Analysis of gravity waves in the stratosphere after the 2011 Tohoku earthquake

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Abstract: After the Tohoku earthquake on March 11, 2011, strong ionospheric disturbances and propagating concentric waves were detected. The slowest waves have been assigned to be the gravity modes of the coseismic atmospheric gravity waves and (Matsumura, 2011) has argued that most the ionospheric oscillations are mainly due to the motion of neutral atmosphere. Using the spatially and temporally nearest GPS radio occultation data we have studied the possible influence of the earthquake situation on the internal gravity waves in the stratospheric region. From the comparison of the vertical wave number power spectral density before and after the earthquake remarkably different modes were selected. The altitude wavelength behavior of these modes was analyzed using the continuous wavelet transform and using the improved algorithm proposed by Gubenko et al. (2012) other parameters of these modes are determined. Finally, suitability of utilization of GPS RO density instead of temperature profiles for analyses of IGW is discussed.

Introduction: After the Tohoku earthquake on March 11, 2011, strong ionospheric disturbances and propagating concentric waves were detected. The slowest waves have been assigned to be the gravity modes of the coseismic atmospheric gravity waves and Matsumura (2011) has argued that most of the ionospheric oscillations are mainly due to the motion of neutral atmosphere.

Advantage of usage of density profiles: Unlike temperature, the general form of density background profile in atmosphere like systems is known from the statistical mechanics theory. In addition, the usage of the hydrostatic balance in the standard dry temperature retrieval not just lowers the amplitudes (Steiner and Kirchengast, 2000) but also leads to the fact that in the resulting equations of motions also the dynamic pressure and density fluctuations are in hydrostatic balance. This results in vanishing of vertical accelerations. The consequence is that the whole group of nonhydrostatic IGWs is filtered out. According to Sutherland (2010), those are the waves with frequency close to the buoyancy frequency and waves with phase line slopes significantly different from zero. This is clearly seen from approximately 2.5 km vertical wavelength (0.4 cycle per km) in Fig. 2, where the temperature fluctuation spectrum begins to decrease more rapidly than the density spectra regardless of the fit order.

Methodology: According to the linear theory of IGWs, separation between a small wave-induced fluctuation and background field has to be performed. For that we are using a new method for the density background state separation presented by Šácha et al. (2014). The method is grounded on the estimation of the background buoyancy frequency profile by some analytical function and on the fact that the atmospheric density should decrease exponentially with height. Then, by solving the ordinary differential equation, the functional dependence of the background density profile on altitude is derived. When fitting the buoyancy frequency with a fourth order polynomial the resulting background density profile has a

form: $\rho_0 = \hat{\rho}_0\, exp\left(-\frac{\frac{A_4 z^5}{5} + \frac{A_3 z^4}{4} + \frac{A_2 z^3}{3} + \frac{A_1 z^2}{2} + A_0 z}{g} - C\right)$

Where and C are constants. After the background subtraction and normalization we gain the normalised density fluctuation profiles suitable for further analysis.

Results: Matsumura et al. (2011) successfully used numerical model to simulate the slower concentric waves propagating after the earthquake in the ionosphere and argued that they are originating from motions in neutral atmosphere. He approximated the earthquake dynamic by displacing the lower boundary (ocean surface) with prescribed vertical velocity of order tenth of the centimetre per second.

Assuming that the sea surface was displaced by tens of centimetres and employing the approximate relation between amplitudes of barotropic and baroclinic waves at the interface (see Sutherland, 2010) we find that the amplitude in atmosphere will be in order of hundreds of meter. After substituting this rough estimate into polarization relations for anelastic gases (Sutherland, 2010) we gain the normalised density amplitude in the order of hundredth, which is a typical maximum value for normalised density perturbations in profiles. Although this estimate is very rough it suggests the possibility to observe IGWs created by an earthquake or consequently by propagating Tsunami waves by means of GPS RO.

Comparison of spectral density prior and after the earthquake

As shown in Fig. 1 the available occultation events are relatively spatiotemporally distant away from the epicentre. The profiles were divided into the three groups, before (or with no chance of being hit by the information), after and long after the earthquake. The vertical wavenumber spectra of these three groups are depicted in Fig. 3 together with mean and saturated spectra. Notice the small peaks in spectra of the "after" and "long after" group around 0.7 cycle per km and 0.5 cycle per km. This peaks are not present in the before and mean spectra and are suspicious of having source in the earthquake. Especially the mode around 0.7 cycle per km (around 1.5 km vertical wavelength) exhibits an expected behaviour when shifting his maximum toward smaller wavelength with time.

Vertical behaviour of "suspicious" modes

Since we cannot rely on the theory (derived using WKB approximations) in the full vertical extend, we have chosen the continuous wavelet transform (CWT) (Torrence and Compo, 1998) method for analysis of the vertical behaviour of IGWs. Further, for the determination of dominant modes and for studying their development with height, we have applied a method of reducing CWT to its skeleton. We have used the same setting for drawing the special lines as Chane-Ming et al. (2000).

In Fig. 4, there are shown results of CWT and its skeleton for profiles 28 and 30 that are above the ocean and could contain information from Tsunami. For comparison, there are results computed for profile 0, which is from geographically similar locations but prior to the earthquake.

Unfortunately the most suspicious mode (around 1.5 km vertical wavelength) is on the boundary with noise floor for geometrical optics (GO) inversion retrieval method. In general, up to 4 km of vertical wavelength, the spectrum is composed by several modes with small vertical extend. Dominant modes visible through the whole profile have vertical wavelengths bigger than 4 km and their occurrence seems to be governed by the orographic and current meteorological conditions.

Data: For our analysis we have chosen a set of sixty spatio-temporally nearest (see Fig. 1) Global Positioning System (GPS) radio occultation (RO) density profiles from FORMOSAT-3/COSMIC mission. Atmospheric density is the first quantity of state gained in the retrieval process and is not burdened by any additional assumptions. Surprisingly, there are no studies elaborating in details the utilization of GPS RO density profiles for gravity waves analyses.

Figure 1: Time-space cone of FORMOSAT-3/COSMIC nearest occultation events. Negative time means occultations prior to the earthquake. For t positive any wave can influence the occultation, if it lies above its line of approximated propagation speed.

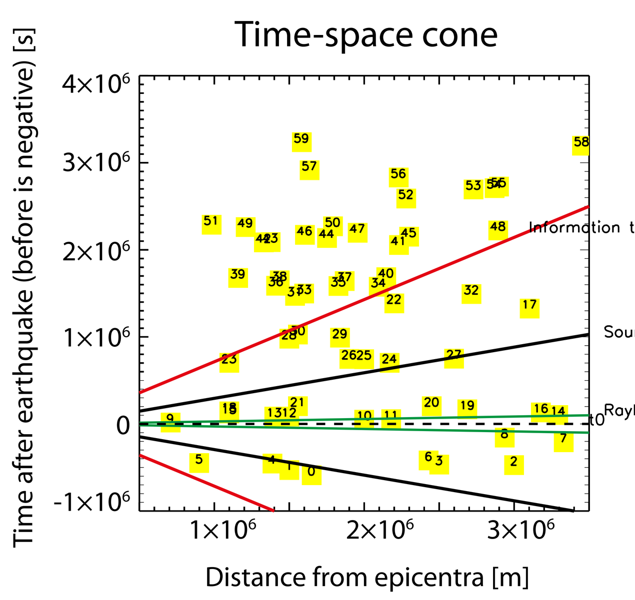


Figure 2: Vertical wavenumber power spectral density for the normalized density perturbations from different backgrounds and temperature normalized perturbations compared with the theoretical saturated spectra.

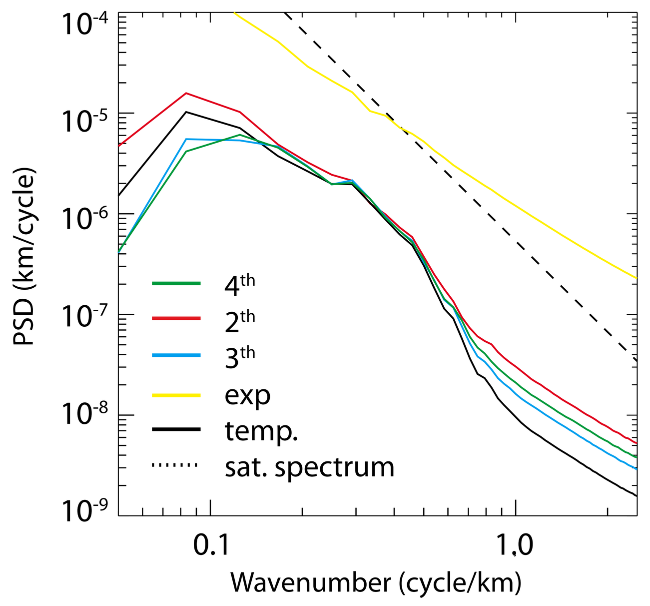


Figure 3: Vertical wavenumber power spectral density for three groups of profiles (before or with no chance of being hit by the information, after and long after the earthquake) compared with the mean and theoretical saturated spectra.

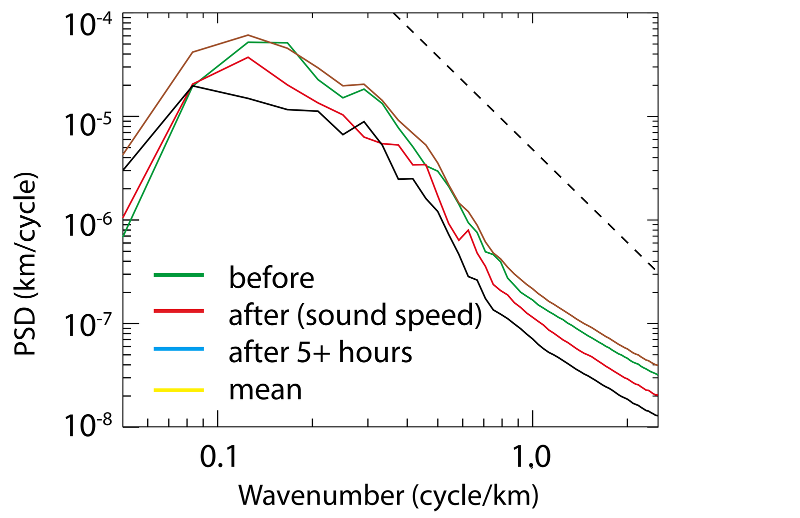
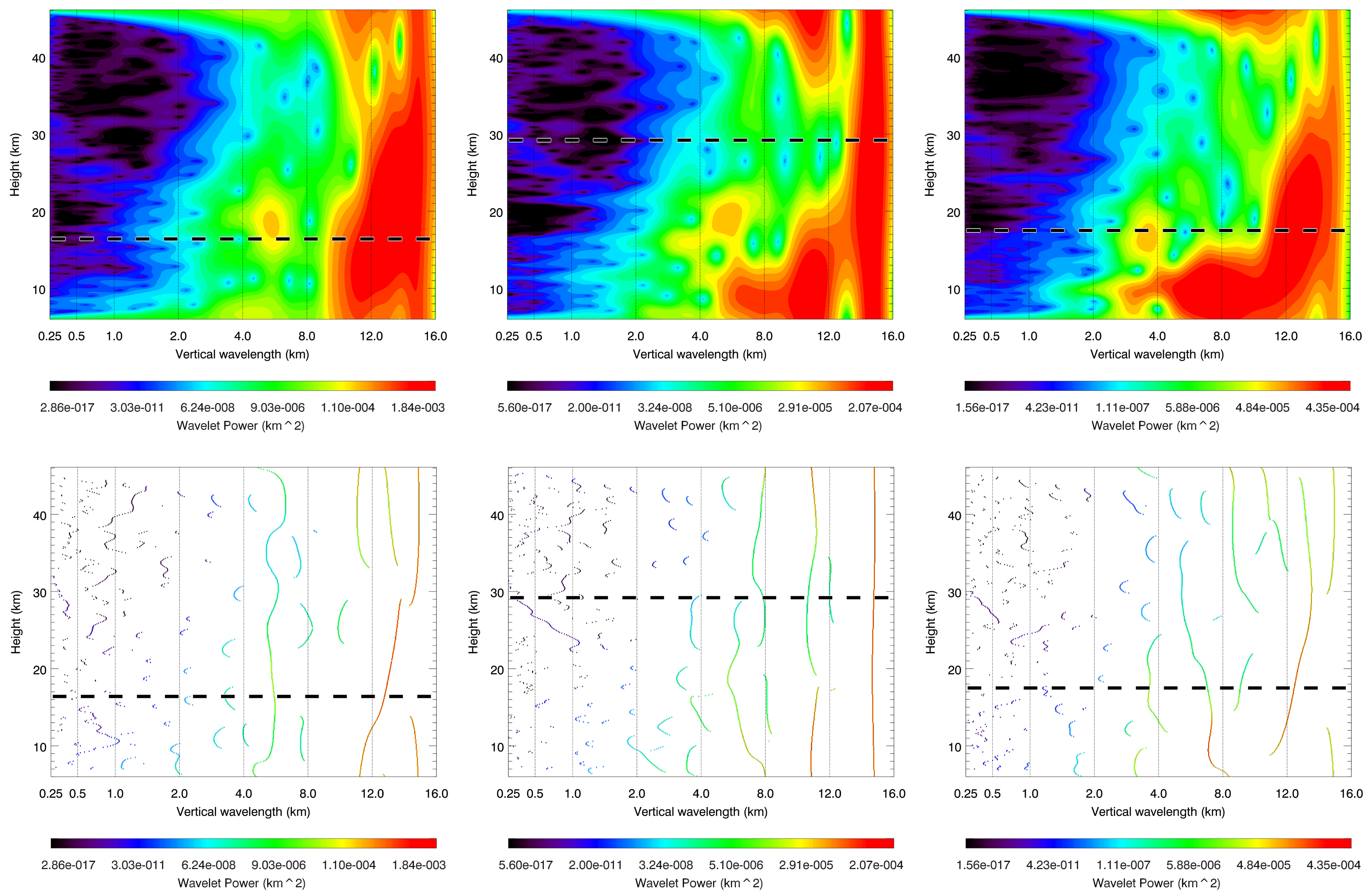


Figure 4: Scaled normalized density perturbations wavelet power spectra of occultation event number 30 (a), 28 (b) and 0 (c). Wavelet power spectra skeletons for profiles 30 (d), 28 (e) and 0 (f).



Conclusions: Usage of density profiles instead of dry temperature profiles for IGWs analysis has many advantages (e.g. background form and nonhydrostatic waves).

Rough estimation suggests that the IGWs created by the earthquake (directly or made subsequently from the propagating Tsunami) are in principle detectable by means of GPS RO.

None of GPS RO events from FORMOSAT-3/COSMIC mission can be (with certainty) considered to include information about the Tohoku earthquake (except possible influence of ionospheric disturbances on the ionospheric residual error).

Without prior knowledge about the vertical wavelengths of modes created by an earthquake it is quite impossible to determine them only from comparison of differently spatiotemporally located occultation events.

References and Acknowledgement

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