# Experimental Constraints on Ocean Wave Erosion of Icebergs and Glaciers

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## Introduction

Global climate changes are leading to a rise in sea level through the melting of glaciers and ice sheets by warm ocean water.

**What processes and parameters control the rate at which waves transfer heat to ice, resulting in melting?**


Ocean wave erosion of iceberg in Ross Sea, Antarctica, Feb 2017

## Theory

In 1980, at the University of Rhode Island, Dr. Frank M. White, and his colleagues, produced a technical paper that developed a theoretical estimate for iceberg deterioration.

The estimates account for iceberg erosion for smooth and rough ice wall types, and includes variation for wave characteristics, such as amplitude and period. Original experiments by White and his team consisted of two trials with two different sized blocks of ice (Figure 1).

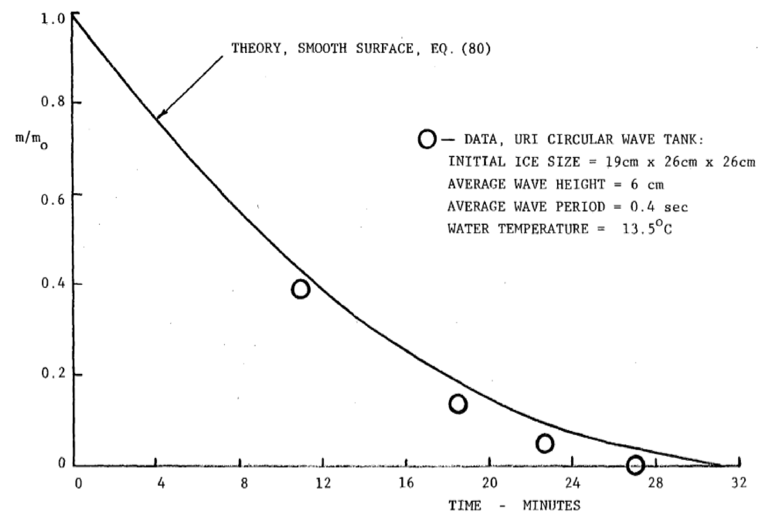


Figure 1: White's theory against his experimental data

Smooth Wall: $$\frac{V_m T}{H} \doteq 0.00015 Re_H^{-0.12}\ ,\ Re_H = \frac{H^2}{T\nu_w}$$

Rough Wall: $$\frac{V_m T}{H} \doteq 0.000146\left(\frac{\epsilon}{H}\right)^{0.2}\ ,\ \frac{\epsilon}{H} = \text{roughness ratio}$$

$V_m$ : erosion rate (m/s/°C)
$H$ : wave amplitude (m)
$T$ : wave period (s)
$\nu_m$ : wave velocity (m/s)

## Research Objectives

- Expand on White's work through:
  - Further experimental parameterization
    - Implement different wave characteristics – amplitude and period
    - Vary temperature – controlled air and water temperatures
    - Create larger database to test White's theory

## Methods

In order to conduct this study, a 1.29 meter long wave tank was used (Figure 2).

This study tested various wave parameters, and followed White's experimental setup as closely as possible. Certain tank size limitations and tank design (linear vs circular) differences were taken into account when comparing results to White's theory (about 0.069 cm/min/°C).

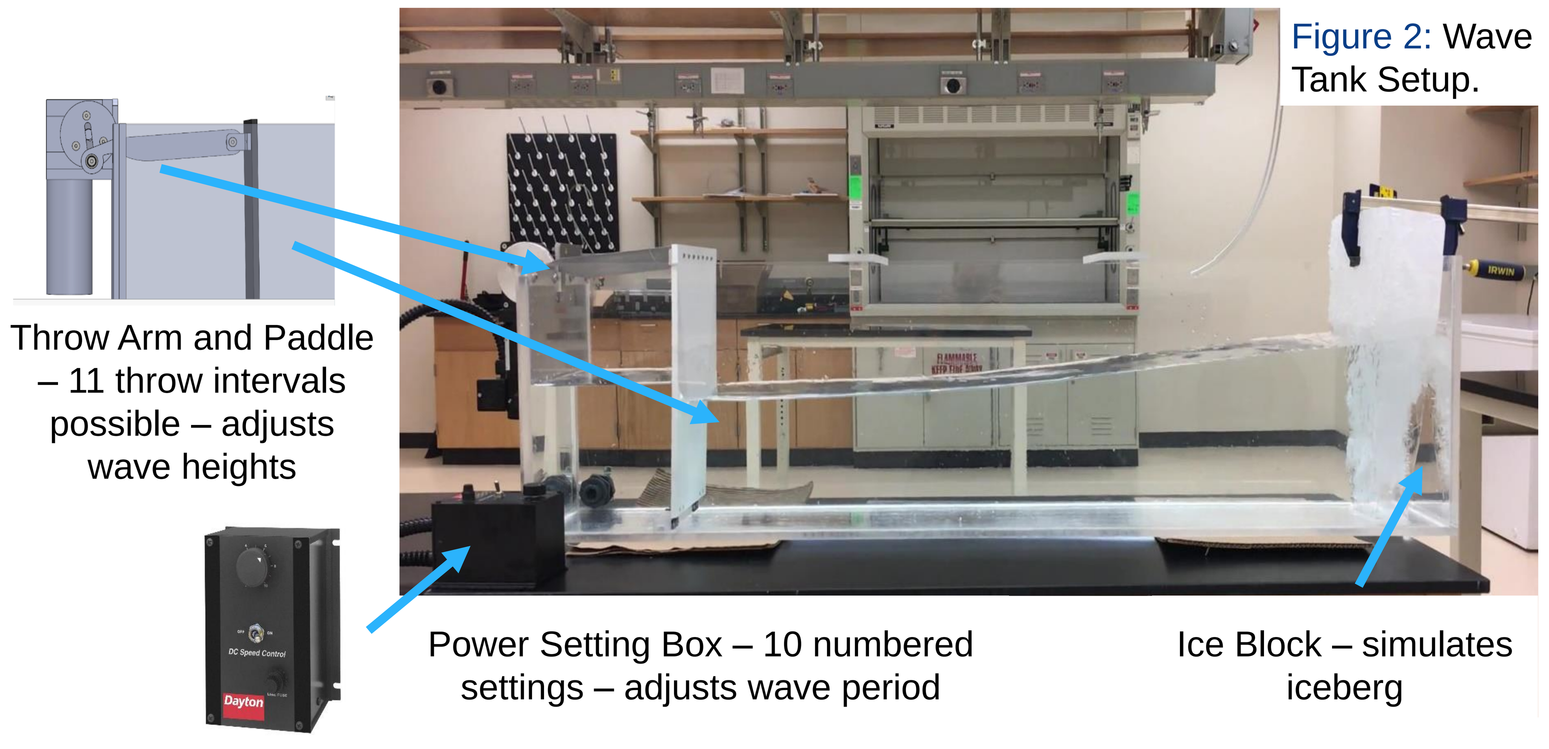


Figure 2: Wave Tank Setup.

## White Replication Experiments

To replicate White's experiments, the best 4 waves, with the cleanest sinusoidal pattern with little interference, were used (Table 1).

| Power Combination | Amplitude Avg (cm) | Velocity (m/s) | Period (s) |
|---|---|---|---|
| TI 12, PS 6.5 | 1.30 | 0.976 | 0.667 |
| TI 11, PS 6.5 | 2.30 | 0.981 | 0.667 |
| TI 9, PS 6.5 | 9.10 | 0.896 | 0.625 |
| TI 8, PS 8 | 4.25 | 0.449 | 0.278 |

Table 1: The four "best" wave characteristics. TI refers to Throw Interval (governed by the throw arm and paddle) and PS refers to the Power Setting (set by black power box).

An "iceberg" was simulated with an ice block made in a freezer in the lab, which was placed at the end of the tank. Video was taken to track changes in erosion (Figure 3).

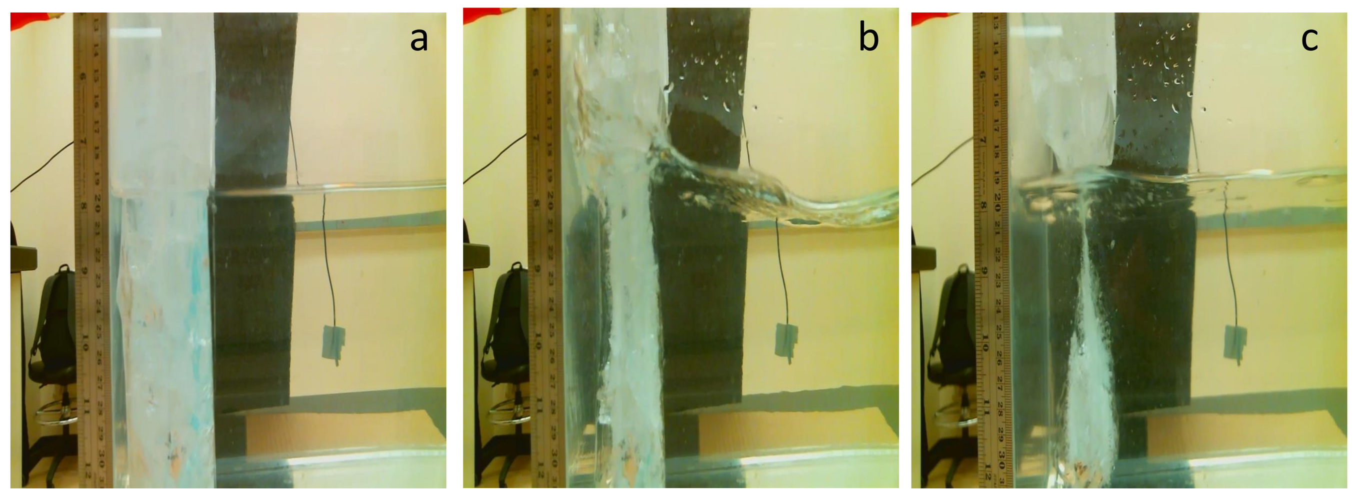
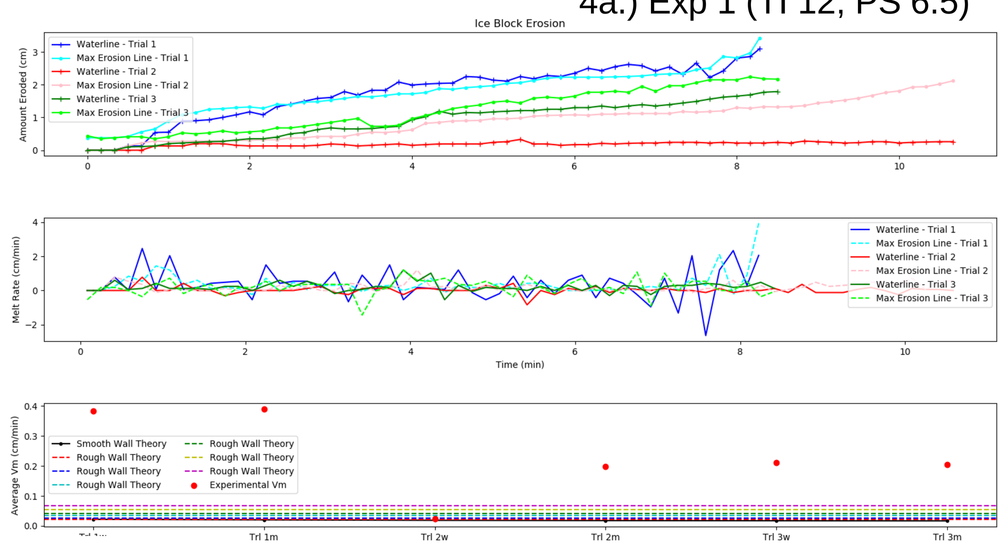


Figure 3: (a) Initial ice block profile before waves start
(b) Ice block profile halfway through total time of erosion – area of interest is on left side, where waves hit directly
(c) Final profile before bottom half of ice block cracked off

## Preliminary Results

The range of average melt rate was higher than anticipated for all experiments, except Experiment 3, which matched White's theoretical estimate most closely, and thus will be used for the remainder of the project (Figure 4).

4a.) Exp 1 (TI 12, PS 6.5)




4b.) Exp 3 (TI 9, PS 6.5)

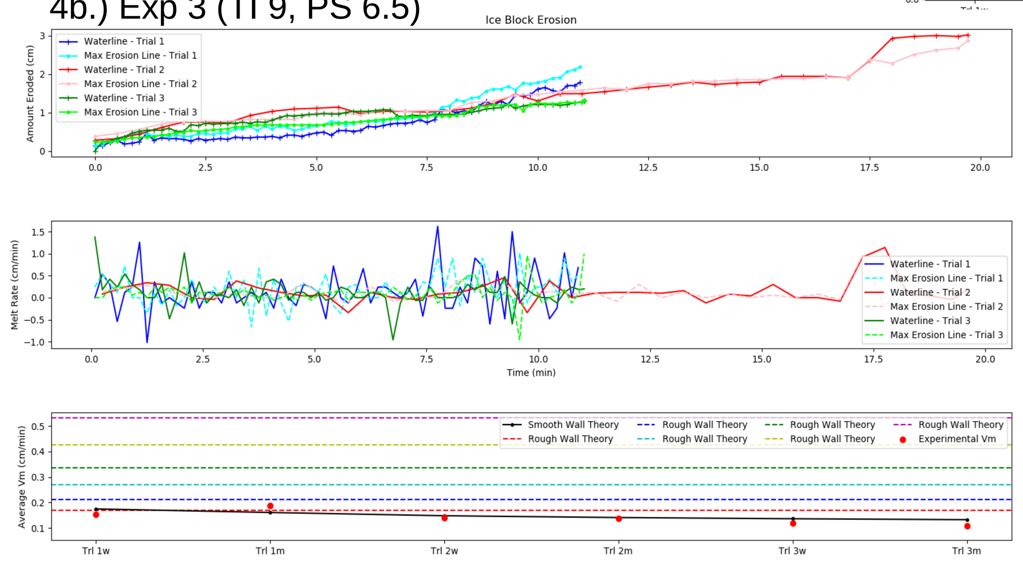



Figure 4a: Experimental data from Exp 1 (TI 12, PS 6.5). This experiment didn't follow White's theory, except during one trial (Trial 2 at the waterline – Trl 2w).
Figure 4b: Experimental data from Exp 3 (TI 9, PS 6.5). This was the experiment that fell most in line with White's theory and will become the basis for future experiments.

## Temperature-Controlled Experiments

The wave tank was moved inside of a freezer to simulate Arctic air and water conditions (Figure 5).

- Wave parameter: TI 9, PS 6.5 (A = 9.10cm, T = 0.625s)
- Initial Water Temperatures: 4°C, 8°C, 12°C, 16°C
- Control Experiment – E5 – outside freezer at 16°C

**Note:** Experiment 1 (at 4°C) was omitted from the comparative analysis due to primarily back side melting of the block, which was outside the designated methodology for this study.


Figure 5: Temperature-controlled experiment setup, in which wave tank was placed into chest freezer.

## Salination Experiments

Arctic Ocean conditions (with salinity at 30 psu) were simulated in the wave tank (Figure 6). Identical experiments were run, with a variance in initial water height:

- Exp1 - Trials 1-3: 11.2 cm
  Trial 4: 11.5 cm
- Exp2 - Trials 1-3: 17.5 cm
  Trial 4: 16.0 cm

Water height showed to be a factor that affected melt rate, which can be explained by the stratification effect of the fresh and salt water.

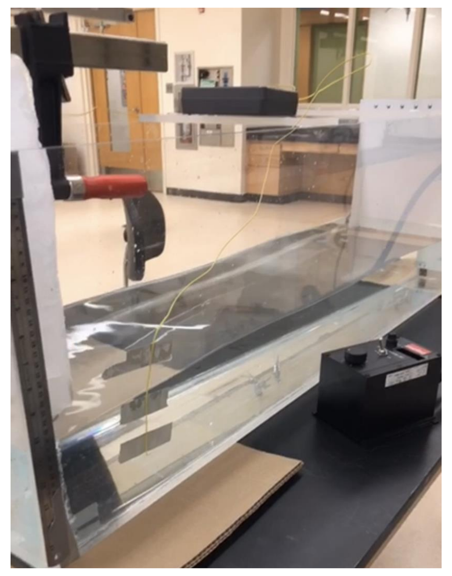


Figure 6: Salt was added to the tank to create a salinity of 30psu to mimic the Arctic Ocean. Stratification of fresh and salt water were seen as the experiments progressed.

## Results

White's theoretical melt rate was about 0.069cm/min, which was about 3 times slower than the experimental rate found (Table 2).

The White replication experiments fell within a factor of 3 of the theoretical estimates, which suggests that the theory is valid for certain waves, but not all (Figure 7).

White's theoretical erosion rate is on the lower end of the overall range – from 0.057cm/min to .158 cm/min (Figure 8).

| Exp Name | Exp # | Salt / Fresh | Average Melt Rate (cm/min) | Ave Init Temp °C | % Error (White) | % Error (Exp) |
|---|---|---|---|---|---|---|
| White Original | 0 | Fresh | 0.069 | 11.60 | | |
| White Replica | 3 | Fresh | 0.1407 | 13.03 | 67.80% | 0 |
| Temp Control | 1 | Fresh | NA | NA | NA | NA |
| | 2 | Fresh | 0.0768 | 7.70 | 10.05% | 58.75% |
| | 3 | Fresh | 0.1584 | 11.57 | 78.09% | 11.87% |
| | 4 | Fresh | 0.1518 | 15.60 | 74.44% | 7.61% |
| | 5 | Fresh | 0.1100 | 15.93 | 45.21% | 24.46% |
| Salination | 1 (Trls 1-3) | Salt | 0.0568 | 21.10 | 20.11% | 85.01% |
| | 1 (All) | Salt | 0.0573 | 21.18 | 19.15% | 84.22% |
| | 2 (Trls 1-3) | Salt | 0.0940 | 20.00 | 30.00% | 39.82% |
| | 2 (All) | Salt | 0.0896 | 20.15 | 25.34% | 44.36% |

Table 2: Overall data. Temp Control 1 was omitted due to primarily back side melting.

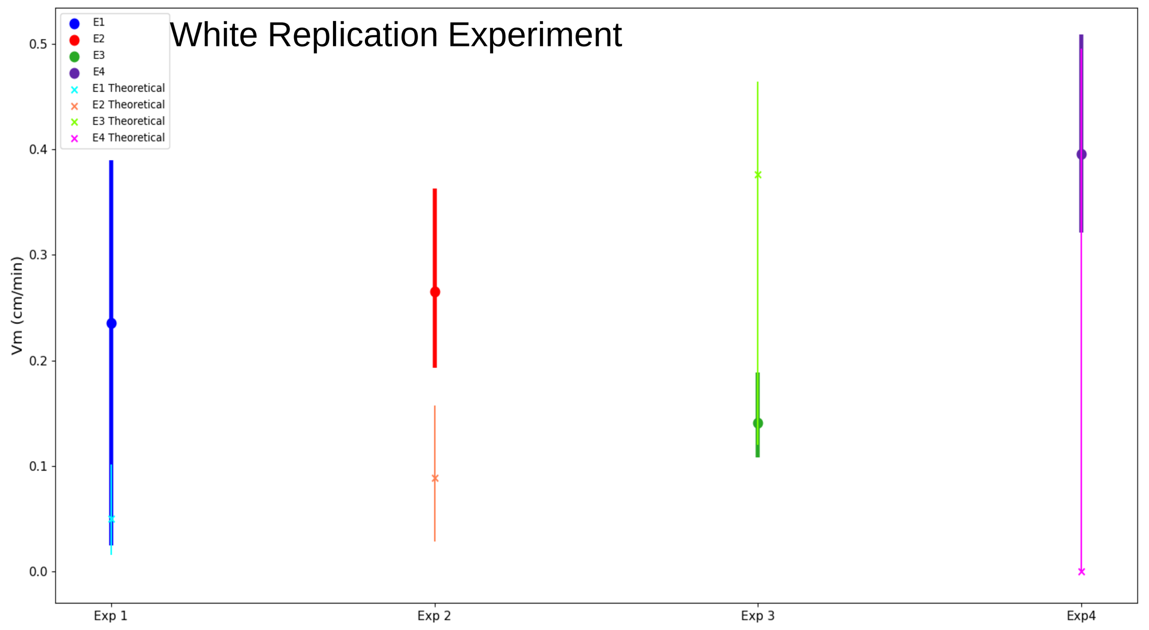


Figure 7: Experimental results from White Replication experiments. Thick lines show the range of the experimental results, with the point representing the average of all trials. Thin lines show the theoretical range.

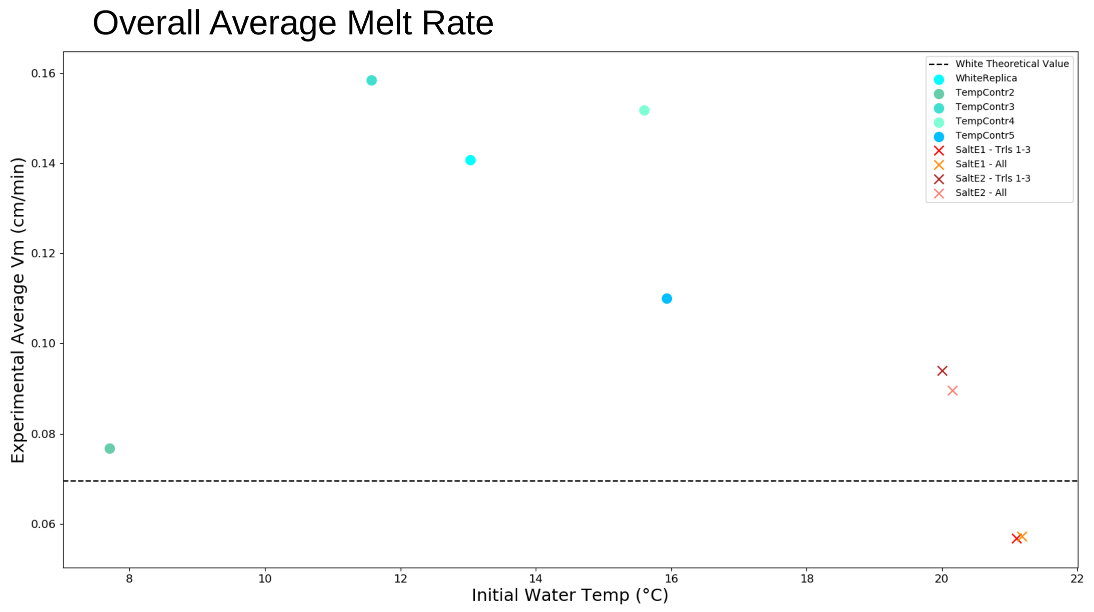


Figure 8: Overall Average Melt Rates. Temp Control 2 shows the impact of initial water temperature on average melt rate for fresh water experiments. Black dashed line represents White's theoretical estimate.

## Conclusion

- **White's theoretical estimates fall within a factor of 3 of our replication experiment**
- **Temperature, water height, and wave parameters play a significant role in melt rates**
- **Further experimentation may lead to a greater confidence in White's theory, by providing insight into the cause of the differences**
- **Difference in experimental and theoretical erosion rates may be caused by systematic differences**

## Future Work

- Manipulation of Ice Conditions
  - Intentionally testing Rough vs Smooth ice walls
- Changing Wave Conditions
  - Simulating changing tides with variation of wave period and amplitude over the course of one trial

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