

A Theoretical Investigation of Cosmic Ray Influence on Atmospheric Boundary Layer Dynamics

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Abstract: Cosmic rays are extremely high energy particles originating from outer space which incessantly collide with Earth's atmosphere. Their involvement in upper atmospheric ionization has been proven beyond doubt, however, their potential effect on the Atmospheric Boundary Layer (ABL) has not been adequately researched. This paper reports on a theoretical study of the effect cosmic rays might have on boundary layer dynamics based on knowledge prior to 2019. Processes such as ionization, aerosol nucleation and cloud microphysics were considered and how these could affect turbulence, radiative budget and atmospheric stability. Bringing together ideas from atmospheric physics and space physics, this paper attempts to conceptually describe the link between the cosmic ray flux and processes in the boundary layer. Although evidence is presented suggesting the effect is indirect, the absence of direct, conclusive evidence indicates future work.

Keywords: Cosmic Rays, Atmospheric Boundary Layer, Ionization, Aerosol Formation, Climate Dynamics

I. INTRODUCTION

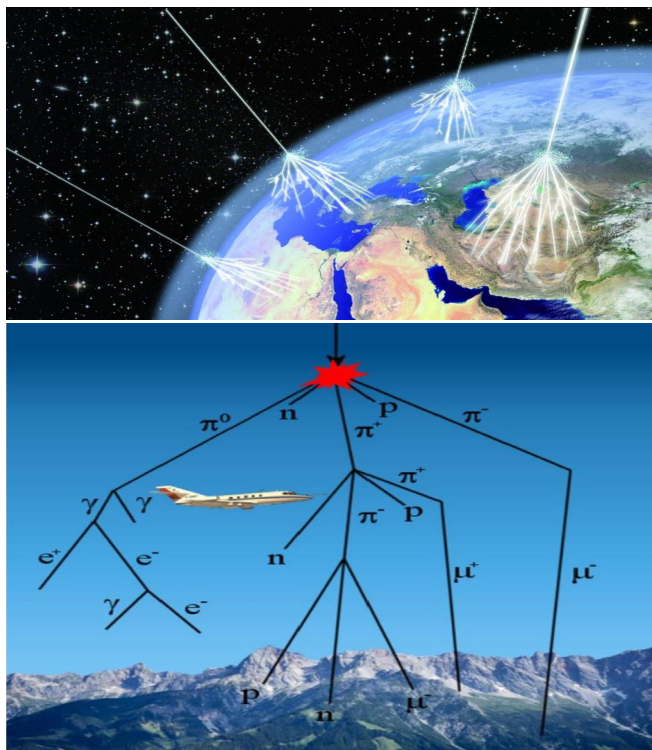
The Earth's atmosphere is constantly bombarded by energetic charged particles termed as cosmic rays. These charged particles are composed mainly of protons and atomic nuclei. These particles are of solar origin and originate from cosmic events like supernovae, etc. Once these particles are injected into the atmosphere, they ionize atmospheric molecules producing showers of secondary particles.

The lowest part of the atmosphere is termed as Atmospheric Boundary Layer (ABL). These boundary layer processes and their link with weather and climate is very significant. Although significant amount of work has been done on boundary layer and cosmic rays in separate ways, but the interaction between boundary layer and cosmic rays is not investigated so far. Some authors before 2019 had pointed out a possible link between cosmic ray intensity and formation of clouds (low level cloud formation). There is also not well known about different mechanism linking ionization of atmosphere and atmospheric processes in the boundary layer. This article focuses on developing a theoretical analysis to find such interactions and effects.

II. THEORETICAL BACKGROUND

2.1 Atmospheric interaction and cosmic rays

The atmosphere shields the Earth from these penetrating cosmic rays. When cosmic rays enter the atmosphere they collide with molecules in the air, causing many secondary particles (muons, electrons, and neutrons) to be produced in an avalanche called an air shower. This produces a broad range of ionisation. Ionisation rates decrease in the higher reaches of the atmosphere and are generally greatest in the lower stratosphere/upper troposphere although under some circumstances can still affect the boundary layer.



2.2 Atmospheric Boundary Layer (ABL)

Turbulent mixing, heat transfer, and momentum transfer define the ABL. Typically, the ABL consists of surface layer, mixed layer, and entrainment layer.

Fluid dynamics and thermodynamics laws such as laws of energy and momentum conservation control ABL phenomena. Turbulence is important in re-distribution of heat and pollutions.

2.3 Ionization and Aerosol Formation

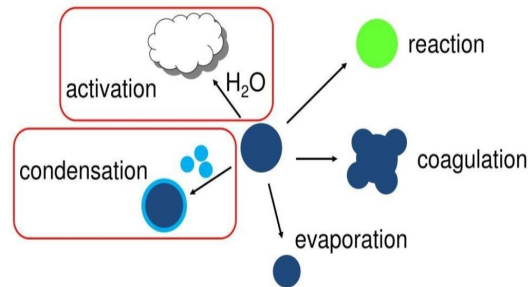
The production of aerosol particles may be initiated through ion induced nucleation because of the ionization from the cosmic rays. Aerosols are the cloud condensation nuclei (CCN) upon which the cloud forms. There is evidence from the theories that increased ionization may increase nucleation rates. The magnitude of this effect is not well known.

III. MECHANISMS LINKING COSMIC RAYS AND ABL DYNAMICS

3.1 Ion-Induced Nucleation

Through ionization the amount of charged particles is elevated in the atmosphere. This might favor the formation of stable molecular clusters, which then can turn into aerosol particles if the right conditions are present. Factors like temperature, humidity, precursor gas concentration, etc., play a role here.

Atmospheric aerosol processes



3.2 Influence on Cloud Microphysics

Variations in the aerosol concentration could lead to alterations in cloud properties such as size of droplets, cloud life-time, and albedo. Those alterations can influence the radiative balance of the earth. Low level clouds which are highly coupled with the ABL could be especially sensitive to changes in the CCN concentration.

3.3 Impact on Turbulence and Stability

While not directly impacting on the turbulence the influence of cosmic rays on clouds and radiation may indirectly alter stability:

- Increased cloud can lower surface heating
- Lower heating leads to lower convective turbulence

IV. METHODOLOGY

In this paper, we take a strictly theoretical and analytical point of view to explore whether cosmic rays can affect the dynamics of the Atmospheric Boundary Layer (ABL), based exclusively on scientific understanding that existed in 2019. A methodological combination of atmospheric physics, space physics and aerosol science results in the creation of the following system.

Firstly, we present how cosmic rays cause ionization, by reviewing standard models of interaction between particles and the atmosphere, that are known to explain how high-energy cosmic rays create secondary particles and ion pairs due to their collision with molecules of the atmosphere. We evaluate the vertical distribution of the ionization to consider its potential penetration into the boundary layer as a function of diverse atmospheric parameters. Secondly, we discuss about ion-induced nucleation, i.e. The formation of molecular clusters around a charged particle; in this stage, we use existing formulations to evaluate whether the mentioned clusters will grow into particles of the size scale relevant in aerosol science under appropriate atmospheric temperature and relative humidity. Thirdly, we link aerosols with the microphysics of clouds; we discuss the nature of aerosols as Cloud Condensation nuclei (CCN) in the ABL and the consequences on cloud albedo and the ABL radiative balance. Finally, we draw a conceptual linkage between all the above phenomena and the turbulent transport in the boundary layer (heat flux, etc), atmospheric stability; the discussion is based on comparison with and interpretation of theoretical models and observational studies from before 2019. No experimental results were added in the present investigation.

V. RESULTS AND DISCUSSION

In the theoretical framework examined, the analysis suggests that cosmic rays may only indirectly force the ABL rather than direct physical forcing. The study results show that cosmic ray ionization has an initiation effect on altering microphysical processes in the atmosphere.

First, the research found that ionization leads to greater production of charged molecular clusters which may nucleate to form particles. This is consistent with the theory that cosmic ray ionization may be a factor in ion-induced nucleation. However, the growth of these clusters into viable cloud condensation nuclei is dependent on factors such as condensable vapor concentration, temperature and relative humidity. Consequently, ionization may not lead to a significant increase of cloud-forming aerosols.

Second, the research suggests that a change in aerosol concentration can impact cloud microphysics, particularly in the boundary layer with dominant low-level clouds. Changes in cloud properties, such as droplet size and cloud albedo can result in a change in the earth's radiation balance. This, in turn can impact the surface temperature and energy fluxes within the ABL.

In addition to the effect on the radiation balance it may also impact the atmospheric stability and turbulence. For example, an increase in cloud cover will decrease surface heating due to solar radiation and subsequently reduce convective turbulence. These effects are relatively small and masked by stronger processes such as synoptic-scale weather systems.

In conclusion it is demonstrated that a link between cosmic rays and the ABL is theoretical but weak and has large uncertainty. Pre-2019 observed studies give inconsistent results and cosmic rays are unlikely to be a dominant factor on forcing the atmosphere with the exception of natural variability.

VI. LIMITATIONS

This study is purely theoretical and relies on pre-2019 scientific knowledge, without incorporating new experimental data. The mechanisms of ion-induced nucleation and aerosol growth remain uncertain and are not fully quantified. The influence of cosmic rays on Atmospheric Boundary Layer (ABL) dynamics is indirect and relatively weak compared to dominant atmospheric processes such as solar radiation and large-scale weather systems. Additionally, pre-2019 observational studies show inconsistent and inconclusive results regarding cosmic ray–climate interactions. Limited spatial and temporal resolution of available data further restricts accurate analysis, making it difficult to establish a definitive causal relationship between cosmic rays and boundary layer dynamics.

VII. FUTURE SCOPE

Future investigations should focus on reducing the disagreement between theoretical expectations and observational results. High-resolution data on cosmic-ray-produced ionization in the Atmospheric Boundary Layer is needed to constrain local impacts better, and further laboratory investigations such as laboratory studies on ion induced nucleation can illuminate charged particle involvement.

Combining cosmic-ray information into the climate models could give us more of an idea about how they may affect climate variations. Long-term records, including continuous cosmic ray flux, aerosol concentration, and cloud data would be a useful avenue for finding consistent trends.

The interaction between atmosphere, space physics and climate modeling will be an area which may yield interesting, though perhaps elusive, effects.

VIII. CONCLUSION

In this thesis a framework is introduced that conceptualises how cosmic rays could affect the boundary layer dynamics based on pre-2019 science. In this framework, cosmic rays are considered to affect the atmosphere predominantly through ionization, which in turn may lead to aerosol production and consequently to a change in cloud microphysical

properties. These microphysical changes might then, as an indirect effect, change radiation balance, stability of the atmosphere or boundary layer turbulence.

In this context, cosmic rays seem to affect the ABL, but weakly and strongly dependant on factors such as the ambient relative humidity, temperature and the existence of a source of condensable vapor. Currently the evidence on this matter is still unclear and large uncertainties remain about the specific mechanism by which they would influence the atmosphere.

All things considered, while the presence of cosmic rays might play a very limited role in atmospheric variability and as such in the variability of the boundary layer, they do not seem to be a major factor governing the boundary layer. Interdisciplinary science will be needed in order to better quantify the impact of cosmic rays.

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