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Effects of lower troposphere vertical mixing on simulated clouds and precipitation over the Amazon during the wet season

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Key points: (≤140 characters)

1. disentangle turbulence/cloud/precipitation processes over Amazon and reveal root cause for sensitivity to PBL schemes using the WRF model.
2. FT mixing becomes prominent in the presence of clouds, which in turn supports maintenance of the FT clouds that would otherwise dissipate.
3. Stronger vertical moisture relay transport in ACM2 PBL scheme supports thicker FT clouds, leading to reduced heating and precipitation.

Abstract

Planetary boundary layer (PBL) schemes parameterize unresolved turbulent mixing within the PBL and free troposphere (FT). Previous studies reported that precipitation simulation over the Amazon in South America is quite sensitive to PBL schemes and the exact relationship between the turbulent mixing and precipitation processes is, however, not disentangled. In this study, regional climate simulations over the Amazon in January-February 2019 are examined at process level to understand the precipitation sensitivity to PBL scheme. The focus is on two PBL schemes, the Yonsei University (YSU) scheme, and the asymmetric convective model v2 (ACM2) scheme, which show the largest difference in the simulated precipitation. During daytime, while the FT clouds simulated by YSU dissipate, clouds simulated by ACM2 maintain because of enhanced moisture supply due to the enhanced vertical moisture relay transport process: 1) vertical mixing within PBL transports surface moisture to the PBL top, and 2) FT mixing feeds the moisture into the FT cloud deck. Due to the thick cloud deck over Amazon simulated by ACM2, surface radiative heating is reduced and consequently the convective available potential energy (CAPE) is reduced. As a result, precipitation is weaker from ACM2. Two key parameters dictating the vertical mixing are identified, p, an exponent determining boundary layer mixing and λ, a scale dictating FT mixing. Sensitivity simulations with altered p, λ, and other treatments within YSU and ACM2 confirm the precipitation sensitivity. The FT mixing in the presence of clouds appears most critical to explain the sensitivity between YSU and ACM2.

Plain Language Summary (≤200 words)

Predictions of weather and climate in terms of clouds and precipitation over the Amazon in South America are quite uncertain. This uncertainty has been largely attributed to errors in the planetary boundary layer (PBL) scheme, which represents turbulent mixing. A lack of understanding of the relationship between turbulence, clouds, and precipitation processes prevents us from improving PBL representation in models to achieve better weather and climate simulations.

This study disentangles the turbulence/clouds/precipitation relationship, and identifies the root cause of model errors in PBL schemes using regional climate simulations over the Amazon.

Two PBL schemes, the Yonsei University (YSU) scheme, and the asymmetric convective model v2 (ACM2) scheme, are examined, which show the largest difference in the simulated precipitation. The main difference between the two PBL schemes is the dissipation (YSU) or maintenance (ACM2) of clouds during daytime above the boundary layer, which modulates surface heating and consequently precipitation. The maintenance of a thick cloud deck over the Amazon in ACM2, is caused by enhanced vertical transport of moisture from the surface to above the boundary layer. Such an improved understanding of the turbulence/clouds/precipitation relationship allow us to propose potential solutions to improve PBL schemes in weather and climate models

Keywords: Clouds, precipitation, free troposphere vertical mixing, regional climate dynamical downscaling

1. Introduction

Climate change can cause shifted weather patterns, more extreme weather events, reduced water availability, change in agricultural patterns and increased exposure to disease (Langenbrunner et al., 2019; Prein et al., 2017; Vera et al., 2006b) and other significant impacts on society. Accurate simulation of regional climate and the development of adaptation strategies and corresponding policies are critical. Global climate model (GCM) simulations are too coarse to resolve local forcing and local weather, and their precipitation simulation is generally poor. Cloud-resolving regional climate model (RCM) simulations have emerged in recent years for dynamically downscaling global climate simulations and climate change responses at spatial scales that are more useful for decision making (Huang et al., 2023; Liu et al., 2022; Prein et al., 2022; Prein et al., 2015; Prein et al., 2017; Sun et al., 2016). However, compared to mid-latitude regions, the performance of RCM simulations in reproducing precipitation over tropical regions, such as the Amazon in South America, is understudied (Chakraborty et al., 2020; Prein et al., 2022; Tai et al., 2021).

Noontime and afternoon mesoscale convective systems (MCSs) are the main source of precipitation over the Amazon and thus Amazonian precipitation has a single afternoon peak in diurnal cycle (Giangrande et al., 2017; Giangrande et al., 2020; Prein et al., 2022; Wu et al., 2021a). Moist advection from the Atlantic Ocean by northeasterly trade winds during the austral summer wet season (January - February) and zonal wind convergence are important for precipitation over the Amazon rainforest (Fu et al., 1999) and cloud and turbulence processes play critical roles in modulating precipitation in the region (Barber et al., 2022; Chakraborty et al., 2020; Chakraborty et al., 2018; Prein et al., 2022; Vilà-Guerau de Arellano et al., 2020; Wright et al., 2017). The relationship between processes of clouds, turbulence, and precipitation in the region remains to be disentangled and their modelling uncertainties and sensitivities need to be understood to improve simulations (Giangrande et al., 2017; Giangrande et al., 2020; Prein et al., 2022).

Simulated precipitation over the Amazon is sensitive to the planetary boundary layer (PBL) scheme, but the root cause for such sensitivity and the cause-effect relationship remain to be disentangled (Prein et al., 2022). Within typical weather and climate models, PBL schemes parameterize unresolved turbulent mixing within the PBL and the free troposphere; the PBL schemes are therefore critical for reproducing the bulk boundary layer structures and profiles in the whole atmospheric column, as well as their subsequent effects on weather and climate simulations. Many studies (Gunwani & Mohan, 2017; Hu et al., 2012; Hu et al., 2013a; Hu et al., 2010a; Hu et al., 2019; Wang & Hu, 2021) have evaluated the performance of various modern PBL schemes, with most of them focusing on continental cloud-free PBL. Compared to continental clear PBL, much less is known about the performance of PBL schemes in presence of clouds (Angevine et al., 2012; Huang et al., 2013; Supinie et al., 2022; Valappil et al., 2023; Yang et al., 2019).

PBL schemes can be classified into local and nonlocal schemes. Local schemes estimate the turbulent fluxes at each point in a model from the mean atmospheric variables and/or their gradients at that point, whereas nonlocal schemes include turbulent fluxes based on the atmospheric variables and their variations over a deeper layer covering multiple model levels through the PBL (Cohen et al., 2015; Hu et al., 2010a). The assumption among local schemes that fluxes depend solely on local values and local gradients of model state variables is least valid under convective conditions when turbulent fluxes are dominated by large eddies that transport fluid over longer distances (Hu et al., 2010a). Previous studies found that traditional local schemes (e.g., Mellor–Yamada–Janjić (MYJ) or quasi-normal scale elimination (QNSE)) predict daytime continental boundary layers that are too cool and shallow; while schemes that include non-local treatment, such as the asymmetrical convective model, version 2 (ACM2, Pleim, 2007a), the Yonsei University (YSU, Hong et al., 2006) schemes and the more recently-updated local scheme (e.g., Mellor–Yamada Nakanishi and Niino (MYNN, Nakanishi & Niino, 2006)) predict deeper and warmer daytime continental boundary layers than MYJ and QNSE (Bright & Mullen, 2002; Clark et al., 2015; Coniglio et al., 2013). Also, nonlocal PBL schemes can reproduce the slightly stable upper convective boundary layer while local schemes often fail to do so (Hu et al., 2019; Wang et al., 2016).

Recent PBL development has started to use the mass flux (MF) approach that has been commonly used in cumulus parameterization schemes for large-eddy nonlocal mixing together with the eddy-diffusivity (ED) closure parameterizing local mixing, such as the MYNN-EDMF scheme (Angevine et al., 2010; Olson et al., 2019a; Olson et al., 2019b; Pergaud et al., 2009). Note that MYNN-EDMF parameterizes specifically nonlocal mixing associated with shallow cumulus clouds, thus a convective parameterization is still needed to parameterize deep convection if the grid spacing is not fine enough to explicitly represent deep convection. Most previous PBL modeling studies focus on treatments within the boundary layer while free-troposphere treatments rarely receive much attention (Hu et al., 2012; Lu & Wang, 2019; Zhu et al., 2021; Zhu et al., 2019), likely because that free-troposphere turbulence is weak under clear conditions and the impact of its parameterization on weather and climate simulations is regarded as minor.

Huang et al. (2021) and Huang et al. (2023) conducted nested-domain RCM simulations with grid spacings of 15 and 3 km over the Amazon with different physics schemes. It is found that the simulated precipitation is most sensitive to PBL schemes with the YSU scheme significantly overpredicting Amazonian precipitation and the ACM2 scheme predicting the weakest precipitation. Extending the work of Huang et al. (2023), this study aims to understand the precipitation sensitivity over the Amazon at a process level and identify the root cause for the different model behaviors, with particular attention paid to the behaviors and effects of PBL schemes in cloudy environments, and both inside and above the PBL. Effects of lower troposphere vertical mixing on simulated clouds and precipitation over the Amazon will be elucidated.

The rest of this paper is organized as follows: In section 2, precipitation data, model configurations, and numerical experiment design are described. In section 3, clouds/precipitation sensitivity to PBL schemes is diagnosed using simulations with YSU and ACM2 and their variants with altered turbulence treatments, followed by discussion of such sensitivity at a finer resolution. Meanwhile the turbulence/cloud/precipitation processes over the Amazon are examined. Finally, section 4 contains a summary and discussion of the main findings.

2. Precipitation data, model configuration and numerical experiment design

a) Precipitation data

Two gridded global precipitation datasets are used in this study to compare with simulations, including (1) half-hourly Integrated Multi-satellitE Retrievals for GPM (IMERG) at a horizontal resolution of 0.1° × 0.1° (Huffman et al., 2019), and (2) half-hourly National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) MORPHing Technique (CMORPH) global precipitation analyses at a horizontal resolution of ~8 km (Joyce et al., 2004).

b) Model configurations

Huang et al. (2021) and Huang et al. (2023) used the Weather Research and Forecasting (WRF) model Version 4.2.1 (Skamarock & Klemp, 2008; Skamarock et al., 2021) to perform historical simulations over South America during January-February 2019 in preparation for future regional climate dynamic downscaling. The simulations used hourly European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5, Hersbach et al., 2020) for initial and boundary conditions. Two one-way nested domains with 15- and 3-km horizontal grid spacings cover the entire South America and the Peruvian central Andes region, respectively (see Fig. 1a for domain coverage). Both domains use 61 stretched vertical levels topped at 20 hPa. Following previous dynamic downscaling practices (Hu et al., 2018; Miguez-Macho et al., 2004, 2005; Wang & Kotamarthi, 2013), spectral nudging technique is applied to the outer 15-km domain to maintain large-scale circulations at a 1500 km scale, while allowing WRF to evolve smaller-scale dynamics and physics. Twelve sensitivity experiments were conducted by Huang et al. (2023) with varied PBL, microphysics schemes, and land surface models while other physics parameterizations were kept the same among the sensitivity experiments, including revised MM5 Monin-Obukhov surface layer scheme (Jiménez et al., 2012), and the Rapid Radiative Transfer Model for GCMs (RRTMG) longwave and shortwave radiation scheme (Iacono et al., 2008). The Tiedtke cumulus parameterization scheme (Tiedtke, 1989) is used on the 15-km outer domain to handle both shallow and deep convections but not on the 3-km inner domain.

These WRF downscaling simulations are found to be most sensitive to PBL schemes with the YSU scheme significantly overpredicting Amazonian precipitation, the ACM2 scheme predicting the weakest precipitation, and the MYNN-EDMF prediction being in the middle. Such relative differences are maintained with altered microphysics schemes and land surface models (LSMs). Simulations with the Thompson microphysics scheme (Thompson et al., 2008), and the Noah LSM (Chen & Zhang, 2009) are chosen to investigate PBL sensitivities in this study. Diagnosing the root cause for the differences between the YSU and ACM2 PBL schemes and disentangle the impact of PBL schemes on precipitation are the foci of this study. Since simulated precipitation is quite sensitive to some other parameterization, such as cumulus schemes (Hu et al., 2018), and there are large uncertainties among different precipitation data (Chen et al., 2022), recommending an optimal PBL scheme in terms of reproducing precipitation is beyond the scope of this study, which may require more advanced profile measurements (e.g., cloud water profile) and more accurate precipitation data to justify as will be seen in our later analyses.

c) Sensitivity simulations with altered treatments in ACM2 and YSU

In addition to the simulations conducted by Huang et al. (2023), eight more sensitivity simulations (summarized in Table 1) are run to help identify the root cause of the differences between ACM2 and YSU, and resolution dependence of the differences, as well as to examine impact of turbulent processes on cloud and precipitation processes. ACM2 and YSU differ in their treatments in both PBL and free troposphere. Sensitivity simulations adjusting either PBL or free-troposphere mixing treatments or both are conducted.

In the PBL, while a counter-gradient term is added to the eddy diffusion equation to handle nonlocal mixing in YSU, ACM2 explicitly simulates the transilient nonlocal mass flux. For the local mixing in the PBL, both ACM2 and YSU use a polynomial function/profile (so called K-profile, Noh et al., 2003) to define the vertical mixing coefficient K_z for temperature and moisture as:

$$K_z = Pr^{-1} k \frac{u_*}{\emptyset} z(1 - \frac{z}{h})^p \tag{1}$$

where Pr is the Prandtl number, k is the von Karman constant, ϕ is the similarity profile function, z is the height above ground level, and h is the PBL height. Thus, ACM2 and YSU are also categorized into the K-profile PBL schemes (Hu et al., 2019). In YSU and ACM2, the value of the exponent p in (1) is set to 2 by default, but its optimal value may vary from 0.5 to 3 depending on flow conditions, with a larger/smaller p yielding smaller/larger K_z (Hu et al., 2018; Hu et al., 2010b; Nielsen-Gammon et al., 2010; Troen & Mahrt, 1986). While a similar local mixing treatment is adopted in ACM2 and YSU, there are many differences in their parameter values, profile functions, methods to diagnose PBL height, etc. ACM2 generally simulates stronger vertical mixing in the PBL and higher PBL height under clear conditions (Hu et al., 2010a). Since p effectively dictates the vertical mixing within the PBL, p is varied in sensitivity simulations to understand model differences and physics processes including turbulence, clouds, and precipitation (see experiment YSUp.5 in Table 1).

In the free troposphere, only local mixing is considered in YSU and ACM2 (Hong, 2010; Nielsen-Gammon et al., 2010; Pleim, 2007b). Both YSU and ACM2 compute the K_z as a function of mixing length l, vertical wind shear S, and the stability function $f(Ri)$:

$$K_z = l^2 S f(Ri) \, , \qquad (2)$$

in which

$$\frac{1}{l} = \frac{1}{kz} + \frac{1}{\lambda} \, , \qquad (3)$$

where Ri is the Richardson number, and λ is the asymptotic length scale. Such first-order parameterizations of turbulent vertical mixing are widely used in operational numerical weather prediction (NWP) and climate models (Beare et al., 2006; Cuxart et al., 2006). ACM2 and YSU differ in their parameter values, Ri calculation within clouds, and stability functions. Both ACM2 and YSU use moist-air Ri calculation adapted from Durran and Klemp (1982), but YSU requires two layers of clouds to activate the moist-air Ri calculation between the two layers while ACM2 only requires one layer, in addition to other differences in parameters. Note that these PBL parameterizations only consider local in-cloud turbulent mixing, non-local in-cloud mixing needs to be accounted for by a cumulus parameterization scheme on the convection-parameterized grid or explicitly resolved by the convection-permitting grid. Much of the improvement to such parameterizations (Eqs. 2-3) in NWP and climate models involved adjusting the stability functions (for example short vs. long-tailed functions) and λ (Cuxart et al., 2006). λ is adjustable and varies between 30 and 250 m in numerical models (Cuxart et al., 2006; Liu & Carroll, 1996; Nielsen-Gammon et al., 2010). λ is set to 30 m in the YSU scheme and to 80 m in the ACM2 scheme. Sensitivity simulations are conducted in this study by replacing the whole free-troposphere treatments (experiment YSUuseACM2free in Table 1) or only altering the value of λ (experiment ACM2λ30 in Table 1).

The sensitivity simulations are conducted with the outer 15 km domain because the difference between inner-domain outputs from our nested-domain runs with different configurations are rooted from the different simulations in the outer 15km domain, as we will see in our analysis. Thus, the conclusions from these sensitivity simulations have implications for regional and global models that run at convection-parameterized resolutions. In addition, four sensitivity simulations with a single domain covering the majority of the Amazon with a 3 km grid spacing (experiments 3kmYSU, 3kmYSUp.5, 3kmYSUp.5useACM2free, 3kmACM2 in Table 1) are also conducted to examine the applicability of conclusions obtained at 15 km grid spacing to convection-allowing simulations.

3. Results

a) Cause of precipitation differences simulated with different PBL schemes

As stated earlier, WRF simulations over South America during January-February 2019 are conducted with 12 different physics schemes, including PBL, microphysics schemes and land surface models (Huang et al., 2023). The simulated precipitation is most sensitive to PBL schemes (Huang et al., 2023) with the YSU scheme predicting the strongest daily precipitation rate while the ACM2 scheme predicting the weakest precipitation over the Amazon during the summer wet season (Fig. 1). The relative strength of simulated precipitation between ACM2 and YSU remains across different resolutions, including the convection-parameterized (15 km grid spacing) and convection-permitting (3 km grid spacing) resolutions. The precipitation rate increases with increased resolution. The YSU runs at 3 km grid spacing (including the nested run focusing on Peru and the single-domain run focusing more on the Amazon) significantly overestimate daily precipitation rate (Figs. 1c-f). The South America Affinity Group (SAAG) led by National Center for Atmospheric Research (NCAR) also reported that a WRF simulation using the YSU scheme at a grid spacing of 4 km over South America overestimated precipitation over the Amazon (Liu et al., 2022).

Precipitation over the Amazon is dominated by mid-day and afternoon MCSs (Giangrande et al., 2017; Giangrande et al., 2020; Prein et al., 2022; Wu et al., 2021a). Huang et al. (2021) and Huang et al. (2023) evaluated the simulated diurnal variation of precipitation. All WRF simulations with different configurations reproduce the afternoon precipitation peak with biases in intensity and timing. ACM2 scheme shows the best agreement with observations and the difference between different PBL schemes are most significant in the afternoon (Fig. 2). Thus, we will focus on the precipitation and related processes during daytime. During mid-day hours, YSU simulates stronger hourly precipitation rates than ACM2 and overestimates precipitation at both resolutions and over different domains (Figs. 2, 3).

Causative factors for the different precipitation simulated by ACM2 and YSU over the Amazon are herein investigated. The impact of different PBL schemes on NWP and climate simulations is more straightforward under clear conditions while their impacts on precipitation is less clear. Often the impact of PBL schemes on precipitation is not conclusive because the schemes produce different (stronger or weaker) precipitation in different cases (Bright & Mullen, 2002; Cohen et al., 2015; Gopalakrishnan et al., 2023; Jankov et al., 2005; Jankov et al., 2007; Li & Pu, 2008; Supinie et al., 2022; Wu et al., 2021b; Zhang et al., 2013). Under clear conditions, ACM2 simulates stronger boundary layer vertical mixing and deeper PBL than YSU due to different treatments for nonlocal fluxes and different parameters/functions in the *K*-profile local mixing (Hu et al., 2010a; Nielsen-Gammon et al., 2010; Shin & Hong, 2011; Xie et al., 2012). How such differences translate to significantly different precipitation with the two schemes is the main question to be answered in this study.

Surface temperature shows distinct differences over the Amazon with the ACM2 simulating lower continental temperatures than YSU by 0.5-0.8 ^{o}C over the simulation domains around noon (Fig. 4), which likely leads to less surface energy to feed MCSs. The lower temperature simulated by ACM2 covers the main precipitation region over the Amazon (Fig. 4g) and can likely explain the precipitation difference. However, such temperature differences cannot be explained by the direct impact of PBL mixing. Prior work has shown that during daytime, ACM2 simulates stronger mixing in the PBL and stronger PBL-free troposphere exchange generally warming up the PBL due to entrainment of free troposphere air with higher potential temperature (Hu et al., 2010a; Shin & Hong, 2011). Thus, the direct impact of ACM2 PBL mixing should lead to higher surface temperature, rather than the lower temperature obtained in the regions of precipitation.

Rather, the temperature difference between ACM2 and YSU simulations is more directly related to the difference in surface downward shortwave radiation. ACM2 simulates less shortwave radiation at the surface over the Amazon region (Fig. 5g), where cloud coverage is significant (Fig. 5j). At 17 UTC (12-14 LST across south America), the average surface shortwave radiation simulated by ACM2 is lower by ~70 W m^{-2} than the YSU runs. Thus, the lower temperature simulated by ACM2 should be due to indirect effects of vertical mixing via interactions with clouds and radiation.

Significant cloud coverage over the Amazon (Kay et al., 2016; Kay et al., 2012) is a characteristic distinguishing this study from most other studies of PBL schemes. Over the Amazonian region, ACM2 simulates a thicker cloud deck (Fig. 6,7), which reduces downward shortwave radiation (Fig. 8), consequently leading to a lower surface temperature. As a result, the surface-based convective available potential energy (CAPE) is lower in the ACM2 simulations (Fig. 9), which would lead to weaker daytime precipitation. The significant difference between YSU and ACM2 is mostly confined over the cloud region (Fig. 5 & 8), which further confirms that indirect effects of vertical mixing over the Amazon via interactions with clouds dominate its direct effects.

The cloud deck over the Amazon therefore appears to be a critical link to disentangle the impact of PBL schemes on simulated precipitation. The low-level clouds are produced by shallow convections and mid-level clouds are produced by deep convections either from isolated convective towers typically in daytime or from propagating MCS typically during nighttime. During daytime, while the clouds simulated with the YSU scheme dissipate gradually from the early morning maxima, clouds simulated with the ACM2 scheme are still sustained through the day (see cloud cross-sections at 11 - 21 UTC in Fig. 6). Daytime cloud thinning is likely due to solar heating under condition of lack of water vapor supply available for condensation (Adebiyi et al., 2020; Burleyson & Yuter, 2015; Painemal et al., 2015; Zhang et al., 2010). The thicker cloud deck simulated by ACM2 appears to be due to enhanced supply of boundary layer moisture to the layers above (Fig. 10a), thus less boundary layer moisture by 0.6 g kg^{-1} and more free troposphere moisture by 0.2 g kg^{-1} compared to the YSU run (Fig. 10b), through enhanced boundary layer vertical mixing (Hu et al., 2010a; Shin & Hong, 2011).

In the nested-domain simulations, surface temperature simulated by ACM2 is lower than YSU in both 15 and 3 km domains (Fig. 4) and the resulting lower precipitation occurs in both domains. The root cause of lower surface temperatures from ACM2 in the nested 3 km domain is less clear due to the possible effect of 15 km simulations via advection through its lateral boundaries. Thus, the main discussions below (in section b) will focus on further investigation of PBL-clouds-precipitation relationship in the outer 15 km domain with additional simulations with altered treatments, while their relationship at the convection-permitting resolution will be examined with additional single-domain simulations with a 3 km grid spacing (in section c).

b) Impact of different turbulence treatments on clouds and precipitation

Lower troposphere turbulence plays important roles in cloud production and maintenance (Lilly, 1968). This section discusses results of sensitivity simulations adjusting turbulence treatments in YSU and ACM2. Since under clear conditions, ACM2 has stronger daytime boundary layer mixing than YSU (Hu et al., 2010a; Shin & Hong, 2011), vertical mixing in the YSU PBL scheme is first enhanced to see if the simulated clouds and precipitation would become closer to those simulated by ACM2. The exponent p in the K-profile in YSU (default value is 2) is reduced to 0.5 in experiment YSUp.5 to enhance daytime boundary layer mixing, as indicated by the K_z profiles in Fig. 10d. With p=0.5, YSUp.5 simulates higher PBL top height (Fig. 10d). As a result, more near-surface moisture is transported to the top of the elevated PBL, where a thicker cloud layer near the PBL top forms (Fig. 7c & Fig. 10c). Note that while the nonlocal mixing is proportional to K_z in YSU, transilient nonlocal fluxes are explicitly simulated by ACM2, which is not shown in Fig. 10. Thus K_z profiles in Fig. 10d are more indicative of total mixing in the boundary layer for YSU, but less so for ACM2. In the free troposphere where there are no nonlocal mixing treatments for either scheme, thus K_z profiles are indicative of free-troposphere mixing for both.

As the PBL grows in the daytime, the PBL top clouds simulated by both YSU and ACM2 keep elevating (Fig. 6). A more prominent/distinct PBL top cloud layer is simulated by YSU (Fig. 6c,e, PBL top is marked by black dash lines) while the PBL top clouds simulated by ACM2 are indistinctive from the free-troposphere clouds (Fig. 6d,f). Existence of a PBL top cloud layer over the Amazon was previously illustrated by cloud frequency data observed during the GoAmazon 2014/5 field experiments (Giangrande et al., 2017; Giangrande et al., 2020). However, that dataset only provides cloud frequency, not cloud amount. To quantitatively verify the simulated PBL top cloud layer, more advanced cloud dataset is needed.

The thickened PBL top clouds simulated by YSU with p=0.5 weakens surface shortwave radiation (Fig. 8) and consequently lowers surface temperature and CAPE (Fig. 9), thus reduces precipitation (Fig. 11). Such a precipitation sensitivity to boundary layer mixing over the Amazon is consistent with that reported over the eastern United States (Hu et al., 2018). However, YSU with p=0.5 does not reduce precipitation to the level simulated by ACM2 (Fig. 11). In comparison, ACM2 simulates a more prominent cloud layer at a higher elevation (~4-5 km above ground) while the clouds simulated by YSU at this altitude (with both default p value and p=0.5) weaken in time during the day (Fig. 6). Thus, boundary layer mixing alone cannot completely explain the different impacts of ACM2 and YSU on clouds.

In addition to the different treatments within the boundary layer, ACM2 and YSU also differ in their treatments in the free troposphere. A YSU sensitivity simulation using ACM2's free-troposphere mixing treatment (named $\mathrm{YSUuseACM2free}$) is conducted to examine the impact of free troposphere mixing. $\mathrm{YSUuseACM2free}$ simulates a stronger vertical mixing up to 7-8 km above the ground, particularly in the presence of clouds, similar to the ACM2 simulation (Fig. 10d). In the absence of clouds, the free-troposphere mixing simulated by different PBL schemes are all similar and weak (Figure S1 in Supporting Information). Higher aloft (>8 km), ice and snow clouds dominate and peak in the afternoon (likely due to detrainment of deep convection), and the sensitivity of vertical mixing is small and K_z is simulated to be mostly less than 1 $m^2 s^{-1}$ by all schemes. Thus, our analysis focuses on the lower free troposphere. As a result of stronger mixing in the lower free troposphere, a thicker cloud deck at 4-5 km above ground (Fig. 7d), similar to ACM2 (Fig. 7b), develops in the simulation, due to stronger moisture supply from the PBL top (Fig. 10a). Consequently, surface temperature is reduced due to cloud shield, and the precipitation is reduced, to be closer to that of ACM2 than $\mathrm{YSUp.5}$ (Fig. 11). Combining both p=0.5 and ACM2's free-troposphere mixing, $\mathrm{YSUp.5useACM2free}$ simulates a similar, but slightly thicker cloud deck (Fig. 7e) and slightly weaker precipitation than $\mathrm{YSUuseACM2free}$ (Fig. 11). The mean free-troposphere clouds over Manaus (Fig. 10c) simulated by YSU, $\mathrm{YSUp.5}$, $\mathrm{YSUuseACM2free}$, $\mathrm{YSUp.5useACM2free}$, ACM2 are 15.4, 17.5, 62.6, 73.7, 72.4 mg kg^{-1} respectively, among which the ones using ACM2's free-troposphere treatment are grouped together. Different clouds are the net results of the different K_z, which is as large as a factor of >20 in the free troposphere in the presence of clouds. These experiments illustrate that free-troposphere mixing is the most critical difference between YSU and ACM2 in terms of simulating clouds and precipitation, while the mixing in the PBL plays a secondary role.

For free troposphere vertical mixing, ACM2 and YSU differ in their parameters, moist-air Ri calculation, and the stability functions. Previous studies identified λ as a critical parameter for free-troposphere mixing (Cuxart et al., 2006; Hu et al., 2012; Nielsen-Gammon et al., 2010), and here its impact is further examined. An ACM2 sensitivity simulation with λ=30 (named ACM2λ30) is conducted to verify its impact on clouds/precipitation. Comparing to default ACM2 with λ=80, ACM2λ30 simulates a much weaker mixing in the free troposphere (Fig. 10d), and consequently a much thinner cloud deck at 4-5 km above ground and meanwhile the PBL top clouds appear thicker (Fig. 7f), due to weaker vertical transport of moisture from the PBL top to higher levels (Fig. 10a). The net result is that the surface radiation is enhanced (Fig. 8f), temperature is higher, and more precipitation is produced (Fig. 11f). The precipitation simulated by ACM2λ30 is not as strong as that simulated by YSU because of other differences in free-troposphere and PBL mixing treatments.

All the above results together suggest a prominent *PBL-free-troposphere moisture relay transport process*: Step 1, boundary layer mixing transports moisture to the PBL top where clouds form; step 2, free-troposphere mixing transports the moisture further to higher levels (~ 4-5 km) to sustain a thick cloud deck at that altitude and reduce the boundary layer top clouds somewhat. *ACM2 simulates a strong PBL-free-troposphere moisture relay transport process.* Comparing to YSU, ACM2 simulates less PBL moisture (by 0.5 g kg^{-1}) and more free troposphere moisture (by 0.2 g kg^{-1} at 3-6.5 km above ground, Fig. 10b) in monthly average. Consequently, the free-troposphere cloud layer is better maintained during daytime. In contrast, the moisture relay transport process simulated by YSU is weaker and the clouds at ~ 4-5 km dissipate quicker during daytime, leading to less cloud coverage, more CAPE and precipitation. Modified YSU with enhanced PBL and free-troposphere mixing (YSUp.5useACM2free) produces similar moisture transport as ACM2 (Fig. 10b,d) hence reduced precipitation. These results suggest that free-troposphere mixing may become prominent in the presence of clouds (which otherwise would be weak as generally regarded) and become an important step in the relay transport process. To verify the strength of such relay transport process, more advanced observations, such as long-term vertical profiles of cloud mixing ratios, are warranted. Our results also suggest that to correctly simulate clouds/precipitation in environments similar to those of the Amazon, the ability of models in reproducing such moisture relay transport processes needs to be carefully assessed.

c) Sensitivity of clouds and precipitation to different turbulence treatments at a convection-allowing resolution

The sensitivity of simulated clouds and precipitation to boundary layer and free-atmosphere vertical mixing discussed above is mainly based on simulations at 15 km grid spacing where cumulus parameterization is employed. Thus, the conclusions are directly applicable to global and regional weather and climate simulations/predictions at convection-parameterized resolutions. Whether these conclusions are still valid at convection-permitting resolutions requires additional examination. To avoid the possible effects of the driving 15 km grid on the nested 3 km grid, single-domain sensitivity simulations are conducted that cover a majority of the Amazon with a 3 km grid spacing that use ERA5 data directly as lateral boundary conditions. These simulations include 3kmYSU, 3kmYSUp.5, 3kmYSUp.5useACM2free, and 3kmACM2 (as summarized in Table 1). Even though simulated precipitation rate is generally higher at the 3 km grid spacing than at 15 km grid spacing, the same turbulent mixing → clouds → precipitation impact/sensitivity holds in these convection-permitting simulations (Fig. 12, 13). That is, 1) YSU simulates stronger daytime precipitation rate than ACM2 (by 60% at noon time, 16 vs. 10 mm day^{-1}, Fig. 13a,b); 2) Stronger boundary layer mixing simulated by YSU with p=0.5 leads to more PBL top clouds (Fig. 12c), which block more shortwave radiation and reduce daytime surface temperature and consequently precipitation (with 13 mm day^{-1} at noon, Fig. 13c); 3) Using the free-troposphere mixing treatment of ACM2 in YSU simulates a more prominent cloud layer at 4-5 km above ground (Fig. 12d) which more effectively blocks shortwave radiation and reduces precipitation (with 11 mm day^{-1} at noon, Fig. 13d) that is closer to the precipitation rate of ACM2 (Fig. 13b).

We repeated our simulations with the scale-aware Grell-Freitas scheme turned on over both 15-km and 3-km domains. The total simulated precipitation is enhanced compared with that using the Tiedtke cumulus scheme (Figure S2-S5 in Supporting Information), which is consistent with our previous study over the southern Great Plains (Hu et al., 2018). The sensitivity of simulated precipitation/clouds to different PBL schemes/treatments (the main focus of this study), however, remains the same (Figure S2-S5 in Supporting Information).

4. Conclusions and discussion

Previous studies by others and a recent study of ours found that precipitation simulations over the Amazon in South America are very sensitive to the PBL scheme used. The exact relationship between the turbulent mixing and precipitation processes in that humid region is, however, not clear. In this study, two-month-long simulations over South America in January-February 2019 are examined to understand the precipitation sensitivity to treatments of turbulent mixing in both the PBL and free troposphere within PBL schemes. Two PBL schemes, the YSU and ACM2 schemes, are the foci of this study since they produced the most and least amount of precipitation among PBL schemes examined. Our results serve to disentangle the turbulence – cloud - precipitation processes over the Amazon and reveal root causes for the sensitivity to PBL schemes, which is a prerequisite for future model improvement. During daytime, while the free-troposphere clouds simulated by YSU dissipate due to solar heating, clouds simulated by ACM2 maintains through the day because of enhanced moisture supply due to enhanced *PBL-free-troposphere* relay transport process: step 1, enhanced vertical mixing within PBL simulated by ACM2 transports surface moisture to the PBL top where clouds first form, and step 2, enhanced free-troposphere mixing feeds the moisture into the free-troposphere cloud deck. Due to the thicker cloud deck over the Amazon simulated by ACM2, surface radiative heating is reduced and consequently CAPE is reduced. As a result, precipitation is weaker from ACM2. In contrast, the moisture *PBL-free-troposphere* relay transport process simulated by YSU is weaker and the clouds at ~4-5 km dissipate quicker, and CAPE is therefore larger during daytime, leading to more precipitation. To verify the strength of such relay transport process, more advanced observations are warranted, for example, of long-term vertical profiles of cloud mixing ratios. To correctly simulate clouds and precipitation, model performance of reproducing such a moisture relay transport process needs to be carefully evaluated.

Two key parameters dictating the vertical mixing in the YSU and ACM2 schemes are identified, which are p, an exponent in the polynomial function determining boundary layer vertical mixing and λ, the asymptotic length scale dictating free-troposphere mixing. Sensitivity simulations with altered p, λ, and other treatments within YSU and ACM2 confirm the sensitivity of precipitation to the mixing strength. Calibrating parameters (p, λ) in YSU and ACM2 or improving their parameterization with non-constant values may be needed for general improvement to simulation results, although this is beyond the scope of this study.

The free-troposphere mixing in presence of clouds become prominent (which is otherwise weak) because of reduced moist static stability and the difference in free-troposphere mixing appears to explain more of the sensitivity to the YSU and ACM2 PBL schemes. The turbulent mixing and cloud relationship over the Amazon simulated with ACM2 suggests strong positive feedback through which regions of lower troposphere clouds create conditions favorable for daytime cloud maintenance. Such feedback is weaker with YSU, which leads to daytime breakup of free-troposphere clouds.

The above results regarding the turbulence-clouds-precipitation processes and their parameterizations have important implications to the understanding and accurate prediction of weather, climate, as well as air quality over the Amazon region that is humid, cloudy and rich in precipitation. South America is experiencing an increasing trend in summer precipitation (Adler et al., 2017), and such a trend is also projected by some climate models (Vera et al., 2006b). Given the negative cloud-precipitation correlation seen in this study for the Amazon region, such a precipitation trend may imply a decreasing trend of cloud cover in the region. Correct representation of turbulence mixing-cloud-radiation interactions within weather and climate models is clearly critical for accurate simulation/prediction of precipitation and water cycles.

Though not shown here, the precipitation over Amazon appears to affect the strength of the south American LLJ. The convection over the Amazon produces upward motion that diverts the low-level easterly flows upward. Since simulated precipitation is weaker with ACM2, such upward diversion is less so that easterly winds leaving the Amazon and impinging on the east side of Andes are stronger, leading to stronger southward LLJ east of Andes when the easterly flows are diverted southward by the mountain range. While south American LLJ depends on the subtropical weather patterns, such as the Bolivia high, the Chaco low (Boers et al., 2015; Montini et al., 2019; Salio et al., 2002; Seiler et al., 2013; Vera et al., 2006a). it is modulated by the convection/turbulence interactions over the Amazon. Thus, the simulated strength of Amazonian precipitation is closely linked to the strength of LLJ east of Andes, which may have implications for the simulation of downstream atmospheric environments including temperature and humidity conditions and air quality (Hu et al., 2013b; Hu et al., 2013c; Klein et al., 2014). These are topics for future studies.

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Data Availability Statement.

The ERA5 reanalysis data (Hersbach et al., 2020) are available at https://doi.org/10.5065/BH6N-5N20. GPM IMERG Final Precipitation dataset is from Huffman et al. (2019). CMORPH dataset (Joyce et al., 2004) is available at https://ftp.cpc.ncep.noaa.gov/precip/CMORPH_V1.0/CRT/8km-30min (last access: 12 November 2020). Figures in this manuscript are produced using the NCAR Command Language (Version 6.6.2) [Software] (2019). Model data produced from this study have been archived at CAPS website https://caps.ou.edu/micronet/Regionalclimate.html and the Luster NSF projects data server at the San Diego Super computer Center, /expanse/luster/projects/uok114/xhu2

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Table 1. Model configuration for sensitivity simulations modifying parameters and treatments in the YSU and ACM2 PBL schemes. p is an exponent in the polynomial function determining vertical mixing strength in the PBL, λ is the asymptotic length scale.

PBL	Grid spacings	Experiment name	Changed parameters/treatments
YSU	15 km	YSU	$p=2$ (default)
		YSUp.5	$p=0.5$
		YSUuseACM2free	Use free troposphere treatment from ACM2
		YSUp.5useACM2free	$p=0.5$ & use free troposphere treatment from ACM2
	3km	3kmYSU	$p=2$ (default)
		3kmYSUp.5	$p=0.5$
		3kmYSUp.5useACM2free	$p=0.5$ & use free troposphere treatment from ACM2
ACM2	15 km	ACM2	$\lambda=80$ (default)
		ACM2λ30	$\lambda=30$
	3 km	3kmACM2	$\lambda=80$ (default)

Figures

Figure 1. Daily mean precipitation rate in Jan-Feb 2019 simulated with (a) YSU in domain 1, (b) ACM2 in domain 1 with a 15 km grid spacing, (c) YSU in domain 2, (d) ACM2 in domain 2 with a 3 km grid spacing, (e) single-domain YSU, (f) single-domain ACM2 with a 3 km grid spacing and from (g) IMERG, (h) CMORPH data. The rectangle in (a) marks the location of the nested domain.

Figure 2. Mean precipitation rate over the Amazon in Jan-Feb 2019 from (left) CMORPH, and simulated by (middle) YSU and (right) ACM2 at (top to bottom) 11, 14, 18, and 21 UTC (7, 10, 14, 17 LST correspondingly).

Figure 3. Hourly mean precipitation rate at 18 UTC (14 LST) in Jan-Feb 2019 simulated with (a) YSU in domain 1, (b) ACM2 in domain 1, (c) YSU in domain 2, (d) ACM2 in domain 2, (e) single-domain YSU, (f) single-domain ACM2 and observed from (g) IMERG, (h) CMORPH.

Figure 4. Average surface temperature at 17 UTC in Jan-Feb 2019 from (a,c,e) YSU, (b,d,f) ACM2, and (g,h,i) their difference (ACM2-YSU) in (top to bottom) different domains. The average difference over land is marked at the lower-left corner in (g,h,i)

Figure 5. Average surface downward shortwave radiation at 17 UTC in Jan-Feb 2019 simulated with (a,c,e) YSU, (b,d,f) ACM2, (g,h,i) their difference, and (j,k,l) column-average cloud water mixing ratios in (top to bottom) different domains. The straight dash lines mark the location of cross-sections in Figs. 5, 6, and 11.

Figure 6. Averaged cross-section of cloud water over the Amazon of each day in Jan-Feb 2019 simulated by (left) YSU and (right) ACM2 at (a,b) 11, (c,d) 14, (e,f) 17, and (g,h) 21 UTC (7, 10, 13, 17 LST correspondingly). The location of these cross-sections is marked in Fig. 5j. The dashed black line and continuous blue line indicate PBL top and terrain surface.

Figure 7. Cross-section of cloud water over the Amazon in Jan-Feb 2019 simulated by (a) YSU and (b) ACM2, (c) $YSUp.5$, (d) $YSUuseACM2free$, (e) $YSUp.5useACM2free$, (f) ACM2λ30 at 17 UTC. The location of these cross-sections is marked in Fig. 5j

Figure 8. Average surface downward shortwave radiation at 17 UTC during January-February 2019 simulated by (a) YSU, (b) ACM2 and 4 sensitivity simulations (c) $YSUp.5$, (d) $YSUuseACM2free$, (e) $YSUp.5useACM2free$, (f) ACM2λ30.

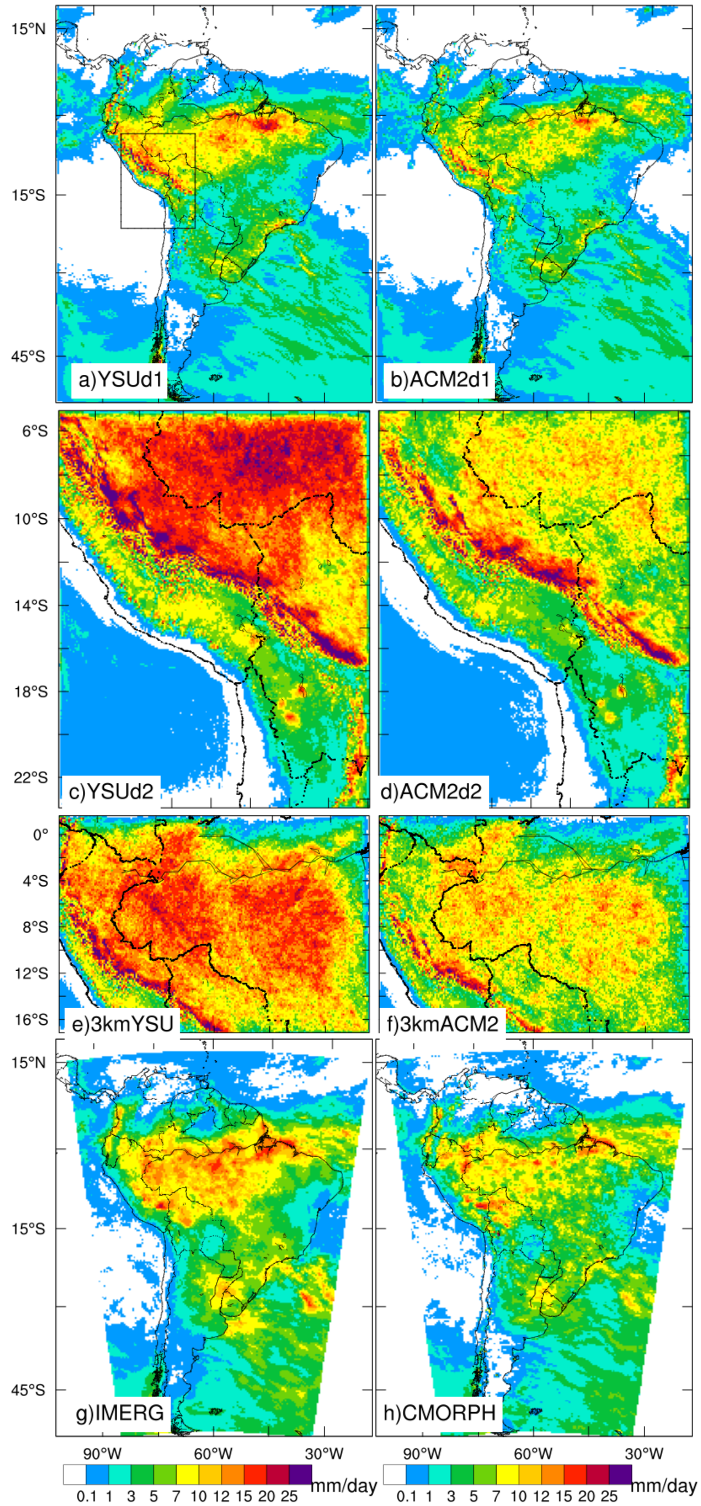
Figure 9. Average CAPE at 17 UTC during January-February 2019 simulated by (a) YSU, (b) ACM2 and 4 sensitivity simulations (c) $YSUp.5$, (d) $YSUuseACM2free$, (e) $YSUp.5useACM2free$, (f) ACM2λ30.

Figure 10. Mean profiles of (a) vertical moisture flux, (b) water vapor difference from that simulated by YSU, (c) cloud water mixing ratio (QCLOUD), and (d) vertical mixing coefficient (K_z) at 17 UTC during January-February 2019 at Manaus (location marked in Fig. 9b) simulated by YSU, ACM2 and 4 sensitivity simulations $YSUp.5$, $YSUuseACM2free$, $YSUp.5useACM2free$, ACM2λ30.

Figure 11. Average precipitation rate at 18 UTC during January-February 2019 simulated by (a) YSU, (b) ACM2 and 4 sensitivity simulations (c) $YSUp.5$, (d) $YSUuseACM2free$, (e) $YSUp.5useACM2free$, (f) ACM2λ30.

Figure 12. Cross-section of average noon-time cloud water mixing ratios over the Amazon in Jan-Feb 2019 simulated by (a) $3kmYSU$, (b) $3kmACM2$, (c) $3kmYSUp.5$, and (d) $3kmYSUp.5useACM2free$. The location of these cross-sections is marked in Fig. 5l

Figure 13. Average noon-time precipitation rate in Jan-Feb 2019 simulated by (a) $3kmYSU$, (b) $3kmACM2$, (c) $3kmYSUp.5$, and (d) $3kmYSUp.5useACM2free$. The domain-averaged values are marked.



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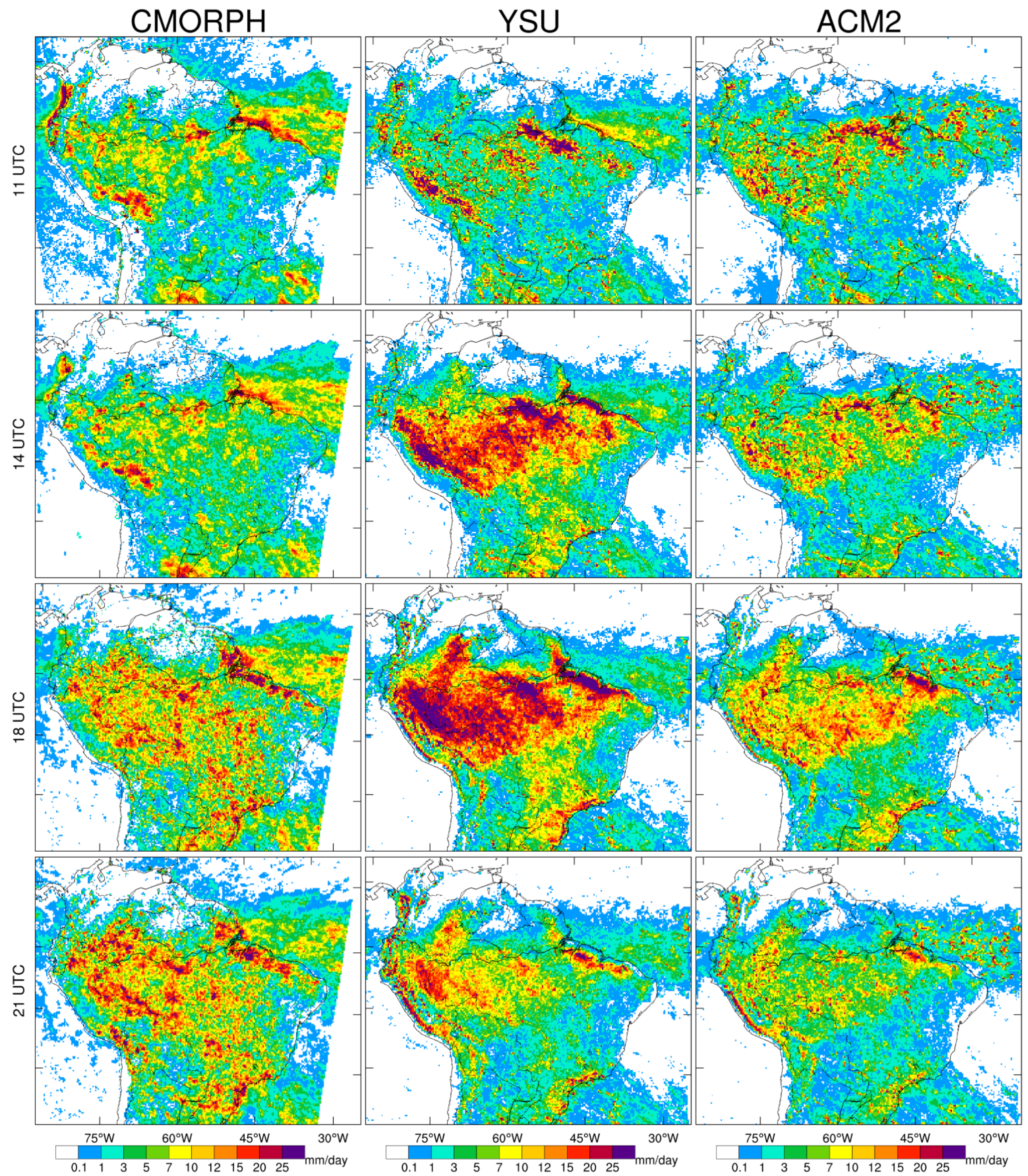

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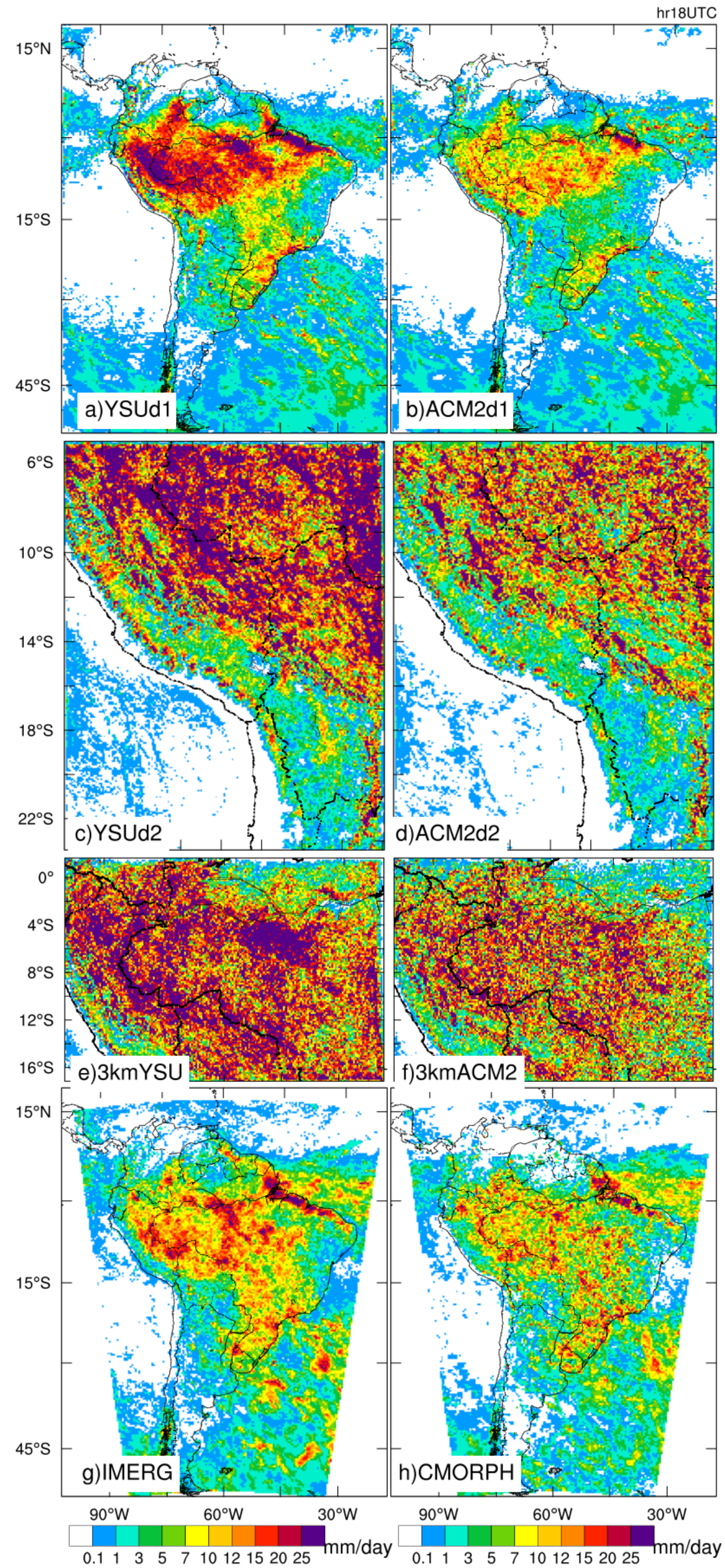

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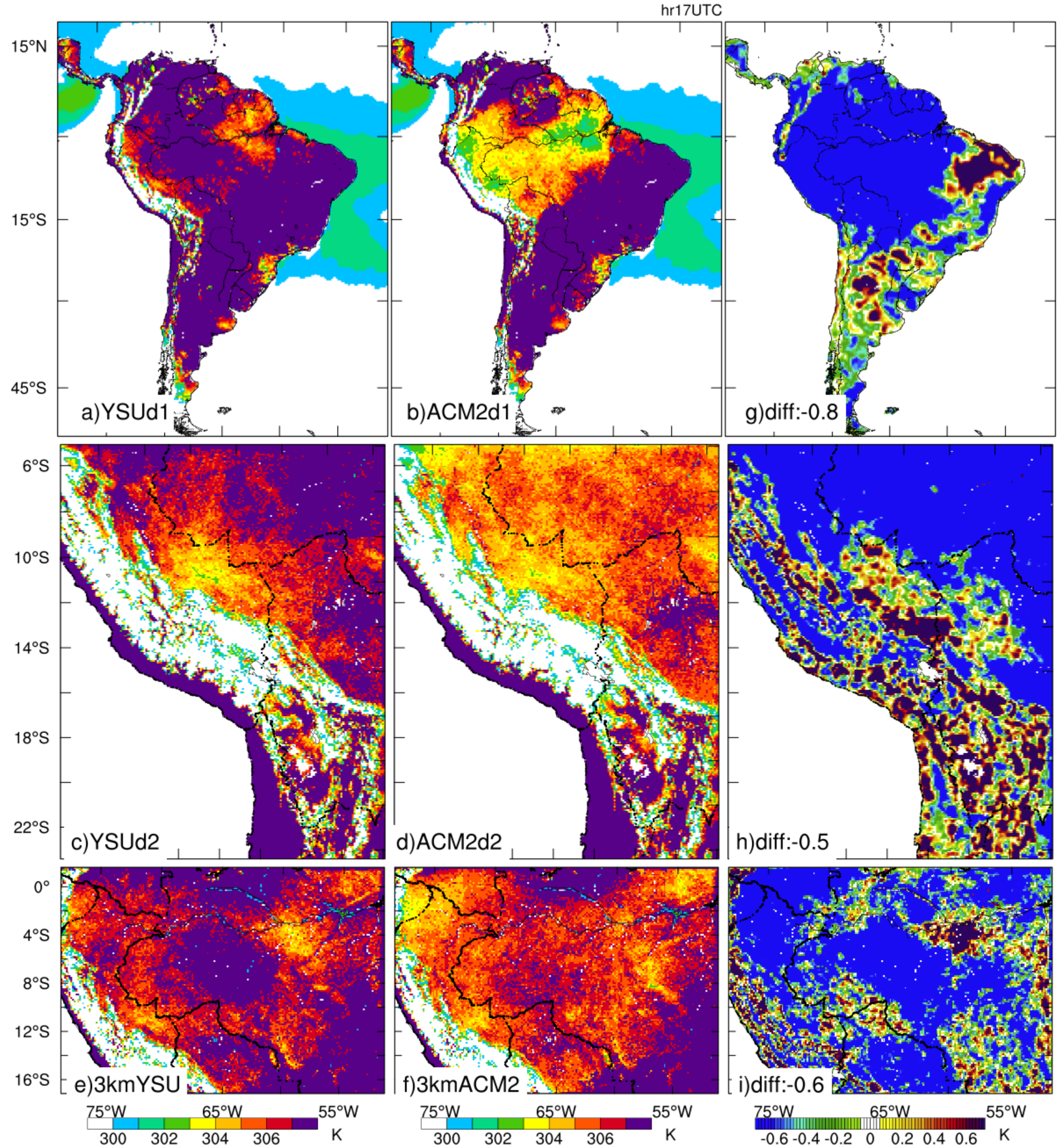

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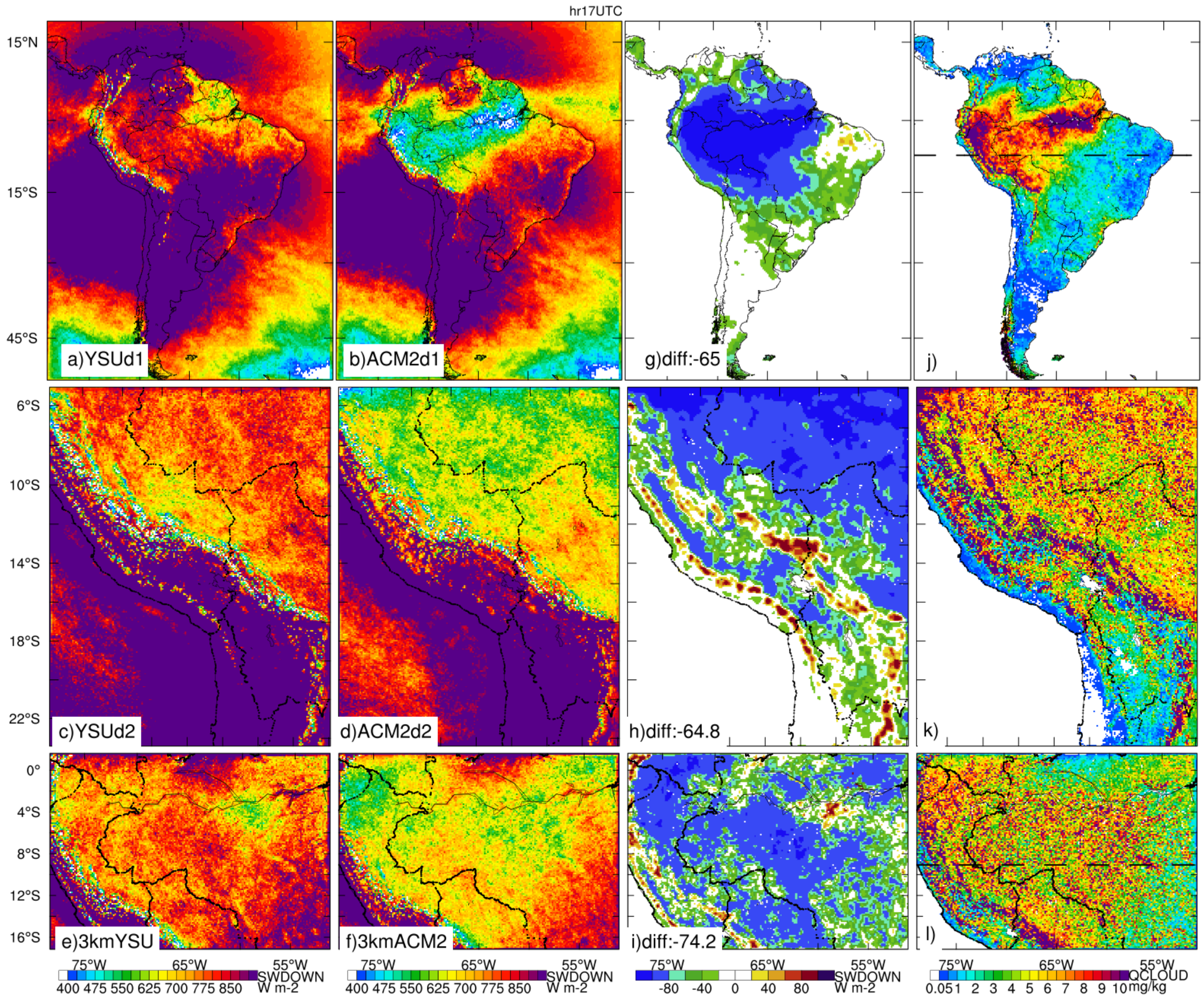

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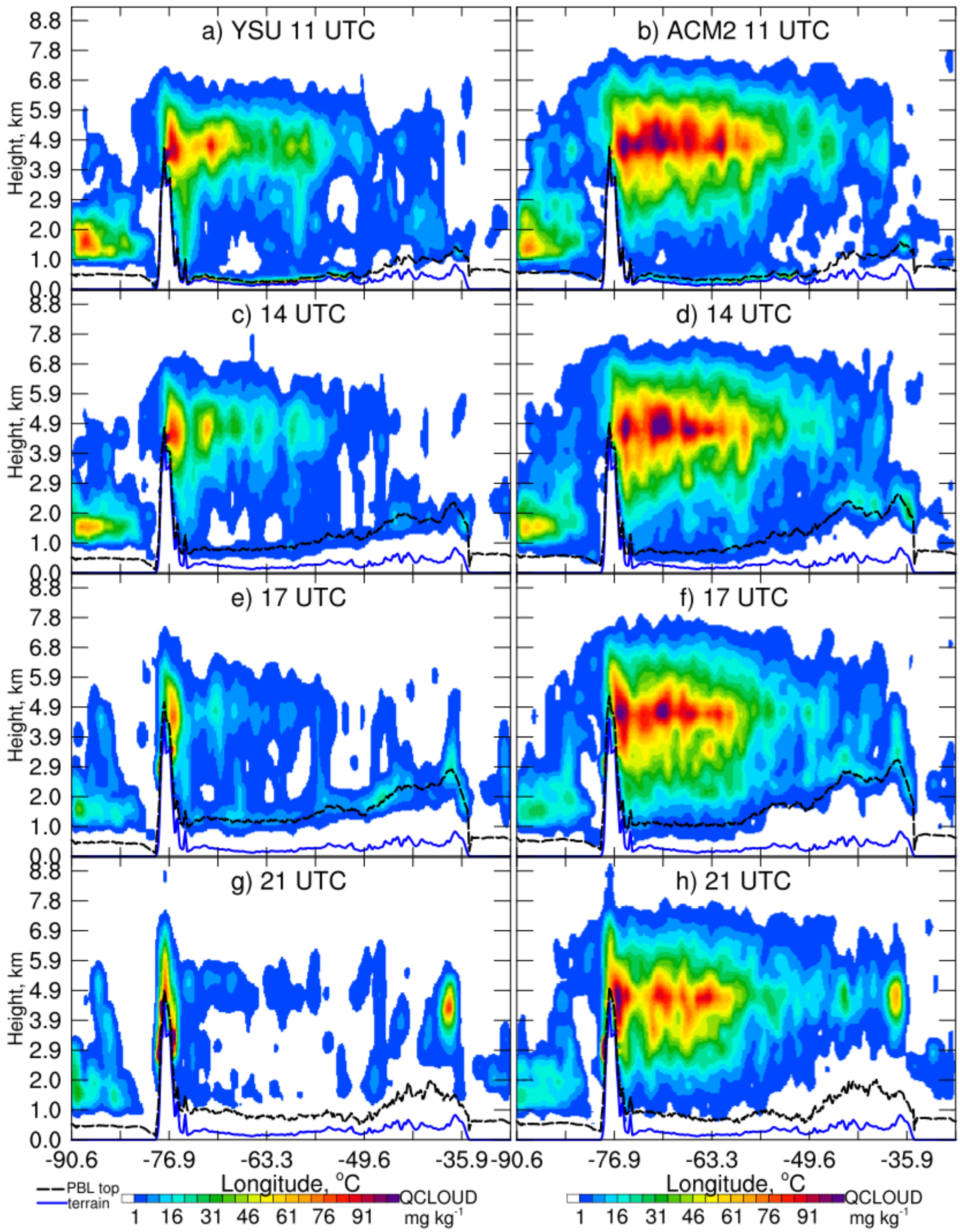

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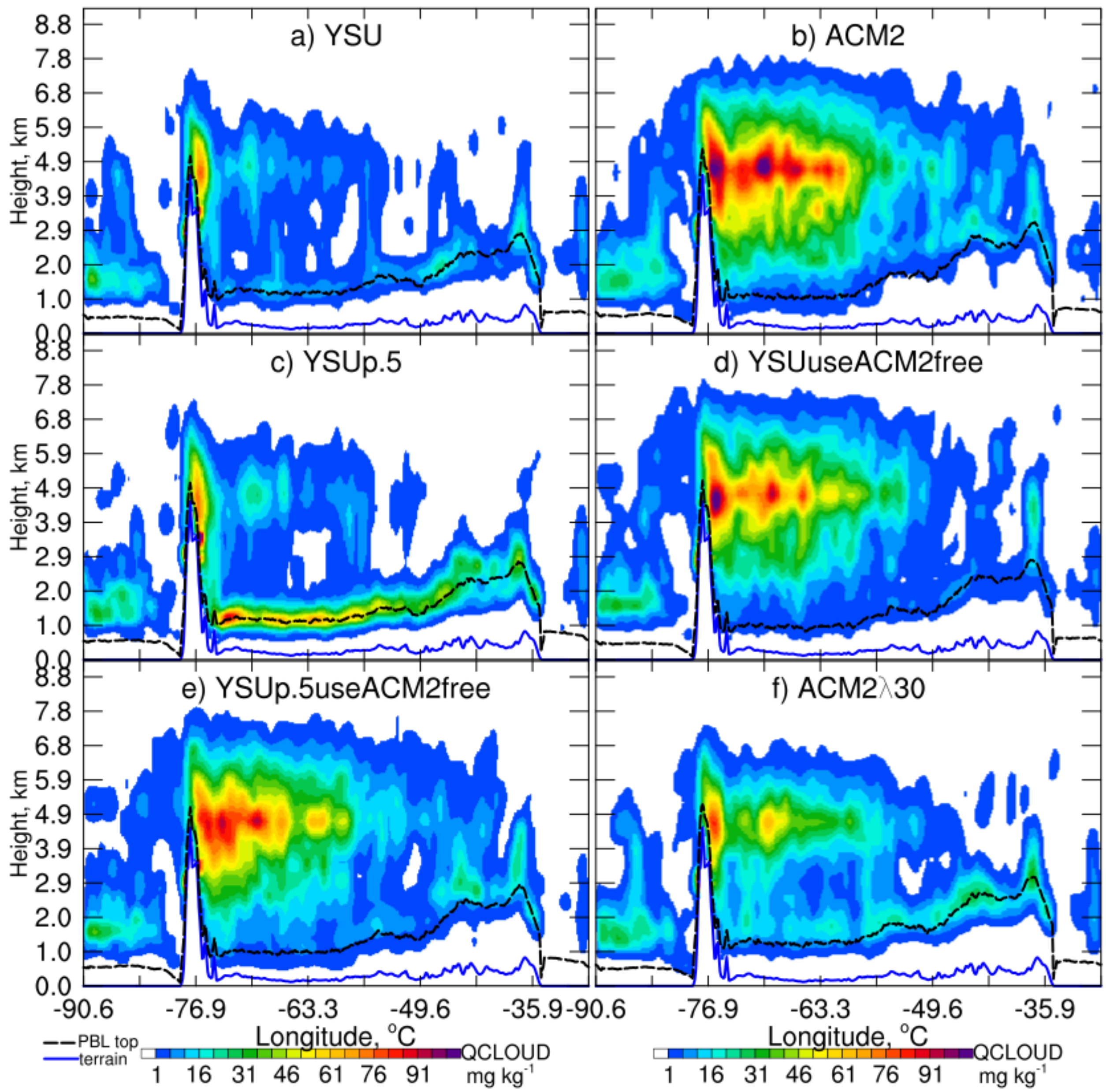


Figure 7. Cross-section of cloud water over the Amazon in Jan-Feb 2019 simulated by (a) YSU and (b) ACM2, (c) YSUp. 5, (d) YSUuseACM2free, (e) YSUp. 5useACM2free, (f) ACM2λ30 at 17 UTC. The location of these cross-sections is marked in Fig. 5j

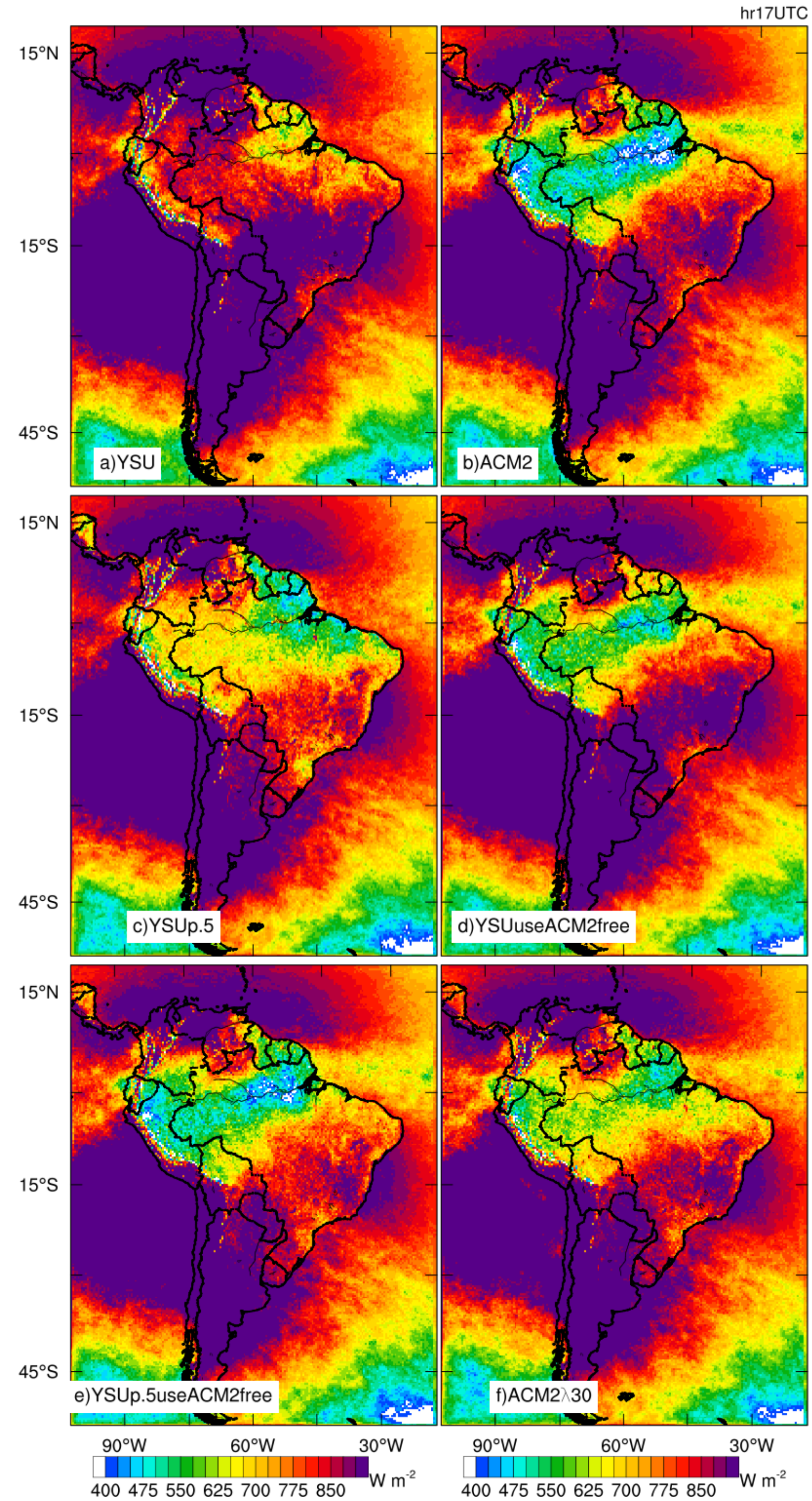
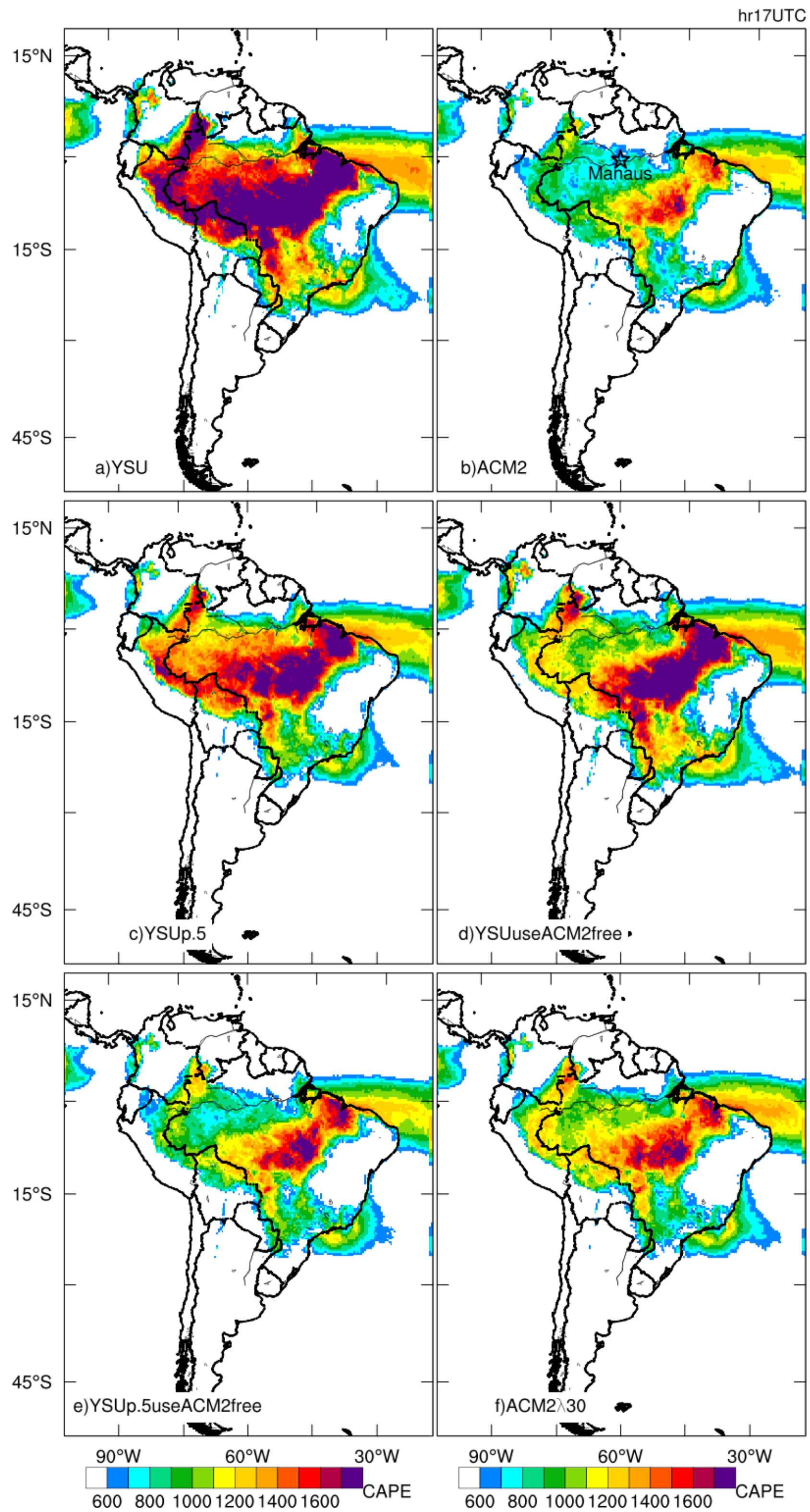


Figure 8. Average surface downward shortwave radiation at 17 UTC during January-February 2019 simulated by (a) YSU, (b) ACM2 and 4 sensitivity simulations (c) YSUp.5, (d) YSUuseACM2free, (e) YSUp.5useACM2free, (f) ACM2λ30.



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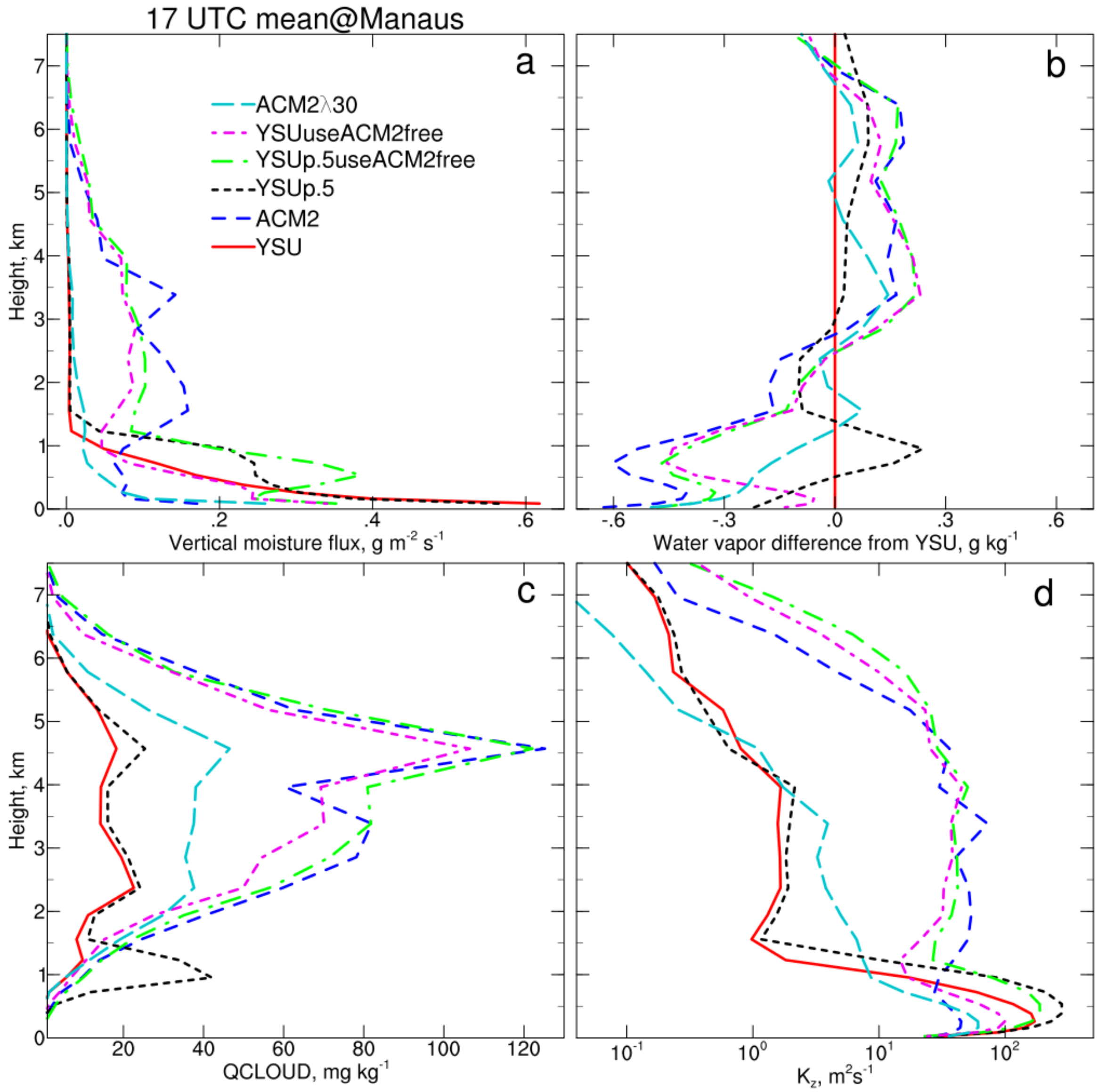

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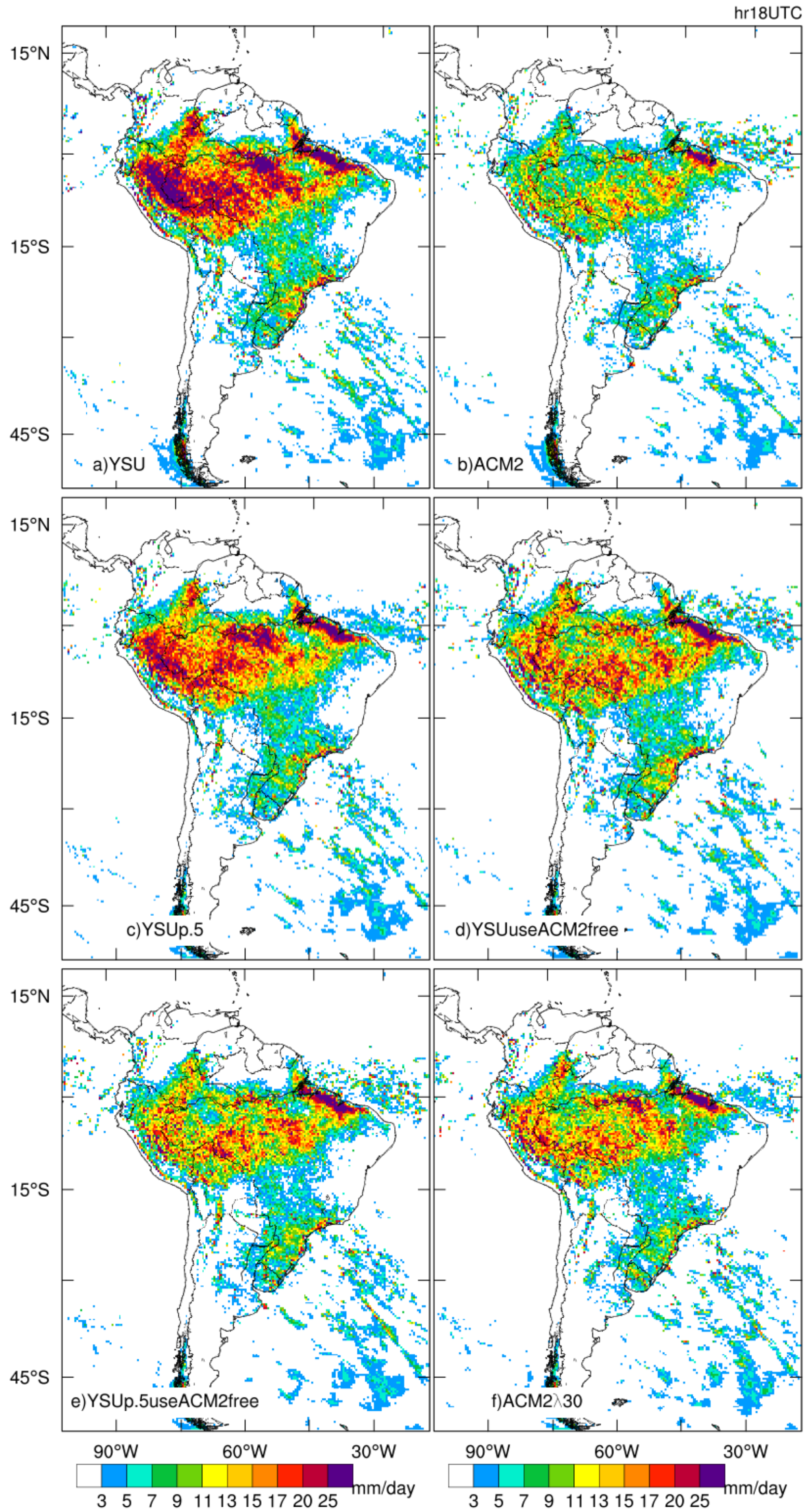

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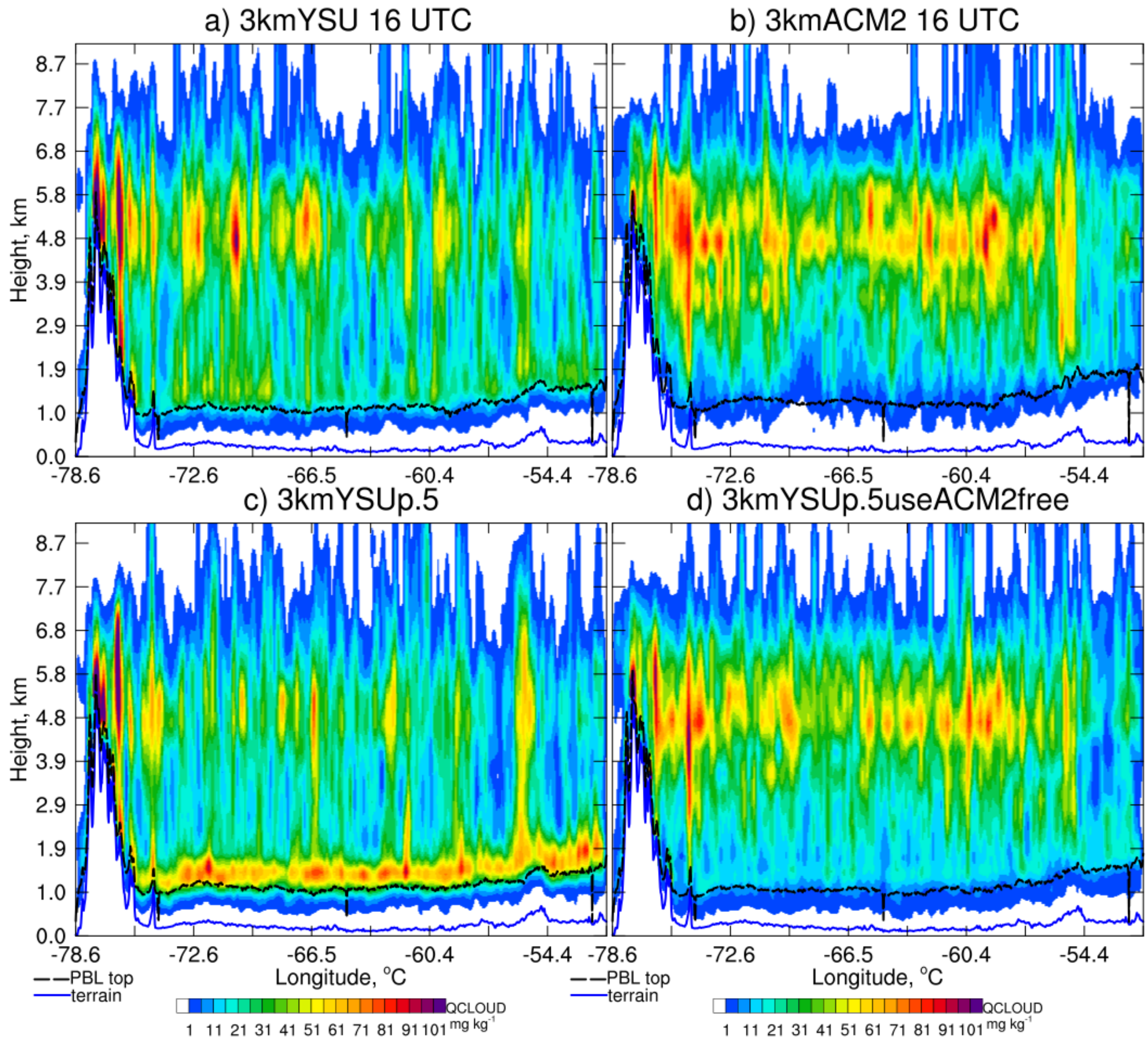
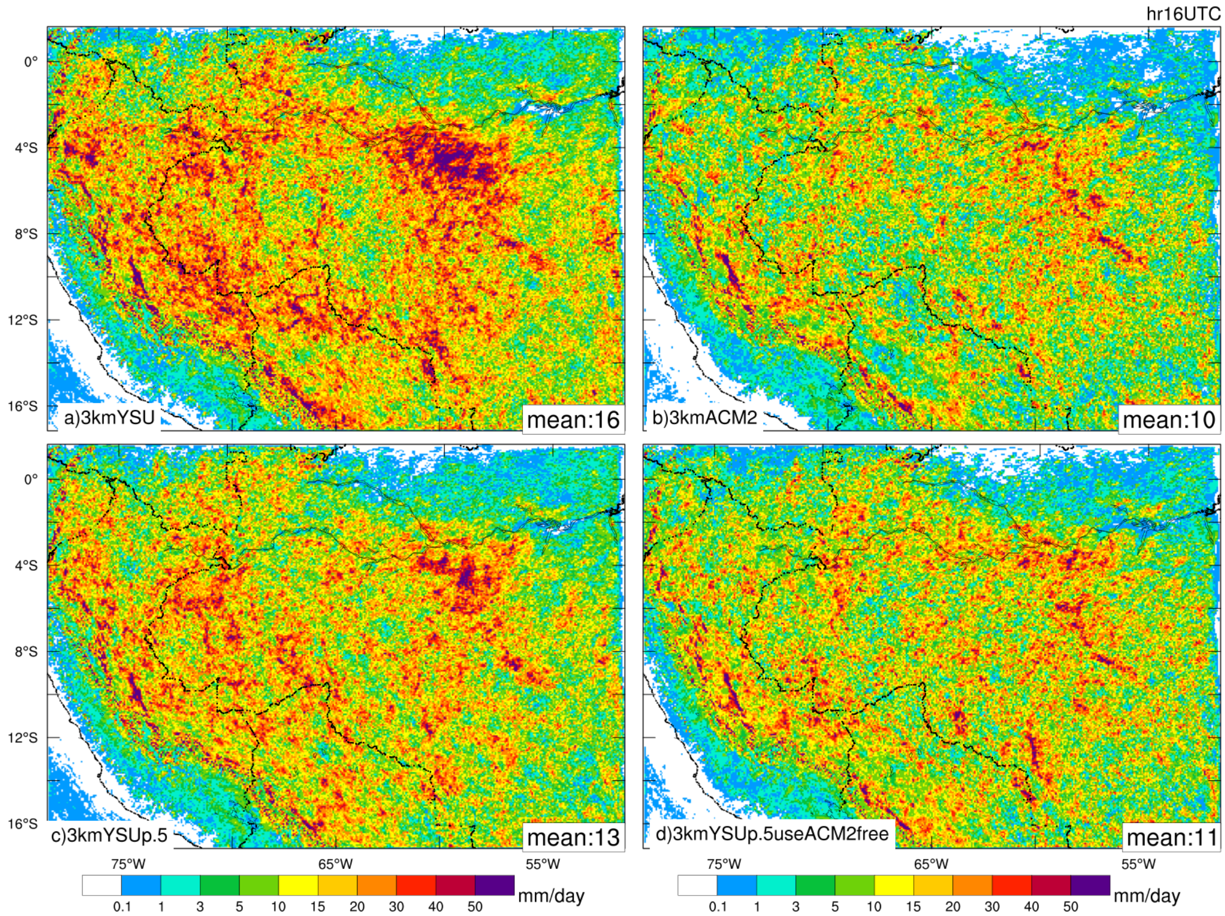


Figure 12. Cross-section of average noon-time cloud water mixing ratios over the Amazon in Jan-Feb 2019 simulated by (a) 3kmYSU , (b) 3kmACM2 , (c) 3kmYSUp.5 , and (d) 3kmYSUp.5useACM2free. The location of these cross-sections is marked in Fig. 5l



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