Supplementary material for "Coupled simulation of landslide, tsunami, and ground deformation for the 2017 Nuugaatsiaq event in Greenland"

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S1. Single force inversion from seismic data

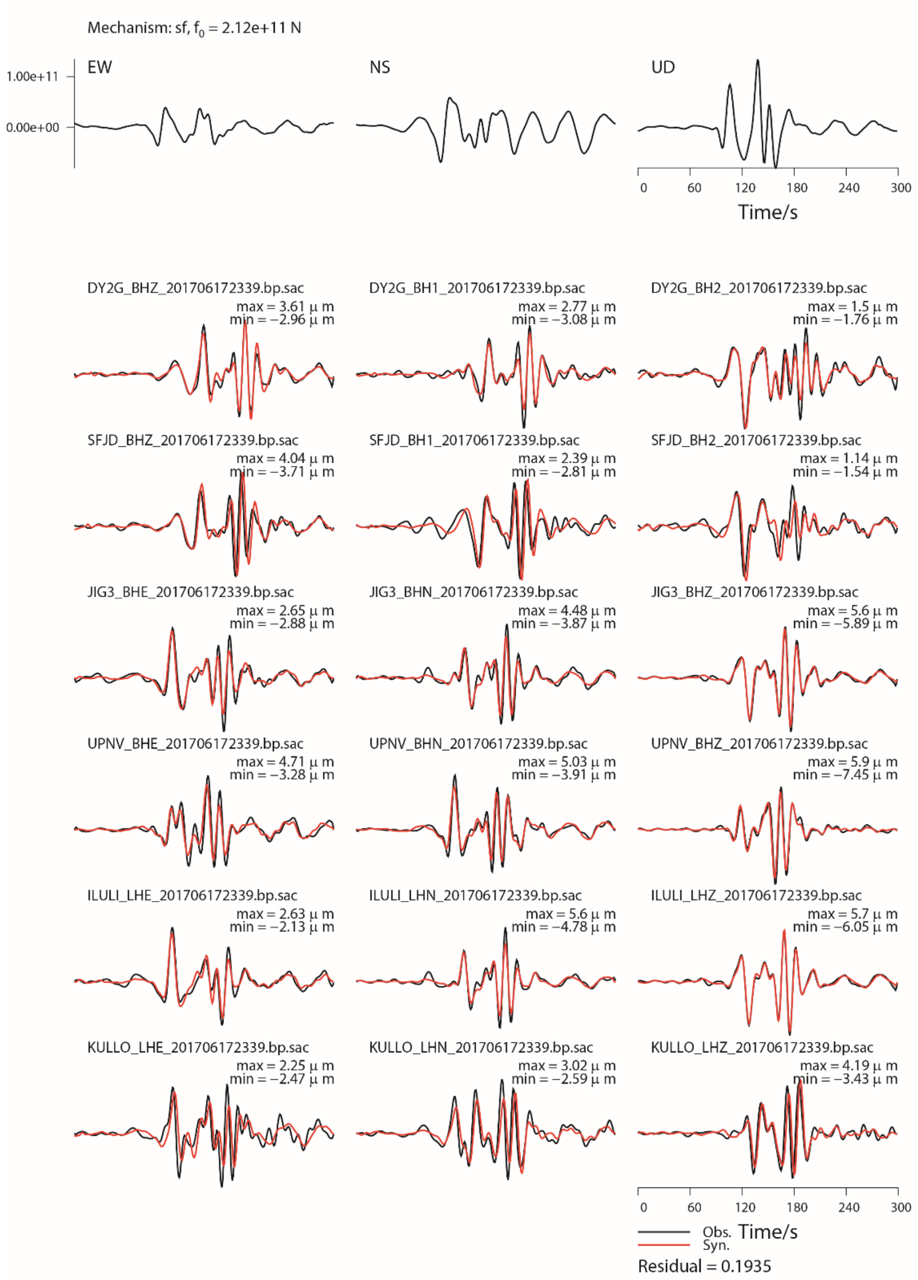

Figure S1. The single force inversion results in detail. Three-component source time function of the single-force mechanism and waveform fitting.

S2. Boussinesq's solution

Solid earth deformation due to surface load or unload (F) is often discussed through the Boussinesq problem (Boussinesq, 1885) and the displacement field in a semi-infinite homogeneous elastic medium (Lamés' coefficients λ, μ) is written, as

$$u_x = \frac{F \cdot x}{4\pi\mu}\left[\frac{z}{r^3} - \frac{1-2\nu}{r(r+z)}\right],\ u_y = \frac{F \cdot y}{4\pi\mu}\left[\frac{z}{r^3} - \frac{1-2\nu}{r(r+z)}\right],\ u_z = \frac{F}{4\pi\mu}\left[\frac{z^2}{r^3} - \frac{2(1-\nu)}{r}\right]$$

where $= \sqrt{x^2 + y^2 + z^2}$, letting the surface load be at the origin of the coordinate. The Poisson ratio is $\nu = \frac{\lambda}{2(\lambda+\mu)}$. The displacement on the ground surface (z=0) is simply written as:

$u_x = -\frac{F}{4\pi\mu}\left[\frac{x}{2r^2}\right], u_y = -\frac{F}{4\pi\mu}\left[\frac{y}{2r^2}\right], u_z = -\frac{F}{4\pi\mu}\left[\frac{3}{2r}\right]$

where it is supposed that $\lambda = \mu$. Note that the positive z-axis is pointed down.

Let us suppose a single force due to the mass change, a square column of water (1 m height over a surface of 100 m x 100 m), i.e. $F = \rho \cdot g \cdot V = 1000 \times 9.8 \times 10^4 = 9.8 \times 10^7\ (N)$. Taking a typical value of the rigidity of the Earth's crust ($\mu = 20\ GPa$), $u_z(r) = \frac{9.8\times10^7(N)}{4\pi\times20(GPa)}\frac{3}{2r} = 0.00058\frac{1}{r}\ (m)$. In this expression, the mass is concentrated at the central point. $u_z = 0.01\ (m)$ requires $r = 0.058\ (m)$. Thus, the impact of a single force is limited.

This static solution is very sensitive to the distance, as $r = 0$ has a singularity. First, we test the discretization effect of the source term, as we are interested in the possible deformation pattern near the coastline. This means that the distance between the source and receiver is small, an order of 100 m, equal to the square source dimension, which we previously considered. Let us consider this unit source. Supposing the source area for $x \leq 0$, namely a square unit area located between $(x, y) = (-100\ m, -50\ m)$ and $(0\ m, 50\ m)$ as left-bottom and right-top corners, we align the receiver position along $x > 0$ along $y = 0$. Figure xx studies the impact of the discretization of the finite source. The total force is equivalent for all the cases.

(a) A single point-source at the position $(x, y) = (-50\ m, 0\ m)$.
(b) A unit source is decomposed by 5 x 5 point sources distributed every 20 m.
(c) A unit source ID decomposed by 100 x 100 point sources distributed every 1 m.
(d) A single point-source at the position $(x, y) = (0, 0)$.

We learn that the discretization between (a) and (c) does not influence the receiver positions for $x > 0$. On the other hand, the approximate positions of the source, (a) or (d), significantly change the estimation at a short distance of $x < 100$ m. In all cases, the deformation patterns converge quickly with distance after a few 100 meters. In this simple calculation, at the position of $x = 100$ m, the vertical displacement is about 10^{-5} m = 10 μm, noting the horizontal displacement is 1/3 of it.

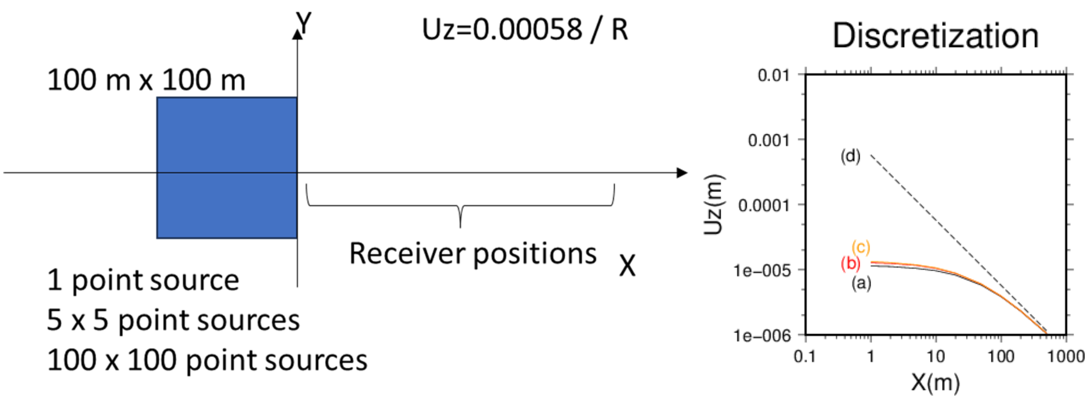

Figure S2. The vertical displacement Uz for a unit surface charge of 100 m x 100m, located at $X \leq 0$. The receiver positions at $X > 0$. (a) A point source approximation was put on $(X, Y) = (-50\ m, 0\ m)$. (b) 5 x 5 point sources distributed every 20 m. (c) 100 x 100 point sources distributed every 1 m. (d) A point source approximation was put on $(X, Y) = (0, 0)$.

S3. Influence of finite source extension

Second, we consider the finite source effect. Let us fix a channel width of 5 km in front of the receivers and suppose a uniform sea height rise over a length of λ along the coastline ($x = 0$). We compare four cases, (b)-(e), comparing to the reference case (a), the same as the last case of (a).

(a) A reference model of a point source of 100 m x 100 m surface.
(b) $\lambda = 1100$ m. (11 elements along the coast over the whole width of the channel of 5 km.)

(c) $\lambda = 2100$ m.
(d) $\lambda = 4100$ m.
(e) $\lambda = 20100$ m.

This numerical test shows the importance of the finite extension of the source area. The length of a few kilometers, cases (b)-(s), gives an important displacement of larger than 0.2 mm. The difference between (d) and (e) is only twice regardless of the difference in extension length (five times). Thus, one can guess that if the sea height becomes higher over a scale of a few kilometers, the vertical deformation at a few hundred meters away from the coast may reach 0.2 mm, which can be observable by a seismograph.

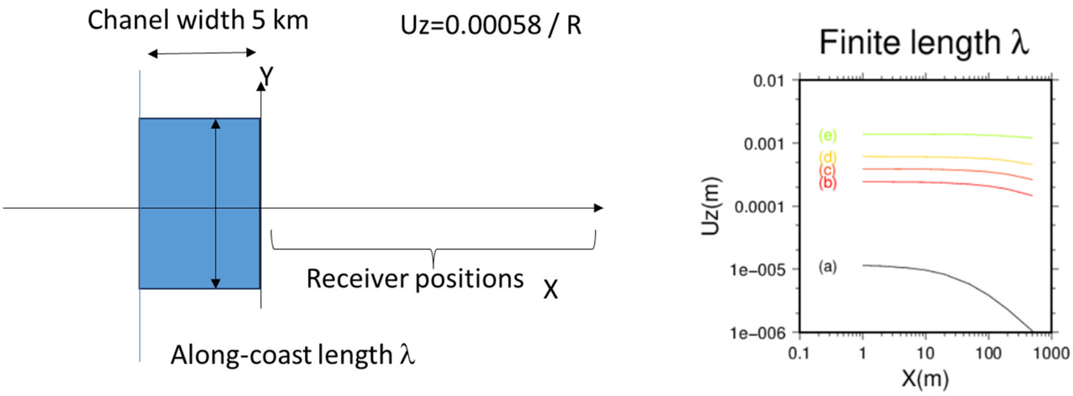

Figure S3. The vertical displacement Uz for a uniform water rise in a channel of 5 km width. (a) A unit surface charge of 100 m x 100m for reference, located at $(X, Y) = (-50\ m, 0)$. (b) Along-coast length of $\lambda = 1100$ m, (c) $\lambda = 2100$ m, (d) $\lambda = 4100$ m, and (e) $\lambda = 20100$ m.

S4. Simulation of temporal evolution

Instead of the static, analytical solution, one can simulate the ground deformation in the elastodynamic equations. Here we use a 3D finite difference method (Virieux and Madariaga, 1988; Aochi and Madariaga, 2003), formulated on a stress-velocity differential equation on a staggered grid. We give the wave height in the form of:

$$h(x, y) = A sin(\omega t - kx),$$

where A=1 (m), ω and k are the angular frequency and wave number. In the following example (Figure S3), the period is set $T = \frac{2\pi}{\omega} = 150$ s and the wavelength is $\lambda = \frac{2\pi}{k} = 4995$ m. The wave speed is $V = \frac{\omega}{k} = \frac{\lambda}{T} = 33.3$ m/s. The water waves move from right to left, approaching the array of receivers along the coastline and perpendicularly at the position of $X = 0$. The grid size is 100 m and the time step is 0.005 s. The output is in velocity so that we integrate it once to get the displacement with no filter. Figure S3 compares the two solutions at two different receiver positions. Regardless of these different frameworks, the two solutions are enough identical. The first peak arriving at around 180 s corresponds to the first passage of the high sea level. Then the ground continues oscillating. The consistency between the two solutions confirms that the ground deformation is very long in wavelength and gradual in time with very little perturbation of seismic wave radiation.

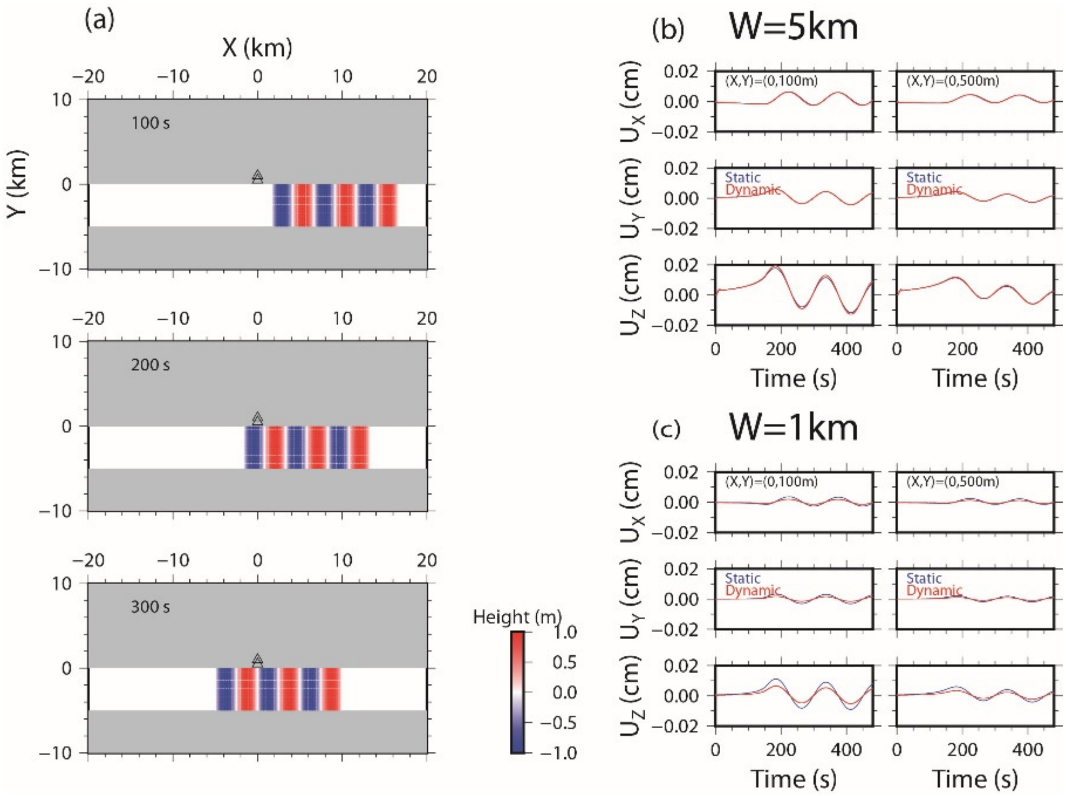

Figure S4. A synthetic test of ground deformation due to the tsunami propagation along the coastline. (a) Snapshot of the given sea level height, propagation towards negative X direction with a wave speed of 33.3 m/s with a width of 5 km. The two receivers are et at (X, Y) = (0, 500 m) and (0, 1000 m). (b) Three components of ground displacement in the case of the channel width of 5 km at two receiver positions using Boussinesq solution (static) and finite difference method (dynamic), respectively. Boussinesq solution is applied simultaneously at every time step. Finite difference synthetics are integrated once to obtain the displacement. No filter is applied. (c) Three components of ground displacement in the case of the channel width of 1 km.