

1 **Comparison of GEOS-5 AGCM planetary boundary layer**
2 **depths computed with various definitions**

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1 **Abstract**

2 Accurate models of planetary boundary layer (PBL) processes are important for forecasting
3 weather and climate. The present study compares seven methods of calculating PBL depth in the
4 GEOS-5 atmospheric general circulation model (AGCM) over land. These methods depend on
5 the eddy diffusion coefficients, bulk and local Richardson numbers, and the turbulent kinetic
6 energy. The computed PBL depths are aggregated to the Köppen climate classes, and some
7 limited comparisons are made using radiosonde profiles. Most methods produce similar midday
8 PBL depths, although in the warm, moist climate classes, the bulk Richardson number method
9 gives midday results that are lower than those given by the eddy diffusion coefficient methods.
10 Additional analysis revealed that methods sensitive to turbulence driven by radiative cooling
11 produce greater PBL depths, this effect being most significant during the evening transition.
12 Nocturnal PBLs based on Richardson number are generally shallower than eddy diffusion
13 coefficient based estimates. The bulk Richardson number estimate is recommended as the PBL
14 height to inform the choice of the turbulent length scale, based on the similarity to other methods
15 during the day, and the improved nighttime behavior.

16

1 **1 Introduction**

2 The planetary boundary layer (PBL) depth is important for surface-atmosphere exchanges of
3 heat, moisture, momentum, carbon, and pollutants. Several studies have attempted to understand
4 the uncertainty associated with the use of different PBL depth definitions and found the
5 estimated PBL depth to depend substantially on the method chosen. Vogelesang and Holtslag
6 (1996) examined the PBL depth by defining it using both bulk and gradient Richardson numbers
7 and found that the choice of Richardson number, the critical number chosen, and the inclusion of
8 surface friction impacted the results. Seidel et al. (2010) tested seven different PBL depth
9 definition methods on radiosonde profiles. Using a single dataset, the estimated PBL depth was
10 found to differ by up to several hundred meters. The use of different methods in their study also
11 produced different seasonal variations. They concluded that it is necessary to compare different
12 PBL depth estimates from different sources using the same method. In a later study, Seidel et al.
13 (2012) recommended a bulk Richardson number based definition.

14 In the present study, seven different methods to compute the PBL depth were incorporated into
15 the Goddard Earth Observation System (GEOS-5) atmospheric general circulation model
16 (AGCM) (Rienecker et al., 2008; Molod et al., 2012) and intercompared using a single climate
17 simulation. The seven methods are based on vertical profiles of the eddy diffusion coefficient
18 for heat (K_h), the bulk (Ri_b) and local (Ri) Richardson numbers, and the horizontal, shear-based
19 component of the turbulent kinetic energy (TKE). In order to provide insight into implications
20 on the regional and global climate scale, results were aggregated onto the Köppen-Geiger climate
21 classes over land (Peel et al., 2007).

22 The purpose of this study is two-fold. First, it analyzes differences among the PBL depth
23 definitions evaluated diagnostically within the GEOS-5 AGCM. Results of this comparison will
24 be used to develop a better state-dependent estimate of the turbulent length scale, which must be
25 specified in the current model's turbulence parameterization. A second purpose of this study is
26 to evaluate the influence of different processes, such as turbulence generated by shear and
27 radiative interactions with cloud, on the PBL depth. The following section provides a model
28 description and a description of the PBL depth diagnostics used. The third section presents
29 results of the comparison and the final section contains the conclusions.

30 **2 Model and PBL diagnostics**

1 **2.1 GEOS-5 model description**

2 The GEOS-5 AGCM is a comprehensive model with many uses, including atmosphere-only
3 simulations, atmospheric data assimilation operational analyses and reanalyses, and seasonal
4 forecasting when coupled to an ocean model (Rienecker et al., 2008; Molod et al., 2012). An
5 earlier version was used for the Modern-Era Retrospective Analysis for Research and
6 Applications (MERRA) (Rienecker et al., 2011). The latitude-longitude hydrodynamical core of
7 the GEOS-5 AGCM uses the finite volume dynamical core of Lin (2004) and the cubed sphere
8 version is based on Putman and Lin (2007). The GEOS-5 AGCM includes moist physics with
9 prognostic clouds (Bacmeister et al., 2006). The convective scheme is a modified version of the
10 Relaxed Arakawa-Schubert of Moorthi and Suarez (1992), the shortwave radiation scheme is
11 that of Chou and Suarez (1999), and Chou et al. (2001) describe the longwave radiation scheme.
12 The Catchment Land Surface Model is used to determine fluxes at the land/atmosphere interface
13 (Koster et al., 2000) and the surface layer is determined as in Helfand and Schubert (1995). The
14 model uses 72 vertical layers that transition from terrain following near the surface to pure
15 pressure levels above 180 hPa.

16 Since details of the turbulence parameterization in the current version of the GEOS-5 AGCM
17 (Rienecker et al., 2008; Molod et al., 2012) are relevant to the analysis of results of the current
18 study, it is described here. The turbulence parameterization is based on the Lock et al. (2000)
19 scheme, acting together with the Richardson number based scheme of Louis et al. (1982). The
20 Lock scheme represents non-local mixing in unstable layers, either coupled to or decoupled from
21 the surface. The parameterization computes the characteristics of rising or descending parcels of
22 air (“plumes”), initiated due to surface heating or to cloud top cooling of boundary layer clouds.
23 The GEOS-5 AGCM implementation includes moist heating in the calculation of buoyancy and
24 a shear-dependent entrainment in the unstable surface parcel calculations. It is formulated using
25 moist conserved variables, namely the liquid–frozen water potential temperature and the specific
26 total water content, so that it can treat both dry and cloudy layers. The turbulent eddy diffusion
27 coefficients are computed using a prescribed vertical structure, based on the height of the surface
28 and radiative parcels or "plumes".

29 The Louis scheme is a first order, local scheme, and the eddy diffusion coefficients are computed
30 using Richardson number based stability functions for stable and unstable layers. The Louis

1 scheme unstable layer stability functions require the specification of a turbulent length scale,
2 which is formulated using a Blackadar (1962) style interpolation between the height above the
3 surface and a length scale based on the combined Lock and Louis schemes at the previous model
4 time step. Many AGCMs specify the length scale a priori to a constant global value (e.g. Sandu
5 et al., 2013). This estimate of the turbulent length scale was designed to provide a state-
6 dependent estimate and to add "memory" to the turbulence parameterization. The eddy diffusion
7 coefficients used for the AGCM turbulent diffusion are the larger of the Lock or Louis
8 coefficients at any time step.

9 The simulation performed for this study uses C180 (approximately $\frac{1}{2}$ degree) horizontal
10 resolution on the cubed sphere grid. The simulation covers January 1990 through May 2013 and
11 is initialized using MERRA analysis on 31 December 1989. The mean climate of this version of
12 the GEOS-5 AGCM was shown in Molod et al. (2012) to compare well with a comprehensive set
13 of observations.

14 **2.2 PBL depth diagnostics**

15 Seven different methods for determining the PBL depth are evaluated using the GEOS-5 AGCM
16 based on several different output variables (Table 1). All methods diagnostically evaluate the
17 same atmospheric profiles and all differences are related solely to the difference in definition of
18 PBL depth.

19 The first method (Method 1) is based on the total eddy diffusion coefficient of heat (K_h) and
20 estimates the PBL depth as the model level below that which K_h falls below a threshold value of
21 $2 \text{ m}^2 \text{ s}^{-1}$. No vertical interpolation is used for this method and the estimated height is the model
22 level edge. This method is the PBL definition used to determine the PBL depth in MERRA, and
23 it is also used in the current GEOS-5 AGCM as part of the state-dependent estimate of the
24 turbulent length scale. The evaluation of this method is one of the goals of the present study
25 because any error in PBL depth shown to be associated with the use of this method may
26 adversely influence the model's simulated climate.

27 Methods 2 and 3 use a variable K_h threshold that depends on the atmospheric profile rather than
28 a constant value. These methods use a threshold of 10% of the column maximum and linearly
29 interpolate between levels to determine the PBL depth. Method 2 uses the total K_h and Method 3
30 uses the surface buoyancy driven eddy diffusion coefficient (neglecting the contribution from the

1 radiative plume). Method 3 therefore neglects the direct influence of clouds, and comparisons
 2 between this method and Method 2 isolate the role of the turbulence due to negative buoyancy at
 3 cloud top associated with cloud-topped boundary layers.

4 The PBL depth definition used by Seidel et al. (2012) is used as Method 4. They selected this
 5 method because of its applicability to radiosondes and model simulations and its suitability for
 6 convectively unstable and stable boundary layers. This method uses a bulk Richardson number
 7 (Ri_b) given by:

$$8 \quad Ri_b(z) = \frac{\left(\frac{g}{\theta_{vs}}\right)(\theta_{vz} - \theta_{vs})(z - z_s)}{u_z^2 + v_z^2},$$

9 where g is the gravitational acceleration, θ_v is the virtual potential temperature, u and v are the
 10 horizontal wind components, and z is height above the ground. The virtual potential
 11 temperature, by definition, is based on water vapor, but not condensate. The subscript s denotes
 12 the surface. The surface winds are assumed to be zero. This bulk Richardson number is
 13 evaluated based on differences between the surface and successively higher levels, assuming that
 14 the surface layer is unstable, and the PBL top is identified as the level at which Ri_b exceeds a
 15 critical value of 0.25. The PBL height is found by linearly interpolating between model levels.

16 Methods 5 and 6 use different versions of the bulk Richardson number, evaluated between two
 17 consecutive levels (rather than between the surface and the current height) that we term the
 18 “local” Richardson number. This local Richardson number (Ri) is calculated as:

$$19 \quad Ri(z) = \frac{\left(\frac{g}{\theta_v}\right)(\theta_{vz1} - \theta_{vz2})(z_1 - z_2)}{(u_{z1} - u_{z2})^2 + (v_{z1} - v_{z2})^2}.$$

20 Here, z_1 and z_2 represent the heights of the model levels above and below the current level
 21 respectively, and θ_v without a subscript is the average virtual potential temperature between
 22 heights z_1 and z_2 . The PBL top is found by assuming that the surface is unstable and linearly
 23 interpolating between the model levels where the critical value is crossed. We test two critical
 24 Richardson numbers to determine the sensitivity of the method to the critical value chosen.
 25 Method 5 uses a critical local Richardson number value of 0.2 and Method 6 uses a critical local

1 Richardson number value of 0. A critical value of 0.0 was chosen because in the Louis scheme
2 of the GEOS-5 AGCM, Richardson number values less than 0.0 are assumed to represent an
3 unstable atmosphere. The Richardson number methods do not directly consider the presence or
4 absence of low-level clouds (Seidel et al., 2012).

5 We use a scaling approximation of TKE to estimate the PBL depth in Method 7. The Lock
6 scheme is not very sensitive to boundary layer shear so we chose a scaling based only on shear
7 sources of TKE to isolate the shear contribution. The top of the PBL is taken to be the height at
8 which the shear-based TKE falls below a threshold value of 10% of the column maximum,
9 vertically interpolating between model levels. The horizontal TKE method should be more
10 sensitive to the wind profile and seasonal changes to it than the other methods, and the daytime
11 PBL heights based on this method should be expected to be lower than PBL height estimates
12 based on static stability.

13 **2.3 Climate classes**

14 The computed PBL depths are aggregated by season onto the Köppen-Geiger climate classes
15 (Fig. 1). The Köppen-Geiger climate classes have been used to group rivers worldwide for
16 comparisons of runoff characteristics (McMahon et al., 1992; Peel et al., 2004). Molod and
17 Salmun (2002) successfully used this aggregation in their study investigating the implications of
18 using different land surface modeling approaches. Their study aggregated results such as canopy
19 temperature, soil moisture, and turbulent fluxes and they were able to use these results to make
20 generalizations that extend to broad climate regions relevant for global models. Aggregation
21 onto these climate classes is a way to characterize similar remote regions and apply findings
22 globally.

23 Peel et al. (2007) recently updated the Köppen-Geiger climate classification, taking advantage of
24 advances in data availability and computing power. They did this by using monthly mean
25 precipitation and temperature data from over 4000 stations (plus additional data from stations
26 reporting only temperature or only precipitation) and interpolating between them using a two-
27 dimensional thin-plate spline with tension. The final map is generated on a $0.1^\circ \times 0.1^\circ$ grid. The
28 highest station density is in the USA, southern Canada, northeast Brazil, Europe, India, Japan,
29 and eastern Australia while the lowest station data densities are located in desert, polar, and some
30 tropical regions.

1 Peel et al. (2007) used the same classes as the original classification system, but with an updated
2 distinction criterion between the temperate and cold climate classes. The classification consists
3 of five main climate types: tropical (A), arid (B), temperate (C), cold (D), and polar (E) with
4 further divisions based on seasonal variations in temperature and precipitation. Peel et al. (2007)
5 provide a full description of the climate classifications including details on how the classification
6 was determined. The broad climate types, defined over land, are relatively insensitive to
7 temperature trends, including those from global climate change (Triantafyllou and Tsonis, 1994;
8 Peel et al., 2007) and are intended to represent long term mean climate conditions and not year-
9 to-year variability.

10 **3 Results**

11 This section describes the results of the comparison of the different PBL depth estimates
12 aggregated to the Köppen climate classes. The first subsection (3.1) provides a quantitative
13 description of the variability within climate classes, explains some of the reasons for this
14 variability, and justifies the reliance on the climate class aggregated analysis. The following
15 subsections show the general PBL depth response to the different definitions, describe in detail
16 the results from classes that deviate from this behavior, and examine in detail reasons for the
17 difference between the PBL depths estimated using the K_h and bulk Richardson number
18 methods. The final subsection reports on the PBL height differences related to the cloud-
19 activated Lock scheme's radiative plume.

20 **3.1 Variability within climate classes**

21 The Köppen-Geiger classification does not explicitly take into account some aspects of the
22 climate system relevant to boundary layer processes such as intensity of precipitation, elevation,
23 terrain, and overlying subsidence. The aggregation of PBL height onto climate classes is
24 therefore useful for examining the behavior of the different estimates globally, but differences in
25 behavior within climate classes are neglected by definition. Figure 2 shows seasonal mean PBL
26 depths computed with Method 1. The error bars show the standard deviation within climate
27 classes as an indicator of the amount of spatial variability within each class. This variability can
28 be characterized in terms of four broad classifications: tropical, arid, temperate, and cold, and
29 examples characteristic of results from each are shown here.

1 Figure 2a shows the annual mean diurnal cycle of PBL depth and standard deviation in the
2 tropical rainforest (Af). Variability is fairly uniform through the diurnal cycle with the standard
3 deviation being about 39% of the mean PBL depth. This climate class will be discussed in
4 greater detail below. Figure 2b shows the summer mean diurnal cycle of PBL depth and
5 standard deviation for the hot, arid, desert. This climate class also produces fairly uniform
6 standard deviations through the diurnal cycle with a mean ratio of standard deviation to PBL
7 depth of about 39%. Figure 2c shows the summer mean diurnal cycle for the hot summer, dry
8 winter temperate climate class. In this class, the variability has a diurnal cycle in which the
9 standard deviation is smallest at night and larger during the day. The mean standard deviation is
10 about 31% of the PBL depth. However, during the dry winter, the variability is more uniform
11 (not shown), similar to the dry climate class represented in Fig. 2b. Figure 2d shows the summer
12 mean diurnal cycle in the warm summer, no dry season, cold climate class. For this class, the
13 standard deviation has lower variability at night than during the day and the standard deviation is
14 about 31% of the PBL depth. In addition to variation of diagnosed PBL depth within climate
15 classes, there are also variations in the functional dependence of PBL depth on atmospheric state
16 or fluxes. The details of two examples of variability within climate classes are presented here.

17 Spatial maps in Fig. 3 show the relationship between PBL depth and surface temperature in the
18 Sahara and Arabian deserts. Figure 3a shows the seasonal mean PBL depth estimated using
19 Method 1 for JJA over the Sahara and Arabian desert part of the BWh climate class that was
20 shown in Fig. 2b. In JJA, the PBLs over the coastal regions of the Saharan and Arabian deserts
21 are more than a kilometer shallower than the PBLs found further inland. This behavior reflects
22 the variability of the surface temperature within the BWh climate class. A spatial map of the JJA
23 skin temperature (Fig. 3b) shows the same pattern as the PBL depth. A scatter diagram (not
24 shown) of PBL heights and skin temperature revealed that >60% of PBL height variability is
25 explained by skin temperature.

26 The second example of intra-class variability is illustrated in Fig. 4, which shows the relationship
27 between PBL depth and 10-meter temperature for the tropical rainforest climate class (Af),
28 shaded according to 10-meter relative humidity. In this climate class, and in the other tropical
29 climate classes, there is a shift in the relationship between PBL depth and 10 m temperature near
30 302 K. This temperature is near the wilting point for broadleaf evergreen vegetation, the
31 dominant vegetation type in the tropics. At temperatures above the wilting point, the vegetation

1 experiences moisture stress, thus severely limiting transpiration and more of the net radiation at
2 the surface is lost as sensible heat flux. Since sensible heat is much more efficient at growing the
3 PBL than latent heat (Ek and Holtslag, 2004), the PBL depth increases rapidly with temperature
4 in this drier regime. In the regime below the wilting point, transpiration increases with
5 temperature and proceeds with little resistance, wetting the lower atmosphere. In this wetter
6 regime, PBL depth decreases with temperature.

7 These different regimes and sensitivities of PBL depth to different variables must be kept in
8 mind when examining climatological boundary layer depth. Although the Köppen-Geiger
9 climate classes are useful for organizing land regions in order to make generalizations and
10 simplify the analysis, they do not capture all the conditions relevant to boundary layer processes.
11 There will therefore be geographical differences within each climate class that will not be
12 captured by this analysis.

13 **3.2 General method behavior**

14 When aggregated by climate class, the PBL depth definitions produce similar results for most
15 classes and seasons. In general, both local Richardson number methods (Methods 5 and 6)
16 estimate PBL depths that are lower than the other methods throughout the diurnal cycle. The
17 bulk (Method 4) Richardson number method estimates shallower nocturnal PBLs than the K_h
18 methods (Methods 1, 2, and 3) and wintertime PBLs estimated by the TKE method (Method 7)
19 are generally deeper than the other methods.

20 The focus of the discussion here is on illustrations of the significant differences based on the
21 behavior of PBL depths from representative climate classes. Figure 5 shows the seasonal mean
22 diurnal cycle for the cold climate class with warm summers and no dry season (Dfb; during
23 summer 5a and winter 5c) and for the hot, arid desert class (BWh; during summer 5b and winter
24 5d). Summer here is defined as JJA in the Northern Hemisphere and DJF in the Southern
25 hemisphere. Winter is defined as DJF in the Northern Hemisphere and JJA in the Southern
26 Hemisphere. The vertical bars are two standard deviation excursions in either direction, where
27 the standard deviation is computed as the deviation from the seasonal mean PBL depth
28 calculated for each climate class and each year and therefore represents temporal variability.

29 Seidel et al. (2012) provided radiosonde-based climatological PBL depths estimated using the
30 bulk Richardson number method (Method 4) as part of their supplemental material. They

1 estimated the PBL depth from the Integrated Global Radiosonde Archive (IGRA) (Durre and
2 Yin, 2008) over Europe and the United States for the period 1981- 2005. These depths are
3 aggregated by climate class and local time, similarly to the model data, and are plotted with
4 green triangles in Fig. 5. The green circles represent the simulated PBL depths estimated using
5 Method 4 and sampled at the radiosonde locations.

6 For these climate classes, the PBL depths estimated by the K_h methods using a 10% threshold
7 (Method 2, red and Method 3, red dashed) are quite similar as expected in climate classes in
8 which the atmosphere is nearly insensitive to the ability of the model to generate turbulence in
9 the radiative plume. The PBL depths estimated using the bulk Richardson number (Method 4,
10 green), and the three K_h methods (Methods 1, black, Method 2, red, and Method 3, red dashed)
11 give comparable midday results. Although the horizontal TKE definition (Method 7, blue) gives
12 similar midday results as the K_h and bulk Richardson number methods under most conditions,
13 during the winter, the horizontal TKE method often gives mean midday PBL depths that are 100
14 m higher than the other methods (Fig. 5c) associated with the greater wintertime wind shear in
15 the winter storm tracks within the Dfb climate class, and are 500 m higher in the winter (Fig. 5d)
16 due to the wind shear aloft in the desert class.

17 Figure 5 also shows that the methods based on the local Richardson number (Methods 5 and 6)
18 estimate PBL depths that are several hundred meters lower at midday than PBL depths using the
19 other methods. This is the case for all the climate classes studied here. This method does not
20 depend greatly on the critical value chosen as the differences between PBL depths estimated
21 using a critical value of zero are only slightly lower than those estimated using a critical value of
22 0.2. The low PBL depths estimated by the local Richardson number methods make these
23 methods impractical for AGCM-based PBL depth estimates.

24 Planetary boundary layers based on Richardson number methods (local and bulk) are lower at
25 night than those based on K_h or TKE for most classes in summer and winter. This has
26 implications for estimating the shallow nocturnal boundary layer that has been shown to be
27 relevant for constituent transport (e.g. Denning et al., 1995, Jacob et al., 1997, Lin and McElroy,
28 2010). For instance, over climate class BWh (Fig. 5b), the bulk Richardson number nocturnal
29 PBL is well under 500 meters while the K_h methods estimate a PBL depth between 1000 and

1 1500 meters at night during the summer. The exceptions to this pattern occur in cold winter
2 climates where PBL depths are low for all methods (Fig. 5c).

3 The BWh climate class (Fig. 5b, 5d) contains radiosonde observations of the nocturnal boundary
4 layer and during the evening transition from a convective to a stable boundary. The observations
5 are from the American Southwest (one coastal station omitted), each represents a single
6 radiosonde station, and do not sample the large desert regions in Africa and Australia, but they
7 provide some insight into how well the model simulates the nocturnal PBL. The observed
8 boundary layers are lower than those simulated by the model by approximately 100 to 300 m.
9 The radiosonde based estimates sample the PBL depth over the Dfb climate class (Fig. 5a and
10 5c) well because much of Eastern Europe and the northern United States belong to this climate
11 class. Each observed point represents between 1 and 14 stations. Similar to the model behavior
12 in the desert climate class, the model estimates higher nocturnal boundary layer depths than the
13 radiosonde-based estimates during summer (mean difference of 210 m), and winter (mean
14 difference of 155m). During the day, the mean difference between the model and radiosonde
15 estimates during both seasons is more variable with differences ranging from approximately 10
16 m up to 150 m, but model estimates are generally lower.

17 **3.3 Bulk Richardson vs. K_h methods**

18 The bulk Richardson number and K_h methods generally give similar midday results, but under
19 warm, wet conditions the estimated daily maximum PBL depth found using the bulk Richardson
20 number method tends to be lower than the K_h methods (Fig. 6). An example of this behavior is
21 shown by examining the tropical rainforest climate class, but this occurs in the other tropical
22 climate classes during their rainy seasons and for temperate climate classes when it is both warm
23 and the climatological precipitation is high (not shown). This difference in estimated PBL depth
24 means that the bulk Richardson number exceeds its critical value at a level below that which K_h
25 decreases below its threshold value. This implies either a virtual potential temperature inversion
26 or a change in the wind speed within a layer of relatively high K_h .

27 Figure 7 shows the annual mean vertical profiles of total K_h and K_h from the Louis
28 parameterization (7a) and the bulk Richardson number and virtual potential temperature
29 perturbations (mean value of 307.9 K, 7b) from a typical location within the Amazonian
30 rainforest. The horizontal dashed lines indicate the PBL depth found using the total K_h (Method

1 1, Fig. 7a) and bulk Richardson number (Method 4, Fig. 7b). The bulk Richardson number
2 method detects a stable layer below the level at which K_h declines. This is due to the presence of
3 a small inversion in the virtual potential temperature profile evident in Fig. 7c.
4 This behavior could occur under several different meteorological conditions. There could be a
5 turbulent layer aloft that is not fully decoupled from the surface layer that is being detected by
6 the K_h methods, but not by the bulk Richardson number method. Since the Louis turbulence
7 parameterization is dependent upon the local Richardson number (Ri), it contains some
8 information about the vertical profile of temperature and shear. While this is a different form of
9 the Richardson number than the one used in the bulk Richardson number method, the Louis
10 scheme can provide information about what to expect from the bulk Richardson number method.
11 If the K_h predicted by the Louis scheme alone (Fig. 7a) has its maximum in a shallow layer low
12 to the ground before decreasing, it can be expected that the PBL depth found using the bulk
13 Richardson number might also be low. If the Lock scheme is strongly active aloft due to
14 entrainment or radiation, the K_h methods will detect a deeper PBL.

15 **3.4 Impact of the radiative plume**

16 In order to examine the impact of radiative cooling at cloud top, the K_h method using a threshold
17 of 10% of the column maximum was compared diagnostically with (Method 2) and without
18 (Method 3) the contribution from the radiative plume. The difference between these two
19 methods is useful for understanding the influence of clouds on PBL depth in the GEOS-5
20 AGCM. Figure 8 shows the PBL depth difference between the two methods for JJA. At all
21 locations, the PBL depth estimated using the radiative plume is at least as large as that without
22 the radiative plume. The largest differences occur over land in the summer hemisphere and in
23 the Tropics during the evening transition. This result also holds for December, January, and
24 February (DJF) (not shown). The timing of the largest differences (evening) is due to the
25 sensitivity of the radiative plume to cloud top. At night, the total K_h decreases due to the lack of
26 incoming solar radiation, but the diffusivity associated with the radiative plume decreases
27 proportionally less since the cloud does not dissipate during the evening transition. The radiative
28 plume eddy diffusion coefficient thus becomes proportionally more important at night and the
29 PBL depth remains greater. The non-radiative method PBL heights are therefore lower at night,
30 consistent with expectations.

1 Although this study focuses on the sensitivity of simulated PBL depths over land, there are
2 persistent regions of relatively large radiative plume impact over the oceans as well, occurring
3 around 30°N and 45°S. This is due in part to the behavior of the microphysics parameterization
4 in the GEOS-5 AGCM and perhaps to the nature of low level clouds in these regions. The
5 GEOS-5 AGCM uses an empirical estimate of cloud particle radii based on temperature,
6 pressure, and wind. The large differences over oceans are located in regions where the boundary
7 layer clouds contain condensate with small prescribed effective radii and are thus more
8 radiatively active. Since the radiative plume is more active in these locations, PBL depths based
9 on methods sensitive to its impact are greater than depths computed using methods that ignore it.

10 **4 Conclusions**

11 Although the PBL depth is important for AGCMs and its realism has implications for climate
12 and weather prediction, observations are limited and no consensus on definition exists.
13 Complicating things further, under certain conditions, different definitions can give significantly
14 different results. This study examines this issue by evaluating the PBL depth using seven
15 different diagnostic methods so that all differences can be attributed directly to the definition.
16 Results were aggregated to Köppen-Geiger climate classes in order to make broad
17 generalizations and simplify the analysis on a global scale. Intra-class variability was shown to
18 be important, but did not impact the ability to make class-dependent characterizations.

19 Under most conditions, the bulk Richardson number, eddy diffusion coefficient, and horizontal
20 TKE methods give similar midday results over land. The horizontal TKE definition is more
21 sensitive to shear and thus winter storms and so estimates greater midday PBL depths during the
22 winter season. Under warm, moist conditions, the bulk Richardson number method estimates
23 PBL depths that are lower than those estimated by the K_h methods. This indicates that the bulk
24 Richardson number is exceeding its threshold value below the level at which K_h decreases to its
25 threshold value.

26 The impact of longwave cooling from clouds on PBL depth was found to have its strongest effect
27 over land during the evening transition. This was due to the persistence of cloud cover through
28 the diurnal cycle. Additionally, regions of influence were found in the marine boundary layer
29 related to the larger radiative impact in these regions.

1 The local Richardson number methods are relatively insensitive to the critical number used and
2 estimate PBL depths several hundred meters lower than the other methods. These local
3 Richardson number methods were therefore found to be inappropriate for use in an AGCM,
4 probably due to the relatively coarse vertical resolution. The PBL depths found using the local
5 and bulk Richardson number methods are generally lower at night than the PBL depth diagnosed
6 using K_h and TKE methods. We speculate that this result is due to the choice of K_h threshold
7 and that this threshold is more applicable to daytime convective boundary layers than to
8 nocturnal PBLs.

9 The bulk Richardson number method (Method 4) provides the best match with radiosonde-based
10 estimates using this method, as expected, and also provides the most credible diurnal cycle, due
11 in great part to its capture of low nocturnal boundary layer heights. It is therefore the method
12 recommended for use in estimating the AGCM turbulent length scale. Future work will include
13 incorporating the PBL depth estimated using the various methods into the calculation of the
14 turbulent length scale in the GEOS-5 AGCM. Through this length scale, the PBL depth is
15 allowed to modify vertical mixing and tracer transport and the implications for air quality and
16 carbon inversion studies will be analyzed.

17

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4

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1 Table 1. Summary of PBL depth Methods

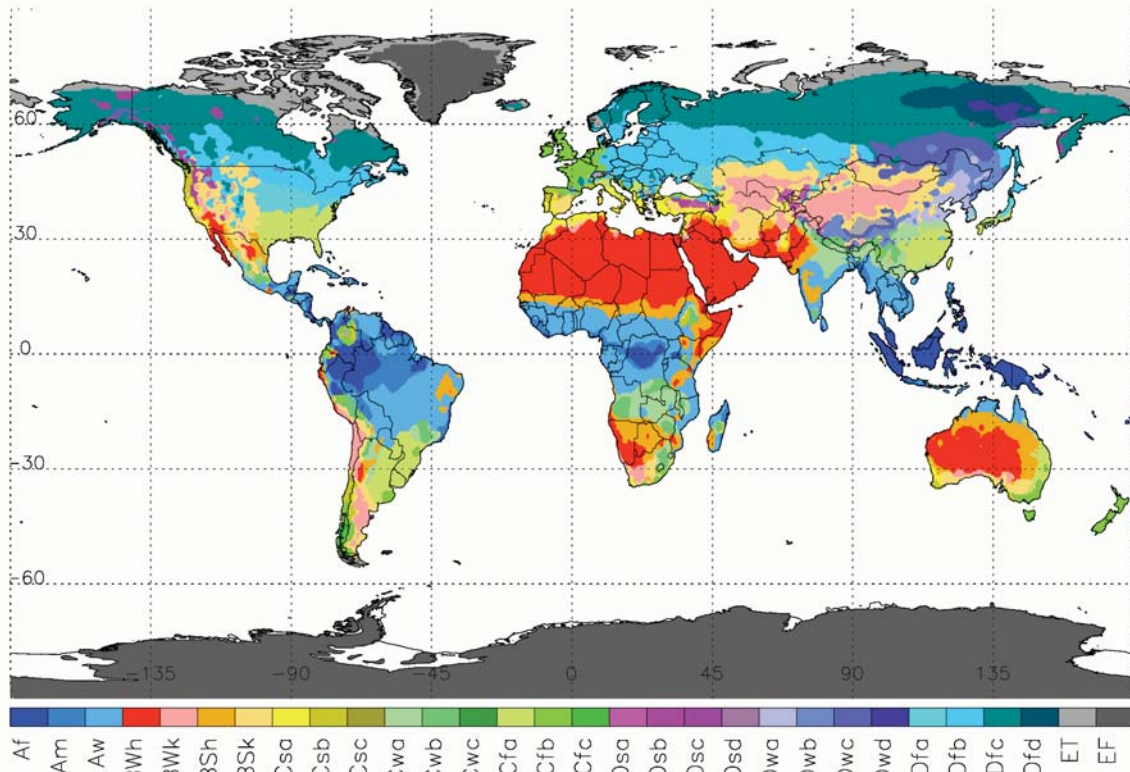
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Method	Abbreviation	Description
1	Kh: 2 threshold	Uses total K_h and a threshold of $2 \text{ m}^2 \text{ s}^{-1}$
2	Kh: 10% threshold, rad	Uses total K_h and a threshold equal to 10% of the column maximum, includes the radiative plume
3	Kh: 10% threshold, no rad	Uses total K_h and a threshold equal to 10% of the column maximum, does not include the radiative plume
4	Bulk Ri	Uses the bulk Richardson number used by Seidel et al. (2012) and a critical value of 0.25
5	$Ri_{crit} = 0.2$	Uses a local Richardson number and a critical value of 0.2
6	$Ri_{crit} = 0$	Uses a local Richardson number and a critical value of 0
7	Horizontal TKE	Uses the diagnosed horizontal turbulent kinetic energy and a threshold of 10% of the column maximum

3

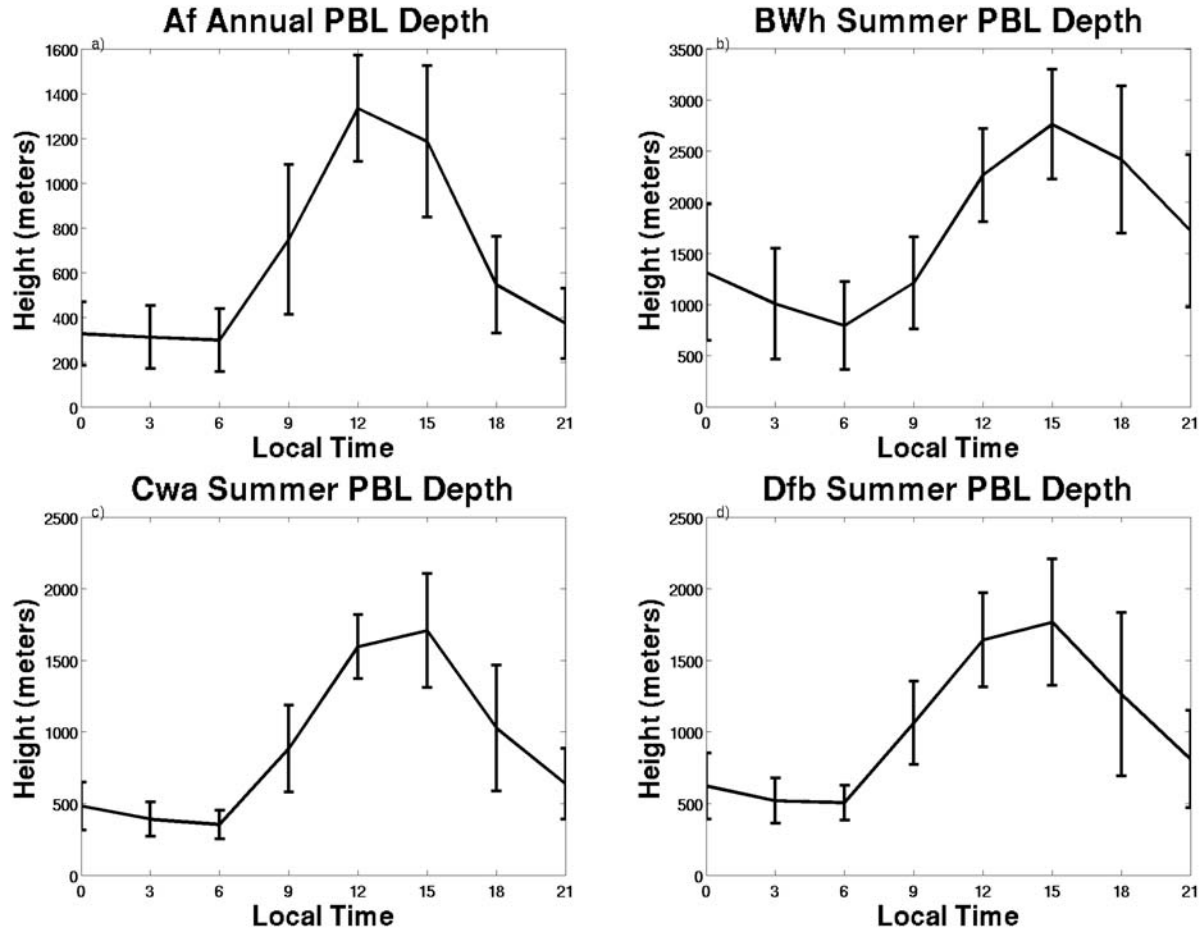
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Köppen–Geiger Classification Types



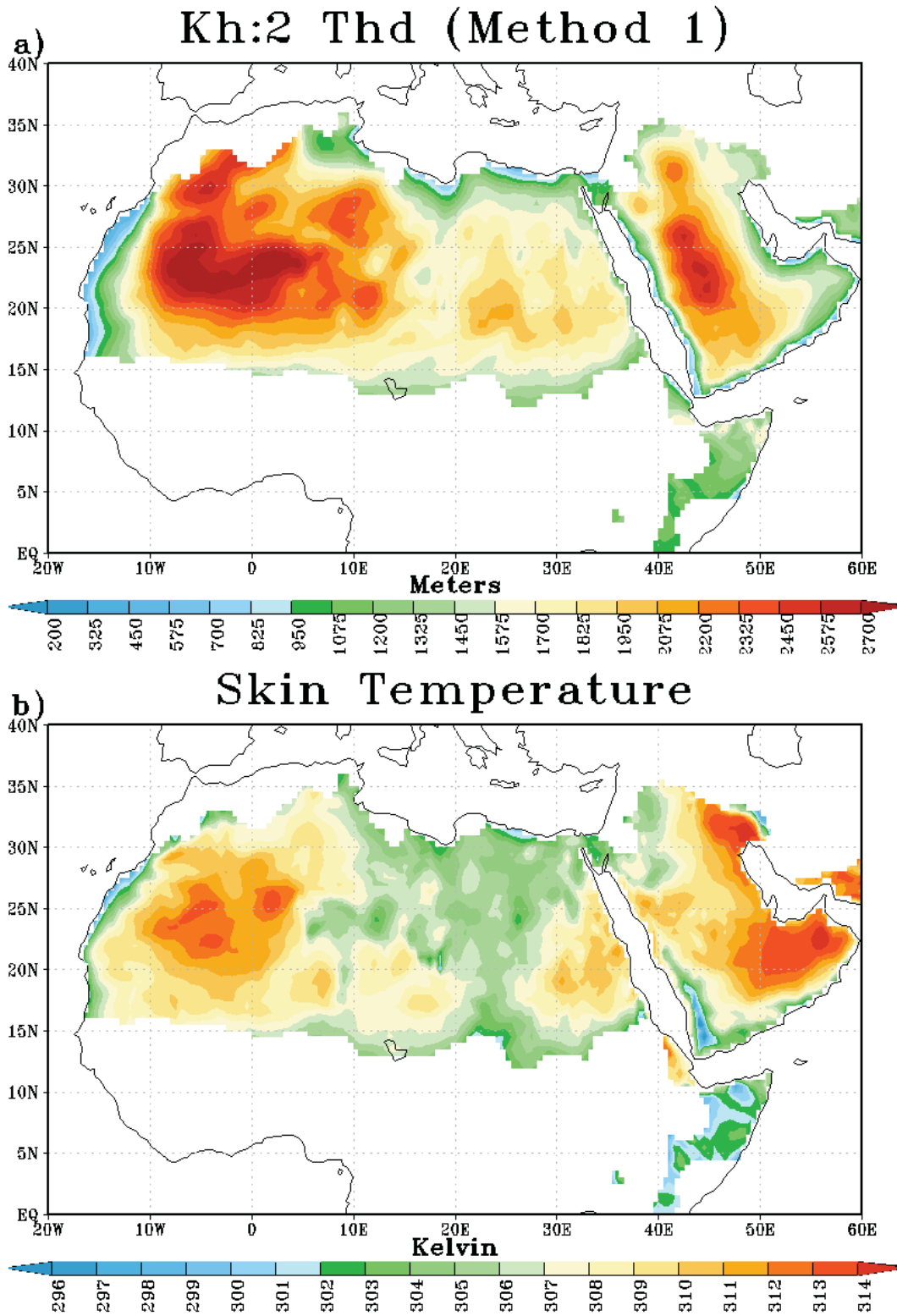
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3 Figure 1. Köppen-Geiger climate classes as determined by Peel et al. (2007) regridded to
4 0.5°x0.5°. The first letter indicates the broad climate class as tropical (A), arid (B), temperate
5 (C), cold (D), and polar (E). Please see Table 1 of Peel et al. (2007) for a full description of the
6 climate classifications.



1
 2 Figure 2. Diurnal cycle of annual mean PBL depth for the tropical forest (Af, 2a) and summer
 3 seasonal mean diurnal cycle of PBL depth for arid, hot desert (BWh, 2b), temperate, dry winter,
 4 hot summer (Cwa, 2c), and cold, warm summer, no dry season (Dfb, 2d) climate classes
 5 estimated using Method 1. Error bars indicate the standard deviation computed globally using
 6 the time mean PBL depth within the climate classes.

7
 8

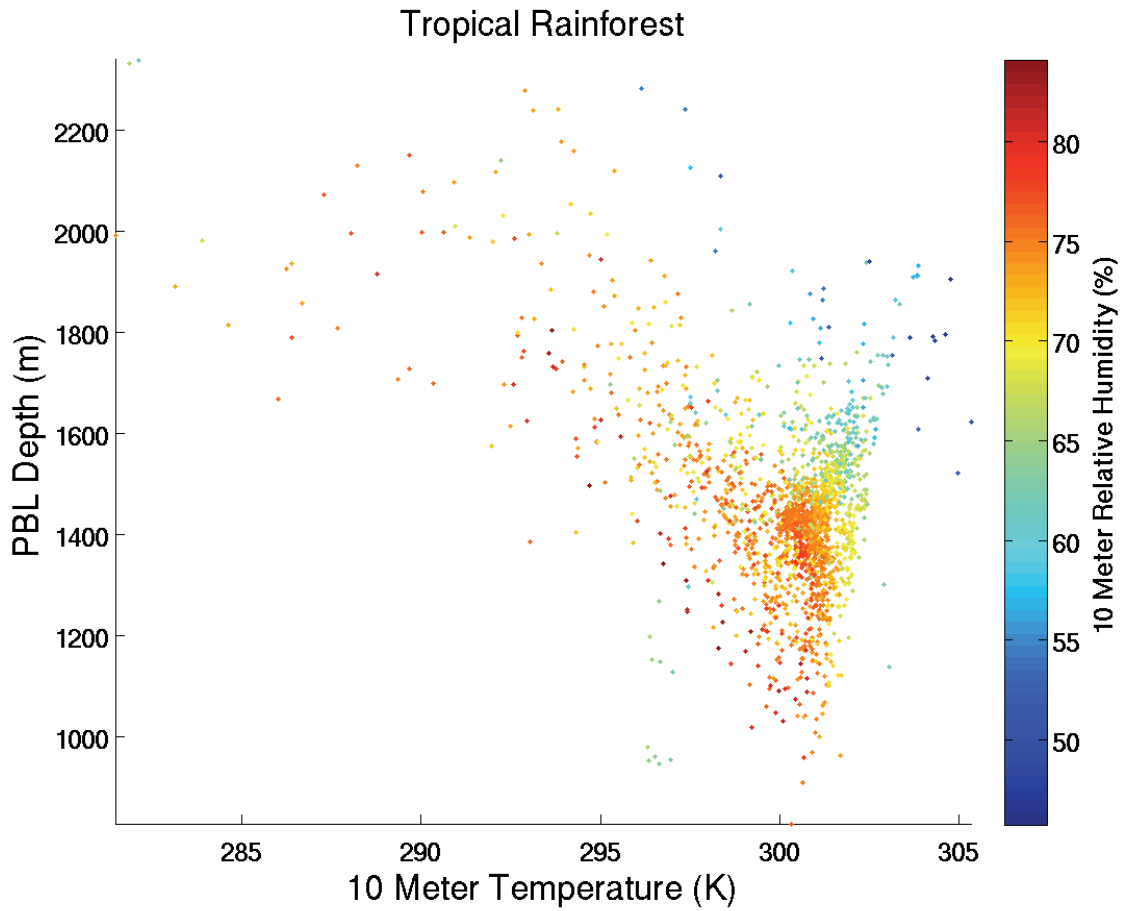


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2 Figure 3. PBL depth (calculated using Method 1) over climate class BWh (hot, arid desert) (3a)

3 and surface skin temperature (3b) in JJA.

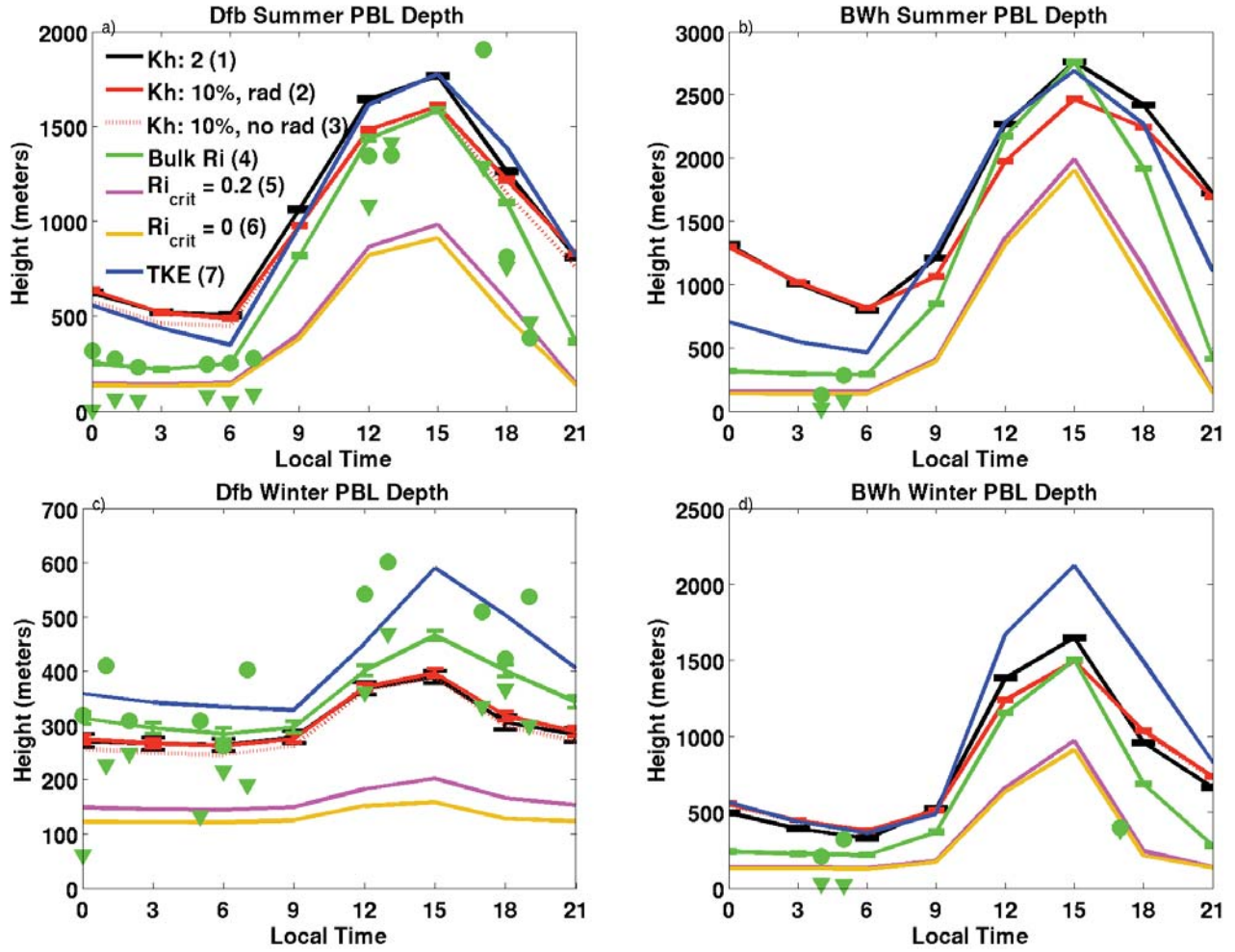
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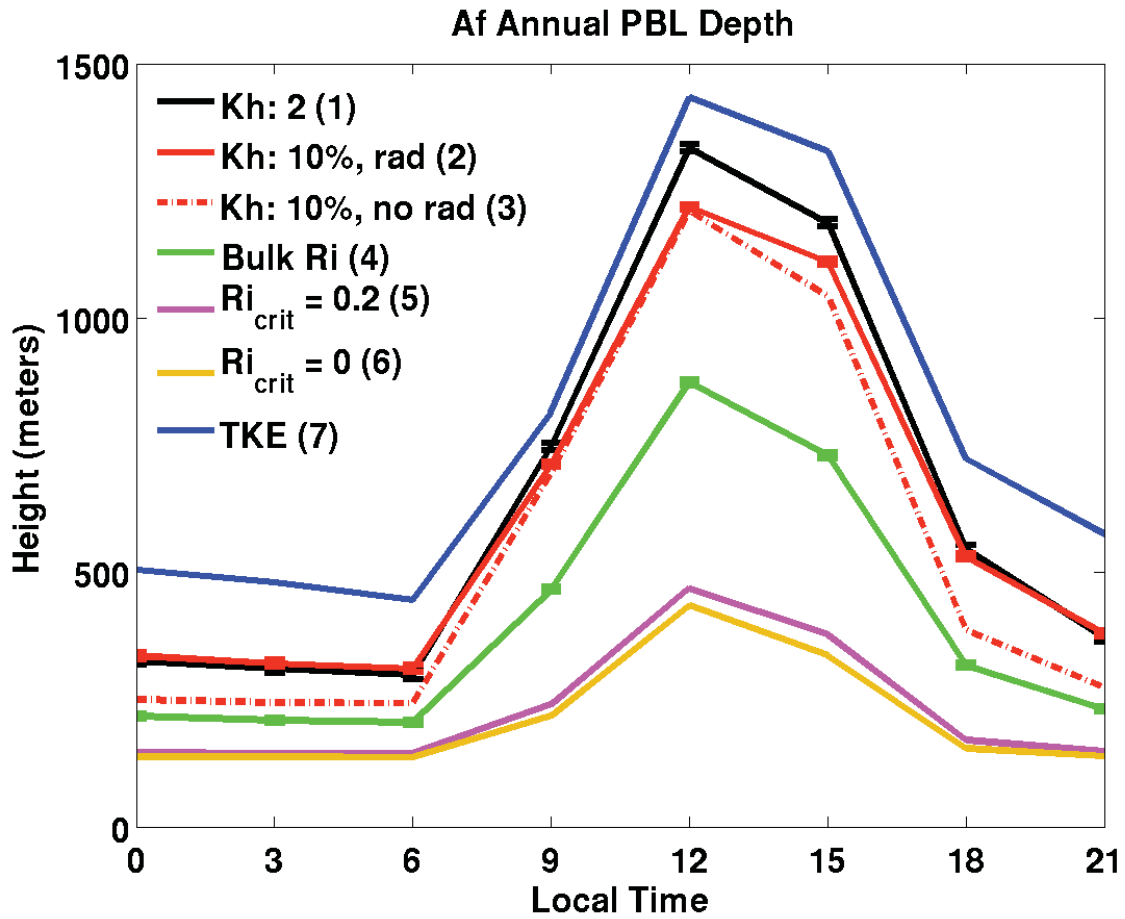
3 Figure 4. Scatter plot of PBL depth versus 10-meter temperature for the tropical rainforest
4 climate class in the annual mean. Each dot represents the mean midday PBL depth and 10 meter
5 temperature. The PBL depth is defined using the K_h definition (Method 1) in the GEOS-5
6 AGCM. The colors highlight the 10 meter relative humidity.

7



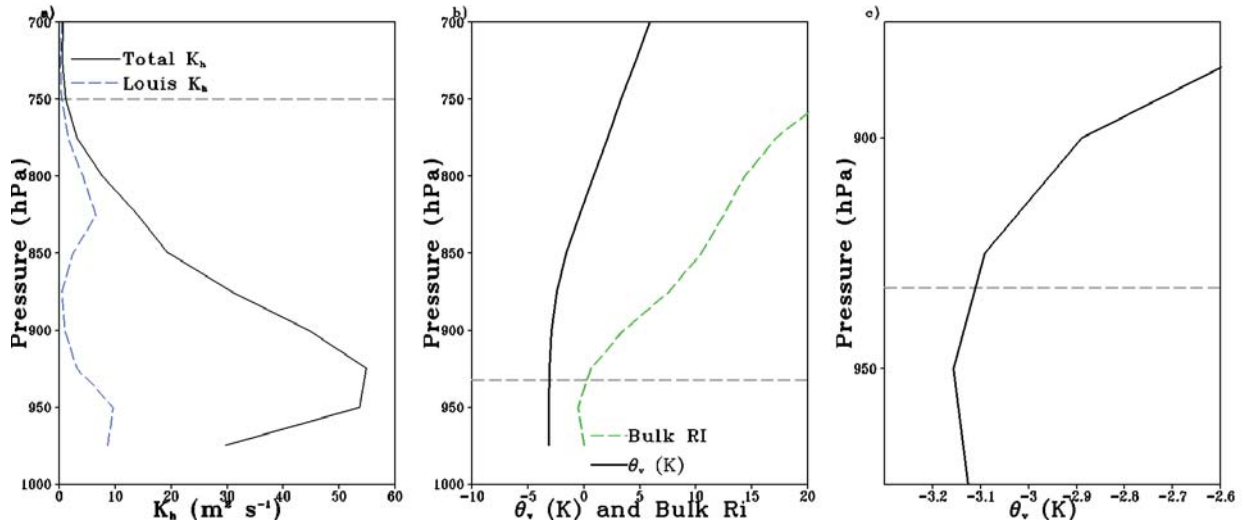
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 2 Figure 5. Seasonal mean diurnal cycle of PBL depth for climate classes Dfb (Cold with warm
 3 summers and no dry season, during summer and winter, 5a and 5c) and BWh (hot, arid desert,
 4 during summer and winter, 5b and 5d) using 7 different methods for estimating the PBL depth.
 5 The error bars represent two standard deviations for methods 1, 2, and 4. The green triangles
 6 indicate the observed PBL depth from the IGRA dataset and the green circles represent the
 7 modeled PBL depth (Method 4, green) at the observation locations.

8



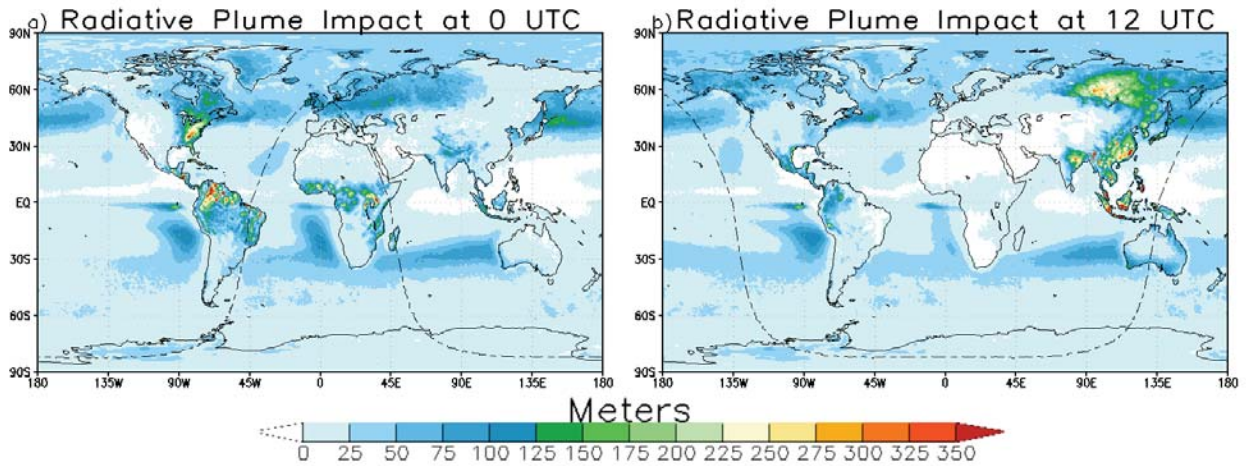
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 2 Figure 6. Annual mean diurnal cycle of PBL depth for climate class Af (tropical rainforest) using
 3 7 different methods for estimating the PBL depth, no radiosonde observations were present for
 4 this climate class. The error bars represent the two standard deviations for methods 1, 2, and 4.

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1
2 Figure 7. Annual mean vertical profile of total and Louis eddy diffusivities (7a), bulk Richardson
3 number and virtual potential temperature perturbation (7b), and a zoomed in image of the virtual
4 potential temperature perturbation (7c) in the Amazonian rainforest (0N, 70W). The dashed lines
5 represent the PBL depth as determined by Method 1 (7a) and Method 4 (7b and 7c).

6



7
8 Figure 8. PBL depth response to radiative plumes during JJA at 0 (8a) and 12 (8b) UTC. The
9 figure shows the K_h method using a 10% of the column maximum threshold including the
10 radiative plume (Method 2) minus the same method, but without the radiative plume (Method 3).
11 The dashed line is the shortwave radiation zero contour line.