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Mesospheric Irregularities: Insights into Upper Atmospheric Variability

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Abstract

The mesosphere is a highly dynamic region of the Earth's atmosphere characterized by complex thermal, dynamical, chemical and electromagnetic processes. However, mesospheric irregularities remain poorly understood due to their diverse driving mechanisms, wide spatial and temporal scales, and the challenges of direct observation. This article aims to systematically examine the major types of mesospheric irregularities, their underlying physical mechanisms, controlling factors, spatial and temporal characteristics, and approaches used for their observation and modelling. It also evaluates the application of lidar, radar, airglow imaging, satellite observations and rocket-borne measurements for characterizing mesospheric variability, together with numerical models used to simulate mesospheric dynamics and chemistry. Furthermore, the article identifies major limitations in present observational and modelling approaches and highlights emerging opportunities through advanced instrumentation, integrated observation networks and artificial intelligence-based analysis.

Keywords: Mesosphere; atmosphere; thermal; radar; satellite

Introduction

Mesosphere is Earth's third atmospheric layer, stretching roughly 50 to 85 kilometres (31 to 53 miles) above the surface. It is a layer of extremes where temperature falls steadily with altitude to around -90 °C (-130 °F) near the mesopause, while air density and pressure drop to a small fraction of sea level values. Despite its thinness, the mesosphere still contains familiar gases viz., Oxygen (O_2), Carbon dioxide (CO_2) and Nitrogen (N_2). It also plays a central role in redistributing energy through the upper atmosphere, and it is often considered as Earth's meteor shield because it generates intensive friction against Meteoroids which enter the atmosphere at extraordinary speed (Roble, 1995; Mlynczak, 2002). Although the mesosphere is located at a considerable altitude in the atmosphere and is relatively isolated from vertical mixing similar to the tropopause. Whereas, it still experiences various irregularities and disturbances. These phenomena are referred to as Mesospheric Irregularities. Notably, the formation of sporadic E (Es) layer (patchy and dense concentration of ionized plasma in the ionosphere capable of reflecting radio waves) is closely tied to mesospheric irregularities through three mechanisms mainly, enhancing wind shear, generating turbulence via Gravity waves and Kelvin-Helmholtz instabilities, and inducing vertical plasma transport by modifying ion drift velocities (Yu et al., 2023). Owing to its considerable altitude, the mesosphere cannot be adequately investigated using conventional weather balloons. Consequently, a combination of specialized ground based and satellite borne observational techniques are employed to monitor and characterize mesospheric irregularities. However, the study of these irregularities is essential because variations in mesospheric temperature, density, winds, and composition can serve as indicators of changes in atmospheric circulation and climate variability (Meriwether and Gerrard, 2004). Investigating these irregularities also contribute to improved understanding of the middle-atmosphere response to climate change. Furthermore, accurate characterization of mesospheric variability is relevant to the prediction of atmospheric drag and the propagation of waves that influence the near space environment (Liu, 2016; Subba Rao *et al.*, 2025. Despite

considerable advances in observational capabilities, mesospheric irregularities remain challenging to detect and characterize because of their small spatial and temporal scales, intermittent nature, complex interactions, and limited availability of continuous observations. Therefore, future research requires coordinated observations from satellites, ground-based instruments, sounding rockets, and advanced remote sensing systems, together with high-resolution numerical modelling and data assimilation techniques.

Types of Mesospheric Irregularities

1. Thermal Irregularities

Thermal irregularities arise from localized heating mainly convection in the troposphere or radiative heating and cooling within the stratosphere and mesosphere. These temperature variations generate gravity waves and oscillations in air density driven by buoyancy. When gravity waves break, they can trigger further instabilities, including Kelvin-Helmholtz instabilities (KHI), caused by velocity shear, and convective instabilities. These processes also affect radio wave propagation, and satellite communication.

1.1 Gravity Waves

Gravity waves are atmospheric waves produced when air parcels are displaced vertically from their equilibrium position by forces such as mountains, convection, thunderstorms, or wind disturbances. In the mesosphere, gravity waves are particularly important because they transport energy and momentum from the lower atmosphere (Francis, 1975). As they propagate into higher altitudes, their amplitude can increase because of decreasing atmospheric density, and they may eventually break or dissipate.

1.2 Kelvin-Helmholtz Instabilities (KHI)

KHI occurs at the interface between two fluid layers of different density when velocity shear between them overcomes the stabilizing effects of gravity and surface tension.

2. Density Irregularities

Density irregularities refer to variations in molecular and atomic concentrations within the mesosphere. Regions of lower density let waves propagate more freely, while denser regions cause waves to refract, reflect, or dissipate altogether (Kozlovsky et al., 2017).

3. Electromagnetic Irregularities

Electromagnetic irregularities involve perturbations within the mesosphere's ionized regions, arising from electromagnetic pulses interacting with mesospheric plasma, solar flares and coronal mass ejections injecting high energy particles and altering ionization rates, or electromagnetic disturbances introducing small scale turbulent eddies that affect large scale circulation. A well-known research effort in this space is the High-Frequency Active Auroral Research Program (HAARP), based in Gakona, Alaska (managed by the University of Alaska Fairbanks Geophysical Institute), which is considered as one of the world's most advanced ionospheric research facilities. HAARP is involved in generating artificial auroras, testing ultra-low frequency waves for submarine communication, detecting meteors and asteroids and studying mesospheric irregularities.

Drivers of Mesospheric Irregularities

Mesospheric irregularities are strongly season-dependent. Gravity waves activity shift with the seasons. Winter tends to bring intense irregularity, driven by strong temperature contrasts and heightened jet-stream activity in the troposphere. Whereas in summer, gravity waves persist with less intensity. Tides and planetary waves, which modulate mesospheric dynamics are likewise affected by seasonal change. A further modulating influence is the Quasi-Biennial Oscillation (QBO). QBO is the periodic reversal of equatorial stratospheric winds between easterly and westerly phases, recurring every 2 to 2.5 years and thought to be driven by gravity waves originating in the tropical troposphere. The QBO affects how waves propagate into the mesosphere and, in turn influences the irregularities that form there (Baldwin et al., 2001; Meena *et al.*, 2026).

Spatial and Temporal Scales of Mesospheric Irregularities

The irregularities discussed above operate across vastly different scales of space and time from meteor trails lasting seconds to cloud structures persisting for days (Table 1 and 2). Broadly, gravity waves and turbulence dominate large-scale mesospheric irregularities, while noctilucent clouds represent long lasting structures shaped by mesospheric temperature and water vapor content.

Table 1. Spatial Scales of Mesospheric Irregularities

Type	Horizontal Scale	Vertical Scale	Examples
Gravity waves (50–65 km)	10 – 1,000 km	5 – 30 km	Atmospheric tides, wave breaking
Kelvin-Helmholtz instabilities (75–85 km)	1 – 10 km	100 m – 5 km	Shear-driven turbulence
Noctilucent	1 – 100 km	500 m –	Ice particle

/ Polar mesospheric clouds (65–75 km)		5 km	formation
Sporadic E irregularities (>80 km)	10 – 200 km	≈ 1 km	Plasma layer disturbances
Meteoric plasma trails (75–85 km)	1 – 10 km	< 1 km	Meteor ablation effects

Table 2. Temporal Scales of Mesospheric Irregularities

Type	Duration	Description
Gravity waves (equatorial)	Minutes to days	Dissipate into turbulence
Kelvin-Helmholtz instabilities	Seconds to minutes	Driven by wind shear
Noctilucent / Polar mesospheric clouds	Hours to days	Seasonal occurrence in summer polar regions
Sporadic E (Es) layers	Minutes to hours	Affected by ionospheric conditions
Meteoric plasma trails	Seconds to minutes	Created by meteor ablation

Ground-based Observations

1. Lidar

Lidar systems transmit laser pulses into the atmosphere and analyze backscattered light through three mechanisms viz., Rayleigh scattering from molecules, Mie scattering from aerosols comparable in size to the light's wavelength, and resonance fluorescence from mesospheric sodium or potassium layers.

2. Radar

Radar systems operate across a wide range of frequency bands, with each band offering distinct capabilities for observing different characteristics and processes in the mesosphere and lower thermosphere. The selection of radar frequency depends on the specific atmospheric phenomenon under investigation, measurement range, and required spatial and temporal resolution (Table 3).

Table 3. Radar Systems Used for Mesospheric Observation

Radar Type	Frequency Range	Primary Use
Medium Frequency (MF)	1 – 3 MHz	Detects irregularities tied to tides and gravity waves; tracks long-term dynamical trends
Very High Frequency (VHF)	30 – 300 MHz	Studies polar mesospheric summer echoes and turbulence; sensitive to small-scale electron density fluctuations
Ultra-high Frequency (UHF)	> 300 MHz	Mesosphere-stratosphere-troposphere (MST) studies; detects fine-scale turbulence
Incoherent Scatter Radar (ISR)	Varies by facility	Measures plasma density and ion-neutral interactions; probes mesosphere-ionosphere coupling

3. Airglow Imaging

Airglow imaging captures faint optical emissions from excited atmospheric molecules using ground-based cameras equipped with CCD or EMCCD detectors and narrow-band filters, revealing both diurnal and seasonal variation in mesospheric irregularities.

Constraints of Ground-Based Techniques

Despite their usefulness in monitoring mesospheric and lower thermospheric phenomena, ground-based techniques have several limitations that can affect the accuracy, spatial coverage, temporal continuity and interpretation of observations. These constraints arise from instrumental limitations, atmospheric conditions, restricted observational geometry and the dependence of measurements on local environmental factors.

Satellite Observations

While ground-based observations provide valuable information on mesospheric processes from specific locations, satellite-based measurements offer a broader perspective by enabling observations over large spatial and temporal scales. Satellites complement ground-based techniques by providing extensive coverage of mesospheric behaviour and allowing the investigation of regional and global atmospheric variability. The major satellite-based observation techniques and their applications are summarized in Fig 1.

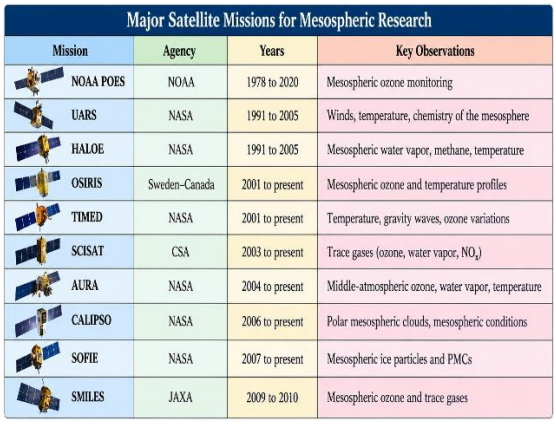


Fig. 1. Satellite Missions for Mesospheric Research

Rocket-borne Probes

Although ground-based and satellite observations provide valuable information on mesospheric dynamics and variability, they are often limited in their ability to obtain direct measurements of atmospheric properties at specific altitudes. Rocket-borne probes overcome this limitation by carrying instruments directly through the mesosphere and lower thermosphere, enabling in-situ

measurements of atmospheric temperature, density, composition, winds, and other physical parameters. The major types of rocket-borne measurements and their applications are summarized in Fig. 2.

Major Sounding Rocket Campaigns for Mesospheric Research

Mission	Agency	Years	Region Studied	Key Observations
Super Loki Sounding Rockets	NASA	1960s to 1980s	Midlatitude mesosphere	Neutral wind turbulence
MIDAS	NASA	1980s to 1990s	High-latitude mesosphere	Electron density irregularities
WAVES Campaign	NASA	2000s	Equatorial mesosphere	Gravity wave breaking
ROCETS	JAXA	2015	Japanese midlatitude mesosphere	Plasma density fluctuations
MAXIDUSTY	DLR	2016	Arctic mesosphere	Plasma interactions
ECHO	NASA	2018	High-latitude mesosphere	Ion-neutral interactions
VORTEX	NASA	2020	Midlatitude mesosphere	Shear instabilities
REXUS	ESA	Ongoing	European Arctic	Plasma instabilities

Fig. 2. Rocket-borne Missions for mesospheric Research

Numerical Models and Simulations

Alongside direct observation, numerical modelling plays a central role in interpreting mesospheric behaviour. General circulation models such as TIME-GCM (developed by NCAR) and WACCM provide broad, long-term pictures of upper-atmosphere dynamics, while high-resolution wave models and chemistry-transport models such as WRF-Chem capture finer-scale structure and composition.

Challenges and Future Directions

Current research on the mesosphere faces several challenges, including limitations in observational resolution and spatial coverage, which restrict the detailed understanding of mesospheric processes. Another major challenge is the difficulty in isolating overlapping atmospheric phenomena, particularly distinguishing gravity-wave effects from other physical processes occurring simultaneously. In addition, numerical models are sensitive to the quality of input data and the parameterization schemes employed, which can introduce uncertainties into simulations and predictions. Future research should therefore focus on developing advanced observational instruments capable of providing higher spatial and temporal resolution and broader coverage. The integration of artificial intelligence and machine learning techniques can further enhance mesospheric data analysis by enabling efficient processing of large datasets, improved pattern recognition, and better identification of atmospheric phenomena. Increased collaboration and data integration between ground-based and satellite observation networks will also be essential for achieving more comprehensive and continuous monitoring of the mesosphere.

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