A New Coupled Weather and Wave Model for Gravity Wave Propagation from Troposphere Weather Systems Deep into the Ionosphere.

FINAL REPORT

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LONG-TERM GOAL

The long-term goal is to develop a new forecasting tool to predict outbreaks of ionospheric disturbances that are driven from below by weather-generated gravity waves. The forecasting tool will combine three coupled models: a weather model to simulate weather events such as convection in thunderstorms and their generation of gravity waves; a wave propagation model to follow those gravity waves from their generation by weather events to altitudes throughout the thermosphere; and an ionospheric model to predict the ionospheric disturbances produced by the gravity waves.

OBJECTIVES

The main objective of the present project was to develop new versions of a wave propagation model that can be coupled to a weather model and that can follow gravity waves from their generation by weather events to altitudes throughout the thermosphere. The main scientific objective was to achieve a better understanding of how weather-generated gravity waves reach and affect the thermosphere and ionosphere. During upward propagation, the atmosphere transmits, reflects, dissipates, and regenerates gravity waves, processes that will ultimately need to be modeled in a way that has predictive skill and efficient computation while also providing the best insights.

APPROACH

Three versions of the wave propagation model were developed for this project. All three are Fourier methods and were used to calculate a realistic spectrum of gravity waves. The three versions are:

1. **The Fourier-ray method**, in which the solution for each Fourier component is determined by a viscous ray approximation.
2. **The Fourier-multilayer method**, in which the background is divided into vertical layers that are a few kilometers thick, and the solution for each Fourier component is calculated in each layer subject to matching conditions at the interfaces between the layers.
3. **The Fourier-WKB method**, in which the solution for each Fourier component is determined by WKB approximation. This is related to the Fourier-ray method but does not involve ray

concepts such as group velocity and ray paths that are problematic at altitudes of moderate to strong viscosity.

The wave propagation model (each version) was coupled to a mesoscale weather model, which simulates the weather events and provides a time-dependent lower boundary condition for the wave propagation model. The altitude of the lower boundary was typically placed in the stratosphere, where the gravity waves have begun to emerge from the weather system.

The mesoscale weather model chosen for this project is the U.S. Naval Research Laboratory regional weather model COAMPS (Coupled Ocean-Atmosphere Mesoscale Prediction System). Our test case was a weather event over the southeast United States. COAMPS was run with sufficient resolution (9 km horizontal grid spacing) to capture convection cells in the weather system and the dominant gravity waves that were generated by the convection.

Personnel. Dr. Dave Broutman (CPI) and Dr. Hal Knight (CPI) have done the major work in developing and testing the Fourier models. Dr. Knight derived the theory and performed the coding for the multilayer method and the Fourier-WKB method. Dr. James Doyle and Dr. Qinfang Jiang (NRL Monterey) ran COAMPS in coordination with Dr. Stephen Eckermann (NRL DC), who selected the Azeem et al. (2015) weather event for use in this project. Dr Eckermann and Dr. Jun Ma (CPI) provided NAVGEM data for initializing the COAMPS simulation. Dr. Jun Ma also prepared the COAMPS output data for coupling to the Fourier model and converted an early version of the wave propagation models from Matlab to optimized Fortran for faster higher-resolution runs. To obtain ionospheric predictions such as TEC perturbations induced by the gravity waves, the solutions from the gravity wave propagation model have been be used as input forcing to the ionospheric model SAMI3. The SAMI3 simulations were conducted by Dr. Kate Zawdie (NRL DC).

WORK COMPLETED

The Fourier-ray method. At the start of this project, a viscous Fourier-ray method was implemented, adapted from a commonly used viscous ray formulation for the thermosphere. It assumes a complex wave frequency, which accounts for viscous (and thermal) damping in the thermosphere, and real horizontal and vertical wavenumbers. However, it became clear in our results that the viscous Fourier-ray method was too dissipative above altitudes of weak viscosity. We identified the cause of this overly dissipative behavior to be the result of the particular assumption in the Fourier-ray method of a real vertical wavenumber. Both the vertical wavenumber and the wave frequency generally need to be complex above altitudes of weak viscosity. Otherwise a compatiblity condition of ray theory is violated, and the ray solutions become inaccurate. If, however, the vertical wavenumber is allowed to be complex, then the ray paths become complex and their interpretation is unclear. Thus the Fourier-ray method was found to be suitable for altitudes of weak viscosity (or inviscid altitudes) but not for higher altitudes. A paper explaining compatibility violation for ray-tracing in the thermosphere is now published in Journal of Geophysical Research, Space Physics (Broutman et al. 2020).

The Fourier multilayer method. Because of the deficiencies of the Fourier-ray method, a new and powerful multilayer method was developed for this project. The multilayer method describes processes that are beyond the capability of standard ray and WKB methods, such as partial reflection, wave tunneling, and the interaction between graivty-wave and dissipative modes.. In the multilayer method, the background is divided into many layers, each a few kilometers thick. A Fourier solution is derived within each layer subject to matching conditions at the interfaces between the layers, a lower boundary condition (provided by the mesoscale weather model), and a radiation condition at the upper boundary. The multilayer method explicitly solves for upward and downward propagating waves, useful for identifying the amount of partial reflection, for example from wind jets of the mesopause region and at higher altitudes from viscosity variations that increase exponentially with altitude. A first publication on this multilayer method, with a detailed theoretical analysis, has now appeared in the journal Wave Motion (Knight et al., 2019*)*.

<u>The Fourier-WKB method</u>. A third Fourier method developed for this project is the Fourier-WKB method. A slowly varying wavefield is assumed but without ray constructs such as group velocity and ray paths that are problematic in moderate to strong viscosity. This new WKB solution was not trivial to derive because the relevant dispersion relation for the gravity waves is sixth-order when viscosity and heat diffusion are included. A draft paper describing this method has been completed and will be submitted for publication.

RESULTS

Figure 1 shows a COAMPS solution at 30 km altitude above a storm system in the south central US on 4 April 2014. There were strong convection cells associated with thunderstorms over the region of Lousiana. The convection cells generated gravity waves that can be seen as concentric rings radiating from the storm region mainly toward the north and northeast.

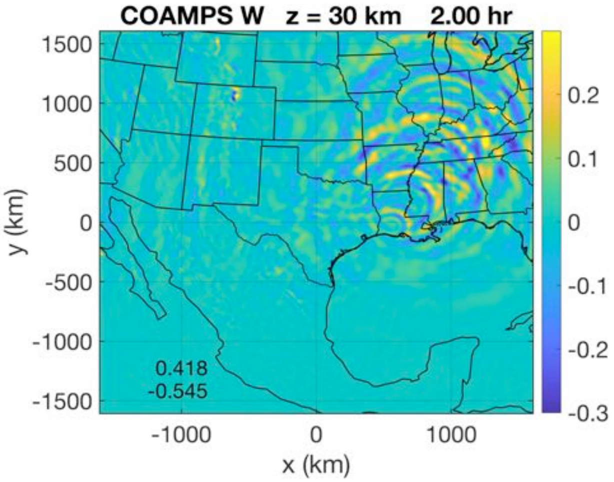

Figure 1. The COAMPS solution for vertical velocity w (m/s) at 30 km altitude and time 2 hr (0800 UT) for weather conditions on 4 April 2014. The range for w is given in the lower left corner of the plot. Color scale is saturated.

Figure 2 shows a vertical cross section (between 30-45 km altitude) of the solution from the wave propagation model, using the Fourier-ray version. It demonstrates the use of the coupling between COAMPS and the wave propagation model. The lower boundary of the wave propagation model is at 30 km altitude, where the COAMPS vertical velocity is indicated (unscaled) by the black curve at the bottom of the plot. This forcing produces high-frequency gravity waves with phases leaning outward with altitude from the center of the storm region over Lousiana, located near r = 0.

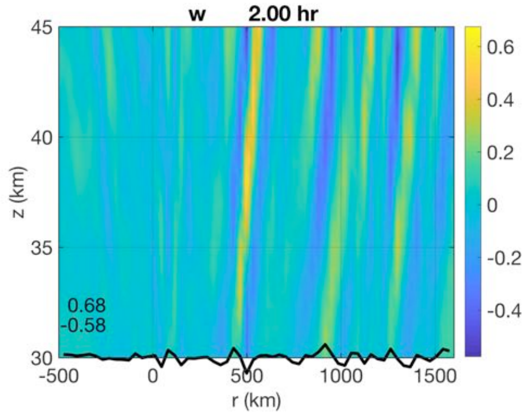

Figure 2. Vertical velocity w (m/s) in a vertical cross section between 30-45 km altitude at time 2 hr. The horizontal coordinate r is the horizontal distance from the center of Lousiana, in the southwest direction for r < 0, and in the northeast direction for r > 0.

For this weather event, solutions from the wave propagation model have also been compared with AIRS satellite observations of the stratosphere (see Azeem et al. 2015 for the AIRS observations). That comparison will be reported in a paper presently being prepared for publication.

Figure 3 shows in the left panel the vertical velocity at 300 km altitude predicted by the wave propagation model using the Fourier-multilayer method. The right panel shows TEC data at approximately the same time. The two plots have quite similar features, revealing wave phases arranged in concentric arcs radiating from the region of Lousiana toward the north-northeast and also into the region over Texas. The dominant horizontal wavelength is about 250 km and the dominant wave period is about 20 min.

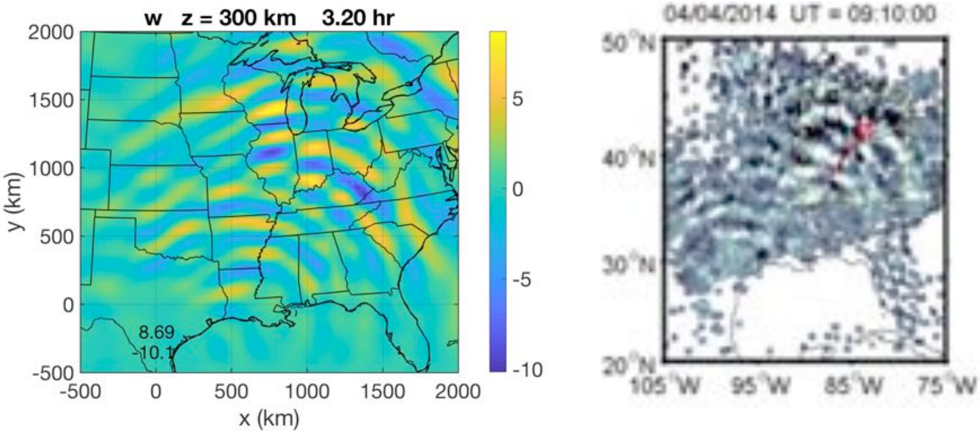

Figure 3. Left: The Fourier-multilayer solution for vertical velocity w (m/s) at 300 km altitude and time 3.2 hr. Right: TEC data for the same time, from Azeem et al. (2015).

Figure 4 shows a vertical cross section of the Fourier-multialyer solution. The wave phases tend to tilt upward with altitude and increasing viscosity, consistent with standard gravity wave theory. Note that the gravity waves reach 500 km altitude. This is very different from our experience with the Fourier-ray method, where the entire spectrum of rays are trapped and dissipatted below 350 km altitude.

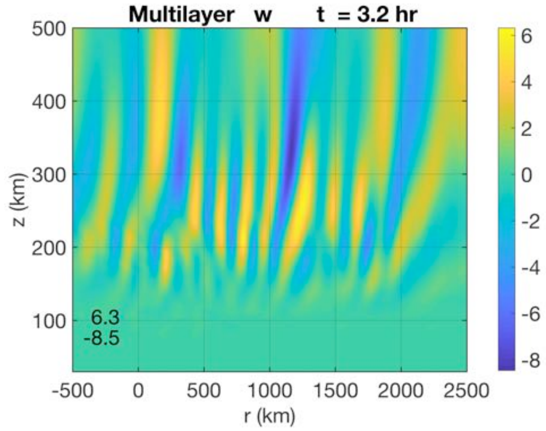

Figure 4. The Fourier-multilayer solution for vertical velocity w (m/s) in vertical cross section.

Further comments. The new idea developed here of coupling a weather model to a Fourier-based wave propagation model is clearly feasible and has the potential to become a new type of forecasting tool. The success here suggests that related problems for gravity waves or acoustic gravity waves could be treated in this same way, by coupling a near-field generation model with a far-field wave propagation model, e.g. for acoustic gravity waves generated by near-ground explosions.

Fourier methods have previously had spectacular successes in explaining gravity wave measurements in the stratosphere (Alexander et al. 2009) and in the mesopause region near 90 km altitude (Eckerman et al. 2016). Now this ability has been extended to much higher altitudes into the thermosphere. For the wavelength scales considered so far, it was not necessary to implement parameterizations for nonlinear processes such as wavebreaking and secondary wave generation, though these processes will need attention in some future applications.

Fourier solutions have been given to Dr. Kate Zawdie (NRL) for input into the wedge model of SAMI3 in order to predict TEC perturbations and to obtain a quantitative comparison of the coupled model with the TEC observations in Figure 3 above. That work is ongoing and will be written up for publication.

IMPACT/APPLICATIONS

This work has developed a new capability for predicting and understanding the effects of weather generated gravity waves on the ionosphere. The general technique should extend to other applications of scientific and national security interest. Events such as weather systems, earthquakes, tsunamis, explosions, rocket launches, generate gravity waves and acoustic gravity waves that can be modeled with the basic technique used here.

RELATED PROJECTS

S. Eckermann, J. McCormack, J. Doyle (NRL): Extending the Navy's Coupled Global-Mesoscale Environmental Prediction System (NAVGEM and COAMPS) into the Lower Thermosphere for Future Prediction of Bottomside Ionosphere. BSION Kickoff Meeting, 12 May 2017. COAMPS is the weather model component of the coupled model used for the present project. Doyle and his colleague

Q. Jiang at NRL Monterey provided the COAMPS simulations. NAVGEM provides background atmospheric profiles for the gravity wave propagation model, and initial conditions for COAMPS.

S. MacDonald, F. Sassi, K. Zawdie (NRL): Understanding the Mechanisms for Generation of TIDs in the Mid- to Low-latitude Ionosphere. BSION Kickoff Meeting, 12 May 2017. Fourier-ray solutions are being supplied to Dr. Zawdie for forcing input to the ionospheric model SAMI3.

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PUBLICATIONS

Two papers have been published, two are in preparation, and two more are planned. The published papers are:

Broutman, D., H. Knight, and S.D. Eckermann (2020), Compatibility conditions, complex frequency, and complex vertical wave number for models of gravity waves in the thermosphere. *J. Geophys. Res: Space Physics.* 125, e2020JAA028011. https://doi.org/10.1029/2020JA028011.

Knight, H., D. Broutman, and S.D. Eckermann (2019), A causality-preserving Fourier method for gravity waves in a viscous, thermally diffusive, and vertically varying atmosphere. *Wave Motion*, 88, 226-256. https://doi.org/10.1016/j.wavemoti.2019.06.001