Tracing Acoustic-Gravity Waves from the Ocean into the Ionosphere through Windows of Transparency in the Air-Sea Interface

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LONG-TERM GOALS

Recent advancements in the theory of wave propagation in the coupled ocean-atmosphere system demonstrate a necessity of and provide means for new estimates of the energy and momentum fluxes that acoustic-gravity waves (AGWs) carry from the ocean to the thermosphere and of their relative contribution into the thermosphere-ionosphere dynamics compared to other drivers. These are the long-term strategic goals of this project. Advanced analytical and numerical models will be developed to describe excitation, propagation, and dissipation of acoustic-gravity waves in a realistic, coupled ocean-atmosphere system.

OBJECTIVES

We propose to confirm experimentally existence of the effects of transparency in the air-sea interface. The experiments will include measurements of spectral, correlational, and coherence properties of the waves propagating through ocean and atmosphere into the thermosphere and will involve marine-based, atmospheric and ionospheric probes of wave motions. Our objective is to estimate and to measure at several locations the energy and momentum that is transmitted from the ocean into troposphere and further into the upper atmosphere and ionosphere. The measurements will be maintained and estimates obtained continuously over a few years long observational period. Eventually, we hope to obtain conclusions about the global significance of this coupling process for the dynamics of the upper atmosphere and ionosphere. We aim to quantify the role of persistent oceanic sources in generating waves in the upper atmosphere and ionosphere.

APPROACH

The following represents a list of specific tasks envisioned for the proposed project with a brief characterization of the methods to be used to accomplish them.

Theoretical Developments

1) The theory of the new type of wave motion that strongly couples the ocean and the atmosphere (Godin, 2012a, b) will be extended to realistic environments by taking into account finite ocean
depth, dissipative processes within fluids and at fluid-solid interfaces, and effects of winds and oceanic currents.

2) The theory of incompressible wave motion of compressible fluids (Godin, 2012a), which was originally developed for linear waves, will be extended to waves of finite amplitudes. This generalization is dictated by our goal to track the waves up to thermospheric altitudes where they likely to become nonlinear. The theoretical approach will build on the kinematic similarity of incompressible motions in compressible and incompressible fluids.

3) In addition to analytical techniques for horizontally invariant and spherically symmetric environmental models, numerical techniques will be applied to model AGW propagation in 3-D inhomogeneous, coupled ocean-atmosphere system. Typical cases of spatially varying bathymetry and orography will be considered.

4) Parameters of the transparency in the air-sea interface will be calculated for specific locations of existing data sources and of dedicated experiments planned within this project.

Experiments and Data Analysis

5) Data of Dynasonde systems favorably located near the ocean coasts (Wallops, Puerto Rico) and obtained with 2 min and faster cadence will be processed using NeXtYZ algorithm to obtain time series quantifying tilts of the plasma layers for calculation of the spectral power densities of AGWs at ionospheric altitudes. We will look for the spectral peaks corresponding to the respective transparency windows in the air-water interface and for the spectral features related to the Wideband Transparency. The high-latitude Tromsø station will be used as reference ones in our comparative studies.

6) We will select time intervals and/or arrange new experimental campaigns when pairs of Dynasondes performing ionospheric soundings and marine observing systems measuring bottom pressure variations operate simultaneously in geographically close locations. The data obtained in this way will be used to calculate cross-correlation functions for the waves propagating through the air-sea interface.

7) One of the above-mentioned Dynasonde systems (Puerto Rico), DART station #42407, and CTBTO IMS station HA05 are closely located in the East Caribbean area (these are only few hundred km apart), making a nice triangle. Another triangle is formed near the US East Coast by the Dynasonde at Wallops, DART station #44402, and CTBTO IMS station IS51. Correlation measurements between the vertices of these triangles will provide valuable information about the directionality of the AGWs penetrating the air-sea interface.

8) A combined approach involving data processing from both marine-based probes and Dynasondes will allow us to distinguish between the ocean-atmosphere wave couplings associated with specific events (underwater earthquakes) and the background.

9) Parameters of the wave structure measured by the Dynasonde methods allow us to back-propagate AGWs from the ionosphere to their generation sites. Combination of the origin information with spectral and correlational results will allow us to connect the wave processes in the ionosphere with existence and properties of the transparency in the air-sea interface.

10) The analytical and numerical models of AGW propagation and generation will be combined with data from our measurements on the seafloor and in the ionosphere to evaluate the vertical energy and momentum fluxes carried by the low-frequency AGWs through the air-sea interface and further into the upper atmosphere.
Responsibilities of the key project participants are distributed as follows. Responsibilities of Prof. Nikolay A. Zabotin (Principal Investigator) include development of methods, algorithms, and software for data processing; planning and conducting of experiments; collecting data from marine-based probes; development of numerical models for AGW propagation; data analysis. He is the primary executor of Tasks 3-4 and Tasks 6, 9, and 10. He also is involved in Tasks 5, 7, 8.

Dr. Oleg A. Godin (Co-Principal Investigator) is responsible for development of analytical approaches in the theory of wave propagation and generation. He contributes to experiment planning, development of algorithms for numerical models of AGW propagation, and data analysis. Dr. Godin is the primary executor in Tasks 1-2, is involved in Tasks 3-4 and in Task 10, and in the planning and results interpretation part of Tasks 5-10.

Responsibilities of Dr. Terence W. Bullett (Co-Principal Investigator) include operating and collecting research-quality data from Dynasondes in Wallops, San Juan, and Boulder; negotiating data exchange with non-CU controlled instruments; collecting supportive ionosphere data from other sources, such as Arecibo and Jicamarca ISR; and participation in the data interpretation. Dr. Bullett thus contributes directly in Tasks 5-10.

Catalin Negrea (Graduate Research Assistant) is involved in studies of acoustic-gravity waves in the upper atmosphere and ionosphere conducted by Dynasonde means as the primary topic of his PhD degree program. His responsibilities include development of algorithms and software for data analysis; data analysis. Catalin is the primary executor of Tasks 7, 8 and contributes to Tasks 5-6, 9, 10.

**WORK COMPLETED**

- Theory of the connection between background IGWs in the ocean and the background AGWs in the atmosphere was developed and published.
- First results of a unique geophysical experiment involving data from marine-based (DARTs) and ionospheric (Dynasondes) probes have been obtained.
- Strong spectral correlation has been discovered between IGWs and AGWs at thermospheric altitudes (up to 0.46) in the frequency range 0.1-3 mHz.
- Dynasonde techniques capable to fill the widely acknowledged thermospheric gap in tidal and gravity wave data have been developed.
- The Dynasonde analysis capability to measure characteristics of the wave activity in the ionosphere/thermosphere system has been improved to include estimates of body forcing.
- A consistent WKB theory describing propagation and attenuation of AGWs in the atmosphere has been developed and published.
- Numerical analysis of wave attenuation for tsunami, IGW, and Rayleigh wave manifestations at ionospheric heights using realistic atmospheric model has been performed.
- Simple, exact solutions of the nonlinear equations of motion for incompressible waves in compressible fluids have been obtained and published.
- Operation of San Juan Dynasonde system has been improved to exclude artificial gaps in the data.
- Results have been presented at 5 conferences. Special session Acoustic-gravity waves: From ocean and land to space has been organized at the 2015 EGU General Assembly.
RESULTS

Significant correlation between spectral amplitudes of infragravity waves in the ocean and acoustic gravity waves in the thermosphere has been revealed as a result of analysis of the data from Wallops Island Dynasonde and the two DART stations (#44402 and #41424). Maximum values of the correlation coefficients reach 0.43-0.46 (Fig. 1). 9 month duration of the data series has ensured a high statistical significance of the correlation values. Figure 1 shows that the correlation remains predominantly positive within the high confidence bounds, on the average decreasing with the altitude from the maximum values to zero, in a very broad frequency band (~0.2–3.4 mHz) and in the altitude range from 140 to 180 km). At the same time the correlation coefficient demonstrates highly uneven structure in the spectral domain with several prominent peaks. These common tendencies are stronger for the closer (and located in the shallower ocean) DART 44402 than the DART 41424. Another prominent feature in the correlations of the normalized spectral amplitudes is that the correlation coefficient becomes predominantly negative at higher altitudes. The negative correlation has been also established with high confidence (Fig. 1). The minimum values of the correlation coefficients are close to -0.3 for the two instrument pairs.

The result can be considered as a direct confirmation of the theoretical concept of coupling between the infragravity waves in the ocean and acoustic gravity waves in the thermosphere [Godin et al., 2015]. The experimentally observed peaks of the correlation occur at the altitudes as low as 140–150 km, where dissipative (linear) attenuation of AGWs is only starting to manifest itself. At higher altitudes, temporal variations of the atmospheric attenuation serve as a natural decorrelation factor for waves originating at the sea level. The transition from the significant positive correlation to significant negative correlation at higher altitudes can be a consequence of AGW nonlinearity at high altitudes, specifically, of wave breaking. A similar effect has been observed during DEEPWAVE campaign [Fritts et al., 2015a,b].

The observed peak values of the correlation between normalized spectral amplitudes of IGWs in the ocean and AGWs in the thermosphere is high enough. While the question of relative significance of the ocean-generated waves remains open, our results call for a change in the existing paradigm, which ignores completely the role of IGWs in supporting background thermospheric wave activity. The empirical findings reveal a previously unrecognized, important link in the coupled ocean-atmosphere system. Adjustments may be necessary in estimates of the momentum deposition by AGWs in the thermosphere.

Further development of Dynasonde’s ability to measure characteristics of acoustic gravity waves resulted in the first empirical estimates of the body forcing rendered on the neutral component of the thermosphere over Wallops Island, VA. Fig. 2 provides a glimpse of the basic properties of this phenomenon using data from 24 October 2013. The resulting acceleration of the neutral component is an integral over the 0.1-4 mHz spectral band of the gravity waves. Different harmonics in the spectrum may prevail at different altitudes, hence the irregular structure of both modulus and direction of the acceleration. Nevertheless the general tendency is clear: average modulus of the acceleration increases dramatically with the altitude (mainly following the exponential decrease in density of the neutral atmosphere) while several spots of dominating colors in the second panel mark prevailing directions of momentum deposition in the time-altitude domain. Both characteristics are highly variable in time.

Ray and WKB approximations have long been important tools of understanding and modeling propagation of atmospheric waves. However, contradictory claims regarding the applicability and
uniqueness of the WKB approximation persist in the literature. We have resolved the contradictions through a rigorous mathematical analysis of the problem (Godin, 2015b). A self-consistent version of the WKB approximation has been systematically derived from first principles and compared to ad hoc approximations proposed earlier. The parameters of the problem have been identified that need to be small to ensure the validity of the WKB approximation. Contrary to the better-studied cases of acoustic waves and internal gravity waves in the Boussinesq approximation, the WKB solution contains the geometric, or Berry, phase. The Berry phase is generally non-negligible for acoustic-gravity waves (AGWs) in a moving atmosphere. In other words, knowledge of the AGW dispersion relation is not sufficient for calculation of the wave phase (Godin, 2015b).

The ray theory predicts unphysical, divergent values of the wave amplitude and needs to be modified in the vicinity of caustics. We have developed an asymptotic theory that describes diffraction, focusing and increased dissipation of acoustic-gravity waves in the vicinity of caustics and turning points. Uniform asymptotics of the wave field have been expressed in terms of Airy functions and their derivatives. The geometrical, or Berry, phase, which arises in the consistent WKB approximation for acoustic-gravity waves, plays an important role in the caustic asymptotics. In addition to the wave field in the vicinity of the caustic, these asymptotics describe wave reflection from the caustic and the evanescent wave field beyond the caustic. The evanescent wave field have been found to play an important role in ionospheric manifestations of tsunamis (see Fig. 2).

Using the ray theory and its caustic extensions, we have modeled propagation of acoustic-gravity waves in three-dimensionally inhomogeneous atmosphere. Huygens’ wavefront-tracing was used to simulate wave propagation from an earthquake hypocenter through the earth’s crust and ocean to the upper atmosphere. We have quantified the influence of temperature stratification and winds, including their seasonal variability, and air viscosity and thermal conductivity on the geometry and amplitude of ionospheric disturbances. We have found, in particular, that

- to relate quantitatively the characteristics of the observed ionospheric disturbances and the underlying natural hazard, it is imperative to accurately model AGW propagation through the actual atmosphere;
- at propagation from ground level to the ionosphere, the differences between AGW attenuation, which is predicted by ad hoc and consistent asymptotic models, are significant and can exceed 10 dB for tsunami-generated AGWs;
- absorption of waves in the upper atmosphere is strongly anisotropic. Critical levels in the atmosphere limit the geographical extent of possible ionospheric manifestations of tsunamis. Both the AGW absorption and attenuation due to diffraction affect the magnitude of the ionospheric signatures of tsunamis (see Fig. 3);
- variability of the neutral atmosphere affects the intensity of ionospheric signatures of earthquakes primarily through the variations in the AGW absorption at ionospheric heights.
Figure 1. Correlations of normalized spectral amplitudes of oceanic and atmospheric waves. Color scale shows correlation coefficient for wave activities in the thermosphere over Wallops Island and in the ocean at the two DART locations (top and bottom panels for DART 44402 and DART 41424 correspondingly) as functions of the frequency and the altitude. The white contours in the plots represent 95% confidence level boundaries for positive and negative values of the correlation coefficient. The red contours correspond to zero value of the correlation coefficient. [The values of the correlation coefficient are shown by the color scale that varies from dark blue (lowest values) to bright yellow (highest values). The colors tend to be yellow near the bottom of every panel indicating peak correlation values.]
Figure 2. Characteristics of the body forcing rendered by the acoustic gravity waves on the neutral component of the thermosphere over Wallops Island, VA estimated from Dynasonde data for 24 October 2013. The left panel uses color scale to show modulus of the acceleration vector as a function of time of day and the altitude. The right panel uses cyclic color scale to show direction of the acceleration vector in the same coordinates. The acceleration vector is defined as integral over AGW spectrum in the 0.1-4 mHz band.

[The two panels refer to the modulus (left) and the direction (right) of the acceleration vector. The values of the modulus are shown by the color scale that varies from dark blue (lowest values) to red (highest values). The colors tend to be blue near the bottom and red near the top of this panel. The display of the azimuth of the acceleration vector is somewhat irregular, but still reveals several spots of dominating colors marking prevailing directions of momentum deposition in the time-altitude domain.]
Figure 3. A realistic simulation of the amplitude of the acoustic gravity waves radiated by the ocean waves (tsunamis/IGWs) in the frequency band 0.1-3.5 mHz for the ocean depth 2600 m using output of the NOAA’s Whole Atmosphere Model corresponding to a weaker atmospheric attenuation. Amplitude is shown by the color scale in dBs of the power relative to one at the sea level vs frequency and for altitude range 0-400 km. The change in the altitude distribution of the wave amplitude that occurs at frequencies higher than 1.7 mHz is caused by domination of the evanescent waves that preserve ability to propagate in horizontal direction and to contribute to observable effects.

[Color scale (from dark blue to bright yellow) is used to show the dB level of the wave power. The strongest manifestation of the wave activity are expected at the altitude range 150-200 km with the favorable frequency band extending up to 2.5 mHz due to the contribution from evanescent waves.]
Figure 4. A global map of the variance of the total attenuation (expressed in dBs) of AGWs caused by the short-period (15 min) tsunamis assuming propagation to 250 km altitude with four different directions of propagation (0, 90, 180, and 270 deg of the azimuth). The total attenuation is defined as a sum of the collisional (viscous) losses and the diffraction attenuation. A single output of the NOAA’s Whole Atmosphere Model has been used to simulate realistic propagation conditions. The variance is shown by the color (varying from dark blue to dark red). Geographic regions where propagation to 250 km altitude was impossible due to presence of critical levels in the atmosphere are marked by black. The variance reaches 25 dB in an important central Pacific region.
IMPACT/APPLICATIONS

The scientific findings of this project would find their most immediate relevance to ionosphere observation, specification and prediction. This information is needed to understand and possibly mitigate impacts of the AGW effects in the ionosphere on Navy radio and radar systems. The findings and data are likely to be useful to future NOGAPS-ALPHA development and operations including more accurate evaluations of thermal balance in the thermosphere. This effort will help future Navy ionospheric modification experiments using high power radio waves or chemical releases and general atmospheric and ionospheric modeling.

RELATED PROJECTS

1. CU Innovative Seed Grant Program (IGP), Study of Ocean Infragravity waves with a Large Array of Seafloor Seismometers, 2012-2013 (PI - Anne F. Sheehan). We have further developed the empirical model of IGW spectrum, this time using data from PLUME experiment near Hawaii.

2. ONR Award Number N00014-08-1-0100, Dynamics and Stability of Acoustic Wavefronts in the Ocean, 2011-2013 (PI – Oleg A. Godin). This effort has resulted in development of a code for acoustical Huygens wavefront tracing in moving media. We plan to generalize the code for AGWs and to use it for AGW back-propagation.

3. Northrup Grumman Mission Systems, subcontract # 7500040060, Systems Engineering Management and Sustainment II: Global Ionosonde data, 2011-2014 (PI – Terence W. Bullett). This effort covers the field site operations and collection of routine ionosphere space weather information from older Digisonde ionosondes located at Wallops Island and Puerto Rico. The existence of this support covers the field site expenses for the present project.

REFERENCES


Fritts, D., R. Smith, M. Taylor, J. Doyle, S. Eckermann, A. Dörnbrack, M. Rapp, B. Williams, K. Bossert, and D. Pautet (2015b), Initial Results from the DEEPWAVE Airborne and Ground-
Based Measurement Program in New Zealand in 2014, paper presented at the General Assembly of the European Geosciences Union, EGU, Vienna, Austria.


**PUBLICATIONS**


