Atmospheric waves and tsunamis excited by the Tonga volcano: Coupled numerical experiment

*Kensuke Nakajima[1]

1. Department of Earth and Planetary Sciences,Flculty of Sciences,Kyushu University

Introduction

Just after 1:00 p.m. (JST) on January 15, 2022, Hunga-Tonga-Hunga-Ha'apai volcano in Tonga erupted, and pressure and sea-level changes were observed for several days around the globe, including Japan. In particular, the sea level change started to be observed in many areas before the arrival time of the tsunami, which is expected in the case of a normal eruption, and was also observed on the other side of the continent such as the Caribbean Sea.
In this study, we survey a wide range of parameters using a linear model to theorize how this atmospheric and oceanic disturbance could be excited by the eruption.

Basic equations

We consider the linear response of the compressible atmosphere and the ocean tsunami coupled with it to the forcing by the volcanic eruption. For simplicity, the system is assumed to be two-dimensional (x, t) horizontally and vertically, and the rotation of the earth and spherical effects are neglected. We assume that the tsunami can be described by the shallow water equation. The atmospheric equation and the tsunami equation are solved numerically at the sea level (z=0) as an initial value problem, coupled by giving the vertical direct current as the boundary condition from the ocean to the lower end of the atmosphere and the pressure disturbance as the forcing from the lower end of the atmosphere to the ocean. The computational domain is 3200 km or 12800 km horizontally and 480 km vertically (with the exception of the sponge layer above 400 km).

Initial results

The results of localized thermal forcing at various spatio-temporal scales are can be summarized as follows.

Excitation characteristics of atmospheric waves

Localized thermal forcing with a wide range of parameters excites Lamb waves and propagates them far away. Lamb waves are dispersive up to a pulse width of about 10 km, after which they behave almost non-dispersively. The altitude dependence of the amplitude and pulse width is also weak. On the other hand, the characteristics of internal gravity waves (vertical wavelength, period, etc.) are very sensitive to the height of thermal forcing. In particular, when the forcing height is higher than about 20 km, internal gravity waves with long vertical wavelength trapped below mesopause are excited with large amplitudes, which may resonate with tsunamis (see below).

Tsunami excitation

In a wide range of forcing parameters, tsunamis propagating with Lamb waves are excited. Barometric pressure anomaly and sea level displacement have the same sign, which is opposite to the cases of storm surge. On the other hand, the internal gravity wave, which is generated when the forcing height is high, resonantly excites tsunamis because it has a wide range of phase velocities covering the typical tsunami velocity (about 200 m/s at 4000 m depth). As a result, the ratio of the tsunami amplitude to the surface pressure amplitude is much larger than that of the tsunami excited by the Lamb wave. Bearing in mind the dispersive nature of internal gravity waves, the sea level change propagated as a "normal tsunami" after the Lamb wave may have been excited relatively close to the volcano resonating with internal gravity waves.

Pressure variation near the volcano

Initial pressure response has an intense negative signature, being consistent with observation. Temporal evolution afterwards is characterized by continuing harmonic oscillation with a period of about 200 sec. This can be identified as the acoustic gravity waves trapped below mesopause with small horizontal group velocity, and can excite free oscillations of solid Earth.

Future development

Combining the results of this study with various aspects of observed waves, we may be able to estimate the eruptive behavior (e.g., distribution of heat from magma to atmospheric heating and seawater evaporation).

Keywords: Tonga Volcano, Lamb waves, tsunamis, meteotsunamis, internal gravity waves, acoustic gravity waves