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Gerald A. Lehmacher
Clemson University, glehmac@clemson.edu

Miguel F. Larsen
Clemson University, mlarsen@clemson.edu

Michael J. Taylor
Utah State University

Jonathan B. Snively
Embry-Riddle Aeronautical University, snivelyj@erau.edu

Aroh Barjatya
Embry-Riddle Aeronautical University, barjatya@erau.edu

See next page for additional authors

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Authors
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VORTEX: A NEW ROCKET EXPERIMENT TO STUDY MESOSCALE DYNAMICS AT THE TURBOPAUSE

Gerald A Lehmacher [(1)], Miguel F Larsen [(1)], Michael J Taylor [(2)], Jonathan B Snively [(3)], Aroh Barjatya[(3)], Franz-Josef Lübken[(4)], Jorge L Chau [(4)]

[(1)] Department of Physics & Astronomy, Clemson University, Clemson, SC 29634 (USA), glehmac@clemson.edu
[(1)] Department of Physics & Astronomy, Clemson University, Clemson, SC 29634 (USA), mlarsen@clemson.edu
[(2)] *Department of Physics, Utah State University, Logan, UT 84322 (USA), mike.taylor@usu.edu*
[(3)] *Department of Physical Sciences, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114 (USA), jonathan.snively@erau.edu*
[(3)] *Department of Physical Sciences, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114 (USA), barjatya@erau.edu*
[(4)] *Leibniz-Institute for Atmospheric Physics, Schloss-Str. 6, 18225 Kühlungsborn (Germany), luebken@iap-kborn.de*
[4)] *Leibniz-Institute for Atmospheric Physics, Schloss-Str. 6, 18225 Kühlungsborn (Germany), chau@iap-kborn.de*

ABSTRACT

The goal of this new investigation is to better understand gravity waves and their interactions as they propagate from the mesosphere into the lower thermosphere, to characterize the mesoscale wind field, and to identify regions of divergence, vorticity, and stratified turbulence. The Vorticity Experiment (VortEx) will comprise two salvoes of each two sounding rockets scheduled to be launched from Andøya Space Center, Norway in February 2022. The rockets will observe horizontally spaced wind profiles, neutral density and temperature profiles, and plasma densities. Additional information about the background conditions and mesoscale dynamics will be obtained by lidars, meteor radars and a hydroxyl temperature mapper. The observational data will be combined with numerical modeling for a comprehensive look at gravity wave propagation, instability and turbulence generation.

1. INTRODUCTION

The Earth's turbopause and mesopause are both at around 100 km altitude and mark a transition from gravity wave (GW) propagation and small-scale turbulence in the weakly stratified upper mesosphere to the strong winds and extreme wind shears in the highly stratified lower thermosphere. Theory and observations of kinetic energy wavenumber spectra, and wave-resolving global circulation models suggest the existence of regions of quasi two-dimensional, stratified turbulence at mesoscales (10-500 km) throughout the atmosphere, but particularly in regions of high static stability ($N^2 \gg 0$), such as the stratosphere and lower thermosphere [1,2,3,4]. The fate of gravity waves in the upper mesosphere, the generation of turbulence and secondary waves is of great importance near the turbopause, since it determines the mixing of momentum, heat and constituents, which impact neutral and plasma density throughout the thermosphere. As viscosity grows and isotropic turbulence becomes less frequent, we plan to study wave mixing and the role of mesoscale vorticity and the relationship to stratified regions in the upper mesosphere and lower thermosphere.

2. SOUNDING ROCKETS

The Vorticity Experiment (VortEx) will comprise two salvoes of each two sounding rockets scheduled to be launched from Andøya Space Center, Norway in February 2022. A proposed layout for the payloads is shown in Fig. 1. One rocket of each salvo will carry a payload with 16 ejectable subpayloads containing ampules with the chemiluminescent tracer trimethylaluminum (TMA). The 16 subpayloads will be released in sets of four on upleg and, using a small rocket motor, will horizontally separate from the main payload by about 30 to 35 km, before releasing the TMA, which will form a rectangular grid for spatially distributed wind measurements on downleg at 90, 100, 110, and 120 km. This technique was most recently used during the AZURE missions in March 2019. It was observed that at these altitudes the released TMA forms individual short trails over a few kilometers. The first rocket will also carry a TMA canister that stays with the second stage motor. TMA will be released from the canister in short puffs to form two trails on upleg and downleg between 80 and 140 km and centered within the smaller ampule releases. All trails will be observed from ground based camera sites to triangulate the absolute position in space and time and to derive horizontal (and possibly also vertical) winds. One camera site will be near the launch site; another 100 or 200 km away; additional observations will be made from an aircraft which can fly above potential cloud coverage. The horizontally spaced wind measurements will be used to estimate horizontal divergence and the vertical component of vorticity at mesoscales of 30 to 60 km.

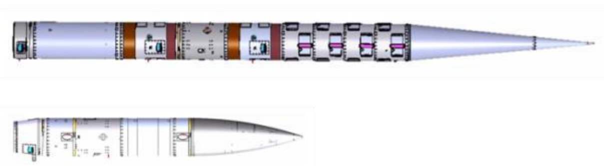

Figure 1. Proposed layouts for VortEx missions. Top: Payload with doors for sixteen ejectables, telemetry (TM) and attitude control system (ACS) sections and subpayload (stays with motor) with TMA canister and separate TM section. Bottom: Payload with instruments stowed under nosecone, TM and ACS sections. Credit: NASA.

The second rocket in each salvo will carry an instrumented payload including two ionization gauges, a multi-needle electron probe and a positive ion probe, the latter two on deployable booms. The instruments will be exposed on upleg after nosecone separation and observe neutral densities (to be used to derive temperatures) between 80 and 130 km, and absolute electron densities and relative ion densities in the E region. The payload will be reoriented near apogee to point again in ram direction for downleg and provide profiles of the same parameters on downleg. All in situ measurements will provide high resolution data sets to derive density and temperature gradients and fluctuations. Brunt-Väisälä frequency and, combined with wind profiles, Richardson numbers will be calculated to assess conditions for atmospheric stability. Additional information about mesoscale processes can be obtained from observing the development of the structure in the TMA trails. Reference [2] found evidence for stratified turbulence when the trails had expanded to scales greater than ~100 to 200 km. An example is shown in Fig. 2. Both rockets in each salvo will be launched in very close sequence, and along the same azimuth, and so that on the downlegs winds and temperatures will be observed in the same volume. The salvoes will be launched on two different nights for different wave forcing scenarios.

Figure 2. Example of TMA trail about thirty minutes after release showing potential signs of stratified turbulence. Photo from 2012 ATREX campaign launched from Wallops Island, Virginia.

3. GROUND BASED INSTRUMENTATION

The experiment will make use of the strong research infrastructure near Andøya Rocket Range. The Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) will host an Advanced Mesospheric Temperature Mapper (AMTM) from Utah State University [5]. It is a narrow-band filtered, near-infrared camera that observes hydroxyl temperatures and intensities near 87 km with a field of view of 160 km x 200 km. The images reveal GW processes at different length scales with high spatial and temporal resolution in real time. We plan to launch a rocket salvo when large amplitude GW are present in the upper mesosphere and are likely propagating up into the lower thermosphere. The rocket measurements will overlap with the field of view of the imager. The Rayleigh-Raman-Mie (RMR) lidar at ALOMAR will observe temperatures and winds up to about 80 km and provide further detailed information about gravity wave activity including vertical wavelengths [6]. A new metal resonance lidar currently under development may become operational for additional wind and temperature measurements between 80 and 105 km. A network of VHF radar transmitters and receivers observes meteor echoes (typically between 80 and 105 km) to estimate the horizontal wind field over an area of 400 km x 400 km [7]. These wind measurements will also be used to estimate the energy spectrum at mesoscales and divergence and vorticity in the wind field. Both lidars and radars are operated by the Institute for Atmospheric Physics in Kühlungsborn, Germany. A layout of rocket and ground based measurements is shown in Fig. 3.

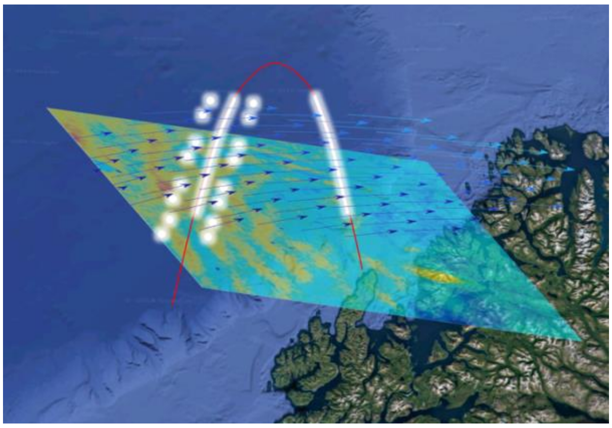

Figure 3. Geographic layout of rocket and ground based measurements. The false color map shows an AMTM image with wave activity in the hydroxyl layer near 87 km. The arrows indicate a wind field derived from meteor radar data. The white blobs and trails indicate the distributed TMA releases at 90, 100, 110 and 120 km. The red trajectory corresponds to the path of instrumented payload. The lidar is located near the launch site and its beam can be directed along the upleg trajectory..

4. MODELING

We will combine observational data with numerical modeling of nonlinear gravity wave dynamics around the mesopause and turbopause using the Model for Acoustic and Gravity wave Interactions and Coupling (MAGIC) [8]. The latest version incorporates a scheme that is shock-capturing and has very low numerical dissipation. The numerical solution may span many scale heights and, for typical resolutions (~100 m), can resolve scales of interest in the lower thermosphere where molecular viscosity becomes dominant. For the proposed investigations involving nonlinear GW dynamics and dissipation, the complete set of viscous and thermal conduction terms in the momentum and energy equations will be included. Time-dependent background profiles of wind and temperature will provide the basis for simulating gravity wave propagation, instability, secondary wave and turbulence generation. Numerical results will include simulations of airglow and tracer species density perturbations, to enable comparisons with observed small-scale structures. An example for a tracer evolution is shown in Fig. 4.

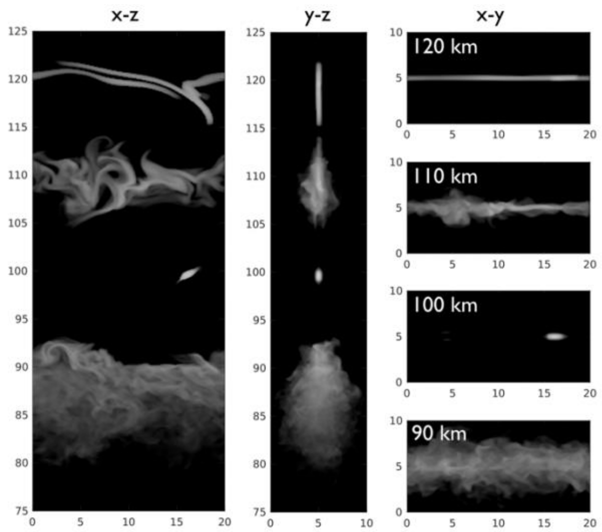

Figure 4. Four simulated tracer concentrations, released at 90, 100, 110, and 120 km, as they are perturbed by a breaking GW in varied stratification. Axes are distances in km; image planes represent integrations through y, x, and z.

5. SUMMARY AND OUTLOOK

The Vorticity Experiment (VortEx) is designed to obtain comprehensive measurements of winds, temperatures, gravity waves and turbulence in the upper mesosphere and lower thermosphere. The goal is to find variations in mesoscale dynamics, such as divergent and vortical motions depending on the background stability. Mesoscales are at the juncture of what current global atmospheric models are able to resolve and what motions contribute to subgrid processes (such as nonlinear GW interactions, GW breaking and turbulence) which are parameterized. GW parameterizations are essential to capture the momentum balance and mixing and obtain the observed wind and temperature distributions, however, they also introduce model biases and uncertainty [9 and references therein]. Subgrid wave processes also impact the thermosphere-ionosphere system, and the generation of secondary waves is another important mechanisms that may need to be considered in models [10]. While global models will evolve to include smaller wave processes with the goal to improve predictability of mesosphere and thermosphere-ionosphere system, our experiment will provide a detailed look at the wave processes that need to be captured by advanced models. VortEx is part of the new Grand Challenge Initiative Mesosphere Lower Thermosphere which connects sounding rocket experiments across the globe with common research goals. The experiment is being supported by NASA's Heliophysics Division through the Sounding Rocket Program Office at Wallops Flight Facility, Virginia under Grant Number 80NSSC19K0776.

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