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Comparison of Estimated Planetary Boundary Layer Height over North Africa Using Three Different Methods

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ABSTRACT

Planetary boundary layer (PBL) height is an essential parameter in atmospheric modeling due to its ability to impact on energy, water vapor, and pollution in the atmosphere. Estimation of PBL height is not easily available and often come from radiosonde observations at 0000GMT and 1200 GMT. In this paper PBL height is computed by three methods at afternoon over Egypt and Sahara Desert. The first method is based on bulk Richardson number, while the second method depends on the existence of the Inversion Layer. The third method is based on a simplified turbulent kinetic energy equation and accounts for the temperature difference across the top of the mixed layer. The results of PBL height by the three methods are compared with those corresponding of The National Centers for Environmental Prediction (NCEP) and the ERA-Interim reanalysis from ECMWF. The comparisons illustrate that the estimated PBL height are differ by some hundreds of meters. The simulations with the first and third methods give much less PBL heights than the second method. Finally, the variation of PBL heights estimates are discussed for each method.

Keywords: Planetary Boundary Layer height, Potential Temperature, WRF Model, Weather Forecast

I. INTRODUCTION

This The PBL is characterized by the presence of continuous turbulence, while turbulence is lacking or sporadic above the PBL. Therefore, the PBL height can be viewed as the level where continuous turbulence stops (Wang et al., 1999; Seibert et al., 2000). There are various methods for determining the boundary layer height both from observations (e.g. in situ measurements such as radiosondes, tethered balloons or aircraft, remote soundings such as radar) and from model simulations. Some of those methods by using high frequency turbulence measurements the PBL height can be readily determined. This is known as the turbulence method. It is highly reliable, but the instruments required by this method are costly. A more economic option is to determine the PBL height through analyzing temperature and wind profiles measured from radio soundings. In this method, the PBL are broadly classified as strongly stable boundary layers, weakly stable boundary layers, or unstable boundary layers (Holtslag and Boville, 1993; Vogelezang and Holtslag, 1996). They are defined using the surface heat flux and the potential temperature profile, as shall be seen later. For strongly stable boundary layers, there is a strong inversion in the potential temperature profile and the PBL height is usually defined as the top of the inversion where the potential temperature gradient first becomes smaller than a certain threshold (Bradley et al., 1993). For unstable boundary layers buoyancy is the dominant mechanism driving turbulence, and the PBL height is defined as the height at which a thin layer of capping inversion occurs. In this paper we are interested in calculating the PBL height for unstable condition over Sahara Desert in summer days by applying three methods and comparing the result with reanalysis data.

II. METHODS AND MATERIAL

The Weather Research and Forecasting (WRF) model version 3.6.1 used for calculating the PBL height over Sahara region (5°N to 40°N ; 15°W to 45°E). The model domain has horizontal grid resolution 54 km with 34 vertical levels. The top model level is at 50 mb (20 km) and the model integrated time step is 300 sec. Physical parameterization schemes used in the present work include the rapid radiative transfer model for long wave, Duhia scheme for shortwave radiation, and the Noah land surface scheme. The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) and the ERA-Interim reanalysis from ECMWF (Dee et al., 2011) all with 6-hourly Products and $0.5° \times 0.5°$ horizontal grid resolution are used for comparison.

A. The First Method

The bulk Richardson number (Rib) is used to calculate the PBL height. This method was applied in Yonsei university (YSU) PBL scheme in the (WRF) model (Hong et al., 2006). The boundary layer height (h) is given by

$$h = Rib_{cr} \frac{\theta_{va} \mid U(h) \mid^2}{g[\theta_v(h) - \theta_s]} \tag{1}$$

where Rib_{cr} is the critical bulk Richardson number, $U(h)$ is the horizontal wind speed at h, θ_{va} is the virtual potential temperature at the lowest model level,$\theta_v(h)$ is the virtual potential temperature at h, and θ_s is the appropriate potential temperature near the surface. The potential temperature near the surface is defined as

$$\theta_s = \theta_{va} + \theta_T \tag{2}$$

where θ_T is the virtual potential temperature excess near the surface. The PBL height is determined by checking the bulk stability between the surface layer (lowest model level) and levels above. The bulk Richardson number between the surface layer and a level z is defined by

$$Rib(z) = \frac{g[\theta_v(z) - \theta_s]}{\theta_{va} U(h)^2} \tag{3}$$

The computed Rib at a level z is compared with Rib_{cr}. The value of h corresponding to Rib_{cr}(=0.5) is obtained by linear interpolation between the two adjacent model levels.

B. The Second Method

This technique was developed by Heffter [1980]. The method relies on the existence of the Inversion Layer. The mixing depth concept is based upon the principle that heat transferred to the atmosphere at the earth's surface results in convection, vigorous vertical mixing, and establishment of a dry adiabatic lapse rate. The depth through which such mixing extends depends primarily upon the initial vertical temperature structure and the heat input at the surface. Neglecting temperature advection, afternoon mixing depths were calculated from potential temperatures at 1200 GMT.

It consists of two mathematical conditions that attempt to identify a critical inversion in the temperature profile. Although inversion in the term Inversion Layer refers to increase of absolute temperature with height, the technique uses potential temperature to find the top of the PBL. The two conditions are

$$\frac{\Delta\theta}{\Delta z} > 0.005°Km^{-1} \tag{4}$$

$$\theta_t - \theta_b > 2°K \tag{5}$$

where $\Delta\theta/\Delta z$ is the potential temperature lapse rate in the inversion layer and θ_t, θ_b refer to the potential temperatures at the top and bottom of the critical inversion layer, respectively. The first condition (Eq.4) looks for a significant change in potential temperature. Potential temperature is nearly constant inside the mixed layer due to adiabatic mixing. As the height increases and the entrainment zone is entered, the air is no longer well mixed, the adiabatic assumption is no longer as effective, and so potential temperature starts increasing with height (Figure 1). The second condition (Eq.5) attempts to ensure the height of the PBL is set at the top of the Inversion Layer, not merely the top of the mixing layer.

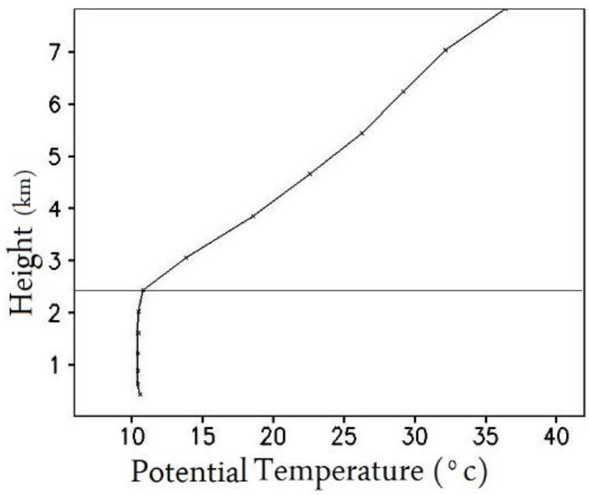


Figure 1. Potential temperature with height (point 25o N and 25o E) at 1200 GMT on July 20. The mixed layer, and the inversion layer are well defined.

C. The Third Method

The PBL height can also be estimated with a simple slab theory for the intrusion of the mixed layer, topped by a constant inversion strength. This highly idealized slab model is based on a simplified turbulent kinetic energy equation and accounts for the temperature difference across the top of the mixed layer by assuming an infinitesimally shallow entrainment layer and specifying the stability of the overlying free troposphere. The Model accounts for the effects of convective and mechanical turbulence. It requires an initial value for the boundary layer height the surface sensible heat flux and friction velocity must be known from the initialization time to the time when the mixed layer top is to be determined (Sugiyama and Nasstrom, 1999). The latter is then calculated by integrating the equation for the mixed layer growth rate. The effects of latent heating, horizontal advection, divergence of the radiation heat flux, and large scale vertical velocities are treated as negligible. When buoyancy generated turbulence is dominant, the rate equation for the convective is given by: -

$$\frac{dh_b}{dt} = (2\beta + 1)\frac{\overline{w'\theta'}}{\gamma h_{pbl}} \tag{6}$$

where h_b is the PBL height generated by buoyancy $\beta = 0.2$ and $\gamma = \frac{\partial\theta}{\partial z}$ is the potential temperature gradient above h_b. This expression is based on the assumptions that the heat flux varies linearly with height and the entrainment heat flux at $z = h_b$ is proportional to the surface heat flux $\overline{w'\theta'_h} = -\beta\overline{w'\theta'_\circ}$.

Mechanically generated shear turbulence is dominant when the surface heat' flux is zero. In this case, assuming once again a linear variation of heat flux with height and specifying the entrainment heat flux at $z = h_m$ as $w'\theta'_h = \frac{-\propto\theta u_*^3}{g h_{pbl}}$, the rate equation for h_m, becomes

$$\frac{dh_m}{dt} = \frac{2\propto\theta u_*^3}{g\gamma h_{pbl}} \tag{7}$$

where $\propto = 2.5$. Given initial values for h_m, these two rate equations may be integrated to determine the time evolution of h_{pbl} for the general case, van Dop et al. (1997) proposed the interpolation formula:

$$h_{pbl} = \left(h_b^3 + h_m^3\right)^{\frac{1}{3}} \tag{8}$$

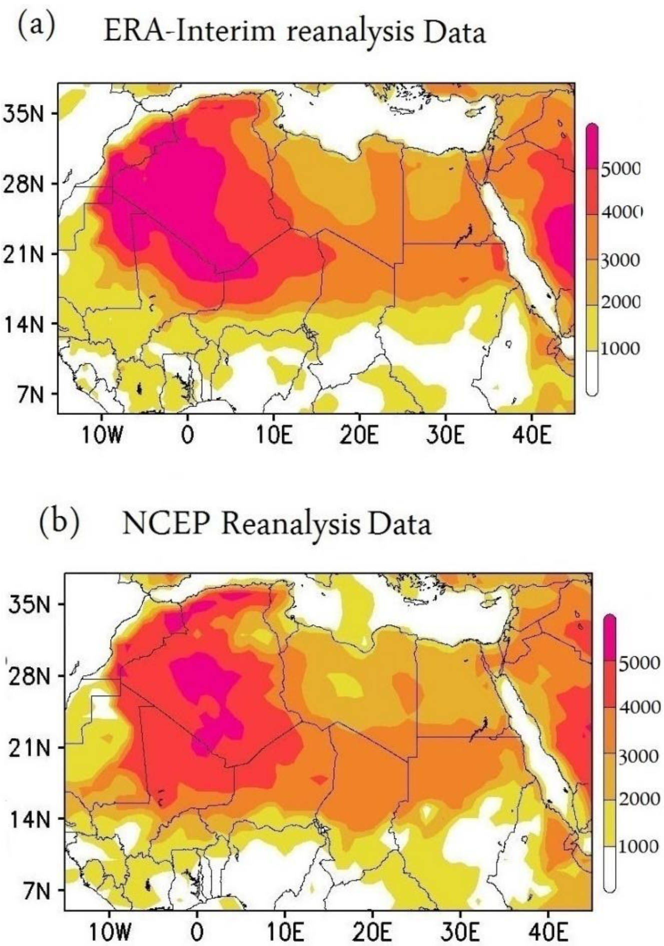
where h_{pbl} boundary layer depths determined for the limiting cases of purely mechanically or buoyancy-generated turbulence.

III. RESULTS AND DISCUSSION

All The three methods of PBL height computation are compared with those corresponding of The National Centers for Environmental Prediction (NCEP) and the ERA-Interim reanalysis from ECMWF with $0.5^\circ X 0.5^\circ$ grid size resolutions. These products of reanalysis data are different in many aspects, such as the numerical schemes, the physical parameterizations in their numerical models, the qualities and quantities of observational data used in the assimilation processes, and the assimilation schemes (Decker et al., 2011; Wang and Zeng, 2012).

Figure 2 shows the horizontal distribution of PBL height (5000, 4000, 3000, 2000, and 1000 m) over North Africa Desert at 1200GMT on 20 July 2003 for ERA-Interim and NCEP reanalysis data and the three proposed methods (a, b, c, d, and e, respectively). The first method was successfully predict the diurnal variation of the PBL height under unstable condition, but the performance yield lower PBL height than NCEP and ERA-Interim reanalysis data (Fig. 2c). This lower of PBL height due to the surface heating on Sahara Desert is larger than estimated by surface layer temperature (θ_s) in equation (1) as a result of that the daytime boundary layer is often not well defined. Figure 2d shows the computed PBL height by using the second method, this method seemed to overestimate the PBL height compared to NCEP and ERA-Interim reanalysis data. This method does not follow the height, where the vertical structure of water vapor mixing ratio began to decrease, which has been shown to be an indicator of the boundary layer height (Berman et al., 1999). For example, the PBL height based on potential temperature and water vapor mixing ratio are shown below in Figure 3. It can be seen from this example that the approximate height of the boundary layer relies on water vapor mixing ratio is 3800 m (Fig. 3a). However, the height estimated from potential temperature is 4600 m (Fig. 3b). This is likely the result of moisture not being taken into the account of this method. The result of the third method gives underestimation of PBL height compared to NCEP and ERA-Interim reanalysis data (Fig. 2e).

Fig. 4a, b display the horizontal distribution of PBL height errors over North Africa for the three methods at 12 GMT on 20 July 2003, the three methods subtracted from NCEP and ERA-Interim reanalysis data respectively. A careful look to this figure indicates that the second method is slightly better than the others. One notes that the error is concentrated over the east north Sahara Desert. Ao et al. (2012) use Global Positioning System Radio Occultation measurements to derive a global climatology of PBL height. Their paper indicates that, the highest PBLH occurs over desert areas in summer months. In other words, the problem related to Sahara Desert due to inaccurate estimation of surface layer temperature in PBL height calculation.



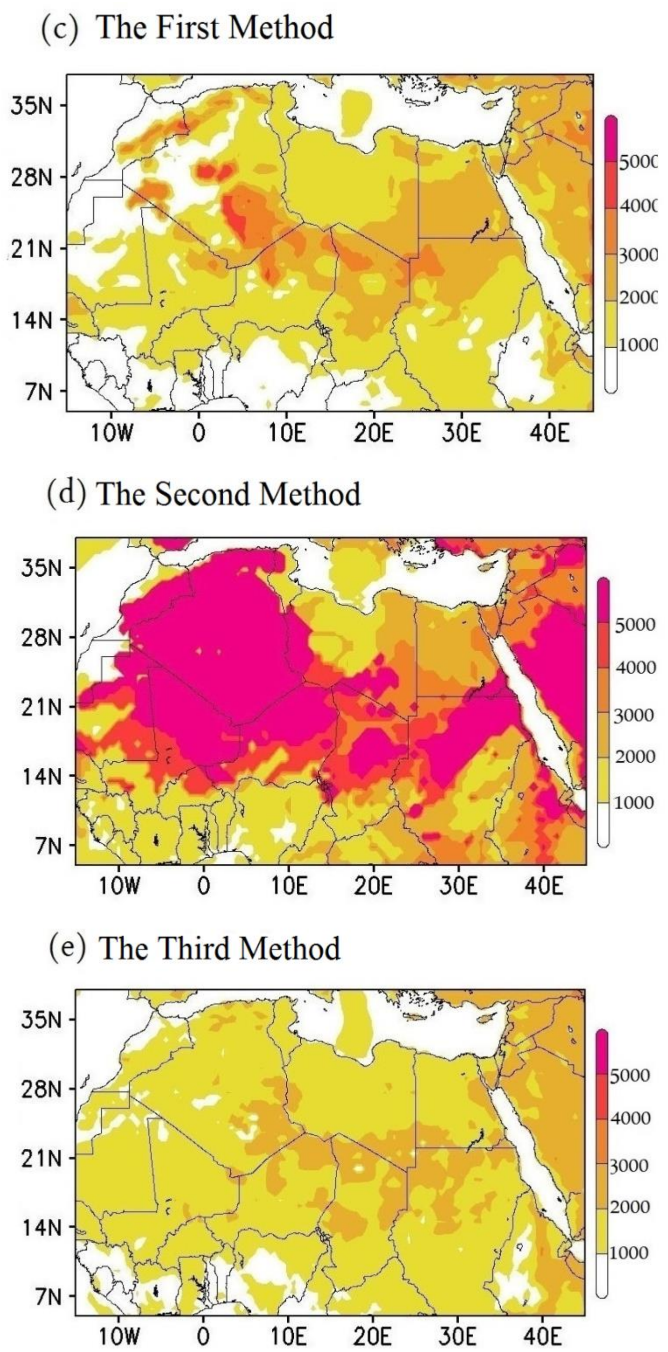


Figure 2. Horizontal distribution of PBL height (in m) over North Africa (from 15o W to 45o'E and from 5o N to 38oN) at 1200 GMT on 20 July 2003. (a) ERA-Interim reanalysis data, (b) NCEP reanalysis data, (c) first method, (d) second method, and (e) third method.

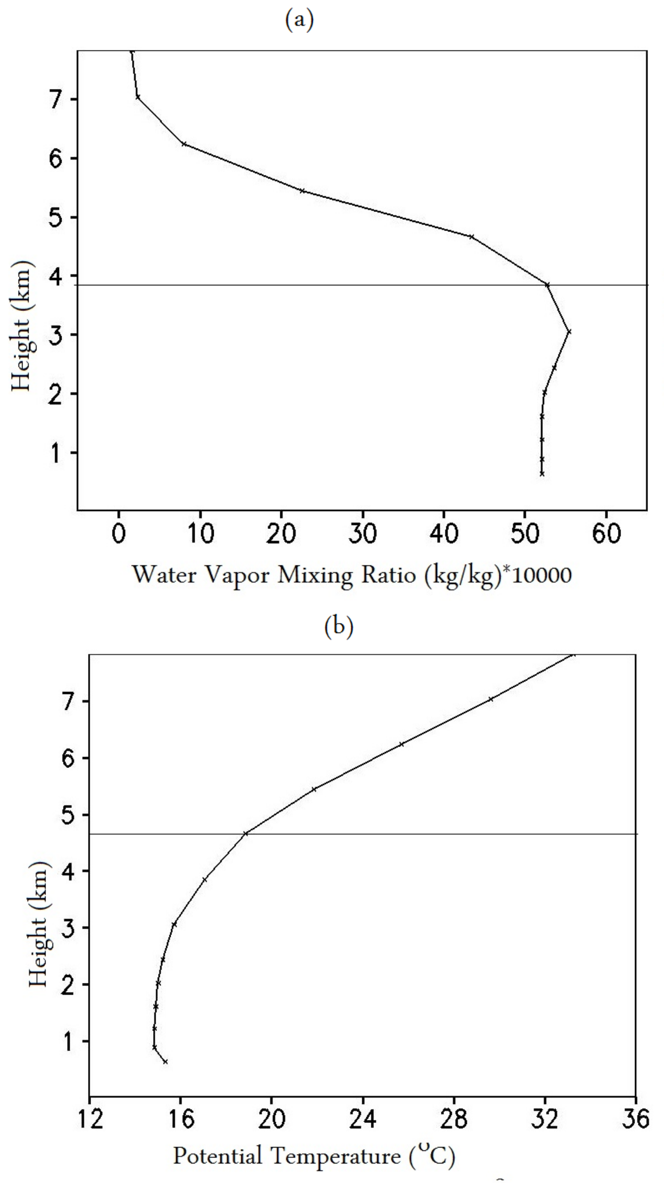
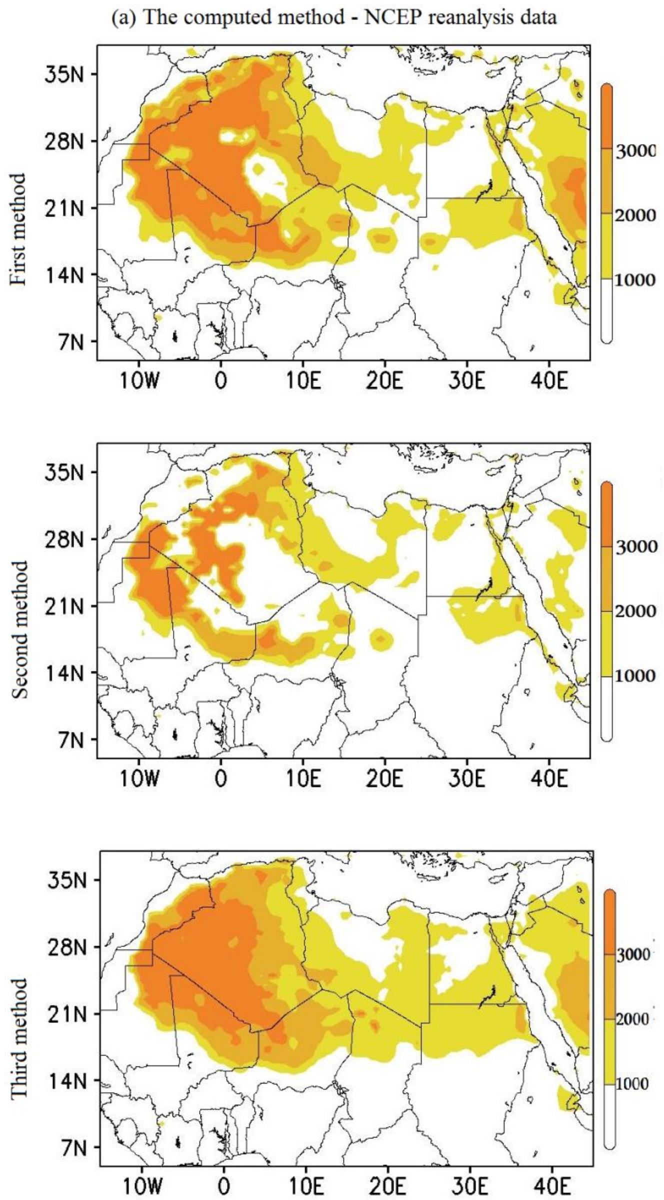


Figure 3. Vertical distribution at 10o E and 21o N. at 1200 GMT on 20 July 2003 for (a) Water vapor mixing ratio, and (b) potential temperature



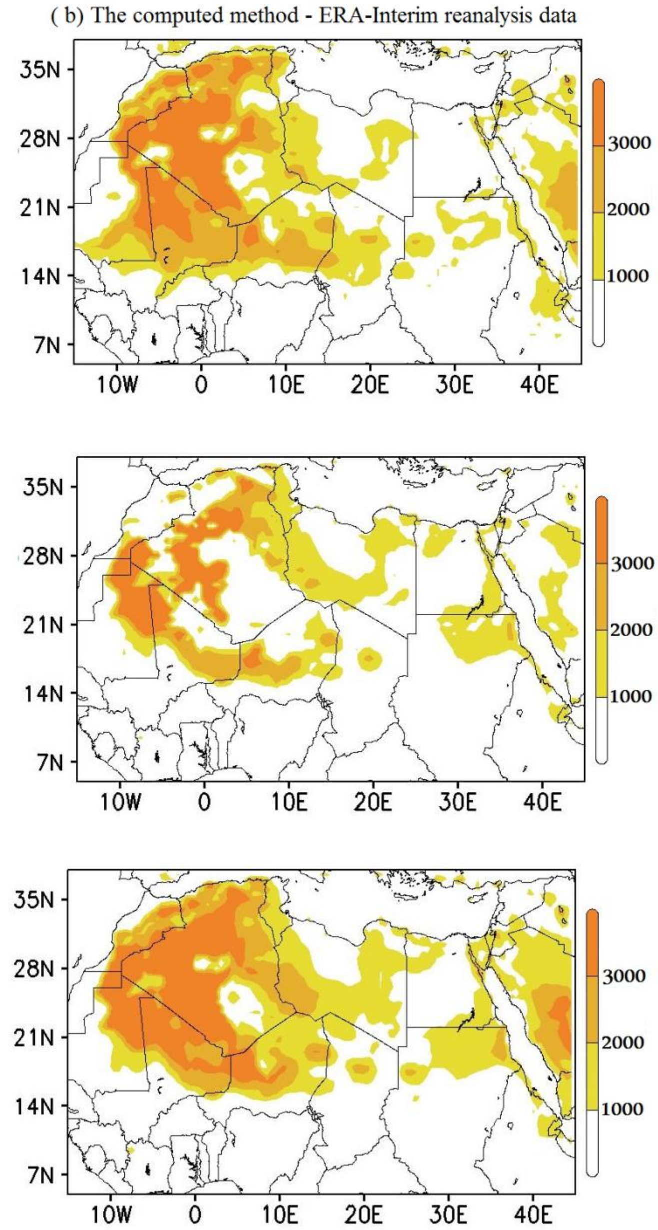


Figure. 4. Horizontal distribution of PBL height errors (in m) over North Africa for the three methods at 1200 GMT on 20 July 2003, (a) the three methods subtracted from NCEP data, (b) the three methods subtracted from ERA-Interim reanalysis data.

IV. CONCLUSION

Although The PBL height is an important parameter in boundary layer research and atmospheric modeling so that the accurate estimates of PBL height are vital for many environmental applications. In this study, we investigated three different methods for computing the PBL height in unstable conditions. The three methods generally display good performance. However, with these apparent features of the PBL height, large errors can be introduced by these methods. The bulk Richardson number method (the first method) is more commonly used in numerical models due to its reliability for all atmospheric stratification conditions, which requires a specified value of the bulk Richardson number for the entire PBL (Zhang et al., 2014). This method requires vertical temperature and wind data so that the equations can be computed accurately. The Richardson number calculated in this method is sensitive to small changes in the temperature profiles. The second method have a problematic during the computation, if the first condition ($\frac{\Delta\theta}{\Delta z} > 0.005^\circ\ \mathrm{Km}^{-1}$) is iteratively relaxed on failure, the second condition ($\theta_t - \theta_b > 2^\circ\ \mathrm{K}$) relaxed on failure. For this reason it needs to several modifications to consider in the implementation by adding another technique to attempt to detect a sharp change in $\frac{\Delta\theta}{\Delta z}$ As soon as the curvature becomes significant. The third method has been used widely in air pollution and dispersion modeling due to its efficiency and simplicity (Sykes, 1996). The method assumes that the vertical distribution of potential temperature within the boundary layer is almost constant with a strong capping inversion above the PBL. The weaknesses of the method are the particular behavior of the formula as $\frac{\partial\theta}{\partial z} \to 0$, which causes overestimation of PBL height for small lapse rates.

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