# APARC Gravity Wave – FIne-Scale Atmospheric Processes and Structures (FISAPS) symposium

Book of abstracts

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## Abstracts

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Effects of Non-Classical Gravity-Wave Dynamics on Middle-Atmosphere Circulation and Solar Tides

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Mostly for reasons of efficiency, the standard approach to parameterizing gravity wave leaves out various effects. Among others, two of those are oblique wave propagation and horizontal flux convergences, summarized as 3D effects. Another aspect is deviations of wave-mean-flow interaction that arise if the mean flow is not balanced, so that pseudo-momentum (Eliassen-Palm) fluxes do not suffice for the quantification of the wave impact on the resolved flow (Wei et al 2019). The comparative importance of these effects for zonal-mean winds and temperatures, residual-mean transport, and solar tides has been investigated, using the Lagrangian gravity-wave parameterization MS-GWaM (Bölöni et al 2021, Kim et al 2021, 2024, Voelker et al 2024) in the global circulation model ICON. Comparisons between ensembles of boreal-winter simulations show that 3D dynamics leads to a statistically significant relative circulation that lowers and cools the summer mesopause but also cools/heats the summer/winter stratopause region and cools the mid-latitude winter stratosphere. Replacing pseudo-momentum forcing by a more general approach mainly affects the summer mesopause in manner opposite to 3D. Downward control (Haynes et al 1991) is used to investigate the relative contribution of gravity waves and modified Rossby waves to the observed circulation changes. Gravity waves seem to be responsible for most of the differences, but modified Rossby-wave fluxes partly compensate their effects, in a manner similar as observed by Cohen et al (2013). Solar tides show a related response, where non-balanced dynamics mostly affects the summer mesosphere / lower thermosphere, but 3D has significant effects on tides in both hemispheres and down into the stratosphere.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Towards a more physical representation of convection-generated gravity waves and the QBO in GFDL global atmosphere models

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Convectively generated gravity wave drag plays an important role in the atmospheric general circulation, especially for the Quasi-Biennial Oscillation (QBO) in the tropical stratosphere. Most of these waves are too small to be resolved in General Circulation Models and thus their drag is represented by parameterization. Recent QBOi assessments identified a major uncertainty associated with the formulation of convection-generated gravity wave parameterization schemes. In particular, no concensus was found on changes to QBO period under future climate conditions. Here, we implemented the gravity wave scheme based on Beres et al. (2005) in the GFDL global atmosphere model. This scheme calculates the gravity wave source from heating rates generated by parameterized deep convection. We explored the sensitivity in the simulated QBO characteristics to Beres scheme parameter choices, including the efficiency factor, the scaling factor for heating depth, and the fractional area of convection per grid cell. As in previous studies, we find QBO period reduces as the efficiency factor increases, but we extend this to show period also decreases as convection area decreases. Both these parameter changes are consistent with a stronger wave forcing and momentum fluxes. When increasing the scaling factor for heating depth from the current NCAR parameter value 0.25 up to the more physical value of 1, the simulated QBO becomes more confined to the upper stratosphere. This is due to the shift in the dominant gravity wave phase speed that is proportional to heating depth. The GFDL convection scheme provides a prognostic value for convective updraft area, so we further relaxed the assumption of constant convection area in the original Beres scheme and instead scale this area with the prognostic updraft area produced by the deep convection scheme. While the default constant convective area and prognostic convective area can yield similar QBO winds in present-day simulations, they yield different QBO responses to surface climate warming. In particular, the model with prognostic convective area simulates a smaller reduction of

QBO period in response to surface warming. The results also motivate a deeper investigation into the physical processes linking parameterized convection to parameterized gravity waves.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Climatology of the Residual Mean Circulation of the Martian Atmosphere and Contributions of Resolved and Unresolved Waves Based on a Reanalysis Dataset

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The objective of this study is to examine the climatology of the residual mean circulation, and the roles of wave forcings by both resolved waves (RWs) and unresolved waves (UWs) . The analysis is performed using data from the Ensemble Mars Atmosphere Reanalysis System (EMARS) over four Mars Years without global dust storms, based on the transformed Eulerian mean equation theory. While the RW wave forcing is estimated directly as Eliassen-Palm flux divergence, the forcing by UWs, including subgrid-scale gravity waves, is estimated indirectly using the zonal momentum equation. This indirect method, originally devised for study on the Earth's middle atmosphere, is applicable to latitudinal ranges where angular momentum isopleths are continuous from the surface to the top of the atmosphere, typically mid- and high-latitude regions. In low latitudes of the winter hemisphere, a strong residual mean flow toward the winter pole is observed in a pressure range between 20 Pa and 0.5 Pa ( 30–60 km), where the latitudinal gradient of the absolute angular momentum is small. The strong poleward flow crosses the isopleths of angular momentum in the regions of its northern and southern ends, indicating the necessity of the wave forcing. Our results suggest that the structure of the residual mean circulation at mid- and high-latitude regions is largely determined by UW forcing, particularly above 2 Pa level, whereas the RW contribution is also significant below the 2 Pa level.

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# Turbulence in the tropical stratosphere, equatorial Kelvin waves, and the quasi-biennial oscillation

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The tropical stratosphere is the gateway to the global stratosphere and a commonly proposed location for solar geoengineering. The dynamics of this remote and difficult to observe region are poorly understood, particularly at turbulent length scales. Existing observational estimates of turbulence frequency and strength vary widely. Furthermore, the sources of turbulence and the relationship between turbulence and the mean flow are largely unknown. We assembled a 21-y database of high vertical resolution (10 m) radiosonde data from four equatorial sites in two ocean basins to study tropical stratospheric turbulence frequency, variability, and sources. Turbulent layers thicker than 200 m are identified using subcritical Richardson number as a proxy for turbulence. We show that the turbulent fraction of the tropical stratosphere is strongly modulated by the quasi-biennial oscillation (QBO). Turbulence is enhanced during the QBO phase shifts, and the atmosphere is most turbulent right before the QBO phase switches from negative to positive, where turbulent instabilities typically occur within specific phases of Kelvin waves. Turbulence is less common when the QBO phase is well established, and the atmosphere is least turbulent during the negative phase of the QBO. The turbulent fraction of the equatorial lower stratosphere varies over a factor of ten depending on QBO phase. This relationship provides a robust observational constraint on the multiscale dynamics within this region, which is useful for studying wave-mean flow interactions in the context of the QBO, informing the operation of stratospheric aircraft and the injection of aerosol for geoengineering, and building and evaluating turbulence parameterizations. We built a data-driven turbulence model trained to predict instabilities in the radiosonde data from inputs derived exclusively from ERA5 reanalysis data, and found that it captured the observed relationship between turbulence frequency, QBO phase, and Kelvin wave activity. This model can be used to stochastically generate turbulence in atmospheric models in a way that preserves the relationship between turbulence frequency and the large-scale flow.

Format: oral
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# Near-global Occurrences of Mesospheric Inversion Layers Observed from 22 years of TIMED/SABER Temperature Measurements

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The long-term occurrence of Mesospheric Inversion Layers (MILs) was analyzed using 22 years (2002–2023) of SABER temperature data. We examined MIL occurrence globally, monthly, and latitudinally, applying multi-linear regression (MLR) to assess trends and responses to El Niño–Southern Oscillation (ENSO), quasi-biennial oscillation (QBO), and solar flux (F 10.7cm ). MIL parameters (top/base heights and temperatures, height/temperature differences) exhibit clear hemispherical asymmetry. In general, MIL occurrences peak during equinoxes and decline during solstices. Latitudinally, tropical regions (30◦ N-30◦ S) show the highest MIL occurrences during equinoxes and the lowest during solstices. In mid-latitudes and polar regions (30◦ -83◦ N/S), MILs peak in autumn and winter, with minimum in spring and summer. Periodicities in MIL occurrences vary globally and by latitude. The tropics feature the smallest mean thickness difference (~{}0.61 km) but the largest mean temperature difference (~{}23.72 K). The latitudinal patterns may reflect seasonal variations in dynamics that have a stronger influence on temperature inversions than on the vertical distributions in the mesosphere. Over 22 years, MLR revealed a global MIL occurrence increase of ~{}534±110 per decade (4.45±1.81 per month), with the 11-year solar cycle exerting significant control. ENSO and QBO modulate MIL occurrences negatively and positively, respectively, reflecting their combined impact on mesosphere dynamics.

Format: oral
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Location: In-Person

# Characteristics of CIT and NCT using satellite and in situ aircraft data in East Asia

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Deep convection and its vicinity are critical areas for turbulence encounters in cruising aircraft, referred to as convectively induced turbulence (CIT). This study identifies deep convective areas (DCA) in East Asia using the infrared channel of the Geostationary Korea Multi-Purpose Satellite-2A (GK-2A) over 49 months (August 2019 to August 2023). CIT events are analyzed using in situ aircraft data adjacent to the DCA. Based on a satellite-based CIT detection algorithm, 13.85%, 15.65%, and 18.23% of the total turbulence cases are identified as CIT over the Korean Peninsula, East Asia, and the full-disk area, respectively, consistent with previous studies. In East Asia, the CIT ratio peaks in summer due to the East Asian summer monsoon, with a secondary peak in winter. This winter peak is attributed to storm tracks associated with the Aleutian Low, which create favorable conditions for CIT encounters along major flight routes in the North Pacific. Two-dimensional density maps of turbulence frequencies centered on DCA reveal that turbulence events are more concentrated to the northwest and southeast, likely influenced by the background wind. CIT intensity decreases rapidly with increasing horizontal distance from the DCA boundary but gradually increases beyond 40 km, particularly in winter. This trend is related to broader DCA areas in winter, driven by stronger upper-level jets and their interaction with storm systems. In addition to these results, a three-dimensional analysis of CIT, incorporating altitude information, has been conducted to further investigate turbulence characteristics near DCA and provide improved guidance for turbulence avoidance around the DCA.

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# Evaluation of COSMO-CLM Model Parameter Sensitivity in the Study of Extreme Events across the Eastern Region of India

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The present study aims to identify the parameters from the Consortium for Small-scale Modelling in CLimate Mode (COSMO-CLM) regional climate model that strongly controls the prediction of extreme events over West Bengal and the adjoining areas observed between 2013 to 2018. Metrics, namely Performance Score (PS) screen out the most persuasive parameter on model output. Additionally, the Performance Index (PI) measure the reliability of the model and Skill Score (SS) establishes the model performance against the reference simulation leading to the optimization of the model for a given variable. In this study, parameter screening for four output variables such as 2m-temperature, surface latent heat flux, precipitation and cloud cover of COSMO-CLM is accomplished. For heat wave simulations, 2m-temperature and surface latent heat flux are explored whereas cloud cover and precipitation are examined for extreme rainfall events. A total of 25 adjustable parameters representing the following parameterization schemes: turbulence, land surface process, microphysics, convection, radiation and soil. Out of the six parameterization schemes, the scaling factor of the laminar boundary layer for heat (rlam_heat) and the ratio of laminar scaling factors for heat over sea and land (rat_sea) from the land surface process is sensitive to SLH, TP. The exponent to get the effective surface area (e_surf) from the land surface has a large impact on 2m-temperature. A few parameters from microphysics (cloud ice threshold for auto conversion), convection (mean entrainment rate for shallow convection) and radiation (parameter for computing the amount of cloud cover in saturated conditions) play a significant role in producing TP, and TCC fields. It is evident from the results that the parameter sensitivities on model performance depend on the choice of the meteorological field. Furthermore, in almost all input model parameters, the model performance reveals the opposite character in different domains for a given meteorological field.

Format: oral
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# Tracer Mixing Due To Gravity Waves & Turbulence Coupling

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Tracer mixing plays a crucial role in understanding how atmospheric constituents are transported, dispersed, and transformed over time. Gravity waves can influence this mixing in various ways like dynamically inducing wind shear, or thermodynamically deforming the potential temperature profile to trigger statical instability. They cause turbulence which then leads to tracer mixing. These gravity waves are especially expected to contribute to turbulence generation (and hence tracer mixing) in the upper-troposphere/lower-stratosphere region. In a typical numerical weather prediction (NWP) model where such waves are not fully resolved, it is thus expected that this mixing can be better represented by coupling the model's turbulence scheme to the corresponding gravity wave parameterization. This coupling however, has not yet been explored by the atmospheric community so far. This work as such, couples the gravity wave parameterization MS-GWaM to the turbulence scheme in NWP model ICON, and demonstrates significant changes in tracer mixing because of it. Further work is also being done on the feedback of this turbulence on gravity waves and additional findings will be reported accordingly.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# A Novel Identification Method for Stratospheric Gravity Waves in Nadir Viewing Satellite Observations

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Stratospheric gravity waves are relatively easy to detect from nadir viewing satellite observations by eye, but detecting them is difficult automatically. This work introduces a new method for detecting gravity waves from 5 years (2010 - 2014) of AIRS temperature data. We use data produced using the Hoffmann and Alexander (2008) AIRS retrieval, and find the temperature perturbations by applying a 4th order polynomial in the across-track direction. A version of the S-transform is then applied onto the perturbations to find the properties of the strongest wave at each voxel. When looking at the horizontal wavelength field from this, it can be seen that gravity waves appear as regions of spatially stable values. This can be used to create a binary mask of wave/no-wave, in a method called the "neighbourhood method".

This method was applied to the 5 years of data, and compared against another widely used method for gravity wave detection, the amplitude cutoff method. It was found that 25% of all waves detected using the neighbourhood method could not be detected when using the amplitude cutoff method, increasing up to 50% when looking at regions of traditionally low amplitude gravity waves. An average year of amplitude and zonal pseudo-momentum flux for gravity waves detected using the two methods was created over three regions, the Rocky Mountains, North Africa, and New Zealand/Tasmania. The proportion of high amplitude wave was significantly greater when using the neighbourhood method instead of the amplitude cutoff method, and the continual low amplitude gravity waves throughout the year that were detected using the amplitude cutoff method were not present when using the neighbourhood method. The wave phase propagation angles were also more physically plausible from the gravity waves detected using the neighbourhood method.

Using the neighbourhood method allows for accurate long-term statistics of local and global GW studies, it compares favourably to another often used GW detection method, and results from using the neighbourhood method are physically realistic.The mean parameters for local and global GWs are not tied to the noise-floor of the AIRS instrument, as is the

case when using the amplitude cutoff.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# Comparing Time-Varying Atmospheric Gravity Waves in Observations against ECMWF Operational Analyses and Forecasts

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Forecasts and observational analyses from the ECMWF model have been used worldwide in a wide range of commercial and research applications, and are among those with the highest skill. These forecasts do not accurately replicate observations on longer timescales, so an analysis of when, and how, the forecast data stops being reliable is necessary.

This study uses the nadir viewing satellite instruments CRIS and AIRS to create a high time resolution dataset over Greenland, with 24 overpasses per day. There are two periods of high overpass frequency, where the time between overpasses is about 30 minutes. The two satellite instruments measure the same spectral bands in the stratosphere, in this case the 4.3 $\mu$m measurements, but have slightly different spatial resolutions. To compare the two it is necessary to fix this, and make AIRS (with the higher spatial resolution) directly comparable to CRIS.

CRIS and AIRS have previously been used for stratospheric gravity wave research, so in this study we use the observations of gravity waves as comparable parameters to compare the ECMWF data against. To measure the gravity waves, the temperature perturbations of both are needed. For the observations, a fourth order polynomial is applied in the across-track direction, which simulates the removal of large scale temperature perturbations. For ECMWF, data with fewer spectral modes is subtracted from data with higher spectral modes. A months worth of satellite observations and ECMWF data (January 2020) is analysed and compared, results are presented here.

Format: oral
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Location: In-Person

# Representation of Tropical Gravity Waves in very-high-vertical resolution Global Simulations

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Atmospheric gravity waves (GWs) play an important role in forcing large-scale atmospheric circulation that significantly impact seasonal and near-term climate predictions. Collectively these waves are known to drive long-term, slowly varying global circulation patterns as e.g. the quasi-biennial oscillation (QBO) in the tropical lower stratosphere. Recent observational case studies found that large QBO forces in the lowermost stratosphere were associated with long-period, long-horizontal-wavelength GWs with very short vertical wavelengths on the order of several hundred meters. Due to their extreme aspect ratio with short vertical wavelengths the simulation of these waves in state-of-the-art global circulation models is challenging and ultra-high vertical resolution in the stratosphere is necessary.

We present very-high vertical resolution global simulations with a grid spacing of 50m in the stratosphere. In our study we use the European Center for Medium-Range Weather Forecasts integrated forecasting system (ECMWF IFS) and Japanese Atmospheric General circulation model for Upper Atmosphere Research (JAGUAR) simulations to study these tropical waves with extreme aspect ratios and determine their impact on the QBO. Furthermore, we validate these simulations with Strateole-2 balloon observations and analyze the differences of the simulated and observed wave fields.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: Online

# Wave-Mean Flow Interactions and QBO-like Oscillations in an Idealized Two-Dimensional Atmospheric Model

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The quasi-biennial oscillation (QBO) is the dominant mode of interannual variability in the tropical stratosphere, and has global impacts on stratospheric dynamics and composition as well as tropospheric weather. Although a general understanding of its principles was established more than 40 years ago, fundamental uncertainties persist regarding the forcing of the QBO and the relative contribution of the different types of waves involved. As a consequence, climate models predict very different responses of the QBO to climate change or geoengineering scenarios.

In this study, we investigate wave-mean flow interaction and QBO-like dynamics in idealized 2D atmospheric simulations using the Weather Research and Forecasting (WRF) model. Our aim is to explore the gap between 1D conceptual toy models of the QBO and general circulation models (GCM) of various resolution with or without parameterized gravity waves. We first reproduce in 2D the minimal 1D configuration described by Plumb (1977) with two gravity waves of opposite phase speed. The waves are forced through thermal forcing and a Newtonian cooling induces radiative dissipation. In this configuration, we obtain a QBO-like oscillation similar to the 1D Plumb model. Then, we explore the evolution of the wave field and the sensitivity of the mean flow to wave and dissipation parameters as well as model resolution and compare with theoretical predictions. Particular attention will be spent on dynamical processes which naturally emerge in the 2D set-up but are negelected in the conceptual model. Potential implications for QBO modelling in GCMs will be discussed.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Recent Updates to the Korean Integrated Model and the Characteristics of Subgrid Orographic and Turbulent Stresses

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The Korea Meteorological Administration (KMA) has been operating the Korean Integrated Model (KIM), a global numerical weather prediction (NWP) model, since April 2020. KIM has undergone continuous improvements, particularly in its physical processes and data assimilation components. Recently, its horizontal resolution was enhanced from 12 km to 8 km, and the data assimilation resolution was upgraded from 32 km to 24 km. Additionally, physical schemes, including the convective parameterization scheme, were optimized to address the challenges in the "gray zone" associated with the 8 km resolution. As a result, KIM's performance for 5-day forecasts of 500 hPa geopotential height and global precipitation has significantly improved compared to the previous 12 km version. The increased terrain resolution has also led to a better representation of orographic precipitation in key mountainous regions, particularly on the Korean Peninsula. Despite these improvements, KIM still exhibits inconsistencies in forecast performance between 00 and 12 UTC (nighttime and daytime), likely due to uncertainties in diurnally varying surface stresses. This study investigates the characteristics of two types of surface stress—mesoscale subgrid orographic stress and turbulent stress —and their diurnal variations within KIM, comparing them with ERA5 reanalysis data at a similar horizontal resolution. Mesoscale subgrid orographic stress accounts for the effects of gravity waves, low-level waves and flow blocking and turbulent stress includes the effects of atmospheric turbulence and turbulent-scale orography. The interrelationship between surface stresses (and drag) and wind biases in KIM is also examined. Results reveal that KIM tends to overestimate subgrid orographic stresses and underestimate turbulent stresses in steep mountainous regions at night compared to ERA5. Moreover the diurnal variations of both subgrid orographic and turbulent stresses are more pronounced in KIM than in ERA5. Wind speed errors and biases are especially evident at night in mountainous regions, such as the Tibetan Plateau, where negative (positive)

biases near 850 hPa (925 hPa) are linked to excessive (weak) mesoscale subgrid orographic (turbulent) stresses and drag. These findings underscore the need for further refinement of surface stress parameterizations and a deeper understanding of diurnal variations to address the systematic biases, particularly in mountainous regions.

Format: oral
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# Atmospheric Turbulence in the Free Atmosphere Estimated Using Operational High Vertical-Resolution Radiosonde Data: Recent Results and Some Issues

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Atmospheric turbulence plays a major role in the mixing of trace gases, heat transfer, momentum diffusion, and aircraft operations. Despite extensive observational studies using campaign experiments and operational data, understanding turbulence in the free atmosphere remains challenging due to its small scale, sporadic occurrence, and the limited availability of observational data. This study addresses these challenges by estimating free-atmosphere turbulence using the Thorpe method and high vertical-resolution radiosonde data (HVRRD) with vertical resolutions of 5–10 m. These data, spanning near-global regions, were provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) through the U.S. National Centers for Environmental Information (NCEI) over six years (October 2017–September 2023). Globally, turbulence is stronger in the troposphere compared to the stratosphere, with peak turbulence occurring approximately 6 km below the tropopause and rapidly diminishing above it. Seasonal analyses reveal stronger tropospheric turbulence during summer and weaker turbulence during winter in both hemispheres, while the stratosphere shows stronger turbulence in spring than in other seasons. Regional analyses show intense turbulence over the South Pacific and South Africa in the troposphere and over East Asia and South Africa in the stratosphere. Some issues on the Thorpe method remain, as spatiotemporal variations of the estimated turbulence are found to be somewhat different from those observed in situ flights, which will be discussed in the conference.

Format: oral
Primary Audience: Gravity Waves
Location: Online

# Vertical Fluxes and Vertical Winds Driven by the Full Spectrum of Gravity Waves and Observed by Lidars in the MLT over McMurdo (77.84°S, 166.67°E), Antarctica

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McMurdo lidar observations have been ongoing for over 14 years since Dec 2010 in Antarctica. The high-resolution Na Doppler and Fe Boltzmann lidar data have enabled numerous eye-opening science discoveries, e.g., the identification of a new class of gravity waves – the persistent gravity waves and the first observational evidence of secondary gravity wave generation. These data and findings plus related theory and modeling studies have led to a new picture of multi-step vertical coupling via gravity waves from the lower to the upper atmosphere. Furthermore, by tracking the meteoric metal Fe and Na layers, these two highly capable lidars have provided unprecedented data, tracking gravity waves from 30 to 200 km. The vertical wind measurements with the Na Doppler lidar further enable sophisticated studies of the vertical fluxes of sensible heat and meteoric Na and Fe in the mesosphere and lower thermosphere, leading to the discovery of positive (upward) sensible heat flux and Na flux.

In this study, we will present further in-depth studies of vertical wind and temperature perturbations induced by the full spectrum of gravity waves. Two major findings are 1) the time-mean vertical winds in winter MLT show tilted profiles over McMurdo on the order of m/s (10-20 times larger than anticipated several cm/s, and 2) positive sensible heat flux occurring in the winter lower thermosphere and then quickly turning into negative flux is a common feature over McMurdo. These surprising results are demonstrated to be real geophysical phenomena via multiple checks on the polarization relation (phase shift) between vertical wind and temperature perturbations and examinations of various correlations among vertical winds, temperatures, Fe/Na densities and layer altitudes. We put forth a hypothesis that regional circulation induced by gravity wave dissipation and then generation

of higher-order gravity waves can possibly explain the surprising observations. These unique observations provide opportunities to investigate the regional circulation and their relations to the spectrum of gravity waves at such a high southern latitude.

Format: poster/flash talk
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Location: In-Person

# Observation of gravity waves generated by convection and the 'moving mountain' mechanism using superpressure balloon observations.

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Convective gravity waves are important for the forcing of the Quasi Biennial Oscillation (QBO). There is a wave component that is stationary with respect to the convective cells that is triggered by convection acting like a barrier to the background flow (moving mountain mechanism). Waves from this mechanism have has only been observed in a few case studies and are not parameterized in climate models. However, the representation of the whole spectrum of gravity waves is crucial for the simulation of the QBO, especially in the lowermost stratosphere (below 50 hPa) where the QBO amplitudes are under-estimated in current global circulation models. In this study, we present analysis of convective gravity wave observations from superpressure balloons of the Stratéole-2 campaigns, in boreal winter 2019 and 2021, retrieving phase speeds, momentum fluxes and drag. We also identify waves generated by the moving mountain mechanism using the theory of the Beres scheme as a basis. These waves do not have a specific period, but are of smaller horizontal scale, on average around 300 km, which is similar to the scale of convective systems. We find below 50 hPa convective gravity waves in general contribute up to 2/3 to the QBO forcing where waves from the moving mountain mechanism are responsible for up to 10

Format: oral
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# Importance of Typhoon Strength and Propagation Conditions on Gravity Wave Variability

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Gravity waves are important for coupling process between the troposphere and the thermosphere/ionosphere. This work focuses on gravity waves generated by typhoon to understand relative importance of gravity wave sources (strength of typhoon) or gravity wave propagation conditions (background wind) for gravity waves observed in the upper stratosphere/lower mesosphere. This work uses 9 years of the high-resolution European Centre for Medium-Range Weather Forecasting Integrated Forecasting System (ECMWF-IFS) data and 45 years of ECMWF reanalysis v5 (ERA5). ECMWF provides amplitudes and spectrum of gravity waves from ground to 30-40 km. Strength of typhoon and background wind speed/directions will be compared to gravity waves at 40 km and examine the relative importance of gravity wave sources and propagations for convectively generated gravity waves. Both ECMWF-IFS with 9 km and ERA5 with 31 km horizontal resolution show concentric GWs at similar locations and timing as the AIRS and CIPS observations. The GW wavelengths are ~{}225–236 km in ECMWF-IFS simulations, which compares well with the wavelength inferred from AIRS and CIPS observations. After validation of ECMWF GWs, 45 years of typhoon events are analyzed using ECMWF-IFS and ERA5 to obtain characteristics of concentric GWs in the Western Pacific regions. The amplitudes of GWs in the stratosphere are not strongly correlated with the strength of typhoons; however, GWs in the stratosphere are more correlated with background wind changes. Our results indicate that amplitudes and shapes of concentric GWs observed in the stratosphere and lowermost mesosphere are heavily influenced by the background wind conditions.

Format: oral
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# Evaluating distinct methods of estimating turbulent kinetic energy dissipation rate using synthetic in-situ observations in Direct Numerical Simulation data

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The turbulent kinetic energy dissipation rate (TKEDR) is a fundamental parameter which characterizes the energy injection scale, the dissipation scale, and the intensity of turbulent flows. The instantaneous TKEDR is quantified by accurately measuring the fluctuating rate of strain components on the order of the dissipation/Kolmogorov length scales which requires very high instrument resolution, sampling rate, and low noise-floor. Due to the limitations in current sensing capabilities, in-situ observations of turbulent atmospheric flows yield a spatial-temporal averaged TKEDR using either one-dimensional velocity or temperature fluctuation measurements. Additionally, Clayson and Kantha 2008 modified the Thorpe sorting procedure, further refined by Wilson et al 2010 and 2011, to evaluate TKEDR from high-resolution radiosonde data. This study will discuss the use of Direct Numerical simulation (DNS) of stationary homogeneous isotropic turbulence to evaluate the distinct estimation methods currently used to infer TKEDR from in-situ atmospheric measurement data. The one-dimensional vertical velocity and temperature time-series obtained by mimicking radiosonde-like vertical profile through the DNS 3D-volume are used to spectrally determine the spatial/temporal averaged TKEDR estimates. Such distributions are evaluated against the DNS pointwise measure of TKEDR, which is considered ground truth data. The analyses are carried out for the growth, stationary, and decaying phases of turbulence evolution.

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# Morphology and Transitional Dynamics Resulting from Gravity Wave modulations of Stable Shear Layers

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Early laboratory experiments of shear flow as demonstrated in Thorpe 2002 provided evidence of Kelvin-Helmholtz Instability (KHI) billow interactions either due to misaligned billow cores or varying phases along the billow axes. Similar evidence has been found in the observations of tropospheric clouds, airglow, and Polar Mesospheric Clouds (PMC) imaging in the mesosphere. Initial High-Resolution Direct Numerical Simulations (DNS) studies performed at Reynolds Number of 5000 (Fritts, Wang, Lund, et al., 2021; Fritts, Wang, Thorpe, et al., 2021) have demonstrated the that misaligned KH billow cores exhibit strong and complex vortex interactions inducing 'Tubes and Knots' (T&K) structures (Thorpe, 2002). The T&K structures accelerate the transition to turbulence in contrast to the secondary instabilities emerging in individual KH billows and yield significantly stronger turbulence than secondary KHI or convective instabilities in billow cores. More recent high-resolution imaging of OH airglow (Hecht et al., 2014, Hecht et al., 2021) provide concrete evidence KHI billows of horizontal wavelength 7-10 km modulated by Gravity Waves of 25 km oriented orthogonal to and propagate along the billow axes which result in T&K structures driving rapid KHI billow breakdown. Similar evidence has been found in recent PMC imaging presented by Kjellstrand et al., 2021. We conducted DNS studies to demonstrate the turbulence energetics of KHI billow interactions in the absence of GW modifications in contrast to the case of KHI billows modulated by monochromatic GWs having small perturbation amplitudes and intrinsic frequency of N/5. Preliminary analysis of our DNS indicates that GW modes with even modest amplitudes promote KHI billow misalignment resulting in complex multi-scale T&K dynamics fixed at specific wave phases. Increase in the GW amplitude resulted in noticeable reduction of KHI billow wavelengths further promoting billow misalignments. The resulting turbulence is expected to consist of broader scale ranges of intense turbulence.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# A strategy for coupling ice microphysics to 3D transient gravity wave parameterization

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The accurate representation of ice cloud properties and their life cycles in global atmospheric models is challenging due to the complex interplay with unresolved processes such as convective updrafts, turbulence, and gravity waves (GWs). To address this, we present a systematic approach for coupling transient GW parameterization with an ice microphysics scheme, aiming for improved temporal and spatial variability of ice clouds. The proposed approach involves the following steps. First, an asymptotic analysis is performed to identify the dominant interactions between gravity waves and cirrus clouds, leading to a closure for the ice nucleation induced by GWs. Second, based on the asymptotic results sub-grid scale fluctuations are constructed from a three-dimensional transient GW parameterization. The fluctuations are used to drive a two-moment bulk ice microphysics scheme. Recognizing the significant influence of GW phase and interference between GWs on cloud formation, the phase evolution of GWs is explicitly included in the parameterization. The approach is validated through comparisons with wave-resolving simulations, focusing on the behavior of superimposed GW packets propagating through an ice-supersaturated region. Key cloud properties, such as the number of nucleated ice crystals and cloud cover, are analyzed and compared between the parameterized and wave-resolving simulations. Finally, we discuss potential applications of this strategy for improving ice cloud parameterizations in global climate models.

Format: oral
Primary Audience: Gravity Waves
Location: Online

# The thermal impacts of GWs in the Martian thermosphere

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Observations of the Martian thermosphere have revealed small-scale, large amplitude fluctuations believed to be associated with atmospheric gravity waves (GWs). Previous analysis of the MAVEN Neutral Gas and Ion Mass Spectrometer (NGIMS) data has described the overall behavior of these waves and their consistency with GW theory. One of the key impacts of these waves as they dissipate is heating and cooling of the neutral atmosphere, from both deposition of the energy and transporting heat. While initial evidence for this has been presented, systematic patterns in this heating and cooling require the analysis of a long-term dataset. This study examines 5 years of NGIMS data to systematically determine the thermal impact of GWs in the thermosphere, and variations with location, season and local time. While both viscous heating and cooling from sensible heat flux are significant at the altitudes seen with NGIMS, cooling tends to dominate in the cases examined. Clear variations in the heating and cooling are seen with the background atmospheric density, with a large degree of variability in addition to this, reflecting the high degree of variations in GWs seen in the thermosphere. Seasonal variations in the net thermal impact of GWs are apparent at mid-high latitudes, and less clear near the equator. During times when MAVEN's periapsis is deeper inside the atmosphere, clear increases in the net thermal impact of GWs with altitude are evident. The overall results are consistent with some prior simulations, but include altitudes and conditions not reported in those studies.

Format: oral
Primary Audience: FISAPS
Location: Online

# A New Method for Obtaining Turbulence Information from High Vertical-Resolution Radiosondes


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In a recently published paper comparing raw and processed temperature data from US High Vertical-Resolution Radiosonde Data (HVRRD), we found increased temperature fluctuations in quasi-biennial oscillation shear zones. We interpreted this as the signature of the turbulence accompanying gravity wave breaking at critical levels. Such increased small-scale temperature fluctuations can likely be used as a qualitative indication of atmospheric turbulence. To explore the possibility of obtaining quantitative turbulence information from small-scale temperature fluctuations, we have used data from a previously published numerical simulation paper on the turbulence accompanying gravity waves propagating through mesospheric inversion layers (MILs). In that paper, it was shown that the Weinstock formula relating the dissipation rate of turbulent kinetic energy, epsilon, to the variance of the vertical velocity, $\langle$[w']$\hat{2}$ $\rangle$, gave results that compared well with the direct calculations of epsilon. Thus, if one could get reliable measurements of $\langle$[w']$\hat{2}$ $\rangle$ from HVRRD, one could use this to determine epsilon in the same manner as is done by the radar community. Unfortunately, we believe that this is difficult, if not impossible, given the noisiness of vertical velocities determined from HVRRD balloon ascent data. However, we then found that there was a close relationship between $\langle$[w']$\hat{2}$ $\rangle$ and $\langle$[T']$\hat{2}$ $\rangle$ in the same numerical simulations of turbulence accompanying gravity waves propagating through MILs. In this talk, we will report on further investigations of the relationship between $\langle$[T']$\hat{2}$ $\rangle$ and $\langle$[w']$\hat{2}$ $\rangle$ in numerical simulations of turbulence. We will furthermore show examples of efforts to determine epsilon from numerical simulations and HVRRD.

Format: oral
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# Intermittency of Waves in the Polar Upper Troposphere and Lower Stratosphere Over Northern Norway Using MAARSY

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We investigate the absolute momentum flux (AMF) and vertical wind variance ($\rho$w'2) of gravity waves (GWs) along with intermittencies in the upper troposphere and lower stratosphere (UTLS) during 2017–2022 using the Middle Atmosphere Alomar Radar System at Andøya, Norway (69.30°N, 16.04°E). We categorized the AMF and $\rho$w'2 into different period ranges (30 min–2 hr, 2–6 hr, 6–13 hr, 13 hr–1 day, and 30 min–1 day) to study the significance of short- and long-period waves. The selection of these period bands was based on the boundary conditions of the available spectra: 30 min (Nyquist frequency), 13 hr (inertial period), and 1 day (based on our interest in maximum long-period oscillations). Through the investigation of the AMF and $\rho$w'2, we wish to determine in detail the GW characteristics at northern polar latitudes. Furthermore, it is crucial to assess the intermittency as it considerably influences and alters the GW attributes. Our novel results indicate for both AMF and $\rho$w'2: (a) seasonal variation with minima during summer (May–September); (b) higher magnitude in the upper troposphere ($<$9.00 km) than the lower stratosphere; (c) short-period components (30 min–2 hr, 2–6 hr) are more intermittent in the entire UTLS; and (d) the long-period components (6–13 hr, 13 hr–1 day) demonstrate lower (higher) intermittency in the upper troposphere (lower stratosphere) in summer implying a plausible wave-filtering mechanism.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Identification and Source Mechanism Investigation of Eclipse Generated Gravity Waves in the Lower Atmosphere using the Nationwide Eclipse Ballooning Project (NEBP) Observations and Ray-tracing Simulations

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Solar eclipse perturbs the entire atmosphere column under its shadow, which in theory should generate atmospheric gravity waves (AGWs). Although the first eclipse-AGW evidence in surface pressure measurement has been recorded more than 50 years ago by Chimonas and Hines (1970), much more abundant observations at different region of the atmosphere are not available until recent decade or so, and studies of the generation mechanism are still lacking. In the troposphere and lower stratosphere, it is a greater challenge to confirm eclipse-AGWs due to its weak magnitude and transient nature compared to strongly varying backgrounds and ubiquitous AGWs excited from other major AGW sources.

One of the key science goals of the Nationwide Eclipse Ballooning Project (NEBP) is to study whether the solar eclipse induced gravity waves can be detected by radiosonde measurements onboard the weather balloons, and if yes, what is the eclipse-AGW generation mechanism. Based on the experience and lessons learnt from the previous 2019 and 2020 ballooning campaigns, we designed a super-site near Albuquerque, New Mexico during the Oct. 2023 annular eclipse by locating 4 pods near-by and launching balloons alternately following a 15-min cadence order. In this work, we will show how this arrangement can effectively rule out other ubiquitous AGW sources (e.g., convection, frontal system, flow over mountains) and detect the weak and transient AGW signals from the solar eclipse forcing in the lower stratosphere. Using this unique supersite dataset together with AGW ray-tracing simulations, we are able to locate the eclipse-AGW source near the tropopause region following a "mechanical oscillator" mechanism through rapid cooling of the tropopause temperature. There are also very high-frequency standing AGWs observed within the planetary boundary layer (PBL) right before and during the eclipse passage. We carried out a similar sized campaign ( 600 radiosonde launches) along the total solar eclipse path during April 2024. Unfortunately, weather didn't cooperate this time and we couldn't differentiate out the eclipse generated AGWs. However, traveling planetary waves were identified in the 2024 data. These two unique datasets will help facilitate our understanding of AGW generation mechanism, coupling between lower and upper atmosphere during eclipse, and understanding better the advantage and limitation in AGW detection techniques.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# How realistic are resolved gravity waves in ERA5 reanalysis compared to satellite observations?

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Numerical simulations of the Earth's atmosphere have developed ever finer spatial resolutions in recent decades, resolving more of the atmospheric gravity wave (GW) spectrum directly. As such, the balance between resolved and parameterised (unresolved) GW forcing in current and future numerical simulations is shifting. Some studies are now using resolved GWs stratospheric reanalyses as proxies for GWs in the real atmosphere, due to the apparent reliability, long timescale, global coverage and real-date data assimilation of these reanalysis products. However, these resolved GWs in reanalyses have not been widely validated against global satellite observations of GWs to assess their realism. Such comparisons are exceptionally challenging due to the limited ranges of GW wavelengths to which any given model or instrument is sensitive (an effect known as the observational filter), resulting from model grid spacing, instrument sampling locations and resolution limits. For a like-for-like assessment of resolved GWs in reanalysis using satellite observations, we must first sample the model using the exact sampling locations, times and resolutions of the selected instrument. Here we use 3-D satellite observations from AIRS/Aqua to evaluate the realism of resolved stratospheric GWs in ERA5 reanalysis. We apply the sampling and resolution of AIRS to ERA5 using a full 3-D weighting function to create synthetic measurements of stratospheric temperature (i.e. ERA5-as-AIRS). We then detrend, regrid and spectrally analyse the AIRS and ERA5-as-AIRS measurements to obtain localised GW amplitudes, wavelengths and directional momentum fluxes between 25-45 km altitude. We investigate the global GW momentum budget and its dependence on horizontal wavelengths. Despite similar resolutions, our preliminary results suggest that AIRS observes 3-4x larger momentum fluxes (GWMF) on average than ERA5-as-AIRS, and that GWMF is distributed towards shorter horizontal wavelengths ($<$ 200km) which are underrepresented in ERA5. Our satellite-sampling methodology is applicable to any GW-resolving model and can provide direct validation of model dynamics that could help to guide future high-spatial resolution atmospheric modelling. This study forms part of the ISSI-funded project "SWANS".

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Long-term changes in gravity wave activity in the middle atmosphere from satellite observations

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Atmospheric gravity waves (GWs) are one of the most important drivers of the circulation of the middle and upper atmosphere and a key coupling mechanism between the atmospheric layers. Numerical simulations have shown extreme sensitivity to GW forcing in recent high-top modelling simulations, and can exhibit significant and limiting biases compared to observations. This uncertainty in the role of GW dynamics in models has made predictions of high-altitude circulation changes under different climate scenarios challenging. This is confounded by a relative scarcity of long-term global GW observations needed to understand these connections. Here we examine results from one of the longest single-instrument satellite data records of GW activity in the middle and upper atmosphere spanning more than two decades. We explore changes in stratospheric GW amplitudes, wavelengths and directional momentum flux from a 22-year climatology derived from global 3-D satellite observations from the AIRS/Aqua instrument. This climatology allows us to examine trends on a global and regional basis, revealing a generally increasing trend in stratospheric GW momentum flux of up to 5mPa per decade in hotspot regions and up to 0.1 mPa per decade in the zonal mean. These trends are directional, with increasing westward trends in winter and increasing eastward trends in summer. However, we also evaluate the statistical significance of these trends and outline reasons for caution, including the consideration of (i) instrument channel degradation and anomalies over time, (ii) chemical changes such as CO2 impacting channel weighting function altitudes and (iii) changes in background wind conditions that affect GW propagation. Finally, we discuss these limitations and best practise for considering observed trends in long-term GW observational data sets.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# Parameterized orographic gravity wave drag and its influence on SSWs

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Sudden stratospheric warmings (SSWs) are one of the largest uncertainties in global circulations models. Modelled frequencies of SSWs depend on many factors such as vortex strength, resolved wave activity and other. In this work we focus on analysing parameterized orographic gravity wave drag (OGWD) and its connection to SSWs. We use CMIP6 data, which have substantial spread in the values of OGWD. This is due to the different parameterization schemes used in models and to the various tuning of the free parameters. We connect those differences in OGWD values to the refractive index and consequently the resolved wave field, having significant correlation with both. This illustrates the importance of OGWD in regards to the propagation and the breaking of the planetary waves, which in turn has significant impact on SSWs. Using linear regression model, we show that OGWD can explain up to 50% of SSW frequency variations, depending on the type of SSW, and even when using known strong predictors such as vortex strength and planetary wave activity, relative impact of OGWD still reaches up to 20%.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# Testing orographic gravity wave parameterizations over idealized orography

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There are many different variations of orographic gravity wave (OGW) parameterization schemes. They differ in the definition of the momentum flux, use of subgrid scale orography (SSO) information, inclusion of effects such as resonance and or reflection of the waves and other. It is known that those variations and tuning of the parameters result in strong differences in the parameterized OGW drag between individual models. Those differences have significant and in cases unwanted influence on the resolved dynamics. We conduct a series of high-resolution simulations with idealized orography, using state of the art numerical model WRF-ARW. We use ERA5 data with a domain over Sierra Nevada, USA, at a time of known strong gravity wave activity. We calculate the resulting momentum flux, focusing on how the minor differences between the shapes of the mountains influence the resulting wave field. We then compare those results to parameterizations applied on low-resolution simulations. By using different variations of the schemes and various components of the SSO, we analyze how each part influences the results. With this work we aim to improve the representation of the freely propagating OGWs and the near surface processes, with the ultimate goal of creating a new parameterization.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# Bridging Observational Disparities in Gravity Wave Studies over Scandinavia: A Multi-Instrument Comparison

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Atmospheric gravity waves play a critical role in driving small and large-scale atmospheric events such as global circulation. As a result of their propagation characteristics, they are responsible for the transfer of momentum and energy over both large and small distances, thereby making them an interesting target of study. Such studies usually include satellite and ground-based instruments. However, depending on the instruments' capabilities and the type of processing performed, comparison of data from different sources is difficult. This study aims to address this limitation by making a comprehensive comparison of measurements from several limb sounders (Microwave Limb Sounder, MLS-Aura; High Resolution Dynamics Limb Sounder, HIRDLS; Sounding of the Atmosphere using Broadband Emission Radiometry, SABER; Atmospheric Chemistry Experiment - Fourier Transform Spectrometer, ACE-FTS), the Advanced Infrared Sounder (AIRS), the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) GPS-RO constellation, Esrange and Sodankylä (68 N, 21 E) meteor radars and radiosondes. Covering from the surface to the upper mesosphere over Scandinavia and using a current gravity wave-resolving process, we expect to identify the similarities and differences in the measurements from these instruments. Additionally, we aim to compare and contrast the waves generated by the Andes, a similar high-latitude orographic source but in the opposite hemisphere. Finally, we will complement the comparison with measurements from the Rothera meteor radar located in Antarctica (68 S, 68 W), at the conjugate latitudinal point of our investigation.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Antarctic Gravity Waves in the MLT: Developing Energy and Spectral Baselines from 14 years of Lidar Observations to investigate Vertical Coupling Processes

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McMurdo, Antarctica is known to be a hotspot of gravity wave (GW) activity which has been monitored by the McMurdo lidar campaign consistently since 2011, enabling numerous GW discoveries such as that of persistent GW in the middle and upper atmosphere, observations of secondary wave generation in the middle atmosphere, coupling between the equatorial QBO and Antarctic GW energies, and many others. While most of these discoveries were developed via case studies, they were recently supported by a statistical study of McMurdo's middle atmosphere GW. The baselines developed by this study revealed previously unnoticed trends and emphasized the regularity of various GW behaviors. This statistical study emphasized previous discoveries and supports the development of a full picture of GW activity over McMurdo, however, this characterization was only performed on the middle atmosphere, yet many important GW discoveries which have come from the McMurdo lidar campaign regard the upper atmosphere as well. This current study develops baselines of GW dynamic properties in the mesosphere and lower thermosphere (MLT) and serves to complement the aforementioned middle atmospheric baselines. GW potential energy, vertical wavenumber, and temporal spectral baselines are developed using wintertime lidar observations over McMurdo Station. For many of these MLT GW parameters, these baselines will be their first statistical characterization, giving us an important look at their average behavior. The comparison of middle atmospheric baselines with these MLT baselines will provide critical insight into vertical coupling processes such as wave breaking/dissipation and secondary/tertiary wave generation as these combined baselines will provide a comprehensive picture of how GW energy and spectra develop from 30-110 km. The process of developing such MLT GW baselines may even allow investigation into the interannual vari-

ability of this region, complementing horizontal coupling studies performed in the middle atmosphere, and may reveal direct observations of wave breaking in the MLT, which is much a sought-after observation. This study ultimately aids the development of a fuller picture of Antarctic GW activity and sheds light on vertical and horizontal coupling processes.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Applying a 3D transient gravity-wave parameterization to mountain waves

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Most operational gravity-wave parameterizations rely on single-column and steady-state approximations, thus neglecting horizontal propagation and transience. Recent studies indicate that these assumptions can lead to inaccurate predictions. Orographic gravity waves, e.g., can propagate over substantial horizontal distances, leading to the deposition of momentum far from their sources. The neglect of this could be a cause of regional momentum-flux deficits in atmospheric models, e.g. downstream of the Andes. Moreover, the variability of low-level winds can make mountain-wave generation a highly transient process, challenging the legitimacy of the steady-state approximation. This motivates the development of more complex models.

MS-GWaM is a Lagrangian gravity-wave parameterization that is based on a multi-scale WKB theory allowing for both transience and horizontal propagation. So far, it has been applied exclusively to non-orographic gravity waves. The present study investigates the ability of MS-GWaM to correctly describe the interaction between orographic gravity waves and a large-scale flow. For this purpose, it is used in idealized simulations within the pseudo-incompressible flow solver PinCFlow. In a recently accepted paper (see https://doi.org/10.48550/arXiv.2408.03139 for the initial submission), two-dimensional flows over periodic monochromatic orographies were considered, using MS-GWaM either in its fully transient implementation or in a steady-state implementation that represents classic mountain-wave parameterizations. Comparisons of wave-resolving simulations (not using MS-GWaM) and coarse-resolution simulations (using MS-GWaM) show that allowing for transience leads to a significantly more accurate forcing of the resolved mean flow. This is especially pronounced at high altitudes, where wave breaking can induce a wind reversal that is captured by the transient parameterization but inhibited in steady-state simulations, due to the assumption of critical-level formation. The investigation is now extended to the more realistic case of isolated mountain ranges, both 2D and 3D. In these new settings, the impact of blocking and horizontal propagation increases substantially, resulting in a more complex wave-mean-flow interaction. First results indicate that the differences between 3D transient and 1D steady-state are significant, despite being smaller than for periodic hills.

Format: oral
Primary Audience: FISAPS
Location: In-Person

# Turbulent fractions in the Tropical Tropopause Layer using STRATEOLE-2 long-duration balloon measurements

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The Tropical Tropopause Layer (TTL) is a gateway for momentum fluxes and atmospheric components to the global stratosphere. The dynamical processes in the TTL remain challenging to characterize, particularly at turbulent length scales, and are still poorly understood. Current estimates of turbulence frequency and intensity vary considerably between observations in this region, although they are crucial for designing efficient and accurate model parameterizations.

Quasi-Lagrangian in situ measurements of thermodynamic parameters and GPS are obtained from STRATEOLE-2 long-duration balloons drifting at isopycnal level around 20 km altitude during several months over the equator. The balloons' vertical oscillations around their density equilibrium position in a stratified environment allow us to estimate local vertical gradients in temperature, pressure and winds. From these estimates we evaluate Richardson numbers, which enable us to characterize the flow as turbulent or laminar during each flight, and thus to estimate turbulent fractions.

Various methods were tested to evaluate local gradient estimates that can be applied directly to the detection of turbulent episodes. For example, using the envelope defined by the local extrema of the time series, we estimate instantaneous local gradients from the ratio of the variables amplitude to the vertical displacement amplitude. This approach enables the reconstruction of temperature and wind increments time series. By calculating correlations between observed and reconstructed increments, we show that our gradients are quite consistent, especially for shear winds estimates.

We deduce the turbulent fraction from the ratio of the mean lifetime of turbulent episodes to the mean interval between two successive ones. Additionally, we describe the distribution of these estimates.

Format: oral
Primary Audience: Gravity Waves
Location: Online

# Gravity waves in the middle atmosphere above South Pole, Antarctica

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In the winter months, the stable southern polar vortex creates a unique environment around South Pole, isolating it from mid-latitude air masses and weather systems. The absence of mountains in the vicinity of the Pole, lack of convection and the low wind speeds in the stratosphere eliminate typical local sources of gravity waves. This is in contrast to the southern tip of South America near the edge of the polar vortex, where strong low-level winds excite the strongest orographic gravity waves above the Southern Andes. The lidar in Rio Grande, Tierra del Fuego, Argentina regularly observes temperature perturbations in excess of 20 K in the stratosphere in winter. Interestingly, at the Amundsen-Scott station at South Pole, simultaneous measurements with a twin lidar instrument reveal a continuous presence of gravity waves throughout the stratosphere and mesosphere during the entire winter season, although of lower magnitude. We find that the gravity wave potential energy density in the stratosphere and mesosphere above South Pole is about a factor of 3 lower than at Rio Grande, and the temporal evolution at both lidar sites, separated by 4000 km, is uncorrelated. Notably, however, the intermittency of daily mean values of potential energy density is comparable at both sites with the exception of the upper mesosphere, where the distribution is more uniform at South Pole. We find evidence of mountain waves in the stratosphere that might be linked to catabatic winds crossing the transantarctic mountains. With our lidar measurements, which started in winter 2023, we complement the OH airglow observations acquired by the advanced temperature mapper and hope to characterize gravity waves from near surface up to the OH layer.

Format: oral
Primary Audience: FISAPS
Location: In-Person

# Diagnosing turbulence on the mesoscale: The good, the bad, and the unknown [sic]

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Our understanding of when and where turbulence occurs in the free atmosphere is guided by knowledge of the underlying flow instabilities, diagnostics for identifying them in numerical model data, and the availability of measurements to match with theoretical approaches. While advances in all three areas have driven ongoing reassessment of the predictive skill and climatological characteristics of diagnostics, as well as their alignment with measurement-based turbulence climatologies, these aspects are rarely examined together within individual studies using the same datasets. We present results from a study that avoids this separation, indicating that the representativeness of diagnostics can be highly context-dependent.

The good: 1. With average occurrence frequencies on the order of 0.1% for consistently reported turbulence intensities, the hundreds of millions of archived EDR reports from commercial aircraft begin to enable robust geographic mapping of UTLS turbulence. 2. The identified seasonal patterns align with the underlaying large-scale dynamics, including baroclinic wave activity, continental convection, and the inter-seasonal shift of the ITCZ. 3. The 99th percentile of the Richardson number in the ERA5 aligns with the identified turbulence patterns. 4. For the analyzed turbulence intensity, the precision and probability of detection of key diagnostics is highly variable, confirming their reliability in certain regions and seasons.

The bad: 1. The precision and probability of detection of key diagnostics is highly variable, confirming their reliability only in certain regions and seasons. 2. Accordingly, there are limits to the extent to which seasonal turbulence frequency features can be inferred from diagnostic frequency maps. 3. At the given average turbulence frequency, over-prediction and a maximum precision of 10% is inherent to the 99th percentile approach. For non-ideal diagnostics it falls below 4%, as they diagnose less than 20% of the observed turbulence.

The unknown: 1. How representative are the archived reports of the overall occurrence of turbulence? How significant are systematic biases due to effective mitigation strategies like cloud avoidance? 2. Do the results change systematically for weaker, more frequent, and more predictable turbulence intensities? 3. How do they change for higher resolution model data, diagnostic combinations like the GTG, and for more sophisticated diagnostic skill metrics?

Format: oral
Primary Audience: FISAPS
Location: In-Person

# Role of Turbulence in Marine Atmospheric Boundary Layer during the Sea Fog Events in the Yellow Sea: Mesoscale and Large Eddy Simulations

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The Yellow Sea is known for its high frequency of sea fog, particularly during spring and winter. Sea fog in these seasons is associated with a small air-sea temperature difference (ASTD), defined as the difference between the air temperature (AT) above the sea and the sea surface temperature (SST). Under such conditions, ASTD reversal is possible due to relevant physical mechanisms of fog, leading to changes in surface heat fluxes and turbulent characteristics within the fog layer. This study aims to understand the role of turbulence in fog formation and evolution, focusing on a sea fog event on 24 February 2019, which appeared to originate locally in the Yellow Sea and spread to the west coast of the Korean Peninsula. We employed the Weather Research and Forecasting (WRF) model with 2-km horizontal grid spacing and planetary boundary layer parameterization for mesoscale simulations. Additionally, we used idealized large-eddy simulation (LES) using Cloud Model 1 (CM1) with 3.125-m isotropic grid spacing and the initial sounding of meteorological variables from the WRF simulation, which enables resolving the fine-scale characteristics of turbulence. The WRF model reproduced the sea fog extent observed in satellite imagery and showed good agreement with observations over the Yellow Sea. Before fog formation, progressive cooling occurred due to negative surface heat flux, small-scale vertical mixing driven by near-surface wind shear under stable boundary layer conditions, and longwave radiative cooling. After fog formed, the presence of fog droplets intensified cooling primarily through longwave radiation, causing AT to drop below SST and resulting in the reversal of ASTD. This reversal led to a shift in surface heat flux to positive values, creating unstable boundary layer conditions. The resulting buoyancy production increased vertical velocity and prompted the vertical growth of the fog layer. To examine the influence of wind shear on fog formation and evolution, additional LES experiments were conducted using constant background wind speeds varying from 1 m s-1 to 6 m s-1. Lower wind speeds weakened

vertical mixing, delaying both the timing of fog formation and its vertical evolution. These results suggest that moderate turbulence intensity is required for efficient formation and evolution of the sea fog.

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Format: oral
Primary Audience: FISAPS
Location: In-Person

# Two Way Interaction between Long-Haul Flight Routes and Wind/Turbulence in response to Climate Change

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The aircraft in cruise phase strongly influenced by upper-level flow, especially the jet stream and turbulence which frequently occur near it. To ensure efficient and safe journeys, flight operators optimize routes daily by maximizing tailwinds and minimizing turbulence risks. This relationship extends beyond timescale of weather and is subject to climate change. Previous studies report a poleward shift in the mid-latitude jet stream and ongoing debates about changes in its wind speed, while clear-air turbulence is projected to increase. However, such findings often based on Eulerian perspectives are not directly applicable to aviation as they neglect the spatial variation of flight routes. Some studies estimated change in flight time due to climate change using simulations of flight routes applied to climate model wind fields. Still, they are limited by the uncertainties inherent in climate model and fail to account for turbulence, overlooking its connection to jet stream. Overcoming the shortcomings of previous studies, analyzing the relationship between atmospheric conditions and air travel using reanalysis data, while simultaneously accounting for both turbulence and flight time changes, is critical for accurate future projections of aviation and for understanding two-way interactions where climate-driven changes in flight times and greenhouse gas emissions feedback into the climate system. This study examines the long-term impacts of atmospheric conditions on trans-Atlantic flight using routing algorithm applied to 44 years of 3-hourly ERA5 reanalysis data (1979–2022). As a result, Eastbound (EB) flights, following the jet stream for tailwinds, experience 70% more turbulence encounters than westbound (WB) flights, with seasonal and altitude-dependent variations reaching up to 100%. Over 44 years, roundtrip flight time shows a statistically significant 2-minute decrease, likely linked to a narrowing Atlantic jet stream, though trends in each direction are insignificant. The increasing trend in turbulence potential is greater for EB flights, suggesting previous studies underestimated this risk by ignoring spatial variation of flight routes. Turbulence-avoidant trajectories deviate more from optimal routes for EB flights and this deviation grows over time reflecting turbulence increase. These findings underscore the need for integrated ap-

proaches linking jet stream dynamics, adaptive flight routes, and their evolving feedbacks within the climate system.

Format: poster/flash talk
Primary Audience: FISAPS
Location: In-Person

# Estimation of Eddy Dissipation Rate (EDR) derived from Vertical Wind Shear using Wind Lidar and Radiosonde data at NARO Space Center in South Korea

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Atmospheric Turbulence mainly induced by vertical wind shear (VWS) in troposphere and stratosphere can cause significant distractions for accurate positioning of space launch vehicles in the space due to the minor distortions in their heading angle during the early stages of the flights. Therefore, real-time detection of the objective magnitude of atmospheric turbulence mainly driven by VWS near the NARO Space Center (NSC) is essential for ensuring successful launch missions of the space vehicles launched from the NSC center. In this study, we estimated an objective turbulence intensity as a function of Eddy Dissipation Rate (EDR) derived from the VWS using the observed wind data measured by both wind lidar and radiosonde at the NSC. First, for the quality control (QC) of the observed wind data wind speeds below 0.4 m s-1 were removed. Second, the climatology of winds at the NSC is calculated by deriving the averaged wind speed ($\mu$) and standard deviation ($\sigma$) at each altitude for different seasons using 30 years of ERA5 data. Finally, those were used to filtering out the spurious wind data exceeding $\mu+3\sigma$ at each altitude for different seasons that were considered as non-physical values and were not used for calculating VWS. After the QC, most of the observed winds are highly consistent with those from the ERA5 reanalysis data (more than 0.9 of correlation in all levels). Probability density functions (PDFs) of VWS for different seasons (MAM, JJA, SON and DJF) and altitudes (Low, Mid, and High levels) were calculated, which were eventually used for constructing the best-fit curves of the prescribed lognormal distributions by minimizing the root mean square errors from actual PDFs. Using the mean and standard deviation of the best-fit curves, relationships between VWS and EDR were established for each season and altitude, which were finally used for developing the real-time EDR estimation of the observed wind data at the NSC. This will be very useful for making a decision of launching vehicle and for evaluating the forecast product of the wind shear guidance module at NSC. This study was funded by the NARO

Space Center Advancement Project of Korea Aerospace Administration (KASA).

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Evaluation of the middle atmosphere circulation and non-orographic gravity wave parameterization in the Korean Integrated Model (KIM)

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Middle atmosphere circulation and gravity wave processes in the Korean Integrated Model (KIM) have been assessed. In the mesosphere, warm (cold) bias in the winter (summer) hemisphere high latitudes is commonly found in the simulations performed with various horizontal resolutions and forecast timescales. Consistent with the temperature biases, the polar night jet and the summer hemispheric easterly jet are underestimated. Those bias patterns indicate that warming (cooling) in the mesosphere at the winter (summer) pole by the meridional circulation due to gravity wave drag is overestimated in KIM. For gravity wave parameterizations in KIM, subgrid-scale orographic wave drag scheme and non-orographic gravity wave drag schemes considering gravity waves induced by convection and fronts are used. To examine the characteristics of gravity wave forcings in different horizontal resolutions, profiles of resolved and parameterized gravity wave forcings were compared in the horizontal grid spacings of 25 km, 12 km, and 8 km. It is found that parameterized gravity wave drag is overestimated more in lower horizontal resolutions. To reduce systematic biases in the mesosphere and to improve scale awareness of the parameterization scheme, the diagnostic of gravity wave generation and the intensity of launch-level momentum flux spectrum in the frontal gravity wave drag parametrization have been modified. The modifications reduce the number of grid points of frontal gravity wave generation and the amplitude of gravity wave momentum flux overall, leading to mesospheric cooling and warming in the high latitudes in winter and summer, respectively. This alleviates temperature bias not only in the middle atmosphere, but also in the troposphere in the extended medium-range timescale.

Format: oral
Primary Audience: FISAPS
Location: Online

# Analysis of Atmospheric Turbulence in the UTLS from Airborne Observations during the DCOTSS Field Campaign

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Atmospheric turbulence in the upper troposphere to lower stratosphere (UTLS) plays a crucial role in momentum and energy exchanges across different scales of atmospheric motions, as well as in the mixing and transport of trace gases. However, characterizing UTLS turbulence remains challenging due to its localized and intermittent nature. While previous airborne-based observational studies of UTLS turbulence have primarily been conducted using in situ measurements from commercial aircraft, such data are limited to typical cruising altitudes (e.g., 7-12 km) along major flight routes. Given the growing interest in high-altitude flight conditions (e.g., high-altitude platform stations), further observational analyses of UTLS turbulence at higher altitudes, such as between 15 and 21 km, are needed. Moreover, the role of turbulence and its subsequent mixing on UTLS composition remains largely unknown. In this study, we investigate UTLS turbulence and its potential relationships to UTLS composition using high-altitude in situ measurements ($z =$ 21.3 km) of turbulence and trace gases measured during the recently completed NASA Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) field campaign in 2021 and 2022. A statistical analysis of UTLS turbulence observed during DCOTSS, focusing on its occurrence frequency and associated environmental factors, will be presented. The relationship between observed turbulence (intensity and frequency) and water vapor mixing ratio will also be presented.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# Impact of obliquely propagating gravity waves on the QBO simulated using the parameterization MS-GWaM

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Gravity wave parameterization (GWP) accounts for wave processes that are simplified to facilitate computations. These simplifications typically include (i) neglecting horizontal propagation of waves assuming the horizontal uniformity of flows (i.e., invariant horizontal wavenumbers) and (ii) neglecting transient propagation under the steady-state assumption (invariant wave frequencies). Consequently, GWPs diagnose the wave processes within each vertical grid column of the atmosphere model. This approach has proven practically useful for representing vertical wave propagation and the associated momentum transfer between atmospheric layers, which is essential for simulating the observed circulation in the middle atmosphere. However, the consequences of these simplifications remain poorly understood.

Here we use a recently developed GWP, Multi-Scale Gravity Wave Model (MS-GWaM), to fully account for wave propagation in all dimensions. In particular, we investigate the role of three-dimensional, transient wave propagation in a simulation of the quasi-biennial oscillation (QBO). Our results reveal that a portion of gravity waves propagate obliquely toward the equator in the lower stratosphere when the ambient flow is weakly easterly. Although this portion constitutes only a minor part of the gravity-wave momentum flux spectrum, these waves appear to induce westward momentum forcing effectively over the equator, thereby contributing significantly to the descent of the easterly QBO phase.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Mechanism driving cycle-to-cycle variations in the quasi-biennial oscillation period

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The quasi-biennial oscillation (QBO) is a prominent stratospheric variability mode, driven by interactions between gravity waves and the mean flow. Its period has fluctuated between 20 and 35 months across cycles since its first observation in the 1950s. While the underlying mechanisms of this fluctuation have long been hypothesized, they remain unresolved due to a lack of observational evidence. In this work, we use the ECMWF Reanalysis v5 (ERA5) dataset to provide evidence that the period fluctuations are primarily attributed to variability in gravity wave activity. We focus on explaining the variations in the descent speed of the easterly QBO phase, which predominantly control the fluctuating QBO periods.

Our findings indicate that gravity waves in the tropical tropopause layer exhibit temporal variations in their momentum flux that are coherent with the variations in the easterly-phase descent speed. Furthermore, in the stratosphere, momentum forcing due to these waves drives the observed flucuations in the speed of QBO phase evolution. The role of stratospheric upwelling in modulating these fluctuations appears secondary but non-negligible. Among the variability in gravity-wave momentum flux into the stratosphere, the seasonal variation explains a large portion of the phase descent speed variations, including the observed stalling of the phase descent. This seasonal variation arises from the seasonality in tropical convection and tropopause-layer wind. These results have implications for realistic modeling of the QBO evolution, particularly in the context of seasonal prediction.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Impact of Small-Scale Gravity Waves on Tracer Transport

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While the large-scale components of global circulations responsible for the zonal-averaged tracer transport are resolved in weather and climate models, small-scale processes, such as gravity wave-induced transport and turbulent mixing, remain unresolved and require parameterization. These subgrid-scale processes significantly influence tracer distributions, affecting Earth's surface climate through their radiative effects. However, these effects are largely unaccounted for in existing parameterization schemes. Using scale asymptotics, we derive expressions for the effects of non-breaking gravity waves and extend a gravity wave parameterization model to quantify their contributions to tracer transport, presenting results from an idealized setup. Additionally, we aim to explore the role of turbulent diffusive mixing in tracer transport. This study provides a foundation for improving the representation of subgrid-scale processes in atmospheric models.

Format: oral
Primary Audience: FISAPS
Location: In-Person

# A New Estimation of Atmospheric Turbulence Using Global High Vertical-Resolution Radiosonde Data

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Previous efforts to estimate turbulence from high vertical-resolution radiosonde data (HVRRD) have primarily used the Thorpe method. The Thorpe method detects turbulence in regions where potential temperature exhibits local overturning in which local Richardson number (Ri) is less than 0 exclusively, and it does not account for wind shear directly. To address these limitations, a new approach based on the minimum Ri (Rimin), which considers the influence of gravity waves on local static stability and vertical wind shear, is introduced in this study. This approach enables turbulence to be detected not only in the Ri $<$ 0 regime but also in the 0 $<$ Ri $<$ 0.25 regime. The results from the four-year (2018–2021) period show that the intensity of turbulence with positive Ri is generally comparable between the troposphere and the stratosphere, whereas that with negative Ri is significantly stronger in the troposphere than in the stratosphere. Seasonal analyses indicate stronger turbulence during winter and weaker turbulence during summer in both the troposphere and stratosphere of the Northern Hemisphere (NH), whereas almost no seasonal variation is observed in the Southern Hemisphere. This seasonal variation in the NH is consistent with that of in-situ flight turbulence observations by commercial aircraft. Regional analyses reveal intense turbulence with positive Ri over East Asia and Oceania in the troposphere and over Siberia in the stratosphere, while strong turbulence with negative Ri is observed over East Asia and South America in the troposphere and stratosphere, respectively. Additionally, a recently proposed method by Kantha that considers wind shear on the Thorpe method will be presented at the conference.

Format: oral
Primary Audience: FISAPS
Location: In-Person

# Estimation of energy dissipation rates from radiosonde observations based on machine learning approach

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In this presentation, we introduce preliminary results of estimation of turbulent energy dissipation rates based on machine learning techniques applied to radiosonde observations. Our approach uses a large dataset of simultaneous radiosondes and VHF radar (PANSY radar) measurements at Syowa Station in the Antarctic region. The machine learning model is a convolutional neural network that takes potential temperature fluctuations as well as zonal and meridional wind components as input. The resulting estimates show good agreement with independent radar-based values, which were not included in the training process. We also demonstrate how the newly developed algorithm can be applied to midlatitude radiosonde observations and compare these results with simultaneous measurements from the MU radar at Shigaraki, Japan.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# Reproducibility of vertical winds and momentum fluxes observed by an MST radar at Syowa Station in the Antarctic

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This study investigates the reproducibility of characteristics of vertical winds and momentum fluxes observed by a large atmospheric radar at Syowa Station in the Antarctic, through numerical simulations with various horizontal grid spacings. In the lower stratosphere, the simulations with horizontal grid spacing ($\Delta$x) of 0.5 and 0.25 km successfully reproduce the vertical winds observed by the radar. In the troposphere. In the troposphere, although simulations with $\Delta$x= 0.5 and 0.25 km well capture strong vertical wind disturbances, they still underestimate the magnitude of vertical winds disturbances, particularly for wave periods shorter than 2h. Momentum fluxes associated with gravity waves are reproduced quantitatively in simulations with $\Delta$x$\leq$ 2.5 km, which are significantly underestimated in the simulation with $\Delta$x= 22.5 km. This result suggests that the simulated momentum flux converges with simulations with $\Delta$x of 2.5 km or finer.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Recent Progress of Subrid Orographic Parameterization in the Korean Integrated Model

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The representation of subgrid-scale orography (SSO) is essential for improving the performance of numerical weather prediction and climate simulations over complex terrains, as orography cannot be fully resolved at coarse resolutions. Subgrid orographic parameterizations (SOPs) account for three types of mesoscale drag—gravity wave drag, low-level wave breaking drag, and flow-blocking drag—and one type of turbulent-scale drag. In the Korean Integrated Model (KIM), the earlier version did not separate the SSO into two scales (Choi and Hong, 2015) and it has been classified on mesoscale orography and turbulent-scale orography at a 4-km resolution to include the turbulent orographic form drag (TOFD) (Koo et al. 2018). An inter-comparison study on orographic drag has shown that the KIM-SOP scheme produces zonal-mean surface stresses similar to those of current operational models at middle (40 km) and low (100 km) resolutions (van Niekerk et al. 2020). In the recent update of the KIM, the SOP scheme was further improved by refining mesoscale stress owing to the SSO drag, together with turbulent-scale stress owing to surface-layer parameterization. These updates included revising SSO ancillary data, optimizing reference height over glaciers, reducing TOFD magnitude, and enhancing surface roughness length. This led to increased mesoscale stress over mountainous regions and decreased turbulent-scale stress (especially over flat area and land-ocean boundary), maintaining total surface stress while clearly improving medium-range forecast skills for both surface and atmosphere conditions by reducing systematic wind speed biases. Further details will be presented at the symposium.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Impact of gravity waves on nucleation of ice particles based on a coupled approach in global NWP model

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Atmospheric gravity waves (GWs) induce temperature and vertical wind fluctuations that are known to significantly influence the formation and lifecycle of ice clouds. Cirrus clouds, in turn, play an important role in the Earth's energy budget, yet their radiative effects remain poorly understood. Despite this, climatological models often neglect the interaction between GWs and ice clouds, leading to uncertainties in the representation of ice miscophysical properties. Current work addresses these limitations and focuses on a detailed representation of GW-ice cloud interactions in global numerical weather prediction (NWP) and climatological scales. Our approach employs the next-generation GWs parameterization Multi-Scale Gravity Wave Model (MS-GWaM), directly coupled to an ice microphysics scheme. MS-GWaM uses a ray-tracing technique, supports multiple GW source types, and allows for 3D GW propagation, enhancing its physical realism. The ice microphysics scheme that captures the homogeneous nucleation of ice crystals induced by GWs was developed and tested on a parcel model by Dolaptchiev et al. (J. Atmos. Sci., 2023). This approach has been implemented in ICON in order to evaluate its performance under realistic conditions and study the effect of GWs on the cirrus formation and lifecycle. First results demonstrate that prototype parameterization performs well compared to a direct time integration of the nucleation process. The influence of GWs on cirrus formation was assessed by comparing results from the new scheme with those from the original ICON setup, where nucleation is described by the Kärcher et al. (JGR Atmospheres, 2022) scheme without GW impact. The results show a notable increase in higher ice number concentrations, particularly in the tropical upper troposphere and lower stratosphere (UTLS), highlighting the possibility of the dominant influence of convectively generated GWs over background sources. Various GW representation options, including the superposition of multiple GWs are to be investigated using the current coupled setup. A detailed analysis of the effects of different source types on ice formation is to be studied for a set of global calculations in ICON. These efforts aim

to enhance the representation of GW-cirrus interactions in climate models and capture their key effects on diagnostic parameters and cirrus occurrence.

Format: oral
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# High-Frequency Gravity Waves and Kelvin-Helmholtz Billows in the Tropical UTLS from Radar Observations of Vertical Wind

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The present study analyzes novel observations of vertical wind in the tropical upper troposphere-lower stratosphere obtained from a radar wind profiler in Cochin, India. Between December 2022 and April 2023, 63 consecutive 4 hr curtains of were measured with a vertical spacing of 180 m and a sampling time step of 44 s, thus resolving almost the whole spectrum of vertical motions. Spectra of strongly vary with altitude. They are generally flat up to the local Brunt-Väisälä frequency (BVF), but sometimes exhibit a peak of variance closer to BVF, a feature which may be attributed to trapped gravity waves. At other times and locations, the profiles reveal Kelvin-Helmholtz billows. Finally, the variability of variance over the 4 month campaign period is investigated. Using brightness temperature from geostationary satellites as a convective proxy, it is found that variance is highly correlated with fluctuations in convective activity.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Impacts of Stratospheric Aerosol Injection on Parameterized Convective Gravity Waves in the Equatorial Stratosphere

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We investigate the impacts of stratospheric aerosol injection (SAI) on parameterized convective gravity waves (CGWs) using Community Earth System Model version 1 (CESM1). The two geoengineering scenarios used in this study are Geoengineering Large Ensemble (GLENS) and GEQ. In GLENS, aerosols are injected at four latitudes (15°N/S and 30°N/S), while in GEQ, aerosols are injected at the equator. Both scenarios maintain the global mean temperature through SAI under the RCP8.5 scenario. In the early future (2020–2040), the absolute zonal CGW momentum flux (CGWMF) at 100 hPa ranges from 1.5 to 1.6 mPa, showing little difference among the scenarios. In the late future (2075–2095), the CGWMF in GEQ is 1.3 mPa and in GLENS is 1.5 mPa, both significantly smaller than 2.2 mPa in RCP8.5. This is because geoengineering scenarios prevent the strengthening of convective heating in the troposphere, thereby inhibiting the increase in CGWMF at the source level. The response of CGW drag (CGWD) to SAI differs from that of CGWMF. During descending westerly in the late future, the eastward CGWD at 30 hPa in GLENS is 0.15 m s-1 day-1, which is smaller than 0.19 m s-1 day-1 in RCP8.5. However, during descending westerly, the westward CGWD in GLENS is -0.19 m s-1 day-1, much stronger than -0.09 m s-1 day-1 in RCP8.5. Since the CGWMF in GLENS is smaller than that in RCP8.5, the stronger westward CGWD in GLENS suggests that differences in background winds caused by SAI are likely to influence the CGWD. In GEQ, the magnitude of westward CGWD decreases until 2040, and around 2040, a permanent westerly appears near 20 hPa in the equatorial region. Consequently, positive wind shear at 30 hPa in GEQ causes eastward CGWD to dominate for most of the period.

Format: oral
Primary Audience: FISAPS
Location: In-Person

# Generation Mechanisms of Near-Cloud Turbulence between Mid-Latitude Jet and Northward Moving Typhoon in East Asia

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Significant frequencies of atmospheric turbulence in the Upper Troposphere and Lower Stratosphere (UTLS) over East Asia and the Northwestern Pacific Ocean (NPO) have been attributed to upper-level jet/front dynamics including shear, convective, and inertial instabilities near the East Asian Jet (EAJ). The upper-level outflow from deep convection and Tropical Cyclones (TCs) interacting with EAJ can contribute to the frequent occurrences of turbulence, called near-cloud turbulence (NCT) that is indirectly related to the convective systems. To understand the generation mechanism of NCT during TC-jet interaction, this study investigated the light-to-moderate turbulence events reported by commercial aircraft across NPO using the Weather Research and Forecasting model with the finest $\Delta$x=200 m and ECMWF Reanalysis version 5 data on native model levels with a vertical spacing of 8 hPa. The model result showed that the simulated NCT collocated with observed turbulence events occurred in the radial outflow in the northwestern quadrant of the northward moving TC Hagibis in 2019 that was adjacent enough to interact with EAJ. It was found that the inertial instability-induced intensification of radial outflow generated the Kelvin-Helmholtz billows, resulting in localized convective instability with 1-km deep convective overturning within the anvil cloud. However, at the early stage of the TC when Hagibis and the EAJ were located far away from each other (i.e., they did not interact), turbulence was not predicted near the TC based on turbulence diagnostics in reanalysis data, though some broad areas of weak inertial instability appeared within the outflow of TC. At the end of TC-jet interaction, there were enhancement of jet streak and ridge amplification, implying the emission of inertial gravity waves throughout geostrophic adjustment processes, which is favorable for the generation of turbulence at the exit of EAJ. References: Lee, J. H., Kim, J.-H., S. B. Trier, R. D. Sharman, and J. D. Doyle. (2025) Generation Mechanisms of Near-Cloud Turbulence Events in the Upper-Level Outflow of Tropical Cyclone Hagibis.

Monthly Weather Review (accepted). Acknowledgement: This research was performed by the Korea Meteorological Administration Research and Development Program under Grant KMI2022-00310 and KMI2022-00410.

Format: oral
Primary Audience: FISAPS
Location: In-Person

# Characterization of Wind and Stability in the Lower Troposphere Using High-Resolution Radiosonde Data in South Korea

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This study investigates the seasonal and spatial characteristics of wind and stability in the lower troposphere below 1500 m using 1-second high-resolution operational radiosonde data collected from five stations (Baengnyeongdo, Heuksando, National Typhoon Center (NTC), Bukgangneung, and Pohang) in South Korea over a 4-year period (July 2016–June 2020). The analysis focuses on four key variables: horizontal wind speed, vertical wind shear (VWS), squared Brunt–Väisälä frequency, and Richardson number (Ri). The results reveal significant seasonal variations in these variables, influenced by both the geographical heterogeneity of the stations and seasonal changes in synoptic patterns. VWS is found to be higher during the spring and summer months at two island stations (Baengnyeongdo and Heuksando) located on the west side of the Korean Peninsula, whereas it is higher in winter at the remaining stations (NTC, Bukgangneung, and Pohang). This leads to frequent occurrences of Kelvin–Helmholtz instability (KHI; Ri $< 1/4$). Below 1000 m, static stability is lower in winter than in summer at all stations, which results in higher convective instability (Ri $<$ 0) in winter. This is attributed to the inflow of the marine boundary layer. The frequent occurrence of convective instability observed in spring at Bukgangneung suggests a potential link with mountain wave breaking and downslope windstorms. The microstructures of lower tropospheric instabilities observed in the radiosonde data are not adequately represented in the high-resolution local numerical weather prediction system, specifically the Local Data Assimilation and Prediction System (LDAPS) of the Korea Meteorological Administration. Notably, the observed convective and KHI instabilities, which account for approximately 45% of the cases over the entire period, are rarely captured by LDAPS (approximately 15%). A self-organizing map clustering algorithm is used to identify synoptic patterns favorable for the occurrence of convective and KHI instabilities. These patterns include: (1) a west-high and east-low pattern with an extended Siberian high in winter, (2) strong low-pressure

systems that are prone to KHI from spring to fall, and (3) weak high-pressure systems with potential convective instability, associated with northerly or north-westerly flows and cold advection at 925 hPa.

Format: oral
Primary Audience: FISAPS
Location: In-Person

# Machine learning-based turbulence intensity estimation over Korea using satellite observations

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Atmospheric turbulence is a significant aviation hazard, and its timely detection and accurate prediction are critical for ensuring flight safety and operational efficiency. To support strategic flight planning, turbulence diagnostics are typically derived using numerical weather prediction (NWP) model outputs and have provided valuable guidance for turbulence potential areas to pilots. However, NWP model-based turbulence diagnostics inherit uncertainties from the NWP model itself, often leading to discrepancies in the intensity and location of turbulence. Observation data, such as radar and geostationary satellite data, can offer a complementary approach. Airborne weather radar or ground-based radar is effective at detecting convective clouds and helps pilots to detour convectively-induced turbulence (CIT) regions, but these datasets are spatially limited, and cannot detect clear air turbulence (CAT) or mountain wave turbulence (MWT). In contrast, geostationary satellites provide data in high spatio-temporal resolutions with wide coverage. The water vapor channel on geostationary satellites is effective in detecting MWT or CAT induced by tropopause folding or gravity waves, while the infrared window channel can be useful in detecting CIT. This study develops a machine learning model to estimate turbulence intensity using data from GEO-KOMPSAT-2A (GK-2A), the Korea Meteorological Administration's geostationary satellite. The model integrates multi-channel information from GK-2A to estimate turbulence intensity at multiple vertical layers. It is trained on turbulence diagnostics used in the Global-Korean aviation Turbulence Guidance (G-KTG) product, which is an operational turbulence prediction system of Korea's Aviation Meteorological Office. Although the machine learning model is trained using the NWP model-based product, it learns the general relationships between satellite observations and turbulence, enabling it to estimate turbulence intensity directly from satellite observations. The outputs of the machine learning model are validated using in-situ turbulence measurements from commercial aircraft, and several case studies are presented to demonstrate its performance. This approach addresses the limitations of NWP model-based diagnostics and highlights the potential of geostationary

satellite data in improving turbulence intensity estimation.

Format: oral
Primary Audience: FISAPS
Location: In-Person

# Gravity Wave Modulation of KHI in the MLT


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High frequency gravity waves (GWs) are a known driver of mixing in the mesosphere and lower thermosphere (MLT), with small scale GWs making the greatest contributions to energy transport and momentum deposition. Kelvin-Helmholtz instabilities (KHI) accompany strong shear throughout the atmosphere and influence GW breaking and mixing processes. Recent observations of KHI interacting with GWs in the MLT (Hecht et al. 2020) revealed the formation of KHI tube and knot dynamics (T&K) and led to several simulation studies of T&K in unperturbed shear layers (e.g., Fritts et al. 2020, Fritts et al 2023a-b, Mixa et al. 2023, Mixa et al. 2025). However, no simulation studies to-date have explored the dominant parameters of KHI-GW interactions and their mixing implications.

Here we present modeling results of KHI advecting through a stationary GW based on observations in the MLT. On 18 July 2018, the advanced mesospheric temperature mapper (AMTM) at Tierra del Fuego captured 30-50 km GWs in the OH layer that remained stationary for several hours. During the event, 8-10 km KHI were observed roughly orthogonal to the GWs and advecting through the wave field in two directions. Simulations reveal that the intensification and rapid evolution of KHI is triggered by shear layer advection through successive GW phases. Local advection and distortion of the shear layer produces disconnected regions of intensified KHI within the GW phase. KHI then develop T&K features and expand axially as the mixing region engulfs the domain. We assess the impact of different KHI scales and shear intensities to determine how KHI-GW interactions promote mixing in different atmospheric environments.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Stratospheric Gravity waves in AIRS observations and high-resolution models

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Atmospheric gravity waves vary hugely in scale; with horizontal wavelengths ranging from a few to thousands of km. Typically, gravity waves are smaller than model grid-size and as a result, their effects are parametrised instead of being explicitly resolved. However, recent computational and scientific advancements have allowed for the development of higher resolution global-scale models. These models have horizontal resolutions of order a few km with around 1km vertical resolution in the stratosphere. At such scales, it should in principle be possible to accurately simulate the majority of GWs without relying on parametrisation.

In this work, we use data from three models from the DYAMOND Initiative (DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains). Specifically, IFS (Integrated Forecast System – produced by ECMWF) at 4km horizontal resolution, ICON (Icosahedral NonHydrostatic) at 5km horizontal resolution and GEOS (Goddard Earth Observing System model) at 3km horizontal resolution. All models are initialised with the same initial conditions and are free running for 40 days. We then compare the properties of resolved gravity waves with observations from the AIRS instrument (Atmospheric InfraRed Sounder) onboard NASA's Aqua satellite. Importantly, we note that the AIRS observations are limited by the 'observational filter', wherein each observing system can only 'see' a limited portion of the full GW spectrum. To account for this, an important step in this work is in resampling the model atmospheres as though viewed by the AIRS instrument.

We compare the representation of resolved waves in the three models and AIRS observations across 40-days in Austral winter. We use a recently developed machine learning wave identification method to separate gravity waves in the dataset and determine gravity wave occurrence frequencies. Next, we use spectral analysis to estimate gravity wave amplitudes, wavelengths and calculate momentum fluxes and the intermittency of gravity waves. This work provides an essential evaluation of the accuracy of current gravity wave modelling capabilities.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Convolutional Neural Network for Detecting Gravity Waves in Satellite Observations and Model Simulations

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Observation-model comparisons of atmospheric gravity waves are crucial for evaluating the accuracy of general circulation model (GCM) predictions particularly in the middle atmosphere and for comprehensively understanding gravity wave characteristics. However, observational noise often obscures these waves, complicating such comparisons. To address this issue, we developed a wave detection method using a convolutional neural network (CNN) for semantic segmentation. The CNN is trained on temperature measurements from the Atmospheric Infrared Sounder (AIRS) with labels indicating the presence or absence of waves based on the detection method proposed by Berthelemy et al. (2025). Their original approach relies on detecting discontinuities in horizontal wavelengths caused by observational noise. In contrast, the CNN provides consistent results even when applied to smoothly-varying model data. Using this method, we conduct a multi-year comparison of stratospheric gravity waves in boreal winters between AIRS observations and a high-top gravity-wave-permitting GCM, JAGUAR.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# Comparison of orographic gravity waves in super-pressure balloon observations and in high-resolution simulations

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High-resolution simulations have been conducted with the Weather Research and Forecast model for a ten day case study of wave above the Southern Andes and the Antarctic Peninsula in October 2010 (Kruse et al, 2022). These simulations have been compared to satellite obervations in the stratosphere. The good agreement validated the description of deep waves.

Observations from superpressure balloons were also available for this period. To compare the balloon measurements and the simulated waves, trajectories of virtual balloons are calculated offline. The timeseries of wind, altitude and temperature are compared: the high-resolution does produce significant flucutations at short intrinsic frequencies, relative to virtual ballons flown in ERA5 reanalysis. Although weaker than the observed fluctuations, there is a qualitative agreement. Comparisons in terms of spectra and estimated gravity wave momentum fluxes will be discussed.

Such comparisons are important for the validation of the motions resolved on short scales in high-resolution simulations. The nature of the observations raises methodological questions for the comparison. Finally, the availability of virtual balloon trajectories makes it possible to evaluate, within the modeled fields, the methodology used to evaluate momentum fluxes from a single balloon timeseries, and to assess its representativity.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Estimating observed gravity wave momentum fluxes from the large-scale flow using machine learning

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Machine Learning is increasingly used to contribute to the improvement of parameterizations in climate models. A number of methodological issues and difficulties arise for this, a major one being to obtain datasets for training that are accurate but also cover a wide range of situations. For gravity wave (GW) momentum fluxes in the lower stratosphere, the measurements made by long duration balloons of the Strateole campaigns constitute a reference dataset. The present study employs machine learning (ML) techniques to probe the relationship between large-scale flow and small-scale GWs within the tropical lower stratosphere, as observed during the Strateole campaigns of 2019 and 2021. Multiple explanatory variables, including total precipitation, wind, and temperature, were interpolated from the ERA5 reanalysis at each balloon's location.

In a first step, three tree-based methods are trained on data from seven balloons of the 2019 campaign and subsequently utilized to estimate reference GW Momentum Fluxes (GWMF) of the remaining balloon. We found that parts of the GW signal are successfully reconstructed, with correlations typically around 0.54 and exceeding 0.70 for certain balloons. The different ML methods show significantly different performances from one balloon to another, whereas they show rather comparable performances for any given balloon. In other words, limitations from training data are a stronger constraint than the choice of the ML method. The most informative inputs generally include precipitation and the local wind near the balloons' flight level. Interestingly, different models highlight different informative variables, making physical interpretation uncertain. This study also discusses potential limitations, including the intermittent nature of GWMFs and data scarcity.

In a second step, data from both the 2019 and 2021 campaigns are used, and the reconstruction of GWMFs ia carried out using Bayesian Neural Networks. This switch to a probabilistic framework makes sense regarding the uncertainties in the representation of unresolved processes, is consistent relative to concerns with the representativity of the balloon sampling within a 'grid box', and is beneficial for the resulting distribution of GWMFs.

Given the intermittent nature of the gravity wave field, this is argued to constitute a more meaningful representation of the small-scale gravity waves.

(For the first part : Has et al 2024, JGR,, 10.1029/2023JD040281 )

Format: poster/flash talk
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# The Strateole 2 project: long-duration balloon observations in the tropical lower stratosphere

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Strateole-2 is a French-American project aimed at improving our understanding of composition, transport, dynamics and physicial processes in the Tropical Tropopause Layer, coordinated by Albert Hertzog (LMD). The originality of the project pertains to the use of CNES long-duration superpressure balloons able to fly for months near either 18 or 20 km altitude. Overall, Strateole-2 will relesase about 50 balloons, and each balloon carries up to four different instruments. Two campaigns have already been performed in boreal winter 2019 and 2021, with respectively 8 and 17 balloons launched from the Seychelles International Airport. The third and final campaign of the project will take place in boreal winter 2026, and is expected to fly 22 balloons.

The poster will provide an overview of the main scientific achievements obtained so far with the observations gathered during the first two campaigns. Long-duration balloons have a quasi-Lagrangian behaviour which is advantageous for diagnosing wave motions and attributing them to the different families of equatorial waves. An emphasis will hence be put on the characterization of planetary and gravity wave activity, and their potential interactions with the life cycle of thin cirrus clouds observed in the vicinity of the tropical tropopause. The wealth of other information gathered by the instruments flown on different balloons, informing on air composition, on thin cirrus and occurences of particles, or on clouds below the balloons will also be briefly presented.

Format: oral
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# Fine Vertical Scales of Tropical Tropopause Layer Cirrus and Their Relationship with Gravity Waves: Insights from High-Resolution Balloon-Borne Lidar Observations

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Cirrus clouds in the Tropical Tropopause Layer (TTL) have a significant impact on the Earth radiative budget and on stratospheric humidity. For a few decades, observational studies have established that TTL cirrus are highly correlated with equatorial and gravity waves, and the associated temperature anomalies. Recently, high-resolution observations collected onboard long-duration stratospheric balloons in the frame of the Strateole 2 project revealed very fine (sub-50 m) vertical scale structures of both waves [1] and TTL cirrus [2]. However, the degree to which those two fine-scale processes are connected remains unclear.

In this presentation, we will characterize the occurrence of narrow, laminar TTL cirrus layers from Strateole 2 balloon-borne lidar with very high vertical resolution (15 m). The dynamical environment governing cloud formation will be examined using backward trajectories initialized from the lidar curtains. Finally, Lagrangian simulations of ice microphysics will be used to assess the impact of various scales of atmospheric waves on the observed cloud properties (optical and geometrical).

References:

1:Bramberger, M., Alexander, M. J., Davis, S., Podglajen, A., Hertzog, A., Kalnajs, L., et al. (2022). First super-pressure balloon-borne fine-vertical-scale profiles in the upper TTL: Impacts of atmospheric waves on cirrus clouds and the QBO. Geophysical Research Letters, 49, e2021GL097596. https://doi.org/10.1029/2021GL097596 2: Lesigne, T., Ravetta, F., Podglajen, A., Mariage, V., and Pelon, J.: Extensive coverage of ultrathin tropical tropopause layer cirrus clouds revealed by balloon-borne lidar observations, Atmos. Chem. Phys., 24, 5935–5952, https://doi.org/10.5194/acp-24-5935-2024, 2024

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Gravity wave spectra in high-resolution ICON simulation


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Gravity waves are an important component of atmospheric dynamics, causing the transport of momentum and energy to the stratosphere and mesosphere. Enhancing our understanding of these waves is essential for improving their parameterisations in atmospheric models. In this study, we tackle this challenge by analysing data from a global ICON simulation with a horizontal resolution of approximately 2.5 km. The data is segmented into triangular subdomains based on a low-resolution ICON model grid, which has a horizontal resolution of about 160 km. We evaluate 3D spatiotemporal spectra within these subdomains and subsequently filter the spectra using linear gravity wave theory, yielding the global distribution of gravity wave spectra. Thanks to the spatial dependence and large number of subdomains, the results can be used to study the variability of the spectra or to link the spectrum to flow properties or gravity wave sources.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# 43 years of gravity wave drag in ERA5 reanalysis

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Simulating the effects of gravity waves (GWs) poses significant challenges for global climate models due to diverse spatial and temporal scales involved. Despite these challenges, incorporating the effects of GWs is essential for accurately representing energy and momentum transport in the atmosphere. This study presents a climatological analysis of resolved GWs in the ECMWF's ERA5 reanalysis with a horizontal resolution of 31 km, and their impacts on mean flow over long-term time scales. We focus on the upper troposphere and lower stratosphere, where the GWs exhibit the strongest effects on the mean flow. The spatiotemporal distribution of the GW drag is investigated, with the short and long-term variability analysed locally above the hotspots and in the zonal mean. The results align closely with the theoretically assumed properties of GWs in the atmosphere, which is very encouraging in relation to the question of whether the resolved GWs in reanalyses are realistic. Our research enhances our understanding of GW drag in the stratosphere and can be used for informing and validating the GW parameterization schemes in climate models.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# Observation of mountain waves and secondary gravity waves over Patagonia


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On the night of 21/22 May 2018, clear-sky conditions enabled a 12-hour-long temperature measurement of the Advanced Mesospheric Temperature Mapper (AMTM) in the mesosphere-lower thermosphere (MLT) region over Río Grande, Argentina. Given a westerly forcing over Patagonia, we observe North-South-oriented phase lines in the AMTM temperature maps exclusively during the westerly phase of the semi-diurnal tide, indicating the deep propagation of mountain waves (MWs) with horizontal wavelengths between 20 km and 40 km. After a wind reversal in the MLT, we observe two large-scale gravity waves (GWs) propagating rapidly in a south-eastward direction. We use one- and two-dimensional wavelet analysis to characterize the observed GWs and find that their wavelengths and phase speeds are consistent with secondary GW theory. Ray tracing results suggest a possible source region for these 2GWs located north-westward, near the Chilean Torres del Paine region. In addition, co-located temperature and wind measurements from the Compact Rayleigh Autonomous Lidar (CORAL) and the Southern Argentine Agile Meteor Radar (SAAMER), in combination with a Monte Carlo approach, allow for the accurate determination of both the GW momentum flux and its uncertainty. Although we exclude a direct cause-and-effect relationship within our field of view, we find that, on average, the observed MWs carry momentum fluxes an order of magnitude larger than those of the 2GWs.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Gravity wave analyseswith the EE11 candidate CAIRT – Temperature measurements, GWMF, and ray tracing


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CAIRT, the Middle-Atmosphere candidate and one of two finalists for ESA's Earth Explorer 11 mission, offers unprecedented capabilities for observing and understanding atmospheric dynamics. With an advanced infrared limb imager with high spectral resolution in the range of 720 cm-1 to 2200 cm-1, CAIRT is designed to measure a wide range of trace gas concentrations and temperature from the upper troposphere and lower stratosphere (UTLS) up to the lower thermosphere. The instrument enables 3D tomographic retrieval along the satellite track with an along-track resolution of 50 km and an across-track resolution of 25 km within a 400 km swath. In particular, temperature observations span altitudes of about 10 to 110 km with a 500 m vertical resolution, making CAIRT well-suited for observing Gravity Wave (GW) activity throughout the middle atmosphere. Here, we highlight CAIRT's capabilities for GW observation and analysis based on model simulations and synthetic retrieval runs. First, we present the methodology to isolate a planetary wave (PW) background directly from the temperature observations, which is essential for deriving the residual, GW-induced temperature perturbations. Secondly, we demonstrate the analysis of the temperature residuals using the S3D methodology (based on sinusoidal fits in limited volume data cubes). The analysis enables robust estimation of individual GW parameters and allows the calculation of GW momentum fluxes and the associated GW drag, thereby shedding light into the role of GWs in the middle atmosphere dynamics. In particular, we investigate the GW contribution to the sudden stratospheric warming (SSW) event during northern hemisphere winter 2018/2019. Furthermore, the S3D methodology determines the 3D wave vector for individual GWs, which we use for the initialization of GW ray-tracing to extend our analysis beyond the observation window, offering insights into GW evolution and potential source regions. If CAIRT is chosen as the Earth Explorer 11 following the User Consultation Meeting in July 2025, the mission would greatly increase our observational capabilities within the middle atmosphere and advance our understanding of the middle atmosphere dynamics.

Format: poster/flash talk
Primary Audience: FISAPS
Location: In-Person

# Online coupling of an urban canopy model with trees and a mesoscale atmospheric model to assess the cooling effects of trees

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Urban trees play a crucial role in mitigating heat stress. Accurately representing the physical processes associated with trees in mesoscale models is essential for reliable simulations of urban environments across city to regional scales. We implement an urban canopy model incorporating trees into the Weather Research and Forecasting model to develop a fully coupled modeling system. The model is evaluated against pedestrian-level temperature, flux tower, and soil moisture measurements from the Seoul metropolitan area. The model demonstrates reasonable performance in reproducing intra-city temperature differences, canyon air temperatures, and sensible and latent heat fluxes. A stronger cooling effect of trees is observed in commercial/industrial areas, with a daily mean temperature reduction of 1.1°C compared to 0.64°C in residential areas. The cooling effect is pronounced at night in narrower and deeper canyons, attributed to the greater longwave cooling of leaves. As soil moisture decreases, the cooling effects of trees diminish; however, significant cooling persists under very dry conditions due to tree shading, which is more prominent in commercial/industrial areas than in residential areas. Our findings indicate that comprehensive studies encompassing various tree and urban configurations are necessary to optimize the role of trees in sustainable cities.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Causes of the abnormally strong easterly phase of the mesopause semiannual oscillation during the March equinox of 2023 revealed byJAWARA

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During the March equinox of 2023, a strong easterly wind of 80 m s$^{-1}$ appeared at an altitude of 82 km in the equatorial upper mesosphere, which is regarded as an enhancement of the mesopause semi-annual oscillation. In this study, a new reanalysis data JAWARA available up to 110 km was used to investigate its momentum budget. The strong easterly acceleration was due to a similar contribution from resolved waves and parameterized gravity waves, but largely counteracted by an upward advection of westerly momentum. This fact suggests the presence of additional westward forcing due to sub-grid scale waves such as gravity waves which are not properly expressed in the parameterization. The significant anomaly in the mean winds was not restricted to the 82 km height, but also included strong westerly winds ( 50 m s$^{-1}$) at 65 km and easterly winds ( 40 m s$^{-1}$) at 42 km. The stratospheric quasi-biennial oscillation was westerly. The mean wind intensification at each height is explained by the acceleration due to upward propagating waves, which do not suffer from critical filtering below.

Format: oral
Primary Audience: FISAPS
Location: Online

# Generation and Evolution Mechanisms of Mountain Wave Turbulence in the Upper Troposphere and Lower Stratosphere over Alaska, USA

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Turbulence in the upper troposphere and lower stratosphere can occur due to instabilities caused by large-amplitude mountain waves or their breaking, which is called mountain wave turbulence (MWT). MWT can affect the aviation safety near mountains, so it is necessary to investigate its mechanisms and the background conditions in which MWT can occur frequently. In this study, generation and evolution mechanisms of a MOG-level turbulence, which was observed in the mountainous region over the southern part of Alaska at 1013 UTC on 30 Dec 2012, were analyzed by conducting numerical experiments with four nested domains with horizontal grid spacings ($\Delta$x) of 9, 3, 1, 0.2 km. In the background flow, southeasterly inflow in the lower troposphere, which was strong enough to generate large-amplitude mountain waves, was induced by a well-developed cyclone in the south of Alaska. Also, the background critical level of mountain waves did not exist, so MWT possibly occurred by mechanisms other than mountain wave breaking near the critical level. At the level of the turbulence encounter, U decreased and N2 increased rapidly with height, providing a favorable condition for wave breaking. In the simulation result, large-amplitude mountain waves propagated vertically but broke down near the tropopause, and subsequent static and shear instabilities generated the turbulent region with Richardson number below 0.25 and nonzero subgrid-scale turbulent kinetic energy (TKE). Then the region extended to the downstream, where the turbulence was observed by the aircraft. Smaller-scale waves were resolved partially within the region, so resolved-scale TKE could indicate the turbulent region especially in the innermost domain. Subgrid- and resolved-scale TKE budgets showed that wind shear played a dominant role in producing TKE and TKE was advected to the downstream by the mean flow. In addition, sensitivity tests to the selection of diffusion schemes were conducted. Subgrid-scale TKE was higher and resolved-scale TKE was lower in MYNN than in MYJ due to the stronger diffusive nature of MYNN. Also, in the inner-

most domain, LES could exhibit the intensity and distribution of turbulence appropriately. Finally, TKE calculated using the simulation results was comparable to that calculated from aircraft observation data. Also, both subgrid- and resolved-scale TKE should be considered to investigate the characteristics of turbulence.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# A simple parameterization of the effects of secondary gravity waves due to orographic primary gravity waves and its impacts in the upper mesosphere of whole atmosphere models

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High-top global models have had difficulties in realistically representing winds and temperature in the winter high-latitude mesopause region. Parameterized gravity-wave (GW) processes are thought of as being responsible for inducing excessive easterly vertical shear and large poleward temperature gradient in winter polar mesosphere. Observations and high-resolution modeling results suggest that those biases may be addressed by secondary GW processes. In this study, a simple parameterization of the effects of secondary GWs induced by orographic primary gravity waves is presented for use in low-resolution, high-top global models. Sources for secondary GWs are specified using two symmetric intrinsic phase speeds in the direction of momentum forcing due to primary mountain waves. Primary (both orographic and nonorographic) GW forcing terms are assumed to vanish upward gradually from the middle mesosphere due to dissipation and dispersion that is implemented through vertically decreasing intermittency of primary GWs. Momentum and thermal forcing due to parameterized primary and secondary GWs are identically computed using columnar Lindzen-type method. Nondiffusive GW forcing due to transient GWs is not considered in both primary and secondary cases. This parameterization is implemented in an in-house high-top mechanistic model called System for Whole Atmospheric Dynamics research (SWAD) and NCAR Whole Atmosphere Community Climate Model (WACCM). Comparison with meteor-radar observations and specified-dynamics model results indicates that both secondary GW forcing and reduced primary GW forcing are important in the simulation of the observed climatological structure of zonal-mean wind and temperature near the winter mesopause region.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Derivation of gravity wave parameters from lidar observation and high-resolution nested UA-ICON simulation

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During the NASA VortEx sounding rocket campaign in March 2023, the horizontal wind and temperature were measured by Doppler-Rayleigh/Mie/Raman lidar at the ALOMAR research station (69°N, 16°E) in the altitude range of 30 to 80 km. For the same time period, a high-resolution nested simulation was carried out with the upper-atmosphere extension of the ICON model (UA-ICON), with a horizontal resolution of 1.25 km and vertical resolution of 600 m in the stratosphere. The ALO-GW method (an algorithm for decomposing temperature, zonal, and meridional wind profiles into quasi-monochromatic gravity waves) was applied to both the high-resolution UA-ICON simulation and the RMR lidar observations for the given period. This allowed for a detailed comparison of wave properties, such as wave propagation direction, intrinsic frequency, horizontal and vertical wavelength, wave energy, and momentum fluxes. Since the lidar data only provides vertical measurements, the ALO-GW method uses simulated data from a single point (at the ALOMAR site). In contrast, the UA-ICON simulations provide 4D information about the zonal, meridional, and temperature fields, enabling a comparison of the results obtained from a single point with the information that is obvious when horizontal information is considered, such as the horizontal wavelength or the wave propagation direction.

Format: oral
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# Turbulence measured in-situ in the northern mesosphere/ lower thermosphere since 1990

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Turbulence in the mesosphere/lower thermosphere (MLT) region plays an essential role in the dynamics of the Earth's atmosphere, since it eventually defines the circulation and thermal structure of the entire atmosphere system. The most precise and detailed turbulence measurements in the MLT are done by sounding rockets. We show and discuss the entire database of the turbulence measurements made with ionization gauges since 1990 and analyzed by a new high-resolution technique yielding 100 m altitude resolution. We also show and discuss the morphology of MLT turbulence field inferred from a combined in-situ rocket and ground-based radar observations.

Format: oral
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# The characteristics of the gravity waves, turbulence parameters, and tropopause height revealed by the combination of the MST radar and radiosonde observations

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The Mesosphere-Stratosphere-Troposphere (MST) radars can provide continuous high time-height resolutions and quasi-simultaneous observations of the horizontal wind, vertical velocities, and spectral width et al. of different height ranges. The observational characteristics of the gravity waves, turbulence, and tropopause height were obtained by combining the high-resolution radiosonde data. Results show that the Inertia-gravity Waves (IGWs) parameters depend on altitude, months, and vertical propagating directions, indicating that wave sources are complicated in the area represented by radar observations. Among the plausible candidates for the IGWs wave sources, such as topography, subtropical westerly jet, shear instabilities, etc., vertical shear of horizontal wind was proven to be essential. The turbulence energy dissipation rate and the vertical turbulence diffusion coefficient in the troposphere–lower stratosphere over the radar site are revealed. It is found that the seasonal variation of turbulence parameters has noticeable differences at different atmospheric layers. Furthermore, the atmospheric static/dynamic stability and turbulence intensity are the influencing factors of turbulence parameters. The tropopause height determined by the radiosonde and MST radar data exhibits discrepancy in the altitude regions of higher water vapor concentration in the upper troposphere. The observational features of the atmospheric structures and dynamics will contribute to further understanding in this research field.

Format: oral
Primary Audience: Gravity Waves
Location: Online

# Evaluation of gravity wave parameterization schemes in a climate model using high-resolution simulations of ICON and IFS

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We evaluate the gravity wave parameterization schemes in the Atmospheric Component of the IPSL Climate Model (LMDZ6A) by incorporating comparisons with high-resolution datasets from the ICOsahedral Nonhydrostatic Weather and Climate Model (ICON) and the Integrated Forecasting System (IFS). The ICON dataset corresponds to 5-km horizontal resolution simulations for spring 2020, coarse-grained to a 100 km grid (1°). The IFS dataset corresponds to 1 km horizontal resolution simulations for winter 2018, coarse-grained to a T42 grid ( 2.8°). The parameterizations have been then run offline using ICON and IFS meteorological fields. The comparisons reveal similarities and differences between the two high-resolution datasets and the parameterization predictions. While the parameterized momentum fluxes align reasonably well with those resolved from ICON in the stratosphere, the IFS shows significantly larger momentum fluxes, particularly in the lower levels, highlighting the importance of considering multiple high-resolution datasets to understand gravity wave characteristics better and tuning parameterization schemes. Using insights from these comparisons, we vary the parameters in the schemes to improve the fit with the high-resolution simulations and test impacts in online runs done with the LMDZ6A climate model. Our results illustrate how high-resolution model datasets can improve gravity wave parameterizations in climate models.

Format: oral
Primary Audience: FISAPS
Location: In-Person

# Unveiling the contribution of gravity waves to vertical shear and mixing in the lower stratosphere

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Mixing plays a pivotal role in redistributing radiatively active trace species in the lower stratosphere, shaping the extratropical transition layer (ExTL). While the contribution of larger scale processes such as tropopause folds, cut-off lows, or stratospheric streamers has been studied extensively, the role of small-scale processes like atmospheric gravity waves (GWs) remains unclear. GWs transport energy and substantially influence the atmospheric energy budget. Additionally, they transport momentum and through breaking, can redistribute chemical species. Next to other processes, such redistribution is an additional dynamical process on small scales to mix chemical species in the UTLS. However, the importance of GWs for overall mixing in the ExTL remains poorly understood.

To study the impact of GWs on transport and mixing in the lowermost stratosphere (LMS), we conducted a series of idealized baroclinic life cycle experiments using the ICOsahedral Non-hydrostatic (ICON) general circulation model. Dry adiabatic simulations with varying spatial resolution were performed to assess the GW occurrence and its dependence on model grid spacing. Further process understanding is gained from experiments incorporating physical processes like latent heating, turbulence, and cloud microphysics. We found that GW occurrence is resolution dependent in dry simulations, while including moisture and cloud microphysics amplifies GW activity and turbulence potential. In a consequent step we move from idealized to a case study of a baroclinic wave from the WISE (Wave-driven ISentropic Exchange) campaign. A baroclinic wave over the North Atlantic on 23 Sep 2017 is analysed for shear and turbulence occurrence using convection-permitting ICON simulations and reanalysis data. The ICON simulations on global and nested scales reveal fine-scale structures near the tropopause within regions influenced by WCB ascent, inertia-gravity waves, and mesoscale modifications of the tropopause structure. The correlation between GW-induced momentum flux and shear suggests a significant role of GWs to turbulence occurrence and ultimately tracer mixing in the LMS.

Our findings underscore the critical role of GWs in enhancing vertical shear and facilitating turbulence in the LMS, thereby contributing to the ExTL formation. These results highlight the necessity of accurately representing GWs in atmospheric models to improve prediction of clear-air turbulence and associated mixing in the UTLS.

Format: poster/flash talk
Primary Audience: Gravity Waves
Location: In-Person

# Gravity Wave Morphology During the 2018 Sudden Stratospheric Warming Simulated by a Whole Neutral Atmosphere General Circulation Model

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Atmospheric gravity waves (GWs) during the February 2018 sudden stratospheric warming (SSW) event are simulated using the T639L340 and T2559L340 whole neutral atmosphere general circulation model. Their characteristic morphology around the drastically evolving polar vortex is revealed by three-dimensional (3D) visualization and ray-tracing analyses. The 3D morphology of simulated GWs is described for the three key days that represent the pre-SSW conditions, the mature stage for the vortex splitting, and the late SSW. The combination of strong winds along the polar vortex edge and underneath the tropospheric winds with similar wind directions consist of the deep waveguide for the upward-propagating GWs, forming GW hot spots in the middle atmosphere. The GW hot spots associated with the development of the SSW are limited to North America and Greenland, and they include the typical upward-propagating orographic GWs with relatively long vertical wavelengths. Different types of characteristic GW signatures are also recognized around the Canadian sub-vortex (CV). GWs having short vertical wavelengths form near the surface and obliquely propagate over long distances along the CV winds. The non-orographic GWs with short vertical wavelengths form in the middle stratosphere through the spontaneous adjustment of flow imbalance around the CV. Those GWs cyclonically ascend into the mesosphere along CV winds. In addition to the original paper published in 2022, the presentation will introduce the phase structure of gravity waves in the upper troposphere and lower stratosphere revealed by geostationary meteorological satellite data.

Format: poster/flash talk
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# Origins of UTLS Turbulence: Insights from the RRJ-ClimCORE Mesoscale Reanalysis - The ACCLIP Flights Over East Asia

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During the Asian Summer Monsoon Chemical and Climate Impact Project (ACCLIP), National Aeronautics and Space Administration (NASA) WB-57 high altitude research aircraft observed strong turbulence at an altitude of 15 to 18 km near the outflow of the Super Typhoon Hinnamnor in the Northwest Pacific. Our analyses based on the trial version of the "RRJ-ClimCORE" mesoscale reanalysis have revealed that a thin layer of strong vertical wind shear (VWS) extending just below the tropopause along the upper surface of the outflow from the typhoon eyewall provides favorable conditions for shear instability. Further analyses of the mesoscale background conditions based on RRJ-ClimCORE as well as the geostationary satellite Himawari-8 cloud imagery suggest that the convolution of such small-scale processes as convectively generated concentric gravity waves and shallow convection appearing as radially-banded cirrus clouds may have further increased the potential for turbulence generation. Absolute vorticity analysis suggests the occurrence of inertial instability to the north of the typhoon, which explains the development of radially-banded cirrus clouds as well as the layer of strong VWS around the flight altitudes. The present study thus demonstrates the advantages of the hourly output of RRJ-ClimCORE over 3-hourly output operational mesoscale analysis for investigating source mechanisms of turbulence in the upper-troposphere and lower-stratosphere. The presentation will also include examples of UTLS turbulence observed near an extremely strong northerly jet over the Korean Peninsula associated with an upper tropospheric Asian Summer Monsoon anticyclone.

Format: oral
Primary Audience: FISAPS
Location: In-Person

# Properties of Atmospheric Turbulence Detected high vertical-resolution radiosondes

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The availability of radiosondes with high vertical resolution (a few meters) makes it possible to detect turbulence from temperature and wind profiles. Two methods are widely used: Thorpe analysis and the Richarson criterion, each with its own advantages and limitations. These methods have been used in recent studies to describe the climatology of atmospheric turbulence from a vast database of high vertical resolution radiosondes. In most of the studies based on the Thorpe method, it is common to quantify turbulence intensity by the kinetic energy dissipation rate epsilon_k, this rate being estimated from Thorpe length alone, L_T. It is assumed that is proportional to the Ozmidov length, L_O, the latter being a function of epsilon_k and $N^2$. This proportionality is far from established, since most authors assume that the proportionality coefficient varies over more than two orders of magnitude. We propose to revisit this approach by estimating various statistics within detected turbulent layers based on temperature measurements: variance, structure-function parameter, dissipation rate. Several estimators are compared. In addition to kinetic and potential energy dissipation rates, these estimates can also be used to assess turbulent transport, i.e. the turbulent heat diffusion coefficient K_H. These results will also be compared with the commonly used method based on the Ozmodov length.

Format: oral
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# Simultaneous Measurements of Quasi-monochromatic Gravity Waves and Estimates of Turbulence in the Polar Night Jet

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Using the Doppler-Rayleigh lidar Kühlungsborn (54 N, 12 E) we have measured simultaneous vertical profiles of horizontal wind and temperatures on the flank of the Polar Night Jet. We show a case study where we have used a modified hodograph technique to extract quasi-monochromatic gravity waves from the high wind speed regime of the poleward flank of the Polar Night Jet. In this analysis, we have seen a reduction in gravity wave kinetic and potential energy in the Polar Night Jet core for both upward and downward propagating gravity waves in response to a strong wind shear layer.

We have used structure-function analysis to assess the energy flux from the lidar observations and have compared the hodograph results and structure function analysis to infer turbulent energy transfer rates in the Polar Night Jet.

We will show preliminary results for the first measured total energy budget accounting for waves and turbulence in the stratosphere and lower mesosphere.

Format: poster/flash talk
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# Can GNSS-RO be used to extend the SABER climatological record?


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The SABER satellite instrument has given us a 22-year record of the short- wavelength gravity waves (GWs) that drive of the QBO, allowing us to compare this driving over many cycles. However, despite vastly exceeding its planned two-year lifetime, the SABER record will inevitably end. Unfortunately, since observations of GWs are strongly mediated by the design of the instrument used (a problem called the 'observational filter' ), this means our long-term records of the part of the GW spectrum that SABER measures will end with the instrument. One way to address this problem is to use GNSS-RO data to bolster the SABER record. While GNSS-RO as a technique is older than SABER in practice measurement densities were insufficiently low to measure QBO driving effectively before the COSMIC programme in 2006. Like SABER, GNSS-RO measures short-wavelength GWs, but with important which lead to quite different spatiotemporal patterns in the estimated GW fields. Correcting for this difference would let us merge the SABER and GNSS-RO records of QBO-driving GWs, increasing measurement density for past cycles and extending the SABER-derived record into the future. To understand these differences, we here sample a 3km-resolution run of the GEOS model as if it were observed by SABER and GNSS-RO, and then systematically vary key parameters of the measurements. This allows us to understand how the observational filter of each instrument influences the observation of GW-QBO interaction. Our results reveal that vertical resolution is the most significant factor driving differences between the two instruments. Since GNSS-RO measurements have higher vertical resolution than SABER and are routinely operationally oversampled, we are further able to demonstrate that GNSS-RO-derived temperatures can be adjusted to match SABER, allowing us to produce GW measurements from both instruments similar enough to be used near-interchangeably for QBO-driving GW studies.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Influences of in-situ excited planetary waves in splitting the polar vortex during the Southern Hemisphere sudden stratospheric warming in 2002

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On September 25, 2002, the Southern Hemisphere experienced its first and only major sudden stratospheric warming (SSW02) since routine upper-atmosphere observations began in 1957. This exceptional event featured the sudden split of the polar vortex, a phenomenon rarely observed even in the Northern Hemisphere. While earlier studies primarily examined the role of tropospheric waves and/or vortex preconditioning which focused these waves into the polar stratosphere, the contribution of in-situ excited planetary waves (PWs) remains unexplored. This study addresses this gap by examining the impact of in-situ generated PWs on the development of SSW02 using the MERRA2 reanalysis data. As the onset approached, the highly displaced polar vortex became elongated and ultimately split into two vortices. The substantial amplification of PWs of zonal wavenumber (ZWN) 2 (PW2) at 10 hPa, which split the vortex, was not solely attributed to upward-propagating PW2 from the lower stratosphere but also to westward PW2 excited at the mid-stratosphere ( 2 hPa) that subsequently descended to 10 hPa. These in-situ generated waves were found to account for approximately 15% to 48% of the PW2 amplification at 10 hPa. The spontaneous generation of stratospheric PW2 was associated with barotropic–baroclinic instability, triggered as the stratosphere became dominated by easterlies descending from the mesosphere. The unusual poleward shift of the polar vortex facilitated the development of easterlies by focusing PWs, primarily the ZWN1 component, into the polar stratosphere, where their breaking deposited exceptionally strong westward momentum. In the generation of PW2 via instability, two distinct mechanisms were identified: (1) the breaking of PW1 not only triggered instability but also produced smaller-scale waves via energy cascading, whose subsequent amplification by the instability could contribute to the enhancement of PW2; and (2) instability amplified PW2 by over-reflecting upward-propagating tropospheric waves. While these two mechanisms partially overlapped, the latter tended to dominate PW2 as the onset neared.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Evidence for nonlinear wave-wave interaction in generation of secondary gravity waves

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Numerical simulations of idealized flow over a mountain using the Upper-Atmosphere ICOsahedral Nonhydrostatic model (UA-ICON) revealed three distinct modes of secondary gravity waves. Compared to the primary mountain wave, these secondary waves exhibit longer horizontal, longer and shorter vertical wavelengths, and lower frequencies. Nonlinear wave-wave interactions are proposed as a potential mechanism for generating these secondary waves, which include upward- and downward-propagating components.

Format: poster/flash talk
Primary Audience: Gravity Waves and FISAPS
Location: In-Person

# Static instability based method for detection of overturning turbulence

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Dissipation of internal gravity waves is intimately tied with the turbulent mixing in the atmosphere. Observational studies of this process are extremely difficult and representation of this process is either completely missing, or only crudely parameterized in current generation earth system models. Here we present a simple and physically consistent method for identification and analysis of turbulence in the free atmosphere using collocated pressure and temperature vertical profiles that can supplement the traditional methods (critical Richardson number, Thorpe analysis) and overcome their limitations. The method is based on deviations from a static stability and in an integral sense, it gets a meaning of a difference between the observed and hydrostatically (piece-wise with a floating level of initialization) derived pressure profiles. Comparing the method with traditional diagnostics in a large eddy simulation demonstrates the utility and precision of the method for identification of the overturning turbulence. However, application to the high vertical-resolution radiosonde data is hindered by the insufficient accuracy of pressure measurements.

Format: oral
Primary Audience: Gravity Waves
Location: In-Person

# Stratosphere-troposphere exchange during a typhoon supported by gravity wave effects.

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Full understanding of the stratosphere-troposphere exchange (STE) is vitally important for its role in shaping the atmospheric composition and global energy budget. The troposphere-to-stratosphere transport can inject anthropogenic pollutants from the Earth's surface into the stratosphere, for instance, the Asian Tropopause Aerosol Layer with a main known pathway via the Asian summer monsoon, has a demonstrated radiative cooling effect on the surface. Here we propose a previously underreported potential pathway contributing to STE connected with typhoons. We document this for a particular episode of the typhoon Molave (October 2020) crossing over the Philippines. Combining a high-resolution WRF simulation and a Lagrangian modeling tool – FLEXPART-WRF, we show that the typhoon induces extremely rapid transport (few hours) of pollutants from the surface to the upper troposphere-lower stratosphere (UTLS) region. In the same time, the typhoon launches strong concentric gravity waves and by the interaction with the pronounced orography of Philippines also orographic gravity waves. We try to disentangle the roles of convection, orographic lifting and gravity waves in this process. Stability analysis reveals that gravity waves of both types get instable in the UTLS region and induce mixing across the tropopause transport barrier. Overall, our study indicates that typhoon episodes can play an important, intermittent and previously insufficiently considered role in STE, influencing emerging topics of highest importance such as the long-range dispersion of microplastics.