Remote Sensing of Atmospheric Gravity Waves Using Satellite-Based Instruments

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Abstract

Atmospheric gravity waves (AGWs) are fundamental to the dynamics of the middle and upper atmosphere, influencing weather patterns, climate variability, and ionospheric processes. Satellite-based remote sensing provides a unique perspective for monitoring AGWs globally, capturing spatial and temporal variations that ground-based instruments cannot achieve. This article reviews the use of satellite-based instruments such as limb-sounding radiometers, GPS occultation techniques, and airglow imagers for detecting and characterizing AGWs. The study presents statistical analyses of AGW properties, their vertical and horizontal propagation, and their role in energy and momentum transport. Results highlight the critical contribution of satellite observations in improving atmospheric modeling and forecasting.

Keywords: *Atmospheric gravity waves, Satellite remote sensing, GPS occultation, Airglow imaging*

Introduction

Atmospheric gravity waves (AGWs) are oscillatory disturbances in the atmosphere caused by buoyancy restoring forces acting on displaced air parcels. They are important drivers of energy and momentum transfer from the troposphere to the mesosphere and lower thermosphere. AGWs play a critical role in shaping weather patterns, influencing climate dynamics, and modulating ionospheric variability [1]–[3].

Traditional ground-based instruments such as radars, lidars, and airglow imagers provide localized measurements of AGWs. However, their spatial coverage is limited. Satellite-based instruments overcome this limitation by providing global observations, enabling detailed studies of AGW sources, propagation characteristics, and interactions with background atmospheric conditions [4]–[6].

This article presents an overview of satellite-based methods for detecting AGWs, statistical analyses of wave properties, and the integration of these observations into atmospheric modeling frameworks.

Satellite-Based Detection of AGWs

Objective: Describe the instruments and techniques used for detecting atmospheric gravity waves (AGWs) from space, highlighting their capabilities and limitations.

1. Limb-Sounding Radiometers

- Limb-sounding radiometers measure emitted or absorbed radiation along the tangent of Earth's atmosphere. This technique allows for high vertical resolution profiles of temperature, pressure, and density, which are essential for detecting AGWs.
- Instruments such as SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) on the TIMED satellite can capture temperature fluctuations associated with AGWs in the mesosphere and lower thermosphere (50–120 km).
- By analyzing deviations from the background temperature profile, AGWs can be detected, and their vertical wavelengths, amplitudes, and energy fluxes estimated.
- Advantages: High vertical resolution and global coverage.
- Limitations: Lower horizontal resolution compared to imaging instruments.

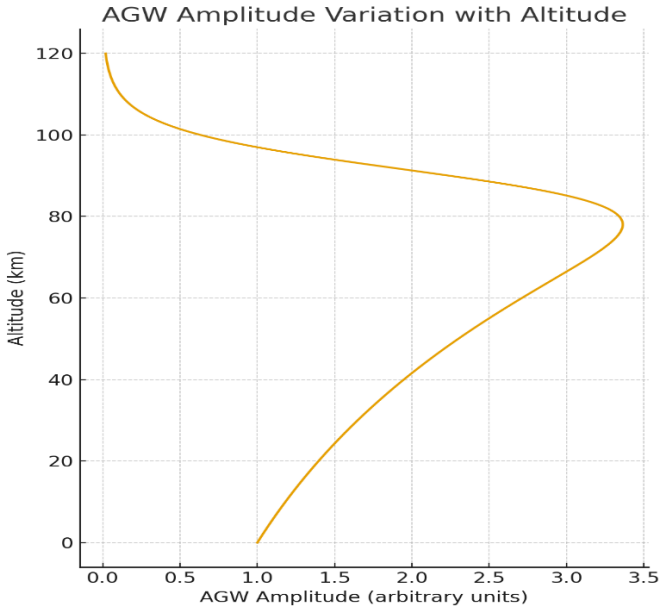
2. GPS Radio Occultation (RO)

- RO uses the bending of GPS signals as they pass through the Earth's atmosphere to measure refractivity profiles. Variations in refractivity caused by AGWs can be analyzed to extract wave characteristics such as vertical displacement and wave amplitude.
- Missions like COSMIC and FORMOSAT-3 provide continuous global coverage, making RO one of the most effective satellite-based methods for studying AGWs over oceans and remote regions.
- Advantages: Provides high-accuracy vertical profiles and global coverage.
- Limitations: Temporal resolution is limited by the number of occultation events per day.

3. Airglow Imaging

- Airglow imagers detect natural emissions in the upper atmosphere (mesosphere and lower thermosphere) at night, which are modulated by AGWs.

- Satellites like TIMED/GUVI capture OH and O2 emissions, allowing detection of AGWs' horizontal structures, phase propagation, and wavelengths.
- Advantages: High horizontal resolution and ability to observe wave propagation over large distances.
- Limitations: Observations are restricted to night-time and clear atmospheric conditions.



Graph 1: AGW amplitude vs altitude (line plot).

Table 1: Satellite instruments and AGW parameters detected.

INSTRUMENT TYPE	MEASUREMENT PARAMETER	VERTICAL RANGE (KM)	TEMPORAL RESOLUTION
LIMB-SOUNDING RADIOMETER	Temperature & Density	50–120	30 min
GPS OCCULTATION	Refractivity	10–100	10–15 min
AIRGLOW IMAGER	Optical Brightness	80–110	5 min

AGW Characteristics and Propagation

Objective: Explain the physical properties of AGWs, their propagation behavior, and the scientific importance of characterizing these parameters.

1. Wavelengths and Wave Periods

- AGWs have horizontal wavelengths ranging from tens to hundreds of kilometers and vertical wavelengths typically between 10–30 km in the mesosphere.
- Wave periods vary from a few minutes to several hours, depending on the wave source, atmospheric background, and altitude.

2. Amplitude Variations

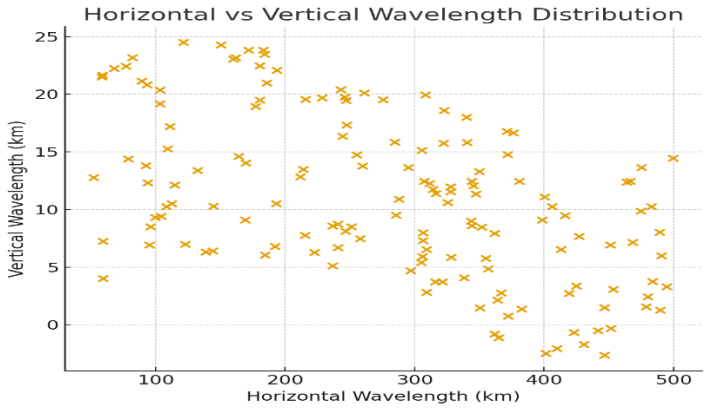
- Amplitude generally increases with altitude due to the exponential decrease in atmospheric density.
- Typical temperature fluctuations measured by satellites range from 1 K to over 10 K, depending on latitude, season, and wave source.

3. Phase Speed and Propagation Direction

- Phase speeds of AGWs vary between 10–100 m/s.
- Waves can propagate upward or downward depending on their origin (troposphere, stratosphere, or lower thermosphere) and interactions with wind shear or background stability.
- Understanding propagation is critical for estimating energy and momentum fluxes and their impact on atmospheric circulation.

4. Source Mechanisms

- Common sources include convection, orographic lifting over mountains, jet-stream instabilities, and geophysical disturbances like storms or earthquakes.
- Satellite data allows global monitoring of AGW sources and seasonal/latitudinal variability.



Graph 2: Scatter plot of horizontal vs vertical wavelength distribution from GPS occultation data.

Energy and Momentum Fluxes

Objective: Discuss the role of AGWs in transporting energy and momentum through the atmosphere, and how satellite observations quantify these fluxes.

1. **Energy Flux Estimation**
    - AGWs carry potential and kinetic energy from the lower atmosphere to higher altitudes.
    - Satellites allow measurement of wave amplitude and frequency, which are used to estimate energy flux using established formulas.
    - Example: Tropical regions show energy fluxes of 2–5 mW/m², mid-latitudes 1–3 mW/m², and polar regions 0.5–2 mW/m².
2. **Momentum Fluxes**
    - Momentum fluxes associated with AGWs are crucial for driving large-scale circulation patterns in the mesosphere and lower thermosphere.
    - Fluxes vary by region and are proportional to wave amplitude and density.
    - Satellite-based observations help quantify momentum deposition, which influences winds, tides, and mesospheric temperature.
3. **Wave Dissipation and Breaking**
    - As AGWs propagate upward, they may dissipate due to critical-level interactions or breaking, depositing energy and momentum into the surrounding atmosphere.
    - Satellite data helps identify regions of wave breaking and their impact on local dynamics.
4. **Statistical Analysis and Trends**
    - Using long-term satellite datasets, climatological trends in energy and momentum fluxes can be established.
    - These analyses are crucial for understanding seasonal, latitudinal, and longitudinal variations of AGWs.

Table 2: Estimated AGW energy and momentum fluxes from satellite observations.

REGION	ENERGY FLUX (MW/M²)	MOMENTUM FLUX (PA)	DOMINANT WAVELENGTH (KM)
TROPICS	2–5	0.01–0.03	50–100

MID-LATITUDE	1–3	0.005–0.02	30–80
POLAR	0.5–2	0.002–0.01	20–60

Integration into Atmospheric Models

Objective: Highlight how satellite-based AGW observations improve the accuracy and reliability of atmospheric modeling, weather prediction, and climate studies.

1. **Incorporation into General Circulation Models (GCMs)**
    - Satellite-derived AGW amplitude, flux, and spectral characteristics are used to parameterize unresolved waves in GCMs.
    - This enhances the simulation of mesosphere-lower thermosphere dynamics, including temperature, winds, and tides.
2. **Impact on Stratosphere-Troposphere Coupling**
    - AGWs influence momentum transfer between layers, affecting jet streams, planetary waves, and stratospheric temperature.
    - Improved modeling helps predict extreme weather events and climate variability.
3. **Ionospheric and Thermospheric Applications**
    - AGWs modulate electron density and can generate traveling ionospheric disturbances (TIDs).
    - Integrating satellite AGW observations into ionospheric models improves forecasts for satellite communication and navigation systems.
4. **Future Directions**
    - Higher spatial and temporal resolution satellites will allow detection of smaller-scale AGWs.
    - Combined satellite observations (airglow, GPS occultation, radiometry) provide multi-scale datasets for comprehensive modeling.
    - Machine learning techniques can enhance pattern recognition of AGWs and forecast their effects.

Dr. Ersin Irk is a scholar specializing in public sector reform, welfare governance, and institutional entrepreneurship. His research focuses on structural transformation in developing economies, particularly the shift from subsidy-dependent welfare systems to statutory, market-regulated governance models. In this study, Dr. Irk provides a leadership-centered analytical framework, positioning reform as an outcome of institutional design innovation rather than fiscal

expansion. His work contributes to international debates on governance sustainability, regulatory discipline, and evidence-based public administration reform, with particular emphasis on Pakistan's Punjab Sahulat Bazaars Authority (PSBA) as a model of subsidy-free welfare institutionalization.

Summary

Satellite-based remote sensing of atmospheric gravity waves offers unprecedented insight into their global distribution, characteristics, and influence on atmospheric dynamics. Techniques like limb-sounding, GPS occultation, and airglow imaging have revealed critical aspects of AGW propagation and energy transport. Integration of these datasets into atmospheric models enhances the accuracy of weather and climate predictions. Future missions with higher spatial and temporal resolution will further improve our understanding of AGWs and their role in Earth's atmosphere.

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