_{\mu \pm \sigma}$ was 0.9056 and using $MODIS_{RAE}$ was 0.932, showing strong relationship between AOD_{MODIS} and $AOD_{AERONET}$. For $MODIS_{\mu \pm \sigma}$, the MAPE was found to be 24% and RMSE value was 0.45 while for $MODIS_{RAE}$, the MAPE was around 12% and RMSE was 0.47. There was only little difference between RMSE for $MODIS_{\mu \pm \sigma}$ and $MODIS_{RAE}$ while for MAPE, the value for $MODIS_{\mu \pm \sigma}$ was quite higher of 24%, as compared to $MODIS_{RAE}$, with only 12%. Based on that, it shows that the selection method using $MODIS_{RAE}$ can also be used to retrieve true value of AOD.

The assessments of ARF conducted by using SBDART model with AOD value retrieved from $MODIS_{\mu \pm \sigma}$ and $MODIS_{RAE}$ as input parameter are shown in Figure 4 and 5.

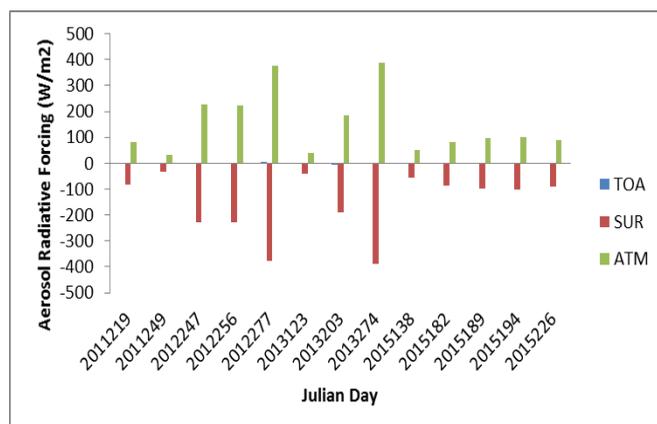


Figure 4. Daily variations of ARF at TOA surface and within the atmosphere using MODIS_{μ±σ}

In Figure 4, the range value for ARF at TOA for AOD_{MODIS} derived using MODIS_{μ±σ} was between -5.95 Wm^{-2} and 0.89 Wm^{-2} and at the surface, was from -389.7 Wm^{-2} to -31.4 Wm^{-2} . The ARF value at TOA was quite low compared with the surface ARF which could reach around -389.7 Wm^{-2} . The daily average ARF value within the atmosphere was at 151.6 Wm^{-2} , which is quite large. Results obtained by Kalluri et al. (2016) stated that atmospheric force was found to be around 36.8 Wm^{-2} during summer due to the combination of dust and carbon aerosols, producing very high AOD value. Thus, high atmospheric force values indicated maximum absorption might be attributed to the mixing of absorbing black carbon with moderately absorbing dust.

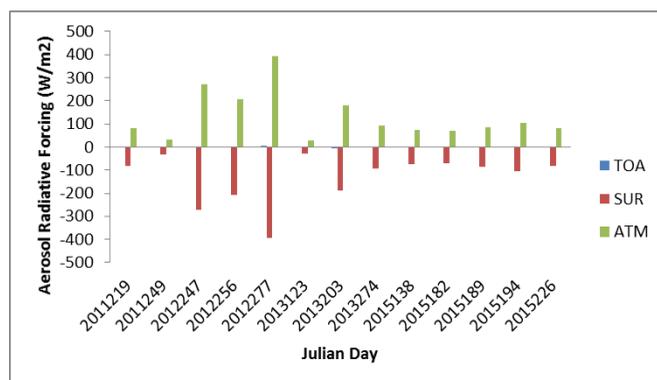


Figure 5. Daily variations of ARF at TOA, surface and within the atmosphere using MODIS_{RAE}

Based on Figure 5, ARF value using MODIS_{RAE} at the surface was within -392.3 Wm^{-2} and -27.3 Wm^{-2} and TOA was between -5.89 Wm^{-2} and 0.98 Wm^{-2} . The ARF value within the atmosphere can be estimated by the difference of ARF at surface and TOA and the average value was 130.4 Wm^{-2} . The results obtained from this study did not show pattern of variations for AOD towards changes in ARF value, causing difficulties in observing the relationship between ARF and aerosol loading. It can still be proven that the slight changes for AOD value as derived from

using $MODIS_{\mu\pm\sigma}$ and $MODIS_{RAE}$ resulted in different values of ARF. As an example, AOD_{MODIS} derived using $MODIS_{\mu\pm\sigma}$ was 0.4, while for $MODIS_{RAE}$ the value of AOD was 0.36 causing ARF estimation at TOA at -2.31 Wm^{-2} and -2.19 Wm^{-2} , respectively. Extremely high negative value at surface which can reach -392.3 Wm^{-2} was probably due to improper retrieval of AOD or when estimating ARF value using SBDART model (Alam et al., 2012).

Theoretically, high negative value at surface aerosol significantly reduced the solar radiation producing a large surface cooling (Kalluri et al., 2016). The difference between ARF value at surface and TOA was a greater absorption of solar radiation within the atmosphere with high positive values in ARF, as a consequence, warming the atmosphere and cooling the surface area (Alam et al., 2012). Research by Wu, Zhu, Che, Xia, and Zhang (2015) showed negative ARF gradually increased with increasing AOD, both at the surface and TOA because of the increase in light scattering and absorption induced by aerosol particles.

On the other hand, linear regression between SBDART and AERONET for $MODIS_{\mu\pm\sigma}$ and $MODIS_{RAE}$ was also analysed. It showed poor relationship between SBDART and AERONET for $MODIS_{\mu\pm\sigma}$ with R^2 value at 0.33, compared to $MODIS_{RAE}$, where the R^2 was 0.724. The $MODIS_{RAE}$ demonstrated significant results, which might be due to high accuracy assessment in terms of statistical method during spatial and temporal averaging. The differences in ARF estimation by using these two statistical methods could be contributed from the variations in AOD value (Alam et al., 2012).

CONCLUSION

As a conclusion, one of the reasons towards the changes in the estimation of ARF value by using radiative transfer model comes from input parameters for aerosol optical properties such as AOD. This is because when there are slight changes for AOD value from using $MODIS_{\mu\pm\sigma}$ and $MODIS_{RAE}$, different values for ARF estimation are derived. These problems may arise due to lack of appropriate aerosol models in the MODIS aerosol retrieval algorithm, or as a result of other factors such as temporal and spatial variability of aerosols. Therefore, it is essential to improve the MODIS retrieval algorithm because radiative transfer simulations should consider uncertainties in the output. Thus, the uncertainty in retrieval of input parameter in radiative transfer model should be improved in obtaining accurate ARF values. For further study of the surface reflectance, ozone concentration and other meteorological parameters can be used as input parameter into SBDART to provide better understanding of the regional and local behaviour and improve the estimation of ARF value.

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