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Real-Time Assimilation of Ionospheric Data for Tsunami Prediction

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LONG-TERM GOALS

Tsunami-generated acoustic-gravity waves propagate in the atmosphere up to the ionosphere, where they have been observed to have an impact on total electron content (TEC). We simulate the wave motions in the atmosphere and investigate its effect on TEC in the ionosphere with the long-term goal of real-time tsunami forecasting.

OBJECTIVES

Our initial objective is to formulate and implement a fast and accurate numerical scheme to compute the internal wave energy that reaches the upper atmosphere due to tsunami forcing of internal waves in a realistic atmosphere. We are also aiming to develop a rapid two-dimensional Eulerian fast marching method to compute the horizontal dependence of internal waves.

APPROACH

During FY15, we continued our research on the propagation of two-dimensional tsunami-generated acoustic-gravity waves (AGW) through the atmosphere up to the lower ionosphere and entended the calculation to three dimensions. For the 2D problem, we simulated the propagation of AGW in a

horizontal wind field whose direction coincides with that of the tsunami propagation. We included compressibility of the atmosphere to understand how this modifies the anelastic results of Broutman et al. (2014). We used a tsunami-perturbed lower boundary and an upper radiation boundary condition. By Fourier transforming in the horizontal, we obtained a vertical structure equation for the vertical velocity of the wave motion which is essentially a compressible Taylor-Goldstein's equation. We calculated the transmission and reflection coefficients for each Fourier component and then inverted the transform to obtain the solution for the vertical velocity in the spatial domain.

For the 3D problem, we used a 3D tsunami-perturbed sea surface as our lower boundary and the same upper boundary condition. Our goal is to understand the effects of varying wind profiles with different profiles, widths and angles to the direction of tsunami propagation on the transmission and reflection of AGW and on the total energy reaching the lower ionosphere.

The second part of the project aims at developing an accurate and efficient numerical method to compute the propagation of tsunami-related acoustic-gravity waves throughout the atmosphere, taking into account inhomogeneities of the medium in all directions. These inhomogeneities consist of vertical and horizontal variations of the horizontal wind and the thermodynamical properties of the atmosphere. The majority of the work so far has consisted in investigating different methods for this. The method we are pursuing decomposes the solution into vertical normal modes and horizontal rays (e.g. Burridge & Weinberg, 1977), taking advantage of the fact that atmospheric properties vary quite rapidly in the vertical, but more slowly in the horizontal.

WORK COMPLETED AND RESULTS

In the 2D problem, we investigate two cases with different wind profiles: an idealized wind jet and a realistic wind profile in the 2004 Sumatra tsunami. Results show that in general, compressibility has a non-negligible effect on the number and height of turning points and enhances the wave transmission through the whole atmosphere. By varying the velocity and the width of the jet, we find that the faster and/or the wider the wind, the smaller the transmission. In the compressible wind jet case, the distribution of propagating and evanescent regions is more symmetric about the central axis of the wind jet than that in the anelastic case. In the compressible 2004 Sumatra tsunami case, the transmission coefficient is reduced for large wavenumbers and enhanced for smaller wavenumbers.

In the 3D problem, we investigated three cases: a wind jet with fixed angle, a wind spiral and the realistic wind profile. In the first two cases, by varying the angle between the peak wind and the tsunami, we observe a clear change of the wave transmission and reflection as well as the distribution of the evanescent regions. Comparing the first two cases, we conclude that winds of varying angles lead to a slightly different pattern of the vertical structure with an enhanced horizontal dispersion.

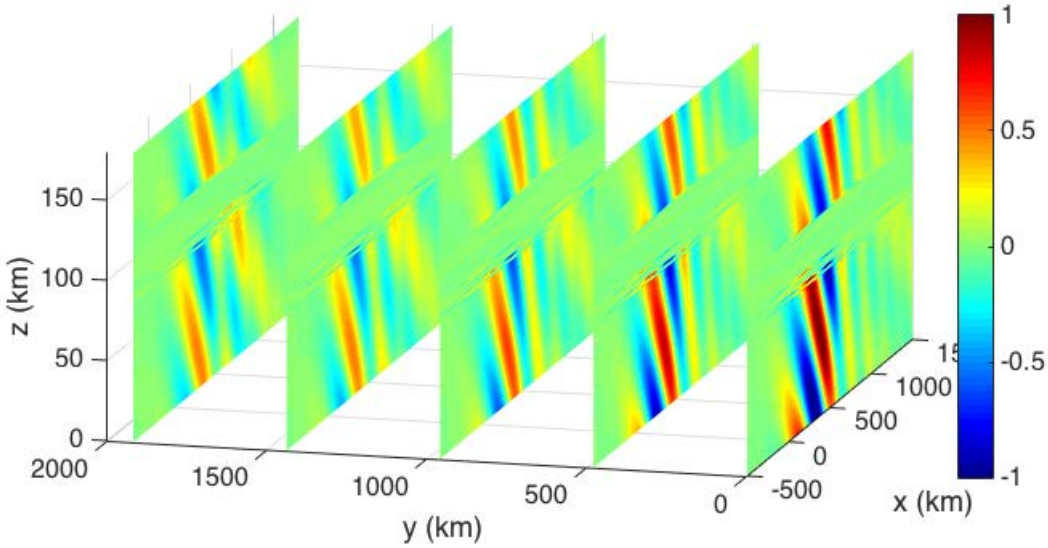

Figure 1. w/W_0 for upgoing waves in the idealized wind jet case.

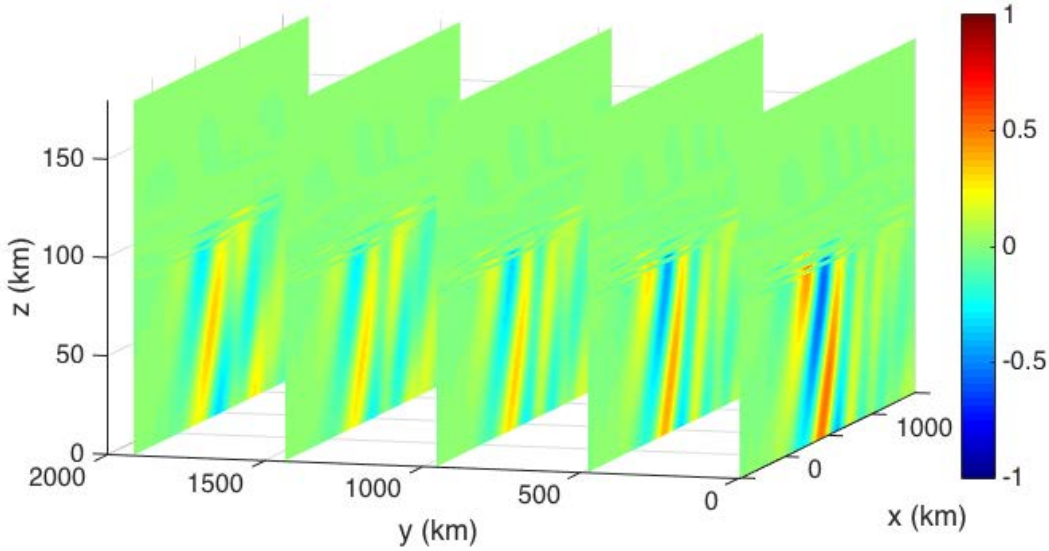

Figure 2. w/W_0 for downgoing waves in the idealized wind jet case.

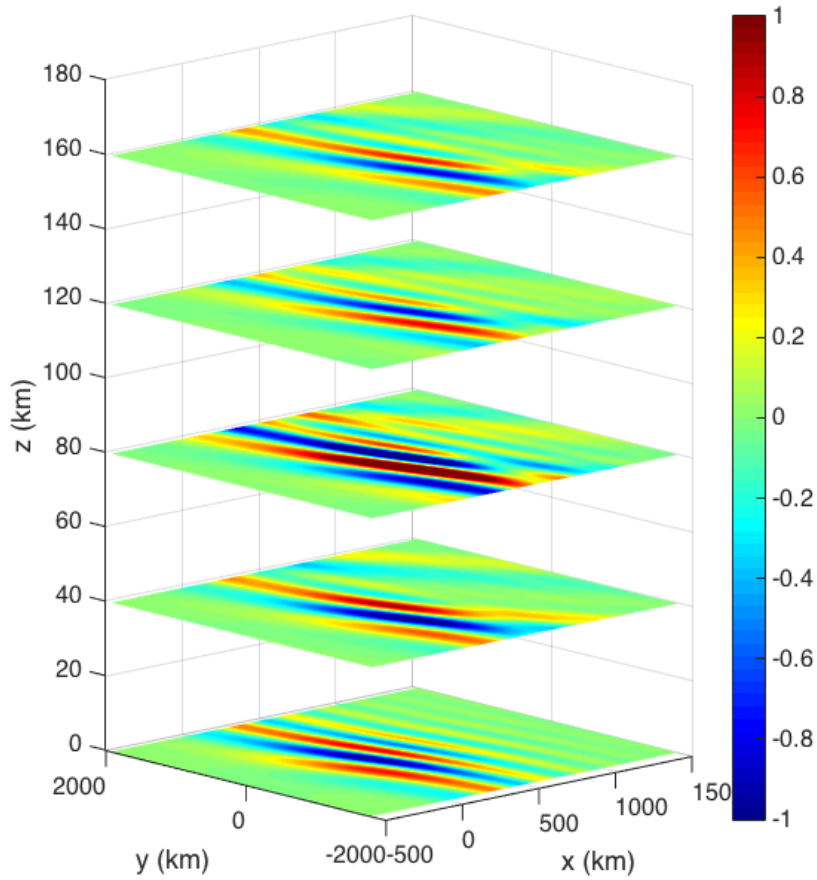

Figure 1. w/W_0 for ODE solutions (upgoing + downgoing) in the idealized wind jet case.

For the second part of the project, we investigated ray tracing and Wentzel-Kramers-Brillouin-Jeffreys (WKBJ) theories in the context of tsunami-generated waves. It was not expected *a priori* that ray theory could be applied directly, mainly because the vertical variation of the atmospheric properties are of the order of the vertical length scale of the waves, and because a large part of the tsunami-generated energy propagates through several reflexion levels where they are partially transmitted (Broutman et al., 2014), which is just discarded by the standard WKBJ approximation. However, ray tracing appears to be the best method to describe the horizontal propagation, because of the existence of efficient numerical methods. We have chosen two that are highly relevant to this problem: 1) level set methods and 2) phase-space (Eulerian or Lagrangian) ray tracing. The latter has been implemented for a simplified (one-dimensional) problem.

We have been working on the proper formulation of wave propagation in terms of vertical normal modes and horizontal rays. This method is customary in waveguide theory (e.g. in optics) and in ocean acoustics (Desaubies & Dysthe, 1995). From the initial system of equations, one decomposes the solution into a sum of normal modes with amplitudes that depend on the horizontal coordinates (but not on the vertical). The vertical modes themselves contain a parametric dependence in the horizontal coordinate, and are given by the solutions of an eigenvalue problem. Then, the horizontal problem (for

each vertical mode) can be solved using ray methods. However, some differences exist between the standard framework of application of this method and the tsunami-related atmospheric wave propagation: 1) the waves considered have a different nature, as only the acoustic branch is retained in the ocean acoustics context; 2) the background flow is usually neglected in acoustics; 3) the upper boundary condition is an outgoing radiation condition in the atmosphere, rigid lid in the oceans; and 4) the forcing by the tsunami spreads over a large area, whereas a point-source approximation is used in ocean acoustics theory.

We have implemented a solver using the above formulation (normal modes in the vertical and horizontal rays) for the propagation of waves generated by an arbitrary forcing at the bottom, in the two-dimensional (vertical and 1D horizontal) space. The horizontal structure is thus given by the WKBJ solution of a Helmholtz equation with slowly varying parameter. Further developments of this numerical code will address compressibility, three-dimensionality (thus implementing a 2D ray tracer in the horizontal) and outgoing radiation condition at the upper boundary. A modified version of the ansatz that correct the coupling between vertical modes is also being developed, which might increase the accuracy of the method.

IMPACT/APPLICATIONS

In December 2014, we presented a poster about our 2D results at the 2014 AGU Fall Meeting in San Francisco. We will present our 3D results at the same meeting this year. In September 2015, we submitted a paper titled "*The Propagation of Tsunami Generated Acoustic-Gravity Waves in the Atmosphere*" to *Journal of the Atmospheric Sciences* and the paper is currently under revision. The ray-tracing work will be presented at the 2015 APS Division of Fluid Dynamics meeting in Boston.

RELATED PROJECTS

None.

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