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Decoding the Dialogue Between Clouds and Land

New research is challenging established assumptions about how clouds form and interact with Earth's surface. One result may be better weather forecasts.

By **Tianning Su** and **Zhanqing Li**
16 February 2024

Clouds hover over radar equipment at the U.S. Department of Energy's Atmospheric Radiation Measurement Southern Great Plains Central Facility near Lamont, Okla. Credit: Nicki Hickmon, Argonne National Laboratory, image courtesy of the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility/Flickr, CC BY-NC-SA 2.0

At the bottom of Earth's atmosphere is a thin sliver of air, typically 0–3 kilometers in thickness, called the planetary boundary layer (PBL). It's in this layer that we humans—at least those of us at ground level—live, breathe, and experience changes in temperature, humidity, wind, cloud cover, and more.

The PBL is directly influenced by its proximity to Earth's surface, which, of course, varies in its topography (think of mountains versus plains) and surface cover (think of the ocean versus arid deserts or lush vegetation). This varying influence means the PBL is a nexus for turbulence and other complex processes governing weather and the interaction between the surface and the overlying atmosphere [***Stull***, 1988].

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Conventional wisdom states that **during daytime**, the main pattern of interaction involves convective heat transfer from the Sun-heated surface into the PBL above. When warm, moist surface air rises and meets cold air from the troposphere above, the moisture condenses and forms low-lying clouds. Conventional wisdom also holds that as Earth's surface cools after sunset, convection currents stop. Surface air remains stationary, and the air above, which was mixed during the day, settles into a stable configuration, forming what's known as a residual layer. Winds in the residual layer, free from the drag of Earth's surface, can more freely accelerate, sometimes forming **nocturnal jets**.

Recent field observations, however, are prompting a reassessment of these assumptions. For instance, some studies have identified scenarios in which the PBL demonstrates stable conditions and decouples from convective systems during the day [***Zhang et al.***, 2018]. Our research, which we outline below, is similarly challenging long-standing perceptions of cloud formation and the PBL. These findings have significant implications for our understanding of atmospheric convection and turbulence, as well as for enhancing our capacity to forecast weather.

Emerging Evidence Requires a Rethink

The idea that low clouds are typically coupled with the convective PBL during daytime is a concept ingrained in atmospheric science. This understanding has been shaped primarily by studies focusing on convective systems that dominate energy and moisture exchanges between Earth's surface and its atmosphere (as opposed to decoupled convective systems that do not drive such exchanges) [***Betts***, 2009].

A layer of cumulus clouds hangs at the top of the planetary boundary layer in the vicinity of Beijing in August 2023. Credit: Zhanqing Li

However, an emerging body of evidence calls into question some of the frameworks that have long guided our understanding of **convective systems and the diurnal (daily) cycles of the PBL**. This new evidence suggests that the evolution of low clouds and their relationship to the PBL requires more rigorous and extensive investigation. Specifically, scientists must scrutinize the intricate interactions between energy, moisture, and turbulence within the PBL [***Santanello et al.***, 2018].

Understanding the nuanced behaviors of the PBL and their implications for cloud formations is at the heart of our research. In particular, we focus on the frequently overlooked coupling processes between clouds and terrestrial surfaces, using state-of-the-art methods supported by field experiment data to enhance existing atmospheric models [*Su et al.*, **2022**, **2023**].

Research Challenges Prompt Innovations

The diurnal cycles of PBL stability and convection are not isolated phenomena but are inherently connected to a web of interactions involving cloud formation and Earth surface processes. Our research has been shaped by the challenges of studying the PBL's labyrinthine, turbulent nature. These challenges have required flexible, but rigorous, technological and methodological innovations.

Historical efforts to study cloud-PBL-surface coupling have been limited by a disproportionate focus on **marine stratocumulus clouds** [***Bretherton and Wyant***, 1997]. This focus has resulted in a conspicuous gap in knowledge about coupling dynamics over continental land surfaces. The gap is compounded by the inadequacy of terrestrial-specific remote sensing methodologies for assessing the coupling states of the cloud-PBL-surface system, especially for low clouds.

To address this lacuna, in our work we characterize cloud-PBL-surface coupling for low continental clouds (Figure 1). This characterization details how the temperature profiles and thicknesses of different regions of the PBL differ in clear-sky conditions versus in scenarios with coupled or decoupled cloud layers.

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We pioneered a lidar-based technique to help determine the coupling state of these clouds and enhance available investigative tools [*Su et al.*, **2020**, **2022**]. The technique uses ground-based lidar data to distinguish between coupled and decoupled cloud states by assessing the vertical alignment of cloud bases with PBL evolution, offering a more direct measure of cloud-PBL-surface coupling compared to previous surface-based diagnoses.

Our research draws upon an array of atmospheric data, including lidar, radiosonde, and surface meteorology records, gathered over 2 decades (1998–2019) at the U.S. Department of Energy’s **Atmospheric Radiation Measurement** (ARM) **Southern Great Plains site**. With this data set, our lidar-based methodology enables simultaneous retrieval of PBL height (PBLH) and cloud coupling states during cloudy periods. This approach integrates multiple atmospheric variables, such as PBLH, **lifting condensation level** (the level at which an air parcel becomes saturated with water), and cloud base, to construct a diagnostic tool for examining cloud-land surface coupling.

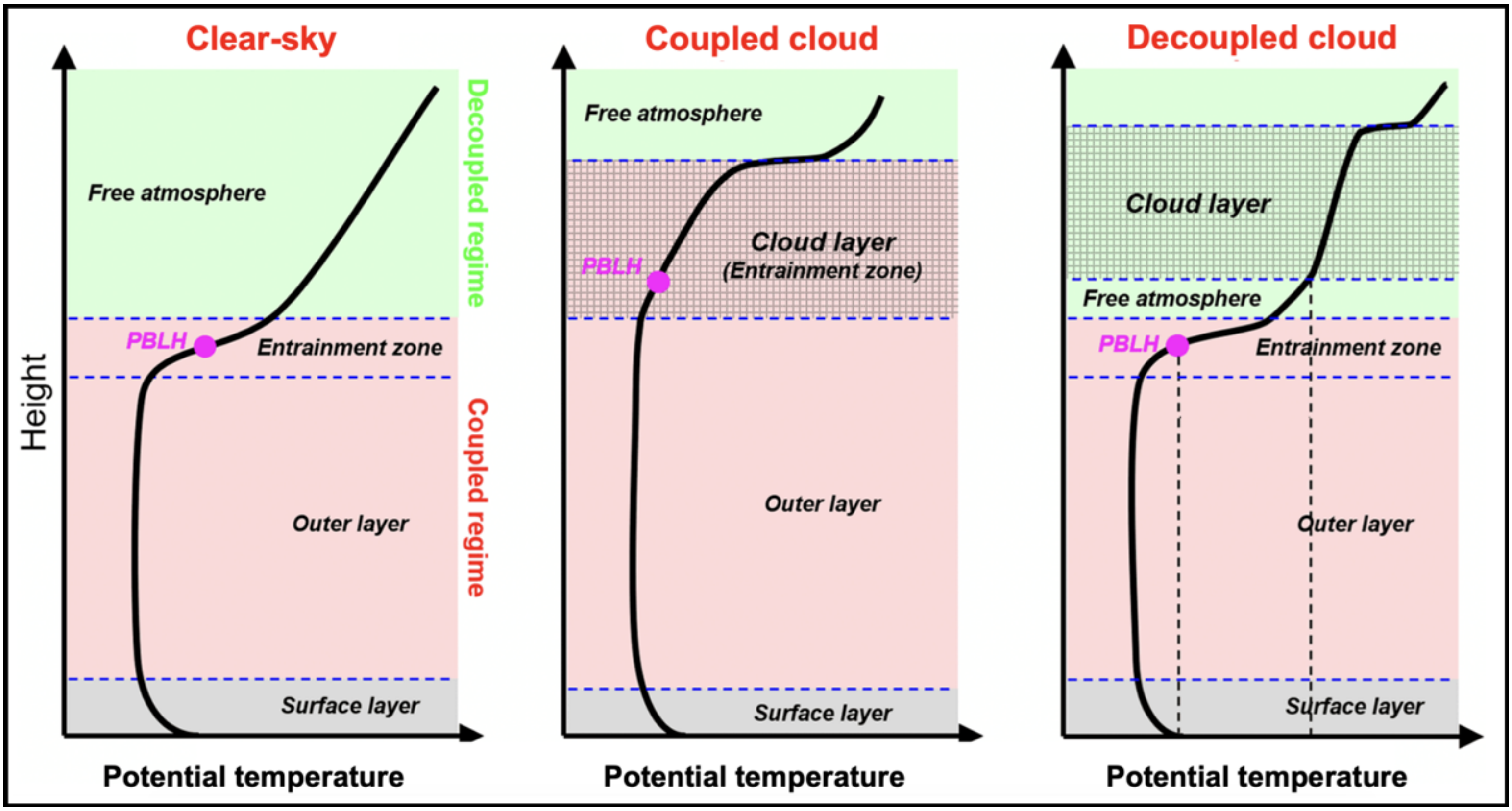

Fig. 1. Idealized vertical profiles (black lines) of potential temperatures (the temperature that the air would be under a standard reference pressure) are plotted here under clear-sky, coupled cloud, and decoupled cloud conditions over land. In each scenario, a near-surface layer (gray) is overlain by an outer layer (pink) that's convectively mixed during daytime but typically stable at night. At the top of the outer layer is the entrainment zone, beyond which is the free atmosphere (green). Cross-hatching represents the position of the cloudy layer within the planetary boundary layer (PBL) entrainment zone in the coupled cloud regime (center) and above the PBL in the decoupled regime (right). Pink dots mark the PBL height (PBLH) as determined from lidar data using the method developed by *Su et al.* [2020, 2022]. Credit: Adapted from *Su et al.* [2022], CC BY 4.0

During our research, we also grappled with significant difficulties in estimating exchanges, or fluxes, of sensible and latent heat between the surface and atmosphere. These difficulties were partly attributable to the complex dynamics of surface radiation budgets influenced by the radiative effects of clouds. This challenge also catalyzed an innovative solution.

We turned to cutting-edge deep learning, a form of artificial intelligence, which enabled us to navigate complex, nonlinear interactions and processes in the PBL with greater accuracy and efficiency. Specifically, we used a deep neural network model to estimate sensible heat using input data on the surface radiation budget, soil moisture, atmospheric humidity, and seasonality of the Southern Great Plains site [*Su et al.*, 2023]. The deep learning model demonstrated high efficacy, particularly for clarifying the influence of cloud radiative effects on surface heat fluxes.

Coupled Versus Decoupled Clouds

With these innovations in hand, we took aim at a central research question: What is the nature of coupled versus decoupled clouds over terrestrial regions? The answer to this question is closely related to convection in the PBL and surface heating processes, which trigger coupling between clouds and the land surface.

Our analyses indicate that coupled clouds over land commonly exhibit bases below the **temperature inversion** that caps the PBL entrainment zone (the zone between the outer layer and the free atmosphere; Figure 1). At this level, these clouds directly encounter the thermodynamics of the PBL, leading to strong cloud-PBL interactions [***Su et al.***, 2022]. In contrast, decoupled clouds form entirely above the entrainment zone and are thus little influenced by PBL conditions.

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Dissecting these coupling dynamics reveals significant differences in cloud-PBL-surface coupling over land compared with the traditional picture rooted in studies of marine stratocumulus clouds.

Further, the occurrence of coupled clouds demonstrates a strong diurnal sensitivity to both surface forcing, such as that from land heating and cooling, and changes within the PBL, including shifts in stability, humidity, and turbulence. In contrast, decoupled clouds exhibit more tenuous links to these forcings, often either emerging as residuals from land-coupled convective systems or being influenced predominantly by horizontal **advections** [***Su et al.***, 2023].

Yet the story doesn’t end here. Our research also indicates that local convection and large-scale synoptic patterns jointly modulate coupling between clouds and the land surface. For example, shallow coupled cumulus clouds are largely shaped by local convection, whereas the formation of stratiform clouds (such as stratus and stratocumulus), which may be in either coupled or decoupled states, is often initiated by large-scale meteorological patterns. These stratiform clouds frequently develop in the trailing regions of thunderstorm systems, particularly in association with weather fronts or mesoscale convective systems.

Dissecting these coupling dynamics reveals significant differences in cloud-PBL-surface coupling over land compared with the traditional picture rooted in **studies of marine stratocumulus clouds**. These differences, including the pronounced links between coupled clouds and local convection and diurnal cycles, underscore that land surfaces uniquely influence coupling and PBL evolution and raise intriguing questions about boundary layer turbulence.

Drivers of Boundary Layer Turbulence

Building on our research into coupling processes, we have also investigated the mechanisms driving turbulence in the PBL. We initially surmised that **radiative effects of clouds** would suppress PBL growth, but our empirical findings have revealed a picture that is far more nuanced and intrinsically tied to cloud coupling states.

Morning transitions from stable to unstable turbulent conditions within the PBL are usually localized phenomena that can ignite convection. In contrast to our initial hypothesis, we found that coupled clouds serve as a catalyst that accelerates the PBL’s morning transition to instability and that these clouds’ radiative effects facilitated PBL convection and growth. Conversely, decoupled clouds did not accelerate development of the PBL in the morning and even seemed to inhibit it slightly in comparison with clear-sky conditions, substantiating the idea that decoupled clouds play a smaller role in PBL dynamics (Figure 2).

Behind these observations are two primary factors that affect PBL turbulence: cloud radiative cooling and surface heating. In clear-sky and decoupled cloud conditions, direct solar heating of the land surface primarily drives turbulence, although the shading effects of decoupled clouds diminish the effect of this surface heating, further delaying the PBL transition to unstable conditions. In contrast, under coupled cloud conditions, cloud radiative cooling and surface heating jointly fuel turbulence, convection, and development of the PBL.

This contrast arises because coupled clouds are closely integrated with the PBL, enabling cooling at the cloud tops to stimulate convection within the PBL. Essentially, both cooling the cloud tops and heating the surface create a tendency for the air below the clouds to rise, thereby driving convection. The insights into the driving forces of boundary layer turbulence gained in this work represent both conceptual and empirical advances in our understanding of PBL processes.

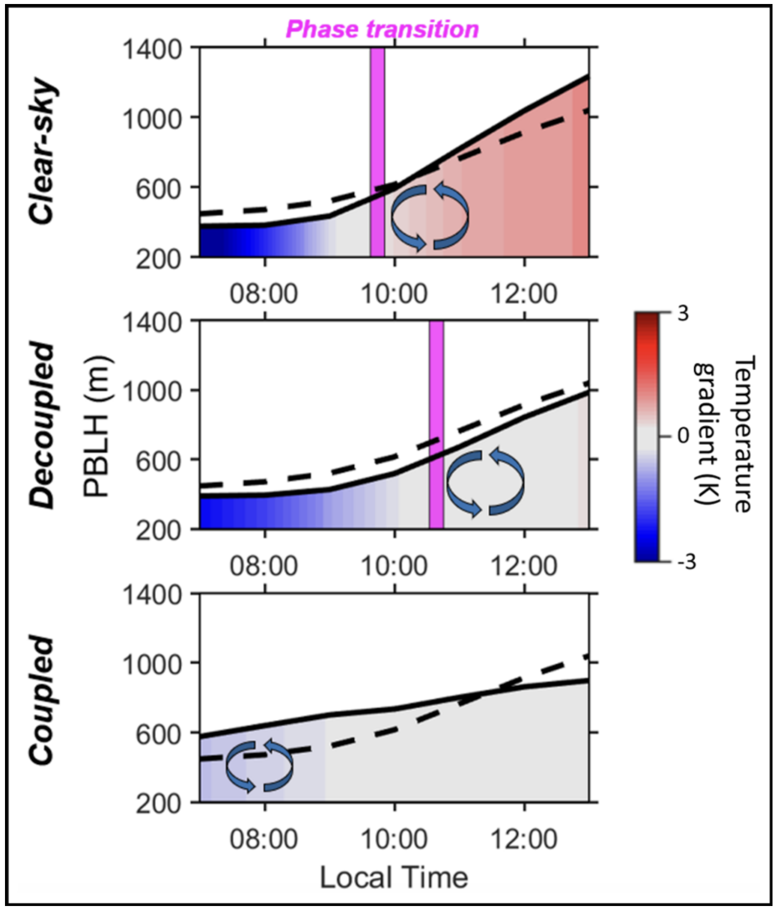

Fig. 2. Typical variations in PBLH (solid black curves) and boundary layer stability during the morning are shown here for clear-sky, decoupled cloud, and coupled cloud scenarios over land. (Dashed black curves indicate the mean PBLH over time averaged from the three scenarios.) The shaded area below the PBLH curves indicates the potential temperature gradient in the surface layer (0–60 meters). Vertical pink bars and swirling arrows indicate the transition from stable to unstable conditions in the PBL. Coupled clouds form within an unstable PBL environment and do not undergo a typical phase transition. Credit: Adapted from *Su et al.* [2023], CC BY 4.0

Enhanced Understanding of Weather and Climate

A key challenge in numerical weather prediction lies in accurately simulating boundary layer processes that govern the vertical distributions of key atmospheric variables, such as humidity, temperature, wind, and pollutants in the lower troposphere. Our recent work has shed light on how the coupling between clouds and land surfaces influences the boundary layer, the formation of convective clouds, and the thermodynamics in the lower atmosphere. Hence, the findings should help enhance predictive capabilities for convective processes and weather forecasting, to the benefit of numerous applications, from agriculture to disaster management.

Convective systems and the PBL are also key elements in the climate system, and examining how these elements evolve over time and with changing conditions is a pressing need, one that we are poised to explore in subsequent studies. For example, we would like to assess the accuracy of climate models depicting the right coupling states between clouds and the land surface.

We recognize there is far more to be learned about cloud coupling processes and the PBL over land. A collective pursuit among researchers is warranted to gain a better process-level understanding of the mechanisms involved. We hope our initial findings serve to germinate more fruit in this pursuit.

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Citation: Su, T., and Z. Li (2024), Decoding the dialogue between clouds and land, *Eos, 105,* https://doi.org/10.1029/2024EO240072. Published on 16 February 2024.