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Observation and Modeling of Tsunami-Generated Gravity Waves in the Earth's Upper Atmosphere

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LONG-TERM GOALS

We will deploy an expanded ground-based observation network using strategically placed optical imaging systems together with a TIDDBIT HF Doppler ionospheric sounder to obtain new information about the ionospheric waves associated with tsunamis. In addition, we will leverage and augment a published and validated gravity wave ray trace model to perform studies of the propagation of tsunami-generated gravity waves through the atmosphere and into the thermosphere/ionosphere system. We will exercise this model using conditions representative of historical tsunami events and use the resultant model simulations to develop and test different observing scenarios and detection algorithms. The successful completion of this project will lay the groundwork for an expanded tsunami monitoring/warning system, possibly including a satellite observing system that could provide warnings of tsunamis in real time. The proposed work will also enhance our understanding of upward coupling caused by all gravity wave sources in the lower atmosphere (not just tsunamis) and how this coupling can generate ionospheric irregularities that affect navigation, communications and surveillance systems used by the Navy and other branches of DoD.

OBJECTIVES

The proposed program will address the lack of measurements pertinent to understanding the generation of the tsunami-airglow signature in the thermosphere/ionosphere by creating a multisite imaging network in the Pacific region, augmented by additional instrumentation in Hawaii. We will also develop a more-realistic, ocean-atmosphere coupling model that will allow for a detailed study of the physical mechanisms responsible for the coupling. The outputs of this model will be validated against observations of historical tsunamis, initially the March 2011 event. Additional events will be studied with the deployed network and model as they occur. Historical events will be studied in the case no tsunamis occur during the duration of the proposed program. Finally, the model will be used to investigate additional observing viewing modalities, specifically from space-based imaging platforms, and to develop and test detection algorithms that will be useful for future deployments of sensors to monitor ocean-atmosphere coupling effects.

APPROACH

Imaging of the earth's naturally occurring airglow layers has been a primary way of studying structures in the thermosphere/ionosphere system for several decades. Optical imaging has the benefit of being able to provide insight into the spatial/temporal development of structures using a single sensing system. The imaging systems operated in this effort make measurements of specific naturally occurring optical emissions selected for study utilizing narrowband filters (2.0-nm full-width, half-maximum) and then captured on very sensitive, thermoelectrically cooled CCD sensors. The primary optics can be designed to either provide higher spatial resolution (~500 m) images over a small field of view or a somewhat coarser spatial resolution (~2 km) image over a wider field of view. These imaging systems are extremely robust and require little maintenance or user interaction once they are deployed. They operate using custom software written by Prof. Makela to automatically collect data using a predefined filter sequence whenever the moon and sun are below the local horizon. Observatories in Hawaii, Chile, and Tahiti will be utilized in this study.

We will also deploy a TIDDBIT HF sounder in Hawaii to study the ionospheric height fluctuations associated with tsunamis to augment and corroborate the optical data obtained from the Haleakala imaging systems. The HF Doppler technique is a sensitive method for detecting transient changes in the ionosphere, especially in the vertical direction. The deployment of the TIDDBIT system will be conducted in collaboration with Dr. Geoff Crowley of ASTRA, LLC.

The modeling portion of this program consists of multiple parts and has been condutcted in collaboration with Dr. Sharon Vadas of Northwest Research Associates. The model first calculates the gravity waves excited by the moving ocean tsunami wave. Next, the model ray traces these gravity waves with their phases into the thermosphere using the atmospheric gravity wave dispersion relation for spatially and temporally-localized sources. We then reconstruct the gravity wave field at z = 200-300 km for comparison to observational data and other models. Importantly, this model includes the dissipative filtering of high-frequency gravity waves in the thermosphere, which is critical for determining the correct amplitudes of the gravity waves in the mid-thermosphere, and is therefore critical for determining the correct amplitudes of the waves in the 630.0-nm images. In the final step, we will calculate the electron density perturbations and ion velocities induced by the neutral perturbations associated with these gravity waves using a single-ion approximation. This approximation is valid above 200-km altitude where the ionosphere consists primarily of O+, and is adequate for our study because the observations of the 630.0-nm emission integrates light from z = 220 to 280 km.

WORK COMPLETED

The following tasks have been completed in the current year:

1) Continued operations of imaging systems in Tahiti and Hawaii.
2) Repaired an imaging system in Chile and reployed that system.
3) Repaired one of the imaging systems in Hawaii. The system will be redeployed by November 2015.
4) Developed an analytical "observing factor" to understand how the relationship of a tsunami's orientation, the magnetic field geometry, and the observing geometry conspire to allow for the

observation of the tsunami-generated gravity wave in the ionosphere. The results have been submitted for publication.

5) Collaborated with S. Vadas at NorthWest Research Associates on the completion of the neutral atmospheric gravity wave model. The results have been accepted for publication.
6) Collaborated with G. Crowley and I. Azeem at ASTRA, LLC on the study of the ionospheric disturbances over the continental US caused by the Tohoku tsunami. The results have been submitted for publication.
7) Collaborated with J. Huba at the Naval Research Laboratory to study conjugate effects in the electron density driven by ion-neutral coupling effects during the passage of a gravity wave through the ionosphere. The results have been published.
8) Spent one month as a visiting professor at Institut de Physique du Globe de Paris collaborating with colleagues there on this project. Worked with G. Occhipinti and his student to study the Haida Gwai tsunami event and collaborate on comparisons of a gravity wave model to airglow observations. Worked with P. Coïsson to study the ability to see electron density perturbations in the conjugate hemisphere.
9) Continued working with G. Crowley of ASTRA, LLC to deploy the TIDDBIT system to Hawaii.
10) Proposed an international workshop on tsunami-atmosphere coupling to be held at the International Space Sciences Institute in Bern, Switzerland. This proposal has been accepted and the first of two workshops will be held in February 2016.
11) An undergraduate student at the University of Illinois completed his senior thesis based on work carried out under this project. The student has been recruited as a graduate student in our program and continues to work on this project.
12) Presented results of the project at the 2014 Fall AGU conference, the ONR BRC Couplings: Ocean-to-Space Program and Science Review workshop, and the CEDAR workshop. In addition, gave a general-audience talk on the project results as part of the Department of Electrical and Computer Engineering's Saturday Engineering for Everyone lecture series. Over 100 people attended this lecture. A total of 8 presentations were given related to this project during the previous year.

RESULTS

We have generated an analytic methodology that predicts the best observing geometry for capturing the ionospheric signature of the atmospheric gravity waves launched by tsunamis. The method only requires knowledge of the observing location and very basic properties of the tsunami (i.e., orientation). Because it does not require a detailed model of the tsunami, it can be quickly computed in realt-time to help plan observations. An example of the observing factor for our imaging system on Hawaii for the recent tsunami generated by the earthquake off the coast of Chile in

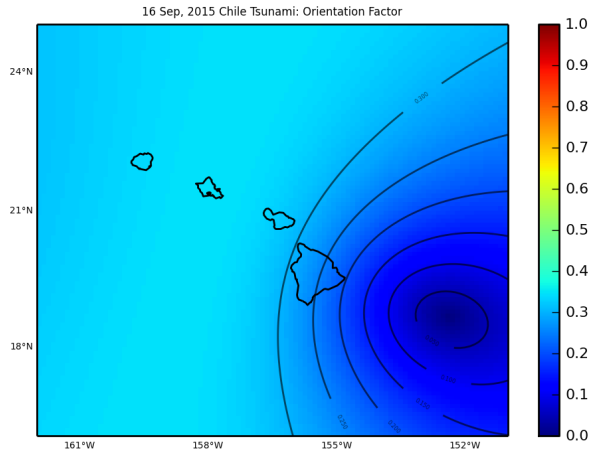

Figure 1: Observing factor calculated for the September 16, 2015 tsunami launched by the earthquake off the coast of Chile. The calculation was performed for the imaging system operated on the Haleakala Volcano and indicates better observations to the northwest of the islands.

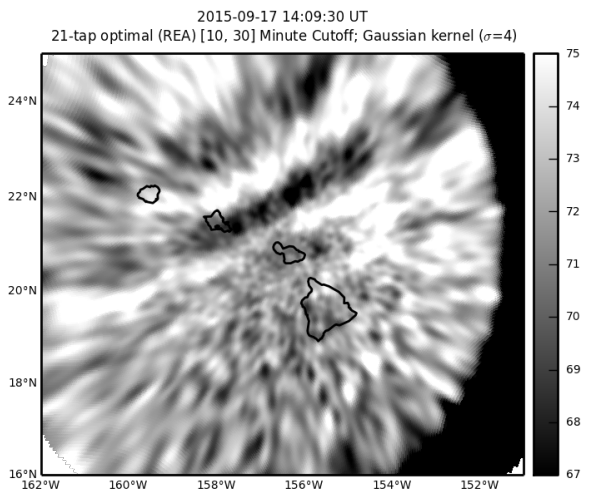

Figure 2: Example airglow image showing waves associated with the September 2015 tsunami. The waves are only observed to the northwest of the observatory, as predicted by the observing factor presented in Figure 1.

September 2015 is provided in Figure 1, indicating the liklihood of observing the gravity waves to the north west of the islands.

For the September 2015 tsunami event, we captured the signature of the gravity waves as they passed through the airglow layer at 250-km altitude using the imaging system operated atop the Haleakala Volcano on Maui, HI. This is the third event that we have captured (complementing earlier results from the 2011 Tohoku and 2012 Haida Gwai events), further cemeting the airglow technique as a viable way to study these waves and, perhaps, serve as a validation for models. An example image showing the waves seen in the airglow are presented in Figure 2. The waves, oriented from the southwest to northeast, are seen in subsequent images to propagate towards the northwest, away from the epicenter off the coast of Chile. Importantly, as predicted by the observing factor presented in

Figure 1, the waves are only observed as they pass to the northwest of the observatory. This confirms the utility of the observing factor methodology.

Working with Dr. Sharon Vadas at NorthWest Research Associates (a collaborator on this project), a new ocean to gravity wave model has been generated. This model takes a novel approch of treating the tsunami in a time-and-space dependent method generating surface wave packets. This allows a more comprehensive and realistic treatment of the effects of these gravity waves on the upper atmosphere once they are ray traced through a background atmosphere. The initial results from this model have been accepted for publication. We will exercise this model in a benchmarking study, conducted for a workshop sponsored by the International Space Sciences Institute, that we are convening in 2016. This benchmarking study will allow for the comparison of the model developed under this program to other state-of-the-art models being used in the community.

IMPACT/APPLICATIONS

This research program has resulted in a gravity wave model, coupled to the ocean surface, which can be used to more realistically study upward wave coupling and energy propagation into the upper atmosphere. The model will be used to investigate the feasibility of detecting the tsunami-airglow signature from a variety of observing platforms, including a spacebased imaging system. Such a system, if shown to be viable, would allow for continuous monitoring for tsunamis from a single space-based platform.

Furthermore, this study will allow investigation of the effects of upward coupling on the generation of ionospheric structures, such as EPBs and MSTIDs, which can have adverse effects on critical navigation and communication capabilities. Perturbations in the neutral atmosphere, similar to those due to the tsunami-generated AGWs, are oftentimes cited as a seed mechanism for these structures. The optical and radio data collected by the deployed sensor network deployed under this project can contribute to our understanding of upward coupling caused by non-tsunami gravity wave sources and how this coupling can generate ionospheric irregularities that affect navigation, communications and surveillance systems used by the Navy and other branches of DoD.

The deployment of instrumentation, including the completed deployment of a new imaging system to Tahiti and the pending deployment of a TIDDBIT radar system to Hawaii will greatly improve the observational capabilities for studying ocean-ionosphere coupling in the Pacific. The pairing of the imaging systems in Hawaii and Tahiti may allow understanding conjugate effects of the tsunami-induced gravity waves.

PUBLICATIONS

Huba, J. D., D. P. Drob, T.-W. Wu, and J. J. Makela (2015). Modeling the ionospheric impact of tsunami-driven gravity waves with SAMI3: Conjugate effects. *Geophysical Research Letters*, *42*(14), 5719 - 5726. doi:10.1002/2015GL064871 [published, refereed]

Grawe, M. A. (2015), Investigating tsunami-ionospheric coupling efficiency. Senior thesis. University of Illinois at Urbana-Champaign. [published]

Vadas, S. L., J. J. Makela, M. J. Nicolls, R. F. Milliff (accepted). Excitation of gravity waves from ocean surface packets, propagation into the thermosphere, and reconstruction of the gravity wave field. *Journal of Geophysical Research*. [accepted, refereed]

Azeem, I. G. Crowley, S. Vadas, J. J. Makela, T. M. Duly, and A. Reynolds (submitted). Observations of Traveling Ionospheric Disturbances (TIDs) Over the United States Assocaited with the Tsunami Generated by the 2011 Tohoku Earthquake. *Journal of Geophysical Research*. [submitted, refereed]

Grawe, M. A., and J. J. Makela (submitted). The ionospheric responses to the 2011 Tohoku, 2012 Haida Gwaii, and 2010 Chile tsunamis: Effects of tsunami orientation and observation geometry. *Earth and Space Science*. [submitted, refereed]

HONORS/AWARDS/PRIZES

M. A. Grawe (undergraduate student working on the project), University of Illinois at Urbana-Champaign, Student Poster Prize, 2015 CEDAR Workshop, Seattle, WA.