

ABSTRACT

Title of Dissertation: EXPLORING CLOUD-PLANETARY
BOUNDARY LAYER COUPLING OVER
LAND: VARIABILITY, CLIMATOLOGY,
AND IMPACT ON AEROSOL-CLOUD
INTERACTIONS

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Planetary boundary layer (PBL) processes regulate land-atmosphere interactions and control the mixing and exchange of energy, water, carbon, and other atmospheric constituents between the earth surface and the atmosphere. They critically influence atmospheric phenomena such as cloud formation, convection initiation, and air quality. Over land, surface fluxes drive convective clouds, creating a coupled cloud-surface system that governs cloud development. However, the coupling state of continental clouds remains underexplored, particularly given the complex and unique land-atmosphere interactions shaped by heterogeneous soil moisture, topography, and land cover, which contrast with those in marine environments.

This study addresses this gap by investigating PBL processes, cloud-surface coupling over five continental Atmospheric Radiation Measurement (ARM) observatories. To this end, a key component of this work involves developing a robust PBL Height (PBLH) dataset capable of capturing diurnal variability across these sites. Using the Different ThermoDynamic Stabilities (DTDS) algorithm, I derived PBLH estimates from ground-based Micropulse Lidars and the spaceborne CATS lidar aboard the International Space Station. Validation against radiosonde-based PBLH measurements revealed strong correlations, with R ranging from 0.6 for satellite retrievals to 0.77–0.93 for ground-based measurements.

This PBLH dataset, along with cloud base height, enabled the classification of clouds into coupled and decoupled regimes. Our analysis revealed consistent coupling thresholds and percentages across diverse climatic and geographical regions, with 66% of clouds classified as coupled and 34% as decoupled. This commonality could reflect shared atmospheric mechanisms across continental regions.

Building on this foundation, we investigated the role of cloud-surface coupling in aerosol cloud interactions (ACI) for convective clouds. The state of the coupling relationship is found to play an important role dictating the strength of ACI. It is only under cloud-surface coupled conditions that a robust positive relationship exists between cloud thickness and aerosol loading—with weaker or no relationship under decoupled conditions. Convective available potential energy (CAPE) also plays an important role in the development of convective clouds; its impact is successfully

differentiated from that of aerosol. The most pronounced joint impacts are found for coupled clouds with high CAPE and low cloud bases below 1km. Decoupled clouds show no such systematic changes. These results suggest that an invigorating effect is possible; however, further research is needed to determine whether these findings hold across other regions.

EXPLORING CLOUD-PBLH COUPLING OVER LAND: VARIABILITY,
CLIMATOLOGY, AND IMPACT ON AEROSOL-CLOUD INTERACTIONS

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Dedication

To my 14-year-old self, who dreamed of being a scientist.

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List of Abbreviations

ACI = aerosol-cloud interactions
ARM = Atmospheric Radiation Measurement
ARSCL = Active Remote Sensing of Clouds
AOS = Aerosol Observing System
CALIPSO = Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CAPE = Convective Available Potential Energy
CATS = Cloud-Aerosol Transport System
CBH = cloud base height
CCN = cloud condensation nuclei
CN = aerosol number concentration
CEIL = ceilometer
CTH = cloud top height
DCC = deep convective clouds
DTDS = Different Thermo-Dynamic Stabilities
DJF = December-January-February
EBBR = Energy Balance Bowen Ratio
ECMWF = European Centre for Medium-Range Weather Forecasts
ECOR = eddy correlation flux measurement system
ENSO = El Niño-Southern Oscillation
ERA5 = ECMWF Reanalysis v5
GMAO = NASA's Global Modeling and Assimilation Office
GNSS-RO = Global Navigation Satellite System Radio Occultation
ITCZ = Intertropical Convergence Zone
ISS = International Space Station
JJA = June-July-August
KDEs = Kernel Density Estimates
KAZR = Ka-Band ARM Zenith Radar
LCL = Lifting Condensation Level
LH = Latent Heat
LMP = Local Maximum Position
LNB = Level of Neutral Buoyancy
LT = Local Time
m.a.g.l = meters above ground level
MAE = Mean Absolute Error
MAM = March-April-May
MERGESONDE = The Merged Sounding value-added product
MPL = Micropulse Lidar
MWR = microwave radiometer
PBL = Planetary Boundary Layer
PBLH = Planetary Boundary Layer Height
RMSE = Root Mean Square Error
RS = radiosonde
SAMLLJ = South American Low-Level Jet
SEM = standard error of the mean
SGP = Southern Great Plains

SH = Sensible Heat
SMAP = Soil Moisture Active Passive
SNR = signal-to-noise
SON = September-October-November
STBL = stratocumulus-topped boundary layer
WCT = wavelet covariance transform
UAP = ultrafine aerosol particles

Chapter 1: Introduction

1.1 Background:

The Planetary Boundary Layer (PBL), the lowest layer of the atmosphere, is characterized by intense turbulence arising from surface forces such as frictional drag, heat, and momentum fluxes (Berg & Stull, 2005; Caughey & Palmer, 1979; Garratt, 1990; Holtslag & Nieuwstadt, 1986; Kaimal & Finnigan, 1994; Mahrt, 1999). These turbulent processes play a pivotal role in determining the PBL Height (PBLH), which exhibits substantial spatial and temporal variability (Guo et al., 2016; Kalmus et al., 2022; Seidel et al., 2010). Variations in the PBL fundamentally mediate the interactions between the Earth's surface and the atmosphere, ultimately helping to connect the atmosphere to other Earth system components and bridging the gap between weather and climate (Moeng et al., 1996; Santanello et al., 2018; Teixeira et al., 2021), and also seriously undermines air quality due to PBL and aerosol interactions (Li et al., 2017).

PBL processes are key players in the formation and evolution of boundary-layer clouds, convection initiation, aerosol-cloud interactions (ACI), and many other atmospheric phenomena (Berg et al., 2013; Berg & Stull, 2005; Betts, 2009; Golaz et al., 2002; Qian et al., 2013, 2016; Teixeira & Hogan, 2002). For instance, surface fluxes of heat and moisture can lead to cloud formation through PBL evolution and growth. This process occurs when the PBLH reaches the lifting condensation level (LCL), resulting in a cloud-surface coupled system (Golaz et al., 2002; Jensen et al., 2016; Jensen & Del Genio, 2006; Santanello et al., 2018). The PBLH provides an integrated measure of boundary-layer structure and mixing depth, serving as a physically meaningful reference for diagnosing interactions between clouds and the surface.

However, not all low-level clouds are directly coupled to surface forcings or to the PBLH. Marine boundary layer clouds, for instance, often rely on cloud-top radiative cooling under weak

surface flux conditions, leading to decoupled cloud–surface systems (Moeng et al., 1996; Bretherton et al., 2007; Moeng et al., 1996; Zheng et al., 2018a). Contrasting interactions between coupled and decoupled clouds result in unique differences in their characteristics, development, and evolution (Hogan et al., 2009; Zheng et al., 2018a). Throughout this investigation, cloud–surface and cloud–PBLH coupling are used interchangeably, as the PBLH represents the maximum height at which surface forcings directly influence the atmosphere.

Figure 1.1 schematically represents this conceptual framework, highlighting the relative positions of the PBLH and cloud base for coupled and decoupled clouds. In the coupled regime (Figure 1.1a), the cloud resides within the PBL and directly interacts with surface turbulent fluxes. The idealized vertical virtual potential temperature profiles depict a superadiabatic surface layer that facilitates the exchange of surface fluxes between the surface and the cloud. In the decoupled regime (Figure 1.1b), the cloud base lies above the capping inversion that separates the PBL from the free atmosphere; therefore, turbulent fluxes cannot reach the cloud base.

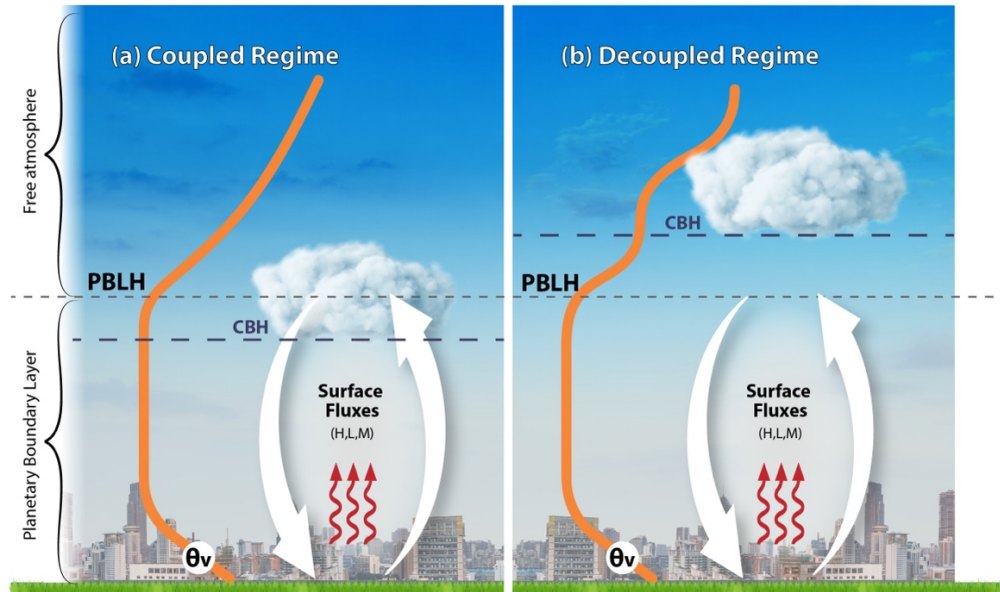


Figure 1.1 Schematic representation of the cloud-PBLH coupling concept for the (a) coupled regime and (d) decoupled regime. The idealized vertical profiles of virtual potential temperature

are displayed with the orange lines. The thin horizontal dash line illustrates to the PBLH, which divides the atmosphere between the planetary boundary layer and the free atmosphere. The bold horizontal dash line illustrates the cloud base height (CBH). Illustration by Estefania Roldán-Henao based on Natalia Roldán-Henao's conceptual design.

This interaction between clouds and the Earth's surface has long been studied. Previous investigations recognized its importance in the characteristics and evolution of marine clouds (Dong et al., 2015), linking the cloud-PBLH coupling state to key marine cloud processes, such as the stratocumulus to cumulus transitions (Bretherton & Wyant, 1997; Wyant et al., 1997; Zheng et al., 2018b, 2021; Zheng & Li, 2019) or the probability of Arctic clouds to contain or form ice (Griesche et al., 2021). However, most of the existing knowledge about cloud-surface coupling focuses on cloud-topped marine boundary layers (Albrecht et al., 1995; Bretherton & Wyant, 1997; Dong et al., 2015; Wood, 2012; Zheng et al., 2018a, 2018b; Zheng & Li, 2019).

In a marine environment, a coupled cloud is one in which the moist conserved variables are vertically well-mixed through the PBL (Dong et al., 2015). However, this definition does not directly apply to continental clouds due to differences in PBL definitions and determination methods (Garratt, 1990; Vogelezang & Holtslag, 1996). For instance, Vogelezang and Holtslag (1996) demonstrated that the calculation of the PBLH performs differently over land and ocean, noting that while bulk Richardson number-based formulations are generally satisfactory over land, they produce unrealistically deep boundary layers over the ocean under high wind conditions. Furthermore, continental regions exhibit greater land heterogeneity, characterized by diverse land cover, soil moisture, topography, and diurnal temperature cycles. Consequently, our understanding of cloud-surface coupling over land is still developing, warranting further investigation to fully

comprehend these complex interactions. These factors are absent or greatly reduced in marine environments, leading to differences in how the PBL behaves in each setting.

Su et al. (2022) attempted to fill this knowledge gap by developing a methodology to assess cloud-surface coupling in continental regions and evaluating it at the Southern Great Plains (SGP) site. While this approach is valuable, the diversity and heterogeneity of continental regions necessitate a more comprehensive understanding of cloud-PBLH coupling. Such an understanding is hinged upon comprehensive investigations of coupling characteristics across different climatic and geographical regimes, as well as over extended periods of time. This dissertation builds on and extends previous efforts by examining cloud-surface coupling over land through its determination, climatological characterization, and its role in modulating aerosol-cloud interactions.

1.2 Gaps in PBLH retrievals:

Accurate estimations of the PBLH are necessary to fully comprehend cloud-PBLH coupling. Traditionally, the estimation of PBLH has relied on in-situ radiosonde data, capturing thermodynamic profiles of temperature, humidity, and wind across various pressure levels (Seidel et al., 2010; Zhang et al., 2018; Li et al., 2021; Seidel et al., 2010; Zhang et al., 2018). Methods used to compute the PBLH with radiosonde data include surface-based inversions, relative humidity and potential temperature gradient methods, Richardson number methods, and the parcel method (Vogelezang & Holtslag, 1996; Bradley et al., 1993; Liu & Liang, 2010; Seidel et al., 2010; Vogelezang & Holtslag, 1996). While radiosondes have been employed as a standard in estimating PBLH, their precision varies notably depending on atmospheric thermodynamic conditions and the methodology used, with no single method proving universally effective across all conditions (Li et al., 2021). Furthermore, radiosonde retrievals face restrictions in terms of

spatial coverage and observational frequency, typically occurring only twice daily at most stations, which limits our understanding of the diurnal variability of the PBLH.

Contrary to radiosonde methods, lidar approaches provide a less reliable estimation of the PBLH but with a better temporal representation that allows the tracking of its diurnal variability (Eresmaa et al., 2006; Sawyer & Li, 2013; Liu et al., 2018; Roldán-Henao et al., 2024). In terms of spatial coverage, lidars can sense either fixed points or large regions depending on their deployment. For instance, fixed ground-based sensors like those used in the Atmospheric Radiation Measurement (ARM) program can only measure the PBLH at a fixed location, but they can track the entire daily cycle over a single day. Note that the different PBL detection algorithms have been applied to the ARM lidar datasets (Sawyer and Li, 2013; Su et al., 2020; Zhang et al., 2025).

On the other hand, lidars on satellite platforms such as Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and the Cloud-Aerosol Transport System (CATS) provide global views of the PBLH, but they cannot track the complete daily cycle on a single day. Therefore, understanding the global daily variations of the PBLH is a challenging task that requires extensive observations and appropriate retrieval algorithms. CATS, a 1064 nm lidar on the International Space Station (ISS) between 2015 and 2017, can address this challenging task of measuring the global diurnal variability of the PBLH. CATS observed the atmosphere at different local times, enabling the statistical resolution of the daily variability of the PBLH from space. However, using CATS to measure the PBLH is itself a challenge. Spaceborne lidars on satellite platforms operate at much greater distances from the Earth's surface, resulting in a decreased signal-to-noise ratio (SNR) compared to ground-based lidars. Consequently, spaceborne lidars struggle to detect weak or distant targets such as thin clouds or aerosol layers, making it difficult

to determine the precise PBLH. In addition, lidar-derived PBLH estimates may have substantial uncertainties, contingent upon the retrieval algorithm used and environmental conditions. Lidars may struggle to estimate PBLH in stable conditions, cloudy situations, or when there are multiple aerosol layers (Kotthaus et al., 2023; Roldán-Henao et al., 2024; Su et al., 2024a; D. Zhang et al., 2022).

Previous studies have demonstrated the limitations of lidar-based PBLH retrievals. For example, Su et al. (2020) noted that lidar-based PBLH estimates show a weaker correlation ($R = 0.14$) with radiosonde-based PBLH when the atmosphere is stable and the PBL is obscured by the residual layer. Zhang et al. (2017) evaluated the performance of daytime PBLH retrievals at nine ARM sites, reporting correlations between ceilometer- and radiosonde-derived PBLH ranging from 0.11 to 0.73 depending on atmospheric stability, with higher correlations observed during convective conditions. Li et al. (2023) tested the performance of three retrieval techniques: the wavelet covariance transform (WCT), the maximum standard deviation (MSD), and the threshold method, under clear-sky and cloudy conditions. They found that WCT yielded the highest correlation with radiosonde-based PBLH ($R = 0.60$), followed by MSD ($R = 0.54$), while the threshold method performed worst ($R = 0.18$) under clear-sky conditions. Cloudy conditions yielded the worst performance overall.

In addressing the challenges of deriving PBLH from lidars, Su et al. (2019) developed an algorithm named Different Thermo-Dynamic Stabilities (DTDS) that showed robust performance in PBLH estimation at the ARM program's SGP site, but unverified performance in other regions with different environmental and geographical configurations. Moreover, generating a more precise PBLH dataset for these areas can deepen our understanding of the PBL's behavior across diverse geographical regions with distinct climate regimes and help us investigate the role of

surface-atmospheric coupling in modulating cloud and aerosol processes. This investigation is thus first devoted to assessing the DTDS algorithm in varying geographical regions and with satellite-based lidars to enhance our understanding of the PBLH and its influence on clouds and ACI.

1.3 Gaps in cloud-surface coupling for land:

Previous research on cloud-land interactions has largely focused on the role of land surface heterogeneity, evaporative fraction, and soil moisture in the development of shallow convection and its transition to deep convection (Santanello et al., 2018). Some studies have linked the strength of cloud-land interactions to cloud development and evolution (Fast et al., 2019; Lee et al., 2019; Xian et al., 2023). However, most efforts primarily examined local convection and its role in precipitation, without exploring the differences in cloud-land interactions across various cloud regimes or locations.

Existing studies remain geographically constrained, with a predominant focus on the SGP (Su et al., 2022; Tao et al., 2019). Additionally, some analyses focus on specific seasons, primarily warm seasons (Fast et al., 2019), and do not assess the temporal variability of this process. These limitations hinder our ability to fully understand the coupling processes between clouds and the land surface and their broader impact on the PBL across different climatic, geographical, and temporal contexts. Since cloud-surface coupling plays a critical role in modulating PBL evolution, stability, and ACI (Roldán-Henao et al., 2026; Su, Li et al., 2024; Zheng et al., 2021), establishing a more extensive climatological framework is essential. A broader climatology of cloud-surface coupling can provide valuable insights into the evolution of cloud dynamics under diverse regions. In particular, how differently the percentages of coupled and decoupled clouds manifest across

environmental conditions and geographical settings, and what forces drive these differences, remain open questions. Finally, examining cloud-surface coupling across various regions and temporal scales could clarify differences and similarities in factors such as vegetation, soil moisture, altitude, and other environmental aspects, as they may influence cloud dynamics, formation, evolution, cloud regimes, and ultimately precipitation.

1.4 Gaps in cloud-PBL coupling for ACI studies

Cloud-PBL coupling is fundamental to ACI, as it directly governs the distribution and mixing of aerosols within the PBL. In coupled systems, surface fluxes mix aerosols throughout the PBL, allowing near-surface aerosol observations to accurately represent aerosol concentrations at cloud bases. In contrast, decoupled systems create vertical stratification of aerosols, which can lead to discrepancies in aerosol concentrations at cloud bases (Quaas et al., 2020; Su et al., 2024a), affecting the dynamics of ACI. While the root of ACI originates from nucleation of aerosol particles as cloud condensation nuclei (CCN), in-situ CCN data are extremely lacking. As such, the vast majority of ACI studies (Tao et al., 2020; Li et al., 2017, 2019; Fan and Li, 2022) have used CCN-proxies derived from either ground-based or satellite measurements of aerosol loading, which often fail to represent the CCN involved in cloud formation. Thus, the coupling between the PBLH and cloud dynamics has profound implications in how aerosols are transported, mixed, and influence cloud formation and intensification. Understanding these interactions is crucial for accurately assessing the aerosol indirect effect in different cloud regimes.

The role of cloud-surface coupling in ACI, particularly in deep convective clouds, remains underexplored. Incorporating cloud-surface coupling into ACI investigations helps distinguish clouds directly influenced by boundary layer aerosols from those that are not, thereby improving the ability to capture the ACI signal. This distinction is especially important for deep convective

clouds, whose response to aerosols is an ongoing and highly debated topic (Igel & van den Heever, 2021; Varble et al., 2023; Fan et al., 2025). Much of the discourse has focused on whether aerosols can invigorate convective storms, with invigoration defined by increased updraft velocities, intensified rain rates, greater cloud tops in convective cores, and enhanced lightning activity.

Two main mechanisms have been proposed to explain how aerosols could invigorate deep convective clouds. The first mechanism proposed, known as freezing-induced invigoration (Andreae et al., 2004; Rosenfeld et al., 2008) or cold-phase invigoration, involves aerosols forming smaller cloud droplets that are carried across the freezing level, leading to the formation of more ice crystals. A higher number of ice crystals can enhance the release of latent heat (LH) from freezing and strengthen convective storms. Questions about this mechanism focus on whether the latent heating from freezing is offset by the additional loading effect of the liquid water transported across the freezing level. The second mechanism, known as condensational invigoration (Fan et al., 2018) or warm-phase invigoration, involves the activation of ultrafine aerosol particles (UAP) within convective updrafts in environments of high supersaturation. This process can lead to increased updraft speeds due to the release of additional latent heat. There are ongoing questions regarding condensational invigoration, particularly concerning whether convective updrafts can actually achieve such high levels of supersaturation.

While both mechanisms have been proposed from theoretical calculations (Fan et al., 2018; Rosenfeld et al., 2008; Tao et al., 2012) and evaluated by various modeling and observational studies (Cotton & Walko, 2021; Fan et al., 2012, 2025; Grabowski & Morrison, 2021; Li et al., 2011; Varble, 2018), the role of cloud-surface coupling has not been incorporated into these analyses. This omission limits our ability to interpret near-surface aerosol observations and their relevance to cloud properties.

One of the most influential observational studies on aerosol invigoration was conducted by Li et al. (2011), who analyzed the relationship between aerosol loading and cloud thickness over the U.S. Southern Great Plains. They concluded that increased aerosols led to thicker clouds and higher cloud tops, particularly in summer and under low cloud bases. Varble (2018) revisited these findings, arguing that the observed correlation between cloud thickness and aerosols was primarily driven by the co-variability between aerosol loading and Convective Available Potential Energy (CAPE), rather than by aerosol invigoration. However, neither Li et al. (2011) nor Varble (2018) included the concept of cloud-surface coupling in their studies, a concept critical for observational ACI research. The finding has been challenged by Fan et al. (2025), who found a faulty use of measurements leading to a false correlation between CAPE and aerosol, but differentiating their effects on the ACI are yet to be conducted.

1.5 Outline of this study

This dissertation is structured around three primary topics: PBLH estimation, characterization of cloud-PBLH coupling, and the role of cloud-PBLH coupling in ACI. The second chapter introduces the dataset. The third chapter assesses the performance and feasibility of using the DTDS method to retrieve the PBLH across five ARM observatories with different geographical and climatological configurations. It also examines the sources of errors and limitations associated with PBLH retrievals from radiosonde and lidar instruments. The fourth chapter extends DTDS to a spaceborne lidar to retrieve the PBLH from space. After establishing the reliability of PBLH retrievals, the fifth chapter uses the PBLH datasets, along with cloud boundary measurements (cloud base height and cloud top height), to characterize cloud-PBLH coupling across diverse geographical and climatic settings. This chapter concludes with a detailed

analysis of the factors influencing coupled and decoupled regimes at SGP, incorporating soil moisture data from the Soil Moisture Active Passive (SMAP) mission and the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) reanalysis data on specific humidity, temperature, and geopotential height. The resulting climatology of coupling then forms the basis for the sixth chapter, which explores the influence of cloud-PBLH coupling on ACI in convective clouds over the SGP. Figure 1.2 presents a schematic flow chart outlining the structure of the dissertation and its main analyses.

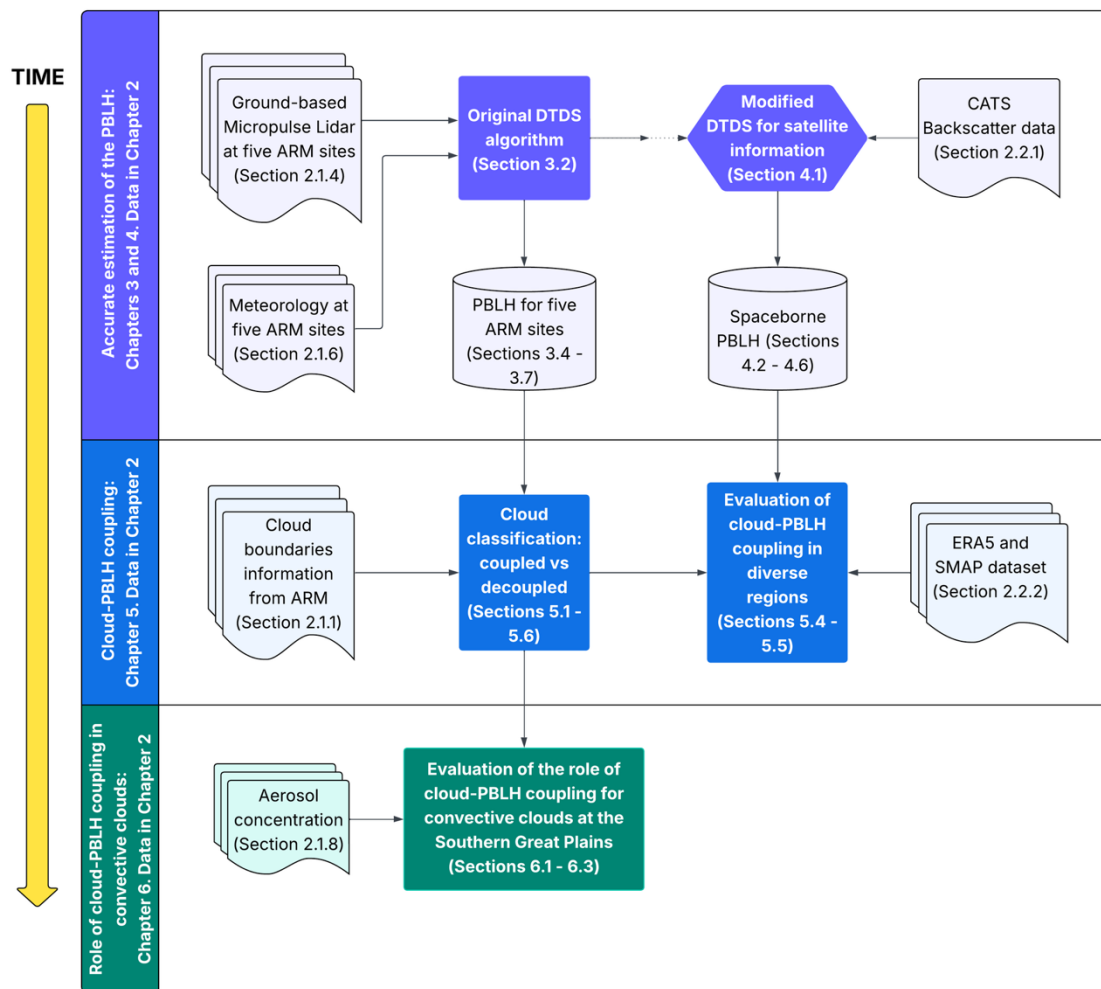


Figure 1.2 Schematic flow chart outlining the structure of the dissertation and scientific connections of the various studies.

Chapter 2: Observational Datasets

This study employs an extensive collection of ground-based, satellite, and reanalysis data to investigate the cloud-PBLH coupling and aerosol–cloud interactions across diverse geographical and climatological regions. The observational datasets comprise backscatter profiles from ground-based and satellite sources, surface meteorological variables, surface energy fluxes, thermodynamic profiles from radiosonde measurements, vertical velocity data from Doppler lidar, soil moisture from satellite observations, and a comprehensive set of ERA5 reanalysis variables.

2.1 Ground-based observations

The ARM User Facility, operated by the U.S. Department of Energy, has been making comprehensive measurements of the atmosphere-surface system since 1992, focused on clouds and aerosol properties and their impacts on the Earth's energy balance at multiple sites across the globe. The variety of geographical and climatical conditions observed by the ARM and the vast set of sensors at each site make ARM data ideal for this investigation.

Data from five ARM sites are employed, including one permanent site, the SGP, and four mobile facilities. The ARM central facility is located in the SGP in the central United States, providing the richest and longest observation for more than three decades (Sisterson et al., 2016). The GoAmazon (MAO) campaign was designed to investigate the tropical cloud lifecycle and atmospheric composition over the Amazon rainforest from January 2014 to November 2015 (Martin et al., 2016). The CACTI (COR) campaign in the Sierras de Córdoba mountain range in Argentina captured cloud systems over complex terrain from October 2018 to April 2019 (Varble et al., 2021). The BAECC (TMP) campaign was deployed in a boreal forest in Hyytiälä, Finland, with the objective of studying the impact of biogenic aerosols on clouds and climate (Petäjä et al.,

2016). Finally, the COPS (FKB) campaign in the Black Forest in Germany aimed to improve understanding and forecasting of convective precipitation in complex terrain (Wulfmeyer et al., 2011). Figure 2.1 presents the site locations, and Table 2.1 provides the latitudes, longitudes, altitudes, and observation periods of the five sites used in this study.

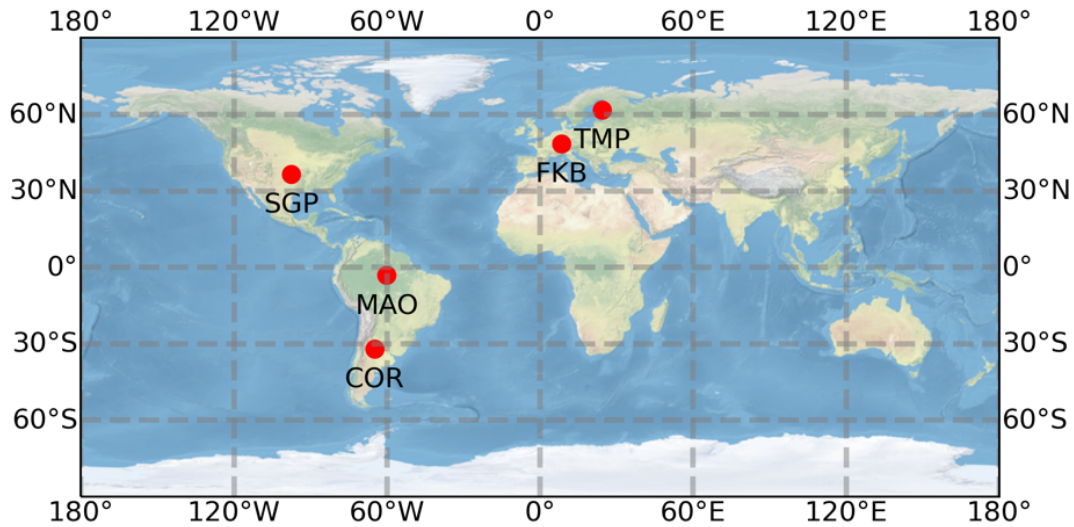


Figure 2.1 Geographical distribution of the Atmospheric Radiation Measurement (ARM) program sites.

Table 2.1 List of ARM site specifics description.

Site	Latitude	Longitude	Elevation (m.a.s.l.)	Period	Description
SGP	36° 36' 26.36" N	97° 29' 15.51" W	314	04/2001 – 09/2019	Midlatitude plain
MAO	3° 12' 46.7" S	60° 35' 53.16" W	50	01/2014 – 11/2015	Tropical rain forest
COR	32° 4' 0.91" S	64° 52' 53.6" W	1141	10/2018 – 04/2019	Midlatitude mountain
TMP	61° 50' 34.8" N	24° 17' 16.8" E	179	02/2014 – 09/2014	Boreal forest
FKB	48° 32' 24.36" N	8° 23' 48.48" E	511	04/2007 – 12/2007	Midlatitude mountain forest

m.a.s.l.: meters above sea level

The data used in this study at SGP site are most comprehensive and longest spanning over 20 years. Such a large data set yields SGP a statistically robust climatology. Conversely, the remaining sites with data records shorter than 2 years have greater uncertainty in their derived statistics. Despite the potential limitations, we include these sites in our analysis as they presently serve as the primary and invaluable source of information for their specific meteorology and environment. The next subsections introduce the ARM products or instruments used for the different atmospheric variables used.

2.1.1 Cloud boundaries

For cloud boundary products, the Active Remote Sensing of Clouds (ARSCL, DOI: 10.5439/1228769) dataset was used (Clothiaux et al., 2000). This product retrieves up to 10 levels of cloud boundaries using a combination of Micropulse Lidar (MPL) and Millimeter Cloud Radar (MMCR) data. According to Clothiaux et al. (2000), the integration of lidar and radar data is critical for obtaining accurate estimates of cloud boundaries from active sensors, as the two instruments have different but complementary sensitivities to cloud particle size distributions. The ARSCL is currently considered the most accurate estimate of cloud boundaries; however, errors arise from signal attenuation, precipitation, and non-hydrometeor clutter such as insects (Clothiaux et al., 2000). At the SGP site, the CLDTYPE product (CLDTYPE, DOI: 10.5439/1349884), derived from ARSCL, was utilized. For the COR and TMP sites, the raw ARSCL product using the KAZRARSCL — Ka-Band ARM Zenith Radar (KAZR) Active Remote Sensing of Clouds (ARSCL) — algorithm was employed (Kollias et al., 2020). For MAO and FKB, the W-band Cloud Radar Active Remote Sensing of Cloud (WACRARSCL, DOI: 10.5439/1987955) was used.

2.1.2 Radiosondes

The ARM SONDE product includes atmospheric thermodynamic profiles obtained from its balloon-borne sounding system. These profiles contain height/pressure, temperature, humidity, wind speed and direction data, captured at least four times daily (at 05:30, 11:30, 17:30, and 23:30 UTC) at each of the five ARM sites selected. Holdridge et al. (2011) provide details about the SONDE product. This study used only radiosonde data collected between 06:30 and 19:00 Local Time (LT). Because the vertical resolution of radiosonde measurements fluctuates in accordance with the balloon's ascent rate, we resampled radiosonde data through linear interpolation to attain a vertical resolution of five hPa.

2.1.3 MERGESONDE data

Radiosonde data, although valuable, provide information only on the atmosphere's thermodynamic state at the time they are launched. However, our investigation required information on the atmospheric state at a higher time resolution. The Merged Sounding (MERGESONDE) value-added product transforms the ARM SONDE product into continuous daily files with thermodynamic parameters on fixed time-height grids. This higher temporal resolution in the MERGESONDE arises from the interpolation of SONDE data, microwave radiometer (MWR) data, surface meteorological instruments, and outputs from the European Centre for ECMWF model. In this investigation, we used the MERGESONDE product available at the SGP site from 2001 to 2015 to compute thermodynamic variables such as CAPE.

2.1.4 Micropulse Lidars

Operating at 532 nm in both parallel and perpendicular polarizations, the autonomous, ground-based Micropulse Lidar (MPL) provides backscattered radiation profiles at a temporal

resolution of 10–30 seconds and a vertical resolution of 30 m. Raw data are corrected for background subtraction, signal saturation, overlap, afterpulse, and range per standard lidar-data processes (Campbell et al., 2002, 2003). Quality-control flags help to omit erroneous data.

2.1.5 Heat Fluxes

Sensible heat (SH) fluxes were obtained from two products: the Energy Balance Bowen Ratio system (EBBR) and the eddy correlation flux measurement system (ECOR). ECOR employs the eddy covariance technique, which analyzes the correlation between the vertical and horizontal wind components, as well as air temperature, water vapor density, and CO₂ density (Tang et al., 2019). In particular, the ARM value-added product quality-controlled ECOR (30QCECOR, DOI: 10.5439/1097546) was used.

EBBR calculates bulk aerodynamic fluxes based on observations of net radiation, soil surface heat flux, and vertical gradients of temperature and relative humidity. Here, we employed the ARM value-added product known as the best-estimate fluxes derived from EBBR measurements and Bulk Aerodynamic calculations (30BAEBBR, DOI: 10.5439/1027268).

2.1.6 Surface meteorology

ARM meteorological data, including relative humidity, temperature, and atmospheric pressure was retrieved from the MET product (MET, DOI: 10.5439/1786358), which uses mainly conventional in situ sensors to obtain 1-minute statistics of surface meteorology.

2.1.7 Vertical velocity

Vertical velocity data were obtained from the ARM Doppler Lidar Vertical Velocity Statistics Value-Added Product (sgpdlprofwind4news, DOI: 10.5439/1178582). ARM Doppler lidars operate in the near infrared (NIR; 1.5 microns) and provide range-resolved measurements of

radial velocity, attenuated aerosol backscatter, and SNR. In this investigation, we only used the doppler lidar vertical velocity data measured at the SGP site.

2.1.8 Aerosol number concentration

Aerosol number concentration was obtained from the Aerosol Observing System (AOS) (DOI: 10.5439/1988399). AOS corresponds to a platform for in situ aerosol measurements at Earth's surface. In particular, this investigation uses observations from the condensation particle counter (TSI Inc.) at 1-minute resolution.

2.2 Satellite observations

2.2.1 The Cloud-Aerosol Transport System (CATS) data

CATS was an elastic backscatter lidar that operated on the International Space Station (ISS) from February 2015 to October 2017. Because the ISS has a precessing orbit with a 51.8° inclination angle, CATS was able to sample the atmosphere with a unique frequency compared to other NASA A-Train sensors like CALIPSO or MODIS (Noel et al., 2018). CATS collected data with a repeat cycle of nearly 3 days (2.3 days in the midlatitudes and 4.3 days in the tropics), passing over the same locations but at different local times (Yorks et al., 2016). This enabled CATS to sample the entire diurnal cycle approximately every 60 days, making it an ideal sensor for studying the diurnal evolution of clouds, aerosols, and the PBLH between 51°S and 51°N (Lee et al., 2019; Noel et al., 2018; Nowottnick et al., 2022; Palm et al., 2021).

CATS provided ranged resolved vertical backscatter profiles and depolarization ratio primarily at 1064 nm, information that is used to retrieve the properties of cloud and aerosol layers on a global scale through their Level 1B and Level 2 products. The Level 1B product primarily consisted of attenuated backscatter coefficients, depolarization ratios, and meteorological data

obtained from NASA's Global Modeling and Assimilation Office (GMAO) (Pauly et al., 2019; Yorks et al., 2016). These data were provided at a horizontal resolution of 350 m (along-track) and a vertical resolution of 60 m. The Level 2 operational data consisted of a layer detection and cloud-aerosol discrimination product that included variables such as the layer top and base, feature type, cloud phase, and aerosol type (Yorks et al., 2021).

2.2.2 The Soil Moisture Active Passive (SMAP) data

The SMAP mission is a NASA satellite initiative that measures the amount of water in surface soil globally (Hersbach et al., 2020). SMAP is designed to measure soil moisture every two to three days, enabling the observation of changes worldwide over time scales ranging from major storms to seasonal variations. The satellite was launched in January 2015 and began operations in April 2015. SMAP operates in a near-polar, sun-synchronous orbit at approximately 685 km altitude. The mission was originally equipped with two instruments: a radar that failed a few months after launch and a microwave radiometer that remains fully operational. SMAP measurements provide direct sensing of the soil moisture between the top 5 cm of the soil column.

This study utilizes the SMAP Enhanced Level-3 Passive Soil Moisture Product (SPL3SMP_E), which provides daily global land surface estimates at a spatial resolution of 9 km by 9 km. The product is a daily composite of SMAP Level-2 (L2) soil moisture, derived from SMAP Level-1C (L1C) interpolated brightness temperatures. This investigation uses SMAP data between 2015 and 2020.

2.3 Reanalyses

This study utilizes ERA5 data, the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis for global climate and weather. ERA5 offers

comprehensive, high-resolution data beginning in 1940. As reanalysis data integrate model outputs with global observations, ERA5 delivers hourly information on surface properties, upper-air processes, and land variables. For this investigation, ERA5 and ERA5-Land retrievals of multiple atmospheric and land variables were employed, including temperature, specific humidity, and geopotential height at 950 hPa, as well as soil water content, latent and sensible heat fluxes, boundary layer height, 2-meter temperature, 2-meter relative humidity, and surface pressure.

It is important to mention that reanalysis datasets are inherently constrained by the quality and density of the observational networks used for assimilation. For ERA5, despite significant advances in spatial resolution and data assimilation techniques, several biases have been documented. These include cold biases in the stratosphere, unrealistic precipitation events, and inaccurate snow depths in regions with complex terrain (Hersbach et al., 2020).

Chapter 3: Ground-based estimation of the PBLH

This chapter estimates the PBLH for both radiosonde measurements and MPLs. Here, radiosonde retrievals are used as the ground-truth to validate MPLs PBLH estimates. However, it is important to note that each method uses different definitions and ways to evaluate the boundary layer. Radiosonde observations are often considered the most reliable and accurate for measuring PBLH because they measure the thermodynamic profile of the atmosphere, which provides important information about the stability and structure of the boundary layer and is a better indicator of turbulent motions. While radiosonde measurements are the most reliable for estimating PBLH, they also have some limitations and errors, which will be discussed later in this chapter (Park et al., 2001).

In contrast, lidar-based approaches rely on the spatial distribution of tracers like water vapor or aerosols. This means their concept of the boundary layer is different from one based on turbulent flow. The difference between the two methods is more noticeable at night when turbulent transport is weak. However, tracer-based methods still represent the convective boundary layer well during the day. In addition to radiosonde estimates, this chapter also uses the existing ARM PBLH product (i.e., Ceilometer-based PBLH) for comparisons. In the next subsections, we explore the methodologies to retrieve the PBLH and evaluate the sources of errors and limitations of our method.

3.1 Radiosonde retrievals of the PBLH

We calculated the PBLH from radiosonde observations (i.e., RS-PBLH) using the well-established method of Liu and Liang (2010). The method starts by characterizing the PBL thermodynamics by comparing the near-surface potential temperature difference with a stability

threshold δs , set to 1 K in continental regions. Under convective conditions, this method identifies the PBLH as the height at which an air parcel rising adiabatically becomes neutrally buoyant. The method first scans upward a level k , where the temperature difference $\theta_k - \theta_1$ exceeds a threshold value δu , which equals 0.5 K. This level is corrected by a second scan searching for the overshooting level, which defines the entrainment zone. The Liu and Liang method defines this overshooting level as the height where $\partial\theta_k/\partial z \geq \dot{\theta}_r$, with $\dot{\theta}_r$ equal to 4 K/km. Under stable conditions, the PBLH is harder to determine because turbulence arises from buoyancy or wind shear. Liu and Liang's method define a stable PBLH as either the top of the stable layer above the ground or at the low-level-jet nose height, whichever is lower.

3.2 MPLs retrievals of the PBLH using DTDS

For lidars, the PBLH is typically estimated at the altitude where a distinct contrast in aerosol loading occurs. In principle, an inversion layer caps the PBLH, trapping aerosols within the boundary layer and creating a pronounced contrast with the free atmosphere (Seibert, 2000). This contrast is observable in the backscattered radiation detected by lidar instruments, renders them particularly effective for estimating the PBLH. However, estimating the PBLH from lidar data becomes challenging under conditions of strong atmospheric stratification and residual layers, cloudy situations, transition hours between stable and convective regimes, or when the inversion layer is low enough to be positioned within the lidar's blind zone. Such scenarios are more prevalent during stable boundary-layer conditions (Li et al., 2017).

Traditional methods to compute the PBLH from lidars include the gradient method and the wavelet covariance transform function (WCT). The former searches for local gradient minima of the corrected total backscatter signal. The latter corresponds to a tool for distinguishing step

changes from noisy signals and it has proven more effective for estimating PBLH using lidar data than the gradient method (Davis et al., 2000). The WCT method is defined as follows:

$$W_f(a, b) = \int_{z_b}^{z_t} B(z) h\left(\frac{z-b}{a}\right) dz \quad (1)$$

where a is the dilation factor, b is the vertical translation factor where the function is centered, $B(z)$ is the backscatter signal, z is altitude, and z_b and z_t are the integration limits of the Haar function (h). The haar function is defined as:

$$h\left(\frac{z-b}{a}\right) = \begin{cases} +1: & b - \left(\frac{a}{2}\right) \leq z \leq b \\ -1: & b < z \leq b + \left(\frac{a}{2}\right) \\ 0: & elsewhere \end{cases} \quad (2)$$

Compared to the previous approaches, the DTDS algorithm addresses the key challenges in measuring the PBLH from lidar data by combining wavelength and gradient methods with a stability model that assesses whether the PBLH is in a growth, decay, or other transitional phase. Rather than relying solely on current PBLH estimates, DTDS incorporates both current and prior PBLH estimates, which improves vertical consistency and enhances temporal continuity. Additionally, DTDS manages cloudy conditions by assessing the cloud-surface coupling. When a cloud is coupled to the surface, its position can effectively represent the PBLH. To determine this coupling, DTDS compares the cloud base height (CBH) with the LCL or the PBLH itself. If the cloud is coupled, the CBH is set as the PBLH. Here, the LCL is estimated from surface meteorological data (relative humidity, temperature, pressure) based on an exact expression (Romps, 2017).

Our methodology consists of evaluating the performance of the retrieved PBLH using DTDS (DTDS-PBLH) at the five ARM sites. To achieve this, we compared our DTDS-PBLH estimations with the RS-PBLH and the current ARM PBLH product. The ARM PBLH product is

based on ceilometer data (CEIL-PBLH) and uses the traditional gradient method. This method involves finding the height where the gradient of the backscatter signal reaches a minimum.

In this study, minor modifications were made to the original DTDS method (Su et al., 2019) to adapt it to various scenarios. Firstly, we tailored the time zone configurations for each site to ensure that DTDS correctly represents the growing and decaying period of the boundary layer according to the geographical location. Secondly, the SGP blind zone is ~ 0.2 km, which makes DTDS retrieve the PBLH above this level. We adjusted the blind zone of MAO, TMP, and COR to ensure peak efficiency. Thirdly, instead of using the traditional morning radiosonde measurements, we opted to use the LCL as the upper boundary for determining the initial position of PBLH to avoid the interference of the morning residual layer. Therefore, our primary use of the radiosonde data was for validation purposes only. Finally, we expanded the dataset's span, incorporating over 20 years of data, marking a significant augmentation from the earlier evaluation duration of 8 years, as reported by Su et al. (2019).

3.3 Ceilometer retrievals of the PBLH

ARM provides continuous estimates of the PBLH using ceilometers (i.e., Ceil-PBLH) at four of the five ARM observatories used in this study: SGP, MAO, COR, and TMP. Specifically, ARM deploys Vaisala CL31 ceilometers, which have a maximum vertical range of 7.7 km (Munkel & Rasanen, 2004). The Vaisala CL31 ceilometer provides a total attenuated backscatter coefficient profile at 910 nm, with a vertical resolution of 10 m and a temporal resolution of 2 s (Münkel et al., 2006). The ARM Ceil-PBLH method starts by averaging the backscatter data to a temporal resolution of 16 s, after which the well-known gradient method is applied. This method searches for local gradient minima of the corrected total backscatter signal. Additionally, the ARM Ceil-PBLH product excludes cloud and precipitation cases and suppresses false layer identification

(Zhang et al., 2022). In this study, we compared the performance of the DTDS algorithm against this existing ARM-PBLH product.

3.4 Overview of the DTDS-derived PBLH product

Figure 3.1 presents examples of normalized backscatter signals from MPLs at the five ARM observatories, along with DTDS-derived PBLHs, radiosonde-based estimates (Liu & Liang, 2010), and ceilometer-derived PBLHs. Figure 3.1a highlights wintertime PBL evolution at SGP, where little diurnal variation leads to a highly stratified aerosol structure. This stratification complicates lidar-based PBLH retrievals, and most algorithms perform poorly. In this SGP case, however, the DTDS algorithm accurately tracks the boundary layer’s evolution and matches the RS-PBLH estimates even with stratified aerosols. Ceil-PBLH retrievals also perform well, showing few jumps between atmospheric layers.

The MAO example in Figure 3.1b shows a nocturnal boundary layer initially capped by clouds. These clouds create a strong step signal in lidar backscatter, which can help or hinder PBLH retrieval depending on cloud type. In this case, boundary-layer clouds help define the PBLH, and DTDS-PBLH and Ceil-PBLH retrievals agree well with RS-PBLH estimates. After 14 LT, the cloud signal disappears, revealing a more complex aerosol structure with multiple layers and complicating PBLH retrieval.

While the Ceil-PBLH retrievals jump between different atmospheric layers, sometimes selecting elevated aerosol layers as the PBLH, the DTDS retrievals consistently track the PBLH. This consistent tracking of the PBLH is due to DTDS’s selection scheme (c.f. Figure 3b in Su et al., 2020) and its consideration of the diurnal variability of the boundary layer. DTDS determines whether the boundary layer is decaying, growing, or in other periods and prioritizes the selection of future retrievals closer to current retrievals. In the case of Figure 3.1b, the strong signal of the

PBLH caused by the presence of boundary layer clouds before 14 LT helps DTDS compute the PBLH after 14 LT. The selection scheme would prioritize heights nearer to the cloud's signal in a decaying boundary layer situation.

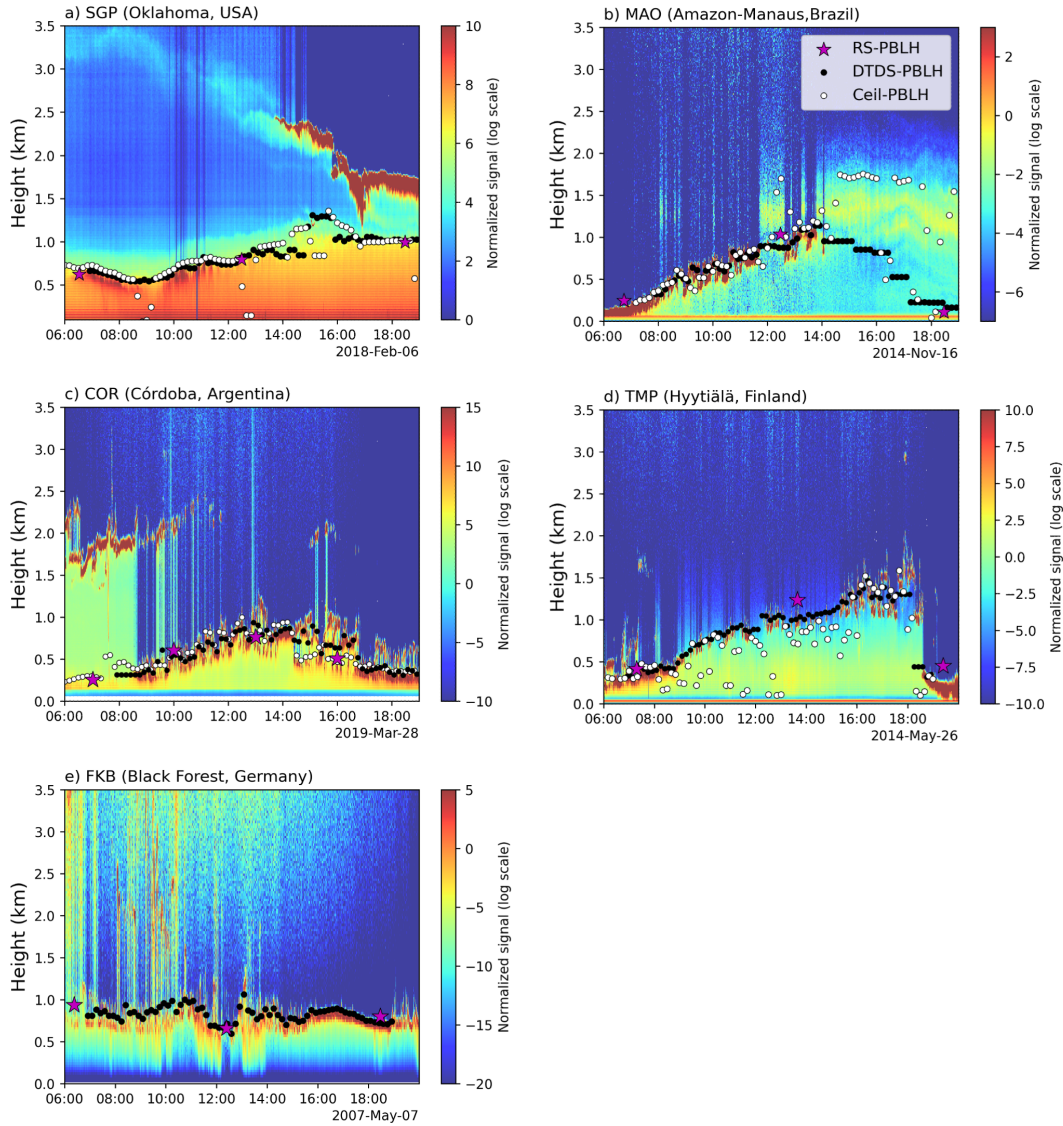


Figure 3.1 Examples of the computed PBLH at the five ARM sites using the DTDS algorithm (black dots), the ARM ceilometer product (white dots), and radiosonde estimates (magenta stars). The colormap corresponds to the normalized backscatter signal measured by the MPL at each site.

In addition to examining cases on specific days, it is also insightful to investigate the climatology of the diurnal cycle when assessing the performance of the DTDS algorithm at the five different sites. Figure 3.2 shows box-and-whisker plots for the diurnal cycles of the DTDS-PBLH retrievals at the five ARM sites. In general, the PBLH is a shallow layer during the morning hours between 06:00 to 09:00 am (6–9 LT). The lowest morning layer is found at FKB, where the entire distribution between 6:00 am and 7:00 am (6–7 LT) is below 500 meters above ground level (m.a.g.l.). COR has the maximum PBLH in the morning hours, with layers extending as high as 1.5 km a.g.l. COR's high topography is one possible reason for this higher PBLH in the morning hours. Since COR is located at 1141 m, it has a much larger surface roughness and might act as an elevated heat source, both causing strong turbulence and convective instability that favors deep boundary layers. COR's topography also favors the formation of orographic boundary layer clouds, which are frequently observed at this site. Many of these clouds grow to congestus depths. Determining the PBLH for this cloud regime is challenging, and most PBLH retrieval methods would estimate it at the cloud base height. However, a further and detailed examination is required to understand this pattern.

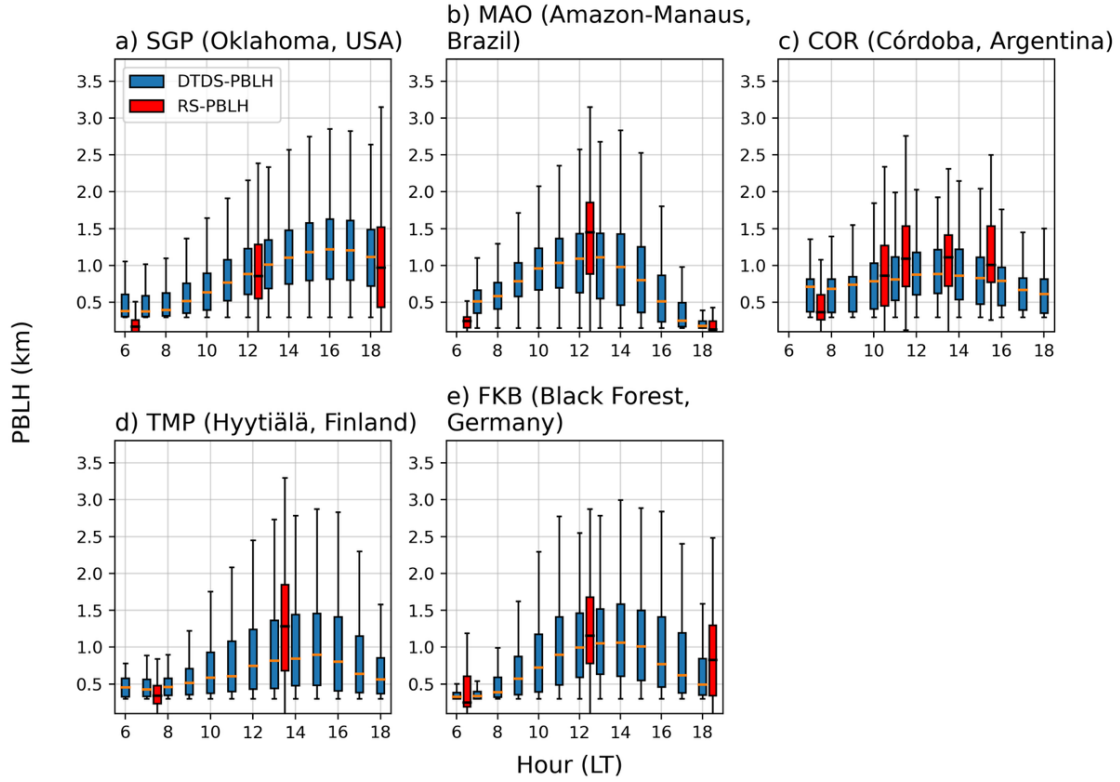


Figure 3.2 Average diurnal cycle of PBLH computed using the DTDS-PBLH and radiosonde PBLH (RS-PBLH) at the five Atmospheric Radiation Measurement observatories. The horizontal orange lines, blue bars, and whiskers represent median values, interquartile ranges, and ranges of the data, respectively. Red bars and their associated whiskers and median line represent the RS-PBLH. Time along the x-axis is Local Time

Some of the differences observed in the climatological pattern of each site may also arise from the different dataset lengths. The SGP dataset spans almost 20 years, allowing this site to have a robust representation of variations related to seasonal forcing, multiple phases of the El Niño-Southern Oscillation (ENSO), and other climate oscillations. On the contrary, the measurements made in the Mobile ARM sites correspond to relatively short campaigns with a dataset spanning almost two years in the best case at MAO. Therefore, the PBLH evolution

observed in Figure 3.2 for the mobile facilities could be highly influenced by unstable and deeper boundary layers occurring in summer or stable and shallower boundary layers in winter. For instance, the FKB site in Germany does not have measurements for the winter months of January, February, and March, potentially leading to an overestimation of the climatology of PBLH for that site.

3.5 Statistical evaluation of the ground-based DTDS-PBLH performance

Figure 3.3 compares the DTDS-PBLH retrievals with the RS-PBLH at the five ARM sites. The colors in the Figure correspond to the Kernel Density Estimates (KDEs), a non-parametric technique that provides a continuous estimate of the probability density function of the PBLH retrievals. The Figure also includes the correlation coefficient (R), the Root Mean Square Error (RMSE), and the Mean Absolute Error (MAE). Notably, there is a robust linear relationship between both sets of retrievals, with correlations varying between 0.77 at SGP and COR and 0.93 at MAO.

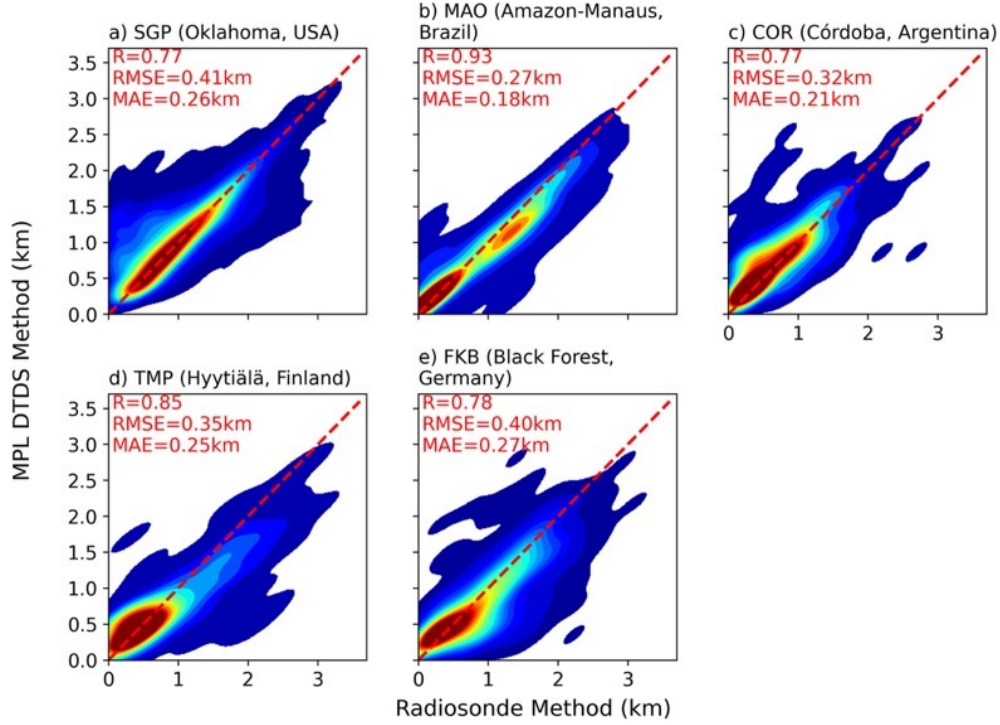


Figure 3.3 Kernel distribution estimates for the micropulse lidar-based DTDS-PBLH and the RS-PBLH based on the Liu-Liang method at the five ARM sites. The correlation coefficient (R), root-mean-square error, and mean absolute error are given in each panel. Dashed red lines correspond to 1:1 lines.

In order to compare our PBLH estimates with existing ARM products, Figure 3.4 shows the same comparison but between the ARM CEIL-PBLH and the RS-PBLH. In general, the relation between Ceil-PBLH and RS-PBLH is highly dispersed, with R ranging from 0.48 at SGP to 0.72 at MAO, RMSE oscillating between 0.48 and 0.7 km, and MAE between 0.28 and 0.46 km. We can conclude that the DTDS-PBLH product outperforms existing lidar-based PBLH retrievals, providing higher correlations and smaller errors. The results presented here can be found in (Roldán-Henao et al., 2024)

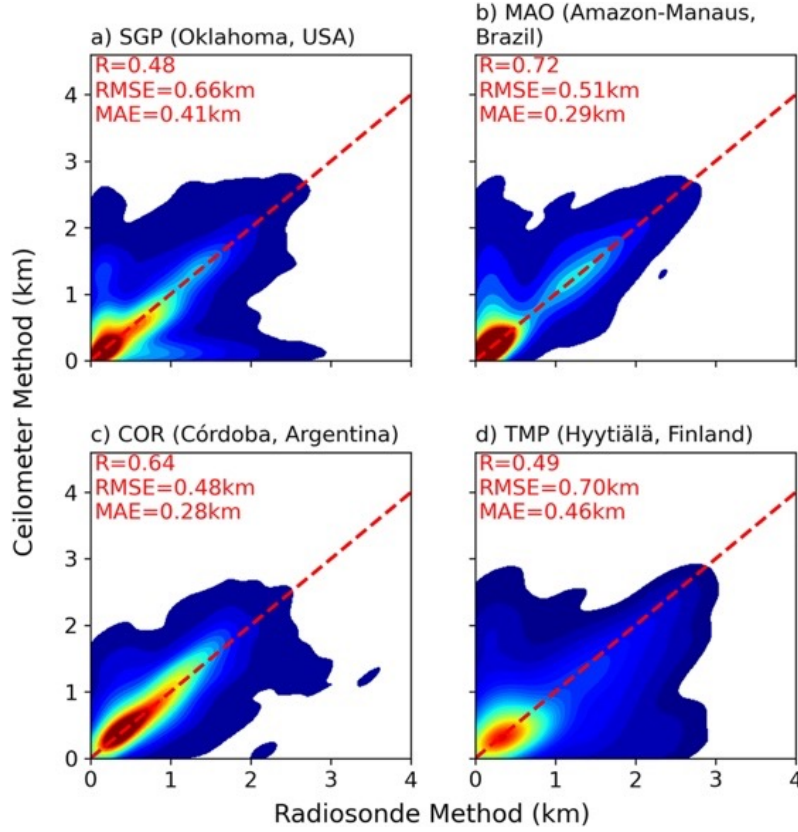


Figure 3.4 Kernel distribution estimates for the CEIL-PBLH and the RS-PBLH based on the Liu-Liang method at the five ARM sites. The correlation coefficient (R), root-mean-square error, and mean absolute error are given in each panel. Dashed red lines correspond to 1:1 lines.

As shown in Figure 3.4, the DTDS algorithm tends to overestimate shallow boundary layers, typically below 1 km, and underestimate deep boundary layers. Such a situation is particularly noticeable at the SGP site. The overestimation of shallow boundary layers generally occurs during the morning hours when the PBL tends to be stable and highly stratified. Both conditions pose difficulties in estimating the PBLH based on backscatter information, which is more related to lidar limitations than to problems in the DTDS algorithm. For example, in the case of extratropical sites like SGP, the performance of the DTDS algorithm varies with season. Retrievals from the SGP site have higher errors during winter because the PBLH tends to be

shallower than in other seasons. The PBLH can sometimes be below the near-surface 150-m MPL blind zone of the region, impeding the correct estimation of the PBLH.

3.6 Analysis of errors and limitations of the PBLH retrievals

Attributing all DTDS algorithm inaccuracies exclusively to the algorithm itself is an oversimplification. Instead, this section comprehensively examines the multiple sources of errors, including those resulting from lidar measurements and limitations, radiosonde measurements, and the RS-PBLH algorithm. By delving into these factors, light will be shed on the intricate interplay between these components, highlighting the inherent complexity of the PBLH retrieval. At the same time, this error analysis will help recognize areas for potential enhancement and underscore the need for further refinement of the DTDS algorithm.

3.6.1 Errors arising from radiosonde estimations

RS-PBLH retrievals are widely accepted in the scientific community as the ground truth. Although radiosonde measurements are the most reliable source for estimating the PBLH, the computed PBLH can sometimes be ambiguous. For instance, radiosonde-based thermodynamic profiles can be ambiguous when multiple inversion layers or no inversions are present. Figure 3.5 illustrates a case in which multiple inversion layers lead to a potentially incorrect PBLH. The figure depicts the PBLH computed at MAO on 14 September 2015, along with the backscatter information. Note the elevated aerosol layer signal in the early morning, that disappears as the day progresses. At noon, the DTDS-PBLH algorithm retrieves the PBLH around 1.5 km, corresponding to the approximate location of the aerosol layer. However, the RS-PBLH algorithm identifies the PBLH at ~2.5 km.

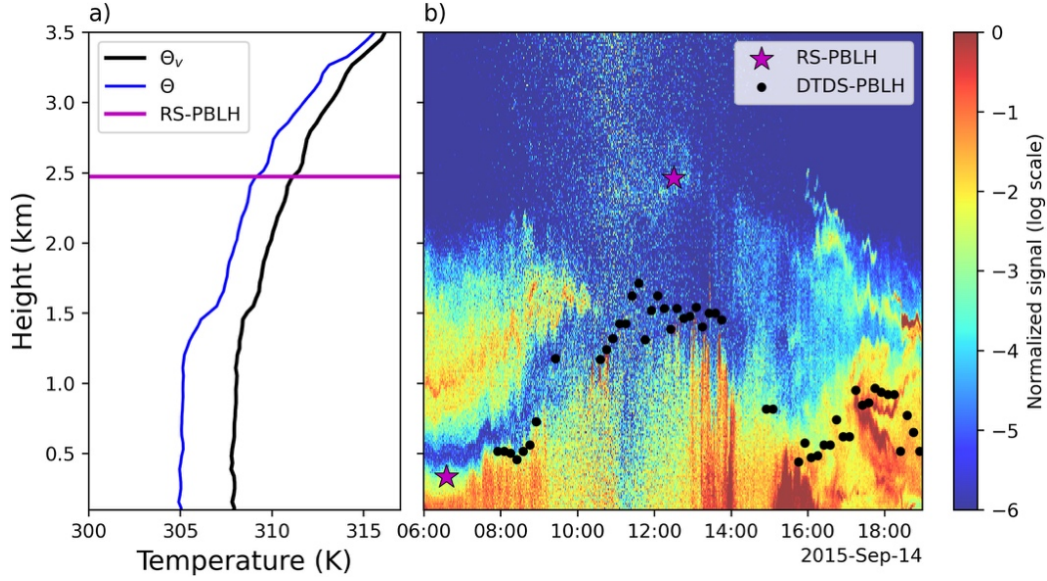


Figure 3.5 PBLHs at MAO on 14 September 2015. (a) Profiles of potential temperature (θ) and virtual potential temperature (θ_v) measured around noon on the same date (black and blue lines, respectively). The magenta line corresponds to the RS-PBLH. In this example, RS-PBLHs based on θ and θ_v , and the ARM RS-PBLH have the same values. Therefore, only one line is shown. (b) Backscatter information for the same day where the colormap indicates the normalized backscatter signal. Black dots correspond to DTDS-PBLHs, while stars are radiosonde-PBLHs (RS-PBLH).

Another source of errors in the radiosonde estimates arises from the algorithms used to compute the PBLH, which require multiple parameters that may not be adjusted to local environmental conditions, such as the multiple threshold values in the Liu and Liang method. Figure 3.6 shows a sensitivity analysis of the threshold values for the same date shown in Figure 3.5. The red lines represent the PBLH using the standard values, while the blue lines indicate a modified version. As demonstrated by adjusting the standard values of $\dot{\theta}_r$ and δu , the Liu and Liang algorithm identifies the first inversion layer at approximately 1.5 km as the PBLH, aligning with the PBLH-DTDS retrieval.

In Figure A.1 (see Appendix A), we present a thorough sensitivity analysis of the effect of the threshold values on PBLH determination based on the MAO dataset. This analysis reveals that varying threshold values may result in shallower or deeper boundary layers compared to the standard values, highlighting the importance of these threshold values on the overall algorithm's performance. Despite the variations observed, the Liu and Liang method consistently provides reliable PBLH retrievals, and using the standard values helps with reproducibility and comparison purposes.

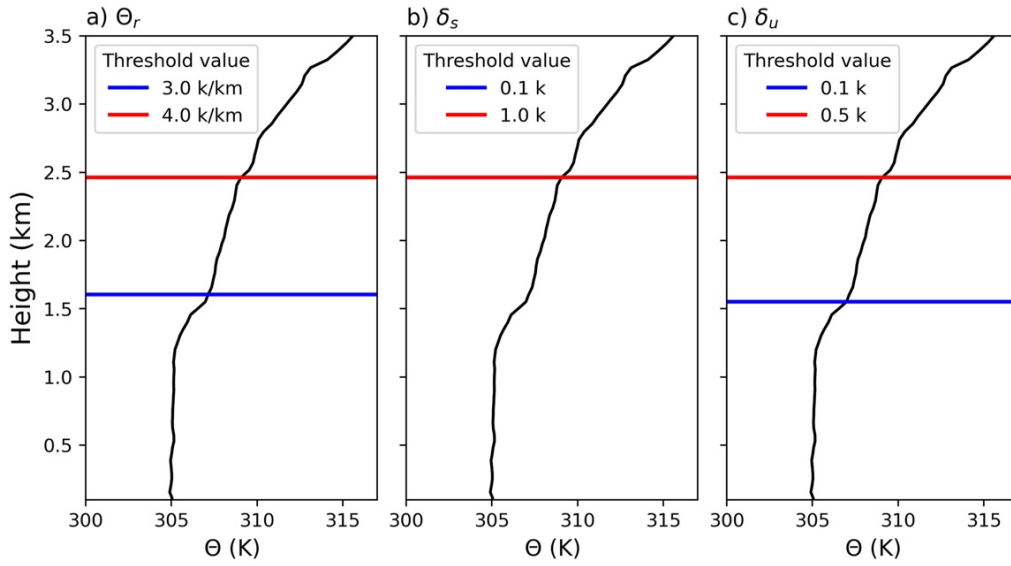


Figure 3.6 Sensitivity analysis comparing the threshold values proposed by Liu and Liang for (a) Θ_r , (b) δ_s , and (c) δ_u at MAO on 14 September 2015. The red lines represent the standard threshold values, while the blue line depicts the modified thresholds.

Differences between the RS-PBLH and the DTDS-PBLH retrievals also depend on the type of temperature used to compute the PBLH. Figure 3.7 is like Figure 3.3 but uses virtual potential temperature (θ_v) instead of potential temperature (θ). While these figures are similar, they are not identical. Overall, the PBLH computed using θ performs better than the one using θ_v because θ_v contains considerable uncertainties due to errors in measuring humidity (Liu & Liang, 2010).

However, for three of the five sites, the correlation coefficient between RS-PBLH and DTDS-PBLH retrievals is higher, going from 0.77 to 0.79 at SGP, from 0.85 to 0.87 at TMP, and from 0.78 to 0.81 at FKB. The higher correlation observed attributed to the superior representation of boundary layer thermodynamics when using θ_v , which accounts for the effects of moisture content in the air.

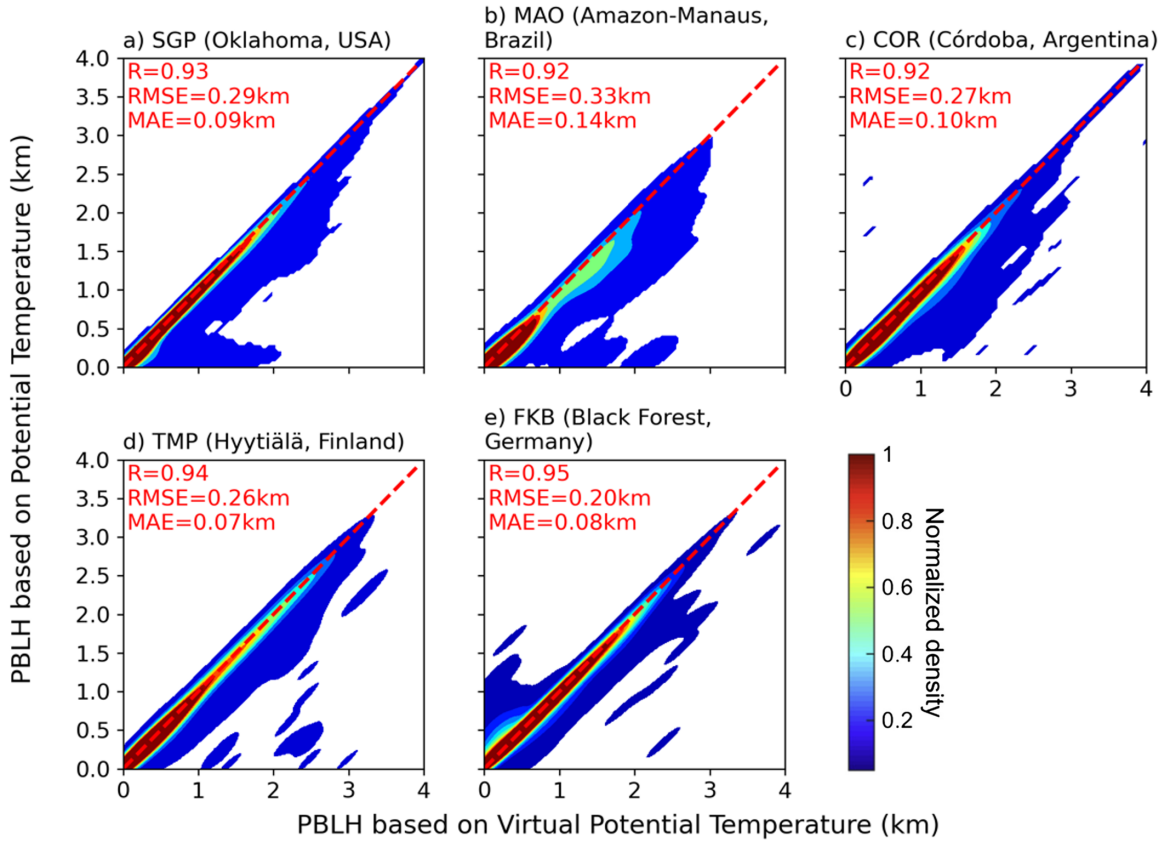


Figure 3.7 Kernel distribution estimates for radiosonde PBLHs based on potential temperature and virtual potential temperature at the five ARM sites. The correlation coefficient (R), root-mean-square error ($RMSE$), and mean absolute error (MAE) are given in each panel. Dashed red lines correspond to 1:1 lines.

3.6.2 Errors arising from lidar estimations

Another important source of errors arising when computing the DTDS-PBLH is that resulting from lidar limitations. For example, Figure 3.8 showcases a situation that occurred over TMP on 15 February 2014. On that day, the presence of a stratocumulus-topped boundary layer (STBL) attenuated the MPL backscatter, preventing the instrument from sensing the atmosphere above the cloud base. In this case, the DTDS algorithm retrieves the PBLH at the same height as the cloud base at ~ 0.7 km. However, in Figure 3.8a, the temperature profiles around noon reveal a well-mixed boundary layer with a strong capping inversion at ~ 1.1 km. This inversion coincides with the cloud-top height shown in Figure 3.8b.

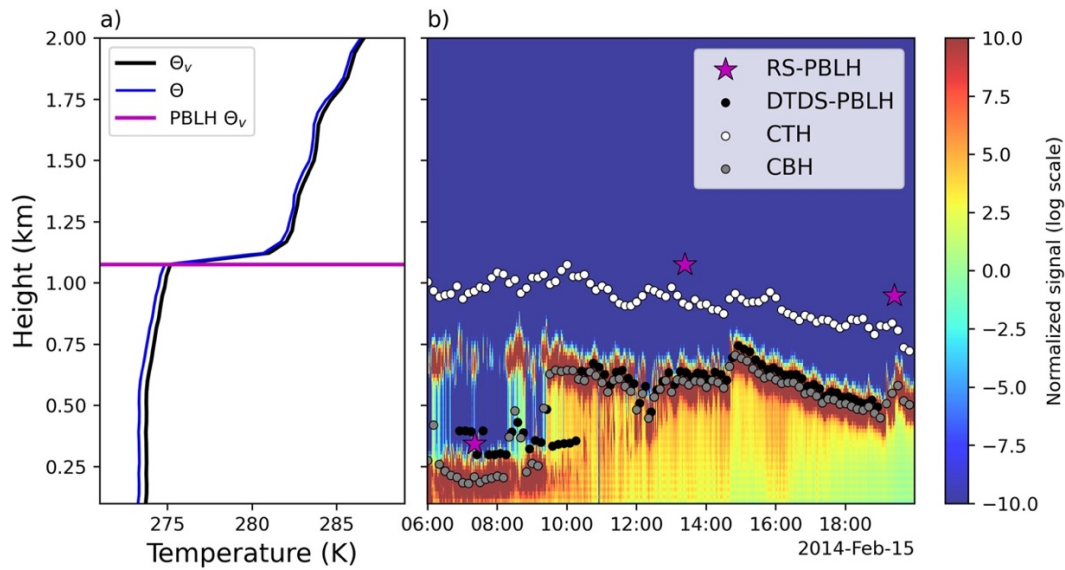


Figure 3.8 PBLHs at TMP on 22 October 2014. (a) Profiles of potential temperature (θ) and virtual potential temperature (θ_v) measured around noon on the same date (black and blue lines, respectively). The magenta line corresponds to the RS-PBLH. For this example, RS-PBLH based on θ and θ_v , and the Atmospheric Radiation Measurement RS-PBLH have the same values. (b) Backscatter information for the same day. Black dots correspond to the DTDS-PBLH, stars are RS-PBLHs, white dots are CTH, and gray dots are CBH.

Finally, the performance of the DTDS algorithm is notably diminished in instances where the lidar instrument is not operating properly. The COR site provides an example of the errors that arise from poor lidar performance. The initial MPL installed at the COR site was misaligned, leading to a consistent spurious signal always present in the backscatter profile. Figure 3.9a,b shows two different days when the MPL at COR was misaligned, one under clear-sky conditions and a second under cloudy conditions. In both cases, a strong constant step signal is visible between 0.5 and 1 km. For reference, this spurious signal is not observed in the backscatter signal of the ceilometer (see Figure 3.9c,b). The spurious signal in the backscatter profile of the MPL impeded the accurate determination of the PBLH on the clear-sky day, resulting in the DTDS algorithm incorrectly placing the PBLH at ~ 0.8 km. In the case when boundary-layer clouds were present (Figure 3.9b), the strong backscatter signal from the clouds counteracted the spurious backscatter signal, helping the DTDS algorithm accurately retrieve the PBLH.

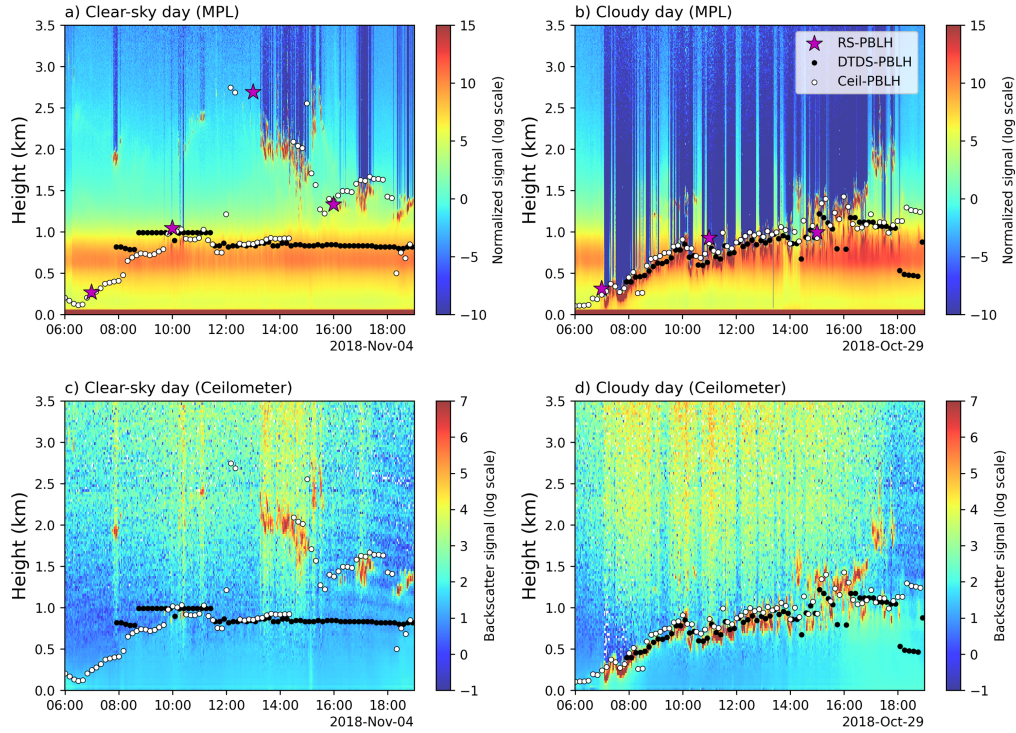


Figure 3.9 PBLHs at COR using the DTDS algorithm (black dots), the ARM Ceil-PBLH product (white dots), and radiosonde estimates (magenta stars) prior to the replacement of the MPL on (a,c) a clear-sky day and (b,d) a cloudy day. The colormap indicates the normalized backscatter signal measured by the (a-b) MPL and the (c-b) ceilometer. The constant orange-red belt observed in (a-b) between 0.5 and 1 km represents spurious signals.

To address the misalignment issue in the MPL, a new lidar was installed at the site on 18 February 2019. This replacement successfully eliminated the spurious signal, leading to a notable improvement in the performance of the DTDS algorithm. Figure A.2 shows an example of the MPL backscatter signal after the sensor was replaced. Figure 3.10 compares the DTDS performance at retrieving the PBLH before and after the MPL was changed under clear-sky and cloudy conditions. Note that erroneous DTDS-PBLH estimates were included because the primary aim is to highlight the pronounced improvements observed in the DTDS performance exclusively

resulting from replacing the lidar. Overall, R is higher (Figure 3.10a), and the RMSE is smaller (Figure 3.10b) under cloudy conditions than under clear-sky conditions. Also, after the MPL was replaced, R increased from 0.58 to 0.7 on average, and RMSE decreased from 0.48 km to 0.37 km. In the case of the MAEs, we also see a slight improvement when the lidar is changed, even considering that the MAE weighs all errors equally.

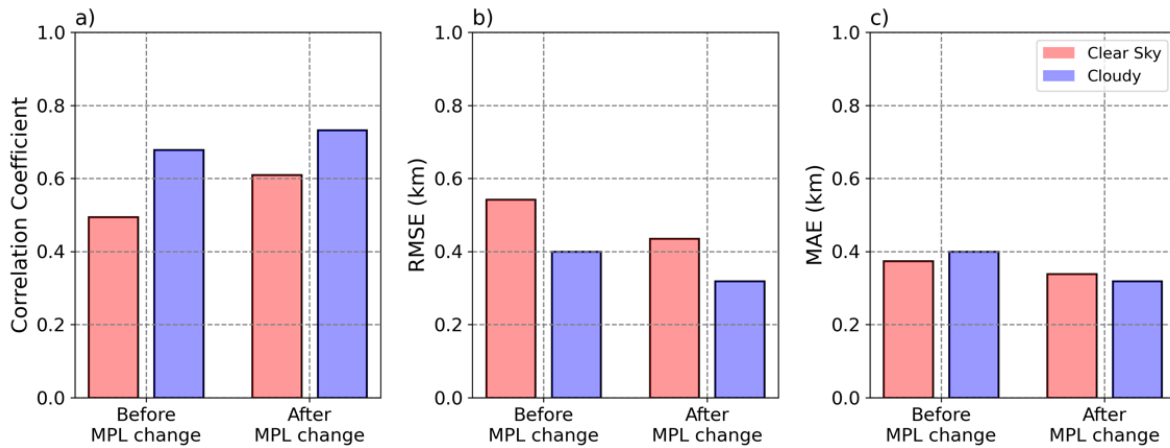


Figure 3.10 (a) Correlation coefficients, (b) RMSEs, and (c) MAEs from the DTDS- and radiosonde-derived PBLH relations before and after the MPL was replaced at the COR site. Red bars correspond to clear-sky conditions, and blue bars represent cloudy conditions.

3.7 Conclusions

A comprehensive understanding of the PBLH is crucial for advancing knowledge of many atmospheric processes, including cloud-PBLH coupling. While radiosondes have long been used to measure PBLH, there is a pressing need to enhance the precision of PBLH estimates, particularly when applying lidar techniques. Lidar systems enable continuous monitoring of PBLH and overcome radiosonde limitations in temporal resolution. However, lidar methods also have limitations and can introduce uncertainties, particularly under stable, stratified, or cloudy conditions.

In this chapter, we utilized ARM MPLs data to assess the performance of the Different Thermo-Dynamic Stabilities (DTDS) algorithm developed by our team (Su et al., 2020) across various atmospheric and geographical contexts. The DTDS algorithm was originally developed and validated for calculating the PBLH at the SGP site, where it demonstrated superior performance compared to conventional wavelet and gradient methods. However, its effectiveness under different environmental conditions remained untested, which was a critical gap to address, as the PBLHs derived here serve as a key input for evaluating cloud-PBLH coupling in subsequent chapters.

Our results show that the DTDS-PBLH and the radiosonde-derived PBLH agreed well, with R ranging from 0.77 at the COR site to 0.93 at the MAO site, and the root-mean-square error ranging from 0.27 km at MAO to 0.41 km at SGP. The correlation and the RMSE instill confidence in the new method's robustness in representing the boundary layer's temporal variability. Compared to existing PBLH products for the same sites, e.g., Ceil-PBLH, the RMSEs of DTDS-PBLH were roughly a third smaller than the RMSE of Ceil-PBLH. On the other hand, the MAEs of DTDS-PBLH were half-smaller than the MAEs of Ceil-PBL. Given this demonstrated robustness, the DTDS-derived PBLHs will be used in the following chapters to investigate cloud-PBLH coupling across the ARM sites.

Despite the relatively superior performance, both the DTDS algorithm and input data suffer from limitations, leading to retrieval errors in the PBL product. Besides, there also exist uncertainties in radiosonde-based PBLH estimates due to the complexity of atmospheric thermodynamics. For example, at the COR site, lidar misalignments in the first MPL installed there produced a spurious signal that hampered the DTDS performance. Further limitations in the DTDS algorithm include constraints in the MPL visibility, such as during cloudy conditions that

attenuate the backscatter signal. Radiosonde measurements may also introduce ambiguity in determining the PBLH, causing disparities between radiosonde and DTDS estimates, especially when multiple inversion layers are present or when there are no inversions. Moreover, the thermodynamic variable used in calculating the radiosonde-derived PBLH (e.g., potential temperature or virtual potential temperature) can introduce variability in the results. A thorough understanding of these errors and limitations is pivotal for continuous improvements in the DTDS algorithm, enhancing its performance and reliability in estimating PBLH.

Chapter 4: Spaceborne estimation of the PBLH

Ground-based observations provide valuable and accurate estimates of the PBLH, but they often lack spatial representation of the PBLH on regional and global scales. In this chapter, we leverage the unique sampling capabilities of CATS to estimate the diurnal variability of the PBLH. Compared to other NASA A-Train sensors like CALIPSO or MODIS (Noel et al., 2018), CATS collected data with a repeat cycle of nearly 3 days (2.3 days in the midlatitudes and 4.3 days in the tropics), passing over the same locations but at different local times (Yorks et al., 2016). This unique capability gives CATS the potential to statistically resolve the diurnal variability of the PBLH. Therefore, in this chapter, we combined CATS data with DTDS to estimate the PBLH.

4.1 Methodology to retrieve the PBLH from spaceborne lidar

The original DTDS algorithm was designed for ground-based lidars, so adapting it for satellite data requires several modifications. Key differences between the original and satellite-adapted versions of DTDS include:

- **Temporal Sampling:** Ground-based lidars provide continuous monitoring over the same area, allowing the original DTDS to detect growing and decaying phases of the PBLH within a single day. In contrast, CATS only captures a snapshot per pass, which does not encompass these phases. Thus, the adapted DTDS algorithm for CATS isn't able to leverage the temporal information during growing or decaying periods as the original DTDS does.
- **Cloud Handling:** The DTDS algorithm assesses cloud-surface coupling by identifying the CBH, easily obtained from ground-based lidars. However, satellite lidars like CATS face

significant signal attenuation beneath the cloud top due to their viewing geometry, especially with optically thick clouds, making CBH detection challenging. To address this problem, we focus on single-layer clouds thinner than 1 km and filter out clouds with a Feature Type classification suggesting high attenuation (classification above 3 between the cloud base and the Earth's surface).

- Since CATS does not have collocated meteorological measurements, the representation of the LCL is not as robust as ground-based meteorological measurements. CATS meteorological data originates from MERRA-2 reanalysis data at coarse horizontal resolutions ($0.5^\circ \text{ lat} \times 0.625^\circ \text{ lon}$), and this data are interpolated down to the CATS horizontal resolution of 5 km; natural variability and interpolation errors can lead to biases in the computed LCL. Therefore, instead of using individual LCL values, our modified version uses the mean LCL value computed from the mean temperature, relative humidity, and atmospheric pressure profiles provided in the CATS data files for the defined ARM-site grid box.

Figure 4.1 presents the modified DTDS, specifically designed for satellite data. As depicted in the figure, we consider each CATS backscatter radiation profile measured within an $8^\circ \times 8^\circ$ area around the SGP site. For daytime files, we employ a deep learning-based denoising approach that enhances the SNR without compromising the spatial resolution (Selmer et al., 2024). This step is not necessary for nighttime data, given the superior SNR during nocturnal hours. Once the dataset is prepared, we resample both daytime and nighttime backscatter to 10 km by averaging vertical backscatter profiles, which approximately represents the least common multiple of the denoised daytime (2 km), nighttime (350 meters), and meteorological input (5 km) spatial resolutions. The algorithm then computes the Local Maximum Positions (LMPs) in the WCT

function for each iteration, and selects the PBLH based on the previous iteration's PBLH ($i - 1$), the current CBH, and the mean LCL.

Additionally, the quality of each PBLH retrieval is evaluated and classified into bad, mediate, and good based on specific criteria by the DTDS. Bad quality refers to the retrieved PBLH showing abrupt changes or inconsistencies. Meanwhile, if the PBLH exceeds the LCL by more than 1 km, it is also considered bad quality. Mediate quality is assigned when suitable LMPs cannot be found to meet the requirement that the gradient significance exceeds a dynamic threshold, equal to three times the noise level. This threshold ensures that the detected step signals in the gradient profiles are significant enough to reliably identify the PBLH. Good quality is assigned if suitable LMPs are found that meet the continuity requirements and exceed the noise threshold, indicating reliable PBLH retrievals. In cases of coupled boundary layer clouds, the quality is automatically set as good, since the cloud base position is a reliable indicator of PBLH. This multi-tiered approach ensures that the PBLH retrievals are classified accurately based on the reliability and robustness of the detected signals. In order to evaluate the performance of the PBLH derived using CATS combined with the DTDS algorithm (CATS DTDS-PBLH), this study uses the ground-based DTDS-PBLH estimates at SGP and the RS-PBLH computed in the previous section. These ground-based estimates are considered more robust and serve as the standard for evaluation.

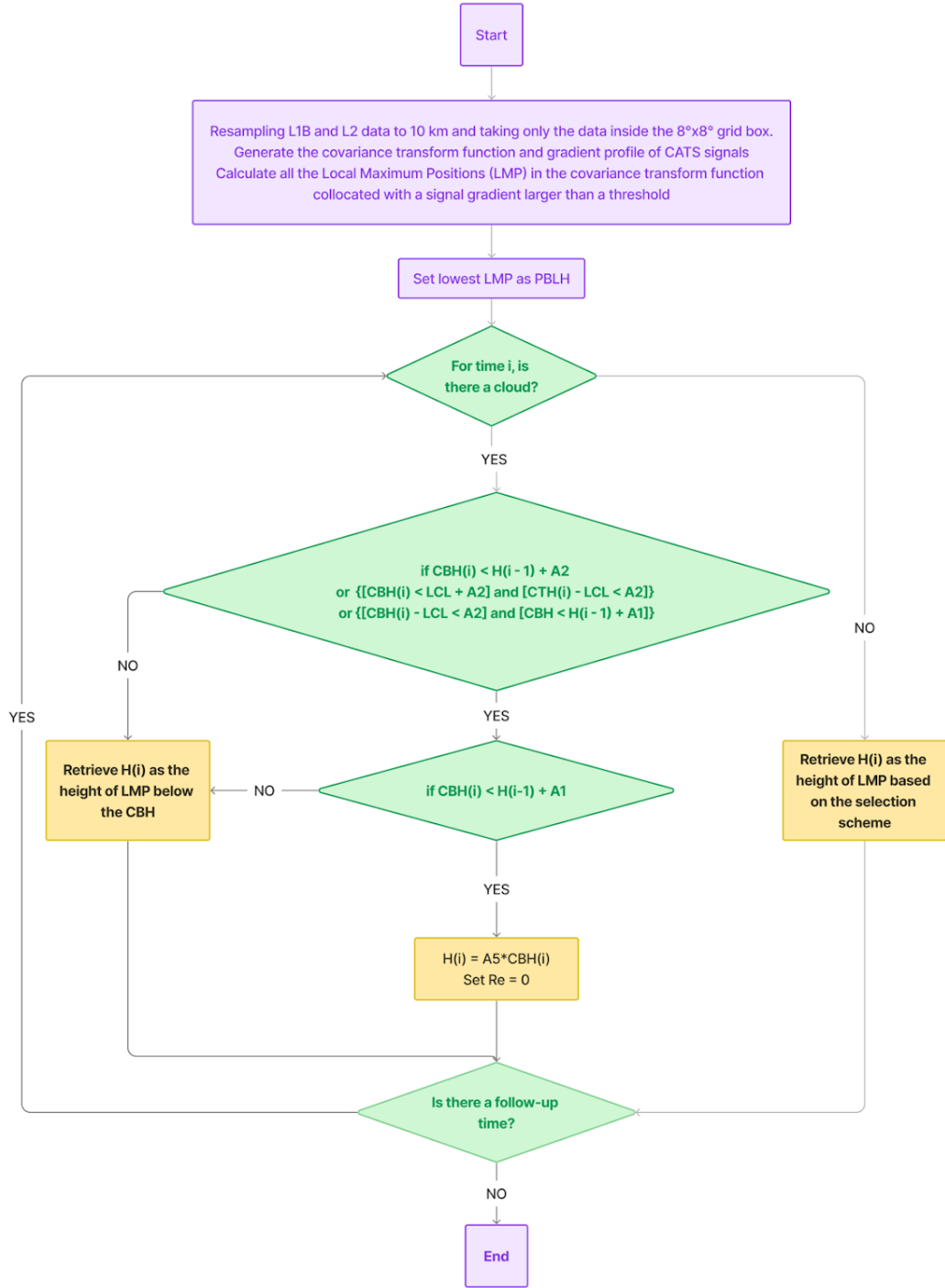


Figure 4.1 Schematic diagram of the modified DTDS algorithm. $H(i)$ represents the PBLH at each spatial interval i ; CBH indicates the cloud base in single-layer clouds with a thickness smaller than 1 km. The PBLH selection identifies the local maximum positions (LMPs) based on

the spatial continuity. PBLH under the cloudy condition is determined by assessing cloud-surface coupling and utilizing information on the adjacent (nearby pixels) PBLH, CBH and the LCL. Empirical parameters $A1$, $A2$, and $A5$ are set to 0.7, 0.2, and 1.1, respectively.

4.2 Assessment of the modified DTDS for CATS

Figure 4.2a depicts a distinct aerosol layer and low-level cloud measured by CATS on 10 January 2016 within the $8^\circ \times 8^\circ$ grid box centered at the SGP site. Black dots represent DTDS-PBLH, and red dots indicate CTH, showing notable alignment between the aerosol layer top and CTH. Figure 4.2b shows mean vertical profiles of attenuated backscatter for the ground-based MPL (black) and CATS (red). While not perfectly correlated, both signals exhibit similar trends, detecting the aerosol layer top at approximately 0.9 km. The primary difference between profiles is the greater signal attenuation below the aerosol layer top in CATS data and above the cloud base in MPL data. Figure 4.2c indicates the distance of the CATS trajectory to the SGP site.

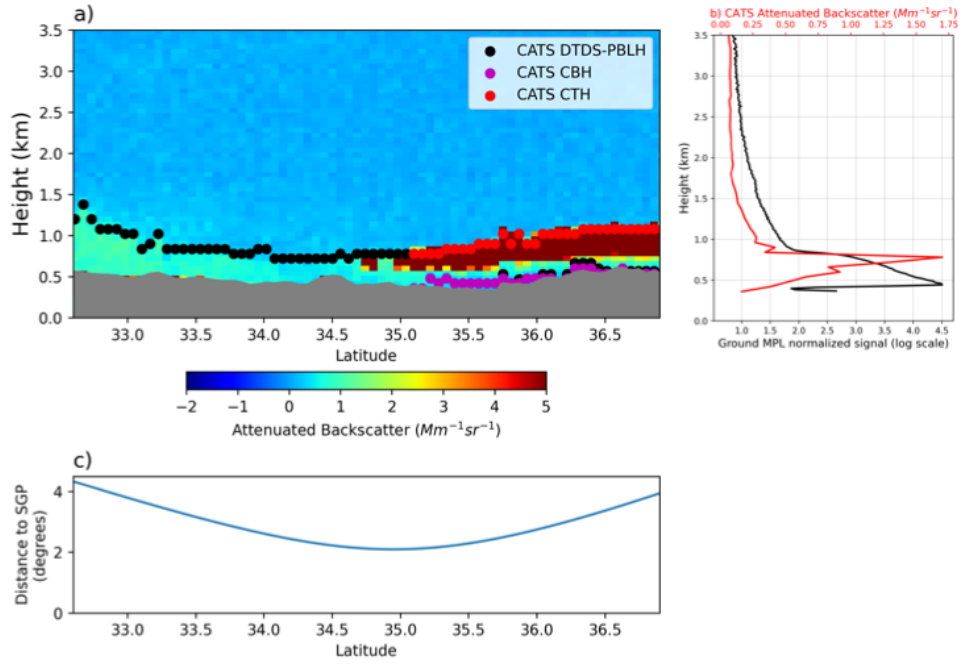


Figure 4.2 a) Example of the computed PBLH on 10 January 2016, the background colors correspond to the total attenuated backscatter measured by CATS over the SGP. Black dots correspond to the PBLH, red dots are the CTH, and magenta dots are the Cloud Base Height (CBH). b) Average vertical profile of the attenuated backscatter measured by CATS (red line), and the ground-based Lidar backscatter profile measured at the same time as the CATS overpass (black line). c) Distance of CATS to the SGP site in degrees.

Comparisons of the traditional CATS WCT-PBLH retrievals with the ground-based MPL and PBLHs derived from local radiosondes demonstrate the limitations of the WCT method. In Figure 4.3a,b, we compare the PBLH estimates derived from CATS using the WCT method (CATS WCT-PBLH) with two different PBLH estimations. The first PBLH estimation is derived from ground-based lidar using the DTDS algorithm (ground-based DTDS-PBLH computed in previous subsection), while the second is derived from radiosondes (RS-PBLH). These two PBLH products are more robust. Relative to them, the WCT-PBLH significantly overestimates the PBLH,

which is particularly pronounced for shallow boundary layers below 1 km, height above which the retrievals start to agree better. In contrast, the quality of new CATS DTDS PBLH retrievals is improved considerably, with smaller bias errors. Figures 4.3a,b include a quality control classification that arises from the DTDS algorithm and is not intrinsically incorporated into the WCT method. Therefore, the two samples shown in Figures 4.3a,b are only to make the WCT and DTDS results comparable.

Given the top-down viewing geometry of spaceborne lidars, the overestimation of PBLHs derived from the traditional method likely results from the WCT function identifying the top of the residual layer or another elevated aerosol layer as the height of the maximum value in the WCT function. This disagreement between the CATS WCT-PBLH and the ground-based DTDS-PBLH retrievals is reflected in the statistical metrics with a correlation coefficient (R) of 0.52 and a large RMSE of 0.74 km. Compared to the RS-PBLH, the CATS WCT-PBLH has an R of 0.5 and an RMSE of 0.81 km when using the good-quality sample.

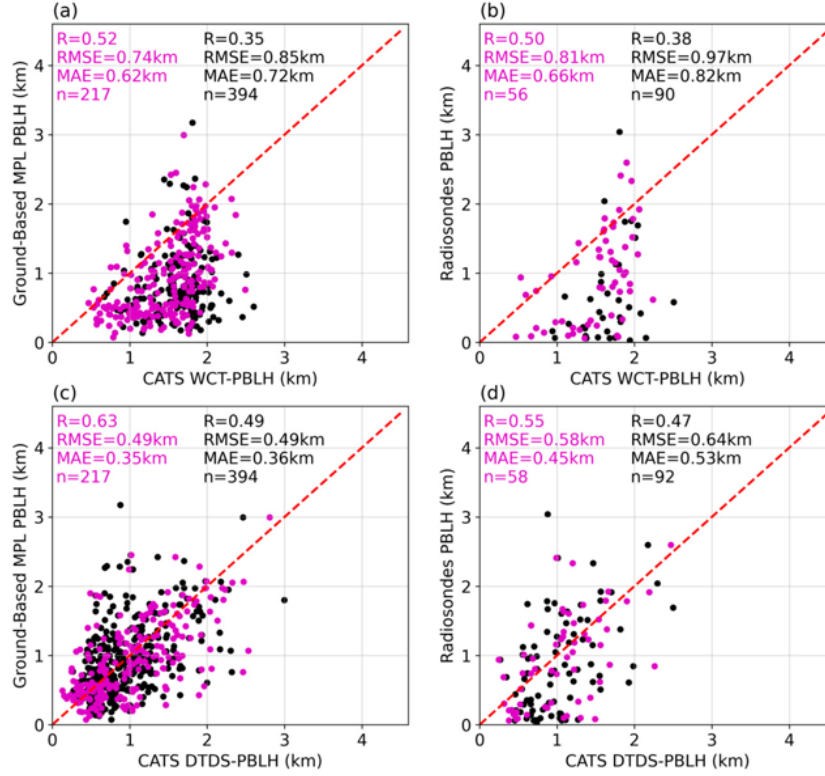


Figure 4.3 (a) Comparison between the ground-based Micropulse DTDS-PBLH and CATS WCT-PBLH for samples classified as good quality only (magenta dots) and samples considered good and mediate (black dots) over the Southern Great Plains (SGP). (b) same as (a) but comparing CATS WCT-PBLH with radiosonde PBLH retrievals. (c,d) same as (a,b) but for CATS DTDS-PBLH.

Our research findings highlight the significant improvements in terms of correlation and RMSE when using CATS PBLH retrievals with DTDS (CATS DTDS-PBLH) compared to the traditional WCT method, especially when considering only good-quality retrievals. Figure 4.3c,d provides a clear visual of these improvements. The DTDS product surpasses the WCT method with respect to comparisons against both the ground-based DTDS-PBLH and RS-PBLH estimate. When looking only at the good-quality retrievals, the correlation coefficient increased by nearly 21%, from 0.52 in the traditional method to 0.63 with the DTDS method, and the RMSE was

reduced by almost 34%, decreasing from 0.74 km to 0.49 km. Similarly, when comparing CATS DTDS-PBLH to RS-PBLH (Figure 2.14d), the correlation increased by 10%, going from 0.5 to 0.55, and the RMSE was reduced by 29%, going from 0.81 km to 0.58 km. The superior performance of DTDS over the WCT method can be attributed to several factors, including the assessment of cloud-surface coupling, the treatment of each local maximum position as a potential PBLH, the use of meteorological data in the retrieval algorithm, and the quality control assessment. Therefore, DTDS can be applied to spaceborne lidar datasets, not just point-based ground lidars, to evaluate regional, seasonal, and diurnal trends in PBLH, especially over continental regions.

The combination of DTDS with CATS unique temporal sampling enables the analysis of the diurnal variability of the PBLH using spaceborne lidar data. Figure 4.4 displays the diurnal variability of the PBLH based on multiple methodologies with 2-hour intervals, for good-quality retrievals only. Notably, the ground-based DTDS-PBLH (black line) and the CATS DTDS-PBLH (magenta line) align well at every 2-hour interval, with an overestimation of nearly 0.1 km at nighttime. Compared to the RS-PBLH, both the CATS DTDS-PBLH and the ground-based DTDS-PBLH overestimate the RS-PBLH. However, this overestimation is small during the day and more significant at night, reflecting the different nature of the PBLH retrieved by the thermodynamic and tracer-based approaches. Nevertheless, both CATS DTDS-PBLH and the ground-based DTDS-PBLH agree better with the RS-PBLH than the CATS WCT-PBLH does. The largest factor contributing to the higher proximity of DTDS retrievals to radiosonde retrievals at nighttime compared to the traditional WCT retrievals is the consideration of local meteorology with the LCL. This parameter assists in the selection of the LMPs as the PBLH and in the assessment of the cloud-surface coupling.

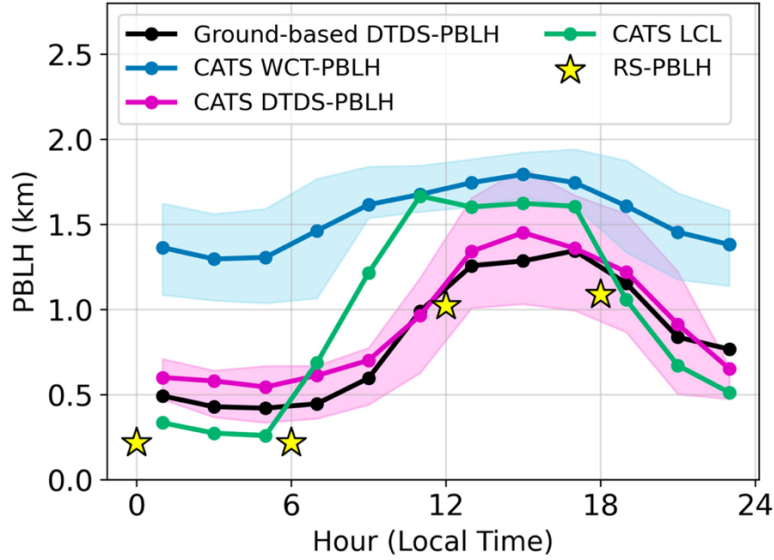


Figure 4.4 Temporal variations of the PBLH with 2 h intervals for different instruments and methodologies over the SGP. The black line corresponds to the ground-based MPL PBLH based on DTDS (ground-based DTDS-PBLH). The magenta line is the CATS PBLH estimated using the DTDS algorithm (CATS DTDS-PBLH), only considering good-quality retrievals. The blue line is the CATS PBLH estimated using the traditional WCT method (CATS WCT-PBLH). Yellow stars are the radiosonde PBLH retrieved using the Liu and Liang method (RS-PBLH). The green line is the computed LCL using the provided meteorological data in CATS files (CATS LCL).

Correctly estimating the nighttime PBL has been a key limitation of spaceborne lidars-derived PBLHs using traditional approaches. The traditional CATS WCT-PBLH retrieval near the SGP site (Figure 4.4, blue) overestimates the PBLH by roughly 0.5 km in the afternoon and around 1 km in the night hours. Not only does the WCT product highly overestimate the PBLH, but it also varies a little throughout the day (~ 0.40 km), with a minimum of 1.3 km in the morning hours and a maximum of 1.7 km in the afternoon. Contrary to the traditional method, the CATS DTDS-PBLH (Figure 4.4, purple/magenta) shows a much better agreement with the ground-based DTDS-

PBLH and the RS-PBLH, with a shallow boundary layer at night that starts growing in the morning hours until it reaches its maximum peak (1.5 km) around 3:00 pm. While DTDS still overestimates the PBLH, this overestimation never exceeds 0.4 km, compared to the traditional WCT that overestimates the PBLH by even 1 km at nighttime. The shaded regions in Figure 4.4 for the CATS WCT-PBLH (blue) and the CATS DTDS-PBLH (purple) illustrate the interquartile range of both estimations. As shown, the ground-based DTDS-PBLH are located between the interquartile range of the CATS DTDS-PBLH, further proving the reliability of the DTDS method.

4.3 The role of the LCL in the PBLH estimates

As stated previously, the inclusion of local meteorological information through the use of the LCL is the primary driver for the robust DTDS PBLH retrievals. The green line in Figure 4.4 illustrates the LCL computed using the meteorological data provided in the CATS data products. The LCL is a crucial parameter in DTDS as it plays a key role in assessing the cloud-surface coupling, particularly in addressing cloudy boundary layers. The meteorological data in the CATS files is obtained from MERRA-2 reanalysis data interpolated to 5 km. In ideal conditions, the PBLH, CBH, and LCL should be located at the same altitudes. However, as Figure 4.4 shows, the computed LCL is consistently below the PBLH retrievals during nighttime and consistently above the PBLH during daytime. This discrepancy between the two retrievals is a potential source of error in the CATS DTDS-PBLH product. Errors in the computed LCL could lead to further errors in the cloud-surface coupling assessment and, consequently, errors in the PBLH retrieval during cloudy conditions. Therefore, the use of more accurate and precise meteorological data is essential for better assessments of the cloud-surface coupling and potentially increasing the robustness of the DTDS retrievals. This underscores the importance of collocated meteorological data and lidar

information, not just as a desirable addition, but as a crucial requirement for future PBLH endeavors.

To investigate the effect of the LCL on the CATS DTDS-PBLH retrievals, we ran DTDS without the LCL conditionals in Figure 4.5, meaning the cloud-surface coupling was only based on the previous PBLH estimates. Figure 4.5 shows how the results of the CATS DTDS-PBLH without the LCL compare to two ground-based PBLHs. Figure 4.5c demonstrates that even without the LCL, DTDS can perform relatively well compared to ground-based MPL retrievals for daytime hours (10–17 LT). When analyzing the good-quality retrievals only, the correlation is equal to 0.43, and the RMSE is 0.67 km, both of which indicate worse performance compared to Figures 4.3c,d and 4.4. Figure 4.5b shows the same comparison against radiosonde observations; overall, DTDS performance is highly compromised, with a 31% smaller correlation and 37% larger error.

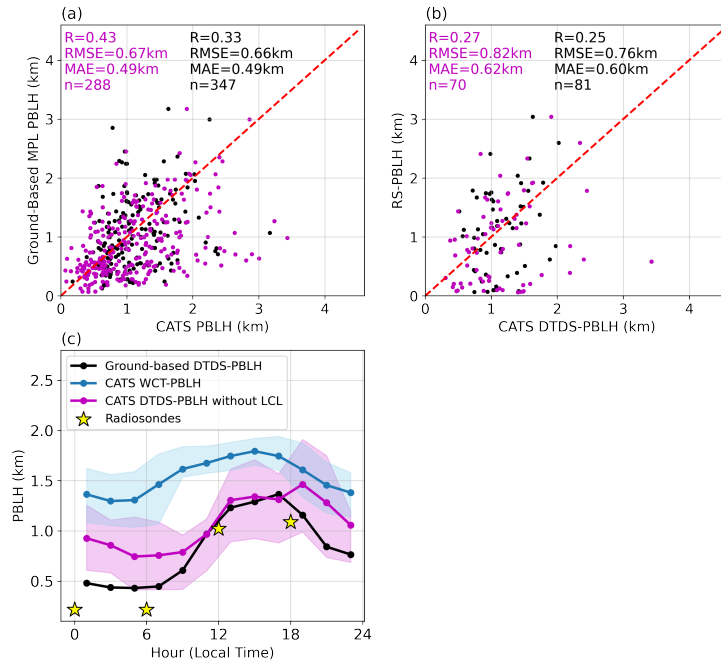


Figure 4.5 (a,b) same as Figure 2.14c,d but without the use of the lifting condensation level (LCL) in the DTDS algorithm. (c) same as Figure 2.15 but without LCL in the DTDS algorithm.

4.4 Regional distribution of the PBLH

One of the main advantages of spaceborne lidars over ground-based sensors is their ability to cover larger areas, enabling the study of the PBLH at a global scale. Following this idea and given the promising results from the previous section, we decided to retrieve the PBLH for the North and South American regions using the modified DTDS algorithm tailored for spaceborne instruments. However, due to the heterogeneity of land surfaces, implementing the modified DTDS algorithm across larger areas required further adjustments to account for topography and climatic differences. The principal adjustments implemented to adapt the algorithm for broader application are as follows:

- In the previous section, PBLH were computed inside a box $8^{\circ} \times 8^{\circ}$ and for elevations below 1 km. However, as land cover extends, topographic variation becomes increasingly significant, particularly when defining the integration limits in equation 1. Fixed values for the upper (previously 4 to 5 km, depending on the site) and lower (ground elevation) limits can result in inaccurate estimates of the planetary boundary layer height (PBLH), especially in elevated regions such as the Andes or the Rocky Mountains. In these locations, applying a fixed integration limit, particularly at the upper boundary, may result in the surface being close to the limit, thereby inhibiting accurate PBLH retrieval. Therefore, varying integration limits were implemented, with the lower limit set at surface elevation and the upper limit adjusted according to time and elevation. Specifically, during daytime hours and at elevations below 1 km, the upper limit was set at 4 km above surface elevation; during nighttime at elevations below 1 km, the upper limit was set at 2.2 km above ground. For elevated areas above

1 km, the upper limit was set at 2 km above ground level, consistent with previous studies indicating a lower maximum PBLH above ground level in mountainous regions.

- As mentioned, the integration limits depended on time and elevation. However, the former can sometimes be a function of social conventions rather than local solar conditions. To address this problem, we decided to use solar time rather than local time.
- Previously, we considered only cloud cases with a thickness of 1 km or less. However, this approach lead us with few samples. We decided to remove this constraint and retrieved the boundary-layer height whenever clouds were present, provided the cloud was transparent, and the signal below it was not fully attenuated.
- Land heterogeneities not only extend to differences in topography but also to differences in vegetation and soil moisture, which impact local temperature, humidity, and hence the LCL. For this reason, instead of using the mean LCL value, we used the moving average of the interpolated LCL values with a window size of seven 10 km profiles.

Figure 4.6 presents the climatology of the CATS DTDS-PBLH for the North and South American regions at 1-degree resolution, computed using the complete CATS dataset. Some well-known geographical features of PBLH mean global distribution are observed. Over North America, the lowest average PBLH is observed around the eastern Pacific, near the West Coast, likely due to the influence of stratiform cloud decks. The highest average PBLH is observed over the Rocky Mountains, likely due to intense surface heating and drier conditions. In addition, lower values are present around the Great Lakes, and relatively high values are observed along the East Coast. Similar spatial variability for the PBLH over North America has been recorded in numerous

studies (Engeln et al., 2013; McGrath-Spangler & Denning, 2013; Santosh, 2022; Zhang et al., 2020).

Over South America (Figure 4.6b), low PBLH values are observed over the Caribbean and the west coast, likely due to the presence of the Intertropical Convergence Zone (ITCZ) in the Caribbean and stratiform cloud layers along the west coast. Low PBLH is also evident in the Amazon rainforest region, which may be attributed to high humidity, deep convection, and heavy precipitation. The highest PBLH values in the region are found in eastern Brazil, where tropical deciduous and dry forests dominate the ecosystem. This type of forest is drier and promotes higher SH and PBLH, especially during the dry season between September and December (Oliveira-Júnior et al., 2021).

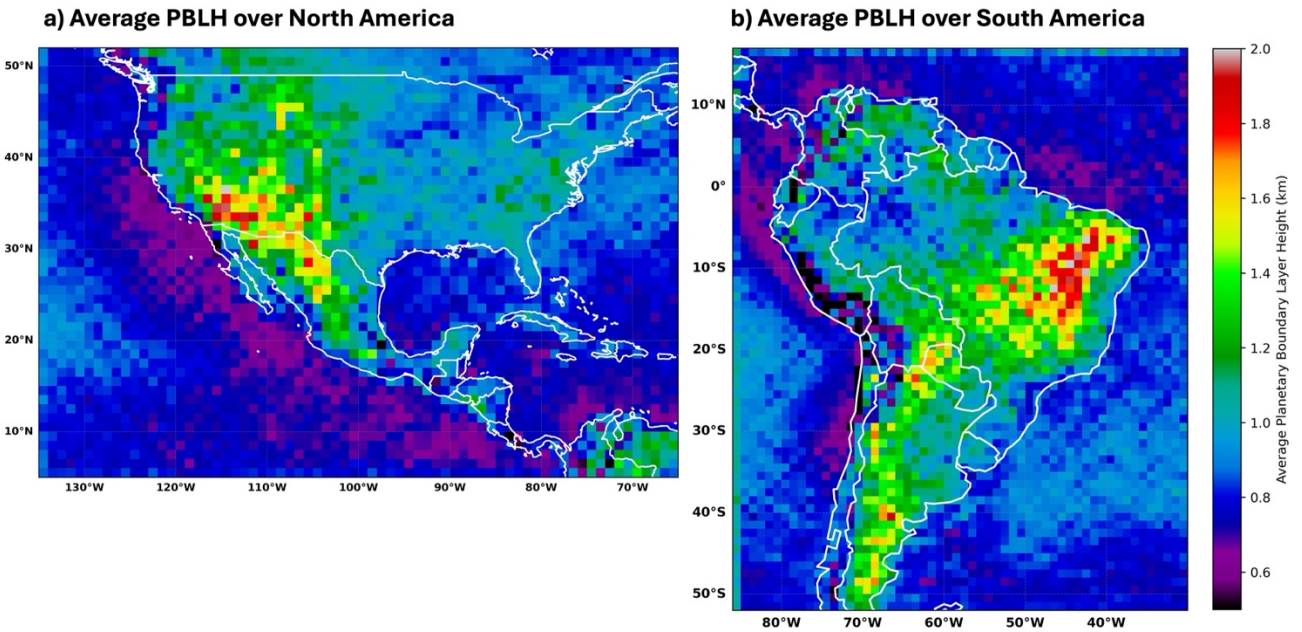


Figure 4.6 (a) Climatology of the PBLH computed using CATS and a modified version of DTDS over North America and (b) South America

Although our CATS DTDS-PBLH retrievals exhibit physically plausible spatial variability and agree with previous investigations, further validation is required to assess their true

performance. For this reason, Figure 4.7 displays a comparison between the ERA5 PBLH for the same operational years of CATS (2015 to 2017) at 18 UTC and CATS DTDS-PBLH retrievals at 17 to 19 UTC. This comparison serves only as a reference and does not constitute a definitive validation of the method, as ERA5 PBLH is estimated using the bulk Richardson method (Vogelezang & Holtslag, 1996; Zhang et al., 2014), which differs from the lidar methodology. Despite this limitation, there is notable spatial agreement between CATS DTDS-PBLH and ERA5 PBLH. Specifically, both methods capture the higher PBLH over the Rockies and the lower values on the U.S. west coast, as well as relatively high values on the east coast. Such a similarity between both estimations suggest that PBLH can be accurately estimated at a global scale using CATS data.

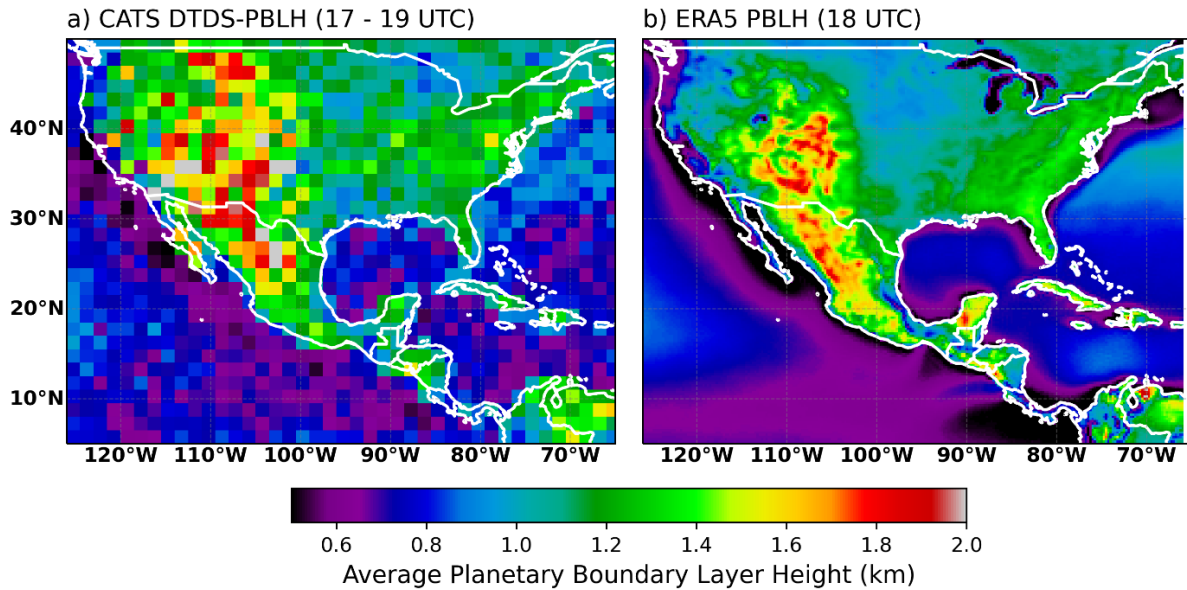


Figure 4.7 (a) Climatology of the PBLH computed using CATS and a modified version of DTDS over North America between 17 and 19 UTC. (b) Climatology of the PBLH from ERA5 at 18 UTC.

Figure 4.8 provides a more robust comparison by evaluating CATS DTDS-PBLH against ground-based DTDS-PBLH using only high-quality daytime retrievals. Retrievals within an $8^\circ \times 8^\circ$ grid box were selected, consistent with the methodology in Figure 4.3. Figure 4.8a further details

the comparison for the SGP site, where retrievals were categorized as either above ($\text{DEM} > 0.5$ km) or below ($\text{DEM} < 0.5$ km) an elevation of 500 meters. Retrievals below 500 meters have a higher correlation coefficient of 0.79 and an RMSE of 0.45 km, while those above this threshold have a correlation of 0.74 and an RMSE of 0.93 km. This substantial difference is likely due to the SGP site's elevation of 315 meters. Therefore, retrievals below 500 meters more accurately reflect the environmental conditions at this location. Figure 4.8b shows the same comparisons, but for the PBLH computed with the traditional WCT. For these retrievals, the correlations are smaller (0.35) and the error is larger (above 0.8 km), attesting to the better performance of DTDS.

In the South American region, the performance of the CATS DTDS-PBLH was evaluated at MAO (see Figure 2.1), which is the only ARM observatory in South America that collected measurements during the same operational period as CATS. No division by elevation was necessary, as the area surrounding MAO is situated below 500 meters. Figure 4.8c presents the results for DTDS, indicating a high correlation of 0.84 and a root mean square error (RMSE) of 0.43 km, which are comparable to the results obtained for SGP. In contrast, the WCT results demonstrate substantially weaker performance, with a correlation of 0.11 and an RMSE of 1.16. These results correspond to high-quality daytime conditions, during which the convective boundary layer is more effectively captured by lidar PBLH techniques.

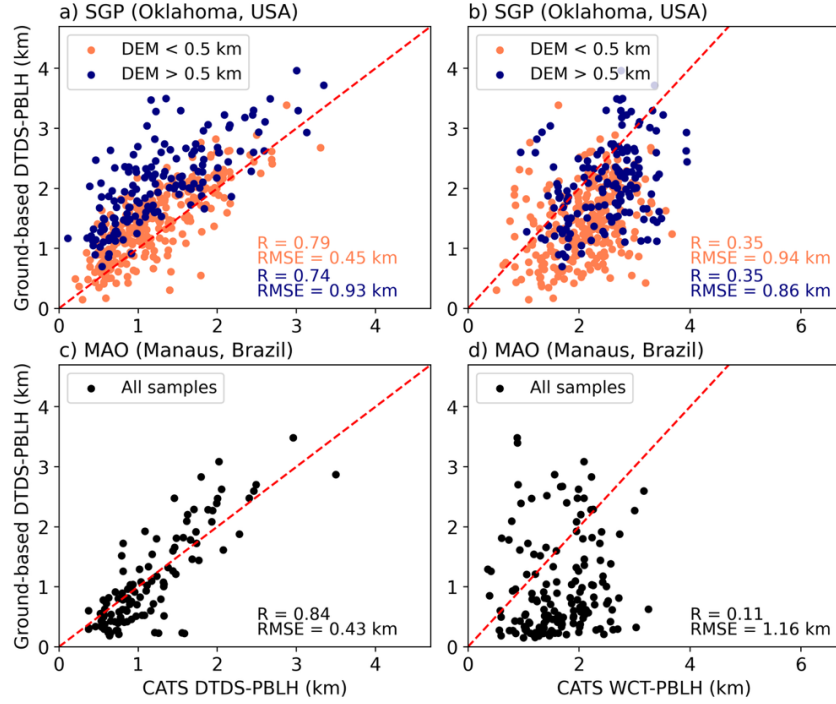


Figure 4.8 (a) Scatter plots showing the relationship between the ground-based Micropulse DTDS-PBLH and CATS DTDS-PBLH for high-quality daytime retrievals at the SGP site. Coral dots indicate retrievals below 500 meters ($DEM < 0.5$ km), while blue dots indicate retrievals above 500 meters ($DEM > 0.5$ km). Correlation coefficients and RMSE are provided. (b) same as (a) but for the CATS WCT-PBLH retrievals. (c) Scatter plots showing the relationship between the ground-based Micropulse DTDS-PBLH and CATS DTDS-PBLH for high-quality daytime retrievals at the MAO site. (d) same as (c) but for the CATS WCT-PBLH retrievals.

4.5 Seasonal and diurnal variability of the PBLH at a regional scale

Figure 4.9 presents the seasonal variability of the PBLH across North America. We observed a marked variability, with higher continental PBLH during June-July-August (JJA), influenced by the boreal summer, while lower continental PBLH values are observed in December-January-February (DJF) during the boreal winter. Interestingly, both the maximum and minimum PBLH values are observed during summer. In this season, elevated PBLH occurs over arid

continental regions, such as California and Arizona, due to dry, hot environmental conditions that drive high SH values. In contrast, low PBLH is found over the western Pacific, near the U.S. West Coast. In summer, the North Pacific High, a subtropical high-pressure system associated with the descending branch of the Hadley Cell, dominates this region. Descending air within this high-pressure system, combined with a continuous supply of oceanic moisture, facilitates the formation of persistent stratiform layers characterized by lower PBLH (Iacobellis & Cayan, 2013).

The seasonal variability over South America is shown in Figure 4.10. High PBLH are observed year-round in the eastern side of Brazil, reaching its maximum in September-October-November (SON), during the austral spring. Such taller PBLH could be associated with low SM and high-water vapor deficit. Such conditions not only facilitates high PBLH, but also are associated with a higher number of wildfires in the region (Ferreira et al., 2025). Similar patterns were found for CALIPSO PBLH retrievals (McGrath-Spangler & Denning, 2013). During the austral winter (JJA), low PBLH are observed around Chile and Argentina.

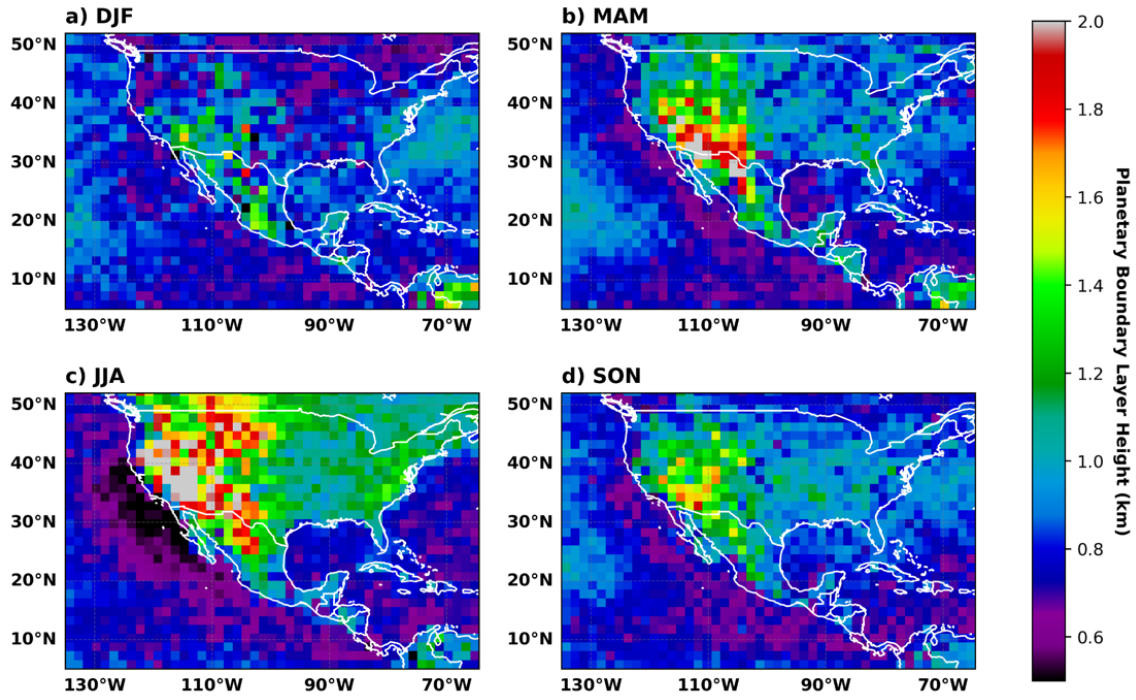


Figure 4.9 Seasonal variability of the CATS DTDS-PBLH over North America for (a) DJF, (b) MAM, (c) JJA, and (d) SON.

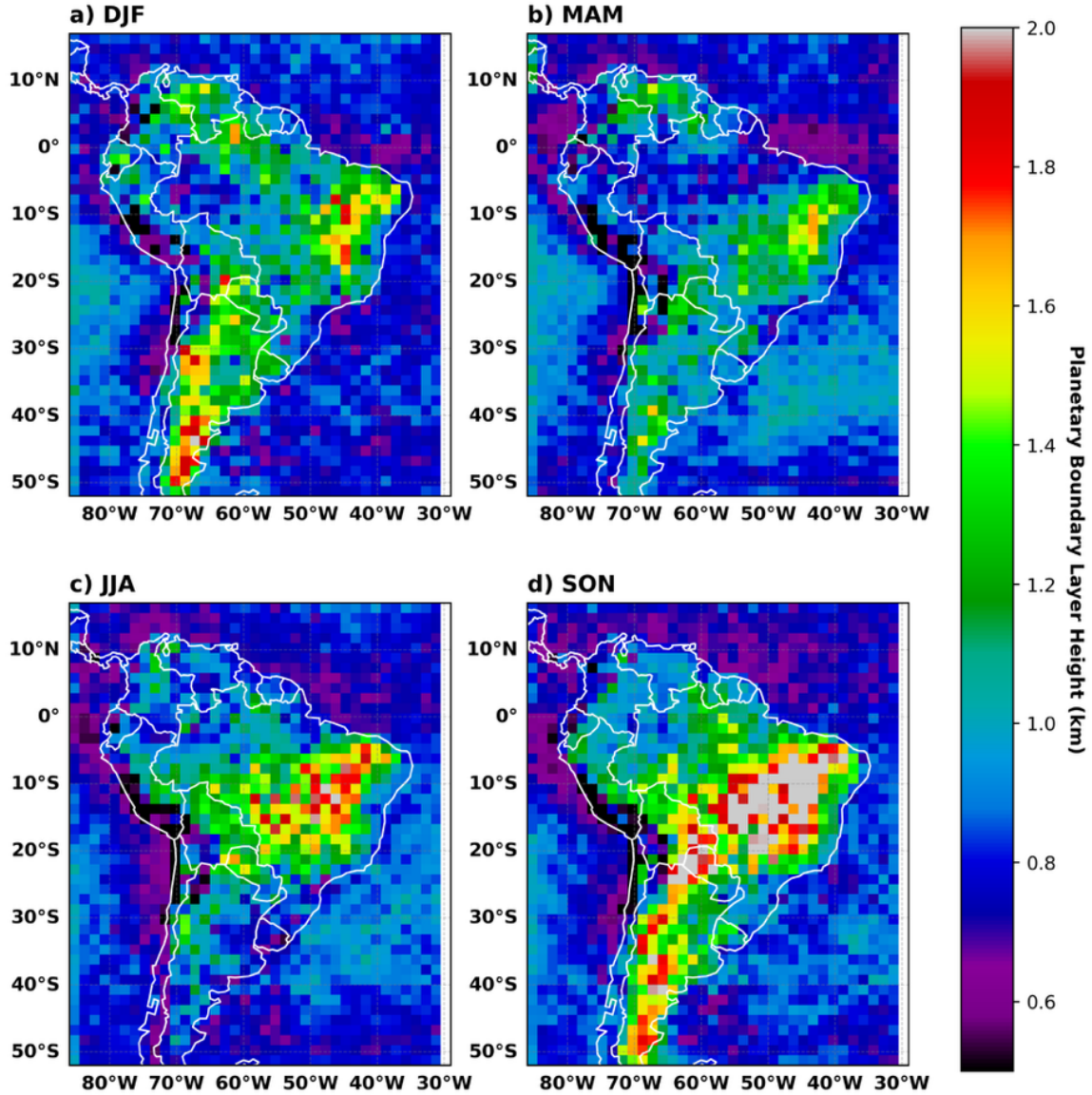


Figure 4.10 Seasonal variability of the CATS DTDS-PBLH over South America for (a) DJF, (b) MAM, (c) JJA, and (d) SON.

A principal advantage of CATS compared to other spaceborne lidars, such as CALIPSO, is its capability to measure the same region at different local times. This feature enables us to construct the diurnal variability of the PBLH at global or regional scales. Figure 4.11 shows the diurnal variability of the PBLH in local solar time (LST) for North America. Compared to seasonal variability, marine regions don't have a marked diurnal variability, given the high heat capacity of

water. On the other hand, continental regions have a strong diurnal cycle, with low PBLH at nighttime, and deep PBLH at daytime, peaking between 12 – 15 LST. The biggest differences between day and night are observed in the western U.S compared to the eastern U.S, likely influenced by a drier environment and more complex terrain.

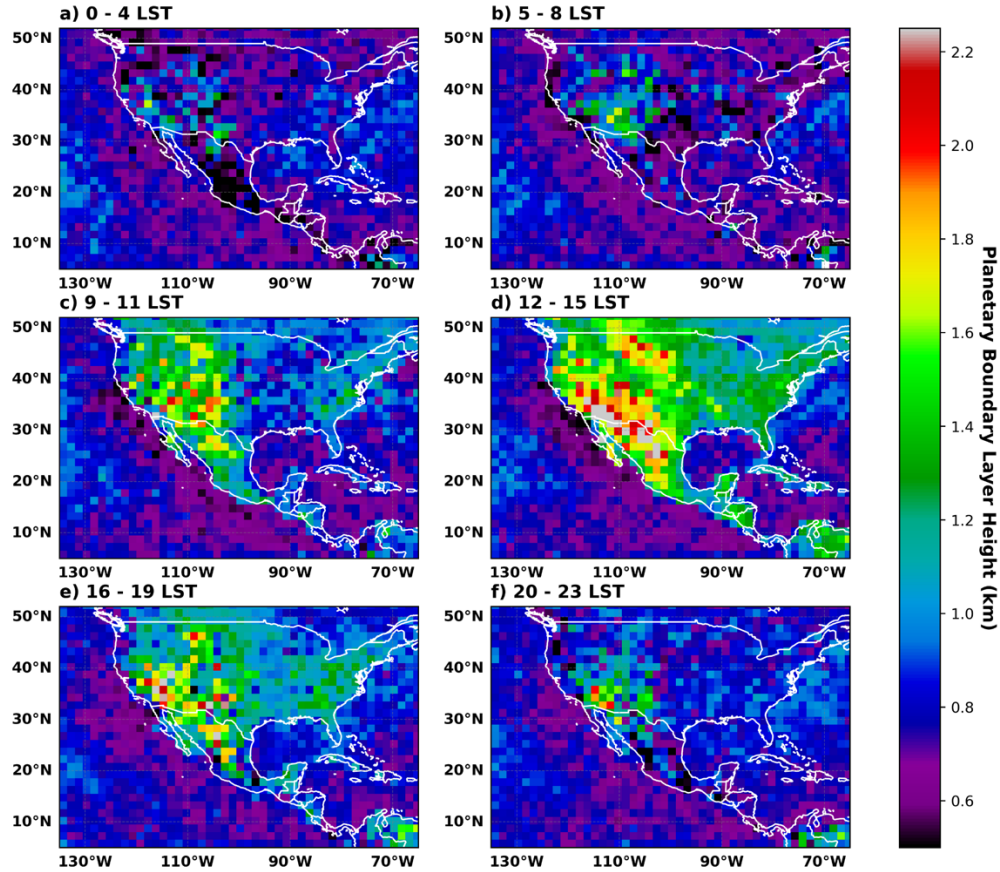


Figure 4.11 Diurnal variability of the CATS DTDS-PBLH over North America at (a) 0 – 4 LTS, (b) 5 – 8 LTS, (c) 9 – 11 LTS, (d) 12 – 15 LTS, (e) 16 – 19 LTS, and (f) 20 – 23 LTS.

Figure 4.12 presents the diurnal variability of the PBLH over South America. Like North America, continental regions exhibit high PBLH during daytime and low values at night. In contrast, marine regions show weak diurnal variability. Contrary to the results found at SGP (Figure 4.4), in this area, the nighttime PBLH values are relatively large, ranging from

approximately 0.8 to 1 km, which are likely overestimated. This overestimation might arise from bias in the LCL retrievals, as MERRA-2 reanalysis critically depends on the data assimilated. The sparsity of measurements in the southern hemisphere can compromise MERRA-2 performance over the region, increasing the uncertainty of its meteorology estimations. As mentioned in section 4.3, the LCL is more critical for nighttime DTDS performance than for daytime performance, which could imply that the retrievals shown in Figure 4.12 have a higher uncertainty at nighttime.

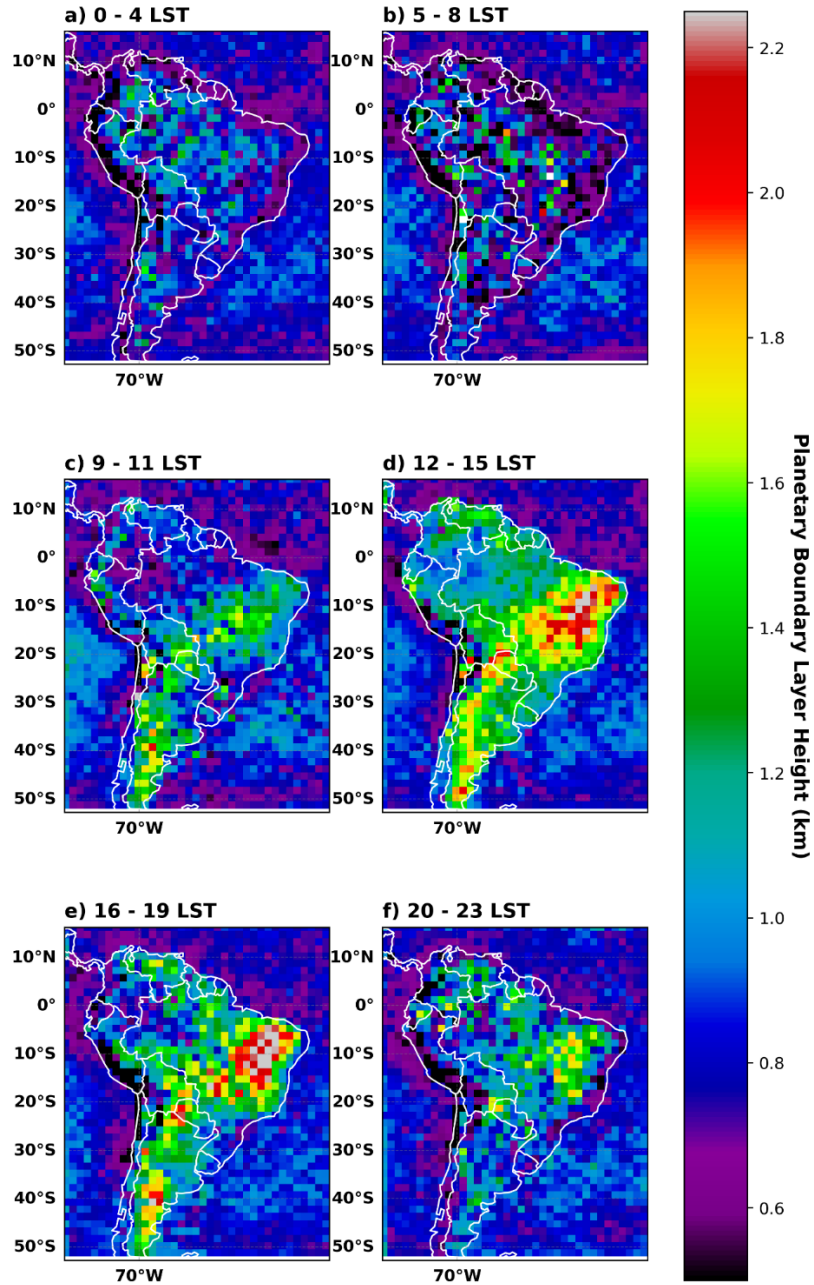


Figure 4.12 Diurnal variability of the CATS DTDS-PBLH over South America at (a) 0 – 4 LTS, (b) 5 – 8 LTS, (c) 9 – 11 LTS, (d) 12 – 15 LTS, (e) 16 – 19 LTS, and (f) 20 – 23 LTS .

4.6 Conclusions

Global monitoring of PBH has been challenging, especially regarding its diurnal variation on a regional scale. This may be possible through the use of spaceborne instruments providing the vertical profiles of atmospheric quantities, such as lidars. This chapter uses the CATS, a spaceborne lidar aboard the ISS, to retrieve the PBLH and statistically resolve its diurnal variability from space. To leverage CATS' dataset, we used the modified and refined DTDS algorithm. The approach computes the PBLH using the traditional wavelet covariance transform function and a scheme for the assessment of the cloud-surface coupling. These characteristics allow DTDS to perform better under stable regimes, including nighttime conditions.

The performance of CATS DTDS-PBLH reveals that CATS consistently captured the diurnal variability of the PBLH for a continental mid-latitude site (ARM's SGP site), having a robust correlation when compared to ground-based DTDS-PBLH. Contrary to the CATS DTDS-PBLH, the traditional CATS WCT-PBLH highly overestimates the PBLH, especially during nighttime, when the residual layer strongly influences the retrieval. DTDS can better capture the nighttime boundary layer by considering each local maximum position of the covariance transform function as a potential PBLH and assessing the cloud-surface coupling. The latter requires a knowledge of the LCL, a parameter used to evaluate whether a cloud is coupled or decoupled to the earth's surface. Therefore, information of on the meteorological conditions can improve the PBLH's estimate.

CATS can statistically resolve the PBLH and measure it on a global scale. Therefore, this chapter also calculates the CATS DTDS-PBLH for the North and South America regions. Our results show strong agreement between CATS DTDS-PBLH and ERA5 PBLH outputs in the afternoon, though further validation is still needed to properly assess the performance of our CATS

DTDS-PBLH estimates at a global scale. Nevertheless, our retrievals can capture some well-known geographical features of PBLH mean global distribution, including the influence of stratiform layers over the west coasts of South and North America, the drastic contrast between marine and continental regions, and the higher boundary layer over arid regions. In addition, CATS DTDS-PBLH retrievals enable the characterization of seasonal and diurnal variability over large areas.

The results found in this chapter demonstrate the potential of using CATS to retrieve accurate PBLH from space. In addition, our results suggest that spaceborne backscatter measurements, in combination with thermodynamic profiles from passive sounders, have the potential to improve the accuracy of the PBLH estimation and its diurnal variability at a global scale.

Chapter 5: Determination, characterization, and climatology of cloud-surface coupling

Following the computation of accurate PBLH estimations, this chapter utilizes these retrievals to enhance our understanding of cloud-PBLH coupling. The chapter introduces the methodologies for identifying coupled and decoupled cloud regimes, which are subsequently applied to investigate the driving factors of such coupling at both local and regional scales.

5.1 Thermodynamic identification of cloud-surface coupling

Thermodynamic definitions of the state of cloud-surface coupling have been widely applied to marine environments based on moist conserved variables (Bretherton & Wyant, 1997; Dong et al., 2015; Jones et al., 2011; Zheng & Li, 2019). In the case of marine stratocumulus, a coupled situation is usually defined when the liquid water potential temperature varies less than a certain threshold (i.e., 0.5–1 K) below the sub-cloud layer (Jones et al., 2011). In other words, coupled cases are characterized by a well-mixed BL with vertically uniform moist conserved variables. On the contrary, a decoupled state occurs when the moisture conserved variables are vertically stratified (Zheng & Li, 2019).

Similarly, we aimed to determine the coupled regime of continental clouds based on their vertical distribution of potential temperature. In this context, a coupled state is defined as a situation where the difference in potential temperature (θ) between the CBH and the PBLH is less than 1 K (Coupled: $\Delta\theta = (\text{CBH}) - \text{PBLH} < 1\text{K}$). This threshold is based on the influence of temperature inversions, which limit the transport of turbulence and heat fluxes between the cloud layer and the land surface, and it was chosen following Su et al. (2022). A well-mixed sub-cloud layer indicates efficient mixing, which promotes turbulent coupling between the cloud, the planetary boundary

layer, and the land surface. It's important to note that potential temperature is not a conserved variable in a moist adiabatic process; however, since the temperature profile is analyzed within the sub-cloud layer, this limitation does not impact the results of our identification.

We employ this thermodynamic approach to compute the coupling state at the five ARM observatories by using the ARM daytime radiosondes. This thermodynamic approach provides a robust determination of the coupling state. However, since radiosonde measurements are limited in time, additional techniques with higher temporal resolutions are necessary.

5.2 Remote sensing identification of cloud-surface coupling

The PBLH is a crucial parameter for diagnosing cloud-surface coupling, as it marks the upper boundary of the turbulent mixing layer where surface-driven forcings are transmitted upward. This characteristic makes the PBLH a reliable criterion for assessing whether clouds are dynamically coupled to the surface, as it provides direct evidence of the PBL's vertical extent and its interactions with cloud bases. Building on this premise, we employed the DTDS-PBLH retrievals from the MPL and the CBH measurements to determine the coupling regime of continental clouds. In this methodology, a cloud is classified as coupled if the CBH is located near or below the PBLH, defined as follows:

$$\text{Coupled: } CBH(i) < PBLH(i) + A_1 \text{ Decoupled: } CBH(i) > PBLH(i) + A_1 \quad (3)$$

where i represents the time step, and A_1 is an empirically derived parameter optimized through sensitivity analysis of commission and omission errors, using the thermodynamic approach as the reference standard. Unsurprisingly, the accuracy of this methodology is highly dependent on the precise estimation of the PBLH. Underestimating the PBLH can lead to an under classification of coupled cases, while overestimating it may result in the overclassification of

coupled cases. To address this, we utilized the DTDS-PBLH outputs computed in Chapter 1, which demonstrated superior performance compared to traditional lidar-based methods.

In addition to equation 3, our evaluation of cloud-surface coupling using PBLH from lidar includes a step to detect clouds that are still coupled to the surface, even if quickly lifted above the PBLH by strong updrafts. Relying only on Equation 3 would misclassify these clouds as decoupled, despite their coupled properties. To address this, we consider both horizontal and vertical cloud extents, since coupling can occur throughout the cloud, not just at a point. For example, updrafts and downdrafts may exist in different cloud regions. Therefore, we included CTH in our analysis. For clouds first marked as decoupled, we checked their prior coupling state. If previously coupled and the current CBH was below the last CTH, we reclassified the case as coupled. Although this final step helps mitigate part of the uncertainty associated with the horizontal and vertical extent of clouds, the evaluation of coupling in the lifetime of a cloud is still uncertain, stemming from the difficulty of tracking a cloud's lifetime and, consequently, its coupling state at different stages using point measurements.

5.3 Retrieving cloud-surface coupling thresholds

Evaluating cloud-surface coupling based on PBLH estimates relies on an empirical coupling threshold, denoted $A1$ in equation 3. We computed this threshold by performing a sensitivity analysis focusing on commission and omission errors, with the thermodynamic approach serving as the reference value. The commission error indicates the percentage of decoupled clouds that are mistakenly categorized as coupled clouds. In contrast, the omission error reflects the percentage of coupled clouds that are misidentified as decoupled. Figure 5.1 displays the results. $A1$ corresponds to the value that minimizes both the commission and the omission errors. Surprisingly, this value oscillates between 0.2 and 0.3 km across different locations,

suggesting that similar mechanisms may govern cloud-surface coupling in continental clouds. An important limitation is that radiosonde measurements are taken at synoptic hours across the globe. Therefore, these similar thresholds might be different when computed at different times.

5.4 Climatological Patterns of Cloud-Surface Coupling Across ARM Sites

Figure 5.2 illustrates the average proportions of coupled and decoupled clouds at the five ARM observatories. Remarkably, these proportions are consistent across all sites, with $65.84\% \pm 10.24\%$ of low-level clouds classified as coupled and $34.16\% \pm 10.24\%$ as decoupled. This uniformity may be attributed to the fundamental role of surface fluxes and the dynamics and thermodynamics of the PBL in cloud formation and evolution. Surface fluxes—such as heat, momentum, and moisture—drive turbulence, a key factor in cloud development. Intense fluxes enhance the coupling between clouds and the surface, a process that appears to persist across diverse environmental conditions, as reflected in the consistent coupling percentages.

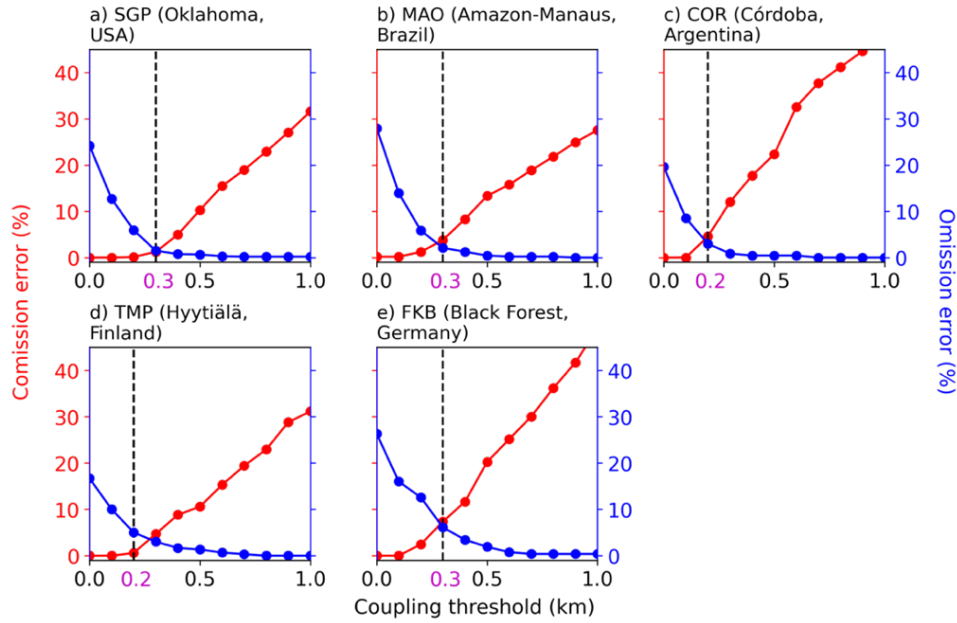


Figure 5.1 Commission and omission errors of the coupling thresholds at the five ARM sites. The dashed line indicates where the commission and omission errors are minimal. The number in magenta is the coupling threshold.

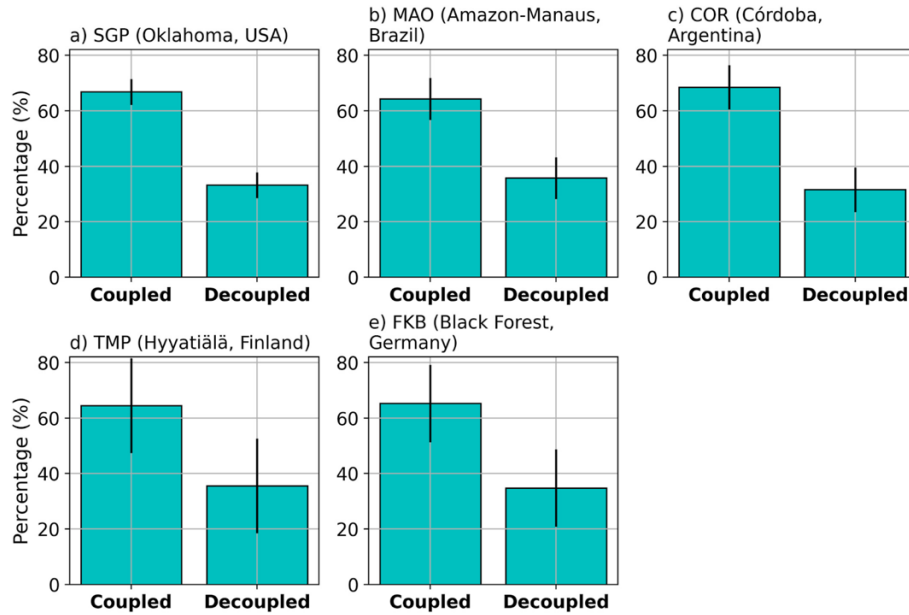


Figure 5.2 Commission and omission errors of the coupling thresholds at the five ARM sites. The dashed line indicates where the commission and omission errors are minimal. The number in magenta is the coupling threshold.

The similarities in the coupling percentages are evident not only in average values but also in the diurnal variability of the two cloud regimes. Figure 5.3 shows that at all five ARM observatories, the percentage of coupled clouds increases in the morning and declines later in the afternoon. Although this trend is similar, each site's peak coupling time differs; for example, SGP peaks around 2:00 p.m., while MAO peaks near 11:00 a.m. Interestingly, during the period between 10:00 and 15:00 local time, when most sites experience elevated coupling, the separation between coupled and decoupled percentages becomes particularly robust, with non-overlapping standard deviations indicating statistically distinguishable regimes.

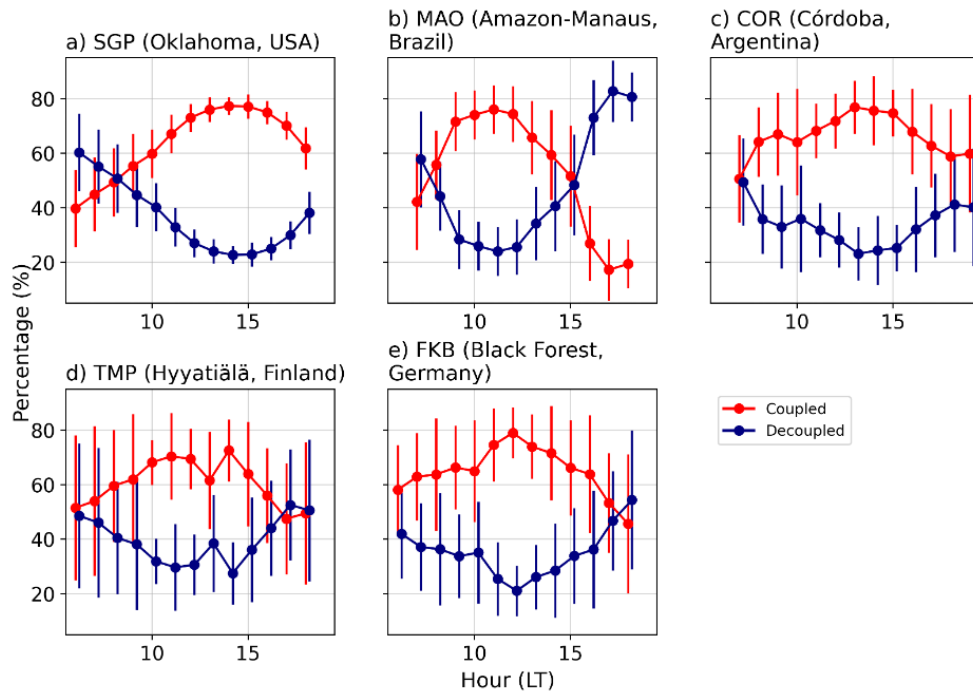


Figure 5.3 Hourly variation of the percentage of coupled and decoupled clouds at the five ARM observatories. The red lines correspond to the coupled cases, while the blue lines represent the decoupled cases. Error bars represent the standard deviation.

The differences in the diurnal variability of coupling percentage can be attributed to local climatic conditions and geographical features that influence the timing and intensity of surface fluxes and PBL development. For the tropical region, such as MAO, the relatively early peak in coupled clouds may be driven by strong latent heat and weak stratification (Tian et al., 2022), which rapidly destabilizes the PBL, promoting convection and cloud formation. The Amazon region's abundant moisture and heat promote the development of strong, deep convective systems. However, the precipitation and albedo effects of these cloud systems stabilize the atmosphere and suppress the PBLH, leading to a faster afternoon decline in the percentages of coupled clouds at MAO compared to other sites. Conversely, SGP typically experiences a delayed peak in coupled clouds due to a different set of climatic conditions. The SGP region, characterized by extensive agricultural land, has a slower buildup of surface heat compared to the Amazon and a relatively late development of PBLH compared to other sites (Liu & Liang, 2010; Roldán-Henao et al., 2024).

Both COR and FKB are mountainous regions where orographic uplifting and intense deep convection are prominent. The elevation and surface roughness at these sites may generate strong turbulence and convective instability, favoring the formation of orographic boundary-layer clouds. At COR, heat and moisture are frequently transported from the Amazon region by the South American Low-Level Jet (SALLJ). Additionally, air often converges east of the COR site in areas with the highest terrain, creating ideal conditions for the formation of boundary-layer clouds coupled with the PBLH. This interaction, combined with COR's subtropical location, influences the diurnal variability of these coupled clouds. In contrast, the forested environment at FKB and TMP provides additional moisture, and the combination of this moisture with limited heat flux, likely supports the formation of coupled stratocumulus layers.

5.5 Differences in Cloud Coupling and Their Influencing Factors

Changes in the diurnal variability of the PBLH and the CBH are key to understanding cloud-surface coupling. Figure 5.4 displays the average diurnal variation of the PBLH at each site (black line) and the vertical distribution of CBH for each hour (heat map). Notably, all five ARM observatories display similar patterns, starting with a shallow boundary layer that deepens throughout the day. As the PBLH increases, more low-level clouds interact with surface forcings, leading to more coupled clouds. As convective conditions strengthen, boundary layer clouds often exceed the PBLH and decouple from the surface as convective thermals weaken and the PBLH declines. At the MAO site, where deep convection is pronounced, this decoupling occurs earlier, with less than 10% of clouds remaining within the mean boundary layer by 1:00 p.m.

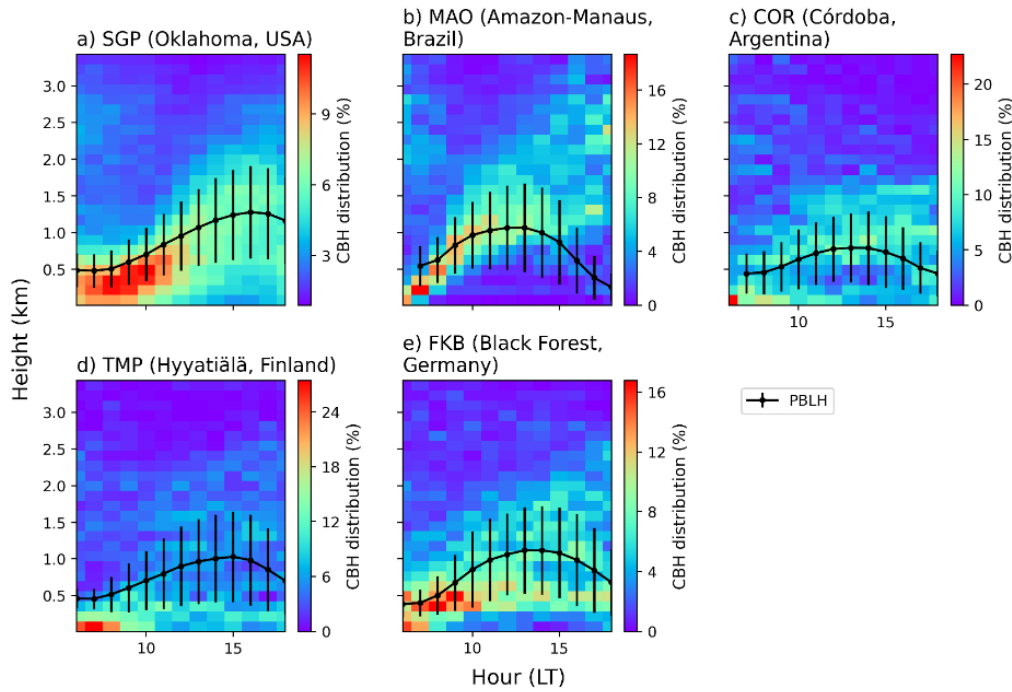


Figure 5.4 The background represents the hourly vertical distribution of CBH at each site. The solid black line is the diurnal variation of the PBLH, and error bars are the standard deviation.

Figure 5.5 compares the diurnal variability of PBLH under coupled and decoupled conditions at each site. Among these, MAO stands out with a noticeably higher PBLH during coupled conditions, likely influenced by stronger sensible heat fluxes. A similar trend appears at SGP, where the mean PBLH is also higher when clouds are coupled. However, the overlapping standard deviation bars between coupled and decoupled conditions suggest that these differences may not be statistically significant.

Interestingly, when clouds are further classified into cumulus and stratiform types, more noticeable distinctions in PBLH emerge. At the SGP site (Figure 5.6a), coupled cumulus clouds tend to occur with deeper boundary layers, while coupled stratiform clouds are associated with shallower PBLH. This indicates that a higher PBLH can facilitate coupling by enhancing turbulence and promoting vertical mixing that links the cloud to the surface. Nevertheless, PBLH alone does not determine cloud coupling. Coupled clouds can form under both deep and shallow boundary layers, depending on cloud type and other environmental factors.

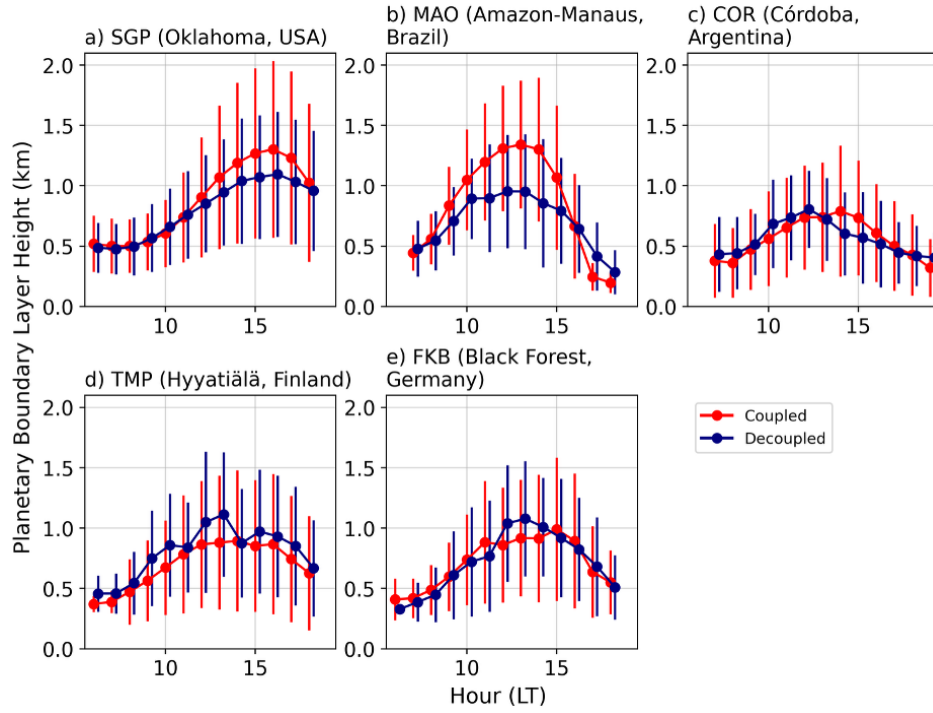


Figure 5.5 Hourly variation of the PBLH for coupled and decoupled regimes at the five sites. The red lines correspond to the coupled cases, while the blue lines represent the decoupled cases. Error bars represent the standard deviation.

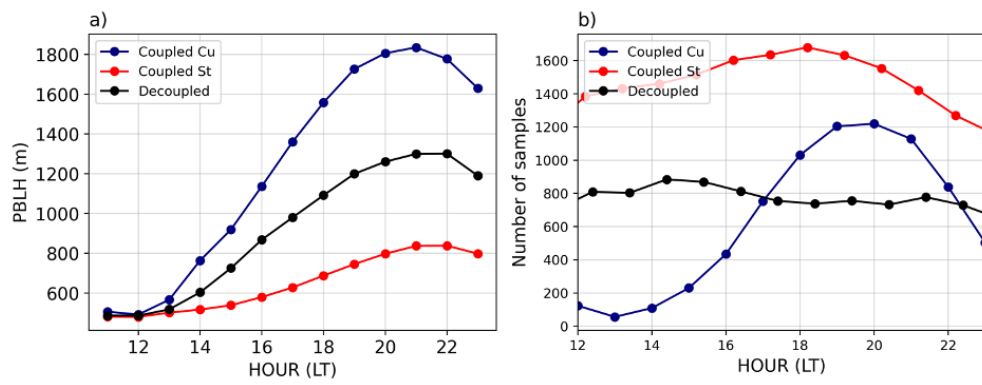


Figure 5.6 a) Hourly variation of the Planetary Boundary Layer Height (PBLH) for coupled cumulus (Coupled Cu), coupled stratiform (Coupled St), and decoupled regimes at the SGP site. b) Diurnal variability of the number of samples of Coupled Cu, Coupled St, and Decoupled clouds at the SGP.

While differences in PBLH mainly appear when cloud types are separated, Figure 5.5 may hint at the diurnal distribution of cloud types during coupled conditions. Sites such as MAO and SGP show slightly higher boundary layers in the late morning and afternoon, suggesting more coupled cumulus clouds at those times, as seen in Figure 5.6b at SGP. Conversely, TMP, where coupled clouds have shallower PBLH than decoupled clouds, likely reflects more coupled stratiform clouds, aligning with TMP's boreal nature.

5.6 Seasonal Variations in Cloud-Surface Coupling at the SGP site

The SGP site provides a data record spanning over 20 years, making it the sole site capable of offering a deep insight into seasonal variations in cloud-surface coupling regimes. Figure 5.7 presents the number of observations for both coupled and decoupled cases across different seasons, along with their respective percentages at SGP. Notably, cloud observations are most frequent in spring. During this season, the Great Plains Low-Level Jet (GPLLJ) transports substantial moisture from the Gulf of Mexico while simultaneously enhancing surface heat fluxes (Liu et al., 2013; Song et al., 2019). Additionally, during spring, the SGP site is often located ahead of an upper-level trough, which promotes low-level convergence and upward motion (Song et al., 2019). These atmospheric conditions collectively contribute to increased cloud formation, leading to the higher number of observed clouds during this season.

Despite the increased number of observed clouds in spring, the percentages of coupled and decoupled clouds don't drastically vary among seasons (Figure 5.7b). Overall, warm seasons have moderately higher coupled percentages, with spring having the maximum percentage with $72.2\% \pm 9.6\%$ being coupled and fall having the lesser percentage of coupled clouds with $63.8\% \pm 14.1\%$.

This moderate peak in the number of coupled clouds during warm seasons likely occurs due to a favorable convective environment that promotes boundary layer cumulus cloud formation.

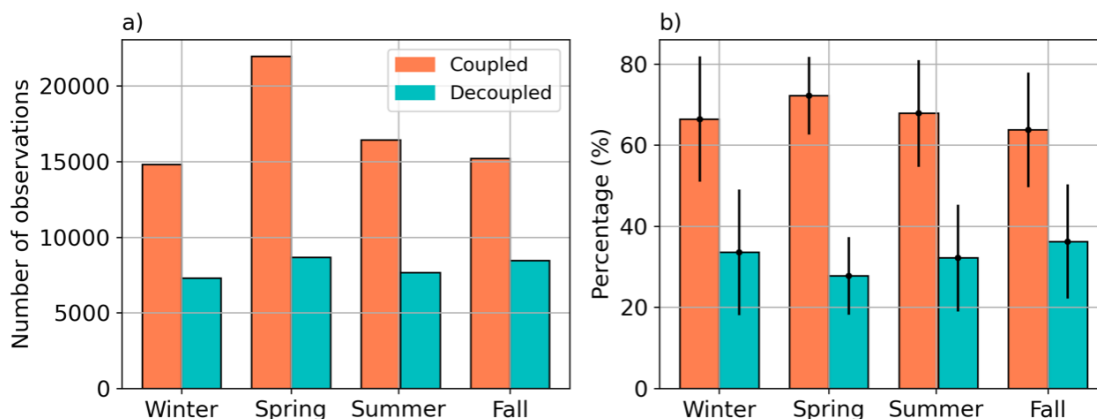


Figure 5.7 (a) Number of cloud samples for coupled and decoupled conditions among the four seasons at the SGP. This value is the count of cloudy samples in intervals of 10 minutes and does not represent the actual number of individual clouds. (b) Percentage of coupled and decoupled low-level clouds for each season at the SGP site.

Figure 5.8 shows the diurnal variability in the number of coupled and decoupled clouds in the four seasons. As shown, the diurnal cycle of coupled clouds is most pronounced during the warmer seasons. In spring and summer, surface conditions play a key role in promoting coupling. The combination of warmer temperatures, higher moisture, and strong afternoon surface heating enhances convective mixing from the ground up. In particular, increased sensible heat flux drives the growth of the PBLH, allowing it to reach cloud base and form coupled cumulus clouds.

In contrast, in colder seasons, especially in winter, diurnal variation is weak in coupled and decoupled clouds. During this season, colder temperatures and weak surface heat flux typically lead to a shallow PBLH. However, these low temperatures also increase relative humidity, creating favorable conditions for stratiform cloud formation. These clouds can connect with the surface

through a top-down convective process, where radiative cooling at the cloud top destabilizes the layer beneath, promoting mixing and establishing a link with the surface.

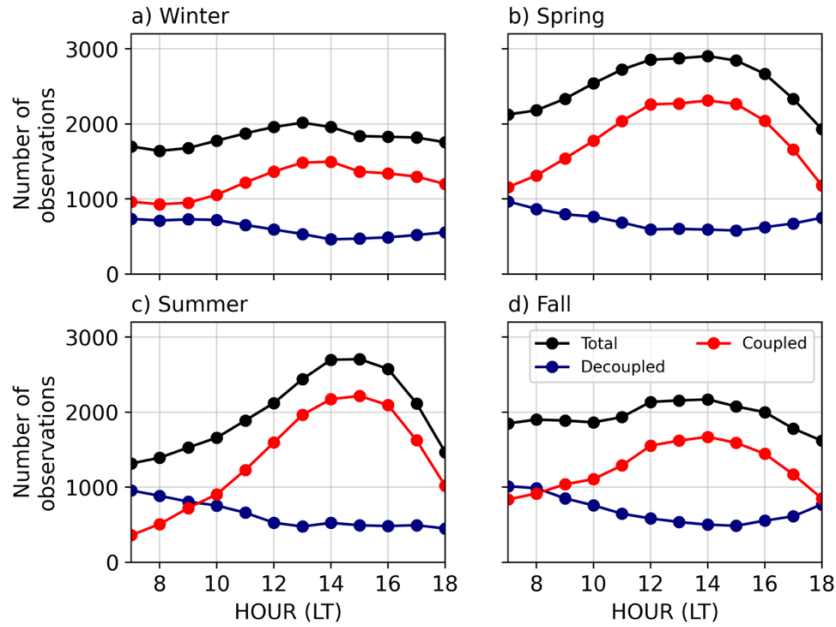


Figure 5.8 Diurnal variability of the number of observations for coupled and decoupled clouds during (a) winter, (b) spring, (c) summer, and (d) fall at the SGP site.

5.7 Dynamic and thermodynamic evidence for the Cloud-Surface Coupling

Vertical movement is pivotal in boundary layer dynamics, intricately linked to the turbulent transport of quantities such as moisture, heat, momentum, and substances (Stull, 1988). To fully understand cloud-surface coupling, a comprehensive grasp of the process's dynamic and thermodynamic aspects is necessary. In this study, we analyzed vertical motions, utilizing the comprehensive data from doppler lidar observations over the SGP central facility site, collected between October 2010 and July 2023.

Figure 5.9 presents the diurnal variation of vertical velocity variance averaged over all cloudy data during coupled and decoupled regimes, along with PBLH, CBH, and CTH. In coupled conditions, CBH closely follows PBLH, making them appear indistinguishable. The PBL starts

shallow with weak morning vertical motions, then deepens as stronger sensible heat fluxes enhance vertical motion to the CBH. This connection allows surface properties to reach the clouds. For coupled conditions, PBLH, CBH, CTH, and vertical velocity variance all rise from morning lows to afternoon peaks.

In decoupled conditions, the PBL also begins shallow in the morning, but its growth is more limited than in coupled cases. A pronounced gap exists between the PBLH and CBH, as well as between vertical motions below the cloud layer, which is clear in the Figure 5.9b heatmap with a region between 1 and 2 km with near-zero vertical velocity variance. With little vertical motion above the PBLH, surface fluxes do not reach the cloud base. As a result, decoupled clouds show minimal diurnal variability, with CBH and CTH staying nearly constant all day.

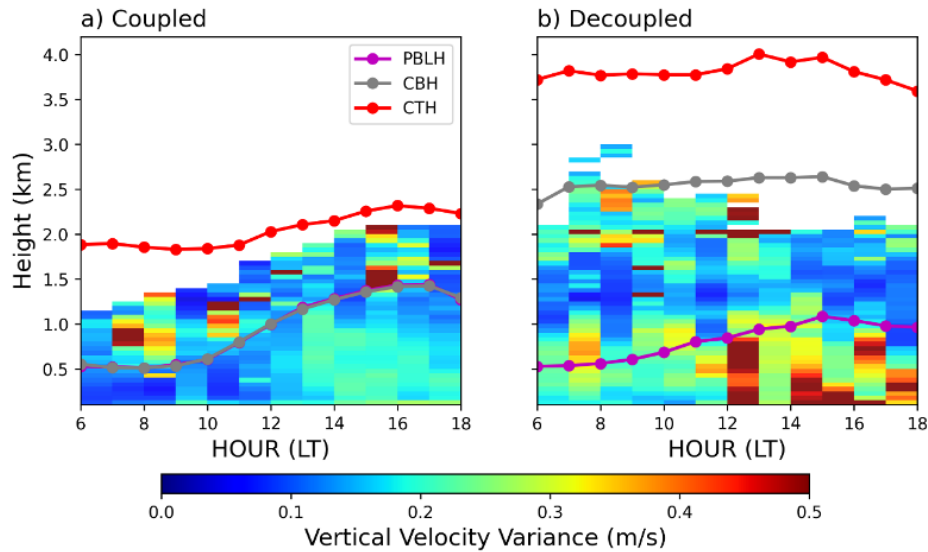


Figure 5.9 Diurnal variability of the vertical velocity variance at different heights measured at the Southern Great Plains for a) coupled and b) decoupled situations. The purple line corresponds to the Planetary Boundary Layer Height (PBLH), the grey line is the Cloud Base Height (CBH), and the red line is the Cloud Top Height (CTH). Notice that in a) the PBLH is not visible since it is almost identical to the CBH.

Understanding the climatology of cloud-surface coupling requires examining both dynamic and thermodynamic aspects. Figure 5.10 shows vertical profiles of equivalent potential temperature and relative humidity for coupled and decoupled cloud conditions at the SGP site, for both morning and afternoon soundings.

For coupled conditions, surface temperatures are lower in the morning than in the afternoon, resulting in a lower LCL and higher near-surface relative humidity (see Figure 5.10). These thermodynamic features align with the stratiform coupling regime, which prevails under low sensible heat (Su et al., 2024b). A shallow PBL and high near-surface humidity in the morning help maintain stratiform clouds coupled to the surface. In the afternoon, increased surface heating deepens the PBL, boosts turbulent mixing, and lowers near-surface humidity. This transition is accompanied by increased buoyancy and lower humidity at cloud base, as revealed by the temperature and humidity profiles in Figure 5.10, favoring a shift to cumulus coupling, where cloud formation is driven by localized convection.

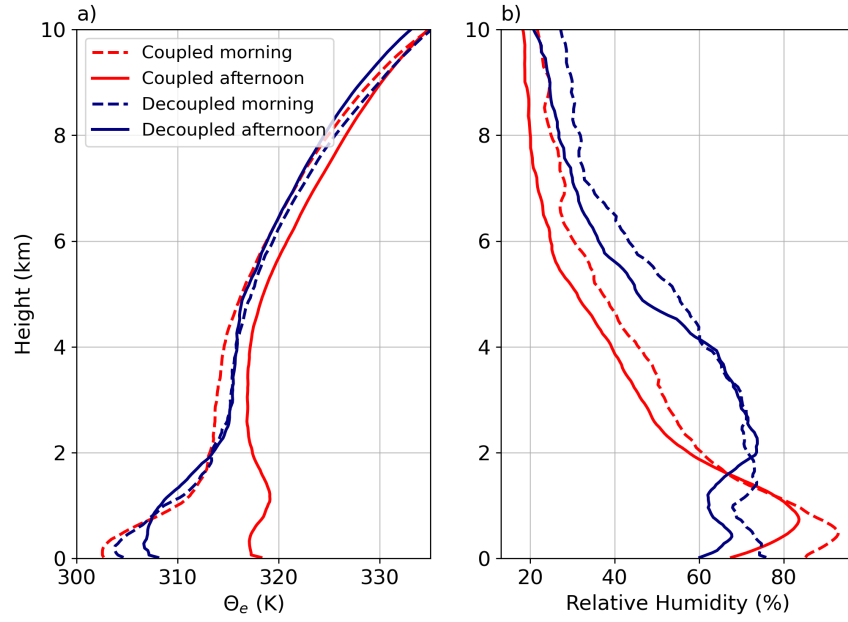


Figure 5.10 a) Average equivalent potential temperature (θ_e) for coupled (red) and decoupled (blue) situations. The dashed lines correspond to the morning radiosondes launched at 6:00 am at the SGP site; the solid line corresponds to the afternoon radiosondes launched at noon. b) same as a) but for relative humidity.

5.6 Evaluation of the spatial distribution of coupling

Different atmospheric and environmental conditions can result in diverse coupled regimes, namely coupled stratiform and coupled cumulus. In this section, we describe the processes that link spatial patterns of soil moisture and atmospheric properties to coupled stratiform, coupled cumulus, and decoupled situations at the SGP site. The description of these processes can be done using the local land-atmosphere coupling (LoCo) process chain paradigm (Santanello et al. 2018). The LoCo chain represents sensitivities of 1) surface fluxes (ΔEF) to soil moisture (ΔSM), 2) PBL evolution (ΔPBL) to the surface fluxes, 3) entrainment at the top of the PBL (ΔENT) to PBL

evolution, and 4) the collective feedback of the atmosphere (Δ Temperature, Δ Relative Humidity) on clouds (Δ Clouds).

$$\Delta SM \rightarrow \Delta EF \rightarrow \Delta PBL \rightarrow \Delta \text{Temperature, } \Delta \text{Relative Humidity} \Rightarrow \Delta \text{Clouds} \quad (4)$$

As noted, the first link of the process chain (equation 4) is soil moisture. This variable can influence land-atmospheric interactions over time, which may affect coupled feedbacks. Therefore, Figure 5.11 shows climatological composites of the spatial distribution of standardized soil moisture anomalies measured by the NASA SMAP mission, in situations where the SGP site reported (a) coupled stratiform, (b) coupled cumulus, or (c) decoupled clouds. These standardized anomalies were computed by subtracting the climatological mean corresponding to each month and hour and dividing by the associated standard deviation. This approach removes both the seasonal and diurnal cycles and expresses variability relative to the typical spread at each time, thereby better representing local departures from climatology. It is important to mention that when constructing the composites, the only dimension matched was the temporal dimension, not the spatial one. In this way, the methodology provides a general view of the spatial distribution of the SM across the U.S. when a specific cloud type is observed at SGP.

Positive SM anomalies were observed around SGP for coupled stratiform clouds, whereas negative anomalies were associated with coupled cumulus clouds and decoupled clouds. Stratiform clouds tend to dominate under conditions of low PBLH and moist atmospheres. In contrast, coupled cumulus clouds are more prevalent during periods of high PBLH and elevated sensible heat flux, conditions that typically coincide with dry SM. Consequently, coupled regimes can occur across a broad spectrum of soil moisture conditions, similar to the variability observed in PBLH.

As learned from the LoCo chain and the previous results, soil moisture is a key variable when studying cloud-surface coupling; however, it alone is insufficient to fully characterize the coupled regime. To provide a more complete picture of the LoCo chain, Figures 5.12–5.14 present composites of ERA5 standardized anomalies of surface fluxes and meteorological variables across three cloud regimes observed at SGP: coupled stratiform clouds (Figure 5.12), coupled cumulus clouds (Figure 5.13), and decoupled clouds (Figure 5.14).

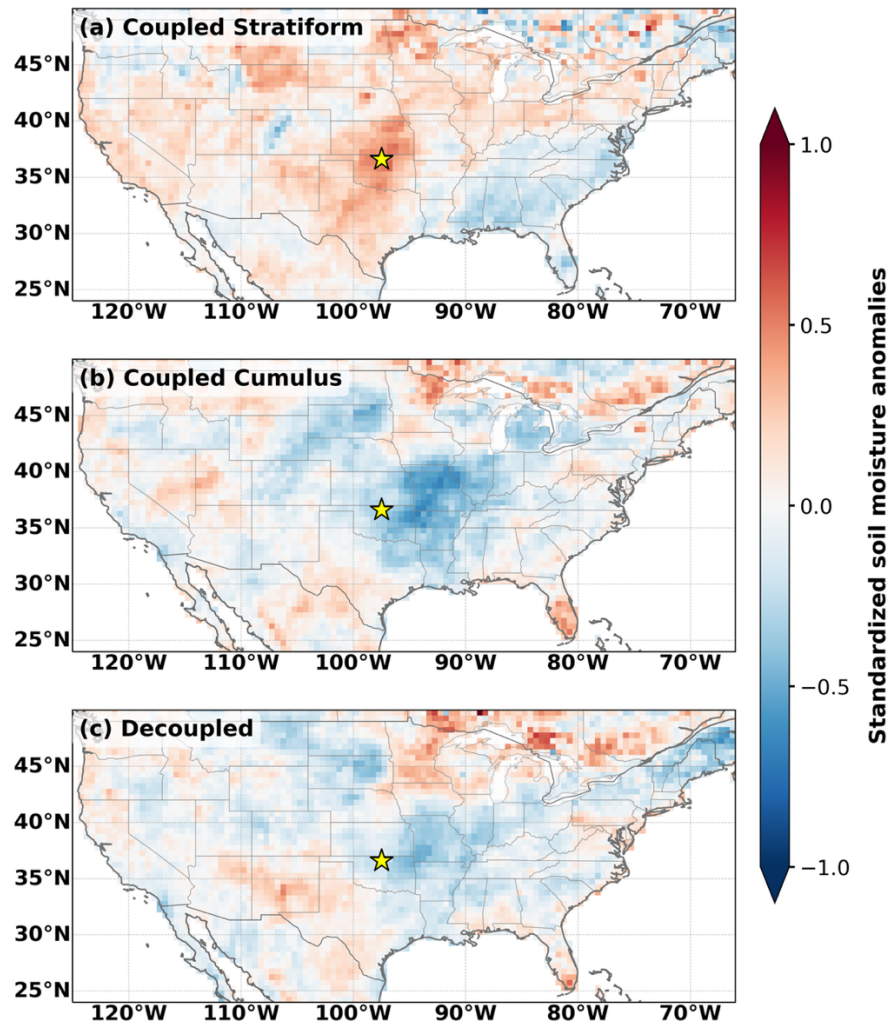


Figure 5.11 Standardized soil moisture anomalies (from SMAP enhanced L3 product) across the continental U.S for situations in which the SGP site reported (a) coupled stratiform clouds, (b) coupled cumulus clouds, and (c) decoupled clouds.

ERA5 anomalies under coupled stratiform conditions reveal anomalously high specific humidity and temperature over the Gulf of Mexico, a low-pressure system over the Southwest, and a high-pressure system over the Northeast. This atmospheric configuration transports warm, moist air from the Gulf toward the SGP region. Over SGP, the combination of anomalously cold temperatures and high specific humidity leads to increased relative humidity. As noted in the LoCo chain, soil moisture anomalies lead to changes in the evaporative fraction. Interestingly, evaporative fraction anomalies are near-neutral, suggesting that already-wet soils can supply sufficient latent heat and moisture to sustain the stratiform regime without requiring anomalously high values. The LCL deficit (computed as $PBLH - LCL$) exhibits strong positive anomalies over a broad region surrounding SGP, likely reflecting a lower LCL that is more easily reached by the PBLH under wet soil conditions.

In comparison to the coupled stratiform regime, ERA5 anomalies associated with coupled cumulus clouds are less pronounced (Figure 5.13). Geopotential height anomalies are generally close to zero, indicating a more stagnant atmospheric state. Positive specific humidity anomalies are present around the Midwest and across a broad region in the Northeast. Although weaker than in the stratiform regime, the LCL deficit also exhibits positive anomalies, while the evaporative fraction is weakly negative. This negative evaporative fraction, albeit small, indicates a greater contribution of SH relative to LH, resulting in taller PBLH. Under these conditions, the PBLH must deepen further to reach the LCL due to drier soil moisture. Nevertheless, positive anomalies in the LCL deficit persist because the PBLH still needs to reach the LCL to facilitate the formation of fair-weather cumulus clouds. In addition, cumulus clouds are less uniform than stratiform clouds, which could lead to a weaker LCL deficit anomaly.

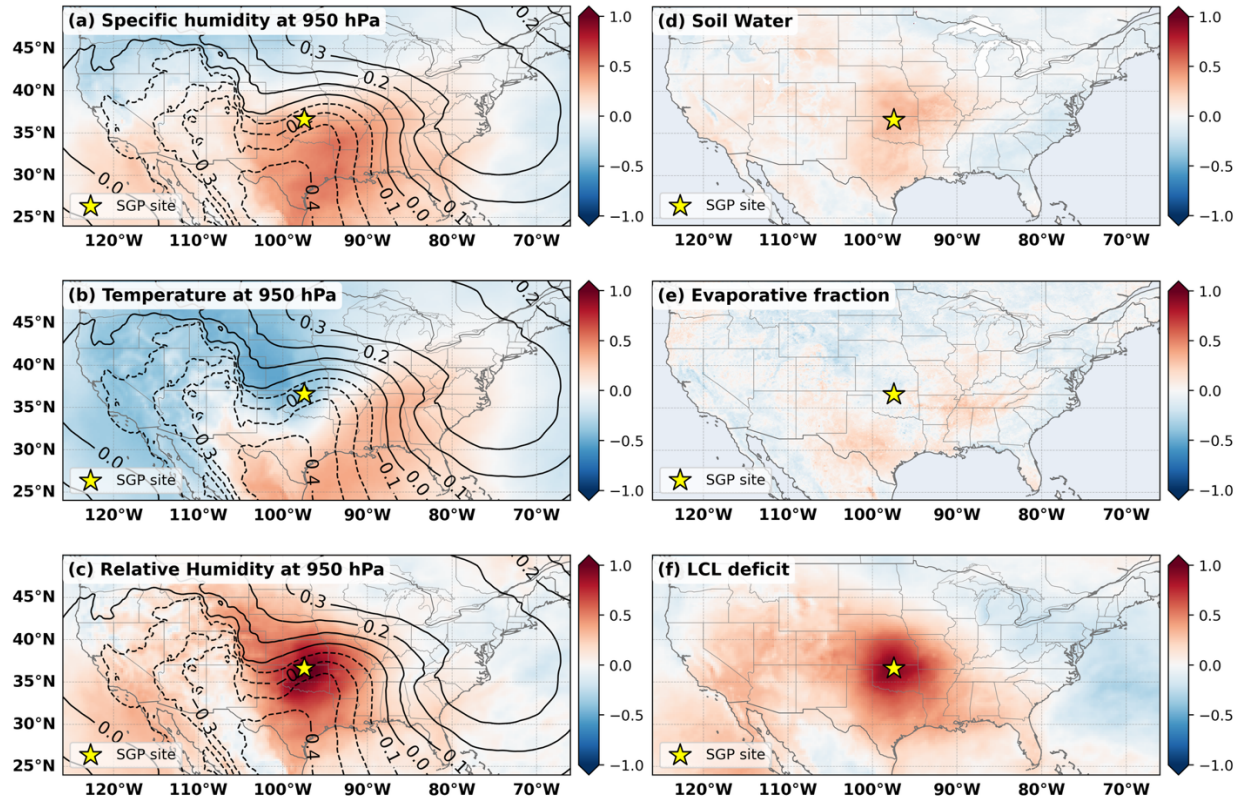


Figure 5.12 Standardized ERA5 anomalies during coupled stratiform cloud conditions at SGP (yellow star). Specific humidity, temperature, relative humidity, and soil water anomalies are evaluated at 12 UTC (07:00 local time). Evaporative fraction ($EF = LH / (LH + SH)$) and LCL deficit ($PBLH - LCL$) are derived from ERA5 outputs at 18 UTC (13:00 local time). Contour lines in panels (a)-(c) correspond to geopotential height anomalies at 950 hPa, where negative values are represented by dashed lines.

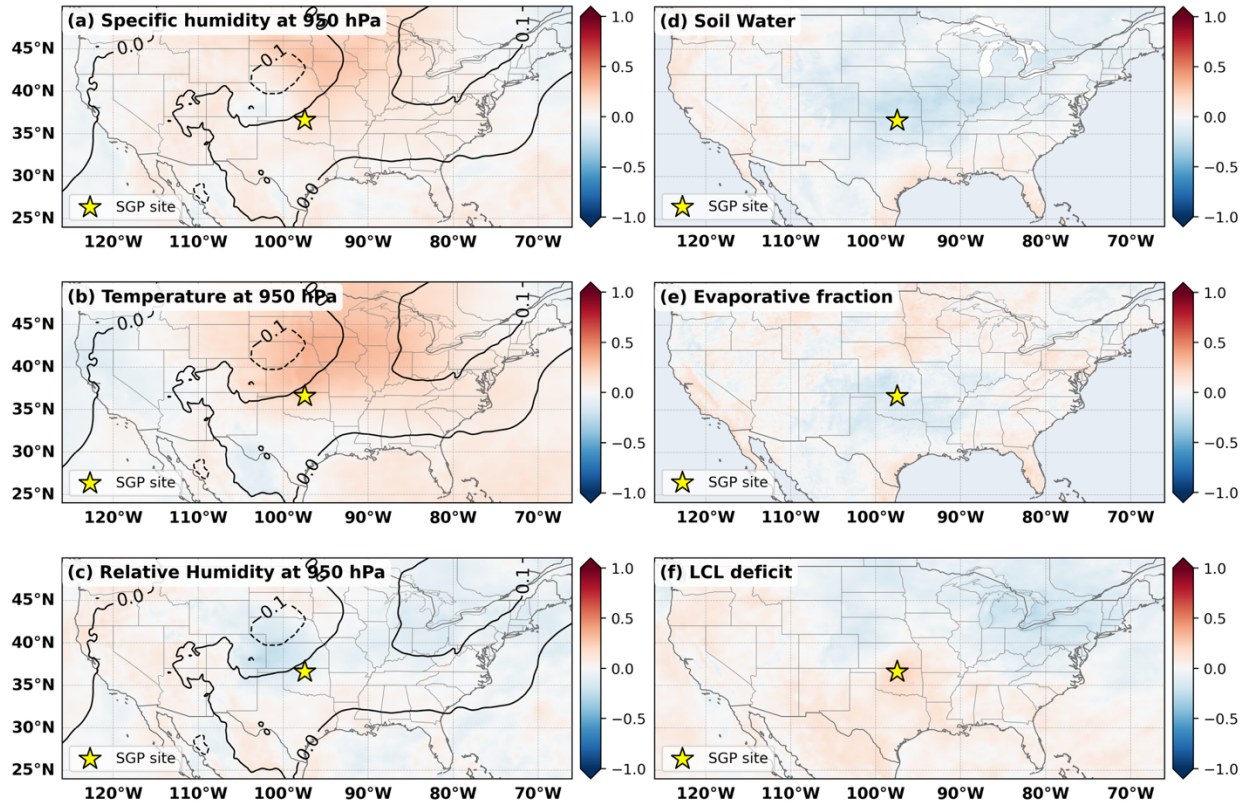


Figure 5.13 Standardized ERA5 anomalies during coupled cumulus cloud conditions at SGP (yellow star). Specific humidity, temperature, relative humidity, and soil water anomalies are evaluated at 12 UTC (07:00 local time). Evaporative fraction ($EF = LH / (LH + SH)$) and LCL deficit ($PBLH - LCL$) are derived from ERA5 outputs at 18 UTC (13:00 local time). Contour lines in panels (a)-(c) correspond to geopotential height anomalies at 950 hPa, where negative values are represented by dashed lines.

Figure 5.14 presents the results for decoupled clouds. For this regime, a weak high-pressure system is present over the western U.S., while a weak low-pressure system is observed over the eastern U.S. This pressure configuration may facilitate the advection of cold, dry air masses from the north toward SGP. During the decoupled regime, negative anomalies are observed for nearly all variables in the vicinity of SGP. The combination of cold temperatures, dry soils, and a negative

LCL deficit suggests an environment that is not conducive to local cloud formation. Decoupled clouds may originate from previously coupled clouds that subsequently decoupled during their life cycle, or they may correspond to clouds advected from remote regions. Interestingly, Figure 5.14 also shows positive anomalies in temperature, relative humidity, and the LCL deficit to the west of SGP, potentially indicating cloud formation in that region and subsequent advection toward SGP. Further investigation is needed to confirm or refute this hypothesis.

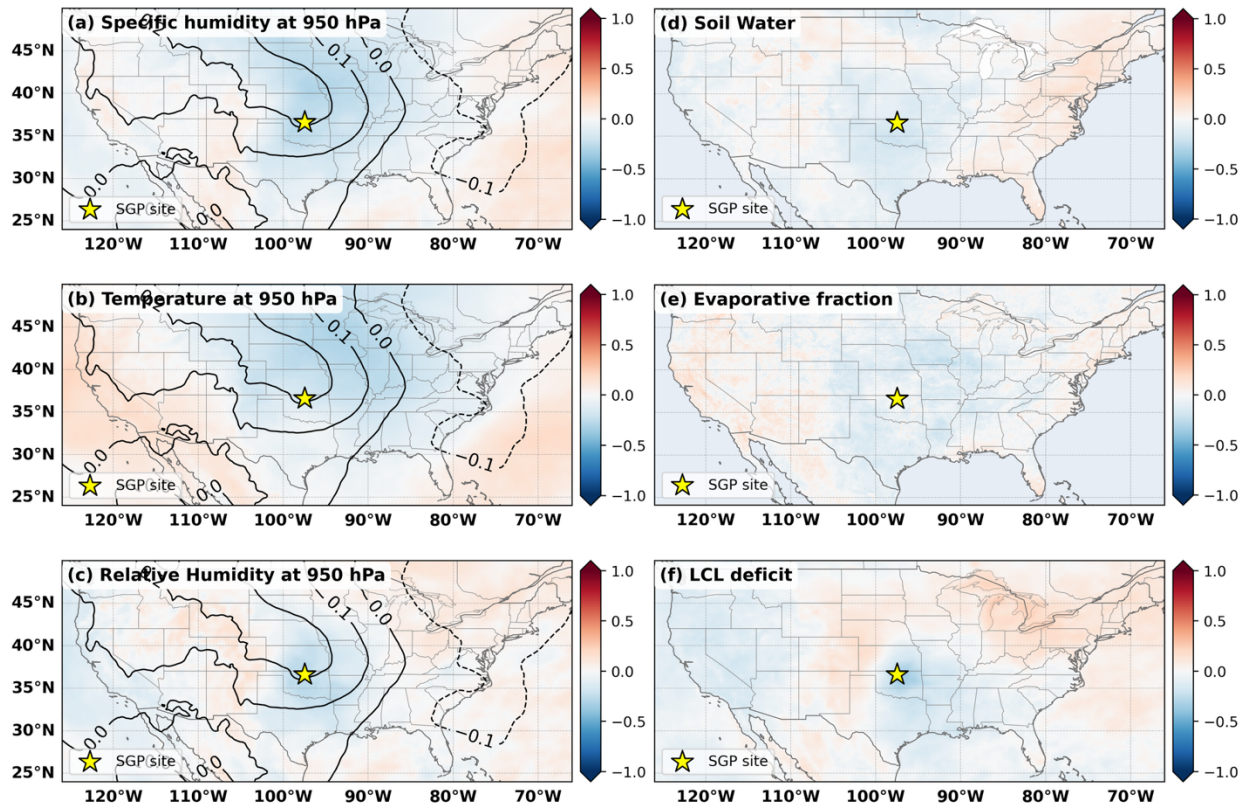


Figure 5.14 Standardized ERA5 anomalies during coupled stratiform cloud conditions at SGP (yellow star). Specific humidity, temperature, relative humidity, and soil water anomalies are evaluated at 12 UTC (07:00 local time). Evaporative fraction ($EF = LH / (LH + SH)$) and LCL deficit ($PBLH - LCL$) are derived from ERA5 outputs at 18 UTC (13:00 local time). Contour lines in panels (a)-(c) correspond to geopotential height anomalies at 950 hPa, where negative values are represented by dashed lines.

5.8 Conclusions

This chapter presents a comprehensive climatology of cloud-land-surface coupling, offering insights into the dynamic and thermodynamic conditions influencing clouds and their interaction with terrestrial processes. Through the analysis of long-term observational data, we refine our previously proposed method of determining the state of coupling with new thresholds, evaluate direct and adjunct coupling mechanisms, and explore the climatological patterns of coupled and decoupled cloud conditions.

Consistent coupling thresholds are revealed across diverse regions, and the fractions of coupled and decoupled clouds out of low-level clouds were computed, averaging $65.84\% \pm 10.24\%$ and $34.16\% \pm 10.24\%$, respectively. Our analysis further highlights distinct thermodynamic and dynamic characteristics between the two regimes. Coupled clouds can occur under either deep or shallow PBLH conditions, strong or weak surface fluxes, and low or high soil moisture anomalies; these variations are attributed to differences in cloud type (cumulus vs stratiform clouds). While a high PBLH facilitates cloud-surface coupling, it is not a determining factor.

Dynamically, coupled clouds are sustained by turbulent vertical motions that connect them to the surface. In contrast, decoupled clouds exhibit a weak connection to surface forcing, and accordingly, no significant diurnal variations are observed. Decoupled conditions are typically favored under weak surface fluxes and drier environmental conditions. These clouds may be driven by large-scale atmospheric processes such as advection or may originate as coupled clouds that become decoupled after being lifted above the PBLH, and after the surface-driven thermals weaken or cease.

Compared to other regions, at the SGP and MAO, coupled conditions are associated with a deeper PBL and stronger sensible heat fluxes, indicating a more convective lower troposphere and an increased presence of coupled cumulus clouds. In contrast, decoupled clouds, often detached from surface influences, occur in a shallow PBL with weaker heat fluxes and small diurnal variation, suggesting that their formation could be driven by large-scale atmospheric processes such as advection. At COR, it is slightly higher for decoupled clouds in the morning and becomes slightly higher for coupled clouds in the afternoon. This may reflect a growing contribution from coupled cumulus clouds later in the day, though further investigation is needed to confirm this pattern. At FKB, PBLH differences between coupled and decoupled clouds are most pronounced in the afternoon, aligning with variations in sensible heat flux. Lastly, at TMP, coupled clouds exhibit a shallower PBLH than at other sites, pointing to weaker surface-driven turbulence and suggesting a dominant presence of stratiform clouds.

Although coupled and decoupled percentages are consistent across sites, different climatic and geographical configurations lead to observable differences in the coupled regime's peaking time and driving factors. The SGP site, characterized by wheat crops and grasslands, has a slow buildup of sensible heat flux and, hence, PBLH growth, causing coupled clouds to peak late in the afternoon. MAO, over the Amazon region, is highly influenced by strong convection and weak stratification, which facilitates the early uplifting of low-level clouds beyond the PBLH and causes coupled clouds to peak in the late morning. COR receives high moisture transported by the SALLJ at nighttime, which likely influences the formation of coupled stratocumulus clouds in the early morning. TMP and FKB, located in colder climates, are characterized by shallow boundary layers and probably coupled stratiform conditions. Seasonal variations at SGP highlight the influence of local thermal and moisture conditions on cloud coupling. Coupled clouds are more frequent in

warmer seasons, particularly in spring ($72.2\% \pm 9.6\%$), when enhanced surface heating and moisture transport promote cumulus cloud formation. In contrast, their occurrence decreases in fall ($63.8\% \pm 14.1\%$), aligning with weaker convective conditions. The diurnal cycle of coupled clouds is most pronounced in spring and summer, peaking in the afternoon when surface heating is strongest. Meanwhile, decoupled clouds remain relatively stable across seasons, suggesting a weaker dependence on surface forcing. Sensible heat fluxes and PBLH variations further support this pattern, reinforcing the seasonal modulation of cloud coupling at SGP.

Using SMAP soil moisture and ERA5 anomalies, we used the LoCo chain framework to describe the processes that link the spatial distribution of meteorological and land surface properties across the U.S. during coupled stratiform, coupled cumulus, and decoupled cloud regimes. These anomalies indicate that coupled stratiform clouds predominate under high soil moisture conditions, where a lower LCL is more easily reached by the PBLH, resulting in a strong positive LCL deficit. In contrast, coupled cumulus clouds are more prevalent under drier soil conditions, where a higher LCL demands greater PBLH deepening. Although the PBLH still reaches the LCL in this regime, as evidenced by the occurrence of cumulus clouds, the LCL deficit anomaly is weaker, reflecting the less favorable moisture state.

Chapter 6: Role of cloud-PBLH coupling in aerosol cloud interactions of convective clouds

To investigate the aerosol effect on deep convective clouds (DCC), we used data from the SGP site in Oklahoma (see Chapter 2). This site was selected for multiple reasons. First, SGP offers a wide range of measurements needed for ACI investigations, including aerosols, clouds, and thermodynamic properties. Second, SGP data spans several decades, making it ideal for observational frameworks that rely on robust statistical analyses. Third, previous investigations have focused exclusively on SGP, including Li et al. (2011) and Varble (2018), both of which set the foundation for this chapter.

SGP is located on 160 acres of cattle pasture and farm land dominated by wheat fields. On this site, the landscape and topography are relatively simple (Krishnamurthy et al., 2021). However, Oklahoma is characterized by greater topographic heterogeneity, with elevations ranging from 300 m to over 1200 m above sea level (Brotzge & Richardson, 2003). The state's climate is influenced by different air masses, including warm, humid air from the Gulf of Mexico and cold, dry air from Canada. Land cover at larger scales is also diverse, with forests dominating the eastern one-third of the state, while the western one-half is primarily agricultural and grassland (Brotzge & Richardson, 2003).

6.1 Methodology for Assessing Aerosol-Deep Convective Cloud Interactions

Understanding aerosol-cloud interaction requires the observation of cloud lifetime and evolution. However, fixed ground-based observations can only capture snapshots of the cloud at the moment it passes over the sensor. With such a limitation, observational studies based on ground-based data rely on statistical approaches that measure different cloud stages at different

times. The ARM cloudtype classification product divides clouds into seven categories, of which only three can potentially be coupled to the surface: low clouds, congestus, and deep convective clouds. For this classification, the cloud-type product depends solely on cloud boundaries (cloud base and cloud top). Therefore, selecting only cases classified as deep convective clouds would only provide a sample of well-mature clouds, hindering our understanding of the impact of aerosols on the life cycle of deep convective clouds, at least from early to late stages of cloud development. Following this idea, we used all clouds classified as low clouds, congestus, and deep convection in the cloudtype product, rather than only those classified as deep convective clouds. This approach, however, has its own limitations. For example, contamination from low clouds that do not develop into convective systems. One way to mitigate this problem is by constraining meteorological conditions that facilitate convection. We also constrained our sample to only cases where the average daytime Level of Neutral Buoyancy (LNB) $< -4^{\circ}\text{C}$.

The PBLH retrievals from chapter 1 are available at a 10-minute temporal resolution and are only accessible for daytime hours, since PBLH retrieved from MPL tends to be misidentified due to the presence of residual layers, especially at night when PBL is generally low due to weak turbulence. As a result, all the variables we studied were resampled to a 10-minute interval, and the analysis was limited to the period from 6:00 a.m. to 6:00 p.m. The CAPE was computed using the thermodynamic profiles of the mergesonde products. For our analysis, we considered CAPE values between 0 and 5000 J/kg. Additionally, we decided to analyze only the months between March and October, during which local convection is more favorable. We categorized our dataset into coupled and decoupled clouds using the cloud coupling classification retrieved in the previous chapter. Subsequently, we analyzed the impact of cloud-surface coupling and CAPE on aerosol-DCC interactions by dividing the data into six aerosol number concentration (CN) categories

ranging from 0 cm⁻³ to 6000 cm⁻³. Finally, as Li et al. (2011) and Varble (18), we evaluate the uncertainty in our estimations using the standard error of the mean (SEM). The SEM indicates how much the mean of our sample may differ from the true population mean. It is calculated using the formula $SEM = \sigma / \sqrt{n}$, where σ is the standard deviation and n is the number of samples.

6.2 Role of cloud-PBLH coupling in ACI for convective clouds

The coupling between clouds and the PBL is strongly influenced by the cloud base height. Figures 6.1a-b categorize clouds into three groups based on their base heights, as was done in Li et al. (2011), but for more data samples: low-base corresponding to clouds with CBH < 1 km, medium-base clouds as those with CBH between 1 and 2 km, and high-base clouds with CBH between 2 to 4 km, for both coupled and decoupled conditions that differs from Li et al. (2011). As seen in Figure 6.1a, clouds of lower bases are more likely to be coupled, with approximately 65% of coupled clouds located below 1 km. Figures 6.1c-d illustrate the difference between CBH and PBLH using a boxplot. Negative CBH–PBLH values imply that cloud bases reside within the PBL, allowing surface fluxes to influence cloud development. In contrast, positive differences indicate that clouds form above the PBL, suggesting reduced surface influence and a higher likelihood of decoupling. Notably, about 60% of decoupled clouds are above 2 km. They tend to have a significant separation from the PBLH, with an average CBH-PBLH difference exceeding 1.5 km (Fig. 6.1d).

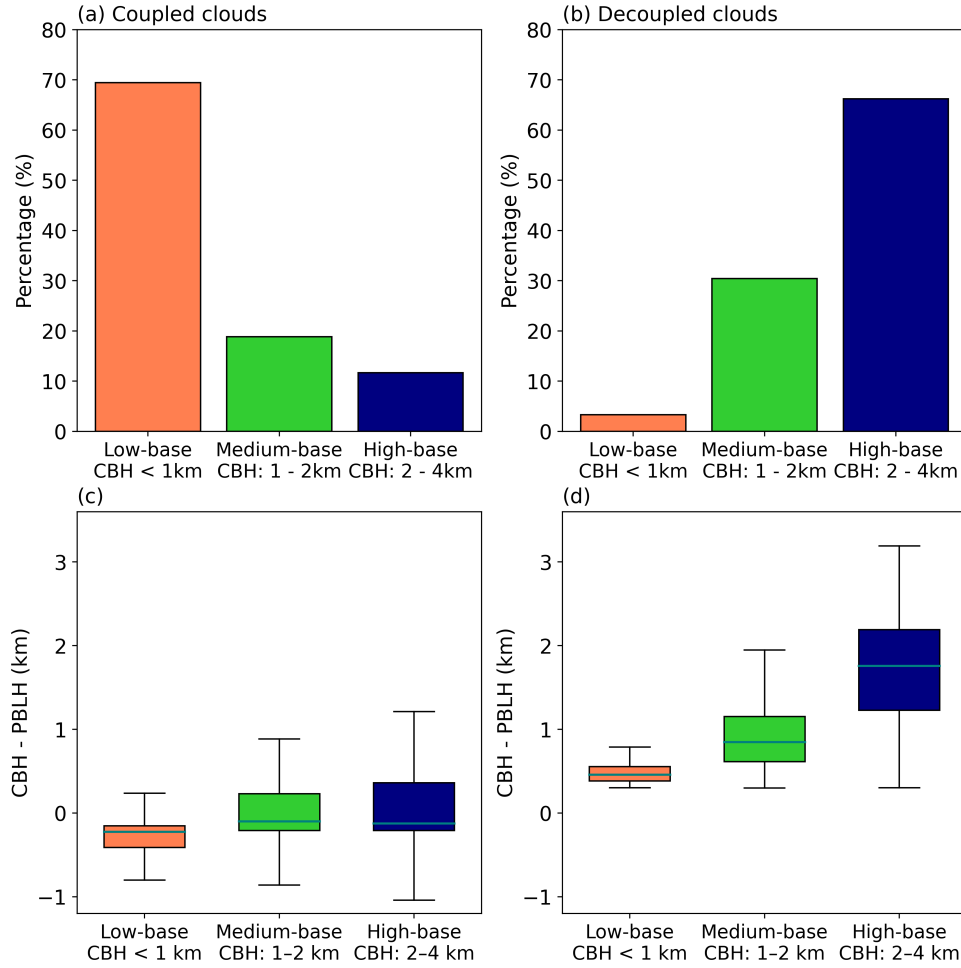


Figure 6.1 (a) Percentages of coupled clouds with bases below 1 km (orange bar), between 1 and 2 km (green bar), and between 2 and 4 km (blue bar). (b) same as (a) but for decoupled clouds. (c) Boxplot for the difference between the CBH and PBLH for coupled clouds with CBH below 1 km (orange bar), between 1 and 2 km (green bar), and between 2 and 4 km (blue bar). The teal horizontal line corresponds to the median value of the distribution. (d) same as (c) but for decoupled clouds.

Figure 6.2 shows changes in cloud thickness and base height with CN for both coupled (black line) and decoupled (red line) regimes. As aerosol concentration rises from 500 cm^{-3} to 6500 cm^{-3} , cloud top increases by about 1300 meters in coupled conditions but decreases slightly

in decoupled conditions. There might be multiple reasons for this difference. One reason is that coupled clouds are inherently more influenced by surface heat, moisture, and aerosol loading due to their proximity to the boundary layer. These factors are crucial for cloud development and evolution, making coupled clouds more susceptible to surface aerosols. Another reason is that, as explained by Su et al. (2024a), coupled regimes have a more uniform vertical aerosol profile between the surface and the cloud base, while decoupled clouds have a more stratified structure. This difference in aerosol vertical distribution allows surface aerosol measurements to serve as a more reliable proxy of cloud condensation nuclei (CCN), the root of the ACI under coupled conditions but not under decoupled conditions.

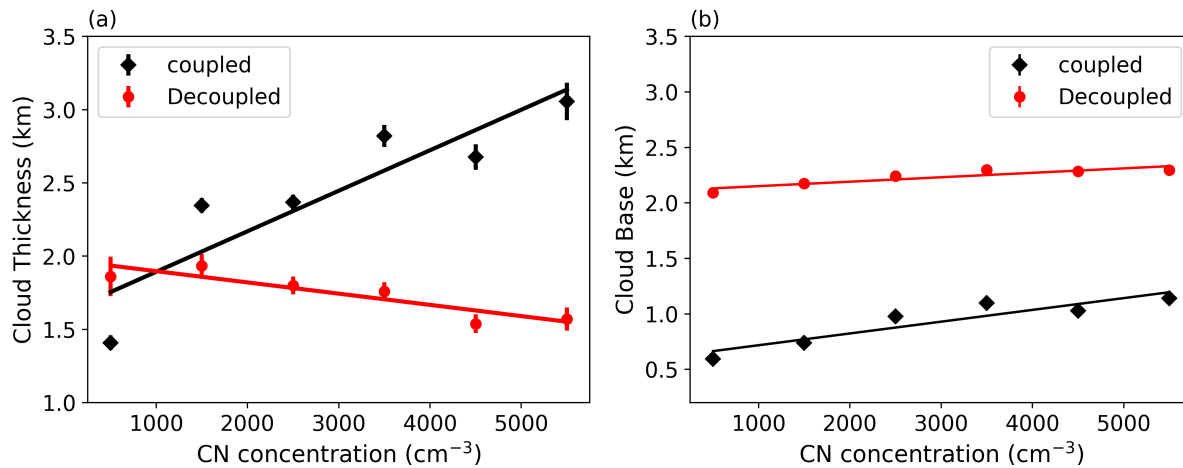


Figure 6.2 (a) changes in the cloud geometrical thickness with the CN concentration for coupled (black) and decoupled (red) conditions. (b) changes in the cloud base height with the aerosol number concentration for coupled (black) and decoupled (red) conditions. Vertical lines correspond to the standard error of the mean.

Figure 6.3a shows the changes in cloud thickness of coupled clouds with CN concentration for various cloud base categories. The most notable increase is seen for coupled clouds with bases below 1 km, where cloud thickness increases approximately 3 km when aerosol concentration rises

from 500 cm^{-3} to 6500 cm^{-3} . Conversely, high-base coupled clouds show virtually no change in thickness with varying aerosol concentration. Based on the theoretical basis, two plausible reasons explain the larger ACI effect observed for lower-base clouds. First, the distance between the cloud base and the melting level would be larger, allowing much more warm rain to form through enhanced collision processes compared to high cloud base clouds. This effect will strongly mediate the freezing-induced invigoration. Second, condensation is much greater at lower altitudes due to higher specific humidity. As a result, the heating from condensation can be significantly greater when compared to clouds with higher bases, leading to a larger degree of condensational invigoration.

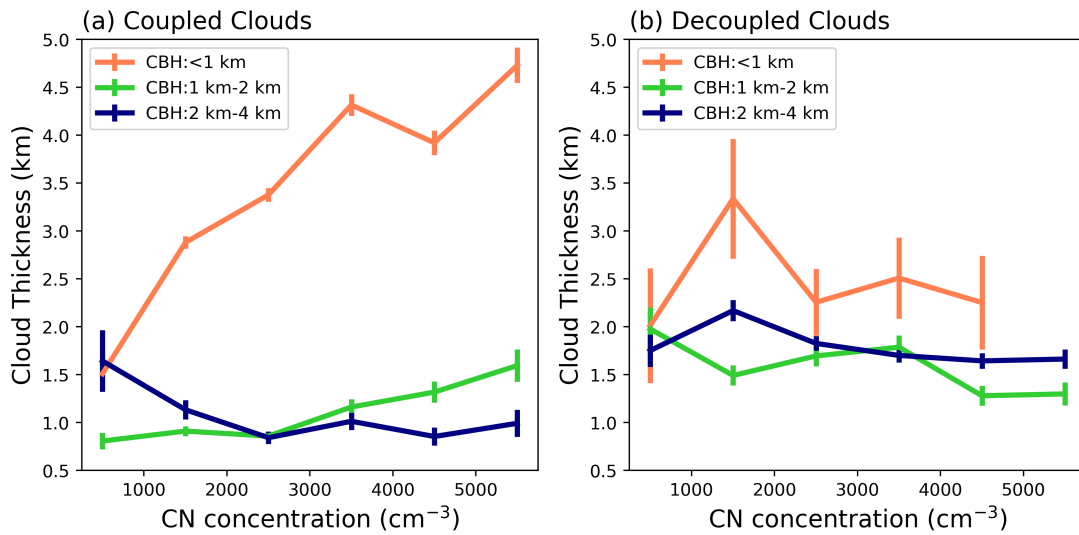


Figure 6.3 (a) changes in the cloud geometrical thickness with CN concentration for coupled clouds with bases below 1 km (orange line), between 1 and 2 km (green line), and between 2 and 4 km (blue line). (b) same as (a) but for decoupled clouds. Vertical lines correspond to the standard error of the mean.

As mentioned in the introduction, Varble (2018) found a positive relationship between CAPE and aerosol loading and argued that CAPE ultimately drives cloud development. Therefore,

an important question arises: could the observed correlations in Figures 6.2 and 6.3 be driven by factors other than aerosol loading, such as CAPE influence? To address this, we replicated the analysis from Figure 6.2, dividing the dataset into CAPE percentiles. Figures 6.4a and 6.4b show cloud thickness vs. CN concentration for low- and medium-base coupled clouds across CAPE percentiles (high-base clouds were excluded due to few samples). Figure 6.4a shows consistent increases in cloud thickness with CN concentration for all clusters of CAPE's percentiles. In particular, low-level coupled clouds thicken between 1 km and 4 km, depending on the CAPE percentile. The positive correlations between cloud thickness and CN concentration are statistically significant at the 0.05 level (Wald and F tests) for nearly all CAPE percentiles, except for the first percentile (represented by the blue line). It is important to note that both CAPE and aerosols affect cloud development. Not surprisingly, the slope of increase correlates with CAPE: steeper for higher CAPE than for lower CAPE. One may thus conclude that the substantial increase in cloud thickness observed in low-base coupled clouds is not solely attributable to variations in CAPE, but to both CAPE and the aerosol invigoration effect. Finally, Figures 6.4e and 6.4f show that, unlike cloud thickness, CAPE remains nearly constant with aerosol concentration, supporting the idea that aerosols help invigorate clouds under coupled conditions. Figures B.1 and B.2 show the same analysis but for LNB and LFC, respectively. Similar conclusions are observed, with cloud thickness increasing with aerosol loading for different percentiles of the meteorological variables.

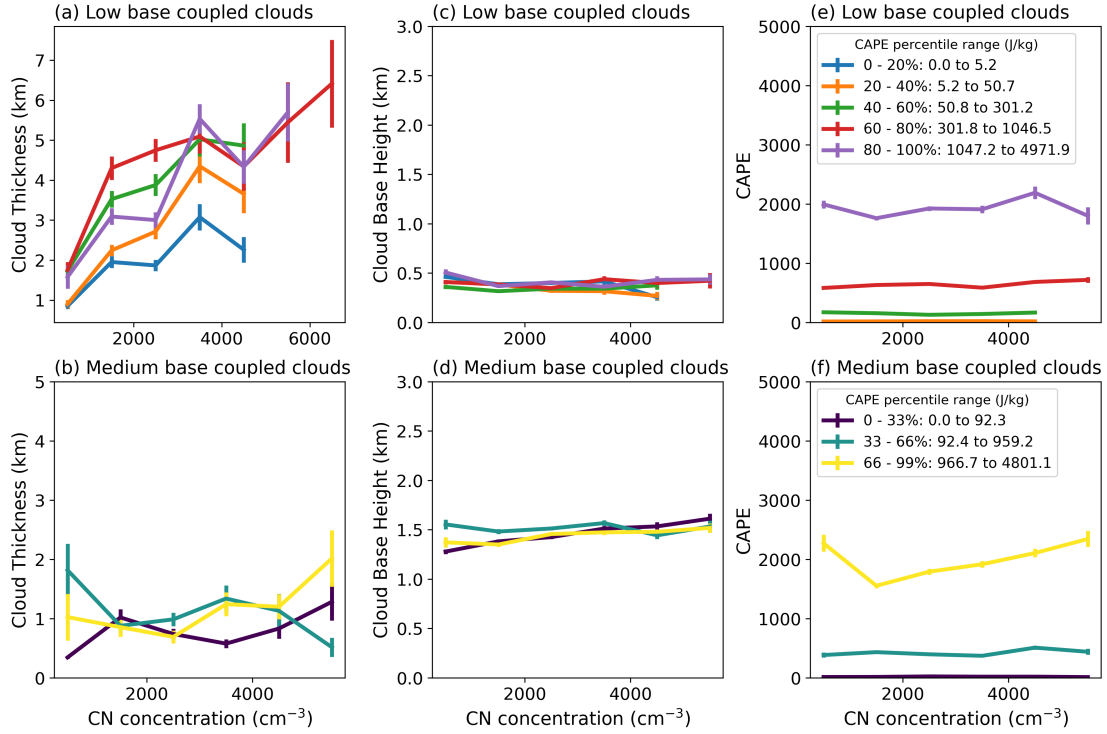


Figure 6.4 CN concentration for different CAPE percentiles for (a) low-base coupled clouds and (b) medium-base coupled clouds. Cloud base height variations with CN concentration for different CAPE percentiles for (c) low-base coupled clouds and (d) medium-base coupled clouds. CAPE variations with aerosol concentration for the different CAPE percentiles for (e) low-base coupled clouds and (f) medium-base coupled clouds. For each aerosol and CAPE interval, mean values are shown only when the sample size exceeds 20. Vertical lines correspond to the standard error of the mean.

Like Figure 6.4, Figure 6.5 shows the sensitivity analysis of CAPE for the relationship between cloud thickness and CN concentration under decoupled conditions for (a) medium-base clouds and (b) high-base clouds. The analysis of Low-base clouds is omitted, given the limited sample size for this category (Figure 6.1b). Overall, no distinct trend emerges between cloud thickness and CN concentration across any CAPE percentile or cloud base height, and none of the observed relationships is statistically significant. However, this doesn't mean that decoupled

clouds are insensitive to aerosol concentration. It is just the reflection of using surface-based aerosol measurements that don't represent cloud base concentrations. The only consistent pattern is the expected relationship between cloud thickness and CAPE; the thicker the cloud, the higher the CAPE, in accordance with the fundamentals of cloud physics.

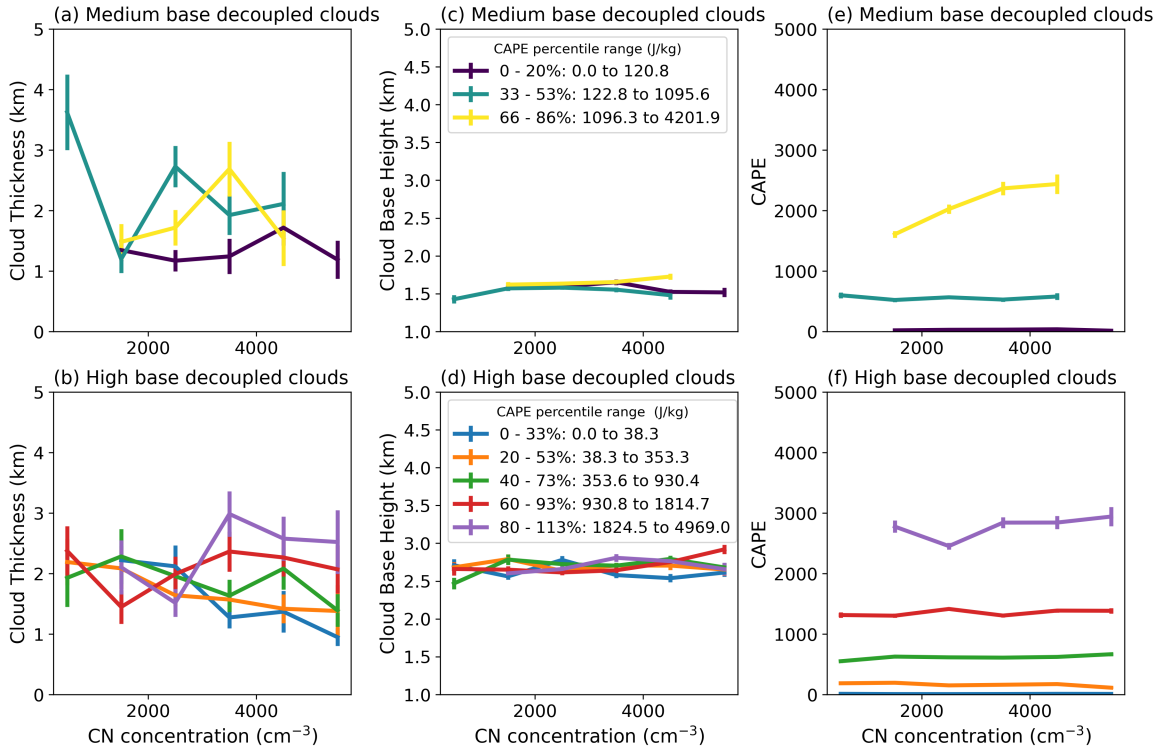


Figure 6.5 CN concentration for different CAPE percentiles for (a) medium-base decoupled clouds and (b) high-base decoupled clouds. Cloud base height variations with CN concentration for different CAPE percentiles for (c) medium-base decoupled clouds and (d) high-base decoupled clouds. CAPE variations with aerosol concentration for the different CAPE percentiles for (e) medium-base decoupled clouds and (f) high-base decoupled clouds. For each aerosol and CAPE interval, mean values are shown only when the sample size exceeds 20. Vertical lines correspond to the standard error of the mean.

6.3 Drivers of the CAPE–Aerosol Correlation at SGP

After finding a positive relationship between CAPE and aerosol loading, Varble (2018) sought to explain this correlation by examining the mean synoptic conditions around SGP. The study found that dirty conditions are associated with higher surface temperatures and a stronger south-southwesterly flow, whereas clean conditions are characterized by lower temperatures and an anomalous upper-level northerly flow. However, Varble (2018) concluded that the magnitude of these differences may be sufficiently small to be comparable to measurement errors. Building on Varble’s approach, the present analysis examined synoptic-scale patterns at 850 hPa for clean ($0 < \text{CN} < 1000 \text{ cm}^{-3}$) and dirty ($4000 < \text{CN} < 5000 \text{ cm}^{-3}$) conditions, further distinguishing between coupled and decoupled clouds. In contrast to previous work, this study focused on climatological anomalies rather than mean values.

Figure 6.6 presents the results of the synoptic-scale analysis. Under coupled clean conditions (Figure 6.6a), surface temperatures around the SGP site (yellow star) are lower, as indicated by the blue shading. We also observed anomalous northerly winds, associated with lower geopotential heights to the east of Oklahoma and higher geopotential heights to the northwest. In coupled dirty conditions (Figure 6.6c), the anomalies are generally weaker than in clean conditions. Under dirty coupled conditions, winds originate from the south, transporting warmer, more humid air masses that may carry both marine aerosols and aerosols from Texas. Not surprisingly, these findings for coupled conditions align with those reported by Varble (2018), as coupled cases account for 70% of the sample (see chapter 5), thereby dominating the mean state.

In decoupled scenarios, the findings do not completely align with those of Varble (2018). While surface temperatures around the SGP site remain lower under clean conditions, the anomalies are somewhat less pronounced. The most notable differences between coupled and

decoupled conditions manifest in the geopotential height field. In clean decoupled conditions (Figure 6.6b), the geopotential height contour lines are more spread-out, indicating weaker wind patterns. Furthermore, the signal of anomalous lower geopotential height observed in Figure 6.6a seems to have shifted westward, now centering near the SGP site. Consequently, the winds should exhibit a stronger easterly component compared to clean coupled scenarios. In decoupled dirty conditions, the anomalies are weakest, approaching zero, with no significant patterns.

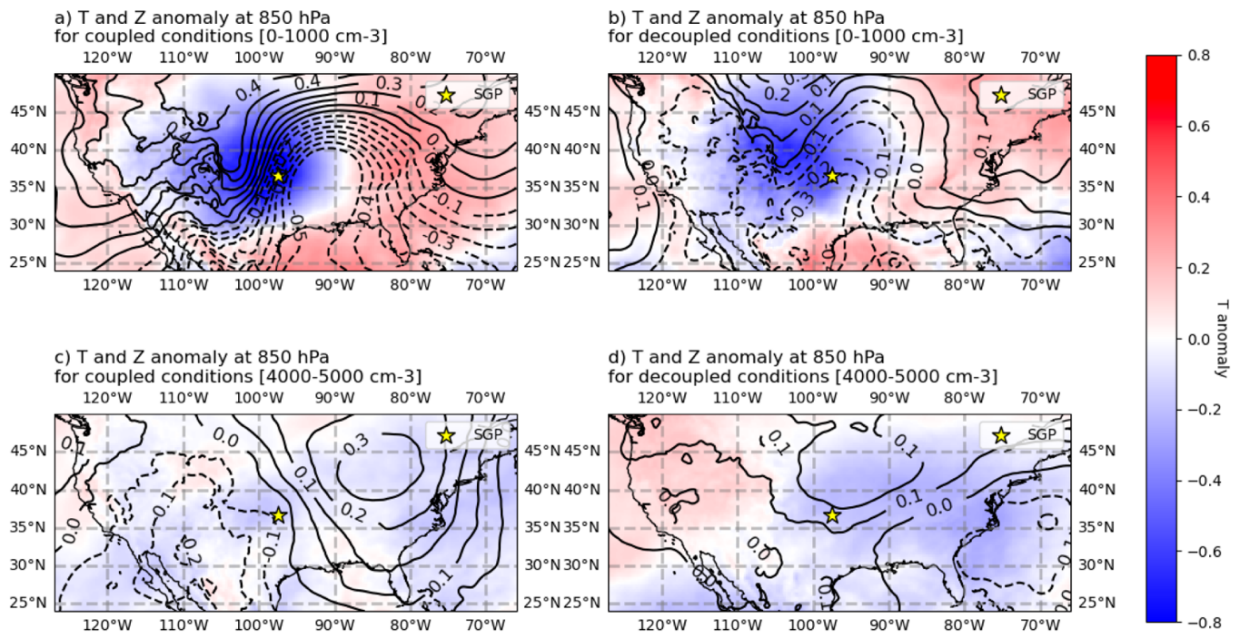


Figure 6.6 ERA5 climatological anomalies at 850 hPa for temperature (T) (shaded) and geopotential height (Z) (black contour lines). Positive Z anomalies are shown with solid black lines, while negative Z anomalies are represented with dashed lines. The yellow star marks the SGP site location. (a) Anomalies for coupled clean conditions, (b) anomalies for decoupled clean conditions, (c) anomalies for coupled dirty conditions, and (d) anomalies for decoupled dirty conditions.

Since the positive relationship between CAPE and aerosol is likely explained by the origin of air masses, we further constrain the influence of meteorology by categorizing air masses based on their origin—either from the south or the north. This separation allows us to minimize the confounding effects of CAPE–aerosol co-variability. We separated the air masses by computing the mean wind direction over the 12 hours preceding each cloud measurement and classifying winds as either northerly or southerly. Figure 6.7 presents an analysis similar to Figure 6.2 but differentiates between these two wind regimes. The same trend is seen: an increase in cloud thickness with aerosol concentration is observed only under coupled conditions. Interestingly, the rate of this increase is steeper for northerly winds than for southerly ones. Overall, northerly winds show an increase of approximately 2 km when CN increases from 500 cm⁻³ to 5500 cm⁻³, whereas southerly winds only increase approximately 500 meters for the same aerosol range. One possible explanation for the difference is that northern air masses tend to be cleaner than southern ones, as shown in Figure 6.6. This suggests that northern air masses represent an aerosol-limited environment, where variations in aerosol loading strongly influence cloud properties. In contrast, southern air masses likely contain higher baseline aerosol concentrations, meaning that additional aerosol loading has a more muted impact on cloud development. However, the additional constraint of dividing air masses reduces the available data in Figure 6.7, and the observed differences between northern and southern air masses should therefore be interpreted with caution, as they may result from the smaller sample size rather than a true physical signal. Nevertheless, the main conclusion of this chapter remains robust, as cloud thickness increases with aerosol concentration for both air masses.

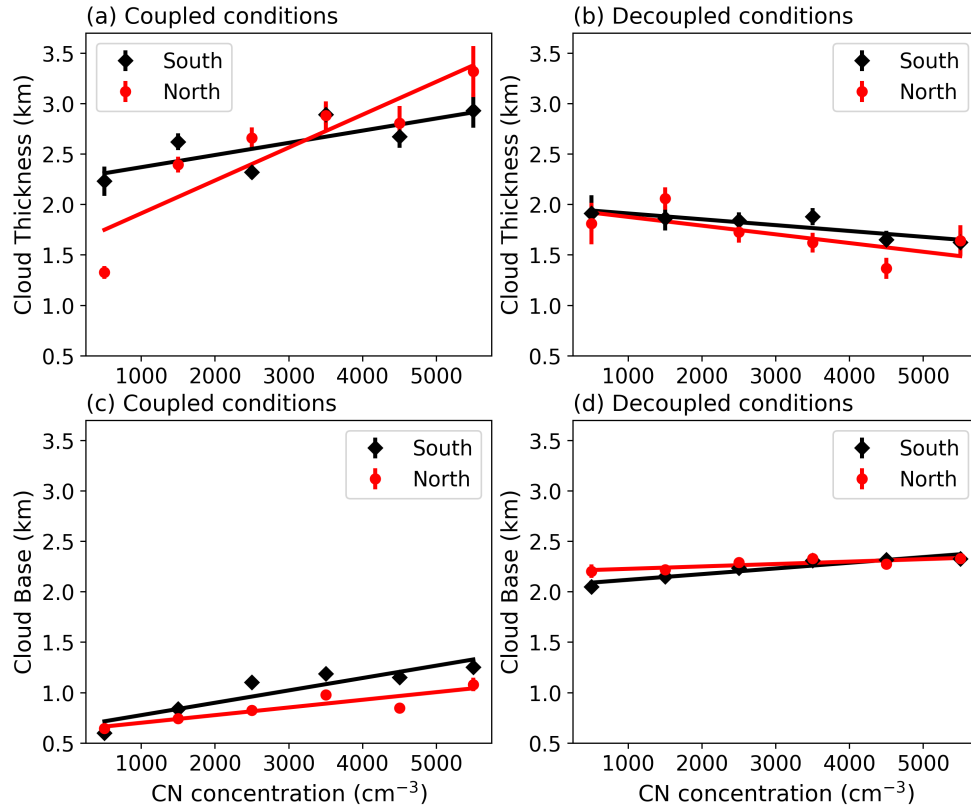


Figure 6.7 Variations in cloud geometrical thickness (a–b) and cloud base height (c–d) as a function of CN concentration under coupled and decoupled conditions. Red lines represent air masses originating from the north, while black lines correspond to air masses from the south. Panels (a) and (c) show results for coupled conditions, whereas panels (b) and (d) correspond to decoupled conditions. Vertical lines correspond to the standard error of the mean.

Finally, a similar analysis as Figure 6.4 was conducted to investigate the ACI by segregating the effects of air mass separated by northerly and southerly winds, atmospheric stability denoted by CAPE, and the state of cloud-PBL coupling. Given the limited sample size, the analysis is constrained to three CAPE percentiles instead of five. The results are illustrated in Figure 6.8. Panel (a) shows a general increase in cloud thickness across different CAPE percentiles for coupled clouds with air masses from the south. However, this trend is statistically significant only for the

last CAPE percentile of 66-99%, where the increase is more pronounced. For coupled clouds with air masses from the north (panel d), cloud thickness also increases across different CAPE percentiles, with a steeper slope between 0 and 2500 cm^{-3} . Our analysis shows statistical significance for the second CAPE percentile (33-66%). It is important to mention that, given the numerous constraints applied to the data in Figure 6.8, statistical significance in these analyses is relatively low.

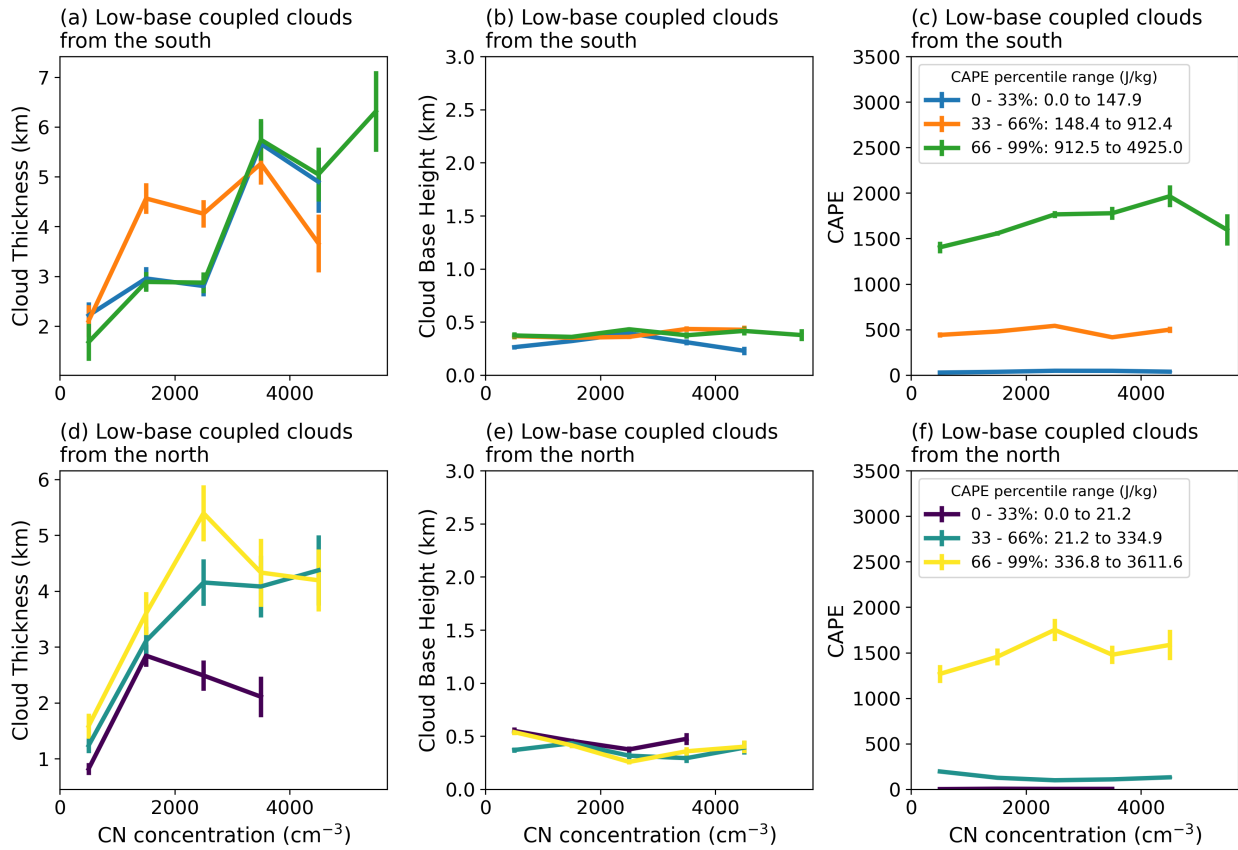


Figure 6.8 Cloud thickness variations with aerosol number (CN) concentration for different CAPE percentiles for (a) low-base coupled clouds from the south and (d) low-base coupled clouds from the north. Cloud base height variations with CN concentration for different CAPE percentiles for (b) low-base coupled clouds from the south and (e) low-base coupled clouds from the north.

6.4 Conclusions

This chapter incorporates the knowledge of cloud-PBLH coupling to revisit the previous findings of Li et al. (2011) on the aerosol invigoration effect, which were later challenged by Varble18. Li et al. (2011) found a positive correlation between aerosol concentration and cloud thickness and suggested that increased aerosols can enhance cloud development. However, Varble18 found a positive correlation between aerosols and CAPE and argued that the enhanced cloud development could be caused by the co-variability between CN concentration and CAPE.

Here, the concept of cloud-PBLH coupling helps to examine whether aerosol measurements made on the ground are a valid proxy for aerosol near the cloud base. Coupling allows for a more accurate assessment of ACI, as it ensures that ground-based aerosol measurements reliably represent the aerosols involved in cloud formation and development, a challenge that has long complicated ACI studies (Quaas et al., 2020). We found a positive relationship between aerosol concentration and cloud thickness only for coupled clouds, under which ground-based measurements are a valid proxy of aerosols participating in the ACI processes. By contrast, little dependence is found for decoupled clouds.

To isolate the aerosol effect from the CAPE effect, we conducted a sensitivity analysis to understand how the correlation found by Varble (2018) between CN and CAPE affects the relationship between aerosols and cloud thickness. To this end, we binned the data samples into percentile ranges of CAPE and analyzed the relationship within each range. Positive correlations between CN and cloud thickness persist across all percentiles only for coupled low base clouds. Moreover, the slope of the relationship is steeper for higher CAPE, attesting to its role in strengthening convective clouds.

We investigate the co-variability between aerosol loading and CAPE. Consistent with Varble (2018), our analysis indicates that clean cases are predominantly associated with northerly air masses, while dirty conditions are linked to southerly air masses. However, this pattern was only evident in coupled conditions. Finally, a caution ought to be exercised in interpreting the findings of this chapter, as they are based on single-site measurements and may not generalize across different climate regimes.

Chapter 7: Final remarks and future work

7.1 Final remarks

The lower troposphere plays a fundamental role in modulating weather and climate. Within this layer, the PBL is particularly important, as it mediates the exchange between the atmosphere and other components of the Earth system, including the ocean, land surface, and cryosphere. PBL processes govern land-atmosphere interactions and regulate the turbulent mixing of energy, water vapor, carbon, and other atmospheric constituents. These processes make the understanding of the boundary layer essential for investigating cloud formation and evolution, aerosol-cloud interactions, and broader feedbacks that modulate regional and global weather and climate.

This investigation focuses on understanding cloud-surface-PBLH coupling, from its definition and quantification to its climatology and, finally, its role in aerosol-cloud interactions in deep convective clouds. To this end, this dissertation began with the accurate determination of the PBLH, an atmospheric parameter representing the maximum altitude to which turbulent fluxes can theoretically reach. The estimation of this layer remains challenging, relying not only on accurate observations of atmospheric properties but also on algorithms and determination methods. In addition, given the lack of measurements of atmospheric turbulence, PBLH retrievals rely on proxies that may not accurately reflect the atmospheric turbulent structure. For instance, lidar-based approaches use the vertical distribution of aerosols as a proxy, which can lead to biased estimates for elevated aerosol layers, transition periods, or nighttime conditions when the residual layer dominates the aerosol signal.

Chapters 3 and 4 focus on the estimation of the PBLH using lidar-based approaches for both ground-based lidars (Chapter 3) and spaceborne lidar (Chapter 4). In these chapters, we apply the DTDS algorithm to compute the PBLH. We found that DTDS is a robust algorithm that

provides better estimates of the PBLH than traditional methods, such as the WCT, and better estimates than existing PBLH datasets, such as the ARM ceilometer PBLH value-added product. With some changes being made to adapt DTDS for its use on spaceborne lidars, its feasibility is demonstrated for applications with different instruments and platforms.

One of the primary advantages of the DTDS method is its integration of lidar signals, such as backscatter, with meteorological data. This special feature was evaluated for our spaceborne retrievals by making estimations with and without the inclusion of the lifting condensation level (LCL). These two different retrievals were compared against the ground-based estimations. The exclusion of the LCL in the algorithm resulted in poorer performance, characterized by higher errors and reduced correlations. This finding leads to the conclusion that future lidar satellite missions aimed at characterizing the PBLH would benefit substantially from the simultaneous acquisition of meteorological measurements.

This dissertation evaluated the performance of DTDS across multiple sites, proving that it is a sound algorithm suitable for diverse climatic regions. In addition, we retrieved the diurnal evolution of the PBLH at a regional scale using missions such as the CATS. CATS's unique sampling capabilities allow us to statistically resolve the diurnal evolution of the PBLH from space. We found promising results, with our retrievals reflecting well-known patterns in the spatial distribution of the PBLH and yielding high correlations with ground-based estimates. These results open new avenues for future investigations in which similar approaches can be used to improve our representation and estimation of the PBLH at a global scale.

Accurate estimates of the PBLH serve as an essential input for studying cloud-surface-PBLH coupling. We found similar coupling thresholds and percentages in diverse climatic regimes, likely reflecting shared atmospheric processes. For instance, the influence of the diurnal

variability of the PBLH, which determines the partitioning between coupled and decoupled regimes, has similar trends regardless of the region, starting with shallow boundary layers in the morning that grow as the day progresses. As the PBLH deepens, more clouds become coupled to the surface and vice versa.

Although we found similar coupling thresholds and percentages, the fraction between coupled cumulus and coupled stratiform clouds likely differs across regions. Based on analyses at the Southern Great Plains (SGP) region, we found that coupled cumulus clouds dominate in warmer environments, with high sensible heat flux, high PBLHs, and drier soils. On the contrary, coupled stratiform clouds are predominant during wet soils, where humid environments facilitate lower LCLs that are more easily reached by the PBLH. Coupled stratiform clouds were characterized by colder environments, shallower PBLH, and lower sensible heat flux. These contrasting atmospheric and surface configurations potentially yield different percentages of coupled stratiform and coupled cumulus at various climatic and geographical regions. For instance, places like the Amazon region, characterized by a constant energy supply and deep boundary layers, are likely strongly influenced by coupled cumulus clouds, especially in the afternoon hours and during the drier season between June and November. But places like TMP, located in a boreal forest, have a net energy deficit. Here, deeper boundary layers were found for the decoupled regime than for the coupled one. This lower PBLH during coupled conditions suggests that the coupled regime in this region is dominated by stratiform clouds, in which the coupled regime is probably sustained by the moisture in the system.

By definition, decoupled clouds are not directly influenced by surface fluxes or evolution. Such a separation was revealed by multiple factors. First, vertical motions exhibit a gap between PBLH and the cloud base height, with vertical motions being nearly zero beyond the PBLH, which

inhibits surface turbulence from reaching the cloud. Second, the spatial distribution of atmospheric and surface properties reveals cold temperatures, dry soils, a dry atmosphere, and a PBLH below the LCL. These conditions would inhibit cloud formation or at least prevent surface fluxes from interacting with the existing clouds.

Multiple paths can lead to decoupled conditions. For example, coupled clouds could decouple after precipitating due to the stabilizing effect of rainfall or during the late afternoon hours when the PBLH retreats and clouds remain elevated after being lifted by the afternoon convection. However, given the observed environmental conditions for decoupled clouds, which are not conducive to cloud formation, it is possible that a great percentage of decoupled clouds corresponds to clouds advected from other regions. At least at the SGP site, where these analyses were made. The same analyses also reveal environmental conditions more conducive of cloud formation to the west of SGP that could be transported by the mean flow.

Overall, the relatively consistent coupling thresholds and occurrence rates observed at multiple sites could be beneficial for guiding future model evaluations or parameterization efforts. While further investigation is warranted, the finding found for coupled vs decoupled regimes mark a leap toward improving the representation of cloud-surface interactions in weather and climate models. Furthermore, by underscoring the need for comprehensive observations and advanced methodologies, this research lays the groundwork for future investigations into the variability and evolution of low-level clouds across diverse climatic regions.

The concept of cloud-surface coupling is critical to several atmospheric processes, such as convection initiation and the stratocumulus-to-cumulus transition. In particular, this dissertation applies this concept to investigate its role in aerosol-convection cloud interactions. Coupling essentially determines whether aerosol surface-based observations are a good or poor proxy for

aerosol below the cloud, which ultimately determines the interaction. Assuming the boundary layer is well mixed, a surface-based aerosol observation would be a better proxy for coupled clouds that interact closely with the boundary layer than for decoupled ones. During a decoupled situation, the best aerosol proxy would be measurements taken below the cloud base in the free atmosphere. Nevertheless, we often lack those observations.

Given that aerosols and cumulus clouds originate from within the PBL, the state of coupling affects the ACI, attested by the finding of a correlation between aerosol concentration and cloud properties in coupled situations, but not in decoupled ones. However, it is important to emphasize that decoupled clouds are still susceptible to the influence of aerosols, and the lack of correlation is the reflection of using a bad proxy for aerosols actually interacting with these clouds.

Aerosol-cloud interaction in deep convective clouds has been debated in the scientific community for several years, with arguments for and against the invigoration effect. Central to this debate are observational-based studies, which haven't been able to fully prove or deny this hypothesis. Some studies found positive signs of the invigoration effect, while others found no relationships or even enervation effects. Confronting this paradox in the frontier of ACI studies, a corner study by Li et al. (2011), also a subject of contest regarding the co-variability between aerosol and meteorology (Varble, 2018), was revisited by accounting for cloud-surface coupling, which matters especially during the early stages of convection when clouds are developing. During later stages of deep convection, the concept of cloud-surface coupling might be more ambiguous given the influence of strong updrafts and the consequent downdrafts.

By including the concept of cloud-surface in our estimations, we observed both positive signs of an invigoration effect and none at all. The coupled regime revealed a strong invigoration signal, reflected in an increase in cloud thickness with increasing aerosol loading, even when

constrained by meteorological factors such as CAPE or the LNB. In the decoupled regime, on the other hand, no invigoration signal is observed, only the relationship between meteorology and cloud thickness. This investigation concludes that the invigoration effect may be plausible.

The processes occurring within the boundary layer are a key component of the Earth's system, as they regulate the exchange of heat, moisture, carbon, and other constituents between the surface and the atmosphere. A better understanding, quantification, and characterization of the boundary layer is therefore important for advancing multiple disciplines, both within and beyond atmospheric sciences, including air pollution, weather prediction, agriculture, and energy production. By providing improved estimates and a more consistent characterization of the boundary layer from both ground-based and spaceborne sensors across diverse regions, this dissertation contributes tools and insights that may support these fields. For example, the results may serve as input for air quality forecasts and data assimilation efforts. In addition, the analysis of errors and limitations in radiosonde- and lidar-derived PBLH may provide a useful reference for future researchers working with automated retrievals from different sensors. Finally, the identification of consistent coupling thresholds and their variability across regimes suggests patterns that could help inform future parameterizations and model development, contributing to ongoing efforts to better represent land-atmosphere interactions in Earth system models and improve precipitation forecasts.

7.2 Recommendations for future work

Although this dissertation presents several advances in the study of PBLH estimation, land-surface-cloud interactions, and aerosol-cloud interactions, some questions remain open or are newly raised. Regarding PBLH, more validations across diverse regions and seasons are still warranted. Among the five ARM observatories used in this research, only SGP provides sufficient

data to robustly assess retrieval performance across multiple years and seasons. The remaining sites offer more limited samples: the Amazon region has nearly two years of data, while TMP, FKB, and COR are confined to approximately six months of observations, restricted to their respective warm seasons. For those sites (TMP, FKB, and COR), validation efforts during the colder seasons could strengthen our validation efforts of DTDS but also deepen our broader understanding of PBLH dynamics under such conditions.

For spaceborne PBLH retrievals, it is a priority to continue validating our product against additional independent data, such as ground-based and airborne estimates across diverse environments, including mountainous, arid, oceanic, urban, and other surface types. Validation efforts would also benefit from cross-comparison with retrievals from other satellite missions, such as CALIPSO, as well as with PBLH estimates derived from alternative spaceborne techniques such as the Global Navigation Satellite System Radio Occultation (GNSS-RO). In addition, the sensitivity of the CATS-DTDS estimates to the MERRA-2 meteorology should be tested. This evaluation could be done by replacing the MERRA-2 by other meteorological reanalysis datasets, such as ERA5 or ground-based data. These efforts would go towards improving global PBL observing system, as necessitated by the NASA PBL incubation study report.

At this moment, cloud-surface coupling classification has been demonstrated using ground-based observations. Our preliminary attempts to extend this classification to a regional scale using spaceborne PBLH retrievals have shown promise, but important limitations remain. One of the most important ones is the dependence on CBH estimated from CATS data, which may introduce large errors and uncertainties. Validation has also proven challenging due to the lack of independent datasets that classify clouds as coupled or decoupled at a regional scale. A large-scale representation of cloud-PBLH coupling is needed.

This dissertation reveals distinct atmospheric and land surface forcings associated with different cloud-surface coupling regimes. However, these conclusions are largely based on observations at SGP, given the lack of continuous measurements at the other sites, which limits our ability to robustly investigate these patterns in other regions. Therefore, an important avenue for future work is to assess whether the relationships identified here between coupling regimes and atmospheric conditions hold across other climatological settings. This investigation of cloud-surface coupling at a larger scale could facilitate our understanding of Land-Atmosphere-Cloud-Interactions and help spaceborne retrievals via improved knowledge of cloud regimes, atmospheric thermodynamic properties, and surface energy fluxes.

Finally, this dissertation explores the role of cloud-PBLH coupling in ACI within deep convective clouds at SGP that might be subject to changes to other meteorological and environmental conditions. Therefore, further investigation is recommended in other regions to ensure the general validity of our findings across different regimes. In addition, open questions remain regarding whether the invigoration signal identified in this dissertation arises from condensational- or freezing-induced invigoration, or a combination of both. Current observational frameworks alone are insufficient to fully answer that question. Future investigations combining model simulations and observational datasets could help disentangle these mechanisms.

Appendices

Appendix A: Miscellaneous supplementary information for Chapter 2

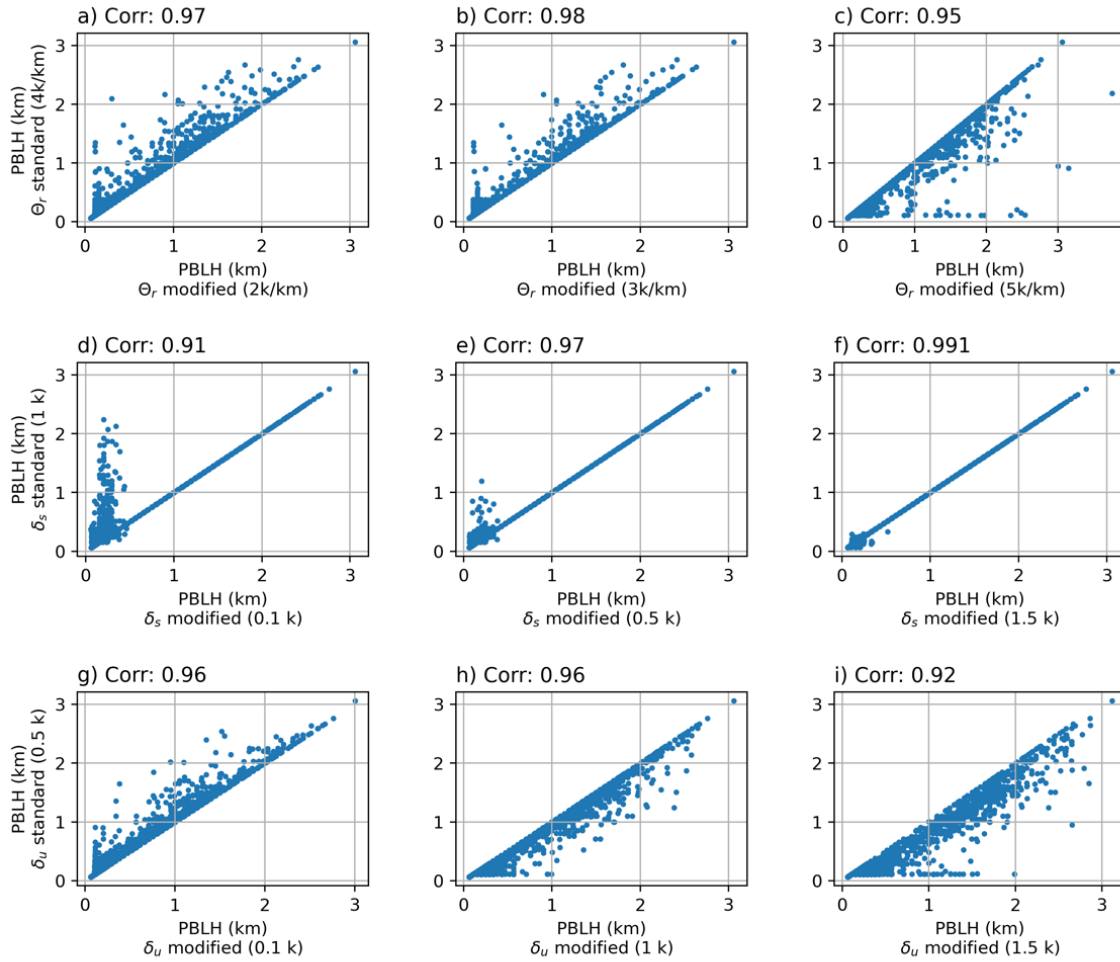


Figure A.1 Scatter plots showing the sensitivity analysis of the effect of the threshold values on PBLH determination of convective and neutral boundary layers based on the MAO dataset. (a-c) Sensitivity analysis of $\dot{\Theta}_r$. (d-f) Sensitivity analysis of δ_s . (g-i) Sensitivity analysis of δ_u .

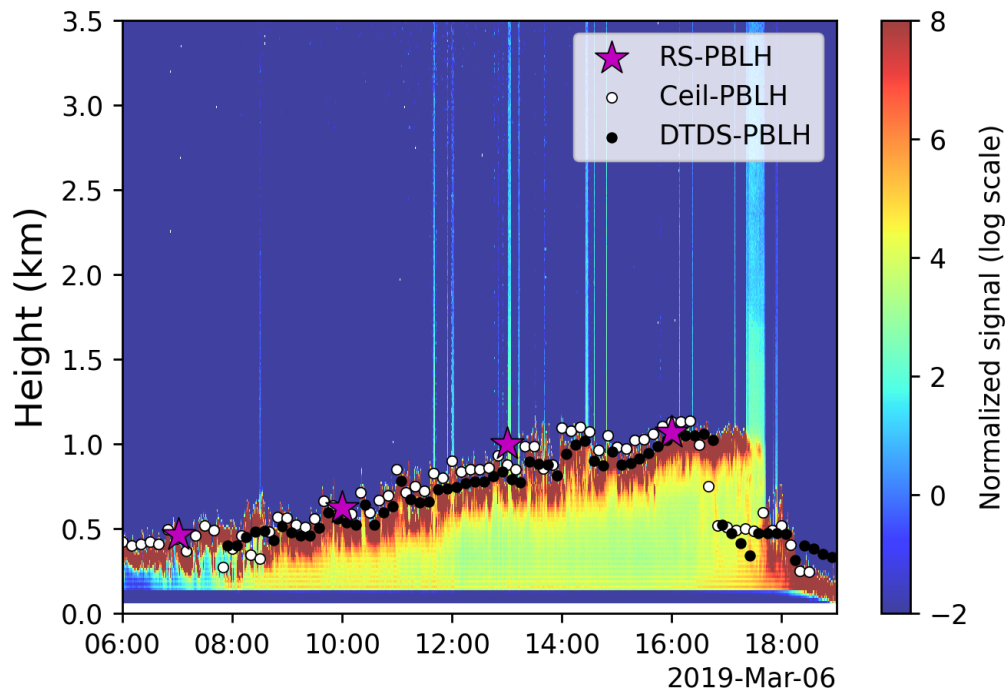


Figure A.2 PBLHs at COR using the DTDS algorithm (black dots), the ARM Ceil-PBLH product (white dots), and radiosonde estimates (magenta stars) after the replacement of the MPL.

Appendix B: Miscellaneous supplementary information for Chapter 4

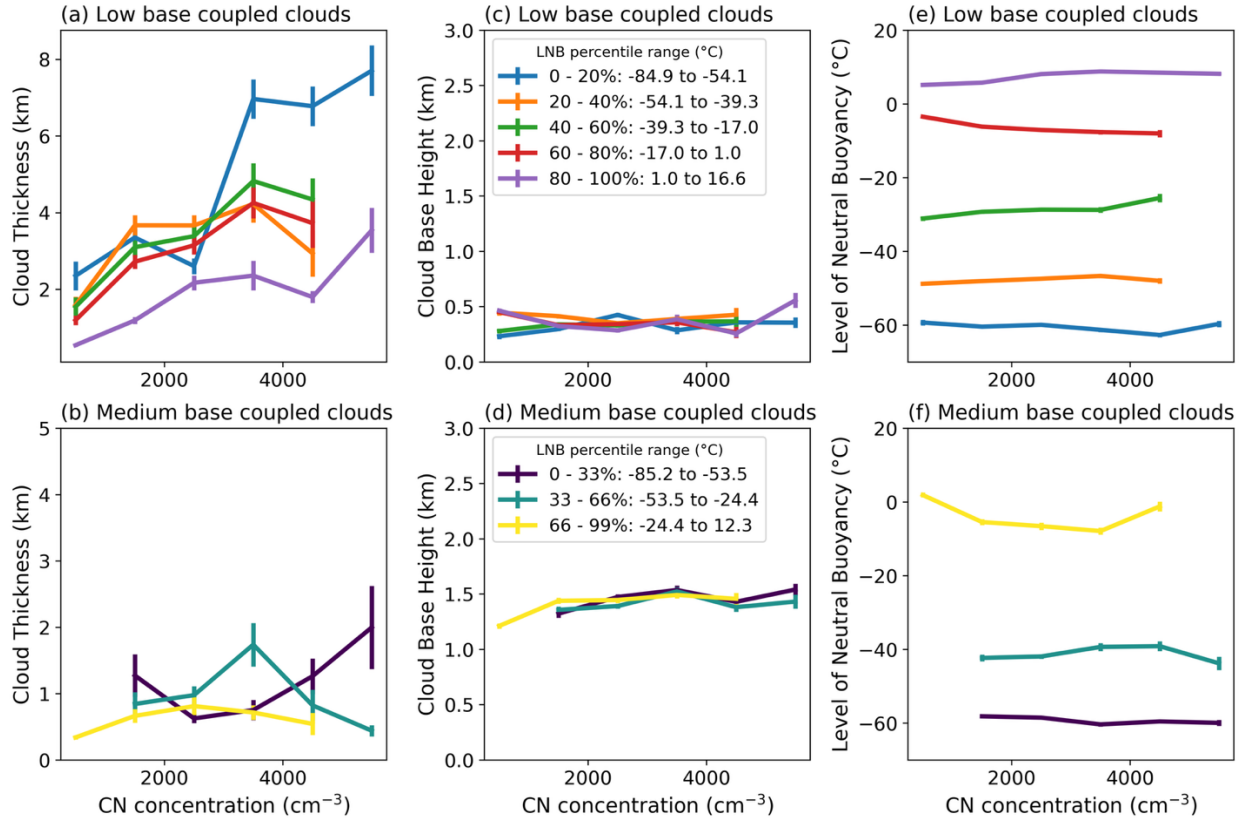


Figure B.1 Cloud thickness variations with aerosol number (CN) concentration for different Level of Neutral Buoyancy (LNB) percentiles for (a) low-base coupled clouds and (b) medium-base coupled clouds. Cloud base height variations with CN concentration for different LNB percentiles for (c) low-base coupled clouds and (d) medium-base coupled clouds. LNB variations with aerosol concentration for the different LNB percentiles for (e) low-base coupled clouds and (f) medium-base coupled clouds. For each aerosol and LNB interval, mean values are shown only when the sample size exceeds 20.

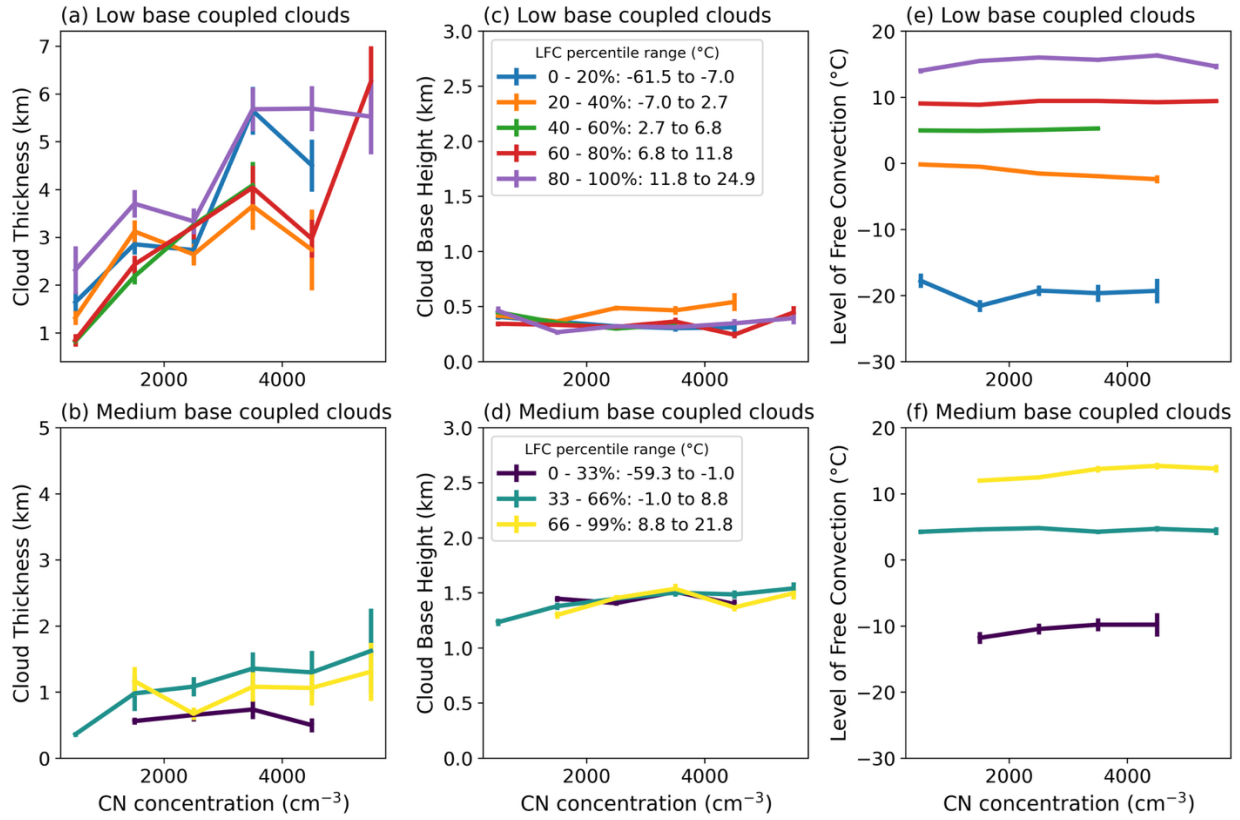


Figure B.2 Cloud thickness variations with aerosol number (CN) concentration for different Level of Free Convection (LFC) percentiles for (a) low-base coupled clouds and (b) medium-base coupled clouds. Cloud base height variations with CN concentration for different LFC percentiles for (c) low-base coupled clouds and (d) medium-base coupled clouds. LFC variations with aerosol concentration for the different LFC percentiles for (e) low-base coupled clouds and (f) medium-base coupled clouds. For each aerosol and LNB interval, mean values are shown only when the sample size exceeds 20.

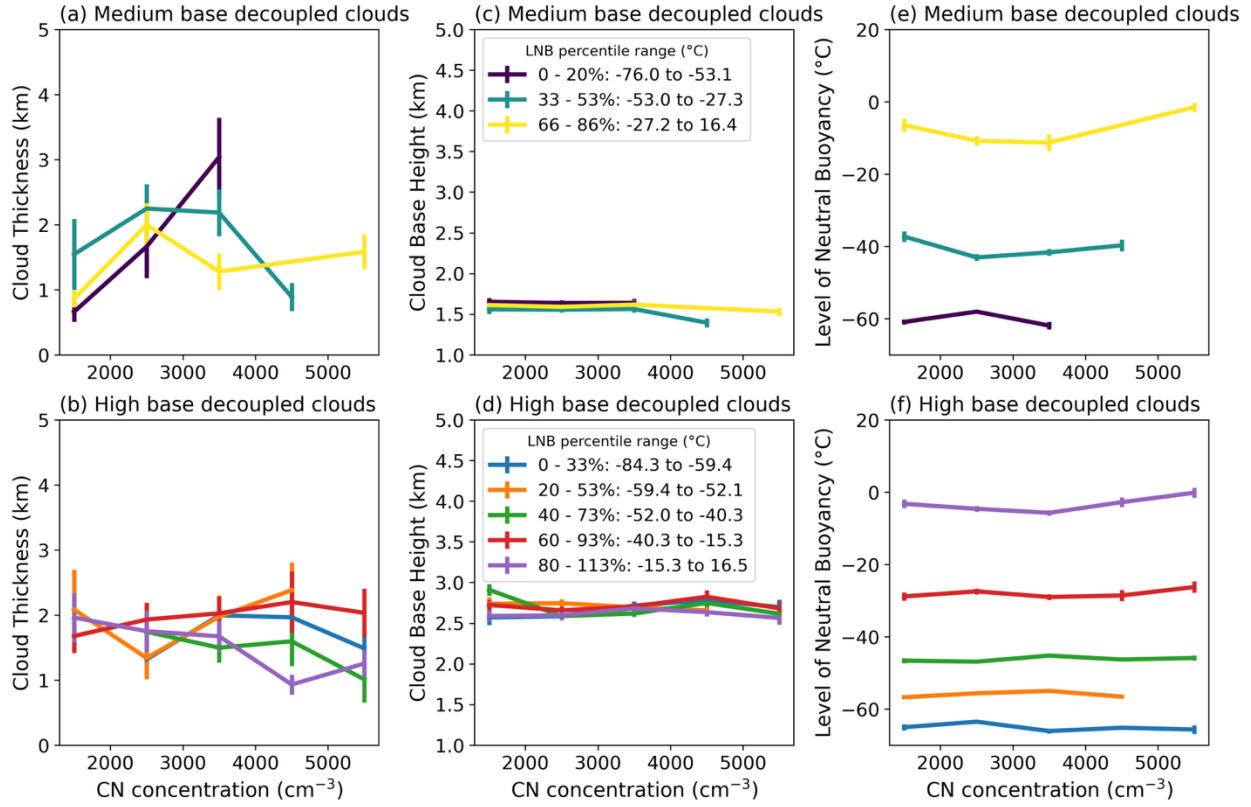


Figure B.3 Cloud thickness variations with aerosol number (CN) concentration for different Level of Neutral Buoyancy (LNB) percentiles for (a) low-base decoupled clouds and (b) medium-base decoupled clouds. Cloud base height variations with CN concentration for different LNB percentiles for (c) low-base decoupled clouds and (d) medium-base decoupled clouds. LNB variations with aerosol concentration for the different LNB percentiles for (e) low-base decoupled clouds and (f) medium-base decoupled clouds. For each aerosol and LNB interval, mean values are shown only when the sample size exceeds 20.

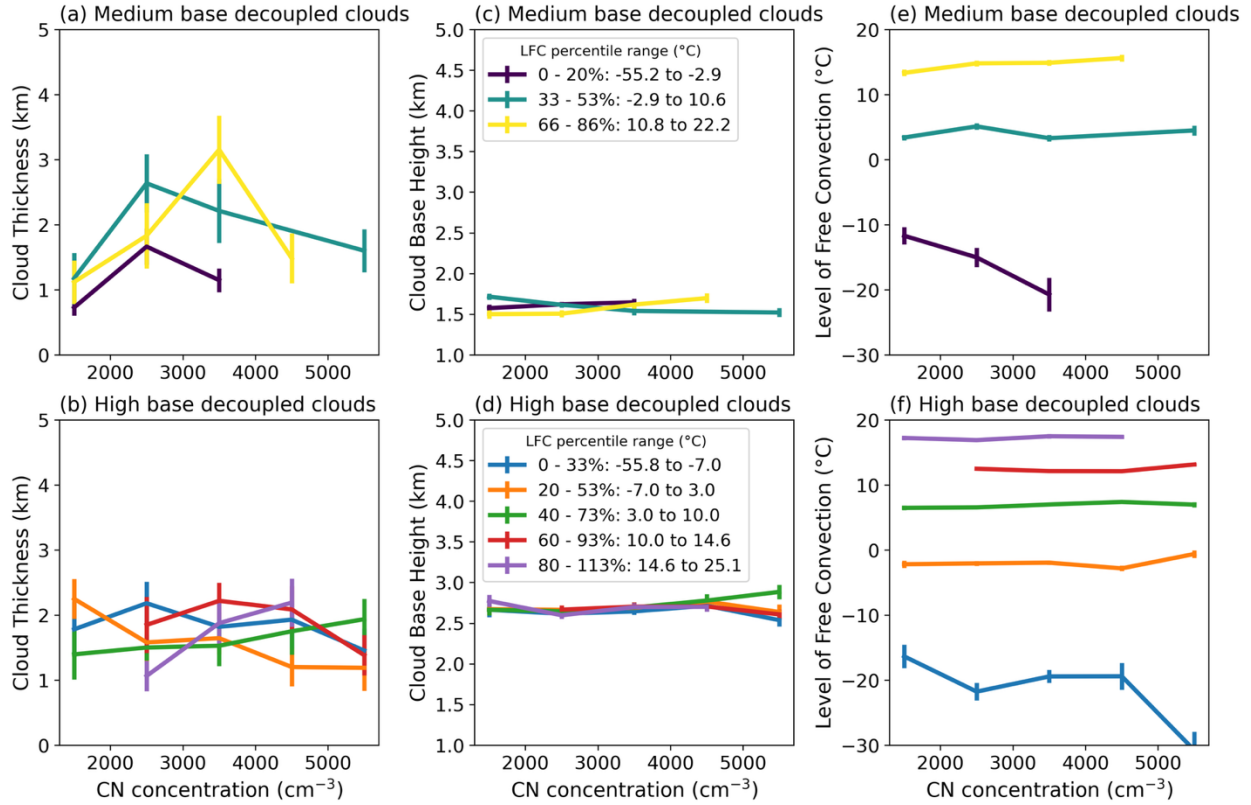


Figure B.4 Cloud thickness variations with aerosol number (CN) concentration for different Level of Free Convection (LFC) percentiles for (a) low-base decoupled clouds and (b) medium-base decoupled clouds. Cloud base height variations with CN concentration for different LFC percentiles for (c) low-base decoupled clouds and (d) medium-base decoupled clouds. LFC variations with aerosol concentration for the different LFC percentiles for (e) low-base decoupled clouds and (f) medium-base decoupled clouds. For each aerosol and LNB interval, mean values are shown only when the sample size exceeds 20.

Appendix C. Statement of Originality

This dissertation is largely based upon the following four papers I lead:

Chapter 3:

Roldán-Henao, N., Su, T., & Li, Z. (2024). Refining planetary boundary layer height retrievals from micropulse-lidar at multiple ARM sites around the world. *Journal of Geophysical Research: Atmospheres*, 129(13), e2023JD040207.

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Chapter 4:

Roldán-Henao, N., Yorks, J. E., Su, T., Selmer, P. A., & Li, Z. (2024). Statistically resolved planetary boundary layer height diurnal variability using spaceborne lidar data. *Remote Sensing*, 16(17), 3252.

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Chapter 5:

Roldán-Henao, N., Su, T., Li, Z., Zheng, Y., & Yorks, J. (2026). Climatology of cloud-land-surface coupling across different ARM sites. *Journal of Geophysical Research: Atmospheres*, 131(1), e2025JD044010.

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Chapter 6:

Roldán-Henao, N., Li, Z., Su, T., Jiwen, F., and Yorks, J. (2026). Constraining the aerosol effects on convective clouds by considering the coupling between clouds and the planetary boundary layer. (Accepted for publication JGR)

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