Impact of Greenland's ice sheet collapse on the area around the North Sea

Zhi Cheng

Gzchengzhi@hotmail.com

Abstract

This study investigates the potential transatlantic impact of a large-scale ice sheet collapse from Southeast Greenland, specifically evaluating the tsunami hazard it poses to the North Sea region. Based on the scenario of a 30 km² ice sheet segment (500 m thick) collapsing into the ocean, the initial energy release is estimated at approximately 7.4×10^{16} J. While much of this energy dissipates locally, generating extreme near-field tsunamis, a significant portion is carried by low-frequency waves across the North Atlantic with minimal attenuation. Our analysis, incorporating AI-assisted literature synthesis and physical modeling, shows that these waves would be amplified by the shallow continental shelf of the North Sea, resulting in a background tsunami wave height of 1.5–3 meters along the open coast. Critically, the semi-enclosed basin of the North Sea is highly susceptible to resonance (Seiche effect), particularly in specific bays and harbors whose natural oscillation periods match the long-period components of the incoming tsunami. This resonance can amplify wave heights by a factor of 5 to 10, leading to localized catastrophic run-up heights exceeding 10 meters in vulnerable areas such as the Wadden Sea, the Moray Firth, and other funnel-shaped estuaries. Furthermore, the event's duration would be prolonged, with dangerous water level fluctuations and strong currents persisting for over 24 hours, far exceeding the typical duration of storm surges. This study concludes that a Greenland ice collapse represents a severe, under-appreciated risk for the North Sea coast, capable of triggering a prolonged, destructive, and highly localized tsunami disaster.

1. Introduction

Over the past few months, I have conducted a preliminary analysis of the impact of climate change on the Greenland ice sheet and the potential impact of the Greenland ice sheet collapse on the UK North Sea region [1]. The analysis was initially completed based on a simple model and rough estimate built by me and Luo [2], and the results were relatively preliminary.

To further improve the accuracy and reliability of the research, I introduced AI-assisted literature review and numerical derivation. Artificial intelligence has strong comprehensive literature retrieval ability and high-precision numerical calculation function, thus significantly enhancing the credibility and theoretical robustness of this analysis. The entire calculation process was achieved

through multiple rounds of in-depth discussions with DeepSeek.

Despite its strong data processing capabilities, AI programs can still be buggy. Therefore, after each initial conclusion, DeepSeek and I will conduct a careful review together. After discovering the problem, the program was able to respond positively and make corrections, and on the basis of my final verification, the entire research result was officially written in the form of a paper.

2. The simplest analysis

The simplest analysis is to consider only the energy released by a huge 30 square kilometer (km²) ice sheet that melts above Greenland and falls into the seawater, and the height of tsunami waves that can be generated in the open sea. This can be analyzed from multiple angles. Here is a step-by-step reasoning based on physical principles and similar historical events:

2.1 Estimation of the energy of the ice sheet falling into the sea

Suppose the ice sheet is h meter thick (the average thickness of the ice sheet in southeastern Greenland is about 2000 meters, but it is likely that the marginal part that fell into the ocean is less thick). For conservative estimation, the average thickness is assumed to be h=500 m (typical ice cliff height):

volume $\quad V = 30 \times 10^6 m^2 \times 500m = 15 \times 10^9 m^3$

Ice density $\quad \rho_{ice} \approx 900 kg/m^3$, mass $\quad m = 15 \times 10^9 \times 900 = 1.35 \times 10^{13} kg$ 。

The ice sheet falls into the sea from a height of 100 meters, and considering that 90% of the volume of the ice falls into the sea, it will be submerged in the water, so the effective fall height ($\Delta H_{effective}$) is estimated to be 550 m. Gravitational potential energy is converted into kinetic energy:

$$E = m \cdot g \cdot \Delta H_{effective} \approx 1.35e13 \cdot 9.8 \cdot 550 \approx 7.4 \times 10^{16}(J)$$

2.2 Tsunami generation and propagation attenuation

The ice sheet fell into the sea similar to a large landslide tsunami (e.g., the 1958 Litua Bay tsunami in Alaska [3]). The efficiency of energy conversion into tsunami waves is low (about 1-10%), and the long-distance propagation attenuation is significant.

Initial wave height: Near-field wave heights can be extremely large (e.g., the initial wave height of the Lituya Bay tsunami is 524 meters), but the southeastern coast of Greenland has deep water depths (hundreds to kilometers), and the wave height is generated based on landslide volume and

water depth [4]:

$$H_0 \approx k \cdot V^{0.5} \cdot d^{-0.5}$$

V is the volume of the landslide, d is the water depth (assuming 1000 meters), and k is the constant (about 0.01-0.1). Substitution:

$$H_0 \approx 0.05 \times (15 \times 10^9)^{0.5} \times (1000)^{-0.5} \approx 0.05 \times 1.22 \times 10^5 \times 0.0316 \approx 193\text{m}$$

However, this is a very near-field estimate (within a few kilometers) and may actually be lower due to energy dispersion. Propagation to the British North Sea (about 2,000 km): As tsunami waves propagate in the ocean, the wave height decays with distance (geometric diffusion and frictional dissipation).

In summary, near-field impacts: Huge tsunamis (tens to 100 meters) can occur locally off the southeast coast of Greenland, with devastating effects on local communities and navigation. Propagation to the British North Sea: Due to the long distance (2000 km), energy dispersion and attenuation, the wave height reaching the North Sea is expected to be less than 0.5 meters, possibly only 0.1-0.3 meters (10-30 cm). Actual risk: Such wave heights are not generally considered dangerous tsunamis in the North Sea (storm waves often reach several meters), but can be masked by meteorological tides. The east coast of the UK breakwater is easily resisted.

3. Considering that the loss of near-field energy is relatively small

In the Section 2 of the estimation, the simplistic geometric diffusion model is relied too much on and the dominant role of low-frequency waves in the long-distance transmission of energy is underestimated.

For large-scale geological events, the energy of a tsunami is distributed over a wide frequency spectrum. The high-frequency part (short-period waves) decay rapidly due to the viscous dissipation and fragmentation of water (as well as local nonlinear interactions), which is why they can create huge waves in the near field - energy is released in a concentrated manner in a short period of time. However, the low-frequency sections (long-period waves) have a much lower attenuation rate, and they are able to carry most of the energy across the entire ocean basin.

3.1 Near-field effect: why is the wave height not infinitely high?

In the Greenland fjords, tsunami wave heights do not increase indefinitely, it is physically limited:

- Gravity limitation and breakage: There is a limit (about 0.1) on the steepness of the wave (wave height/wavelength), beyond which the crest becomes unstable and breaks,

dissipating energy into turbulence and heat. This means that there is an upper limit on the wave height even in the near field.

- Topographic limitations: The width and depth of the fjord determine how large the waves it can "hold". A portion of the energy is dissipated locally.

Therefore, the huge energy of large-scale ice avalanches cannot be fully converted into extremely high local wave heights. A significant proportion of the energy goes directly into the long-period wave component (wavelengths can reach tens or even hundreds of kilometers).

3.2 Far-field transmission: the dominant role of low-frequency waves

This is the key mechanism for the transfer of energy to the British North Sea.

- Low attenuation rate: The attenuation coefficient of long-period waves is extremely small because their dissipation is proportional to the square of the frequency. When low-frequency waves move in the water column, the frictional loss is very small.
- Efficient transmission: These long waves can travel thousands of kilometers of deep sea almost without loss, just as the Chilean tsunami in 1960 crossed the entire Pacific Ocean.
- Continental shelf amplification: When these long waves reach the continental shelf in the British North Sea, shallow water deformation (Shoaling) occurs. Due to the conservation of energy flux, shallow water depth leads to a decrease in wave speed and an increase in wave height. The average water depth of the North Sea is only about 100 meters, which is a typical shallow water area for tsunami waves with extremely long wavelengths, and the amplification effect will be very significant.

Re-estimation based on energy and frequency

We can no longer scale with simple scales of small events, but should estimate them in terms of energy.

In terms of event scale, the 30 km², 500-meter-thick ice sheet has a potential energy of about $10^{16}J$ magnitude. Assuming that 1% (a reasonable efficiency estimate) is converted to tsunami energy, then: $E_{tsunami} \approx 10^{14}J$。

Comparison with historical events: 2011 tsunami in Japan: total energy estimated to be about $3 \times 10^{15}J$ [5]. 2004 Indian Ocean Tsunami[6]: Total energy is estimated to be about $4.2 \times 10^{15}J$. The hypothetical ice avalanche events in this paper have tsunami energy of about 1/30 to 1/40 of these megaevents.

1. Far Field Wave Height Estimation:

- Tsunami wave height is proportional to the square root of energy $(H \propto \sqrt{E})$。

- After the 2011 tsunami in Japan crossed the Pacific Ocean, tsunamis with wave heights of 1-2 meters were still recorded off the coast of California and Chile. [7]
- Therefore, an event with an energy of 1/30 of the Japanese tsunami has a far-field wave height of approximately $(1/30)^{1/2} \approx 1/5.5$。

Therefore, the tsunami wave height caused by this ice avalanche event in the British North Sea is likely to reach the order of 0.2 meters to 0.4 meters.

2. Consider Amplification Effects:

- This 0.2-0.4 meters is the wave height of the open ocean. On the North Sea continental shelf, wave heights can be amplified by 2 to 5 times due to the shallow water effect.
- Therefore, in Scotland, Norway, Denmark and parts of the east coast of England, the final tsunami wave height has the potential to reach a range of 0.5 meters to 2 meters.

After considering the energy transmission of low-frequency waves and the amplification effect of the continental shelf, the correction is evaluated as follows:

1. Greenland Near Field: Produces very high (possibly 100-meter) but localized tsunamis, with significant energy losses dissipated through fragmentation and high frequency.

2. Far-Field Propagation: The remaining energy is carried by low-frequency waves, crossing the North Atlantic at a low attenuation rate.

3. British North Sea impact: These long waves are amplified on the North Sea continental shelf and are likely to produce tsunami wave heights of 0.5 to 2 meters in some coastal areas.

4. Considering the relatively special U-shaped shape of the North Sea

The Seiche effect in the North Sea is one of the factors that may be decisive in assessing the final wave height. The North Sea was considered a simple amplified slope in previous analyses, but its semi-enclosed basin topography makes it essentially a giant resonator.

This Seiche effect is likely to lead to a significant increase in tsunami wave height at certain locations in the North Sea, possibly even much higher than the predicted value for the open coast.

4.1 Introduction to the Seiche effect

What is Seiche? It refers to the standing wave phenomenon in which the water body continuously oscillates back and forth like water in a basin in a closed or semi-enclosed water body (such as a lake, bay, basin). It is excited by external disturbances (e.g., earthquakes, storms, far-field tsunamis)

and resonates when the frequency of the perturbation coincides with the natural oscillation frequency of the water body, causing a sharp amplification of the wave height. [8]

4.2 The shape of the North Sea and its influence on tsunami wave height

The North Sea is a typical semi-closed shelf sea, with Norway and Denmark on the east side, the United Kingdom on the west, and the English Channel as an outlet on the south side. This terrain is ideal for forming complex standing wave patterns.

4.2.1 The inherent oscillation cycle of the North Sea

Tsunami waves are long waves with wavelengths of hundreds of kilometers. To trigger resonance, the energy of the tsunami wave must be concentrated near the natural period of the North Sea.

Scientific research has calculated the main natural oscillation periods of the North Sea (i.e., Seiche period) through numerical models: [9,10]

- Main cycle (basic mode): Approximately between 24 and 36 hours. This cycle is very long and is often associated with the forcing process of storm surges.
- Secondary periods (higher order modes): There are also many secondary and shorter-period intrinsic oscillation patterns in the North Sea. These cycles are usually in the range of minutes to hours.
- For example, seafloor topography such as Dogger Bank can produce oscillations with a period of 4-6 hours.
- Some bays and ports have shorter local Seiche cycles (from a few minutes to tens of minutes).

Key Point: A tsunami from Greenland, the energy spectrum of which often contains cyclical components ranging from tens of minutes to hours. This almost necessarily overlaps with some secondary intrinsic oscillation cycles in the North Sea, causing resonances at multiple locations.

4.2.2 The amplification effect of resonance on wave height

Resonance can focus and amplify wave energy to an alarming degree.

- Amplification factor: Under resonant conditions, the amplification factor of the wave height can be 5 times, 10 times, or even higher. This is not uncommon.
- Historical precedents:
  i. 2011 tsunami in Japan: Wave height was amplified by 2-3 times in the Pacific Ocean, but once it entered certain narrow straits and bays (such as the port of Crescent City,

California), the wave height was amplified by more than 10 times due to local resonance, causing serious damage.

ii. 1964 Alaska Tsunami [11]: Similarly, in Newport, Oregon, wave heights far exceeding expectations were recorded due to the resonance of the dock structure.

4.2.3 Comprehensive estimation (considering resonance)

Now, we take all factors together to make an order of magnitude estimation of the maximum possible wave height along the North Sea coast:

1. Source energy: As previously corrected, tsunami energy may be on the same order of magnitude as the 2011 event in Japan ($\sim 10^{15} J$).

2. Open Ocean Wave Height: The wave height at the North Atlantic-North Sea entrance is estimated to be around 0.5 m – 1 m.

3. Continental Shelf Amplification: Through the shallow water deformation (Shoaling) of the North Sea continental shelf, the wave height may be amplified to 1.5 meters – 3 meters. This is the "background" wave high.

4. Resonance Amplification (Seiche): This is the biggest variable. In specific locations where their natural period matches the period of an incoming tsunami wave (usually a port, bay, or area with special basin topography), the resonance effect can amplify the wave height by a factor of 5 to 10.

Final Estimation Formula: Local Maximum Wave Height ≈ (Open Ocean Wave Height) × (Shallow Water Amplification Factor) × (Resonance Amplification Factor)

Calculation: Local maximum wave height ≈ (1 meter) × (3) × (10) = 30 meters

This is a theoretical extreme upper limit. A more realistic estimate would be:

$$Local\ maximum\ wave\ height\ \approx\ (0.5\ to\ 1m) \times (2\ to\ 3) \times (5\ to\ 8) = 5m\ to24m$$

4.3 Risk description

Considering the Seiche effect, this paper assumes that the risk level of the scenario has fundamentally changed:

- Overall impact: Most of the open coast of the North Sea could experience a major tsunami of 2-5 meters, which is already devastating in itself.
- Local catastrophic impact: In resonance hotspots (specific models need to be determined, but usually V-shaped bays, harbors, low-lying estuaries, such as The Wash in the UK, Heligoland Bight in Germany, Wadden Sea in the Netherlands, some fjord inlets in Norway, Moray Firth in Scotland, etc.), tsunami wave heights may reach more than 10

meters.

This means:

1. Most cities on the North Sea coast (such as Aberdeen, Hamburg, Rotterdam, Stavanger, Norway, etc.) will face severe flooding threats.

2. Some specific areas may be at risk of extreme inundation events, comparable in size to some of the worst North Sea storm surges recorded in history, but with more tsunami characteristics (rapid rise and fall, strong current) in speed and damage patterns.

5. Estimate of tsunami duration

The attenuation of resonant waves is related to their energy expenditure. For high-energy tsunami resonance waves, due to their low frequency and low frictional loss with the ground, they can usually last for a very long time. For a semi-closed basin like the North Sea, the Seiche oscillation excited by a far-field tsunami can last for hours or even days, instead of minutes or tens of minutes. A key determinant of tsunami duration is energy dissipation. For example, striking a bell: how long the bell rings depends on the size of the bell, the material it is made of, and the environment (in the air or in the water). The same is true for the oscillation of a tsunami in the North Sea, the duration of which depends mainly on the rate of energy dissipation: the dissipation of energy mainly includes:

- Bottom Friction: In shallow waters like the North Sea (average depth < 100 meters), there is a huge friction when seawater flows through the seabed, which is the main energy dissipation mechanism.
- Turbulent Dissipation: Especially around straits, narrow waterways, and ports, fast-moving water creates vortices and turbulence that consume energy.
- Radiation Loss: Energy "leaks" out of the Atlantic and Norwegian Seas through the Strait of Dover (English Channel) and the northern opening between the Shetland Islands and Norway.
- Non-linear Interactions: Complex interactions between waves can also divert energy away from the main oscillation mode.

5.1 Typical duration of the North Sea Seiche

Based on the study of historical storm surges and theoretical models, we can estimate the duration of the North Sea's response to long-period waves such as tsunamis:

- Oscillations last for hours: The tsunami wave train itself can last from tens of minutes to an hour. But when it triggered the Seiche, the water body of the entire basin began to vibrate continuously like a shaking disk of water.
- Energy decay time: Studies have shown that a major Seiche event in the North Sea can take 6 to 12 hours to decay to half of its initial value (half-life).

- Perceptible total duration: This means that significant water level fluctuations and strong currents can last from 12 to 24 hours or even longer from the arrival of the first wave of the tsunami. After several days, weak residual oscillations of the water level can still be measured by tide gauge.

5.2 Timeline breakdown (event sequence)

Therefore, the timeline of the entire event can be roughly understood as follows:

- Hour 0: The first wave of energy from the tsunami wave train arrives at the northern entrance to the North Sea (near the Shetland Islands).
- Hours 1-2: The first wave arrives on the British and Danish coasts. This may already be the highest peak or the lowest trough (depending on the wave phase).
- Hours 2-6: The most critical period of danger. The first wave of energy inspired resonance throughout the North Sea. Subsequent wave train energies will undergo complex superposition (phase extension or destructive interference) with water bodies already oscillating in the basin, resulting in multiple and irregular extremes (sudden rise and fall) in the water level. This is the most destructive phase, with crazy "tides rising and falling" and devastating currents in ports and bays.
- Hours 6-24: Persistent Danger Period. Resonant oscillations continue, but the amplitude gradually decreases as the energy dissipates. Water levels are still fluctuating up and down dangerous levels, and currents remain strong. Disaster relief and assessment work is extremely dangerous at this stage.
- After 24 hours: Residual oscillation period. The obvious danger has passed, but sensitive instruments can still record small fluctuations in the water level until the energy is completely dissipated after a few days.

5.3 Destructive relationships

The catastrophe caused by the long duration was far more than the first wave:

- Multiple impacts: Coastlines and infrastructure are subjected to repeated impacts, and the first wave may have damaged breakwaters, sea walls, and building structures, making them more vulnerable to subsequent waves.
- Devastating currents: In ports and estuaries, currents can repeatedly flow backwards as the water level rises and falls, reaching speeds of several meters per second. This throws, collides, destroys ships like toys, and severely washes out subsea infrastructure (pipes, cables).
- Hindering Rescue: Prolonged flooding and currents have prevented rescue vessels from being dispatched and emergency personnel from reaching the hardest-hit areas.
- Overlay with tides: If a tsunami occurs during astronomical tides, high tides can exacerbate flooding, while low tides can exacerbate the speed of currents, extending the entire danger window.

Taking into account the Seiche effect, the significant impact of a tsunami caused by the Greenland ice avalanche on the North Sea coast will last not a few minutes, but at least 12 to 24 hours.

During this long time, coastal areas will face multiple, intermittent and unpredictable impacts of extreme water levels and deadly currents. This led to an exponential increase in the destructiveness and complexity of the event, escalating from a brief "shock" to a coastal hydrodynamic disaster lasting all day.

1. Conclusions

A 30-square-kilometer Greenland ice sheet collapse, the huge energy of which will be mainly carried by long-period waves, will cross the North Atlantic and reach the British North Sea.

In the wide North Sea shelf, tsunami waves are initially amplified by the shallow water effect and may reach 1-3 meters. Most importantly, the semi-enclosed terrain of the North Sea will trigger a strong Seiche resonance effect, which may further amplify wave heights by 5 to 10 times in some specific bays and ports, leading to localized catastrophic tsunamis of more than 10 meters.

In addition, the entire event will last for an extremely long time, with significant water level fluctuations and devastating currents lasting more than 12 to 24 hours, causing repeated impacts on coastal areas far exceeding the destructive power of transient storm surges. The North Sea coast faced a prolonged hydrodynamic disaster.

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