Final Technical Report of the Grant by the Dept of Energy
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Investigation of Surface and Marine-Cloud Coupling and its Impact on Cloud Droplet Number Concentrations and Cloud Cover Over the Southern Ocean

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Research Topics: *High-latitude atmospheric processes*
Project Area: *c) cloud-aerosol interactions; d) surface-atmosphere interactions*

Summary of the Study and Achievements

The proposed work involves characterizing and quantifying both the thermodynamic and dynamical coupling of marine low clouds (MLC) with the sea surface using Atmospheric Radiation Measurement (ARM) observations during MARCUS field campaign and an LES model. ARM data from multiple sensors will be used (e.g., Doppler cloud radar, ceilometer, and microwave radiometer) to characterize the MLC-surface coupling by virtue of the vertical structure and integrated quantities of boundary-layer clouds, aerosols, as well as atmospheric profiles and surface meteorology. We have used a combination of case studies and statistics-based composite analyses to find any linkages between large-scale dynamics, MLC-surface coupling, and cloud and boundary layer properties, the sequence of which reflects the chain of causality. An LES model with explicit aerosol physics, which includes the cycle of aerosols by being consumed as CCN and be regenerated following cloud droplet evaporation, has been run to determine the sources and sinks of N_d and their dependence on the degree of MLC-surface coupling. We have examined the systematic differences in both N_d and cloud occurrence between the two clusters under different meteorological conditions and further examine their respective roles, as well as causal relationships by means of LES modeling. This study helped improve our understanding of the ACI by differentiating the dynamic role of the coupling and cloud physics denoted by N_d, bridging the linkage in the chain toward understanding mechanisms governing the persistence of MLC over the Southern Ocean, solving the long-lasting problem of the cloud cover underestimation over the SO by GCMs. Ample ARM data and LES model have been employed to achieve the objectives of the study:

- Use a variety of data from the U.S. (SGP) and China (AMF-China IOP data), as well as satellite data, to investigate if, how, and how much aerosols influence clouds, precipitation, and regional climate;
- Incorporate a large volume of observed and inferred aerosol and meteorological quantities into a cloud-resolving model to better understand the mechanisms behind the influence of aerosols on clouds, precipitation, and regional climate.

Major accomplishments, recognitions, and program services:

*(1) **15** papers have been published (Science 1, GRL 6, JAS 3, JGR 2, ACP 2, RSE 1).*
(2) a finding was selected as a highlight in the 2020 ARM annual report (Zheng and Li, 2019).
(3) our PBLH algorithm (Su et al., 2020) will be used to generate an ARM CAPI VAP product.
(4) Z. Li is one of 7 ARM/ASR members on the list of Clarivate highly cited researchers in the world for 3 consecutive years.
(5) Y. Zheng was elected to the ARM User Executive Committee on Cloud Measurements and Cloud Modeling.
(6) Z. Li and Y. Zheng were featured on the ARM/ASR News for their substantial contributions to the ARM/ASR programs.

Summaries of major scientific findings:

(1) Discovered a new mechanism of cloud-surface decoupling due to temperature advection (Zheng and Li, 2019; Zheng et al., 2020a). We found that cloud-surface decoupling is stronger in the colder setting such that cumulus penetration above the main boundary-layer temperature inversion does not occur. Boundary-layer clouds over the Southern Ocean have lifespans of

several tens of hours, longer than previously believed. These finding may correct present underestimates derived from satellite data. The study also suggests that under conditions of strong decoupling, surface-generated aerosols such as sea spray and biogenic particles may not reach cloud bases easily from cold waters. “This opens inroads into nascent investigations of cold-ocean aerosols”, quoted from the ARM report.

(2) An improved understanding of cloud-surface interactions (Zheng et al., 2018b; Zheng, 2019; Zheng et al., 2020b; Zheng et al., 2021a). We have developed a series of theories to elucidate the interactions between marine clouds, radiation, turbulence, and surface fluxes.

(3) Developed new satellite methodologies of inferring the cloud-surface decoupling state (Zheng et al., 2018a) and cloud-top radiative cooling (Zheng et al., 2019, 2021). Both quantities had been unavailable from the satellite perspective, and our study filled these observational gaps.

(4) Advanced our understanding of the influence of cloud-surface decoupling on aerosol-cloud interactions (Rosenfeld et al., 2019).

(5) Developed a new lidar-based method to retrieve the diurnal variations of PBLH (Su et al., 2020a). This method combines aerosol backscattering and a stability-dependent model of PBLH temporal variation. Relying on the physical process of PBL diurnal development, different schemes are developed for growing, maintenance, and decaying periods. The comprehensive evaluation of this new method shows much better tracking of diurnal PBLH variation under different thermodynamic conditions.

(6) Investigated the aerosol-PBL interactions under different aerosol vertical distributions (Su et al., 2020b). By using lidar observations and a radiative transfer model, we found that the vertical distributions of aerosol significantly affect aerosol-PBL interactions through altering the aerosol radiative forcing on the vertical scale.

(7) Proposed a novel method of determining cloud-surface coupling from a lidar and a suite of surface meteorological instruments (Su et al., 2022). The cloud-surface coupling derived from this method is highly consistent with those derived from radiosondes. This method can generate high-quality retrievals of PBLH under cloudy conditions. As the first remote sensing method for determining the cloud-surface over land, this method paves a solid ground for investigating the coupled land-atmosphere system and impact on cloud development and aerosol-cloud-interactions.

(8) Carried out large-eddy model simulations examining the deepening-warming decoupling mechanism for the stratocumulus-to-cumulus transition (Zheng et al., 2021b). We found that an increase in surface latent heat fluxes is not necessary for initiating boundary-layer decoupling during the shallow-cloud transition (Figure 1). Other factors, such as the inversion strength, can be equally important for cloud-surface decoupling.

(9) Performed a series of large-eddy simulations to investigate the decoupling physics of stratocumulus-topped boundary layer (STBL) moving toward cold water as well as the mechanisms of low-cloud response to the decoupling (Zheng et al. 2021c; Zhang et al. 2022). We found that stratocumulus decks in warm-air advection is unambiguously decoupled from sea surface with weakly negative buoyancy flux throughout the sub-cloud layer, which is notably different from the stably stratified STBL in cold-air advection. In warm-air advection. Furthermore, we firstly examined via LESs that stratocumulus decks persist longer in warm-air advection than the cold counterpart due to the weaker mixing of cloud air with the entrained overlying dry air when clouds become more decoupled as illustrated in Figure 2.

Publications (Total: 15)

2018 (2)

Zheng, Y., D. Rosenfeld, and Z. Li (2018a). Estimating the decoupling degree of subtropical marine stratocumulus decks from satellite. *Geophy. Res. Lett*, 45. doi: 10.1029/2018GL078382.

Zheng, Y., D. Rosenfeld, and Z. Li (2018b). The relationships between cloud top radiative cooling rates, surface latent heat fluxes, and cloud-base heights in marine stratocumulus. *J. Geophy. Res. Atmos.*, 123. doi:10.1029/2018JD028579.

2019 (3)

Zheng, Y. and Z. Li (2019). Episodes of warm-air advection causing cloud-surface decoupling during MARCUS. *J. Geophy. Res. Atmos*., 124. doi:10.1029/2019JD030835.

Zheng, Y. (2019). Theoretical understanding of the linear relationship between convective updrafts and cloud-base height for shallow cumulus clouds. Part I: Maritime conditions. *J. Atmos. Sci.*, 76(8), 2539–2558.

Zheng, Y., D. Rosenfeld, Y. Zhu, and Z. Li (2019). Satellite-based estimation of cloud-top radiative cooling rate for marine stratocumulus. *Geophy. Res. Lett*, 46, 4485–4494.

2020 (4)

Su, T., Z. Li, and R. Kahn (2020a). A new method to retrieve the diurnal variability of planetary boundary layer height from lidar under different thermodynamic stability conditions. *Rem. Sens. Environ.*, 237. doi:10.1016/j.rse.2019.111519.

Su, T. Z. Li, et al. (2020b). The significant impact of aerosols vertical structure on lower-atmosphere stability and its critical role in aerosol-PBL interaction. *Atmos. Chem. Phys*., 20(6), 3713–3724.

Zheng, Y., D. Rosenfeld, and Z. Li (2020a). A more general paradigm for understanding the decoupling of stratocumulus-topped boundary layers: the importance of horizontal temperature advection. *Geophy. Res. Lett.*, 47, e2020GL087697.

Zheng, Y., M. Sakradzija, S. Lee, and Z. Li (2020b). Theoretical understanding of the linear relationship between convective updrafts and cloud-base height. Part II: Continental conditions. *J. Atmos. Sci,* 77, 1313–1328.

2021 (4)

Zheng, Y., H. Zhang, D. Rosenfeld, S.S. Lee, T. Su, and Z. Li (2021a). Idealized large-eddy simulations of stratocumulus advecting over cold water. Part 1: Boundary layer decoupling. *J. Atmos. Sci.*, 78(12). doi:10.1175/JAS-D-21-0108.1.

Zheng Y., Y. Zhu, D. Rosenfeld, and Z. Li (2021b). Climatology of cloud-top radiative cooling in marine shallow clouds. *Geophy. Res. Lett.*, 48, e2021GL094676.

Zheng, Y., H. Zhang, and Z. Li (2021c). Role of surface latent heat flux in shallow cloud transitions: a mechanism-denial LES study. *J. Atmos. Sci.*, 78(9), 2709–2723.

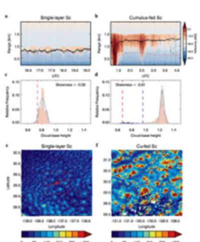
Zheng, Y., D. Rosenfeld, and Z. Li (2021d). Sub-cloud turbulence explains cloud-base updrafts for shallow cumulus ensembles: first observational evidence. *Geophy. Res. Lett*, 48(6), e2020GL091881.

2022 (2)

Su, T., Y. Zheng, and Z. Li (2022a). Methodology to determine the coupling of continental clouds with surface from lidar and meteorological data. *Atmos. Chem. Phys*, 22, 1453–1466. doi:10.5194/acp-22-1453-2022.

Su, T., Z. Li, Y. Zheng, T. Wu, H. Wu, and J. Guo (2022b). Aerosol-boundary layer interactions modulate the entrainment process. *npj Clim. Atmos. Sci.*, 5(64). doi:10.1038/s41612-022-00283-1.

Seven Research Findings as Highlighted in the ASR Homepage:



The role of cloud-top radiative cooling in marine stratocumulus

Li Z • 19 November 2018 • Cloud Processes •

Everything cools radiatively. This study investigates how the cooling of oceanic low clouds drives their physical properties including (1) the bases of clouds, (2) surface energy fluxes, and (3) their coupling with sea surfaces.

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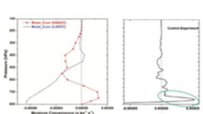

Competing aerosol effects trigger convection over the Indo-Gangetic Plain

Li Z • 17 February 2021 • Cloud-Aerosol-Precipitation Interactions •

Competing aerosol-induced thermodynamic and microphysical effects are examined using observational and modeling frameworks to characterize their relative roles in deep convection over the Indo-Gangetic Plain. This is an important science issue in the study of cloud-aerosol-precipitation interactions, especially in the [...]

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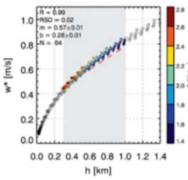

A theory for sub-cloud updrafts and cloud-base height

Zheng Y • 1 November 2019 • Vertical Velocity •

We develop a new theory that explains why air flows are more energetic under higher bases of oceanic shallow clouds

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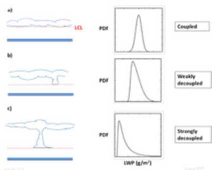

New satellite method to estimate the decoupling degree of marine low clouds

Zheng Y • 23 November 2018 • Cloud Processes •

This study develops a new satellite remote-sensing method to estimate to what degree subtropical marine clouds are coupled with the underlying sea surfaces. The "coupling" could be understood as the exchanges of moisture, energy, and mass.

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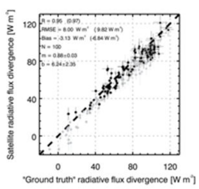

Retrieving cloud-top radiative cooling for stratocumulus from space

Zheng Y • 17 June 2019 • Radiation Processes •

We develop a new algorithm for estimating the cloud-top radiative cooling rate (CTRC), the rate at which marine clouds radiate energy, from space.

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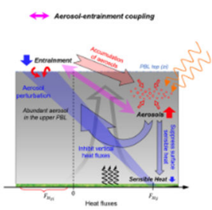

Aerosol-boundary-layer interaction modulated entrainment process

SU T • 28 February 2023 • Atmospheric Thermodynamics and Vertical Structures •

This study proposes a new mechanism of aerosol-entrainment coupling that demonstrates the interactions between aerosols and the entrainment process and highlights the importance of accounting for this effect in numerical model simulations of the boundary layer.

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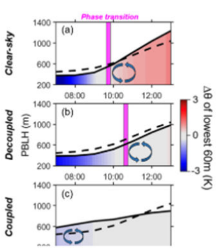

Cloud-surface coupling modulates boundary-layer development

SU T • 19 April 2023 • Cloud Processes •

The contrasting effects of decoupled and coupled clouds on the development of the planetary boundary layer (PBL) are discovered, advancing our knowledge and understanding of boundary-layer processes and cloud dynamics.

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